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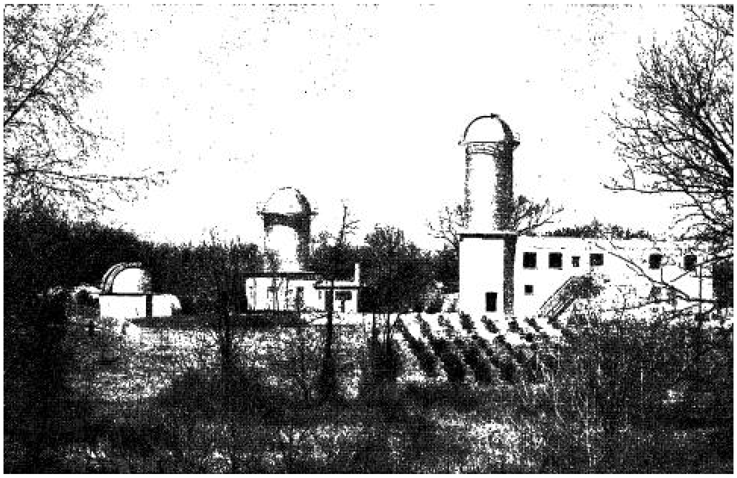

McMath-Hulbert Observatory

Compiled by Jim Goodall,

President of the

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The Spectroheliokinematograph

Robert R. McMath
Robert M. Petrie

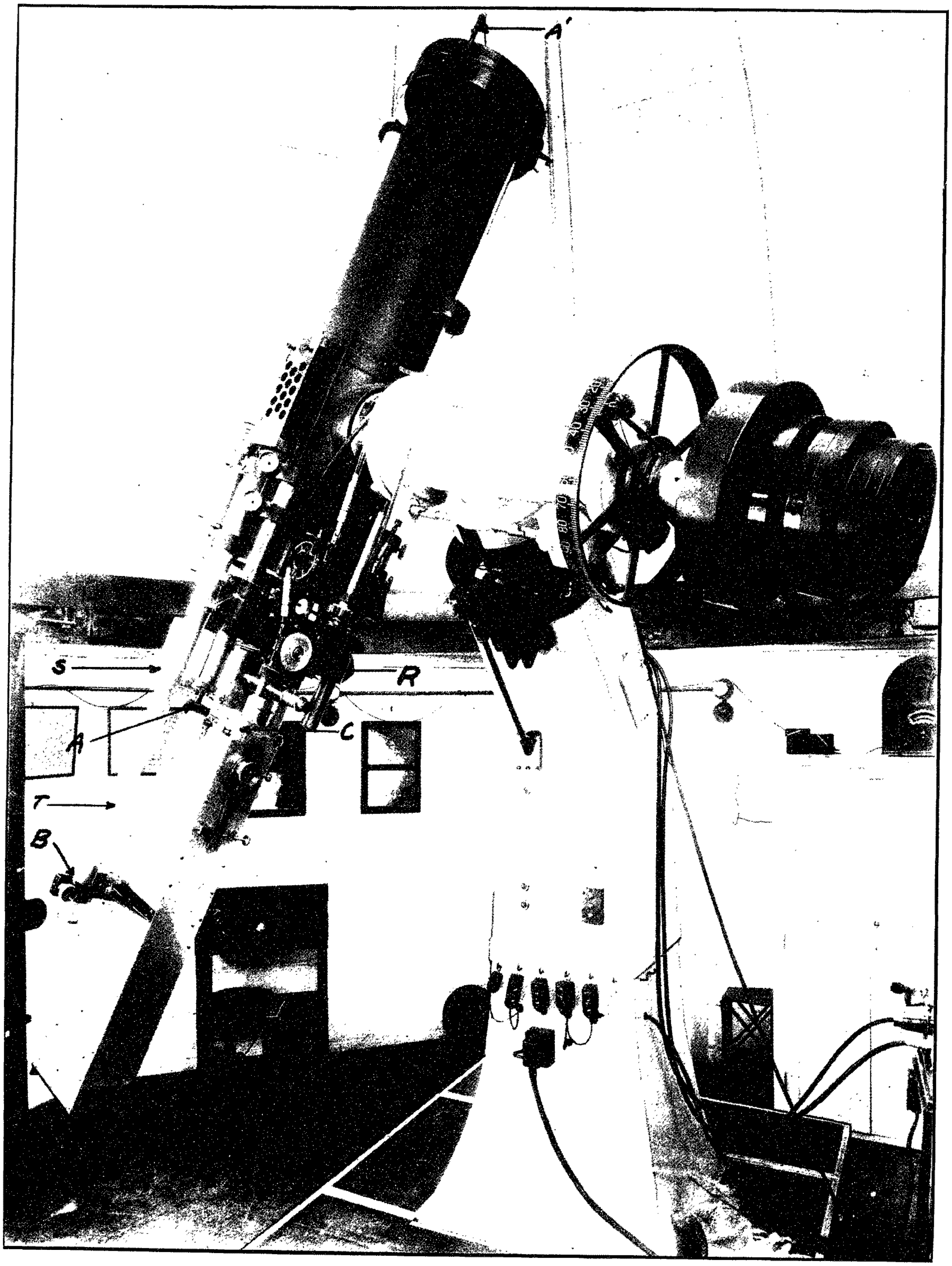

PLATE I. The Spectroheliokinematograph Mounted on the Telescope.

PUBLICATIONS OF THE OBSERVATORY

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VOL. V, NO. 8.

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THE SPECTROHELIOKINEMATOGRAPH

BY ROBERT R. MCMATH AND ROBERT M. PETRIE.

INTRODUCTION.

This paper presents a description of the apparatus and methods employed in certain solar photographic researches which are being carried out at the McMath-Hulbert Observatory of the University of Michigan, with particular reference to the application of the motion picture method in recording phenomena of motion or change in the solar surface and solar prominences. The application of this method to other celestial objects has been described in an earlier number of these publications (*5*, 53, 1931), to which reference should be made for additional details.

As with any new type of instrument employed in a hitherto untried field of work, responsibility for the design and improvement of the spectroheliokinematograph is divided among a number of individuals, to whom the authors extend grateful acknowledgements.

Following the original suggestion of Francis C. McMath in 1931 that the solar prominences should prove a fertile field for motion picture record with the McMath-Hulbert telescope, and his generous offer to assume the cost of all optical parts, suggestions as to the type of instrument were made by Burns, of Allegheny Observatory, and detailed drawings were made by Curtis. The instrument, in its original form, was constructed by Colliau and Smock in the instrument shop of the University Observatory. Literally months of work have been expended by the authors in tracking down difficulties as they arose; many changes were found necessary in the telescope mounting and in the spectroheliokinematograph itself, carried out, for the greater part, in the shops of the Motors Metal Manufacturing Company, from designs by Robert R. McMath and under his supervision. Judge Henry S. Hulbert and Robert R. McMath bore the expenses involved in the telescope alterations. Petrie spent the first semester of the year 1932–33 at Lake Angelus, and the summers of 1932 and 1933, under grants from the Faculty Research Fund of the University of Michigan and from the Bache Fund of the National Academy of Sciences, respectively. The instrument can now be pronounced successful, all the usual solar phenomena being observable with it, and the writers feel sure that with the reappearance of solar activity, motion pictures of the type desired can be secured.

The Spectroheliokinematograph.

The spectroheliokinematograph consists of a spectrohelioscope and a 35 mm. motion picture camera. The spectrohelioscope was especially designed for use on our equatorial reflector. The camera has been described in the previous paper.

The attachment of the instrument to the telescope necessitated the use of a spectrohelioscope of short focal length, and hence it was not practicable to use the form described by Hale.[1] Ordinarily the use of a longer focus instrument is preferable, since with a short focus instrument inherent optical difficulties are introduced. Our spectrohelioscope consists of a Littrow type spectroscope, equipped with Anderson prisms in order to broaden the slit images.

The optical system of the spectroheliokinematograph is shown diagrammatically in Figure 1. In this figure, P_1 and P_2 are the Anderson prisms, S_1 and S_2 the first and second slits, M_1 and M_2 are plane mirrors, R is the Ross collimating-telescope lens, and G is the plane grating. Z is a Zeiss Biotar[2] lens of 50 mm. focal length working at f 1.4, and is used to transfer the image from the plane of the second slit up to the film F. The distance of the optical center of this lens from the plane of the film is twice its focal length plus 0″.005, thus securing critical focus without sensible magnification, in white light. The Ross lens is a very important part of the instrument. Due to the short focal length, it was thought inadvisable to use concave mirrors for collimating and focusing the spectroscope, since they would have to work with beams considerably off the axis. This lens, of 72 inches focal length and 4 inches aperture, was specially designed by Ross to give good definition over a wide field, the angle between the incident and diffracted rays being nearly 10 degrees. The lens is of four piece construction, the glass being ordered specially from Germany, and gives excellent definition. It was computed to have the same focal length at Hα and [K].

At first we used a grating with rulings of 15,000 lines per inch. Desiring higher dispersion, this was replaced by a 20,000 line grating, with material improvement. The linear dispersion in the plane of the second slit is then 13 A/mm. The first slit, of course, receives the solar image from the Cassegrainian combination and the grating is set so that Hα is brought into the second slit which is narrowed to exclude other wave lengths. The prisms, being then set in rotation, broaden the slit images and give an image of the sun in the light of Hα. The mirrors M_1 M_2 may be moved for purposes of collimating and focusing the spectroscope. The grating mount is equipped with a clamp and slow motion for setting at the proper angle.

[1] Mt. Wils Contr *No. 388* (1929).
[2] J Soc Mot Pict Eng *20*, 31 (1933).

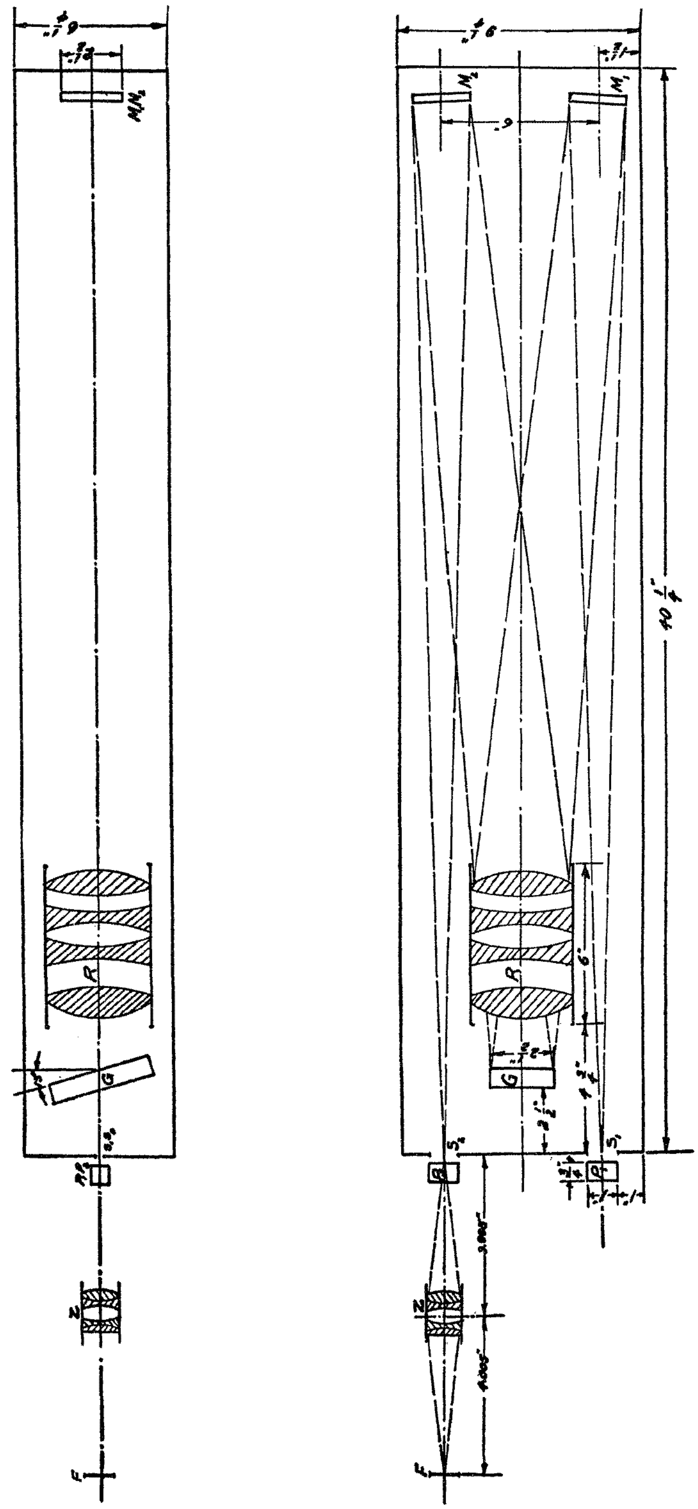


FIGURE 1. Optical system of the Spectroheliokinematograph.

This is shown in Plate 3 (*C*). The grating is an excellent one, giving very little diffused light, and the spectroscope as a whole produces exquisite definition.

When Anderson prisms were decided upon as an optical means of broadening the slits, considerable thought was given to the method of driving them. The use of a small air turbine was suggested by Robert R. McMath, and has been found very satisfactory in use. The turbine has one jet and two exhaust ports and runs without vibration as there are no unbalanced parts. The prisms turn freely and without image flicker at an air pressure of ten pounds. An air compressor, driven by a one horse-power motor, pumps into a large storage tank which acts as an initial water separator. This compressor is installed outside the observatory, the air being piped through a filter which removes any remaining water and entrained oil. The pressure is regulated by a reducing valve, and a soft rubber hose takes the air to the turbine on the head of the spectroscope. This installation has given complete satisfaction.

During the summer and fall of 1932, Anderson prisms measuring 0''.500 on a side were used but these were replaced in 1933 by larger ones measuring 0''.750. The original prisms allowed us to photograph an area on the film measuring 0.65 cms. by 2.25 cms. which gave a field approximately 4'.4 by 15'.5. With our larger prisms the area photographed on the film measures 1.15 cms. by 2.25 cms. and the field has consequently been increased to 7'.8 by 15'.5.

The spectroheliokinematograph is ordinarily used with the Cassegrainian combination with equivalent focal length of 200 inches. At times, however, it is desirable to use a smaller solar image and so include more of the sun in the picture. For this purpose a three inch lens of 74 inches focal length was secured. It was designed by Ross and figured for Hα and [K]. Its mounting is designed to be interchangeable with the usual secondary mirror. This change-over is quickly made; a cap for the telescope tube excludes the sunlight from the 10½ inch mirror and the rest of the instrument is used as before.

Our general practice is to photograph prominences in the Hα line of hydrogen. The lens in the spectroscope, however, brings Hα and [K] of ionized calcium to the same focus on the second slit, so that prominences may be photographed in either wave length. The longer exposure with the [K] line has induced us to use the red line of hydrogen as our usual procedure. Photographs of the sun in any wave length may be quickly secured by setting the grating, focusing the spectrum on the second slit by moving the plane mirrors M_1 and M_2, Figure 1, and proceeding as usual.

The instrument is shown in working position in Plate 1. The new tubular fork carrying the spectroheliokinematograph is marked *T;* the guiding screen is in position at *S;* and the camera is shown at *R* in position on the supplementary brass tubes. The hand focusing device for the secondary mirror is shown at *A*, *A'*.

Plate 3 shows the upper end of the instrument in greater detail. The clamp and slow motion for the grating is shown at *C;* the eyepiece used for scanning and composition at *E;* and the position of the Zeiss reproducing lens at *Z*. *F* shows the secondary mirror hand focusing device. Plate 6 shows the head of the instrument with the casting removed. The Anderson prisms are shown at *P;* and the air turbine and feed pipe at *I*. The slit jaw motion and indicator is marked *D;* and the first slit is seen at *S*. The arm *A* allows for rotation of the prism axis about its center. The mechanism for rotating the slits is shown at *F*.

Alterations in the Telescope.

As soon as the plans for the spectrohelioscope were completed it became evident that considerable alterations would have to be made in the telescope. Provision had to be made for changing the Cassegrainian focus from that required for lunar and planetary work; a means had to be devised for attaching and supporting the new instrument; and its seventy pounds of additional weight required the strengthening of the tube if undue flexure was to be avoided. These modifications were designed by Robert R. McMath and constructed in the shops of the Motors Metal Manufacturing Company in Detroit.

In order to provide for the shifting of the secondary tube and the use of the solar lens, a new secondary supporting web was made. It is of welded steel construction and has proven to be very rigid. The secondary mirror cell tube and solar lens tube are designed so as to be quickly interchangeable. Plates 8 and 9 show the upper end of the telescope tube under the two conditions. In Plate 8, the secondary mirror tube is shown at *C*, and the focusing motion at *F*. The counterbalance weights W_1, W_2 are used only in solar work. *G* is the guiding telescope objective used in direct photography of the moon and planets. The solar lens is shown in position at *L*, Plate 9. The focusing pinion is at *F*, and the cover *C* shields the 10½ inch mirror from the direct sunlight.

A new mirror cell tube was made for the primary mirror. It is cast in aluminum, the previous aluminum section rings being replaced by steel forgings. New counterweights were made in both co-ordinates to provide for the difference of balance between solar and night operation. In designing these parts attention was given to the problem of easy change-over from solar to planetary or lunar work. Hence, the counterweights were made removable and the telescope can be completely changed over by one man in about twenty minutes. (See Plate 8, W_1 and W_2).

From an examination of Plates 2 and 3, it will be seen that the camera changes its position between solar and night observation. The camera faces the sky for direct photography and is placed in the optical axis of the reflector, while for solar work it is reversed and placed off to one side, on two supplementary brass tubes.

An examination of Plate 1 will show that the spectrohelioscope box is supported on the two tubes *T*, which carry the camera in direct photography. These tubes are of special construction, being of graduated thickness in order to minimize flexure. A casting, *C*, which is firmly attached to the slit head, receives the draw-tube from the telescope, providing additional rigidity. When the clamps on the supporting cross member, *B*, are released the instrument can be quickly racked into the approximate Cassegrainian focus. The camera and the Zeiss lens, Plate 3, *M* and *Z*, fit into a tube in the casting directly above the second prism and slit.

The problems and methods of guiding for solar work are in general similar to those outlined previously for lunar and planetary work. The motion of the sun in declination is generally much less than that of the moon, however. For example: the hourly rate in declination for the sun, including refraction, is $-28''.2$ on July 23, 1933, for hour angle 2^h *E*, whereas the average lunar rate is approximately $600''$ per hour. A one to ten reduction was therefore devised for use with the standard declination drive already described. This is shown in position on the drive carriage in Plate 4. The one to ten reduction is attained through the chain drive. The change gears are shown in position on top of the carriage. The lever *C* allows one to engage and reverse the drive. With this attachment it becomes possible to use the lunar declination drive and change gears for solar work. The rates for various gears are given below in Table 1. The first column gives the rate in seconds of arc per hour; then follow in order the gears to be used in combination.

Before a subject is photographed we compute the rates to be used in right ascension and declination. In observing the moon, for example, the geocentric rates are taken from the American Ephemeris, and combined with the rates due to refraction and geocentric parallax, found in Maxwell's Tables.[3] The final rates are evaluated for half hour intervals, and an assistant observer takes care of the large variations in the declination rate with the change gears, whenever such a change is indicated. In our previous work the first approximation to the final rates was secured by the observer at the eyepiece, who varied the speed of the frequency changer from the telescope control box, shown in Plate 2 *B*. This procedure has given good results but is essentially a method of trial and error, and sometimes consumes valuable time at the beginning of an observation.

In order to give a quicker approximation, tachometers have been installed on the frequency changer control motors. These tachometers and the frequency changers are shown in Plate 7. The control motors are indicated by *M*, the tachometers by *T*, and the frequency changers by *F*. The upper frequency changer is for right ascension, *G* showing the change gears in position. The right ascension

[3] *These Publications 4*, 53 (1932).

TABLE 1. GEAR CHANGES FOR SOLAR DECLINATION DRIVE.

Seconds of Arc per hour	A	B	C	D
″				
6.00	24	96	22	98
7.14	30	90	20	100
8.04	30	90	22	98
8.94	30	90	24	96
10.74	40	80	20	100
12.00	43	77	20	100
13.50	40	80	24	96
14.28	48	72	20	100
15.00	43	77	24	96
16.08	48	72	22	98
16.44	52	68	20	100
17.88	40	80	30	90
20.52	52	68	24	96
21.48	60	60	20	100
23.82	48	72	30	90
25.92	59	61	24	96
26.82	60	60	24	96
28.08	68	52	20	100
30.00	43	77	40	80
31.50	68	52	22	98
33.36	58	62	30	90
34.98	68	52	24	96
35.70	48	72	40	80
38.40	77	43	20	100
40.98	52	68	40	80
43.14	77	43	22	98
45.78	52	68	43	77
46.80	68	52	30	90
48.00	77	43	24	96
49.80	78	42	24	96
53.64	80	40	24	96
55.98	58	62	43	77
57.96	59	61	43	77
59.88	60	60	43	77
61.92	61	59	43	77
64.02	77	43	30	90
66.30	78	42	30	90
70.08	68	52	40	80
71.58	60	60	48	72
73.86	61	59	48	72
76.50	62	58	48	72
80.46	90	30	24	96
82.08	60	60	52	68
84.78	61	59	52	68
85.80	96	24	20	100
89.76	72	48	43	77
96.00	77	43	40	80
99.42	78	42	40	80
103.32	77	43	42	78
111.00	78	42	43	77
116.10	80	40	42	78
120.00	80	40	43	77

tachometer is equipped with a reverse gear since this frequency changer is used both to speed up and slow down the telescope.

Under certain conditions, i. e., lunar photography, the telescope will be required to gain 70 seconds per hour upon the sidereal rate, due to our lunar gear, while it is sometimes necessary to use a rate 135 seconds per hour slower than the sidereal. For the sun the average rate will be about 11 seconds per hour slow. To provide for these variations the change gears are used and the proper tachometer reading obtained.

Since these instruments were described, the right ascension frequency changer has been rebuilt. The unit has been made heavier and ball bearings installed throughout, giving ease of operation and long life.

The declination frequency changer is always driven so as to slow down the synchronous motor operating the declination drive. The right ascension frequency changer tachometer, after applying a factor depending upon the change gears, reads in seconds of time per hour fast or slow. The declination tachometer after applying the factor one-third, reads in per cent slow. As an example, we find the following rates for the sun for July 23, 1933:

E. S. T. 10.41 A. M.

Hour Angle $-2^h\,00^m$

Declination $+20°$

Rate in right ascension $= +9^s.94 + 0^s.62 = +10^s.6$ per hour.

Rate in declination $= -30''.7 + 2''.5 = -28''.2$ per hour.

The tachometer would, therefore, read 21.2 (factor ½) in right ascension. In declination, change gears giving a rate of $-30''.0$ per hour would be used, and the tachometer reading in that co-ordinate would therefore be 18.0, which is 6.0% slow on $-30''.0$, or a net rate being -28.2 seconds per hour. Tables giving the rates due to refraction for solar work have been constructed and are described later in this paper.

It is well to emphasize here the importance of this equipment for following celestial bodies, particularly in motion picture photography. In our solar, lunar and planetary work all the pictures are time exposures, often of the order of one minute in duration. During an average exposure the moon's motion upon the film would amount to at least 0.5 mm. if the telescope were given only the conventional sidereal rate in hour angle. The displacement of the solar image would similarly be about 0.1 mm. This displacement, of course, would make good definition impossible, especially in motion pictures, where the projection magnification is so great. Guiding, no matter how accurately done, gives a series of definite corrections of an appreciable size and results in an inferior picture. It has, therefore, been found that the telescope must be made a *following* rather than a *guided* instrument. That this goal has been attained will be realized from the statement that the telescope will remain upon a small guide crater on the moon, using the frequency changers and declination drive, with deviations usually smaller than the image fluctuations due to indifferent seeing.

The solar following is equally successful. Photographs in the Hα line of hydrogen can be secured on any day of average seeing, in which fine filaments in prominences are visible, with exposures of 45 seconds or more. It is urged that these refinements have *not been devised in order to give easier guiding; they are necessary in order to secure that sharp definition essential in motion picture work.* These remarks apply with equal force to the problem of perfect focus, a matter which will be discussed later.

Adjustments of the Spectroheliokinematograph.

The various adjustments of this instrument have been found to be quite critical in order that good spectroheliograms, free from distortion and ghosts, may be secured. Due to its short focal length and consequent use of "off axis" rays, the various parts had to be very carefully aligned. Hale's description,[4] of the adjustments of his standard spectrohelioscope could not, unfortunately, be followed entirely, due to differences in construction and the small space in which the instrument is confined.

After some experiment, we found that the instrument could be well adjusted on a fine face plate with indicators reading to one one-thousandth of an inch. The design and construction made provision for adjustment of the prisms, slits, mirrors, and grating. The axis of rotation of the grating cell was first carefully levelled on the face plate and used as an axis of reference. The face of the grating was then brought into this axis, and set by clamped levelling screws in the back of the cell. The surface of the grating will then rotate so that the spectrum moves along a line at a right angle to the axis of the second slit, when the grating is rotated. The slits were then brought into the plane perpendicular and parallel to the center line of the grating (at normal incidence). Due to the type of instrument, it is necessary to incline the slits slightly to this line as a final operation. This adjustment, which makes the second slit accurately parallel to the spectral lines, is done when the instrument is on the telescope and producing a solar spectrum. Each slit is rotated independently about its center by finger screws, Plate 6 *F*, while the observer uses high magnification to insure parallelism.

When using Anderson prisms, it is essential that they be accurately square and true with each other, and rotate about the same axis. Our second set of prisms were set upon this axis by Mr. Charles Gunther, in the shops of the Motors Metal Manufacturing Company in Detroit, so that no perceptible deviation was found

[4] Mt. Wils Contr *No 388* (1929).

when they were tested with a specular beam of light. The axis of the prisms was then placed in the plane of the grating on the face plate axis, and after these adjustments, each separate part was dowelled to the top plate of the instrument.

One of the most persistent troubles was that of scattered light. The chief source seemed to be in the many reflecting surfaces of the Ross lens but other sources contributed. The grating, of course, supplies a certain amount of scattered light. The first Anderson prism, exposed to the direct solar image, reflects and picks up a great deal of diffuse light from the walls of the casting enclosing the slit head. The various metallic parts and the Zeiss lens add their share, and finally the use of the Cassegrainian reflector adds sky light to the image.

We found that a fine quality of black felt was the best material to use for minimizing reflections. Light reflected from the various surfaces of the Ross lens gives sharply focused slit images at various points in the optical path. These were eliminated by attaching small pieces of felt to targets placed to catch the in-focus images. Diaphragms of felt-covered aluminum were constructed, felt lined tubes were run between diaphragms and occulting bars devised. A felt bellows was placed between the grating and Ross lens, and a small felt lined, light tight chamber built over the second prism and slit. All screw heads were painted black and covered with felt wherever possible. The various occulting bars and strips used have undoubtedly reduced the brightness of our image appreciably, but were found necessary in order to give a properly dark field. At present we have succeeded in minimizing the scattered light so that a black sky is obtained without the use of any filter. Exposures of 45 seconds on supersensitive panchromatic film show no appreciable sky fog nor spurious images.

A day's photography of the sun consists of about 600 separate spectroheliograms. These are laid down on a strip of motion picture film which later shown in a projector, becomes a motion picture on the screen. It is obvious that the registration of these separate photographs should be as perfect as possible. Hence, some adequate method of guiding must be used to take care of inequalities in refraction, errors in the gears, and instrumental deflection. The use of a separate guide telescope has not proved practicable, largely due to differential flexure.

After some experiment an optical flat was used in the casting, above the first slit, and as close to it as possible. This flat, set at 45° to the optical axis, reflects about 10% of the incident light. A large negative lens is placed in the reflected beam and projects a portion of the solar image, about four inches in diameter, upon a screen rigidly secured to the casting. After the desired composition on the film has been secured, tangent lines are drawn to the projected solar limbs, should no sun spot be available, and it is the observer's task to maintain the lines tangent to the projected image. Plate 5 shows the casting removed from the head. The optical flat is indicated at F, and the negative projection lens at N. The screen S

receives the enlarged guiding image. *D* indicates the position of an occulting disc used to produce an artificial eclipse.

While this device eliminates the effects of flexure of the box and telescope as a whole, another deflection is troublesome. This is the minute shifting of the second mirror with respect to the second slit. Our usual practice is to use a slit width of 0''.005 on the second slit, so that a change in inclination of the second plane mirror of a few seconds of arc will shift Hα off the second slit. We usually find it sufficient to check the centering of Hα at thirty minute intervals.

Our method of focusing requires some description. The light which finally forms the image upon the film passes through two Anderson prisms and two compound lenses. Inasmuch as the final picture is enlarged 150 diameters on the standard screen, microscopic definition is essential and ordinary methods of focusing are inadequate. The method used has given excellent results in lunar photography and has been modified for solar work.

We employ a small totally reflecting prism, one face of which contains a number of small pits, produced by fine grinding and polishing. This prism face is placed accurately in the plane of the film. A microscope is mounted upon the camera and carefully focused on the prism face by means of the small pits, using light of wave-length 6550 A. After this is done, the camera is moved by a slow motion screw until the jaws of the second slit are sharply focused in the plane of the small prism face. As described in the previous article, we use a focal tester consisting of a totally reflecting prism and an eyepiece. This is inserted in the cone of light in the bellows tube for composition and focusing, and withdrawn while photographing.

The microscope mentioned above is also used in the focal tester. The next step, therefore, is to remove the microscope from its position on the camera and place it in the focal tester, where it is focused on the slit jaws and secured. The camera is now sharply focused on the second slit, and the final step is to focus the solar image. For this purpose a microscope magnifying twenty diameters, and giving a flat field with little depth of focus is used. It is placed in the focal tester and focused upon the second slit. The solar image is then focused by moving the Cassegrainian secondary. A focusing device, Plate 3, *F*, allows the observer to do this while looking through the eyepiece. We have thus been able to focus the image after the light has traversed the entire optical system, and the results fully justify this critical method.

The exposures with this instrument are rather long as solar photographs go. This is not entirely surprising when one recollects that the light suffers thirty-one reflections in all, and passes through several inches of glass. With our dispersion the hydrogen line has a total width of approximately 0''.005 and we have found that slits 0''.006 in width enable us to see and photograph prominences and flocculi, although the contrast is rather low. For bright prominences, exposures of about 36 seconds are sufficient, but for the fainter variety, unfortunately common at the present time, exposures of 50 seconds or one minute are necessary. The solar disc with slit widths of 0''.005 photographs in Hα in 28 seconds near the limb, and 20 seconds at the center. Exposure tables have been constructed in order to give a uniform density over a series of photographs taken at widely different hour angles. The results are summarized in Table 2. This table takes into account the atmospheric extinction, the absorption coefficient at Hα being secured from Fowle's measures.[5] For exposures on various parts of the disc, the usual law of darkening was assumed to be sufficiently accurate. Table 2 gives the extinction at Hα in

TABLE 2. EXPOSURE FACTORS FOR ATMOSPHERIC ABSORPTION.
(Region of Hα).

Decl. \ H. A.	$0^h.0$	$0^h.5$	$1^h.0$	$1^h.5$	$2^h.0$	$2^h.5$	$3^h.0$	$3^h.5$	$4^h.0$	$4^h.5$	$5^h.0$	$5^h.5$	$6^h.0$
+24	0.96	0.96	0.96	0.96	0.97	0.98	1.00	1.01	1.04	1.08	1.13	1.23	1.40
+22	0.96	0.96	0.96	0.96	0.97	0.98	1.00	1.02	1.05	1.09	1.14	1.26	1 45
+20	0.96	0.96	0.96	0.97	0.97	0.99	1.00	1.03	1.06	1.10	1.18	1.29	1.51
+18	0.96	0.96	0.97	0.97	0.98	0.99	1.01	1.03	1.07	1.11	1.19		
+16	0.97	0.97	0.97	0.97	0.98	1.00	1.01	1.04	1.07	1.13	1.26		
+14	0.97	0.97	0.97	0.98	0.98	1.00	1.02	1.05	1.09	1.14	1.29		
+12	0.97	0.97	0.98	0.98	0.99	1.01	1.03	1.06	1.10	1.18	1.32		
+10	0.97	0.98	0.98	0.99	1.00	1.01	1.04	1.07	1.11	1.21	1.40		
+ 8	0.98	0.98	0.98	1.00	1.00	1.02	1.04	1.07	1.12	1.23	1.45		
+ 6	0.98	0.99	1.00	1.00	1.01	1.02	1.06	1.08	1.14	1.26	1.57		
+ 4	0.99	1.00	1.00	1.00	1.01	1.03	1.07	1.10	1.16	1.29			
+ 2	1.00	1.00	1.00	1.01	1.02	1.04	1.08	1.12	1.19	1.32			
0	1.00	1.00	1.01	1.02	1.03	1.06	1.09	1.13	1.21	1.35			
− 2	1.01	1.01	1.01	1.03	1.04	1.07	1.10	1.16	1.26				
− 4	1.01	1.02	1.02	1.04	1.06	1.08	1.12	1.19	1.32				
− 6	1.02	1.03	1.03	1.05	1.07	1.10	1.14	1.23	1.35				
− 8	1.03	1.04	1.04	1.06	1.08	1.11	1.16	1.26	1.45				
−10	1.04	1.05	1.06	1.08	1.10	1.14	1.19	1.29	1.51				
−12	1.06	1.07	1.07	1.09	1.11	1.16	1.21						
−14	1.07	1.08	1.09	1.11	1.13	1.18	1.26						
−16	1.09	1.10	1.11	1.14	1.18	1.23	1.32						
−18	1.11	1.12	1.13	1.18	1.21	1.26	1.35						
−20	1.13	1.14	1.16	1.19	1.23	1.29	1.45						

terms of declination and hour angle. From an examination of the prominence, the exposure on the meridian can be estimated after a little experience. The extinction table then enables us to secure a uniform density throughout the day. The tabulated values are factors which are applied to the exposures estimated for zero degrees of declination and meridian transit

In order to secure the rates for the sun, due to atmospheric refraction, tables were constructed giving the values in both co-ordinates with hour angle and declination as arguments. These were computed for every two degrees of declination and at half hour intervals in hour angle. The tables are based upon formulae given by King,[6] and are evaluated for the adjustment of the polar axis upon the

[5] ApJ *38*, 392 (1913).
[6] Harv Ann *41*, 154 (1902).

refracted pole, rather than the true pole. For work on the sun with summer temperatures, a coefficient of mean refraction $k = 0'.88$ was adopted. The formulae, slightly transformed for ease of computation become

$$\frac{d\alpha}{dt} = + \frac{1^s.084 \cos^2 M}{\sin N} \frac{\sin (\delta + N)}{\cos \delta \sin^2(\delta + M)} - 1^s.00 \tan \delta \cos t$$

$$\frac{d\delta}{dt} = + 15''.0 \sin t \left[\frac{\cos^2 M}{\sin^2 (\delta + M)} - 1 \right]$$

where $\tan M = \cot \varphi \cos t$, and $\tan N = \dfrac{\cot \varphi}{\cos t}$.

Tables 3 and 4 give these rates in right ascension and declination, respectively. The values in right ascension are always added algebraically; those in declination are subtracted algebraically for eastern hour angles, and added algebraically when west of the meridian.

In observing the sun these rates are added to the geocentric variations, tabulated in the Ephemeris, and allow one to pick the proper change gears and set the tachometers at the correct values. It is easily possible to open the dome, compute rates and exposures, focus the camera and commence photography in twenty minutes.

TABLE 3. SOLAR RATES IN RIGHT ASCENSION FROM REFRACTION.

Decl. \ H. A.	$0^h.0$	$0^h.5$	$1^h.0$	$1^h.5$	$2^h.0$	$2^h.5$	$3^h.0$	$3^h.5$	$4^h.0$	$4^h.5$	$5^h.0$	$5^h.5$	$6^h.0$
°	s	s	s	s	s	s	s	s	s	s	s	s	s
+24	+0.3	+0.4	+0.4	+0.4	+0.5	+0.7	+0.8	+1.1	+1.4	+1.9	+2.6	+3.9	+6.5
+22	0.4	0.4	0.4	0.5	0.6	0.7	0.9	1.1	1.5	2.0	2.8	4.0	7.8
+20	0.4	0.4	0.5	0.5	0.6	0.7	0.9	1.2	1.6	2.1	3.1	5.0	9.3
+18	0.5	0.5	0.5	0.6	0.7	0.8	1.0	1.3	1.7	2.3	3.4	6.0	11.3
+16	0.5	0.5	0.6	0.6	0.7	0.8	1.0	1.3	1.8	2.5	3.8	6.6	14.3
+14	0.6	0.6	0.6	0.7	0.8	0.9	1.1	1.4	1.9	2.7	4.2	7.7	18.4
+12	0.6	0.6	0.6	0.7	0.8	1.0	1.2	1.5	2.1	3.0	4.8	9.2	25.5
+10	0.6	0.7	0.7	0.8	0.9	1.0	1.3	1.6	2.2	3.3	5.5	11.3	35.0
+ 8	0.7	0.7	0.7	0.8	0.9	1.1	1.4	1.8	2.5	3.7	6.4	14.0	57.0
+ 6	0.7	0.8	0.8	0.9	1.0	1.2	1.5	1.9	2.7	4.2	7.5	18.3	+98.6
+ 4	0.8	0.8	0.8	0.9	1.1	1.3	1.6	2.1	3.0	4.7	8.9	24.4	
+ 2	0.9	0.9	0.9	1.0	1.2	1.4	1.7	2.3	3.3	5.4	11.0	34.5	
0	0.9	0.9	1.0	1.1	1.2	1.5	1.8	2.5	3.7	6.3	13.8	+53.2	
− 2	1.0	1.0	1.0	1.1	1.3	1.6	2.0	2.8	4.2	7.4	17.8		
− 4	1.1	1.1	1.1	1.2	1.4	1.7	2.2	3.0	4.8	8.9	24.2		
− 6	1.1	1.1	1.2	1.4	1.5	1.9	2.4	3.4	5.5	11.0	35.2		
− 8	1.2	1.2	1.3	1.4	1.7	2.0	2.7	3.8	6.4	14.0	+54.3		
−10	1.3	1.3	1.4	1.6	1.8	2.2	3.0	4.4	7.8	18.5			
−12	1.4	1.4	1.5	1.7	2.0	2.5	3.3	5.1	9.5	26.0			
−14	1.5	1.6	1.6	1.8	2.2	2.7	3.8	6.0	11.9	37.9			
−16	1.6	1.7	1.8	2.0	2.4	3.0	4.3	7.2	15.6	+64.0			
−18	1.8	1.8	1.9	2.2	2.6	3.4	5.0	8.9	21.7				
−20	1.9	2.0	2.1	2.4	2.9	4.0	6.0	11.3	31.8				
−22	2.1	2.2	2.3	2.7	3.2	4.6	7.4	15.2	+52.6				
−24	+2.3	+2.4	+2.6	+3.0	+3.7	+5.5	+9.3	+21.3					

TABLE 4. SOLAR RATES IN DECLINATION FROM REFRACTION.

Decl. \ H. A.	0h.0	0h.5	1h.0	1h.5	2h.0	2h.5	3h.0	3h.5	4h.0	4h.5	5h.0	5h.5	6h.0
°													
+24	0″.0	−0″.9	−1″.8	− 2″.5	− 2″.8	− 2″.7	− 1″.8	− 0″.2	+ 3″.0	+ 8″.5	+18″.4	+36″.7	+52″.6
+22	0 .0	−0 .9	−1 .7	− 2 .4	− 2 .6	− 2 .5	− 1 .5	+ 0 .3	+ 3 .9	+10 .2	+21 .4	+43 .2	
+20	0 .0	−0 .9	−1 .7	− 2 .3	− 2 .5	− 2 .2	− 1 .2	+ 0 .8	+ 4 .7	+12 .0	+25 .1	+50 .8	
+18	0 .0	−0 .8	−1 .6	− 2 .1	− 2 .3	− 1 .9	− 0 .7	+ 1 .6	+ 6 .1	+14 .0	+29 .2	+60 .2	
+16	0 .0	−0 .8	−1 .5	− 2 .0	− 2 .1	− 1 .6	− 0 .4	+ 2 .4	+ 7 .5	+16 .6	+34 .2		
+14	0 .0	−0 .8	−1 .4	− 1 .9	− 1 .9	− 1 .2	+ 0 .3	+ 3 .4	+ 9 .2	+19 .5	+40 .1		
+12	0 .0	−0 .7	−1 .4	− 1 .7	− 1 .5	− 0 .8	+ 0 .9	+ 4 .4	+10 .8	+22 .8	+47 .8		
+10	0 .0	−0 .7	−1 .2	− 1 .5	− 1 .3	− 0 .4	+ 1 .6	+ 5 .6	+13 .0	+27 .1	+57 .0		
+ 8	0 .0	−0 .6	−1 .1	− 1 .3	− 0 .9	+ 0 .1	+ 2 .4	+ 6 .9	+15 .6	+31 .9	+61 .9		
+ 6	0 .0	−0 .5	−1 .0	− 1 .0	− 0 .5	+ 0 .8	+ 3 .3	+ 8 .6	+18 .4	+37 .9			
+ 4	0 .0	−0 .5	−0 .8	− 0 .7	− 0 .1	+ 1 .5	+ 4 .4	+10 .5	+21 .9	+45 .2			
+ 2	0 .0	−0 .4	−0 .6	− 0 .4	+ 0 .4	+ 2 .3	+ 5 .6	+12 .7	+26 .1	+54 .4			
0	0 .0	−0 .3	−0 .3	+ 0 .1	+ 1 .0	+ 3 .2	+ 7 .0	+15 .5	+31 .1	+66 .4			
− 2	0 .0	−0 .2	−0 .1	+ 0 .4	+ 1 .7	+ 4 .3	+ 8 .6	+18 .5	+37 .5				
− 4	0 .0	−0 .0	+0 .2	+ 0 .9	+ 2 .5	+ 5 .5	+10 .7	+22 .4	+45 .4				
− 6	0 .0	+0 .1	+0 .5	+ 1 .4	+ 3 .4	+ 7 .1	+13 .2	+27 .1	+55 .4				
− 8	0 .0	+0 .3	+0 .9	+ 2 .1	+ 4 .5	+ 8 .8	+16 .0	+32 .8	+69 .3				
−10	0 .0	+0 .5	+1 .4	+ 2 .9	+ 5 .8	+11 .0	+19 .0	+40 .4					
−12	0 .0	+0 .8	+1 .9	+ 3 .8	+ 7 .4	+13 .7	+24 .0	+50 .3					
−14	0 .0	+1 .1	+2 .6	+ 5 .0	+ 9 .3	+16 .8	+29 .6	+62 .7					
−16	0 .0	+1 .4	+3 .3	+ 6 .3	+11 .6	+20 .9	+36 .0						
−18	0 .0	+1 .9	+4 .4	+ 8 .1	+14 .3	+26 .1	+46 .2						
−20	0 .0	+2 .4	+5 .6	+10 .2	+18 .2	+32 .8	+60 .0						
−22	0 .0	+3 .1	+7 .0	+12 .8	+23 .0	+41 .8							
−24	0 .0	+3 .9	+8 .9	+16 .1	+29 .4	+54 .9							

Description of Spectroheliokinematograms.

The summer of 1933 has shown remarkably little solar activity. Many small, faint prominences have been seen, but, as yet, no bright, active eruption nor active spot has been observed. Consequently, a motion picture showing actual prominence movement has not been secured. Numerous faint prominences and bright and dark flocculi have been photographed—a few being reproduced in Plate 10, indicating the possibilities of the instrument. Since we ordinarily use a second slit considerably wider than is usual in spectroheliographs, the contrast on the disk is not high. A short description of the various pictures follows.

Plate 10 (*a*)—A prominence near the east limb, photographed June 16, 1933. The first and second slits were respectively 0″.006 and 0″.007 in width. The exposure was 36.4 seconds at hour angle 2^h West. The prominence can be seen partly in projection on the solar surface and extending partly beyond the limb. The total length of this object is 67,000 kms., the extension beyond the limb measuring 28,000 kms. At its greatest width it measures 20,000 kms. Some little distance from this prominence another extremely small one is visible. This latter is little more than a "hump" in the chromosphere, having a height of not more than 6,000 kms. It is clearly visible in the original negative.

Plate 10 (*b*)—A faint prominence observed near the west limb on June 29, 1933. The exposure is again 36.4 seconds, the sun on the meridian. This prominence consists of a cloud connected with the chromosphere by two "legs" forming an arch. The total height is 50,000 kms. and the maximum width across the base is 55,000 kms. The left branch of the arch is 10,000 kms. wide and the right 24,000 kms. The dark space is roughly circular, measuring 12,000 by 14,000 kms.

Plate 10 (*c*)—Bright flocculus on July 13, 1933, near eastern limb of the sun. The first and second slits were respectively 0".005 and 0".004 in width. The exposure was 24.2 seconds at hour angle 2 hours East. The flocculus is made up of two long bright filaments joined near their centers by a "bridge." These filaments are 60,000 kms. and 40,000 kms. long, the separation being 10,000 kms. The eastern edge of this cloud shows a strip of dark hydrogen gas.

Plate 10 (*d*)—This photograph shows a group of prominences on the northeast solar limb on July 15, 1933. The slit widths were 0".006 and 0".0055 respectively, and the exposure was 45.4 seconds at hour angle 2^h west. Five separate outbursts are visible in the original negative but all are small and faint. The largest shows considerable structure, being joined to the chromosphere by two extensions. At its highest point it measures 28,000 kms. and its greatest width, where it joins the chromosphere is 32,000 kms.

These photographs were taken on supersensitive panchromatic motion picture film, without the use of any filter. The subjects shown are small in most cases, and the emulsion used has rather low contrast. The instrument can be seen, therefore, to give excellent definition and resolution, faint detail being usually discernible in the prominences. The results secured to date leave the authors confident that solar prominence phenomena of motion and change can now be recorded with the spectroheliokinematograph as soon as a large prominence of the eruptive type may appear.

THE MCMATH-HULBERT OBSERVATORY
OF THE
UNIVERSITY OF MICHIGAN.
LAKE ANGELUS, MICHIGAN.
August, 1933.

PROMINENCES OF THE ACTIVE AND SUN-SPOT TYPES COMPARED*

ROBERT R. McMATH[1] AND EDISON PETTIT

ABSTRACT

The tower telescope.—The 50-foot tower telescope at Lake Angelus, Pontiac, Michigan, records solar phenomena by means of the motion-picture camera. All instrumental motions are electrically driven; the coelostat flat and camera are operated by the McMath-Hulbert controlled frequency drive and declination control.

The scout camera and spectral-line control.—Both H and K are used, K for the motion-picture camera; the H line, thrown to one side, enters a plate camera so that a prominence under observation can be photographed and developed for inspection at any time. To set the H and K lines on the slits of the spectroheliograph and to check their positions an auxiliary fixed slit fed by a mercury arc is used.

Observing and measuring.—For the bulk of the work a focal length of 40 feet was used for the solar image. Exposure is determined by a photronic photometer and is usually of the order of 20–25 seconds on prominences with $2\frac{1}{2}$ seconds between exposures. The films are measured by projecting the frames upon a milk-glass screen; the position of a knot or streamer along its trajectory is determined with a flexible celluloid scale or, in some cases where the motion is small, by a cathetometer.

Activity within a sun-spot group.—The ejection of bright flocculi has been observed. The velocity is about 100 km/sec, and the phenomenon occurs at intervals of about an hour.

Prominences of the sun-spot type.—Detailed measurements of the motions of knots and loop ends along their trajectories show that class III prominences obey the first law of motion of eruptive prominences and, when the projection factor is small, the second law as well. Many streamers have their origin high above the chromosphere, and the appearance cannot be accounted for by Doppler effect. The simplest explanation requires the presence of a chromospheric atmosphere in the corona.

Surges.—These rise from and sink back into the chromosphere in the vicinity of sun-spots, forming class III*d*. They are mostly small, but one was observed which reached a height of 80,000 km with a velocity of 240 km/sec. The first law of motion seems to prevail in this type also.

Quasi-eruptions.—A case where an active prominence rose to a great height, nearly reaching the eruptive stage, before being drawn back to the center of attraction is cited. This forms a connecting link between active and eruptive prominences and substantiates the idea that eruptions are extreme cases of the active or class III*c* stages.

Active prominences.—Detailed measurements on these prominences show that the streamers and knots move along their trajectories, obeying both laws of motion of eruptive prominences.

Previous observations on prominences have been obtained principally with spectroheliographs of the ordinary kind such as those of the Yerkes and Mount Wilson observatories. In following the rapid motions of prominences and their changes of form it has long been

* *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington,* No. 568.

[1] Director of the McMath-Hulbert Observatory of the University of Michigan.

seen that an automatic instrument which would take the pictures on film at regular intervals would be very desirable. This has been realized in the new tower telescope of the McMath-Hulbert Observatory of the University of Michigan, as a logical development of the pioneering work with the spectroheliokinematograph at the same observatory.

This equipment has already been described[2] elsewhere, but for the sake of completeness a short description is given here. The tower is situated at Lake Angelus, Pontiac, Michigan, near the 10½-inch telescope, which is equipped with the spectroheliokinematograph and underground control room of the McMath-Hulbert electric drive.[3] Plate VIII is a perspective drawing of the tower telescope by Dr. Russell W. Porter illustrating its salient features. The 50-foot tower, of steel throughout, stands over a spectrograph well 30 feet deep. The 22-inch coelostat and 18-inch flat mountings are modeled after those of the Astrophysical Laboratory of the California Institute of Technology.[4] The flat mounting of the Porter type enables the observer to move the solar image in right ascension and declination at any season of the year. The coelostat is driven by the controlled frequency A.C. current from the underground control room (lower right in Pl. VIII), and all slow and fast motions of both coelostat and flat are controlled by push buttons.

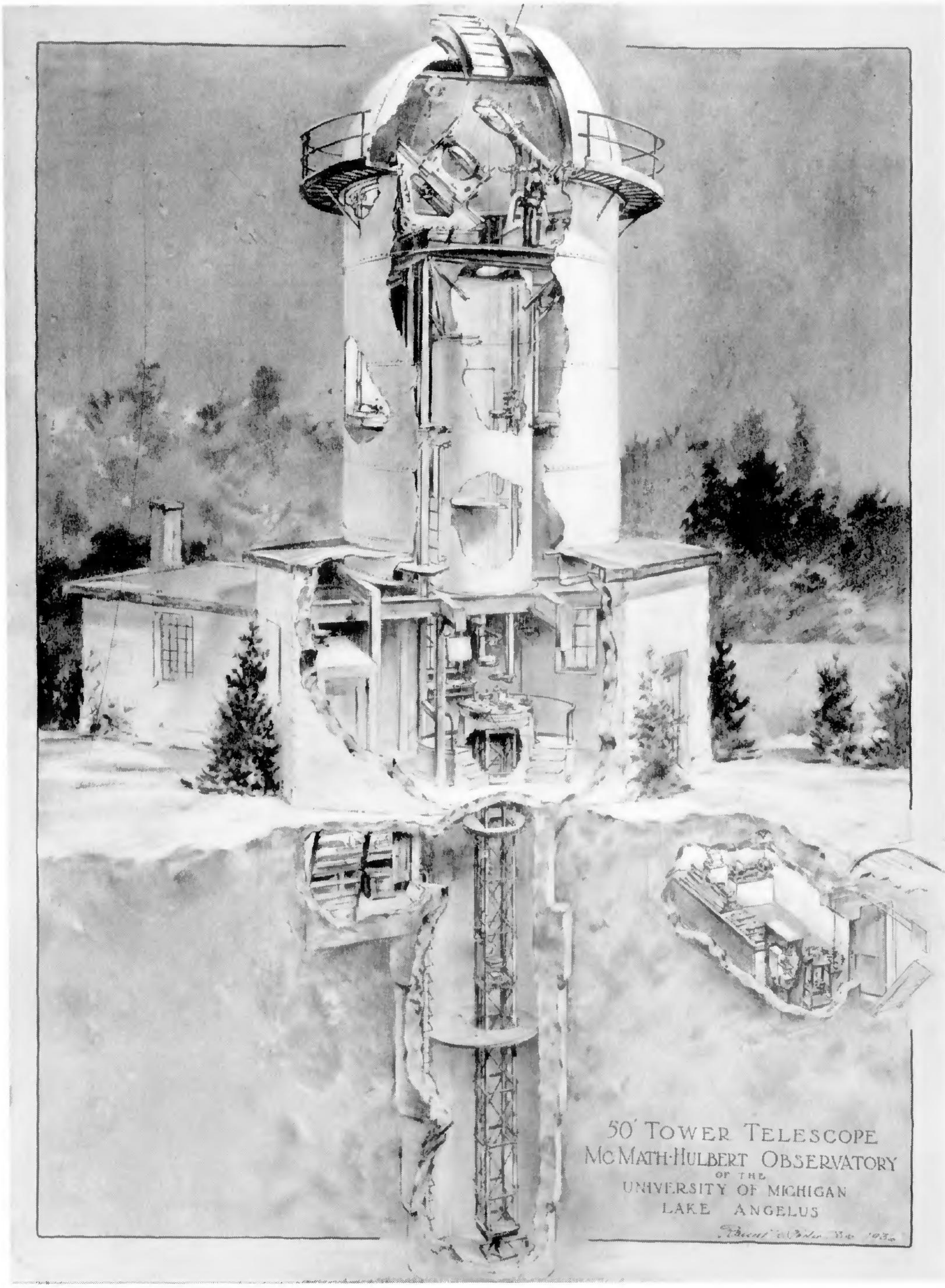
The image-forming system of the tower consists of two off-axis concave mirrors of 16 inches diameter, 40 feet focal length, and 12 inches diameter, 20 feet focal length, respectively. From one of these mirrors light returns up the inner tower to a flat which can be moved vertically, on rails, either electrically or by hand from the spectrograph head. After leaving the flat the light comes to a focus at the spectrograph head upon a centrally placed slit. A 6-inch lens mounted on the mirror carriage can easily be substituted for the mirror. For guiding purposes a 4-inch lens and enlarging mirror form a 16-inch solar image which is maintained within a circle, drawn on a screen, by the slow-motion and rate buttons of the coelostat and flat.

[2] *Pub. Obs. U. Mich.*, **7**, No. 1, 1937.

[3] *Ibid.*, **5**, No. 10, 1934, and **5**, No. 8, 1933.

[4] G. E. Hale, *Ap. J.*, **82**, 111, 1935.

PLATE VIII


50' TOWER TELESCOPE
McMATH-HULBERT OBSERVATORY
OF THE
UNIVERSITY OF MICHIGAN
LAKE ANGELUS

THE SPECTROGRAPH

The spectrograph is of the Littrow type. The combined 6-inch plane grating and 6-inch collimator lens-mounting can be moved electrically to any level desired in the 30-foot pit. A 15-foot and a 30-foot focus collimator lens are provided, the former for spectroheliographic work. The spectrograph may be rotated through a complete circle for orientation purposes, and its head carries an index for reading position angle (Pl. VIII).

For the motion-picture spectroheliographic work here discussed the arrangement of the spectrograph head is as follows: The first and second slits, 1 inch long, are attached by links to the opposite ends of an equal-arm, first-class lever. This slit linkage is given a continuously oscillating motion by a motor-driven cam. The motion of the slits is uniform during the 1-inch stroke of a half-second duration. Thus, if the K line is passed through the second slit, it will continue to pass through for any position of the slit in the stroke, thus fulfilling the conditions of the spectroheliograph.

Above the second slit is the motion-picture camera box, containing a Bell and Howell 35-mm precision film gate driven by a selsyn motor operated by a selsyn generator on the timing drive in the control room. The shutter, operated by the camera, is located beneath the second slit. A remote-control board near the spectrograph head (not shown in Pl. VIII) is provided with an electric tachometer which enables the observer to set the timer to any desired exposure for each frame of the motion-picture film. The interval between the end of one exposure and the beginning of the next may be varied from $2\frac{1}{2}$ seconds, normally used, to more than 1 minute.

THE SCOUT CAMERA

In all studies of prominence motions it is important to follow the motion and the changes of form as they take place. To accomplish this, the H line of Ca^+ is thrown to one side by a right-angle prism, just beneath one jaw of the K slit, and passed through a third or H slit whose jaws are in a plane perpendicular to those of the K slit; thence horizontally to a second right-angle prism; and then vertically through a transfer lens to a plate camera box which we have called the "scout camera." The prisms, H and K slits, and camera transfer lens are all mounted together on a slide and partake of the oscillatory motion of the slit drive.

The scout camera is a metal box 28 inches long containing a plate-holder for plates 2 × 12 inches. Exposures are made by a hand-operated shutter and developed at any time to enable the observer to follow the motion of the prominence without interfering in any way with the exposures being made on the motion-picture film through the K slit.

Ordinarily exposures are made with the scout camera at intervals of 5–10 minutes, and plates are developed at the end of each hour or half-hour. If interesting developments appear, the number of exposures is increased and the plate cut off for development at 15- or 20-minute intervals.

THE SPECTRAL-LINE POSITION CONTROL

In any spectroheliograph where exposures are carried over a number of hours, it is very desirable to be able to check the setting of the chromospheric line upon the camera slit (second slit) without disturbing the exposure which is in progress. In this case the solar spectrum itself cannot be used, as in the Rumford spectroheliograph at Yerkes, since it is in continuous oscillation. A fixed slit and mercury arc are therefore used. By setting this slit in the solar spectrum band about 9.5 inches toward the red from the mean position of the K slit, the yellow line λ 5790 appears in line with the fixed slit and in the same direction and distance (4 in.) as the first slit from the K slit. A microscope, which can be clamped in position with a single field thread upon the line, serves to check any movement of the spectrum with reference to the slits. If at any time the line shifts from the microscope field thread, it can be returned by the grating hand slow-motion.

In a similar equipment for $H\alpha$ neon is used with the same guide microscope, but with the neon arc and slit on the opposite side of the K slit and 11 inches away, beneath the spectrograph head.

METHODS OF OBSERVING

The methods of observing are, in great measure, adapted from those in use at the 10½-inch telescope already described.[5] It was

[5] *Pub. Obs. U. Mich.*, **5**, No. 8, 1933.

originally supposed that the bulk of the work would be done at the 20-foot focal length, but after some preliminary trials it was found that the general atmospheric definition and tower performance were sufficiently good to permit constant use of the 40-foot focus. A brass plate with a curved edge masks the solar disk but exposes the prominences in the frame of the camera so that, when the film is run through a motion-picture projector, the chromosphere appears along the lower border.

In beginning the work for the day a chart indicating position angles of the prominences is drawn at the $10\frac{1}{2}$-inch spectroheliokinematograph used as a spectrohelioscope. The prominences are then photographed on the 40-foot scale with the scout camera at the tower, the spectrograph head being set to the corresponding position angles. The exposure time for the prominence selected for the day's run is determined by a photronic cell and blue filter, set in the beam from the second flat.

Because the 12- and 16-inch mirrors were not completed in time to be used in the 1936 observing season, substitutes were obtained in a 40-foot focus, 10-inch on-axis mirror used off-axis and an 18-foot focus, 6-inch objective on loan from Mount Wilson. The 6-inch grating, with 600 lines to the millimeter and a bright first order, was also lent by Mount Wilson. This grating will be replaced shortly by one ruled by Babcock especially for our work. With this temporary optical system and a good sky, prominences were usually photographed on Eastman Par Speed film in 20–25 seconds; on Eastman I-O film in 10 seconds. The average summer sky somewhat increased these exposure times, however; but the 12- and 16-inch off-axis mirrors now available will considerably reduce them.

A magnetic counter operated from the motion-picture camera drive records the number of frames taken. This counter is set to zero; and a piece of glass with a camera frame and the date and film serial number inked upon it is placed above the aperture in the mask over the first slit during the zero frame exposure, in order to identify the film or scene. We regard a film pertaining to a particular prominence on a particular day as a scene. At this same time the electric chronograph is thrown into the magnetic counter circuit, and the time corresponding to one of the succeeding frames is determined from a chronometer checked from wireless time signals and marked on the chronograph sheet. Guiding then proceeds on the 16-inch solar image, which is kept within a closely fitting circle by means of the slow-motion and rate buttons.

The drive of the instrument in right ascension and in declination may be modified by rate buttons to allow for the changing coordinates of the sun. After the first half-hour the rates are so well established that only occasional correction is needed. Correction tables based on mean refraction in hour angle and declination have been made to apply to the fundamental rates, but in practice these are unnecessary save as an occasional check. We regard 40 or 45 feet of film as a good day's run, but as many as eighteen hundred frames have been taken.

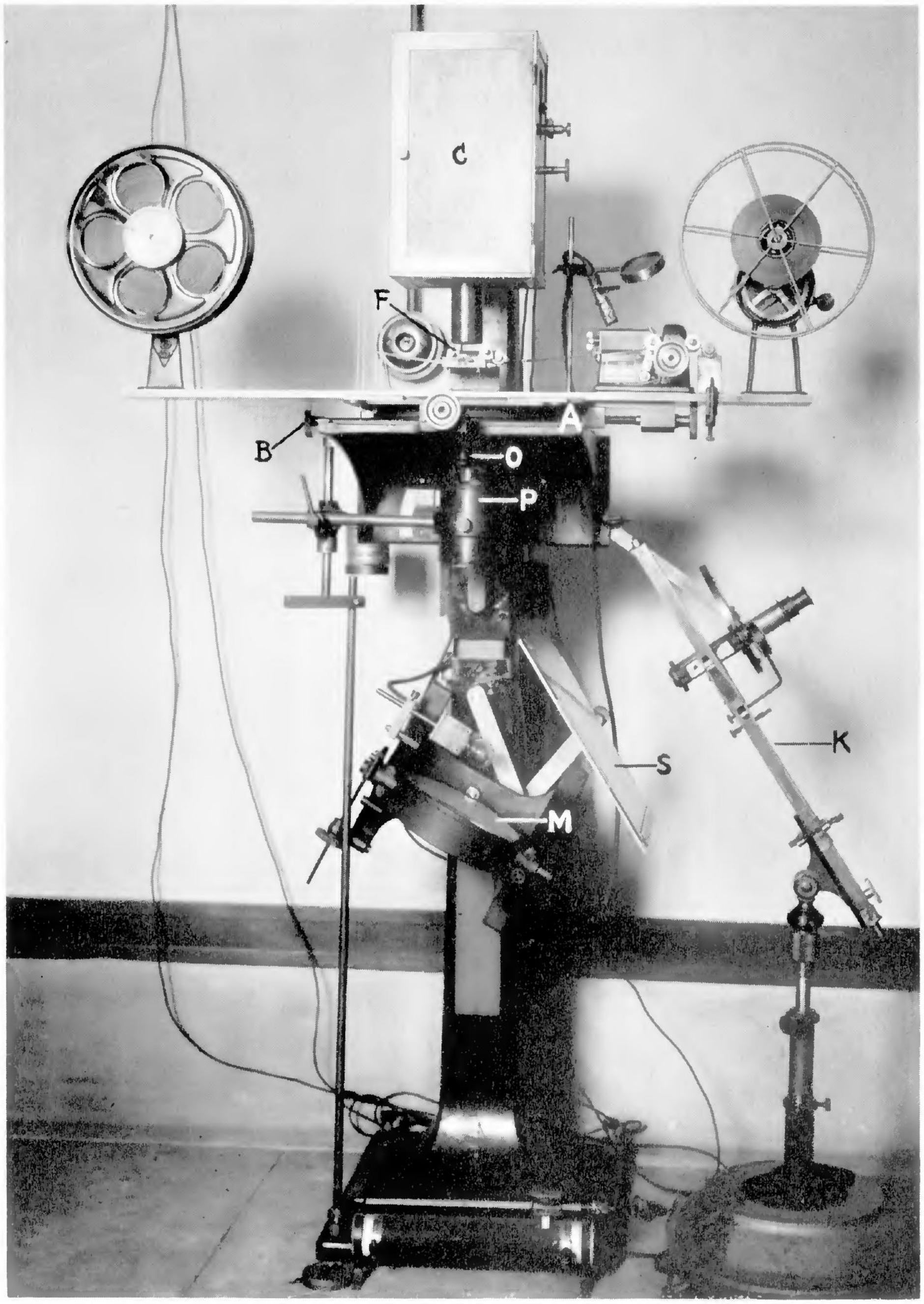
In operating the coelostat between the first of April and the first of September no shift is needed to avoid the shadow of the 18-inch flat, and one shift suffices the rest of the year. All film is developed commercially, a master positive and a duplicate pink negative being made of scenes suitable for projection and measurement, respectively.

MEASUREMENT OF THE FILM

Obviously the simplest procedure is to measure the projected images of the film frames. In most prominences the motions take place along curved lines; hence the measurements must be made with a curved celluloid scale, which is most easily done on the reverse side of a translucent screen which avoids shadows. There must also be slight adjustments to correct for guiding errors, and for orientation of the image in certain cases where radial motions are measured by microscope. When measurements are made on $H\alpha$ images from the $10\frac{1}{2}$-inch telescope, which cannot be oriented on the film, means must be provided for orientation through an angle of 180°. These conditions have been satisfied by the measuring machine illustrated in Plate IX.

Two reels and a frame counter are mounted on a double slide A, which also has a rotation ring operated by a worm screw B. Light from a 50-watt automobile lamp in a projector C passes through the film F, which is projected upon a milk-glass screen S with a motion-

PLATE IX



MACHINE FOR MEASURING IMAGES ON FILMS

picture projector objective at *O*. Just in front of this objective is placed a reversing prism *P* by means of which the image on the milk-glass screen may be rotated through any angle. A plane mirror *M* in front of the prism places the screen in a convenient position for the operator. The magnification employed gives a scale on the screen of 2000 km/mm.

For the measurement of ordinary prominence motions along their curved paths a transparent celluloid millimeter scale was used. The outline of the chromosphere and small prominences was first marked on the screen (reverse side) and, after the scene was run through the projector, the path of the prominence (knot or streamer end) was faintly marked. All measurements were then made along this path with reference to its intersection with the chromosphere as origin. Thus the center of attraction becomes the origin in these measurements, instead of the point where the knot or streamer leaves the prominence, as in similar measurements on class III*c* prominences already given.[6] The letter *C* at the end of each plot (Figs. 1–6) indicates the zero of ordinates in each case, i.e., the position of the chromosphere in the measurements. On all succeeding frames after the first the chromosphere was made to match the outline on the screen by use of the double slide and orientation screw, when necessary, before measurements were made. Small eruptions, which we have called "surges," were measured on the screen with a microscope attached to a cathetometer *K* reading to 0.1 mm.

ACTIVITY WITHIN A SUN-SPOT GROUP

The appearance of bright flocculi within a sun-spot group is well known, but detailed records of the phenomenon have been difficult to secure with the ordinary spectroheliograph. The group Mt. W. 4955 in latitude 21° N., longitude 36° E., photographed by us in K2 with the 18-foot objective on July 11, 1936, furnished material for detailed study. The leading principal spot had a field of R 1800 and the following spot V 2000 gausses.[7] An irregular floccular area surrounded the group in which two lanes (Pl. X, *A* and *B*) lead from the preceding spot. Along one edge of lane *A* three eruptions of

[6] *Mt. W. Contr.*, No. 552; *Ap. J.*, **84**, 319, 1936. See Fig. 2.

[7] *Pub. A.S.P.*, **48**, 279, 1936.

bright chromospheric matter were seen to travel at intervals of about an hour. Table 1 gives the G.C.T. of the beginning of the eruption, the interval between eruptions ΔT, the duration, period of growth, width and length, and measured velocity. Plate X shows six exposures at intervals of about a minute, illustrating the development of one of these eruptions. They seem to arise from a point just within the umbra and move along the edge of the dark lane *A* with velocities of about 110 km/sec. Their width, 2000 km, and length, 8000 km, make them difficult objects to measure. The period of growth, about 1.5 minutes, was determined from exposures at intervals of 18.6 seconds. So far as can be determined, the period

TABLE 1

ERUPTION OF BRIGHT FLOCCULI WITHIN A SUN-SPOT GROUP

G.C.T.	ΔT	Duration	Period of Growth (Sec)	Width (Km)	Length (Km)	Velocity (Km/Sec)
A 15^h35^m48	....	4^m34	73	1500	8000	110
A 16 31.81	56^m33	4.35	74	2000	8000	108
A 17 40.64	68.83	6.48	94	2400	10,000	106
B 18 28.69	48.05	11.74	259	2400	18,000	70

following maximum extension is occupied, first, by a general increase in brightness, then by a fading-away. We can only guess what the brightness is in terms of the chromosphere. It has already been shown[8] that the floccular area about a sun-spot group is about 50 per cent brighter than the chromosphere in K2. We estimate the bright flocculus *A* to be about 50 per cent brighter than the floccular area surrounding the spot group, which would make it about twice as bright as the chromosphere.

Just what is the three-dimensional character of these bright floccular eruptions is difficult to decide with our present material. Nothing in the exposures on sun-spots at the limb corresponds to them, and it is probable that they do not rise sensibly above the chromosphere. This idea is verified by the appearance of the last eruption in Table 1, which began along the lane *B* between the spots and moved to the preceding spot 18,000 km away. When observed

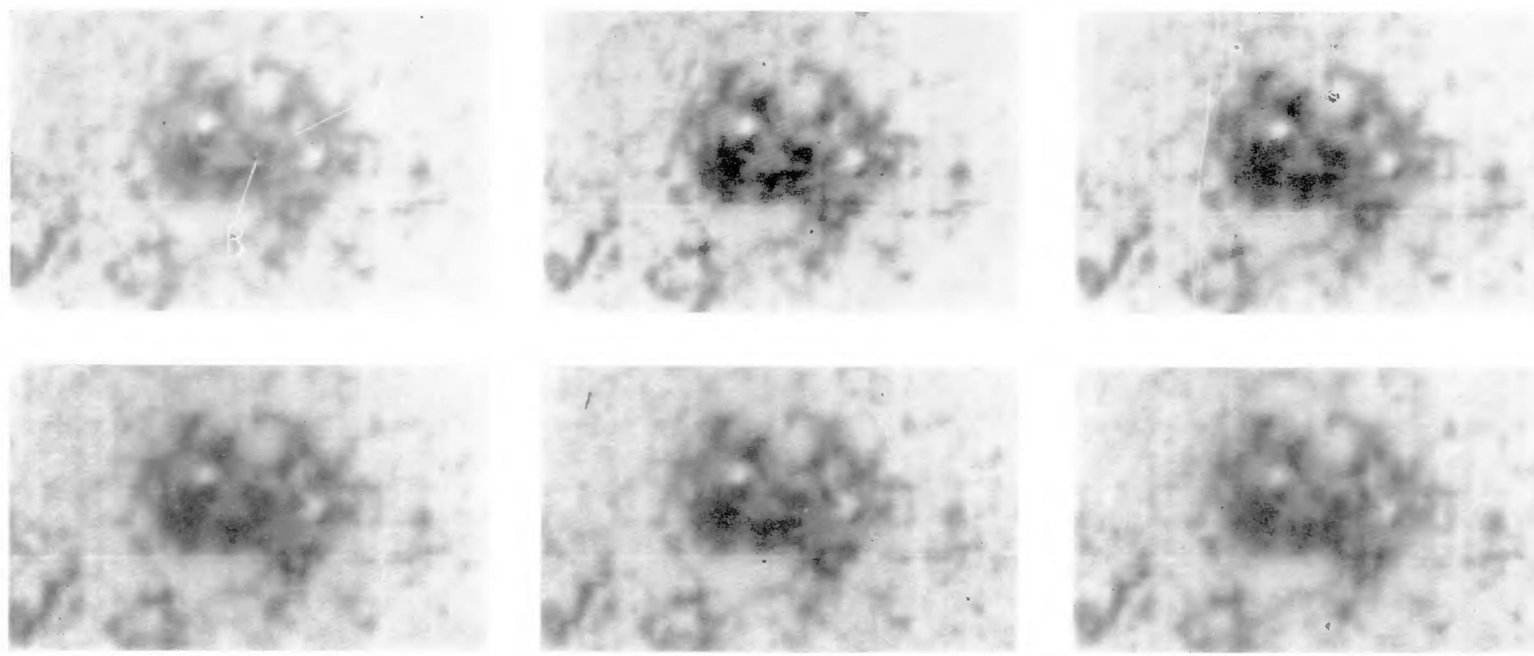
[8] *Ibid.*, p. 332, 1936.

PLATE X

Nos.

1–3

4–6



Bright Floccular Eruptions in a Spot Group, July 11, 1936

Exposures at 90-second intervals. Note the formation of a flocculus in lane at *A* (negative) with a motion-picture projector, it appears to run beneath the surrounding flocculi at some points in its path.

No eruptions occurred in the following spot over the entire period of observation, $6^h 21^m$. Very slow movements are observable in the

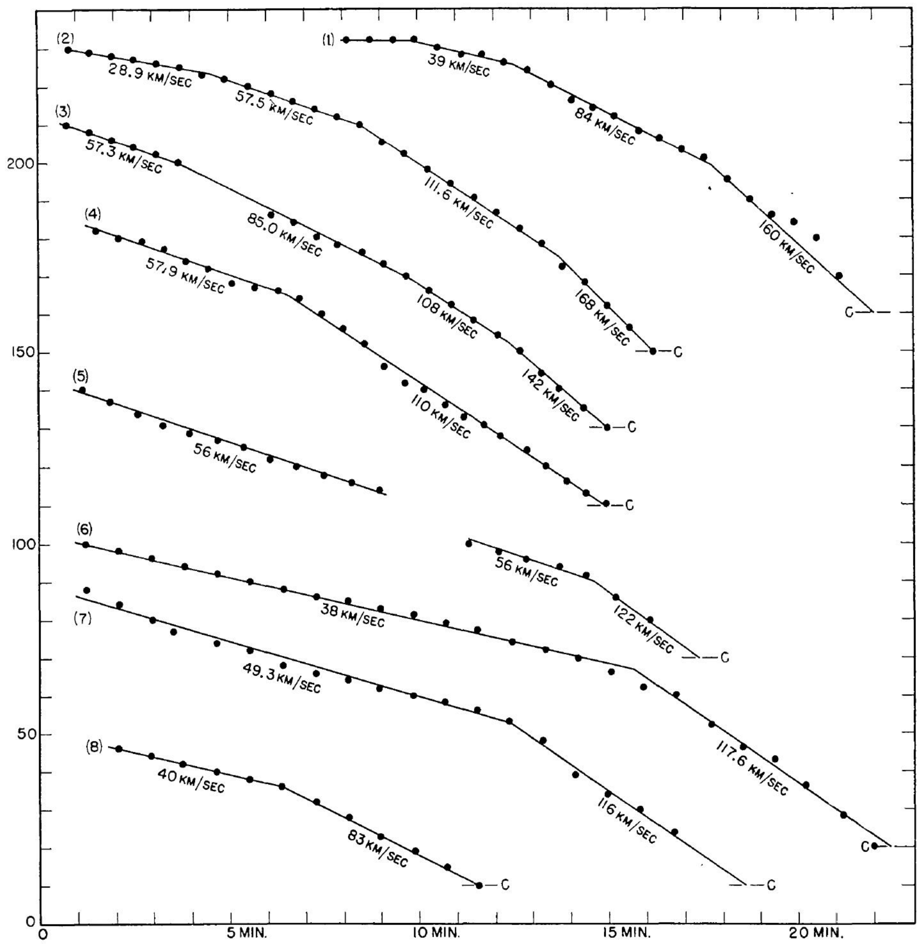


FIG. 1.—Motions of knots and streamer ends in sun-spot type prominence, class III*b*, of July 16, 1936 (Pl. XII, Nos. 1–5). Ordinates in this and succeeding figures are distances from chromosphere, C, in thousands of kilometers. The level of C is varied for convenience in plotting.

details of the floccular area and some of the surrounding flocculi, but these are not easily measured. The general outline of the floccular area remained remarkably fixed. Further discussion of these phenomena will be reserved until more observational data have been accumulated.

PROMINENCES OF THE SUN-SPOT TYPE

The general features of the subdivisions of this type (class III) have already been described.[9] Detailed measurements were given

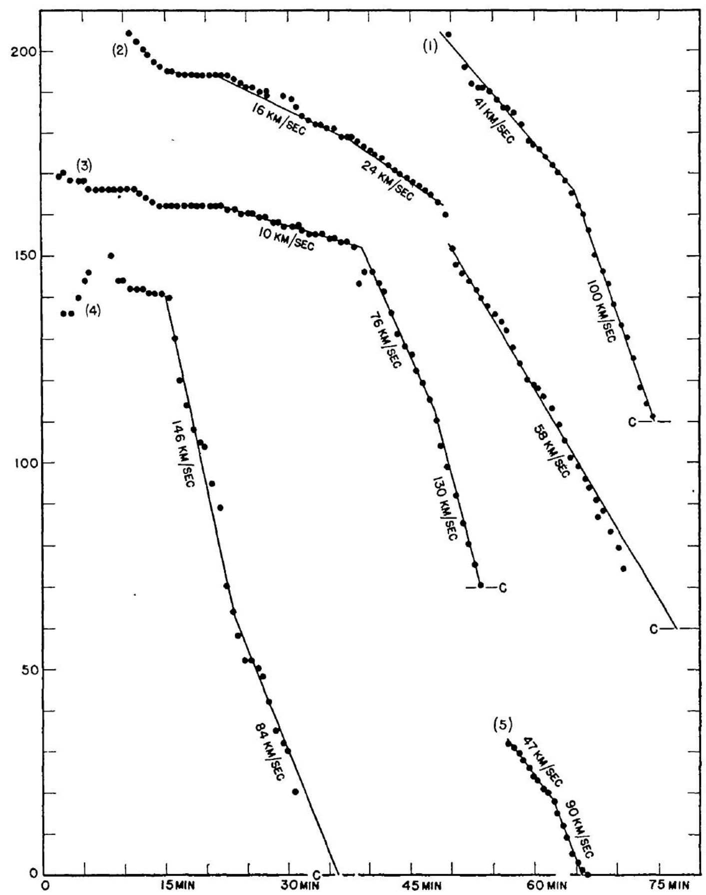


FIG. 2.—Motions of knots in the sun-spot type prominences, class III*a*, of August 24 (Pl. XI), plots 1–4, and August 8, 1936 (final stage after disappearance of great surge of Pl. XIII), plot 5.

for class III*c*. Similar measurements are given here for class III*a*, which consists of broken filaments or sections of loops moving radially into the spot area from different directions, and also for class III*b*, in which the prominence consists of fountain-like loops rising from and returning to the spot area.

[9] *Mt. W. Contr.*, No. 552; *Ap. J.*, **84**, 319, 1936.

In Figures 1, 2, and 3 are collected the time-distance diagrams for loops and broken streamers of several prominences of classes III*a* and III*b* observed during the months of July and August, 1936. It is clear that the prevailing feature of their plots of motion along the streamer trajectories is uniform motion broken at intervals by suddenly increased velocities. On the other hand, one or two cases, where several breaks occur, might be represented by curves; but, if we examine the circumstances, we find that they are cases where the loops

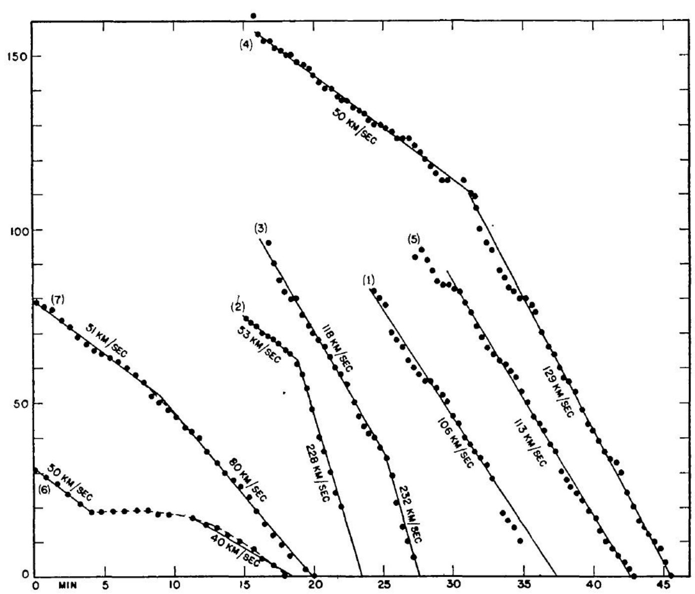


FIG. 3.—Motions of knots and streamer ends in the sun-spot type prominences class III*a* of August 20 (Pl. XII, 6–10), plots 1–5, and August 22, 1936, plots 6 and 7.

were formed at large angles of projection. Diagrams No. 3 (Fig. 1) for July 16, No. 2 (Fig. 2) for August 24, and Nos. 6 and 7 (Fig. 3) for August 22 are examples in point. Uniform motion along a curve will give rise to an apparently accelerated motion if the angle of projection is large, and this may be the reason for the general curvature in these diagrams. This factor of projection will also appear in apparent deviations from the second law of motion[10] of eruptive prominences, i.e., when the velocity of an eruptive prominence changes, the new velocity is a simple multiple of the old. Cases of this sort are

[10] *Ibid.;* see also *Mt. W. Comm.*, No. 118; *Proc. Nat. Acad.*, **22**, 249, 1936.

seen in July 16, No. 3 (Fig. 1); August 22, No. 7 (Fig. 3); and August 24, No. 3 (Fig. 2).

There are a number of examples, however, where the second law of motion holds with considerable precision. In Table 2 are collected data for seven such cases. The third column gives the observed successive velocities shown in Figures 1, 2, and 3, and the fourth column the factors by which each must be multiplied to obtain the following velocity. A simple inspection will show how closely these factors apply.

TABLE 2

VELOCITIES IN SUN-SPOT TYPE PROMINENCES WHICH OBEY THE SECOND LAW OF MOTION OF ERUPTIVE PROMINENCES

Date	Identity (No.)	Velocities (Km/Sec)	Factors	Quality
July 16	1	39, 84, 160	2, 2	G, F
July 16	2	28.9, 57.5, 111.6	2, 2	G, G+
July 16	4	57.9, 110	2	G
July 16	6	38, 117.6	3	G
July 16	8	40, 83	2	G
August 8	5	47, 90	2	G
August 20	3	118, 232	2	G

The period of duration of uniform motion at a given velocity is for the most part a half or a third of the duration of the streamer or knot, generally about 5 or 10 minutes. The maximum duration of a single velocity in the prominence of July 16, No. 6, is 15 minutes; August 24, No. 2, is 20 minutes; and two parallel-moving knots of August 20, No. 4, have a single velocity of 15 minutes' duration. The numerous observations can leave little doubt as to the character of the motion. It will easily be seen that these observations could scarcely be secured with a manually operated spectroheliograph.

In general, the streamer section or knot lengthens rapidly as it approaches the chromosphere, often making measures impossible or of doubtful value. This explains the general tendency of the last three or four measures to deviate from the straight lines in the diagrams in Figures 1, 2, and 3.

1937ApJ....85..279M

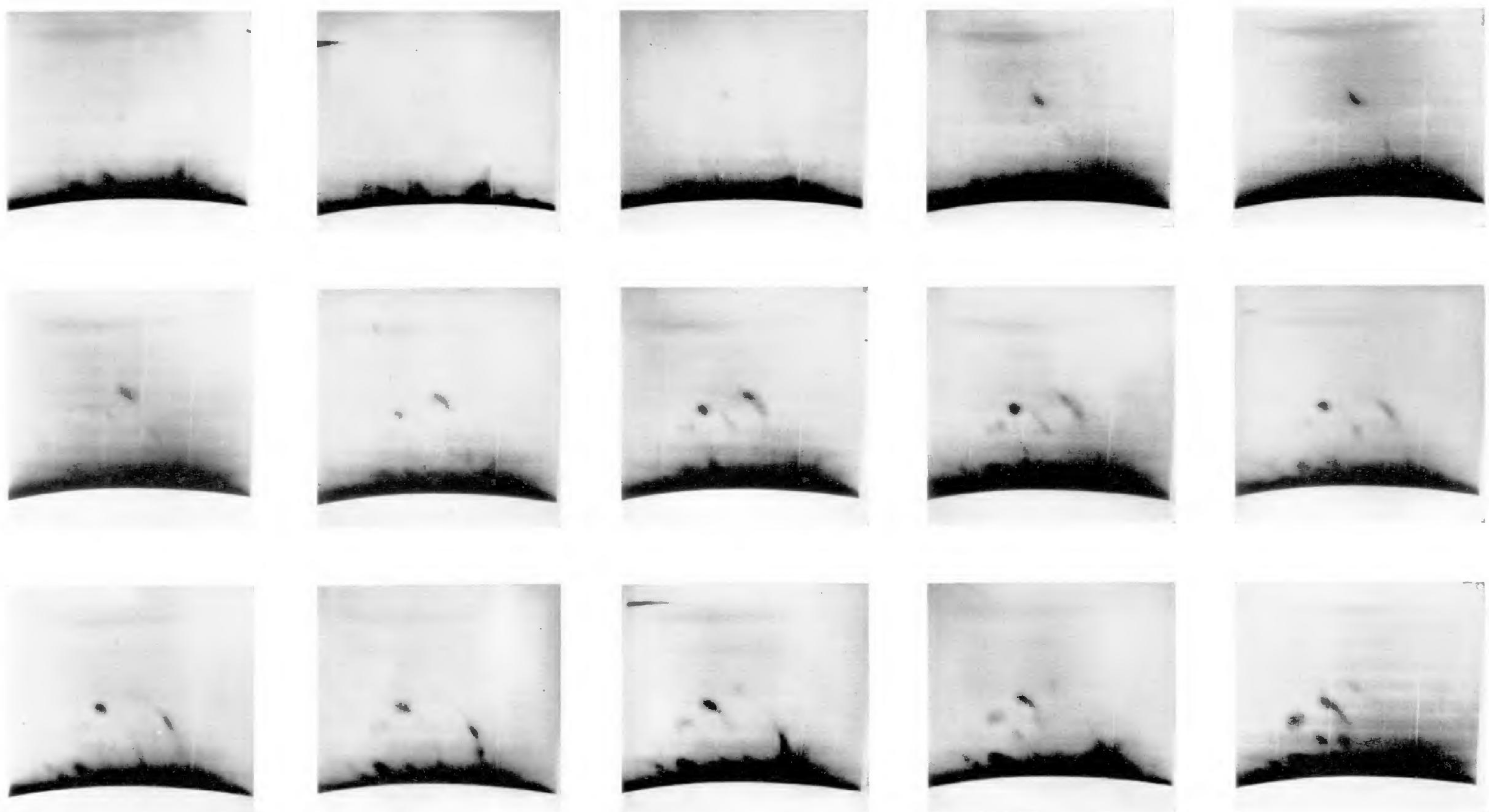
PLATE XI

Nos.

1–5

6–10

11–15



Class IIIa Sun-Spot Prominence, August 24, 1936

Showing development of a prominence high above the chromosphere and movement into the spot. Intervals 3.8 min.

STREAMER ORIGIN

When we observe the action in prominences of classes III*a* and III*b* with a motion-picture projector, it is evident that many streamers seem to have their origin high above the chromosphere and pour into the spot area. Frequently a faint spot of light, essentially round,

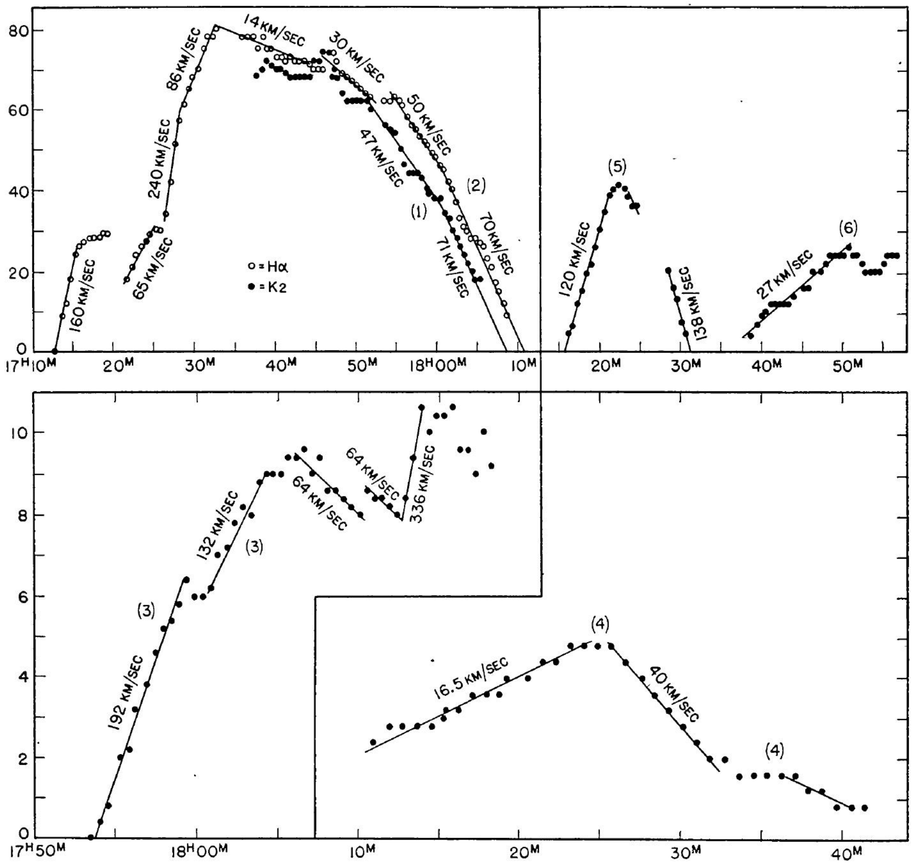


FIG. 4.—Rise and fall of surges, sun-spot type prominences, class III*d* (Pl. XIII), August 8, 1936, plots 1–3; July 16, plot 4; and August 22, plot 5. Plot 6 is a similar eruption connected with the tornado of July 15, 1936.

will appear from 75,000 to 150,000 km above the chromosphere, rapidly brightening over a period of 2 or 3 minutes. The class III*a* prominence of August 24, shown in Plate XI, illustrates this phenomenon. Here every fifth frame is shown to speed up the action. The time-distance diagrams corresponding to this plate are Nos. 1 and 3 in Figure 2.

Number 3 in Figure 2 is an extreme instance of this kind. The period of increase in brightness covered 20 minutes, with two periods of 8 minutes when the velocity was zero, or sensibly so. In other cases —notably July 16, Plate XII, 1–5 (Fig. 1, Nos. 2 and 3)—a very faint streamer completes the loop of a class III*b* prominence. After

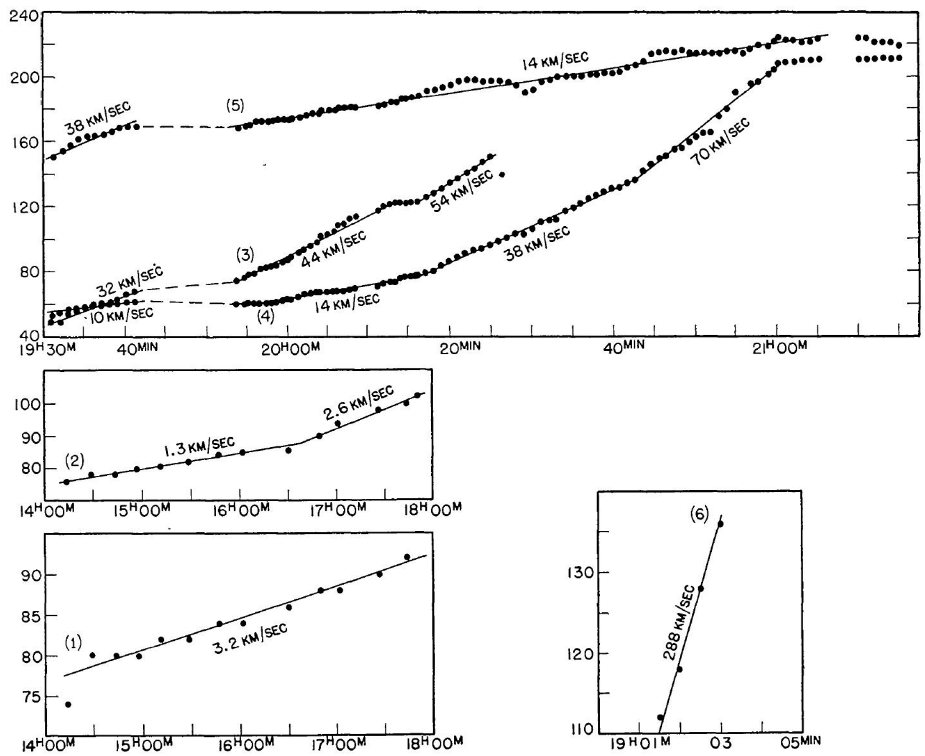


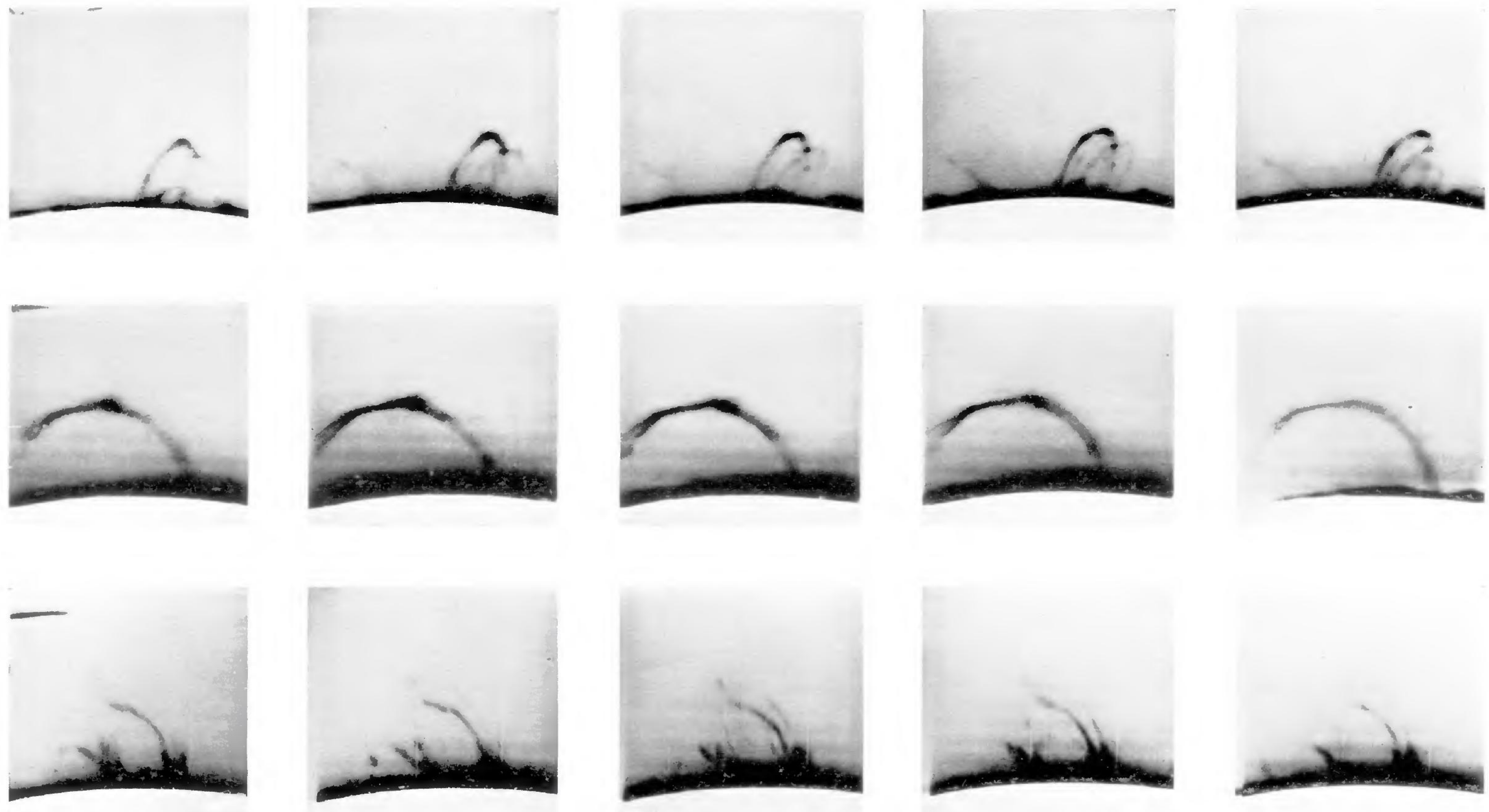
FIG. 5.—Motions of knots and streamer ends in the quasi-eruption of July 24, 1936. Vertical motion of the crest, plots 1 and 2; vertical rise of stem, plot 3; horizontal motion of head, plots 4 and 5. Vertical motion of the eruptive prominence of August 15, 1936, plot 6.

the stationary period, which may also not exist in most cases as an examination of Figures 1, 2, and 3 will show, the spot of light or knot descends into the sun-spot area, gradually being stretched out into a streamer section. Whether we set upon the center or upon one end of this streamer section, measurement results in uniform motion diagrams.

This phenomenon raises the question of the origin of chromospheric matter at so high a level. Possibly the most obvious explana-

PLATE XII

Nos. 1–5, 6–10, 11–15



SUN-SPOT PROMINENCES

July 16, 1936, Nos. 1–5, intervals 2.95 minutes; August 20, 6–10, 3.01 minutes; August 24, 1936, 11–15, 4.5 minutes. Note motions of knots and streamers into the spot area.

tion is that radial velocity resulting in Doppler displacement of the line on the second slit has modified the picture, so that one branch of the closed loop of a class III*b* prominence has been eliminated.

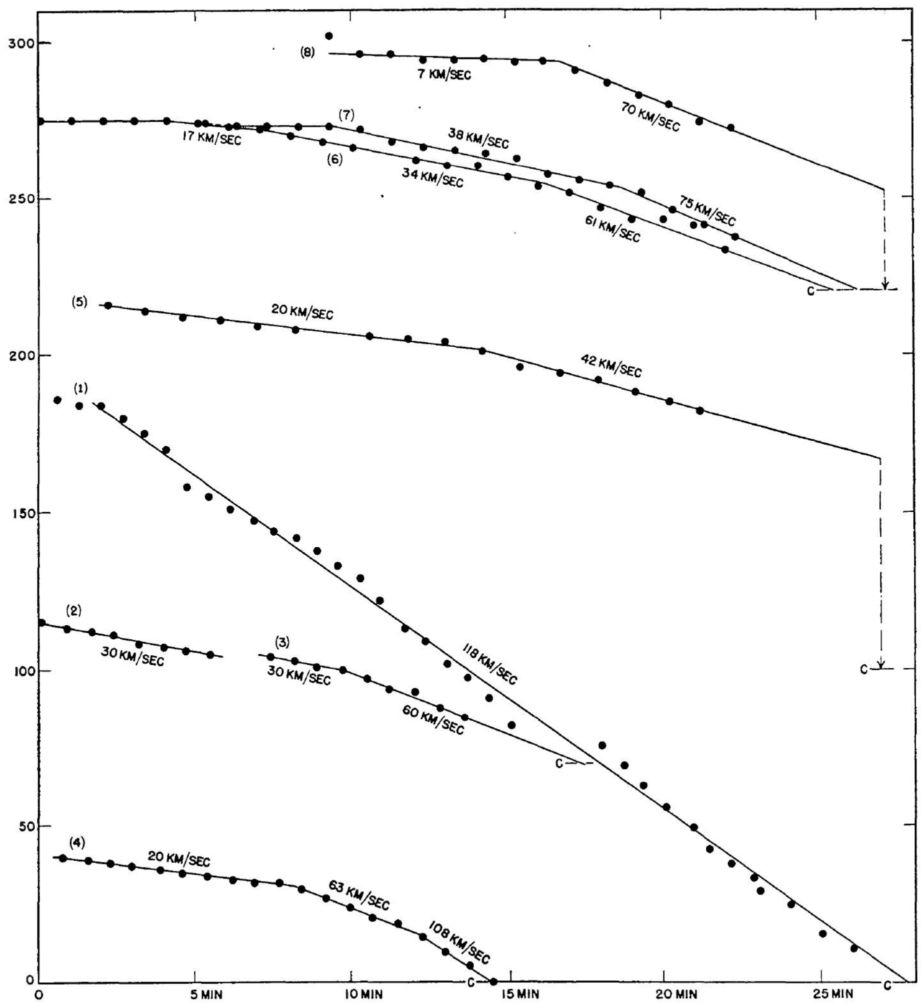


FIG. 6.—Motions of knots and streamer ends in active prominences. Quasi-eruption of July 24, streamer pulled to center of attraction, plot 1; July 27, plots 2–4; August 1, plot 5; August 11, plots 6–8.

While we have not followed the radial velocities during these particular scenes, the following arguments seem to substantiate the reality of the pictures.

1. In most of the scenes complete loops are visible in diverse

angles of projection. Examples will be found in Plates XI and XII. This condition could not follow if Doppler displacements seriously affected their appearance.

2. The slit width in use, 0.35 mm, is equivalent to about 1 A with our dispersion. A radial velocity of ± 76 km/sec would therefore be required to produce a serious displacement of the line from the second slit. While velocities as high as 150 km/sec are observed along the trajectory (loop) in these prominences, they occur at the end of the loop as it enters the chromosphere, where the component is nearly radial to the sun and perpendicular to the line of sight. In the middle of travel at the top of the loop the velocity along the loop seldom exceeds 40 or 50 km/sec.

3. The same results would be obtained mechanically if the spectrograph adjustments failed and the line shifted to an improper setting. The effect of such maladjustment was tested at our tower on a class III*b* prominence by taking exposures with the line set at normal position, then 0.5 A on either side by use of the mercury-arc spectral-line position control and spectrum drifter attached to the angstrom dial. When these frames were compared, no substantial difference was noticeable save in sharpness of image, which is of course best for the normal line position. In any case, this defect does not affect our results, since the adjustment is accurately maintained at all times by the spectral-line position control.

4. Since the normal setting is kept intact, we would expect that, in loop formations, only that part from the point on the chromosphere where the prominence rises to the point where the radial velocity exceeds about ± 114 km/sec would appear in the picture; and that it would always be the latter half of the loop, from the crest to where it re-enters the chromosphere, which would be lost. Since the reverse condition prevails, this argument does not apply. It is expected that, during the coming observing season, a regular record will be kept of the radial velocity of each prominence under observation.

By far the simplest idea is that a tenuous chromospheric atmosphere prevails, mixed with the inner corona, and that the electrical field of the spot area condenses this atmosphere and pulls it back into the chromosphere. There are several objections to this notion.

First, it seems that we must attribute chromospheric lines in coronal spectra to scattering in our own atmosphere, since they are found on the dark face of the moon. It is a little difficult to say whether a weak chromospheric spectrum would be found with ideal eclipse conditions, but E. P. Lewis[11] states that no chromospheric lines were present in his coronal spectra taken at Flint Island in 1908. Lewis attributes his results to having begun exposure 5 seconds after second contact. Again, there is no mechanism for the propulsion of neutral hydrogen atoms, although observational evidence for the identity of these prominences in $H\alpha$ and K2 is still uncertain. Neutral atoms such as those of hydrogen or helium are always difficult to handle when we consider how they may be propelled along with ionized calcium. So far, resort must be had to collisions to produce a drag of the hydrogen atoms upon the calcium gas passing through it, but the relatively small proportion of ionized chromospheric atoms present with the hydrogen would vitiate the effect. We expect to examine more closely the relative forms of sun-spot prominences in hydrogen and calcium during the coming observing season.

Occasionally faint streamers develop at an elevation of 150,000–200,000 km above the spot area and descend into it. These are of irregular form and apparently not associated with the loops and broken streamer sections. They are too faint for measurement, but on the screen their motion is very apparent. A similar case will be noted in our study of active prominences.

The prominence of August 20 (Pl. XII, 6–10) was one of peculiar action. From the time it was first observed on the west limb of the sun it seemed to consist of an arch, the matter in which moved down both branches from the crest toward the chromosphere. Only the right branch, which entered the growing sun-spot group Mt. W. 5001, was measurable, however. On this branch velocities as high as 129 km/sec were observed (Fig. 3, Nos. 1–5). Toward the end of the observing period a faint arch of slightly greater radius appeared over the left branch and, entering the right branch, fed matter into it. An examination of Mount Wilson plates reveals no prominence outside our frame which could feed this streamer into it. It seems,

[11] *Lick Obs. Bull.*, 5, 11, 1908.

therefore, that we must admit that a source of chromospheric matter exists high above the chromosphere from which these streamers are fed into sun-spot areas.

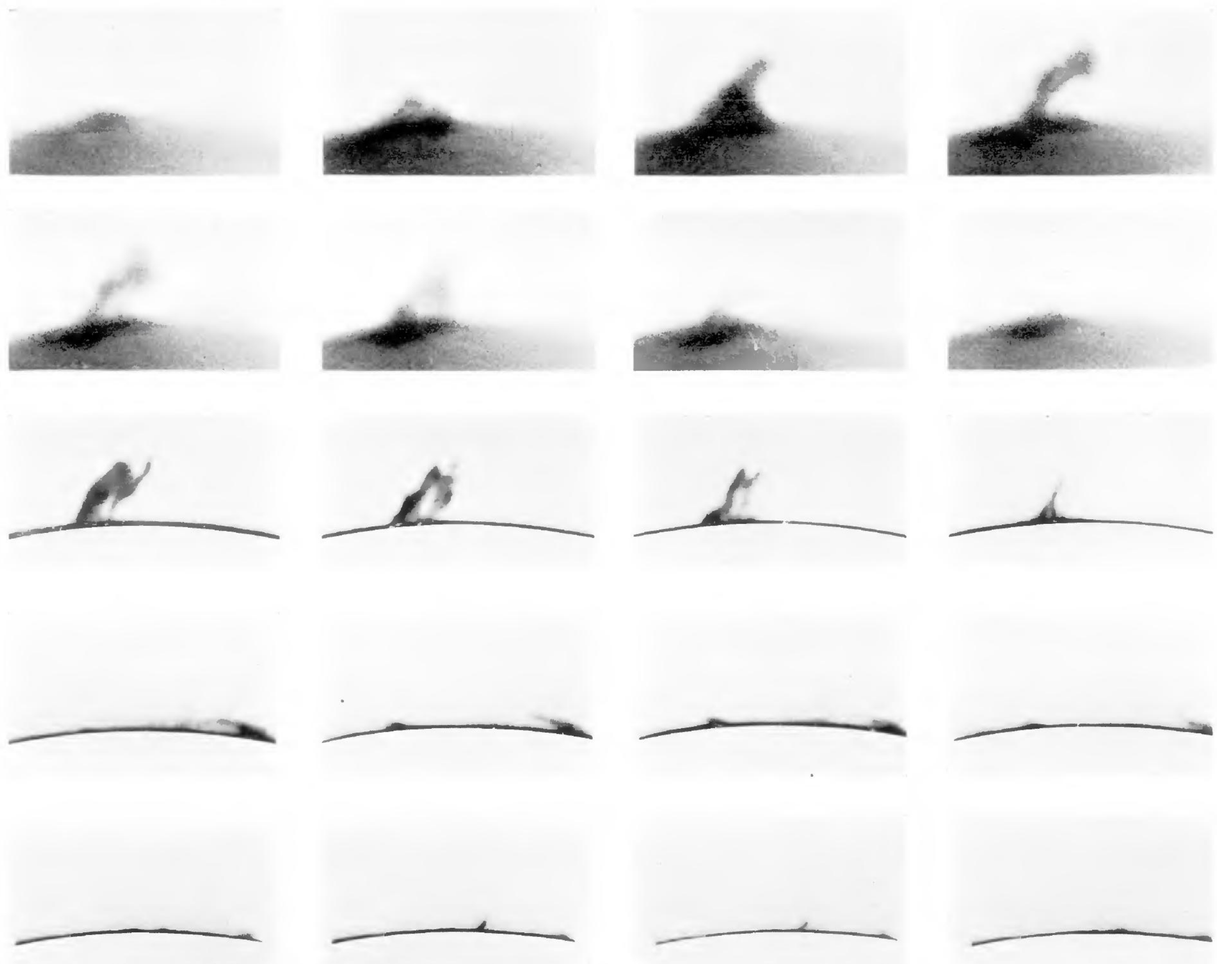
SURGES

Beside classes III*a* and III*b*, a class III*c*, in which lateral, probably accidental, prominences pour into a sun-spot group in company with either of the other two types, has already been described.[9] In all three classes the characteristic motion is toward the spot group. It now appears that there is a fourth subdivision of class III, of transient nature, which we have called "surges" and tentatively assigned to a new subclass, III*d*.

When observed by projection with a motion-picture machine, the chromosphere in the vicinity of a sun-spot group appears to be in continual motion. Slight elevations take place which endure only 1 or 2 minutes, and larger elevations rise and fall back into the chromosphere. These surges have some analogy to the rise and fall of the ocean on the coast line. There are also elevations which persist during the taking of a scene, possibly 2000 km high and 15,000 km long, an example of which, 5000 km high and 60,000 km long, appears in Plate XII, 6–10. Plate XIII shows three examples of surges observed in 1936. The first two rows show the rise and subsidence of the great surge of August 8, observed at the $10\frac{1}{2}$-inch telescope with the spectroheliokinematograph in $H\alpha$. The third row shows simultaneous frames taken at the tower telescope during the subsidence in K2 for comparison with the second row in $H\alpha$. This great surge appeared over the region of a spot on the west limb in position angle 255°, in latitude S. 27°, longitude 79° W. of the central meridian. This spot was a member of a complicated triple group (Mt. W. Nos. 4974, 4975, and 4982), the principal member of which had nearly disappeared; but the spot in question, a member of No. 4974, was increasing in intensity, having a polarity of V 1400 gausses on the previous day. About midday a brilliant floccular area was seen by H. Sawyer over this region, and the spectroheliokinematograph at the $10\frac{1}{2}$-inch telescope was set upon it in $H\alpha$. After photographing for about a half-hour, the great surge that rose out of this floccular area was seen visually in this instrument; the tower was then set

PLATE XIII

Nos.
1–4
5–8
9–12
13–16
17–20



SURGES, CLASS III*d*, AUGUST 8, 1936

Numbers 1–4, rise; 5–8, fall in $H\alpha$; 9–12, fall in K_2; intervals 6 minutes. Numbers 13–16 and 17–20, small surges of July 16 and August 22, 1936; intervals 12 and 3.7 minutes, respectively.

upon it, and exposures were begun just before maximum height. In Figure 4 are the time-height diagrams for this surge in $H\alpha$ and K2, the height being measured along the direction of motion, at an angle of 42° to a solar radius. Here it will be noted that the rise was very abrupt, indicating a velocity of 240 km/sec, while the maximum velocity of recession was 71 km/sec. The maximum height attained was 80,000 km. Here, again, it is seen that the first law of motion of eruptive prominences applies, although the second does not, and that the motion in $H\alpha$ and K2 is practically identical. When near maximum height the prominence seems to rise and fall slightly for some 20 minutes before beginning to descend, the total life being about an hour. An examination of Plate XIII shows that the form of the prominence was practically identical in $H\alpha$ and K2.

Just as this prominence subsided, another, but very much smaller, surge appeared at its base, moving nearly at right angles to it and rising to an elevation of only 10,000 km (Fig. 4, No. 3). This prominence did not seem to be the same in $H\alpha$ and K2, but this appearance may be a photographic effect due to the small size of the image, especially in $H\alpha$. The area then developed several fountains typical of class III*b* prominences approximately the same in $H\alpha$ and K2.

The surges of July 16 and August 22 (Fig. 4, Nos. 4 and 5, respectively) were relatively very small and were measured with the cathetometer attachment. These measurements show the principal features of the great surge described above. The rise and fall seem to be with uniform motion of high velocity. These surges are too small for us to be sure of the oscillations at the time of greatest rise. Another small surgelike prominence appeared at the base of a tornado on July 15 and was projected at an angle of 45° to the vertical with a velocity of 27 km/sec. The plot of this prominence is No. 6. In this last instance, although the height attained was only 26,000 km, the oscillation at the time of greatest extension seems to be established. The uniform character of the velocity during the rise is also patent.

This rise and fall of surges suggests that the chromospheric matter forming them comes from the lower layers of the chromosphere and carries with it, in its explosive rise, a considerable amount of the surrounding gases.

QUASI-ERUPTIONS

When a class II prominence or one of class III*c* becomes very active, the attractive force at the center of attraction or of the sun-spot area pulls off increasingly stronger and more numerous streamers, which rise higher and move in arcs of greater curvature toward the chromosphere. Finally, the prominence is torn apart and pulled bodily along these elliptical arches into the center of attraction or the spot area, the arches or streamers often overshooting the mark and returning to the chromosphere in an opposite direction. The prominences of September 22, 1919,[12] and August 27, 1935,[9] are examples which have already been discussed. It was shown that these two prominences obeyed both laws of motion of eruptive prominences, and it was suggested that eruptive prominences result when the force of attraction suddenly becomes very large, causing the elliptical streamers to rise until the two branches, ascending and descending, are nearly parallel, when the prominence rises and leaves the sun entirely, continuing to obey the laws of uniform motion with sudden increases by small multiples.

A case which we have called a "quasi-eruption" was observed with the tower at Lake Angelus on July 24, 1936. The type, being intermediate between classes I and II, fills this gap in classification and confirms the idea of the origin of eruptive prominences expressed above.

This prominence appeared at a point on the east limb of the sun in latitude N. 23° and poured streamers into an area of attraction located at latitude 0°. There was no sun-spot area in this neighborhood, the nearest being a group which appeared two days later in latitude S. 27° on the east limb, and we have therefore classified it as primarily an active type developing eruptive characteristics.

Plate XIV illustrates twenty stages of this prominence at intervals of about 5 minutes, and Figure 5 shows the time-distance plots. Numbers 1 and 2 in this figure refer to the vertical motion of points on the crest before the eruption began. Numbers 4 and 5 show the horizontal motion of the bright linear condensation toward the center of attraction, and No. 3, the vertical rise of the stem of the prominence. Plot No. 1 in Figure 6 refers to the motion of two knots

[12] *Pub. Yerkes Obs.*, 3, Part 4, 1925.

PLATE XIV

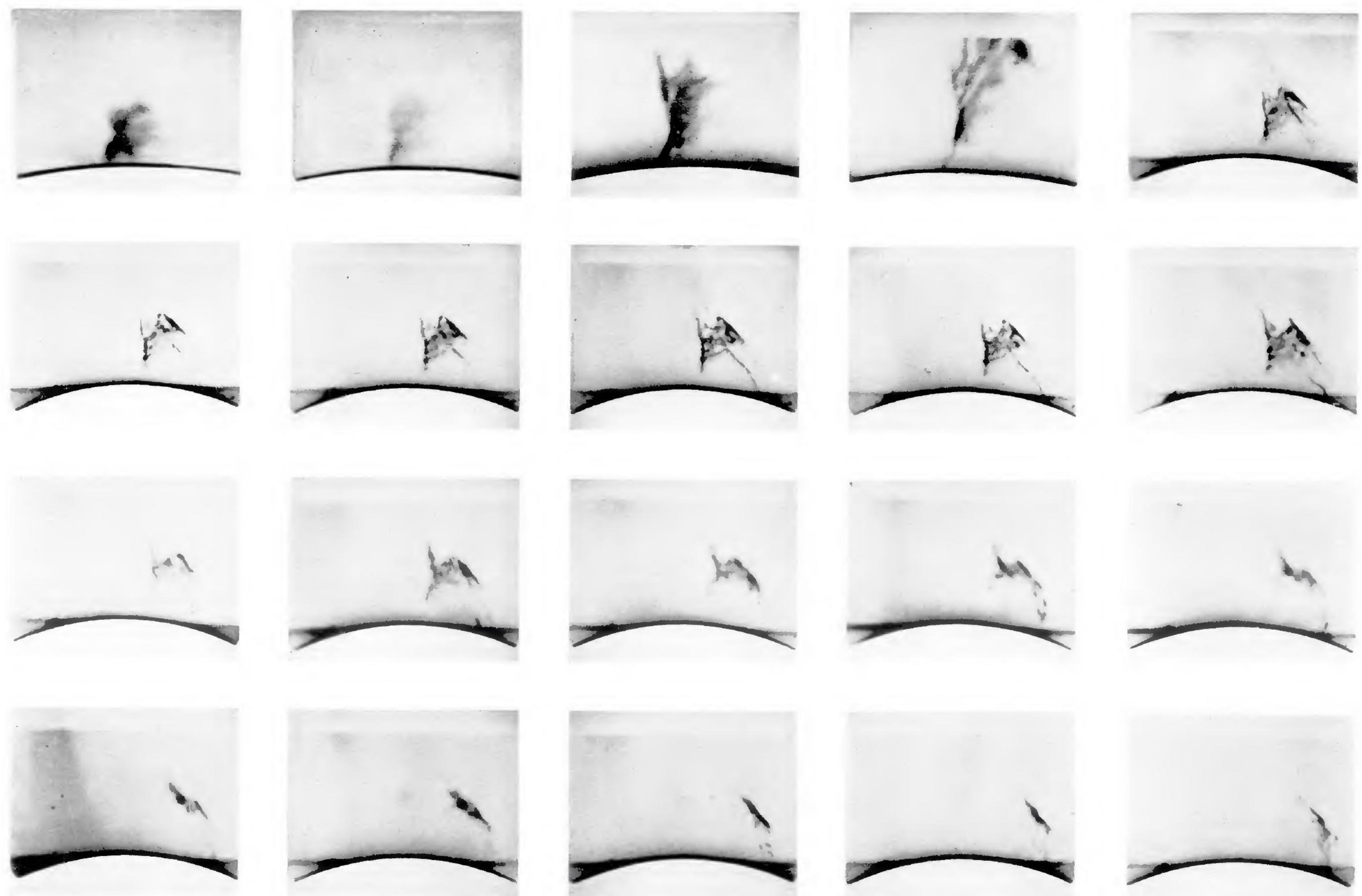
Nos.

1–5

6–10

11–15

16–20



QUASI-ERUPTION, JULY 24, 1936

Exposures 1–4 with 40-foot focus at 1-hour intervals. Remaining exposures, 5–20, with 18-foot focus at 6-minute intervals moving close together and in parallel directions along a streamer into the center of attraction. All these plots indicate the uniform motion which is characteristic of both active and eruptive prominences and very approximately satisfy the second law of motion as well.

One of the striking features of this prominence was the spiraling of the entire mass, at the greatest height attained. The rotation was about an approximately horizontal axis, each point making about half a revolution as the motion was converted from an ascent into a descent by the center of attraction. A very similar phenomenon was observed in the great eruptive prominence of May 29, 1919, which was associated with a sun-spot group. In this instance, spiraling about the magnetic lines of force from the spot would account for the observed facts; but in the quasi-eruption of July 24, 1936, no spot group was present. The half-revolution observed could be accounted for, however, by the mechanical change of direction produced by the center of attraction. Two bundles of streamers from this prominence reached a height of 325,000 km, directly in the line of ascent, and have the appearance of a true eruption.

We have, so far, no very great evidence of any brightening of the photosphere or chromosphere beneath or near an eruptive prominence which might furnish a propelling force. A careful review of a film taken at the $10\frac{1}{2}$-inch telescope in $H\alpha$ showing an eruptive prominence on the disk in the neighborhood of a small sun-spot[13] seems, however, to indicate a brightening in the chromosphere near the spot, not exceeding 5 per cent (for only a few frames), just before the eruption took place. It is possible that this fact is in no way associated with the eruption, but it is here made a matter of record.

An instance of true eruption combined with horizontal spiraling was observed on August 15, 1936. This prominence rose in latitude S. 35° on the east limb, pouring into a center of attraction in latitude S. 19°. No sun-spot appeared near this region. Because of clouds only four frames of the eruptive stage are measurable. They show (Fig. 5, No. 6) a uniform motion of 288 km/sec, the prominence rising from 112,000 to 136,000 km in 88 seconds. The northern portion of the prominence, still in the active state, then moved bodily into the center of attraction in the form of a horizontal spiral of

[13] *Pub. Obs. U. Mich.*, **6**, No. 4, 1934.

cyclonic characteristics, 60,000 km in diameter. The motion to the center of attraction, 50,000 km distant, was horizontal, with a mean velocity of 17 km/sec, although the end velocity was much higher than the average. A very rapid brightening of the cyclone during the last few frames, after the rest of the prominence had nearly faded away, is a prominent feature of its destruction; but this effect may be due partially to changes of atmospheric transparency for the low evening sun.

ACTIVE PROMINENCES

Only two prominences of the active type, torn apart by a center of attraction, without the presence of a sun-spot, have so far yielded sufficient material for time-distance diagrams with the older forms of the spectroheliograph.[9] Here, again, the chief difficulty in determining the character of motion has been the short duration of the streamer or knot in its trajectory; and for all such cases the motion-picture method has the advantage in securing very much more observational material.

During the season of 1936 four of these rather evanescent phenomena were observed at Lake Angelus with the tower telescope, for three of which, five stages are shown in Plate XV. The first, observed on July 27, was on the east limb at 7° N. latitude. The nearest sun-spot was a complicated group on the same limb, 34° southward. Plots Nos. 2, 3, and 4 in Figure 6 refer to the streamers projected from the inclined crest over a curved trajectory to a center of attraction situated nearly at the base. The measurements refer to the end of the falling streamer. Two of these streamers were measured, following the same trajectory, but the first only part way, as the diagram shows.

The second prominence was observed August 1, on the west limb at latitude S. 27°, pouring into a center of attraction situated in latitude S. 40°. Another center developed in latitude S. 21°. No spots were near either position, and the motions must be referred to centers of attraction. The fifth diagram in Figure 6 refers to the end of a streamer which was projected into the more southerly center. A high streamer appeared over the northerly center 120,000 km above the chromosphere, condensing into a knot at 100,000 km which

PLATE XV

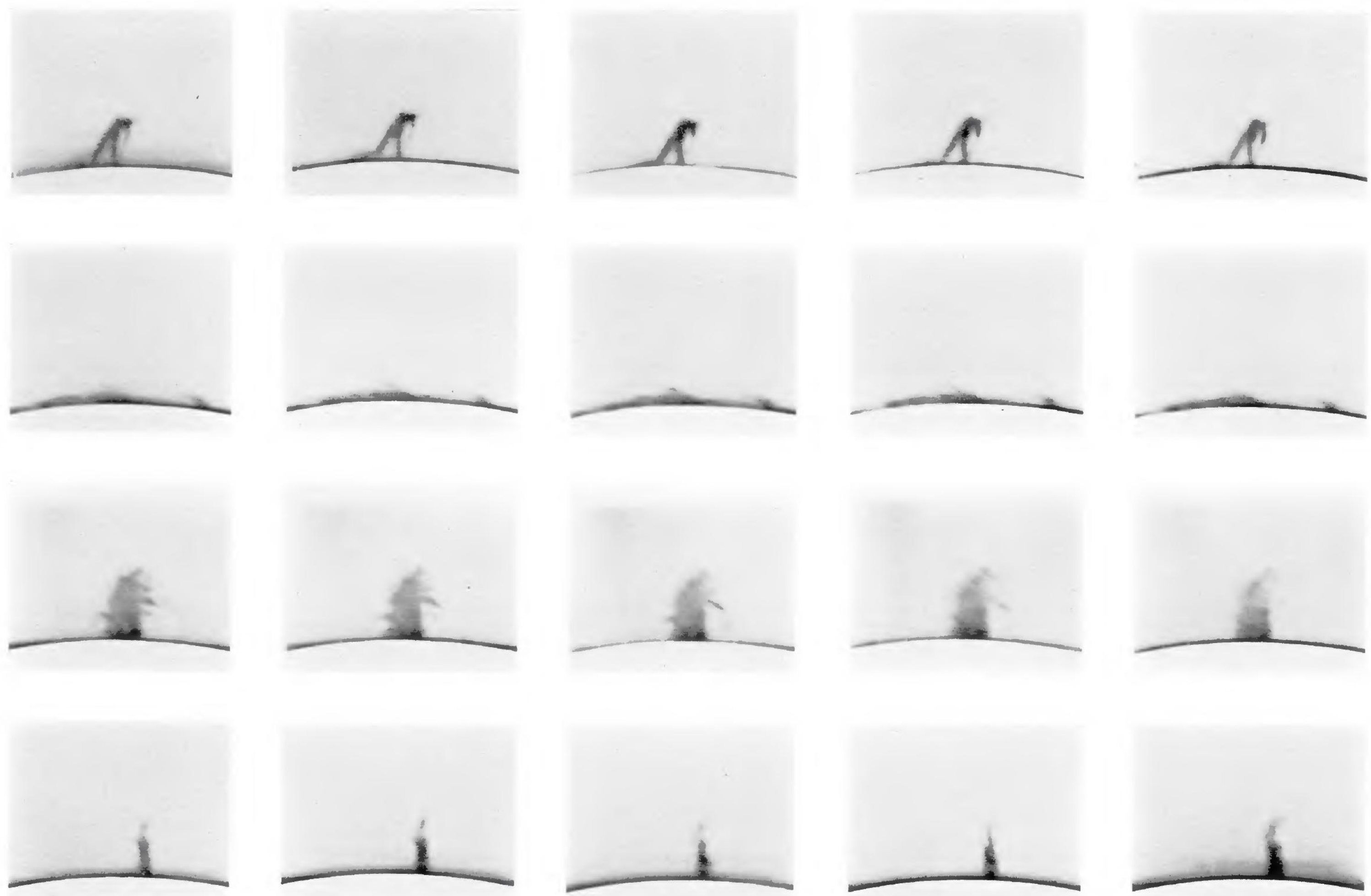
Nos.

1–5

6–10

11–15

16–20



ACTIVE AND TORNADO PROMINENCES

Numbers 1–5, 6–10, 11–15, active prominences of July 27 (3.6-minute intervals), August 1 (8-minute) and August 11, 1936 (8.2-minute), respectively. Numbers 16–20, tornado of August 10, 1936, at 20-minute intervals.

descended to the 70,000 km level and fed a streamer into the center of attraction. The faintness of this object made measurements impossible. As in the case of the class III prominences previously described, an examination of the Mount Wilson plates reveals no source outside the Lake Angelus frames which might contribute this streamer. We therefore conclude that it formed in the space high above the chromosphere. Disconnected streamers which seem to be formed high above the chromosphere are thus found in the region of active prominences as well as in that of spot-type prominences.

The third case appeared on the east limb of the sun on August 11, in latitude S. 66°. Streamers leaving the top of the prominence

TABLE 3

VELOCITIES IN ACTIVE PROMINENCES WHICH OBEY THE SECOND LAW OF MOTION OF ERUPTIVE PROMINENCES

Date	Identity (No.)	Velocities (Km/Sec)	Factors	Quality
July 27	1	30, 64	2	G
July 27	2	20, 63, 108	3, 2	G, F
August 1	1	20, 42	2	G
August 11	1	17, 34, 61	2, 2	G, G
August 11	2	38, 75	2	G
August 11	3	7, 70	10	G

poured into a center of attraction situated in solar latitude S. 69°. The prominence had the appearance of a column 86,000 km high and 42,000 km wide. Three streamer ends were measured, two coming from a point about a third the way down and moving along the same trajectory and one from a point higher up. The time-distance plots are given in Figure 6, Nos. 6, 7, and 8.

A streamer from the top of the quasi-eruption of July 24 (Pl. XIV) was pulled into the center of attraction with constant velocity over a great distance (180,000 km). Plot No. 1 in Figure 6 refers to this streamer.

In Table 3 are collected the velocities of these active prominences for all cases where more than one velocity occurred. Here, again, the laws of motion of eruptive prominences apply, the motion being uniform and increasing suddenly at intervals by a small multiple of the velocity. It has now been shown that these two laws of motion, here stated as one, apply to active, eruptive, and spot-type prominences and all their subdivisions. Such motion seems to be characteristic of prominences whether measured in the vertical direction, as in the eruptive type, or along the trajectory or streamers, as in the other types.

TORNADOES

These objects are so small that only the best atmospheric conditions will show their details. Three of them have been so far observed. In one, that of August 10, which appeared on the east limb, 52° N. latitude, a knot, which developed near the top at about 40,000 km above the chromosphere, spiraled down in front to a level of about 10,000 km and disappeared. The faintness and indefiniteness of the knot did not warrant detailed measurement, but a mean velocity of 10 km/sec was indicated. Plate XV, 16–20, shows five stages of this knot movement. This tornado, 50,000 km high, increased from 10,000 to 20,000 km in diameter during the 7 hours it was under observation.

A feature of this prominence which is typical of those already examined[14] is the formation of a smokelike column at the top of the vortex. This seemed always to be present, reaching a height of 90,000 km above the chromosphere, fading and brightening now and again, finally becoming as brilliant as the vortex itself. It then inclined strongly, bent, and detached itself, and, in the last stage observed, floated as an isolated cloud set at an angle of 45° to the vertical, expanded to several times its original volume. Plate XV also shows five stages of this phenomenon.

As in the cases of tornadoes already cited, no movement of translation in solar latitude could be positively detected during the 7 hours it was under observation. In no case was atmospheric definition sufficiently good to examine critically the rotation of the vortex, but we think the tornado of August 7, 1936, which appeared in latitude N. 61° on the east limb, shows some rotation when projected on the screen.

The tornado of July 15, which appeared in latitude S. 43° on the west limb, exhibited an ejection at the base which had the appear-

[14] *Mt. W. Contr.*, No. 451; *Ap. J.*, **76**, 9, 1932.

ance of a surge, although no sun-spot was present. This eruption first appeared as a small hemispherical bump at the base of the tornado and rapidly grew into a streamer projected at an angle of 50° to the vertical. This subsided, and the ejection was repeated at approximately hourly intervals. Because of interference by clouds only one ejection could be measured; the results are plotted in Figure 4, No. 6 with the surges, although we do not think that the ejection and the surges are the same phenomenon. The velocity, 27 km/sec, is much lower than that exhibited by surges.

We are indebted to Messrs. H. Sawyer, J. Brodie, and R. C. Williams for assistance in the observing program and for help in many other ways.

McMath-Hulbert Observatory
of the University of Michigan,
Carnegie Institution of Washington
Mount Wilson Observatory
February 1937

PUBLICATIONS OF THE OBSERVATORY

OF THE UNIVERSITY OF MICHIGAN,

VOL. VI, NO. 4.

PUBLISHED FROM THE LAWTON FUND.

A SHORT-LIVED SOLAR DISTURBANCE.

By R. M. Petrie and Robert R. McMath.

The following is a brief description of rapidly moving hydrogen flocculi that were associated with a sunspot which was under observation on June 19, 1934. One of these flocculi exhibited such rapid movement and such a short total life that the phenomenon may perhaps best be described as a "solar bomb." All the exposures were of twenty-four seconds duration with an interval of slightly more than a second between exposures. The pictures were made with the spectro-heliokinematograph[1] of the McMath-Hulbert Observatory of the University of Michigan, set at the H-alpha line of hydrogen. The times noted in the description are Eastern Standard Time (five hours later than G.T.).

The sun-spot region was close to the solar equator, the spot evidently belonging to the old cycle. Prior to the outbreak here described, the region surrounding the spot had exhibited some quiescent bright flocculi and a few dark and indistinct markings.

The activity herein described took place between 2:25 and 2:45 P.M., or a period of twenty minutes, though the effective life of each of the phenomena described was much shorter. At 2:15 P.M. a faint dark streak had appeared about 40,000 km. to the Southwest of the spot. There was a slight degree of activity in this region, the dark area slowly growing in size, but no phenomena are shown on the photographs from which the explosive outbreak occurring at 2:34 P.M. could be anticipated. At this time a great mass of dark gas about 50,000 km. long and 23,000 km. wide was explosively ejected from the spot; in the course of about three minutes this mass expanded and swept outward to a distance of about 100,000 km. Its measured speed was 70 km/sec., and uniform, though this velocity showed a tendency to diminish as it receded from the spot. The solar radius through the spot at this time made an angle of about eleven degrees with the line of sight. The measured velocity is, of course, perpendicular to this line, nor is it possible to determine what proportion of the motion of this cloud was radial and what proportion tangential to the solar surface; it is evident, however, that the measured velocity must be a minimum value. The total active life of this unusual "bomb" was not more than ten minutes.

[1] *These Publications*, *5*, 103 (1933).

Four individual frames have been selected from the negative herein described and enlargements thereof are reproduced as illustrations accompanying this report. Unfortunately a motion picture cannot be published as such and the four pictures reproduced herewith fail entirely to give any idea of the explosive action which is so clearly shown when the entire picture is projected on the screen. By our method it is possible to watch repeatedly a phenomenon such as the one which has been described.

After the fading out of the jet described above, a second stage of activity was manifested in a dark, rod-shaped flocculus which approached the spot and apparently accelerated into it at 3:00 P.M. It is perhaps more probable to regard this returning jet as an independent manifestation involving matter different from that of the first bomb, but it is not impossible that it may have been the same gas in the process of being sucked back into the spot.

This flocculus which appeared after the first outburst was about 65,000 km. in length and with a fairly uniform width of 12,000 km. The farther end of this strip moved uniformly toward the spot with a velocity of 40 km/sec. The nearer end, on the other hand, approached the vortex with an accelerated motion. At 2:53 P.M. it was 40,000 km. distant from the spot and moving toward it at 40 km/sec. At 2:58 P.M. the distance had decreased to 23,000 km., while the velocity had increased to 65 km/sec., and at 3:01 P.M. this end of the strip had entered the spot with a velocity between 200 km/sec. and 300 km/sec.

The values given above have been secured from a series of measures of more than forty photographs taken between 2:25 P.M. and 3:01 P.M., and in all cases the determined distances and velocities are referred to the center of the sun-spot as an origin. The velocities are deemed reliable since they depend upon many observations in a relatively short time interval. Accelerated motion is found with certainty in only one instance, e.g. that of the gas entering the spot, but there seems to be no doubt of it in that case.

Photographs of the region, enlarged from the motion-picture film, are reproduced as exemplifying the changes. They are as follows:

1. At $2^h27^m30^s$ P.M., E.S.T. This shows the sun-spot region a few minutes before the appearance of the dark flocculus.

2. At $2^h31^m40^s$ P.M., E.S.T. This picture shows the dark flocculus after ejection from the spot region.

3. At $2^h33^m45^s$ P.M., E.S.T. The receding flocculus has moved farther away from spot and is becoming indistinct. The approaching dark flocculus shows.

4. At $2^h36^m15^s$ P.M., E.S.T. The second flocculus prior to its motion into the spot.

The McMath-Hulbert Observatory of the University of Michigan,
Lake Angelus, Michigan.
June, 1934.

PUBLICATIONS OF THE OBSERVATORY

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VOLUME VII, NO. 1.

PUBLISHED BY A GRANT FROM THE MCGREGOR FUND.

THE TOWER TELESCOPE OF THE McMATH-HULBERT OBSERVATORY.

By Robert R. McMath.

Foreword.

Several considerations have motivated the choice of material included in this publication. As indicated by its title, the primary purpose has manifestly been the detailed description of the new fifty-foot tower telescope of the McMath-Hulbert Observatory of the University of Michigan. This tower was completed on July 1, 1936, and the first solar prominence films were secured on the following day; it has since been in almost continuous operation recording the motions and changes in solar prominences. The resulting films which with the earlier work of the spectroheliokinematograph are the first *continuous* records ever secured of solar phenomena, have been shown before numerous scientific societies and have aroused great interest because of the intrinsic wonder of the phenomena thus depicted and the unique character of the record. A study of these records, in their character as documents of research, will be reserved for a subsequent paper; the present article will limit itself to a description of the new apparatus and the technique that has been developed in recording solar phenomena by the motion picture method.

But certain additions have been found both advisable and necessary. Perhaps to a greater extent than is the case in most other observatories, the McMath-Hulbert Observatory, both in its original plan and in its subsequent evolution, is a highly specialized plant forming a coherent and intimately interdependent whole. The new tower itself may be regarded as merely a logical and more powerful extension of the spectroheliokinematograph, made necessary when the earlier instrument had shown the tremendous promise of the virgin field offered through the continuous record of solar changes, and the scientific value of such researches on that nearest star called the sun. As a concrete illustration of such interdependence,—it has, for example, been customary to run the smaller spectroheliokinematograph at Hα concurrently with the tower exposures at calcium K_2.

Moreover, a large sum was saved in the construction of the new tower through the utilization of the apparatus and methods that had been evolved in connection with the application of the motion picture method to other celestial objects in the earlier work of the observatory. The gear-change mechanism that makes possible any desired alteration of exposure and dark time on the film was ready for use in the underground control room built through the generosity of Neil C. and Margaret K. McMath. Here also was available the almost infinitely flexible McMath-Hulbert electric drive, utilizing a precise control of the electrical frequency through resistance stabilized thermionic tubes. To utilize these in the new tower meant only the extension of the electrical circuits to the appropriate tower mechanisms, and any complete description of the tower must inevitably include these adjuncts, even though their earlier applications have been described in previous publications of the Observatory of the University of Michigan.

In addition, requests have been received from a number of astronomers for the segregation in more convenient form of the description and circuit diagrams of the McMath-Hulbert frequency control and electrical telescope drive. This drive has been applied to the 80-inch reflector of the new McDonald Observatory in Texas, will be used by the Radcliffe Observatory of Oxford in the large reflector it is planning for South Africa, and is under consideration for a number of other large installations. In the earlier description of this drive, limitations of space made it necessary to include all circuits,—electric drive and frequency control, telescope slow motions and controls, camera exposure mechanisms, etc.—in a single circuit diagram. This combined circuit diagram, although easily read by the experienced electrician or physicist, gave some astronomers an unwarranted impression of complexity, though the electric drive unit is relatively simple when separated from the circuits used for other purposes. To meet such requests, the McMath-Hulbert electric drive and frequency control has been described anew in this paper, with a single simple diagram including only the essential circuits of this drive.

It will be found, in the opinion of the author, that such partial repetitions of descriptions of this apparatus published earlier are apparent rather than real, and that these are extremely essential to any adequate and complete description of the new tower, in that they are as much a part of its function as the structural elements to be described later.

Earlier descriptions of the apparatus, the technique, and the results of the application of the motion picture method to astronomical photography may be found in the following Publications of the Observatory of the University of Michigan:—

Some New Methods in Astronomical Photography, with Application to Moving Pictures of Celestial Objects, by Francis C. McMath, Henry S. Hulbert, and Robert R. McMath. Volume IV, pp. 53–73 + 11 plates, 1931.

The Spectroheliokinematograph, by Robert R. McMath and Robert M. Petrie. Volume V, pp. 103–117 + 9 plates, 1933.

A New Method of Driving Equatorial Telescopes, by Robert R. McMath and Walter A. Grieg. Volume V, pp. 123–131, + 2 plates and 4 diagrams, 1934.

A Short-Lived Solar Disturbance, by R. M. Petrie and R. R. McMath. Volume VI, pp. 43–44 + 1 plate, 1934.
Relative Lunar Heights and Topography, by Robert R. McMath, Robert M. Petrie and H. E. Sawyer. Volume VI. pp. 67–76 + eight diagrams, 1935.

On the frequent occasions when it may be necessary to refer to these papers, the abbreviated form,—IV, p. 60, 1931,—will be employed, with the omission of title and author.

Acknowledgments

There would be very few paragraphs, in the description that follows, without one or more names of friends, colleagues or foundations that have given helpful advice, useful suggestions, expert supervision, and financial assistance. At this point and before proceeding further, the writer desires to express his most grateful appreciation for all such help and support extended to him since the founding of the McMath-Hulbert Observatory.

To the Trustees of the Horace H. Rackham and Mary A. Rackham Fund for the grant of $25,000 toward the construction of the tower telescope.

To the late Tracy W. McGregor for his great interest in this project, and to the Trustees of the McGregor Fund for subventions for construction, support, publication, and books, amounting in all to $25,000.

To the Board of Directors of the Alexander Dallas Bache Fund of the National Academy of Sciences for a grant of $724 toward the purchase of a Bell & Howell precision gate mechanism for the motion picture camera of the tower.

To the Motors Metal Manufacturing Company of Detroit and its Board of Directors, who made it possible to build all of the instrumental portions of the tower telescope in their shop. Mr. Otto Mattick, Superintendent of the Tool Division, assisted with the design of many details and constantly supervised the progress of the work. Mr. George Malesky made all the drawings from which the instrumental parts of the tower telescope were manufactured.

To Mr. Gustavus D. Pope and family for the gift of the 6-inch by 15-foot collimating lens.

To Mr. Willard Pope, who gave the Observatory its 6-inch by 30-foot collimating lens.

To Mr. W. R. Kales, who provided for the acquisition of the 16-inch by 40-foot off-axis mirror, and also the welded all steel roof.

To Mrs. L. Trent McMath, whose gift of $1,200 towards the construction of the tower telescope was the first received.

To Col. Sidney D. Waldon, who not only designed the landscaping around the tower telescope, but gave and planted many large trees to carry out his plan.

To Mary R. McMath, who laid out the Observatory grounds, superintended the grading operation and assisted in many other ways.

To Neil C. McMath and Margaret K. McMath, for the construction and equipment of the underground control room.

To the Observatory of the University of Michigan and its Director, Dr. Heber D. Curtis, for continued assistance and advice; to Mr. H. J. Colliau and Mr. Nuel Smock for the construction in the Observatory Instrument Shop of considerable portions of the 10.5-inch reflector mounting, the spectroheliokinematograph, and other accessories; to Dr. Curtis further for detaching Dr. Petrie and Dr. Williams from their teaching duties to assist in observational work at Lake Angelus. To Dr. Robert M. Petrie, now of the Dominion Astrophysical Observatory at Victoria, B. C., for his unflagging zeal and energy in assisting with observations and calculations; to Dr. Robley C. Williams for assisting during the summer of 1936 and for aluminizing all the mirrors of the various instruments; and to Dr. Allan D. Maxwell for the calculation of lunar tables used in the observational work.

To Dr. Keivin Burns, of the Allegheny Observatory, for helpful advice on many occasions. Dr. Burns devised and furnished preliminary sketches of the ingenious plan by which the optical parts of the spectroheliokinematograph were compressed within a volume 42 by 9 by 6 inches.

To Director Walter S. Adams and members of the staff of the Mt. Wilson Observatory, to Mr. Russell W. Porter and others of the staff of the California Institute of Technology, and to Dr. George E. Hale, for constant helpful advice and for placing unreservedly at my disposal their accumulated experience in tower telescope construction and technique, as well as drawings of many parts of their apparatus and accessories. The writer, accompanied by his brother, Neil C. McMath, visited California in June, 1935, in preparation for making the design of the tower. Every possible assistance was given us, and every facility placed at our disposal. We received everywhere helpful advice leading toward the best solution of our particular problem. Of even greater importance, we learned what *not* to include, and what accessories or devices should be omitted as of slight or doubtful value.

To Harold E. Sawyer, Assistant Astronomer, and John Brodie, Assistant, of the staff of the McMath-Hurlbert Observatory, for their unremitting zeal in carrying on the observational work and assisting in the construction of the new tower. Mr. Sawyer installed the entire electrical system. His assistance was made possible through a special grant to the McMath-Hulbert Observatory from the Horace H. Rackham Endowment Fund.

Our special thanks are due Dr. Edison Pettit, of the Mt. Wilson Observatory. Dr. Pettit was not only always ready with advice and helpful suggestions during the designing and construction of the tower telescope, but spent the past summer at Lake Angelus carrying on observations. To him, more than any one person are due numerous valuable and essential details of the tower telescope design, among which may be singled out the design of the all-reflection optical train that makes possible much shorter exposure times than can be secured with any other

similar installation, also the scheme for the scout camera. His long experience in photographing and investigating solar prominences was invaluable to us.
The entire cost of the McMath-Hulbert Observatory in its original form was assumed by the three founders,—Francis C. McMath, Henry S. Hulbert, and Robert R. McMath. This included the 10.5-inch pyrex reflector, its dome, the motion picture cameras and accessories, the optical parts of the spectroheliokinematograph, as well as other financial contributions in which all three have shared. The founders subsequently transferred the observatory by deed of gift to the University of Michigan, making it a component part of the Observatory of that institution. It is impossible to express my full obligation to my two colleagues. Mr. Francis C. McMath carefully checked the design of the steel work of the new tower, and we are indebted to him for many valuable suggestions. Judge Henry S. Hulbert has ever given freely of his valuable advice and counsel.

The Motion Picture Problem.

The work done at our observatory falls naturally into two major divisions as regards intent and scope;—scientific and educational;—and the scientific aim may well be treated first.

From the very inception of our program we have realized that a continuous record of certain celestial phenomena would be of tremendous value, for any phenomenon involving rapid changes requires continuous records made up of many individual observations secured at minimum intervals of time. With all previously existing instrumentation it has been difficult to secure photographs at frequent intervals,—such as 2 to 10 exposures per minute. The motion picture process, however, permits one to secure many hundred successive photographs in an unbroken series and in a very constant manner. Occasional unexpected values have resulted in our earlier work because of these characteristics. For example,—using the data obtained from many hundred frames of a motion picture of the lunar crater Theophilus, we were able to compute the cross-sections of such parts of the crater floor and ramparts as were traversed by the moving shadow tips. Because of the large number of individual photographs and the uninterrupted continuity of the record, we were able to obtain considerable detail in the results.

The physical manipulation of the hundreds of exposures that make up a motion picture record does not present any particular problem while the treatment of the negative does present many such, as well as many unique advantages. The film contains many hundreds of successive frames that form our observational data, and the negative can be stored in a very small space after it has been developed, fixed, and washed. Very fortunately, also, a picture taken for scientific purposes on motion picture negative may be printed and repeatedly projected; no other technique for securing continuous records possesses this tremendous advantage. In consequence, the observer may see repeated as often as he chooses the action that took place while the telescope was trained on the celestial object, in a manner that is not only convenient and rapid, but which also possesses definite advantages from either the scientific or the educational standpoint. The factor of compression may vary between 160 and 960 times depending, of course, upon the object itself and the speed with which the successive photographs may be taken. Experience has shown that the resulting films are of great aid in teaching classes in astronomy and physics, and the scientist may thus observe phenomena of whose existence he was sure but is now for the first time able to study in motion repeatedly, by means of projection, thus affording him unusual opportunities for detailed investigation.

The technique of treatment of the negative after the observer takes the final exposure of a run is fortunately thoroughly standardized commercially, thus relieving the observer of responsibility for a development process that is delicate and difficult if uniform results are desired. There are in existence in several places in the United States very extensive laboratories devoted solely to the handling of motion picture film, and a great deal of money has been spent in evolving the art of processing motion picture negative. In a first class laboratory, all negative is developed against time and temperature in baths that are held rigorously to standards as regards strength of solutions, motion of fluids, temperature, etc. Consequently, if the original negative is consistently exposed in accordance with such standards, great uniformity results. It is very difficult in a private laboratory or dark room to secure negative processing that will be equivalent to that available at a low cost commercially. In commercial plants, after the development of the films, fixing, washing and drying are carried out under closely controlled conditions, including humidification and de-humidification, as well as the cleansing of the air used in drying the negative, giving negatives that are clean and without dust-marks, scratches, or other incidental disfigurement. After due consideration of all the above advantages, standard 35 mm. film was chosen for our work, and the processing given over to firms properly fitted for treating it. It may be added here that the Eastman Kodak Research Laboratories have also very generously coated motion picture negative stock for us with many of their various spectroscopic emulsions and sensitizers.

The taking of successful celestial motion pictures is far from being as simple as it appeared to be in advance. The occasional visitor to the McMath-Hulbert Observatory is often impressed with the seeming complexity of the apparatus and the various electrical controls. Some of this is due to the radical differences between the technique of the motion picture and that of the ordinary astronomical photograph. Relatively speaking, our observatory does not photograph faint objects, and an exposure of one minute is regarded as fairly long, which is not the case in ordinary celestial photography. As a consequence of our short exposure, it is imperative that no guiding be *necessary* or performed while an exposure is being made. This consideration led to the evolution of a telescope that is inherently a *following* telescope rather than a telescope which is driven at a uniform sidereal rate; hence the actual rate of the driving mechanism is made variable at the will of the observer. We have found such a variable drive in declination, with similar close control, just as important for our work as that in right ascension. The advantages of these types of drives can be best appreciated after actual use by an observer experienced in the earlier form of telescope drive and guiding; their description will be reserved for a later section of this paper.

Experience has shown that about 40 feet of the 35 mm. standard film makes an ideal picture for general audiences; this lasts for 40 seconds when projected at 60 feet per minute and is not unduly shortened even when projected in the normal sound projector at 90 feet per minute. This leads to the necessity for careful planning in advance of the relation between exposure and dark time, and the number of pictures to be taken per minute. In certain types of work the observer must take as many pictures per minute as is possible in order to secure adequate footage; in others, the required exposure is so short that a definite dark interval is demanded between exposures. For the convenient control of this problem, the camera drive and timing device shown in Plate 15 was developed. The reader should, however, constantly keep in mind the fact that the apparent complexity of this device is for this special end, and that it is in no sense a part of the telescope drive or the control system. It is instead merely a piece of accessory apparatus which has been developed to cope with the highly specialized requirements of the motion picture process as employed at our observatory, and would be a necessity only in installations where the program involved extensive motion picture work.

To recapitulate:—The taking of continuous celestial photographic records brings up problems and requirements that do not exist in ordinary astronomical photography. We have found by experience that a very stable and heavy instrument is an essential, and that this instrument must be a following, and not a guided instrument. The actual production of several hundred exposures on a continuous basis necessitates rather elaborate timing and control devices which have to do with the camera only. It is our belief, when this special problem is considered, that no unessential piece of equipment is in operation at our observatory.

Reverting now to the educational standpoint, the films obtained by this new technique make it possible for the instructor in astronomy to show in a few minutes celestial changes that would require hours of observation at the eyepiece of a telescope. As an example,—our standard lunar film, ordinarily projected in about 20 minutes, is the equivalent of 92 hours of lunar observation. Instruments available to the student are often quite few in comparison with the size of the class. In consequence, the student often finishes a semester's work with the employment of comparatively few minutes at the eyepiece of a telescope, especially in climates where clear nights are infrequent in the winter season. We are constantly adding to the amount of suitable films available for purposes of instruction, in the firm belief that visual education is just around the corner, if not already here.

Historical

The present observatory is the successor to an earlier observatory established by Francis C. McMath in 1927 near Clarkston, Michigan, which was equipped with a 4-inch equatorial and dome; and it was with this original equipment that the first experimental motion pictures were made by Robert R. McMath, the subject being the moon. The late R. H. Curtiss urged building a larger instrument in order to develop the latent possibilities of celestial motion pictures for educational purposes and as a new method of research. Henry S. Hulbert joined the enterprise, and the McMath-Hulbert Observatory was built in 1929, equipped with a 10.5-inch equatorial and dome; in 1931 the institution was deeded by the founders to the University of Michigan.

The founders of the McMath-Hulbert Observatory,—Robert R. McMath, Henry S. Hulbert, and Francis C. McMath,—have always been primarily interested in what may be termed the kinetic side of astronomy. It is probable that at the start of our work the predominant aim was the production of films showing motion and change in celestial bodies, with the expectation that such films would find their main value as adjuncts to astronomical education, and would help to impress upon the student the conviction that astronomy is a kinetic rather than a static field of science. However, as is so often the case in any extensive program based upon long continued observational records in a definitely restricted field, it was soon found that the scientific results produced from this homogeneous line of attack, thought at first to be merely by-products of the educational aim, promised instead to overshadow completely any probable purely instructional value.

The initial program and scope of the attack on our problem may well be illustrated by the quotation of the following sentence from the first published paper describing the observatory in its original form,—"The McMath-Hulbert Observatory . . . was founded for research in the field of motion picture photography of celestial objects, and for the development of an instrument and a technique for the production of astronomical motion pictures of both popular and scientific interest which would be of value to high schools and colleges in their courses in descriptive astronomy." (IV, p. 53, 1931.) But the future application of this method to the sun was regarded as a vital part of the plan from the first,—". . . the rotation of the sun as shown by the spots, the drift of the sunspots and their changes, the more active type of solar prominences showing changes of form . . ." (*ibid.*).

In pursuance of the plan for the extension of this method to the sun, the spectroheliokinematograph was built (V, p. 103, 1933), and a considerable number of films secured showing prominence motions, culminating in an astonishing and remarkable record of the ejection of an eruptive prominence from a sunspot (VI, p.

43, 1934). The entire life of this phenomenon was of the order of ten minutes, and it brought home to the writer and to many astronomers interested in solar studies the fact that there must be a very large number of such phenomena, of very short duration and hitherto unknown, to be studied adequately only by the motion picture method, and that here could be envisaged a most promising, new, and entirely unworked field of solar research. Moreover, although the spectroheliokinematograph produced good results, it was limited to work in the Hα line in the red end of the spectrum. Burns' ingenious design had made it possible to compress the instrument in a volume 42 $\times$ 9 $\times$ 6 inches in size, a restriction set by the space available in the 10.5-inch dome, but because of this compactness the light beams had to traverse several inches of glass and there were 32 air-glass surfaces. Literally months of labor were necessary on the part of Dr. Petrie and the writer before troublesome secondary reflections could be conquered and successful films secured. In addition, the scale of the pictures was limited to 168 inches focal length because of the fact that the instrument must be fed by the 10.5-inch reflector, giving an image size of about 1.5 inches. However, notwithstanding these handicaps, its use proved it to be a successful instrument, and made it clear that much more satisfactory results could be obtained from a large tower telescope especially designed for this type of work.

The tower telescope may then be regarded as the logical and concrete result of this conviction, with its raison d'être going back to the prominence films secured with the spectroheliokinematograph, crude and imperfect as some of these appear in comparison with the results now being secured with the vastly more powerful later instrument.

Because of the highly specialized nature of the work of the original apparatus of the McMath-Hulbert Observatory,—namely,—the motion picture record,—it is scarcely too much to say that all its earlier apparatus was built around the motion picture camera. In planning the tower telescope to be described in this paper, first importance was also and naturally ascribed to the motion picture type of research, and our original plan called for a comparatively small and highly specialized instrument to be devoted solely to the taking of solar motion pictures.

The writer found considerable interest in the project among professional astronomers, particularly those located on the Pacific Coast; nearly everyone, however, advised the construction of a larger and more adaptable instrument. Upon returning from our western trip of inspection, a conference was held between the founders and Director Curtis, and it was decided to plan for a larger instrument of greater power, which would be conveniently adaptable to all lines of solar spectrographic research. This involved a larger coelostat and second flat and, in consequence, a larger dome, thus increasing the scale of the entire tower telescope; about 10 feet had to be added to the over-all height called for on the original plan.

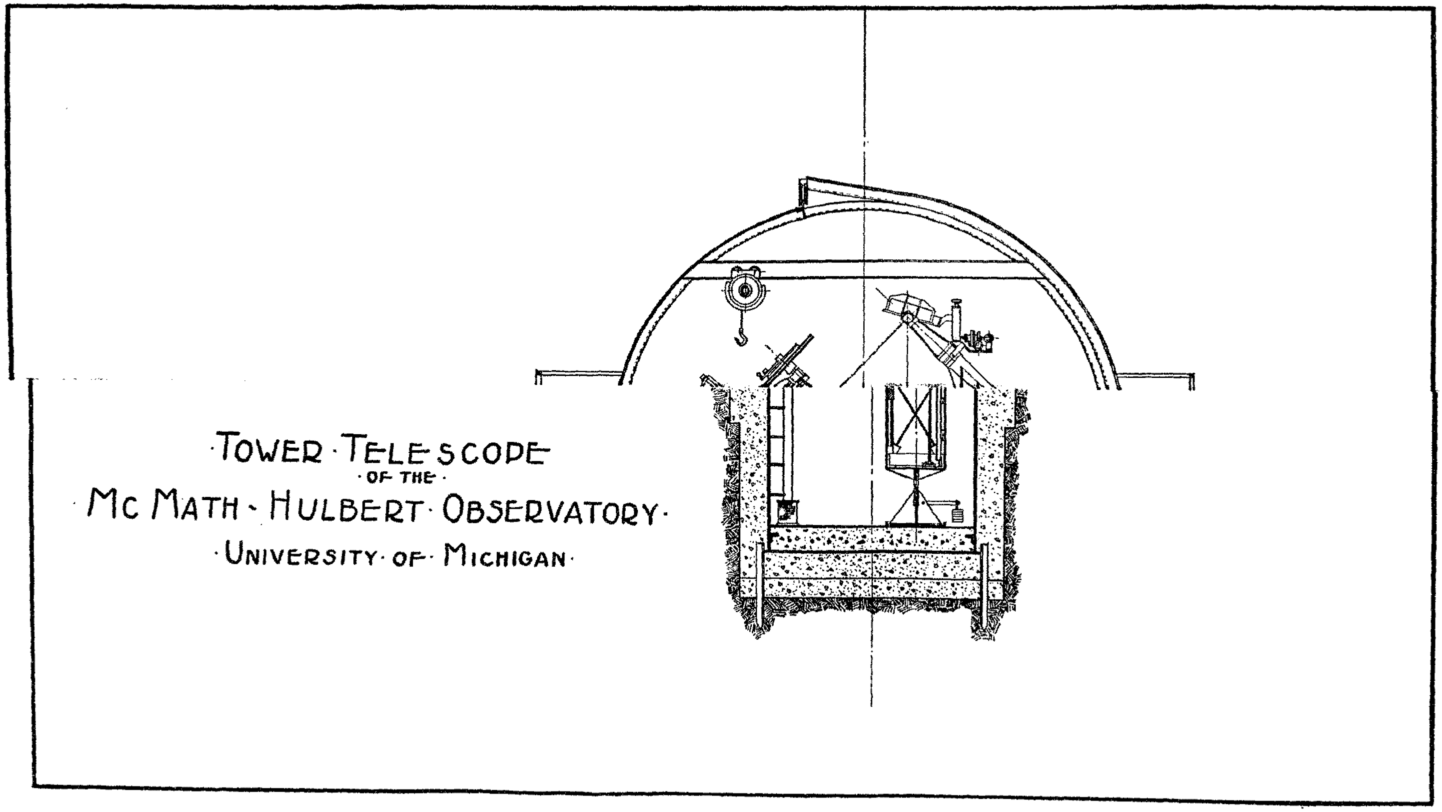
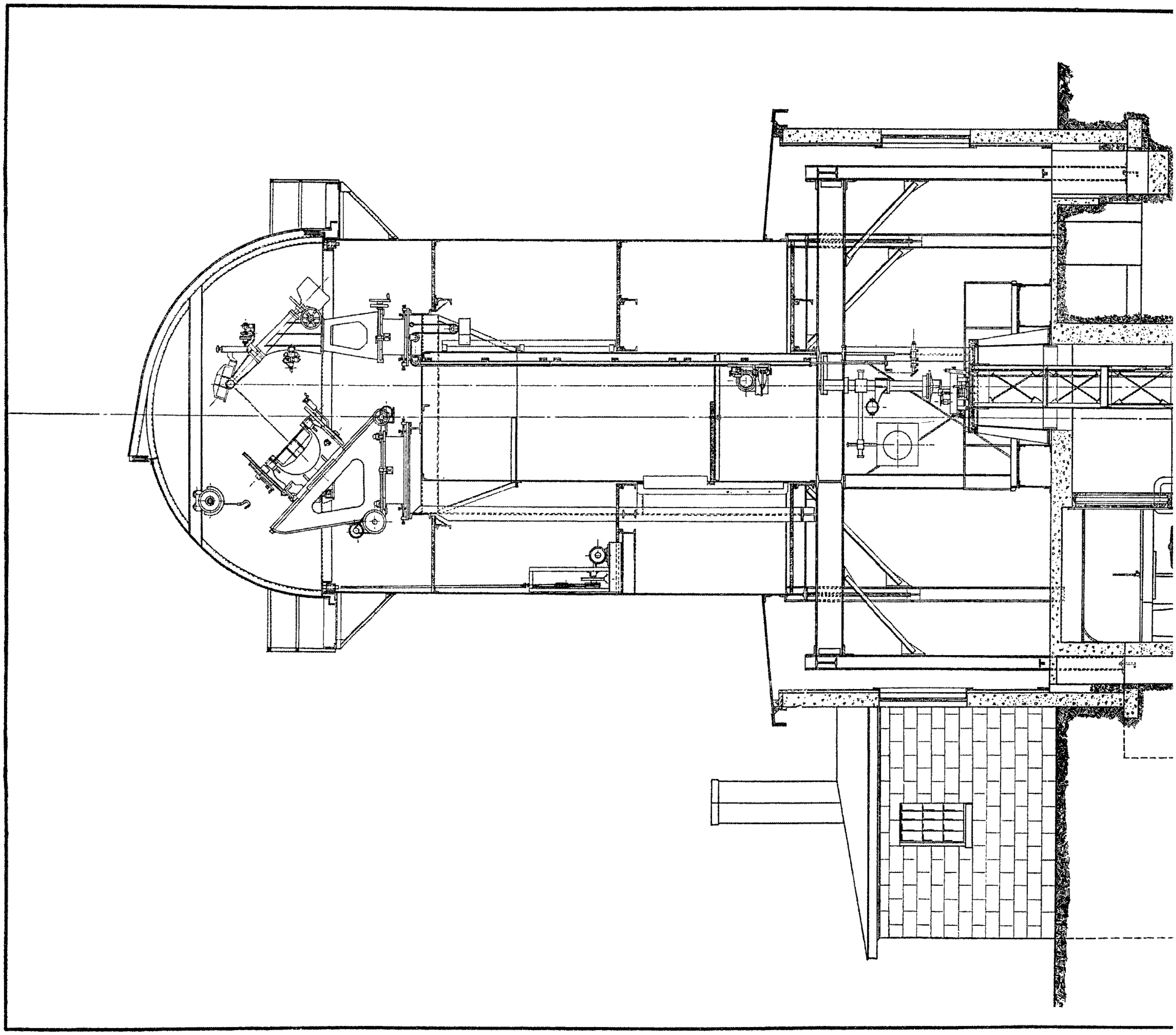
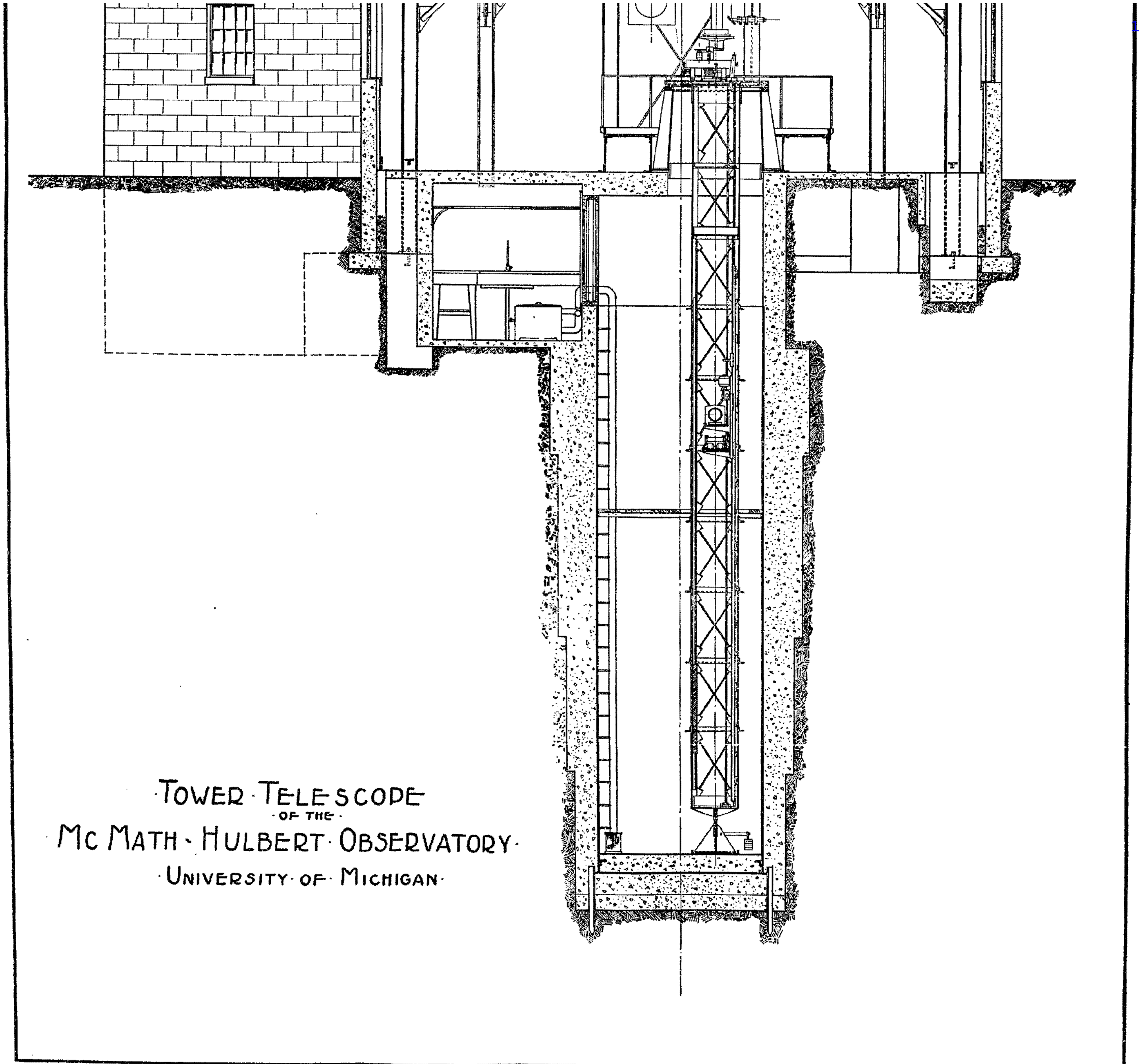


FIGURE 1. Cross Section Diagram of the Tower and the Spectroheliograph Well, from a Drawing by John Brodie and G. Malesky.





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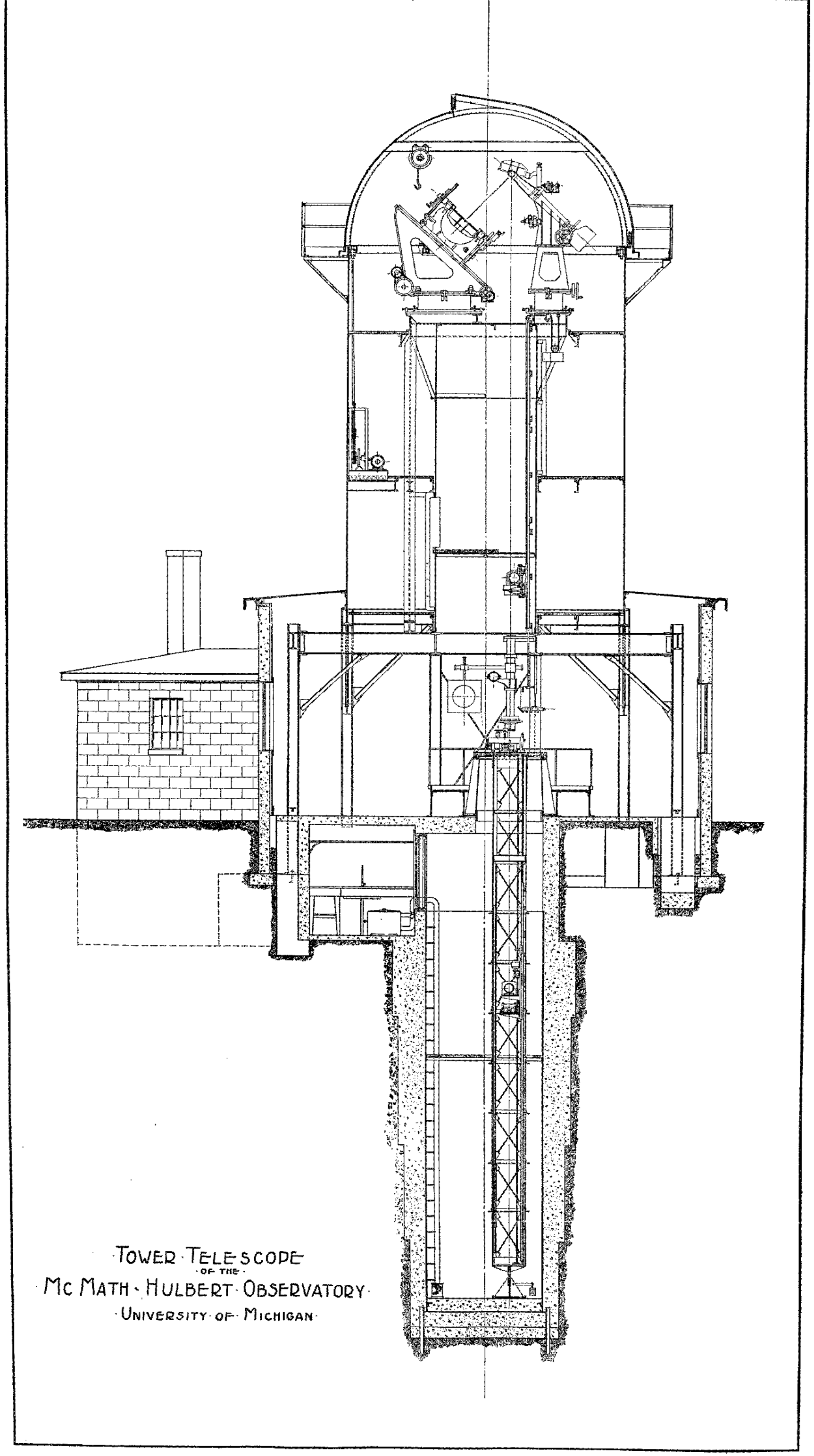

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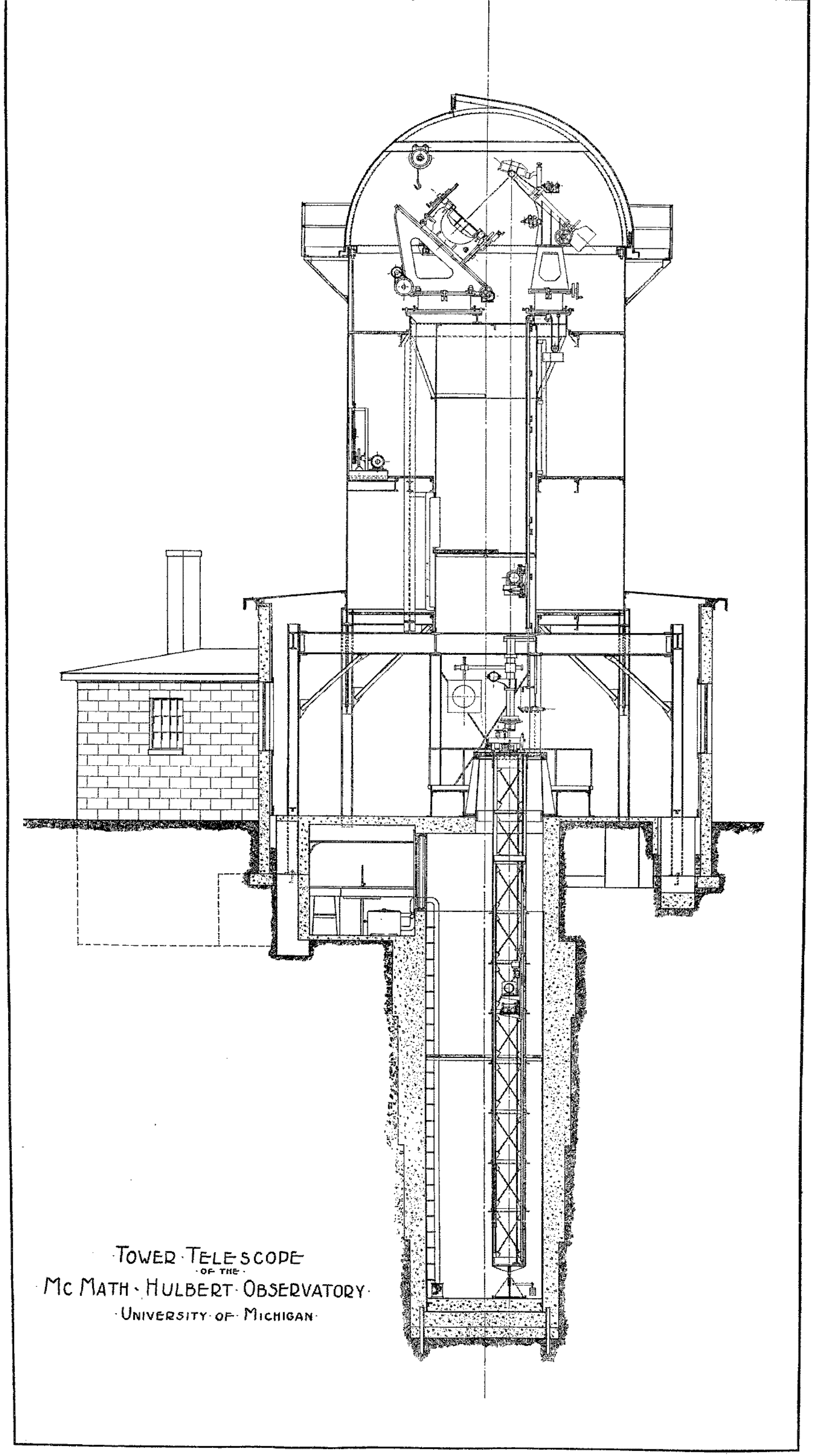

FIGURE 1. Cross Section Diagram of the Tower and the Spectroheliograph Well, from a Drawing by John Brodie and G. Malesky.

The concensus of opinion among the astronomers consulted was that a spectrograph of 30 feet focal length would be sufficiently powerful to take rank among the larger instruments of this type in the world, and to provide for spectrographic work of a fundamental character. When it was decided to make provision for such a spectrograph, the decision then involved the deepening of the spectrograph well from 15 feet to 31 feet, and the spectroheliograph now requires two collimating lenses of 15 and 30 feet focal length respectively.

To emphasize further the fact that the new tower telescope will not be a single-purpose instrument, exclusively for solar motion picture work, but will be instantly adaptable for other work of a fundamental character spectrographically, it may be mentioned at this point that an additional top cover plate to fit the spectroheliograph head (see Plate 10) was machined at the same time the present equipment was manufactured. These two cover plates fit the same dowels on the pedestal that covers the well, and this spare plate has been bored and drilled to take the various rods and other controls which will be common to both instruments. As soon as funds are available, we expect to complete this spectrograph head. By design, it is possible to pick up either instrument head by means of a chain hoist and exchange it for the other without interfering with any of the mechanisms or controls. Thus the future program of the tower telescope will in no sense be limited merely to motion picture studies of solar action forms.

The Tower: Location

It has already been pointed out that the new tower telescope as a whole represents a logical development from the earlier apparatus which has been devised and put into service at this observatory, and it also has been noted earlier how intimately interconnected are all the mechanisms serving the difficult technique of securing with perfect registration a thousand or more separate exposures or "frames" of a given celestial object. Thus no question could arise as to the location of the tower, inasmuch as it was obvious from the start that the tower must be near enough to the original plant to utilize the already existing control and drive mechanisms. These mechanisms are in the underground control room (see Plate 14), adjacent to the 10.5-inch reflector dome, and were the deciding factor in locating the tower 50 feet to the north of that dome. Work on the sun during 1934 and 1935 had already convinced us that our day seeing would be of sufficiently good quality to warrant the expense of the new instrument, and test borings had shown that the foundations would be built in the omnipresent stable glacial drift of lower Michigan.

The location of the tower in reference to the 10.5-inch dome may be seen in the plates reproduced with this paper. Plate 1 is from a photograph made for us by Colonel Sidney D. Waldon, and affords an excellent idea of the plant in its present form. The Frontispiece is from a sketch by Russell W. Porter, of the California Institute of Technology, whose high artistic skill in the depiction of complex astronomical apparatus is well-known to all astronomers. A complete diagram of the tower and well in cross-section is shown in the folded insert, Figure 1, and other plates or line diagrams show the structural elements in greater detail.

The location chosen is on a sidehill affording good drainage, and the terrain from the northeast to the southwest is wooded and hilly. Lake Angelus lies directly south of the tower telescope at a distance of about an eighth of a mile. It is now a matter of record that our faith in the quality of the seeing was justified, for, on a scale of ten, the seeing has averaged, by daily comparison, at least two points better in the tower telescope than in the conventional 10.5-inch dome.

Outer and Inner Towers

As with any new type of instrument in a relatively untried field of work, responsibility for many elements of the design is divided among a number of individuals to whom the author once more extends his grateful acknowledgments. Many suggestions have been worked out jointly by the author and Dr. Pettit, or others; details that promised to be necessary and useful have been freely incorporated from earlier instruments of this type. But in all cases the actual embodiment of such suggestions in mechanical form, the preparation of the detailed design, the working drawings, and the supervision of the machine work when necessary, have been carried through by the author.

A great deal of study was given to the design of the inner and outer towers. It was recognized that maximum rigidity was imperative, in the inner tower especially, and that it was very important to secure as uniform air temperatures as possible on all sides of the inner tower which supports the coelostat and second flat in order to secure equal heat expansion or contraction in all supporting members. Unequal changes in length due to temperature changes would tend to tilt the coelostat and second flat. Mr. Leo J. Knapp of the Whitehead and Kales Company suggested that the employment of two circular towers would provide the maximum amount of rigidity for the amount of steel used, and also give a large air space between the two towers, practically preventing uneven heating of the inner tower. This space also permits easy access to the coelostat from the workroom floor by means of stairways. After considering several other designs the circular one was chosen.

The outer tower is 16 feet 6 inches in diameter and is made of one-quarter inch steel plates with all joints riveted. It is supported by four 12-inch I-beams to which its base ring is riveted. These supporting beams are riveted to four 8-inch H-columns. Substantial knee braces from the beams to the columns take care of any wind stresses. The inner tower is 6 feet in diameter, also made of one-quarter inch steel plates welded together. At its top it spreads into a very substantial welded steel platform upon which is carried the massive coelostat and second flat mountings. It was most necessary to construct the inner tower as rigidly as possible, thus reducing deflections and vibrations to a minimum, and consequently the construction is far stronger than would be required merely to carry its loading. The inner tower is riveted at its base through heavy steel plates to four 16-inch I-beams which are supported by eight 8-inch H-columns, all heavily knee braced to the beams. Sway bracing between each pair of columns has been provided, consisting of 1 1/8-inch round adjustable steel rods, and horizontal diagonal bracing of similar rods is used in the panels of the 16-inch supporting I-beams. These bracing systems force all of the columns to act together as one rigid mass to reduce deflection and vibration to the minimum. Inasmuch as the coelostat at the top of the tower is north of the center of the inner tower, an eccentric loading results. To provide for this eccentricity an additional system of two 8-inch H-columns was added to support the north end of the coelostat platform.

The Whitehead and Kales Company of Detroit furnished and erected all the structural steel used in the construction, including the dome; and I wish to acknowledge the assistance given by my brother, Mr. Neil C. McMath, Vice-President of the above firm, who personally supervised this work.

Reference to Figure 1 will show that access to the dome and the coelostat is given by means of stairways and diaphragm floors between the two towers. Figures 3, 4 and 5, from drawings by Brodie, show floor plans of the tower at various levels. A welded steel roof covers the space between the outer tower and the walls of the workroom; this roof has been painted on both sides with aluminum, and has proven to be excellent from the heat standpoint.

The octagonal observing room at the foot of the tower proper is built of cement blocks, and is approximately 28 feet in "diameter." On the inside, an air space of about 1 inch has been provided, next to which is aluminum foil and then a layer of plaster to provide heat insulation. For thermal reasons, I was particularly anxious to enclose the main supporting columns completely, and to obtain sufficient headroom for this, the cement-block walls were carried to a height of 13 feet. Thus the two independent and mutually isolated systems of columns and cross beams just mentioned are contained inside the workroom. The outer tower, as noted, serves both as a windbreak and sunshade for the inner tower, and as the mechanical support of the dome.

With both doors into this room closed, we have a horizontal stratification of the air in the inner tower throughout the summer. A 1,000 cu. ft. per minute ventilating fan was accordingly installed to draw the air off from just underneath the steel roof, exhausting the air outdoors on the north side.

Attached to the northeast side of the main workroom is a small combined

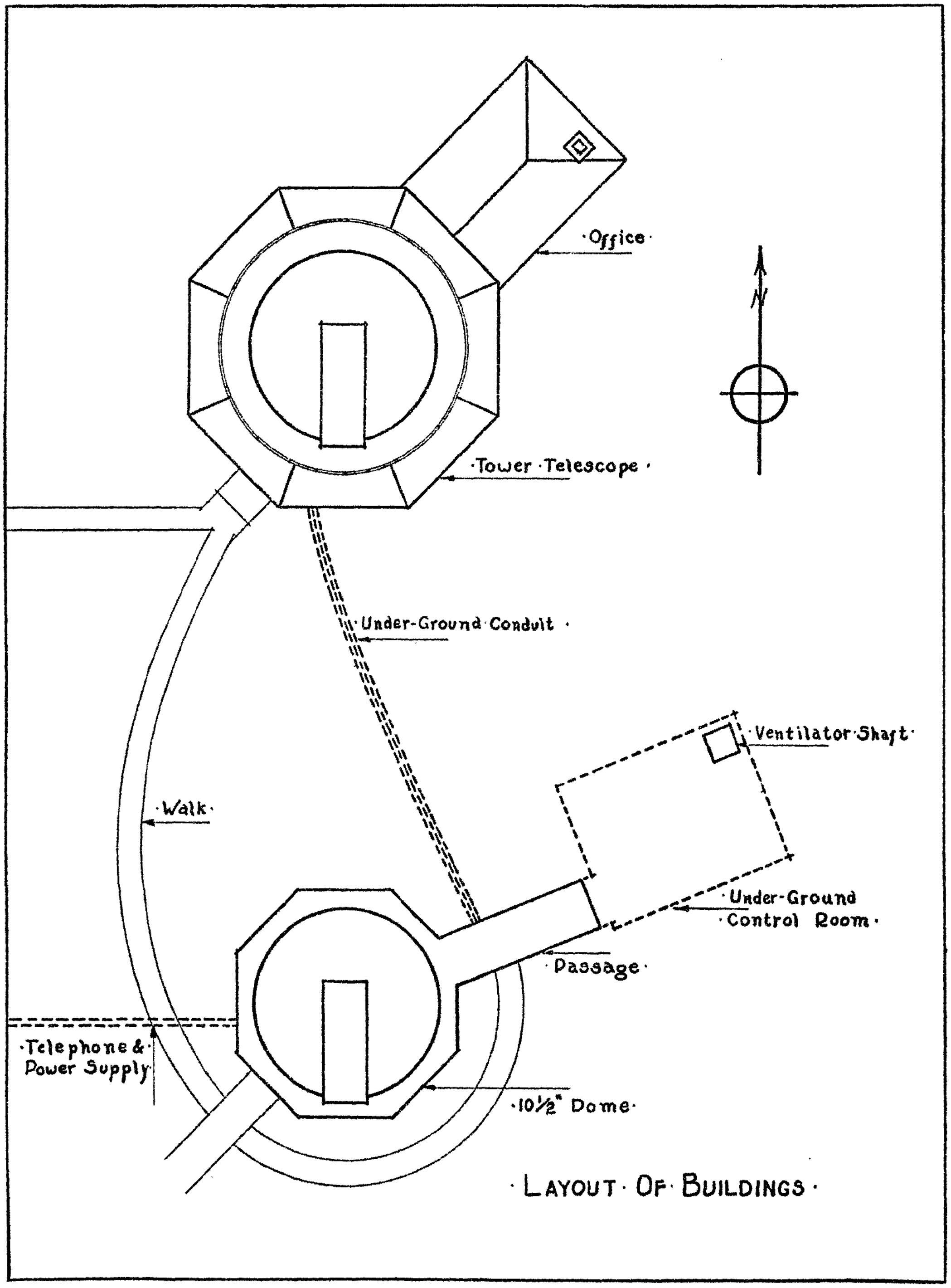

FIGURE 2. Layout of Buildings of the McMath-Hulbert Observatory.

office and workshop; this annex is also of cement-block construction and is provided with a cellar of the same area, which is used as a general storeroom. The office is equipped with a desk, bench, etc., and shelves provide for a small working library, radio and chronometer. This office is heated for occupancy during the winter months.

The main workroom is provided with fenestra steel windows on each wall for ventilation. During actual observing time these windows are kept closed, and have been well-covered with aluminum paint to provide for darkness inside and to minimize the heat transmitted from without. Every effort has been made to provide a thermally stable structure, and to this end the entire steelwork of the tower is painted with several coats of aluminum paint.

The floor of the main workroom at the foot of the tower is of reinforced concrete poured with ½ inch of felt between it and the outside curtain walls; it is separated from the outside column footings by a space of about ½ inch, and is carried upon the brick separating walls around the foundations of the inner tower.

Access to the workroom when observing is in progress is normally had by entering the office room first; then, after closing the outside door, it is possible to enter the workroom without the smoke-stack effect causing the air to sweep up through the central tower. The foundations of the two towers have been kept as completely separate as possible. The footings that carry the columns for the inner tower are about 7 feet deep, and the upper 3 feet have been blocked off with a 3-inch air space all around in order to isolate these inner tower columns from surface tremors. The foundations for the columns carrying the outer tower are 5 feet deep, and were poured simultaneously with the curtain wall that carries the cement-block wall surrounding the workroom.

The design and construction has proved very successful in preventing vibration of the inner tower from wind pressure against the outer tower, and from surface tremor shake. While moving the dome by the electric motor provided for this purpose there is a noticeable vibration of the image, which, however, damps out almost instantly after the dome stops. To obviate this, an electrical interlock has been provided for the dome motor circuit which makes it impossible for the observer to move the dome while the camera shutter is open. Ground was broken for this tower on July 16, 1935; the dome was erected on October 15, 1935; and on July 2, 1936, the completed tower telescope was in actual use.

The Dome

Perhaps because of the comparative rarity of such commissions, domes contracted for in the usual manner from commercial sources are apt to prove a very expensive feature, and the method here adopted for building the dome housing the instruments at the top of the tower possesses some elements of novelty.

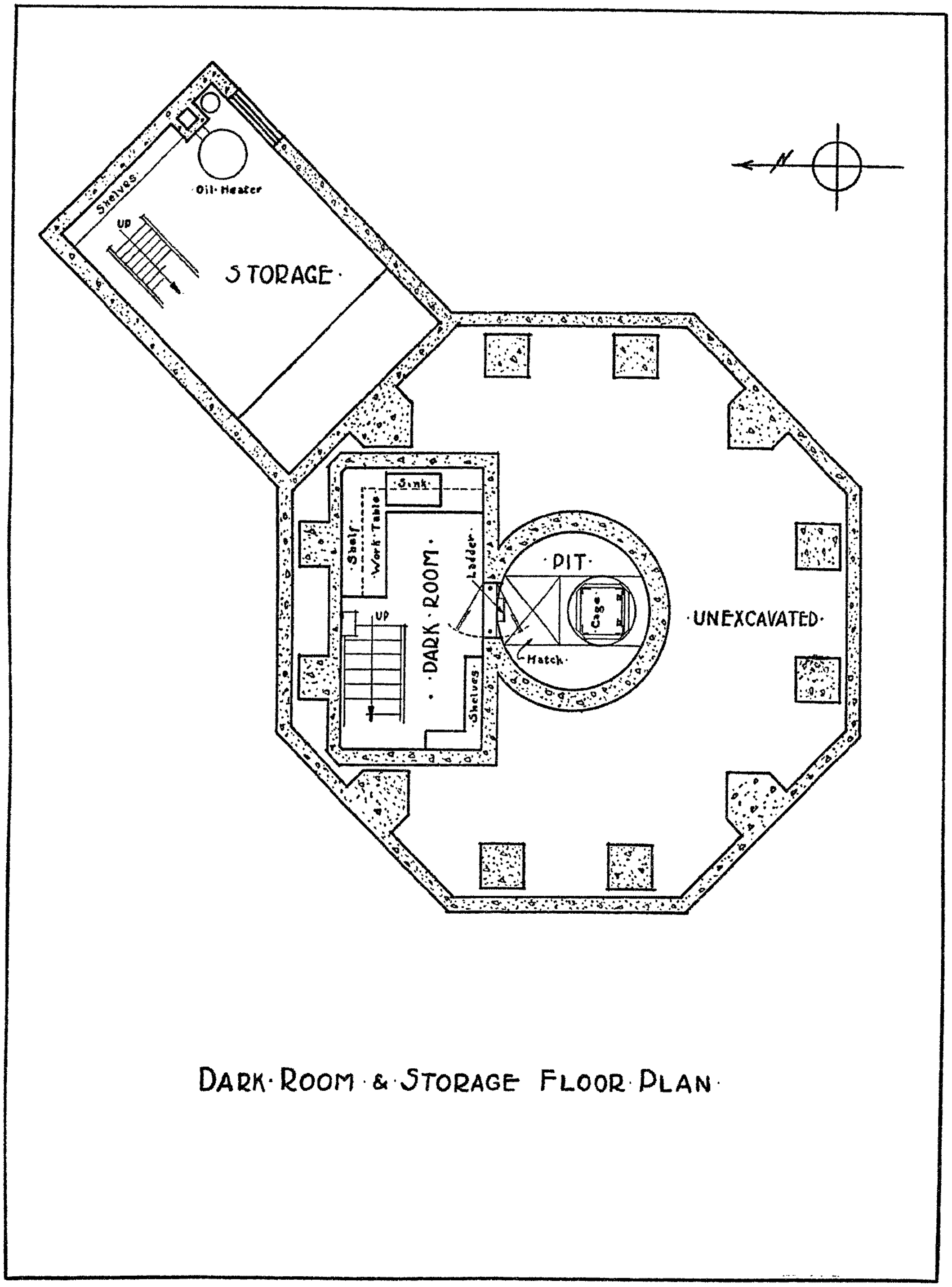

FIGURE 3. The Tower Telescope; Dark Room and Storage Floor Plan.

The hemispherical bottoms of commercial water tanks are a well-standardized product, and can be purchased on short notice in a variety of sizes ready to ship and set up; and the tower dome, 17 feet 6 inches in diameter and steel throughout, is actually the hemispherical bottom of a standard water-tower tank turned upside down, with plates one-eighth inch in thickness.

After the dome plates were riveted together, a 6 × 8 × ¾ inch angle bent in a true circle was welded to the bottom edge of the hemisphere. The shutter opening was then cut out by means of an oxy-acetylene torch. A double-leaf shutter is provided, giving a clear slit opening of four feet; a narrow slit dome was considered advisable in this locality because winds are prevalent throughout most of the year. The one-eighth inch dome plating was reinforced by steel angles welded to the plating at each edge of the slit, and to the angle on one side a steel beam chord was welded to support a one-ton hoist. This chain hoist was used to handle the heavy coelostat parts during erection, and is also used to remove and replace the large coelostat mirrors when aluminizing is necessary.

The dome rolls on eight steel rollers bearing on the base angle ring, and is kept concentric by means of lateral spacing rollers. It is turned by an electric motor operating a ½-inch steel cable placed around the 6 × 8 × ¾ inch base angle, and may be operated from the workroom as well as from the dome floor itself by means of pushbutton controls. Access to the outside of the dome is by means of a circular footwalk carried on brackets attached to the top of the outer tower. This type of dome construction has been found to be very rigid as well as inexpensive, and has proven to be most satisfactory in service.

The Spectrograph Well and Darkroom

The modification of the earlier design to provide for a spectrograph well 31 feet deep has been previously noted. The construction of this well in our water-carrying glacial drift presented some difficulty. The contract for the well was awarded to the firm of George R. Cook & Company, on the basis of merit, and the writer suggested that a welded steel water-tight cylindrical liner of suitable design be used as the inside liner for this pit; after due consideration this design was adopted. A steam crane was employed to make the excavation, which was shored by a method much used by Mr. Cook. In this method the well was shored in four steps of about 8 feet each by means of 2-inch staves supported on the inside by welded steel circular rings.

Considerable water was encountered while sinking the well, and the last 15 feet was dug through blue "Detroit River" clay. Heavy steel angles were driven into the clay at the bottom of the pit to serve as guides for the steel liner shell. A concrete bottom was poured and allowed to harden, after which the steel shell was lowered into place. This shell liner was used as the inside form and all the concrete

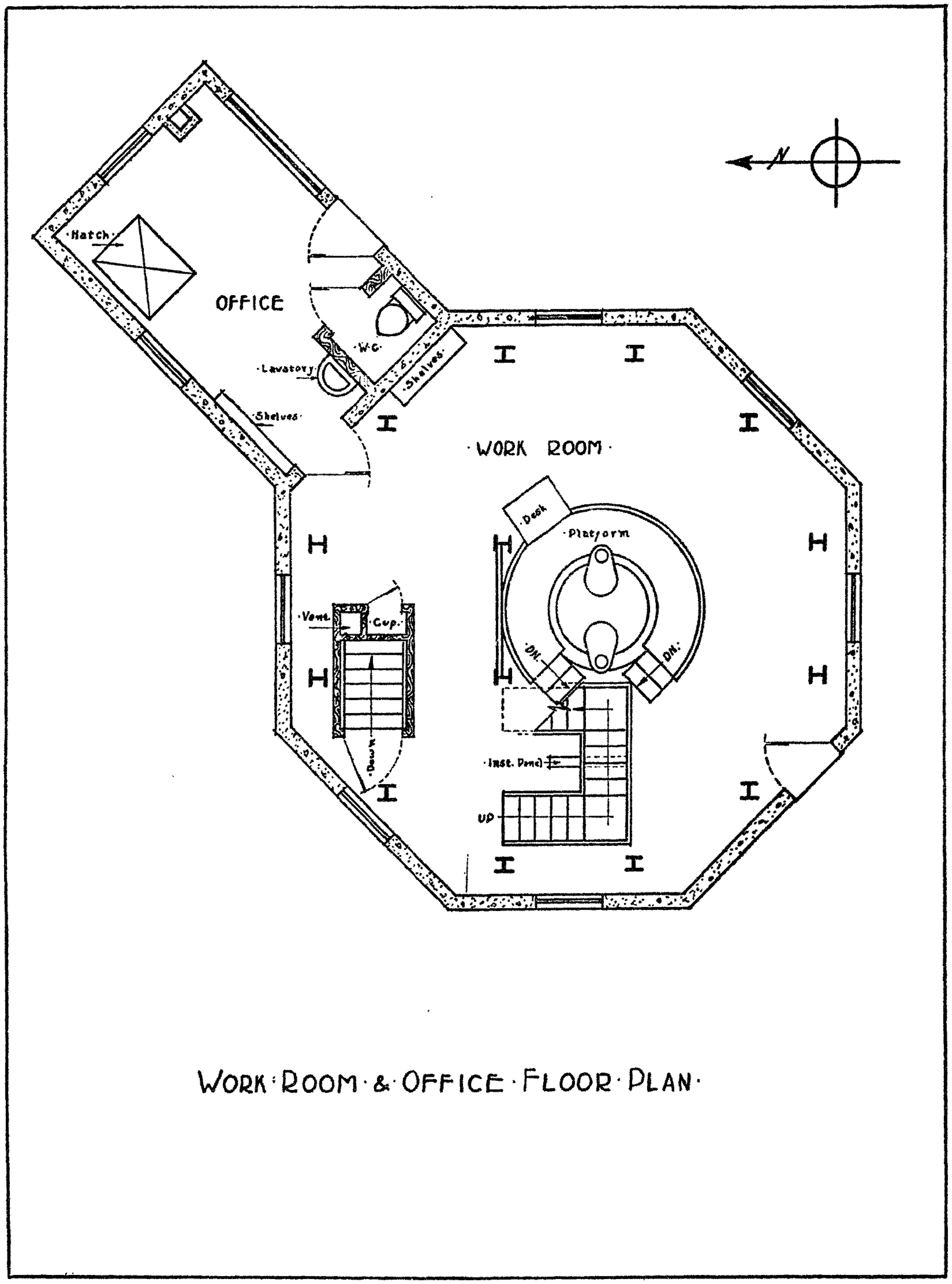

FIGURE 4. The Tower Telescope; Workroom and Office Floor Plan.

(about 85 cu. yards) was poured on the same day. A space under the floor of the workroom was excavated for a darkroom to the north of the well, and the steel liner stops at this level where a door provides easy access to the well. The upper six feet of the well wall was poured into wooden forms and the final pit cover with its central hole 4 feet in diameter is about 12 inches thick. As will be seen from the drawing, Figure 1, this design results in thicker walls as one proceeds toward the ground level. This is necessary because of the fact that an open lined structure of this sort in water-bearing soil has a very high flotation value, and sufficient concrete must be added to the walls to prevent an actual floating up. A wooden diaphragm was built in the well at a height convenient to the 15-foot spectrograph level, and individual steel rungs were welded in the shop to the inside of the steel liner to provide a ladder reaching to the bottom of the well.

This well has proved to be absolutely water-tight, and has shown no signs of settling. This absence of settlement is presumably due to the manner in which the forms were set, because no concrete was poured on disturbed ground in the plan of construction followed. Local climatic conditions engender a comparatively high relative humidity throughout the year, making de-humidification necessary inside the well most of the time. This is accomplished by blowing the pit air over a screen carrying commercial calcium chloride.

An essential part of an observatory is a suitable photographic darkroom. Our summers in Michigan are apt to be both hot and humid, making work in an ordinary darkroom difficult and uncomfortable. To secure good working temperatures, it was decided to locate the darkroom underground, and the location chosen is on the north side of the spectroscope pit, under the floor of the workroom. This location provides easy access to the well by means of a double door between the darkroom and the upper part of the well. The darkroom is 7×13 feet in floor plan, and is equipped with the usual benches, shelves, monel metal sink, etc. The blower which ventilates the workroom is arranged to ventilate the darkroom as well, and during the past very warm summer quite comfortable temperatures were maintained. The opening in the floor of the workroom is covered by a double celotex walled structure, built in the form of a companionway, which carries the ventilating fan and ducts.

This darkroom has proved to be a very useful adjunct to the work with the solar tower, more particularly for the prompt development and examination of the scout camera plates (see p. 40), which are taken continuously through the period of a solar prominence exposure at brief intervals as a check on the performance of the spectroheliograph and the progress of the changes taking place in the solar formation. As noted earlier, no actual processing of our films is done in this darkroom, since it is far more efficient to have this done commercially in laboratories adequately equipped for the purpose.

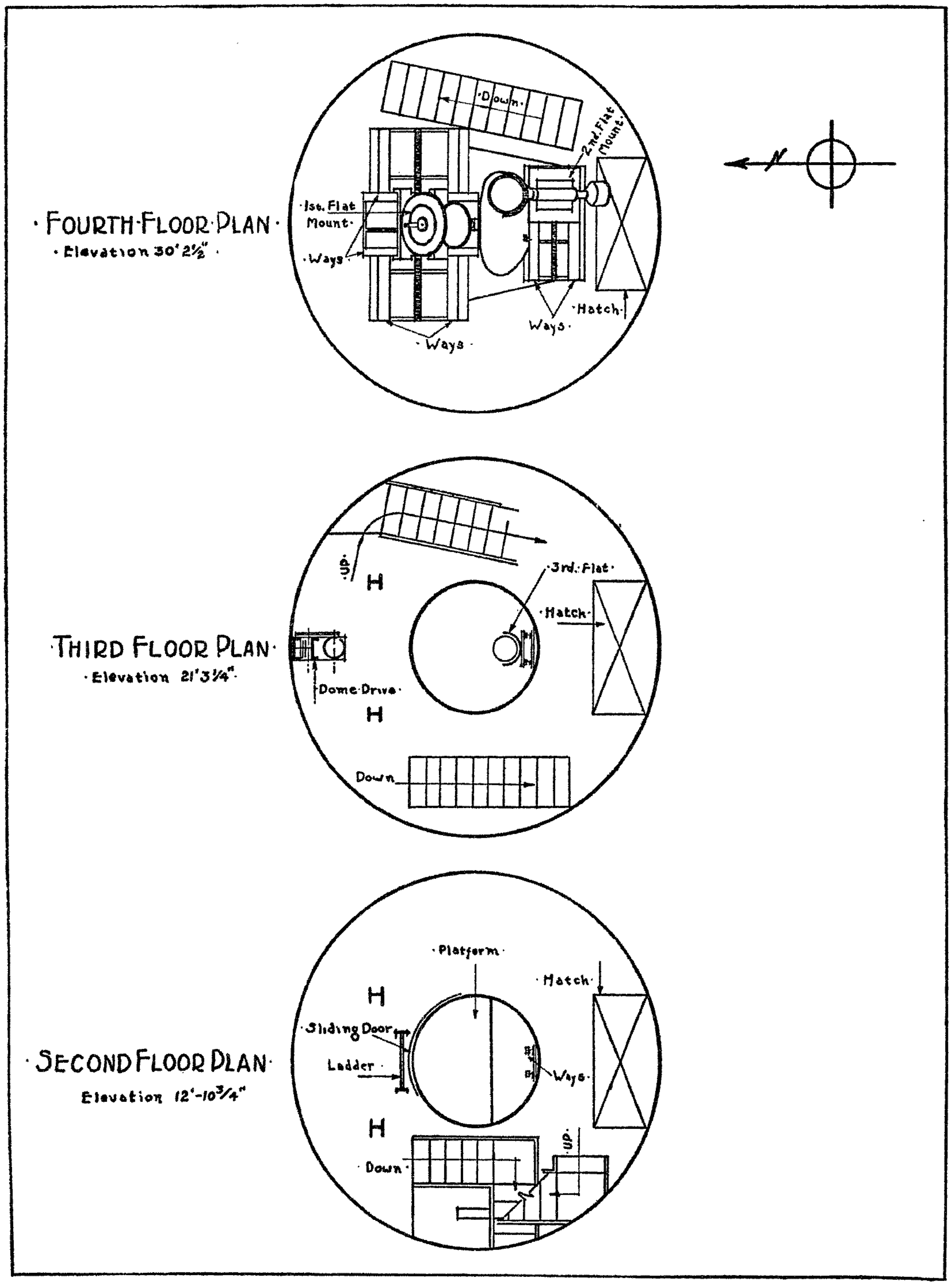

FIGURE 5. The Tower Telescope; Second, Third and Fourth Floor Plans.

The Tower: General

The operations during the summer of 1936 have demonstrated the wisdom of the adoption of the circular design of the towers. The outside tower proved an excellent sunshade and windbreak for the inner tower as was expected, and, at the same time, proved a satisfactory and economical support for the dome. It is believed that this type of design can be extended to larger towers with real economy, and details of the structural steel used in the two concentric towers will be gladly furnished to those interested.

Both doors of the workroom are kept closed when the tower is in use for observation. The air inside the workroom and the inner tower shows horizontal stratification as demonstrated by smoke tests, and upon many occasions operation of the 1000 cu. ft. per minute ventilating fan just under the workroom roof appeared to improve this condition during the hottest hours of the day. The inner tower is normally wide-open during observing, as are the stairways leading to the coelostat. We have often been able to observe up to an hour angle of six hours west during the past summer. It is believed that the general design of the two towers represents an advance since it provides both rigidity and excellent temperature control, with their resultant effect upon the quality of the image.

Our practice is to examine the sun early in the morning with the spectroheliokinematograph used as a spectrohelioscope. A map of the sun is drawn up from this examination, showing the location of the sunspots and with all prominences classified as to brightness, and these are inserted on the limb at their approximate position angles. This map is taken into the tower telescope, and, by applying a rotation factor (varying from 0° in the summer season to 21° in winter) to the map, the spectroheliograph head is set by means of its divided circle to the desired prominence. A scout plate is then taken and developed of each prominence thought worth investigating. These pictures are then used in determining which prominence will be photographed in the main camera for the day's work. An hourly check at the spectrohelioscope is made throughout the day, which occasionally results in a change of the spectroheliograph setting. We believe that the spectrohelioscope is an essential accessory to the spectroheliograph. When the prominence is particularly important, it is our practice to photograph simultaneously with both the spectroheliograph and the spectroheliokinematograph, the first in calcium K_2 and the latter in $H\alpha$. As far as is known, this observatory is unique in its ability to make *continuous* accurately timed records simultaneously in both calcium K_2 and hydrogen α, with the additional check which is provided by the scout camera plates taken in the H line of calcium, without in any way interfering with the operation of either of the other two cameras.

The Coelostat

Before adopting the final design of the coelostat and the second flat mounting, a thorough investigation was made of similar instruments at other institutions, and wooden models to a small scale were built of each type to estimate their convenience in use. It was finally decided to adopt, in general outlines, the design followed by Abetti at Arcetri, the chief merit of which is to reduce to a minimum the space occupied by the coelostat within the dome. Valuable suggestions were also derived from Dr. Hale's paper,—"The Astrophysical Observatory of the California Institute of Technology," Astrophysical Journal, Vol. 82, p. 111, 1935. As worked out for the Lake Angelus installation, the east and west ways are 104 inches long, and the polar axis ways 88 inches in length. I think it was Mr. Russell W. Porter who first suggested to the California Institute of Technology the device of mounting the second flat in a fork on a polar axis, a feature which has been incorporated in our own design, thereby adding a declination motion to the solar image. The merit of this latter innovation is that it makes a coelostat mechanically equal to an equatorial telescope and adapts it to our form of telescope control. The polar axis of this flat mounting also affords a second motion in right ascension which is secured through a coarse worm wheel and hand operated worm, for setting purposes only.

The coelostat mirror is 22 inches in diameter and 5 3/8 inches thick; like all the other mirrors of our optical train, it is made of optical pyrex with its attendant very low coefficient of expansion. This mirror and the 18-inch second flat were figured by Lundin, of the Warner & Swasey Company, and possess surfaces of unusual optical perfection. If the reader will refer to Plate 2, he will notice that the polar axis of the coelostat itself extends through the main worm wheel and ends in a hand crank, marked *A*. By means of this crank and a clamp screw the coelostat mirror can be rotated in hour angle until its beam fills the second flat. At *B* will be seen one of the three collimating jackscrews which are also used to lower the mirror into its cell. At *C* (partially concealed) will be seen the main drive in right ascension. It consists principally of a synchronous motor which is driven by the McMath-Hulbert electrical telescope drive system through circuits extending from the underground control room. Superimposed on a large aluminum flange on the drive shaft are two small reversible motors which rotate with the drive shaft, as suggested by Curtis. One of these gives the guiding motion, one second of arc per second of time, and the other motor gives the slow setting motion of 45 minutes of arc per minute of time; the fast setting motion is made by hand as described above.

At *D* on the same plate is shown the end of the declination drive fork on the second flat cell. This fork is driven by a nut on the long screw shown between the vertical side plates. At *E* is shown the motor which when driving straight through the planetary train gives the slow setting motion of 45′ per min., while the declination drive is obtained by means of a Selsyn driven from the control room. This Selsyn is shown at *A*, Plate 4. The fast setting motion is applied by unscrewing a locknut (not shown) and then turning the fiber handle, shown at the top of the driving screw, Plate 2.

From the mechanical standpoint, both the coelostat and second flat mounting are built entirely of welded steel construction, even the mirror cells being fabricated in this manner. In this locality such structures built up by welding can be bought for about the price that would be asked for the pattern alone for a complicated casting. These large welded constructions were all double- or triple-annealed in order to normalize all strains, then sand-blasted complete and painted. This method of construction entirely obviates the necessity for seasoning castings.

The coelostat alone is shown in Plate 3. The ways *G* were built of heavy section I-beams welded to a bottom plate and reinforced with several diaphragms. To the top of each way was bolted a machined nickel-iron way *H;* nickel cast iron was chosen because it is very close-grained, hard, and takes a high finish. The ways are supported on six jackscrews for leveling, and are swung in azimuth by the usual type of adjusting screws. The polar axis ways are traversed by means of the motor drive *E*, which actuates a pinion engaging in a long rack. Relieving rollers and levers *F* were installed, spring loaded at *K*, which by construction assume 80% of the total weight; in consequence, the coelostat head may be easily traversed by hand if desired through the large pulley wheel of the motor drive.

At *D* is shown the motor which drives the long declination worm. A herring-bone gear reduction was chosen for this motor in order to superimpose a hand adjustment by means of the hand wheel shown just below and to the right of *K*. The declination worm runs in bronze bearings and is equipped with ball thrust bearings at both ends.

The throat carrying the coelostat polar axis was torch-cut from a steel slab 3½ inches thick, making it one homogeneous piece. The polar axis itself runs in four Precision SKF ball bearings, as does the main worm wheel *A*. On the southern extension of the coelostat polar axis there will be noted the large gear *B*. Just below this gear is the other counterweight gear, mounted in ball bearings; this gear carries the counterweight arm and the counterweight *C*. Immediately above the counterweight itself will be noted a small hand crank; the counterweight is raised or lowered by this hand crank so as to maintain a constant pressure against the main thrust bearing of the driving worm both in the morning and the afternoon.

The second flat is also of optical pyrex, 18 inches in diameter by 5¼ inches thick. These, and all other mirrors, were aluminized by Dr. Williams at the University of Michigan Observatory. The mounting of the second flat is shown on Plate 4; the ways are of similar construction to those just described for the coelostat head. They are long enough to permit moving the second flat 18 inches east or west of the optical axis of the inner tower optical system. As this mounting is much lighter than that of the coelostat, it is easy to traverse the second flat head by means of gears and a hand crank shown at *G*. At *D* are shown the worm and worm wheel which rotate the second flat about its polar axis, and at *E* will be seen the counterweight installed to balance the second flat mounting about a vertical axis. The Selsyn which is driven from the control room to provide a uniform drive in declination is shown at *A*.

A 4-inch aperture by 40-foot focal length single element guiding lens is shown mounted at *C;* its mounting provides for motion both east and west and north and south, in order not to interfere with the main beam. This lens is collimated by means of motors shown at *B*, controlled by pushbuttons located in the main workroom.

The writer believes that there can be no substitute for mass when the designer is endeavoring to secure rigidity and freedom from harmful vibration. The total weight of the coelostat and second flat mountings is a little more than 6½ tons, exclusive of the weight of the mirrors.

An auxiliary 4-inch pyrex mirror will be installed eventually just underneath the second flat in such position as to fill the guiding lens *C* on Plate 4. By means of this auxiliary mirror it will be possible to spot our guiding image at any desired location in the workroom below. An experimental set-up of this sort with a crown glass mirror proved exceedingly useful during the summer of 1936.

The entire coelostat mechanism has proved wholly satisfactory in actual use. It was easily placed in position and has maintained its adjustment throughout the first summer's use; there is apparently no wandering of the image due to local heating of the steel. It is manipulated and adjusted for the observations of the day with great speed and entire convenience. From April 1st until September 1st the coelostat is kept in a fixed position just north of the flat giving true readings of position angle on the spectrograph head; at other seasons one shift must be made every day resulting in position angle corrections up to 21°.

Third Flat and Lens Mounting

One of the objectives set in advance for this tower telescope was great ease and rapidity in changing the focal lengths to be used, or in changing from an all-mirror system to the use of an objective lens. After consideration of several possible designs, it was decided to mount the third flat and the lens upon a carriage with a large range of vertical movement within the inside tower. The ways on which this carriage runs are well shown in Plates 5 and 6; a great deal of care was expended in scraping these ways so that their outer edges would be strictly parallel. As will be seen at *A* in Plate 5, these ways are doweled to track plates *B;* the adjusting screws and holding bolts are clearly shown in the illustration. For the adjustment of these ways, a fixture was made which slid up and down the ways, provided with a very small hole at the outer end through which was passed the string of a plumb bob. This plumb bob string was secured at its upper end to the center of rotation of the second flat, and by this means the ways were accurately aligned in all directions.

At *C* will be seen the reversible motor that operates the power drive to run this third flat mounting up and down the inside tower; the drive is through a planetary gear system. At *D*, the planetary train case is locked by the worm and worm wheel *E*, with the final drive through the pinion and gear *F*, engaging in the rack *G*. This vertical drive runs at a rate of 10 feet per minute.

A hand or fine setting adjustment is also provided, actuated by the square brass rod *H*. This rod extends down to the workroom where it terminates in a hand crank located at a point convenient to the small telescope used to read the focusing scales; a typical scale is shown at *J*. The whole carriage weighs 350 lbs., and is counterweighted to secure ease of fine adjustment; the counterweight cable is visible at *K*. The mirror itself is mounted in a heavy steel fork *L*; this fork has motor-driven adjustments for collimating the main image in both coördinates. One of the motors for this purpose is shown at *M*; the other is concealed behind the cell.

By loosening the hand operated clamp screw this mirror cell is reversible to permit the mounting of the Cassegrain hyperbolic secondary mirror on the back of the cell. It is now planned to make the rear surface of our present third flat convex, in order to provide for an increased focal length. This third flat is 9½ inches in diameter by 3½ inches thick; it is of optical pyrex and was figured by the F. C. Henson Co.

By referring to Plate 6 it will be seen that both the third flat and the lens mounting are carried on leaves which are hinged on taper pins to the base plate. Hanging on their safety chains *N* and *O* are the locating taper pin and screw clamp respectively. An examination of these two plates will show the reader how easy it is to change the mirror system for a lens, or vice versa. Due to delays in the delivery of some of our optical train, we are at present using a 6-inch Clark visual objective of 8-foot focus here, together with a small negative lens to secure a focal length of 10 feet; the present lens leaves will accomodate any aperture up to 10 inches. In practice, it takes about seven minutes to change systems and focal lengths employed. Consequently such a change is easily made during the progress of a picture if the prominence develops unusual activity or shows eruptive characteristics. The lens mounting is lowered to the inner tower diaphragm level, where the observer usually makes the change of systems; all the motors are controlled from push buttons at the spectroheliograph head.

The Optical System

It was recognized from the start that the utmost attainable photographic speed and complete achromatism were absolutely necessary if this tower telescope was to produce a thousand or more satisfactory spectroheliograms of solar prominences or disk phenomena per day. For these ends, the all-mirror projection system suggested by Pettit has proved very satisfactory in use. As described above, the coelostat and second flat are of 22 inches and 18 inches diameter respectively. The beam from the second flat next illuminates either a 16 inch off-axis parabolic mirror of 40-feet focal length, or a 12 inch off-axis parabolic mirror of 20-feet focal length, *D* or *C*, Plate 8, depending on which may be the most suitable for the solar formation under observation. The 16-inch mirror is figured 31.5 inches (3° 46′) off-axis, and the 12-inch mirror 28.5 inches (6° 53′) off-axis. The converging beam from either one of these two mirrors is reflected up the inner tower to the third flat, and thence downward to a focus on the first slit of the spectroheliograph where, in the case of work on prominences, a well-finished disk of the proper diameter screens off the solar image up to the base of the chromosphere. Both these off-axis mirrors are of optical pyrex. The 12 inch mirror received its final figure at the works of the F. C. Henson Co., of Pasadena, and the final correction of the 16 inch mirror has been carried out in the Optical Shop of the California Institute of Technology.

When a lens system is employed the second flat is of course placed in the optical axis of the tower as has been the customary procedure hitherto. So far as is known, this tower telescope represents the first all-mirror projection system to be placed in operation. We have not experienced any difficulties with this optical train due to focal changes. The larger mirrors in the coelostat apparently do not give us any perceptible change of focus even when the sky is partly cloudy, and the same appears to be true of the off-axis and third flat mirrors. This absence of focal change is extremely essential when securing continuous records, as a shut-down for focusing would involve the loss of several frames in the motion picture camera.

It was originally thought by both Pettit and the writer that it would be necessary to use the shorter 20-foot focal length off-axis mirror for perhaps 90% of the time, and the 40-foot focal length mirror was added merely to take advantage of those rare seeing conditions which would make its use feasible. Instead, due to the superior performance of the tower telescope as a whole, and the quality of the seeing experienced during the summer of 1936, the 40-foot focal length was actually employed about 95% of the time. This result, while unlooked for, is a definite tribute to the excellence of the mirrors and the design of the tower telescope.

It is perhaps most logical to treat the various parts of the mechanism of the tower telescope roughly in the order followed by the light beam as it passes through the instrument. The next portions of the apparatus to be described would then be the lower elements of the all-mirror reflection system, already mentioned, and the workroom arrangements for visual guiding, leaving certain other arrangements for what may be termed spectroscopic guiding until after the path of the beam has been followed from the grating through the second slit and into the motion picture camera. While it may be necessary to deviate occasionally from this plan, the effort will be made to place the descriptions in approximately this progression.

WORKROOM

Visual Guiding Apparatus

A general view of the workroom is well shown in Plate 8. The off-axis parabolic mirrors are mounted on the two bracket assemblies, *A* and *B*, attached to the structure of the inner tower; these brackets were designedly made very heavy and the supporting 6-inch tubes have a wall thickness of ¾ inch. The brackets proper that support the mirrors *C* and *D* are welded up from ¾-inch steel plates, and these brackets are located in position by means of a tapered pin *E*, so arranged that it can be withdrawn by means of a nut. It is therefore easy to revolve a bracket out of the way if necessary and yet replace it with great accuracy when needed again.

The main pedestal *F* that carries the spectroheliograph head, to be described later in greater detail, is of welded steel construction. The top plate *G* is 52 inches in diameter and to date has provided ample space for our requirements. The pedestal top is 49 inches above the workroom floor and is surrounded with the railed working platform *H*, which is 20 inches high and makes it easy for the observer to lean over the spectroheliograph head when making the necessary adjustments.

At *J* will be seen a portion of the first flight of stairs leading to the dome and coelostat. Just below these stairs is the main electrical junction box and instrument panel *K*. At *L* will be seen the ventilating fan previously mentioned which ventilates either or both the darkroom and workroom. Under certain temperature conditions the seeing has been greatly improved by the use of the ventilating fan. At *M* is the observer's desk, which is mounted on a pedestal in order to make it more convenient. Some portions of the rather intricate supporting steel structures can be seen on this photograph.

At *N* is a convex spherical mirror of 100 inches radius (being a surface of a 6-inch lens) that receives the guiding beam from the flat *O* at a point just inside the focus of the 40-foot focus 4-inch guiding lens. This amplifying mirror is so mounted that it may be used for focusing the final guiding image on the easel *P*. A very substantial arm *R*, on which is mounted the auxiliary flat *O*, is arranged so that the flat may be placed in any desired position to intercept the beam from the 40-foot focus guiding lens above. The spherical amplifying mirror (being unaluminized) passes about 95% of the light from the guiding beam. The remaining 5% is reflected from the convex front face of the amplifying mirror and forms an excellent image on the easel *P* about 16.5 inches in diameter, corresponding to an equivalent focal length of about 150 feet and of suitable brightness for continuous guiding without dark glasses. In practice this image disk is placed concentrically within a circle of about the same size drawn on the easel sheet, and it is the observer's duty to keep these two circles concentric in his visual guiding.

At *S* will be seen a small telescope of about 2 inches aperture, by means of which the focusing scales inside the inner tower are read. The black case *T* carries at its lower end a mirror set at 45°; it also acts as a light shade. At *U* will be seen a square easel carrying a draftsman's T-square. On this easel pad is a set of curves giving the computed revolutions per minute of the motor of the declination drive system for any hour of the year; this is for the convenience of the observer while establishing the actual driving rate used in declination. The RPM's of this motor are read directly on the electric tachometer shown at *W;* the other tachometer *X* shows the RPM's of the motor located in the control room which drives the camera timing gears.

Another view of the relation of the off-axis mirrors and their supports, and also of the guiding train to the spectroheliograph head, may be seen in Plate 12; and certain elements of this arrangement are again emphasized here because of the very important part played by the guiding system. At *A* will be seen the 7-inch flat mirror which receives the beam from the 4-inch by 40-foot lens mounted on the second flat carriage and described previously. Located at *B* is the nut controlling the friction joint device which is part of this mounting. This friction joint makes it possible to swing the mirror *A* to any desired point above the spectro heliograph head; and to give greater range to this adjustment of mirror *A*, the rod *C* unscrews from the fork *E*, and several different lengths of rod are provided. When the adjustment is finished, the large clamp *F* is securely tightened before starting to work.

The 16.5-inch image of the sun falls on the easel *G*, which provides a guiding power of about 4 × with the 40-foot image, and a correspondingly higher power for shorter focal lengths. Any change of focus that may be necessary during the work of the day is performed with the main camera shutter closed. Due to the fact that the third flat is inserted at a slight angle in the beam from the off-axis mirror, and because focusing is accomplished by moving the third flat either up or down, there is a small displacement of the image when the focusing operation is performed. In order not to disturb the relation between the guiding image and the main image, the latter is adjusted by means of the collimating screws shown at *H*, after the focusing is completed. It should be noted also that the mirrors *J* and *K* are so mounted that they can be readily interchanged or removed entirely when it becomes necessary to clean their surfaces.

The Spectroheliograph: General Considerations

In designing this spectroheliograph, every effort was made to combine the good features of instruments already in existence with such new features as experience with our own spectroheliokinematograph had indicated were necessary. Simplicity is usually the result of good engineering and scrupulous attention to detail; and it was recognized from the start that an instrument convenient for the observer and rapid in manipulation was an indispensable prerequisite for the continuous observation which was contemplated in the making of unbroken records of solar phenomena. A study of existing instruments made it clear in the earlier stages of our work of design that it would be necessary to depart rather radically from previous practice.

So far as is known, there is in existence no spectroheliograph rotatable through an entire circumference, and further study convinced us that complete rotation was a necessity in our work. It was consequently necessary to keep the entire lower portion of the instrument within a relatively small horizontal compass, and to avoid spreading out the component parts of the apparatus. I also wished very much to make it possible to change the focal length of the spectrograph in a comparatively short time and yet avoid any need for entering the spectrograph well, with resulting disturbance of its atmospheric and temperature conditions. As has been said before, the maximum focal length to be provided for had been set at 30 feet, and it was anticipated that most of the work would be carried out with a spectrograph of 15-feet focal length.

The long steel cage in the well, Figure 1, which carries the spectrograph grating and the collimating lens, was made 2 feet square on the inside. This fixed the dimensions of the rotatable table that forms the spectroheliograph head and of other parts to be described later in this paper in their proper order.

It was decided to use irrotationally moving slits. These differ from the ordinary oscillating slits used in the Hale spectrohelioscope and similar instruments, where the slits are an integral part of an arm oscillating about a pivot midway between the two slits, and where each slit possesses a slight motion of rotation in addition to that of translation. In our design, to be described in detail later, the slits are given opposite motions in finely finished parallel ways; they thus are subject to a motion of translation only, without rotation. For lack of a better term, we shall occasionally refer to them as oscillating slits, though essentially different from the ordinary oscillating type. This slit design was adopted in order to average out the seeing in each frame and has, of course, the great advantage of reducing the mass of the parts of the spectroheliograph in motion, as well as avoiding the loss of light by absorption and reflection that has been found to be very serious in the Anderson rotating slit prisms of the spectroheliokinematograph.

The Spectroheliograph Cage

As will be noted from Plate 7 and the insert diagram Figure 1, the steel cage that carries the collimating lens and grating is of very heavy construction. The corner angles are 3 × 3 × 3/8 inches in section, and the length of one panel of bracing is 3 feet 1 inch. This structure is so rigid that the weight of a man standing on one of the horizontal braces deflects the spectral lines only about one-half of an angstrom.

The total weight of the rotating parts of the spectroheliograph is just a little under three tons. About two-thirds of this weight is carried on a 1 inch steel ball at the lower end of the spectrograph cage. Provision has been made at this point for expansion or contraction by mounting the ball for this bearing on a counterweighted arm shown in Figure 1. The upper and lower halves of this bearing are made of phosphor bronze, and provision has been made for adequate lubrication.

The remainder of the weight of the cage and head is taken by a special ring ball bearing under the top plate of the working table on the pedestal in the workroom. This upper ball bearing is just behind the brass strip *Y*, Plate 8; it is 48 inches in diameter and contains 151 1-inch steel balls that run in V-shaped races turned in the top face of plate *AA* and the bottom face of plate *BB*. These two plates were turned from 2-inch stock to a finished thickness of 1¾ inches. Plate *BB* is fitted to carry the spectrograph cage, leaving about ¼ inch between the bottom face of plate *BB* and the top face of the cage. The pedestal is provided with leveling screws (not shown) as well as azimuth adjusting screws. The spectrograph cage was shop-assembled and bolted and riveted as a unit, then delivered to the site and lowered into the well in one piece.

The next step was to level very accurately the top of the pedestal, including the cover plate *G*, which had been provided with a central hole bored while the entire unit was assembled. After this careful leveling, a plumb bob was suspended through the central hole in plate *G* and the lower part of the bottom center bearing accurately located in position; this was possible because the upper part of this bearing was made removable by means of bolts and taper dowel pins.

After the lower bearing had been located, the spectrograph cage was placed on this bearing and bolted loosely to the upper plate *BB;* these bolts were drawn finger-tight only. Following this, babbit was poured between the top face of the spectrograph cage and the bottom face of the upper bearing, plate *BB;* after the babbit cooled, the holding bolts were drawn up tight with a wrench and the result is a cage which rotates freely and accurately.

It was originally thought probable that some kind of gear drive would be necessary for rotating this cage assembly. In order to avoid the expense of cutting a large gear around one of the bearing plates, this plate was instead grooved to receive a standard roller chain which can be seen in Plate 8. As a matter of fact, the entire assembly rotates so easily by hand that no gear drive has been necessary, settings being made with entire ease by hand to the nearest tenth of a degree. This method of building and setting up a completely rotatable spectrograph is comparatively easy and inexpensive, two men having completed the entire adjustment, including the pouring of the babbit, in less than two days. In practice, we find that the maximum displacement of the K_2 line is about 0.5 angstroms when the spectroheliograph is rotated through 360°.

The Grating Carriage

The grating carriage, as well as certain other cage accessories, is clearly shown in Plate 7. Here *A* is the collimating lens with its round occulting disk and square diaphragm. Its supporting leaf is swung on taper pin hinges. A similar leaf is shown at *B*, on which the 30-foot collimating lens will ordinarily be mounted; the clamp screw *C* is loosened by the observer in order to make the change of collimating lenses. At *D* will be seen the grating which during the past summer was Mt. Wilson No. 47, a 6-inch aluminized grating of 15,240 lines to the inch; we are indebted to the Mt. Wilson Observatory for the loan of this grating pending the ruling of our own grating by Dr. Babcock. As used last summer, the dispersion employed was 3.5 A/mm.

Located at *E* is the upper part of the nickel-iron base casting which carries the lens and grating assembly; each constituent part of this assembly was purposely made quite heavy, the total weight being just under 500 lbs. At *F* will be seen the vertical drive which is an exact duplicate of the drive described earlier in connection with the third flat mounting; *G* is the device for focusing by hand. The total travel provided for this lens and grating carriage is 18 feet at a speed of 12 feet per minute, which makes possible the use of the spectrograph with focal lengths of 12 to 30 feet.

The grating box *H* is mounted on a sub-plate *J* carried on the main grating bracket *K*, which is of welded 5/8-inch steel construction. An auxiliary plate with its upper face carefully ground to secure a flat surface was introduced between plates *J* and *K* and is adjustable by three leveling screws. At the time of installation, this plate was carefully leveled so as to permit the rotation of the plate *J* about the optical axis. This rotation is secured through the reversible motor *L* and the tangent screw *M*, and makes it possible for the observer to rotate the grating about its own vertical axis in order to make the spectral lines parallel to the slit jaws.

A second motor *N* is used to tilt the grating box assembly about a horizontal axis parallel to the slit ways, thereby making it possible for the observer to center the spectrum on the jaws of the second slit. The motors for both these motions are controlled by means of push buttons at the spectroheliograph head and enable the observer to control the grating from above when changing focal lengths or performing any other instrumental adjustments; and so far as is known, this is the only spectroheliograph so completely equipped for convenient control. Electric power for these motors and other circuits is carried to the spectrograph cage by means of a divided cable and large pulley around the entire cage, shown just below the floor-level on the frontispiece. This cable was divided into two parts of equal length and weight, and arranged so that the pull of each part is tangential, equal and opposite. Consequently there is no bending moment introduced into the spectrograph cage at any position angle. The usual telescope has been provided by means of which readings can be made on the spectrograph focusing scale located at *O*. The vertical motor drive of the grating assembly is ordinarily used only for changing focal lengths; in practice the spectrograph is always focused by hand and manual operation is preferred in the more delicate adjustment of drifting the spectrum. The mechanical details of these finer adjustments are as follows.

The square rod *P* engages with a one-to-seven gear reduction located just under the main cover plate; the pinion gear of this pair carries a dial graduated into 100 angstroms, and this dial is read through a large hole in the main cover plate of the spectroheliograph head as shown at *D* in Plate 10. An arrow shows the direction of motion to move toward either the red or the violet end of the spectrum. The rod *P* passes through a square hole in the worm on the grating carriage, and this worm meshes with a worm gear attached to the axis of the grating box. The design of this worm and worm wheel presented some difficulty, as it is manifestly necessary to allow for the two rotations of adjustment of the grating. Either rotation of the grating, as is evident, will result in drifting the spectrum across the second slit; any such drifts, however, are quickly and easily compensated for by the use of this spectrum drifter. Two long spring-actuated keys have been inserted on this square drifter rod at the points corresponding to the various spectrograph focal lengths that will be used, and these keys serve to take up any slack that may exist between the spectrum drifter rod and the square hole in the worm through which the rod has to slide when focal lengths are changed.

The shafts for all these adjustments are brought up to the top plate of the spectroheliograph head (see Plate 10), and their upper ends are squared. At *A* will be seen the crank normally used on any of these three squared shaft ends. There are four holes in the main cover plate; when used at *B* the crank operates the hand focusing rod; at *C* is the hole giving access to the shaft for the slow spectrum drifter device. The hole at *E* contains the shaft for the fast spectrum drifting motion; if the hand crank *A* is inserted here, three and three-quarter revolutions of the handle will shift the spectrum from Hα to K. The fourth hole, *D*, is for the angstrom reading dial, as already noted.

The carriage carrying the lens and grating assembly weighs 500 lbs. and is counterweighted by a lead weight of 475 lbs. running on a set of auxiliary ways inside the spectrograph cage. The counterweight cables are shown at *R* in Plate 7. By keeping the counterweight a little lighter than the carriage, all slack is obviated in the planetary and other gears constituting the various power and hand adjustments. The plate *S* is so made that it may be fixed at any desired point on the main ways *T;* it carries two intermediate steadying bearings, one each for the hand-focusing device and the spectrum drifter rod. The main ways *T* were mounted so that they may be adjusted by push and pull screws in both coördinates. For their adjustment a fixture was made similar to that described in connection with the location of the ways of the third flat, providing for adjustment about a plumb bob line suspended from the center of the first slit of the spectroheliograph. After adjusting these accurately, the holes *B*, *C*, *D* and *E* (Plate 10) were located and the plate that carries the upper bearings and the spectrum drifting gears was installed. This design makes it possible to remove the entire spectroheliograph head by hoisting up the top cover plate *F*. A second cover plate was made at the same time and is available whenever it may be necessary to convert this instrument into an ordinary spectrograph. These two cover plates are rendered accurately inter-changeable by taper dowel pins and are easily removed by a conveniently located chain hoist. All electrical connections are by separable plugs, so that it is only necessary to lift a cover plate a few inches and reach in to disconnect the circuits before proceeding further.

The Spectroheliograph Slits

The slits and slit drive were built only after the most careful consideration of several designs. As noted previously, it was finally decided to employ oscillating, or rather irrotationally vibrating slits, because it appeared that the use of slits of this design would tend to average out hazy or cloudy exposures, while the earlier standard forms with moving slit or moving plate often show diffused portions due to the passage of a small cloud or poor seeing conditions. Moreover, from the standpoint of an accurate time record, the vibrating slits offer a decided advantage because the entire frame may be recorded as having been taken at the mid-point of the exposure. This is not true with the customary spectroheliograph slit mechanism, for here the slit may reach the base of a prominence shortly after the start of an exposure and where the exposures are of several minutes duration the observer must make allowance for this fact when using the base of a prominence as a reference point for measurement. It was recognized from the start that all the elements of the slit driving linkage must be practically perfect as to mechanical execution; a very slight error in the length of one arm of the oscillating driving beam would mean that the chosen spectral line would not fall accurately within the jaws of the second slit at all points of the stroke. Provision had also to be made for taking up wear at all moving surfaces or bearings, and the clearance at all points made as nearly zero as possible. Differential expansion between the constituent parts had to be eliminated, and the weight of all moving parts made as small as possible consistent with adequate strength and rigidity. Anderson rotating prisms were regarded as out of consideration because of resulting light losses.

The following description, unless otherwise noted, is based on Plate 10 and on the outline and cross-section drawing of the second slit shown in Figure 6.

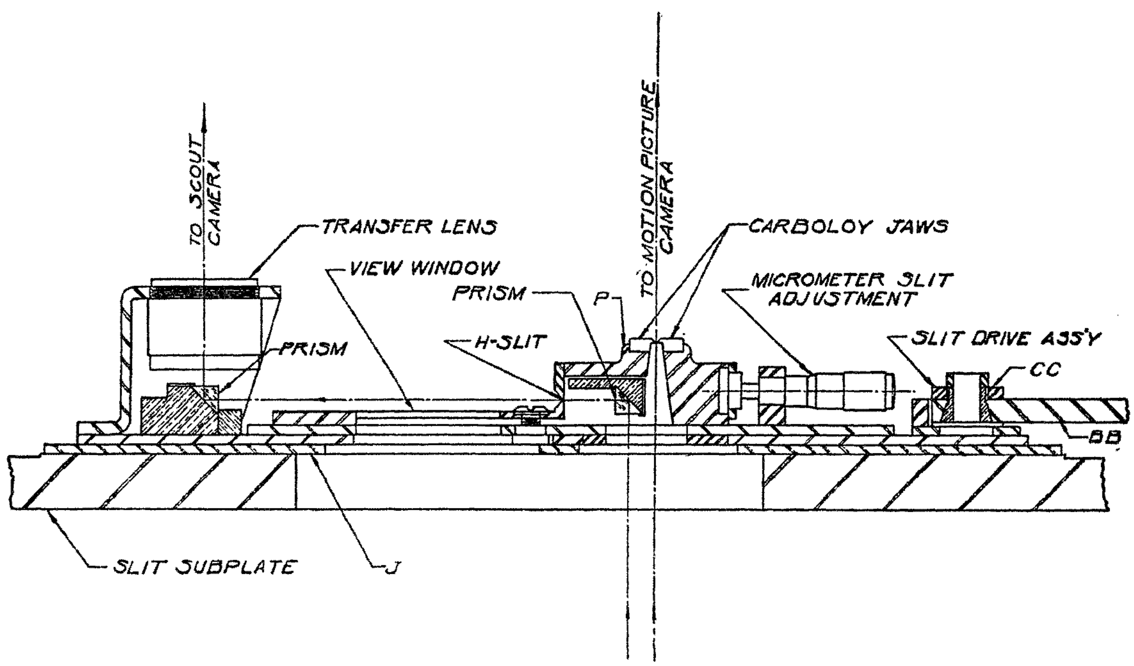

FIGURE 6. Cross Section; Second Slit Assembly.

The requirements for perfection in the slit jaws and the ways in which they move are highly rigorous. Furthermore, even with the extremely small tolerances allowed, there can be no clamping or binding due to minor irregularities in the surfaces of the larger elements to which these mechanisms are attached, or that result from minute differences in expansion or contraction due to temperature conditions. Such injurious binding was obviated largely by the use of invar where possible in the slit block and ways, and more particularly by the devices of point support and relief of mutually sliding surfaces familiar in instrument making practice.

The main cover plate *F* has a machined surface. The plate *G* was made of triple-annealed steel, its lower surface relieved so as to rest on *F* only through three small projections or feet; plate *G* is bolted and doweled to *F* with taper dowel pins, so that it may be replaced with entire accuracy if ever removed. The portion of *G* which was to receive the slit ways was then relieved with the exception of comparatively narrow tracks for the guide ways, and these bearing tracks were carefully hand scraped both longitudinally and diagonally. The plate *J* and the ways *K* are of brass; these parts were heated nearly to a red heat and then quenched in water for thorough annealing; the central portion of *J* was relieved on both top and bottom. The slit base plate *L* is of standard steel gauge stock, thoroughly normalized before machining and scraping. This design results in seven surfaces which must be rigorously flat and parallel, an exacting task which Mr. Charles Guenther of the Motors Metal Manufacturing Company's tool division carried through with entire success. The above description applies to both slits except that the second slit assembly is twice as long as that of the first slit, for reasons which will appear later.

It will be noticed that *both* jaws of the first slit are adjusted by means of micrometer screws. This was provided because no one could tell before actual completion and test just how sensitive would be the action of the spectrum drifter *C;* hence the provision for a movable "fixed" jaw for the first slit, which also insures extraordinary sensitivity in placing the K_2 line on the second slit. The micrometer screws are the commercially available and convenient L. S. Starrett and Company micrometer barrels.

The actual slit jaws *M* were made of carboloy by the Carboloy Company of America. This material was adopted in order to secure very hard jaws which would take a knife-edge and retain it through many hours of use. Carboloy is very close to the diamond in hardness; as a matter of fact, it was necessary to shape the jaws with diamond powder. We have been assured by astronomers of long experience in the use of spectrographs that these carboloy slits are rather exceptional; their closure is of an "instantaneous" and perfect character that must be seen to be appreciated. These carboloy jaws, which have a length of one inch, are mounted on the blocks of invar, *N*. By design the tongue which slides in the ways, *O*, is also invar and, as a matter of fact, this entire piece was machined from a single block of invar; and this construction has obviated any difficulties that might have arisen through local heating of the jaws and mounting of the first slit.

Provision is made in the mounting of the second slit for the prisms and the third slit provided for the use of the light of the H line of calcium in the scout camera. A totally reflecting prism is fixed inside the block *P*, and is mounted in a piece of brass which is adjustable in all coördinates in order to collimate the H line on the third slit. The jaws of this H slit are of stainless steel and the slit itself is located under the arrow marked *R*. By making the movable jaw of this H slit from a long piece of stainless steel it was possible to provide a small spectrum view window, *S*. The box *T* houses the second totally reflecting prism and the transfer lens, a Bausch & Lomb anastigmat of excellent figure; this lens is so set that it focuses the H line on the photographic plate of the scout camera, to be described later. These three slits and their mountings have proven thoroughly satisfactory throughout the past season, and no difficulty whatever has arisen in their use.

The Slit Drive Mechanism

At *U* will be seen the 1/20 HP synchronous motor that provides the power to drive the vibrating slits. At first this motor was connected to an ordinary commercial 1:30 worm and worm wheel speed reducer. In practice the small errors of this commercial reducer resulted in a reseau background pattern on the photographs, and this reducer is now being replaced by one manufactured to precision standards. The reducer drives a vertical shaft in ball bearings on which is mounted the cardioid shaped cam *W* used to secure uniform rectilinear motion. Since the motor runs at 1,800 RPM and the reduction is 1 : 30, the slits make one complete cycle per second or one stroke each half-second; this frequency being chosen as it was thought it was about as fast as the small weights involved could be accelerated and decelerated without noticeable vibration of the spectroheliograph. The slits are electrically interlocked with the camera shutter in the manner to be described in the electrical section of this paper.

X is the fork on the cam follower, and the follower itself is a ball bearing mounted on a trunnion that passes through the jaws of the fork. The cam follower guide is located at *Y;* this guide was machined from nickel cast iron and ground all over to very close limits to obviate any sideplay in the fork *X*. The springs mounted just above are used either single or double as may be necessary, depending upon the temperature of the assembly. *Z* is a long open fork attached directly to the sliding base plate of the second slit, and it is this assembly, carrying the prisms and the transfer lens, that is moved directly by the cam and the follower, a design that reduced to a minimum the mass to be moved by the rocker arm *AA*. This rocker arm is mounted on a ball bearing carried in an eccentric bushing, a feature that provides for the final precise equalization of the lengths of the two arms of the rocker. Two connecting rods *BB* transfer the motion of the rocker arm to the slit assemblies, and in construction were doweled together and then bored in a jig to insure equality of length. The bearings for the rods are tapered phosphor bronze so mounted that any play can be removed by means of the adjusting collars *CC*. In testing this assembly a pull of 100 lbs. failed to show any play or lost motion as great as 0.0001 inch. During the first four weeks of use it was found possible to make a minute adjustment at each of the four bearing points after eight to twelve hours of operation, but after that period it was only possible to adjust about once a week, and after two months no further adjustment could be made. The bearings were designed by Mr. O. Mattick, Superintendent of the Motors Metal tool division, and have proved entirely satisfactory in use. The reader should remember that this apparatus is started up fairly early in the morning on a clear day, and normally runs continuously for between eight and ten hours. Instead of an *instrument* for occasional and sporadic use, it was necessary to provide a *machine* capable of continuous duty; accordingly all bearings and other parts have been given generous proportions to minimize wear and to secure adequate rigidity.

The Motion Picture Camera

After the light beam reaches the spectroheliograph head in the form of a spectrum, the K_2 line of calcium is segregated and the resulting picture spread upon the film in the motion picture camera through the action of the second slit. The third slit similarly isolates the light from the calcium H line and sends it into the scout camera. Mercury and neon arcs, properly housed, and using the same grating and collimator lens as the beam from the sun, make it possible to set the K_2 line quickly on the second slit and to keep continuous check on its position. All this apparatus is grouped on the upper plate of the spectroheliograph head which is illustrated in Plates 9, 10, 11, and 12. Plate 9 is a general view from the south, and Plate 11 is a similar view from the north. The rectangular box housing the motion picture mechanism is a prominent feature of all these plates.

The motion picture camera presented a number of difficulties in design. The emulsion side of the film must be as close as possible to the plane of the jaws of the second slit. The gate mechanism which changes frames between exposures must be of the highest precision and the camera as a whole easily removable for loading fresh film in the dark room. It is also necessary to have a light-tight junction between the camera and the spectroheliograph head, while at the same time providing for convenient and rapid access to the second slit, the micrometer head, and the view window to be mentioned later. It is further self-evident that the camera must go back precisely into position after it has been removed.

A thorough investigation of all motion picture cameras commercially available only served to prove that none of them could be utilized to meet all these rigorous requirements. The most difficult specification of all proved to be the one demanding the smallest possible distance between the film and the plane of the second slit. Investigation of the devices obtainable showed that only one could meet this requirement,—the Bell and Howell Superspeed check-pawl mechanism, which is made only on order for the large Western picture producers, and especially for the super-speed "slow motion" sound camera. A grant from the Bache Fund of the National Academy of Sciences made it possible to purchase this Bell and Howell precision gate mechanism, and the company cordially consented to make a special aperture plate in accordance with our designs. This mechanism is manufactured to exceedingly close tolerances and, from our standpoint, it possesses the great advantage that the pull-down claws operate only from the back of the film and do not pass through the perforations of the film into a groove cut in the aperture plate. This feature made it possible to place the emulsion side of the film within 0.08 inch of the plane of the second slit (cf. Plate 18). Certain other essential gears were purchased from the same company and incorporated in our camera design. For other gears, constant-speed sprocket, spindles, and the take-up drive, we used the material from a secondhand 35 mm. camera purchased in the open market.

All of the above parts were mounted on ball bearings inside the motion picture camera box *MC*, shown tilted back on its taper pin hinges *HH* in Plate 10. In this position the second slit assembly is conveniently accessible. The bottom face of the camera nests in a light-tight box, tongued and grooved, which had to be made and placed in position with extreme accuracy. The same box provides the slides for the various eyepiece carrying bridges which are used in adjusting the spectral lines between the jaws of the second slit and in the basic adjustments of the spectrograph collimating lens and the grating. This box may be easily removed to provide access to the ways of the slit jaw mechanism for cleaning, oiling or adjusting. It was necessary to set the supports for the taper pin hinges *HH* to the nearest ten-thousandth of an inch and their height was carefully studied in order that the camera box might rise out of its light-tight grooves without interference due to the fact that it rotates about its hinge point. It will be noticed in Plate 10 that a clearance has been milled in the bottom plate of the camera to permit the micrometer barrel, etc., to vibrate freely. At *SY*, in Plates 11 and 12, will be seen the Selsyn slave camera drive, which is driven by the master Selsyn on the camera drive carriage in the control room, shown at *SY* on Plate 15. It is, of course, the function of the camera drive to impart the proper number of revolutions to these Selsyns when pictures are being taken. By design this is 16 revolutions, as there are 10 teeth in the pinion which meshes with the large 160-tooth gear *D* on Plate 11. Thus 16 revolutions of the Selsyn *SY* impart one revolution to gear *D*, resulting in one complete camera cycle.

The shutter, not shown on any plate, is located underneath the main cover plate *F*, Plate 10. This shutter is in segment form and is operated by a solenoid magnet; and by design, the shutter is opened electrically and closed by a spring. At *A* and *B*, Plates 9 and 11, will be seen two brush holders carrying brushes that bear against the commutator *M;* a section of the commutator is of brass, the balance being bakelite. Shortly after the Selsyn drive starts to operate the brush *B* makes contact, thus opening the shutter circuit and permitting the spring-actuated shutter to close; and while the shutter is closed, the film-changing mechanism moves a new film frame into position. After the film has been moved, brush *A* makes contact, energizing the shutter solenoid and opening the shutter. The Selsyn *SY* comes to a stop during the actual exposure and remains so until another cycle is started by the time shaft shown at *F* in Plate 15.

By means of suitable electrical relays the chronograph is tied in with the solenoid operated shutter, and here also the dome circuit is tied in so that the observer can not rotate the dome while the camera shutter is open; altogether, there are six relays involved in this electrical hook-up. The entire camera has been very satisfactory during the past season's use, and the only changes contemplated are minor ones that will bring the emulsion side of the film even closer to the plane of the second slit jaws.

As noted earlier, the slits are driven at the rate of one complete cycle per second. In other words,—slit No. 2 will scan the film twenty times during a ten-second exposure. It was thought advisable to interlock the camera shutter with the slit drive mechanism in order to avoid partial "scans," and this was accomplished in the following manner. Immediately above *W* on Plate 10 there is a bakelite commutator with two short brass bars inserted in its periphery 180° apart. A single brush holder carries a double brush bearing on this commutator, and the commutator is so set that these brushes make contact only when slit No. 2 has reached either extreme of its travel; contact through these brushes is needed to complete the shutter circuits. This results in a whole number of scans for each exposure taken during the run, and the resultant small variation is clearly shown on the chronograph record. This variation is of course of no importance on long exposures, say of a minute or more. However, it is now apparent that certain types of solar disk photography will be carried out later with exposures of the order of 5 seconds, and it is our belief that very uniform exposures will be secured through this electrical interconnection of the slit drive and the shutter.

The separable plugs, used when the camera is taken to the dark room for loading or unloading, are shown at *E* in Plate 11. It should be noted that the entire front of the camera is composed of a removable dark slide marked *F* on Plate 9. This dark slide has been chromium plated to prevent as far as possible the passage of heat from the solar image on the first slit. This design opens up the front of the camera completely, making it much easier to load or unload in the dark. The entire camera weighs 40 lbs.; it was designedly made heavy to secure rigidity, and, of course, easy portability was not a requisite in so highly specialized a camera. The camera box, marked *N* on Plates 9 and 11, is made of steel gauge stock as is the rest of the main camera assembly. The camera drive Selsyn comes against a stop of sponge rubber when the camera box is tilted back as on Plate 10. The entire construction is so substantial that it is possible to lean on the camera box when it is tilted down. This has been a great convenience in operation, as it is not necessary for the observer to be over-careful of the camera.

At *J* in Plate 11 will be seen an auxiliary box having four toggle switches. One of these switches provides an independent means of opening the main camera shutter during the set-up period, or for checking the spectrograph adjustments; a second switch starts or stops the slit drive mechanism; the third switch energizes the camera drive slave Selsyn, making it possible to control the main camera drive in the control room from the observer's working position at the spectroheliograph head; and the fourth switch is as yet unused.

Spectral Line Position Control

I wished above all things to minimize the time necessary to adjust the spectroscope each day before starting work. One of the adjustments that heretofore occupied considerable time before observations could begin, is the setting of the chromospheric line upon the second slit. There is also the need to check this adjustment and return the line to the slit at any time without interfering with the exposures at the motion picture camera. It is also desirable to check the centering of the spectrum upon the second slit. The solar spectrum itself could not be used as it is in continuous oscillation during the observing period. Recourse was therefore had to a laboratory source of light and an auxiliary fixed slit which enables the observer to set the spectrum, even before the dome is opened. The idea was suggested by Pettit and the optical design is by him, and I have here reduced it to practice. For K_2 the mercury arc is used and for $H\alpha$ the neon arc has been adopted.

The mercury quartz tube arc is shown at *MA*, Plate 12, and other portions of the device are shown on Plates 9 and 11. The transformer for the arc is at *TT*, controlled by means of the switch *SW* on Plate 10. The light from the mercury arc passes first through a yellow filter and then through the slit jaws *JJ*, shown on Plate 12, which are located in the continuation of the second slit ways. Consequently the light from this mercury arc slit passes through the spectrograph in the opposite direction to the light coming from the first slit. The resultant emission spectrum is found along the line of the first slit and is viewed by means of the eyepiece *EP*, a 20-power Bausch & Lomb microscope so mounted that it can be tilted along the line of the spectrum, and by design the slit and the eyepiece are mounted close together on a single base plate which is free to move in ways along the line of the spectrum and which may be firmly clamped when the desired position is attained.

Just below this eyepiece is located an adjustable reticle whose spider thread can thus be brought to a focus at the same time as the spectral line, and the apparatus, which is 9 inches from the second slit toward the red of the spectrum, is adjusted so that the mercury line at 5790 A is on the wire when the K_2 line of calcium is accurately between the jaws of the second slit. Once adjusted, the device is firmly clamped in place and as a result the setting of the K_2 line may be made or checked at any time prior to or during the operation of the spectroheliograph. By design, the width of the mercury arc slit is 1/3 A at the dispersion used, and it is easy to set the K_2 line on the second slit within 1/20 A when viewing it with the 20-power microscope. In practice we check this setting every half-hour during the work of the day; a displacement as large as 1/6 A has never been found in such checks, the usual error being of the order of 1/20 A.

A neon tube has also been provided for use in setting the Hα line on the second slit jaws. This device is installed underneath the main cover plate of the spectroheliograph and is located beneath the letter *Z* on Plate 10. A short quartz tube filled with neon is excited by a current from the same transformer *TT*, Plate 12, by means of a selecting switch. Jaws are mounted so that the light passes through a small totally reflecting prism and thence to the collimating lens and grating and back to the eyepiece *EP*. The tube and jaws are provided with a lateral motion to focus the line on the spider thread in the same microscope used for the 5790A mercury line, and the whole assembly is movable by a rack and pinion to bring the desired line into coincidence with the thread. There are many bright neon lines in the red region available for this purpose, and in changing over from K_2 to Hα use is made of the angstrom reading dial to be sure that the proper line of neon is placed on the spider thread. Thus it is also possible to check the setting on the second slit when working at Hα. These auxiliary arcs have proved thoroughly satisfactory throughout the first season's use.

The Scout Camera

It is a matter of the highest importance in work of this type to have some independent means of "checking up" on the performance of the instrument as a whole. The length of the picture being taken may run as high as 1,200 individual frames, and in all previous installations of this type it has been necessary, in effect, to "run blind" in so far as any check on the performance is concerned. It would be practically impossible to check the K_2 image visually, and this process might in addition mean the loss of vital parts of the run, at least in the case of our own instrument where there may be an interval of but 10 or 15 seconds between the mid-points of the pictures. There is no convenient way of cutting the negative and developing sections of it from time to time in order to keep track of the performance of the instrument and the activity of the prominence under observation. It is also necessary, in the case of a prominence of an active or eruptive type, for the observer to know its rate of increase and to determine whether or not the prominence may actually erupt beyond the limits of the motion picture frame, thus necessitating a change in the focal length employed. It is also very desirable to be able to center the motion picture frame accurately on the prominence or other phenomenon which it is proposed to photograph. For all these reasons, it was decided to build a scout camera to take concurrent pictures in the light of the H line of calcium as frequently as might be needed during the run being made on the K_2 line in the main motion picture camera. The design and mechanical features of this scout camera were worked out by the writer from Pettit's original suggestion.

The scout camera, visible as a long black box, is shown on most of the plates of the spectroheliograph head, Plates 9, 10, 11, and 12; and also in the outline drawing Figure 7. In each illustration the box bears the letters *SC*. In our spec-

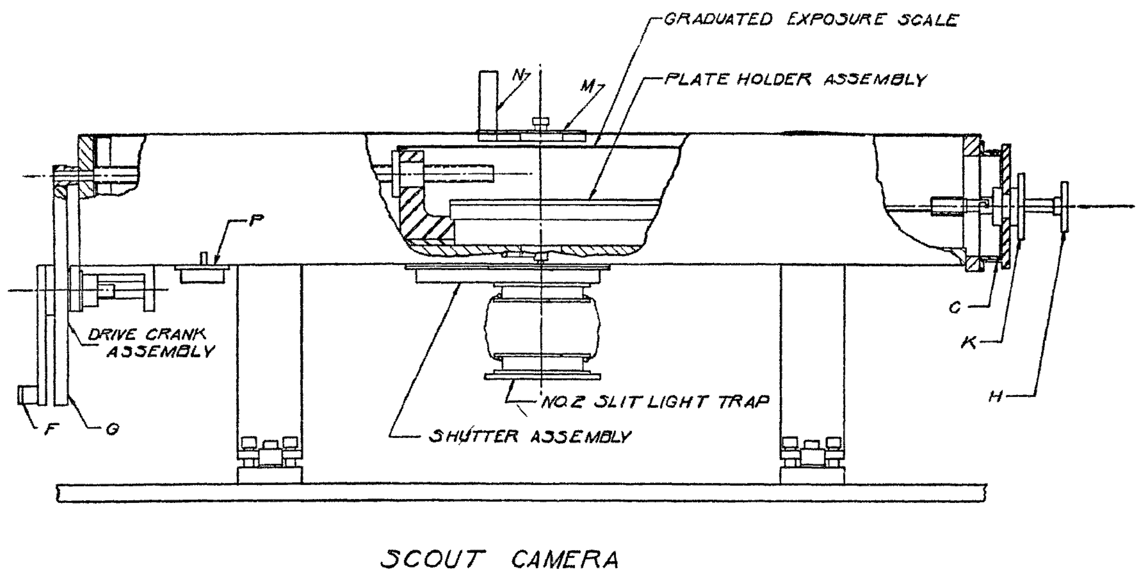

FIGURE 7. Diagram of the Scout Camera.

troheliograph as ordinarily used with a focal length of 15 feet, the H line of calcium lies 9.62 mm. to the red of the K line. As noted earlier in the description of the slit assemblies, a totally reflecting prism was introduced below and to the red side of the second slit and provided with universal adjustment in order to direct the H line squarely through the third or H slit. The plane of this H slit is at right angles to that of the K or second slit, and lies at the point marked *R* on Plate 10. After passing through the H slit, the light travels horizontally to a second totally reflecting prism concealed inside the box *T*, Plate 10. This second prism directs the light vertically upward through the transfer lens already mentioned, and this transfer lens focuses the light on the plate inside the scout camera *SC*.

Our scout camera plate-holder is designed to take a thin glass plate 2 × 12 inches in size, and we normally use the Eastman 33 emulsion. Inside the box *SC* are a set of ways to guide the plate-holder as it travels from one end of the camera to the other; *H* in Plate 9 is the handle attached to a rod that screws into one end of the dark slide of the plate-holder. At *K* is a sleeve carrying a bayonet lock and at *C* will be seen the cap that serves to make the loading orifice of the camera light-tight. In practice, the plate-holder is inserted through this hole, the rod is screwed into the dark slide, and the assembly put in place. Next, the knurled head *H* is withdrawn until the bayonet pin slips into the lock, thus exposing the first inch of the plate. The plate-holder is fastened to the main slide by bullet-headed pins, and this main slide is actuated by the gear and pinion shown at *G* in Plate 11. Just behind *P* on Plate 11 there is located a spring-actuated stop pin. When it is desired to advance the plate, this stop pin is pulled out and one rotation of the handle *F* moves the plate forward exactly one inch. The shutter is located at *S*, Plate 12, and is manually operated. A push button at *P* lights a small lamp inside the camera shown at *M* on the same Plate. A small mirror *N* makes it possible to look straight into the camera and read the numbered slide showing the number of the exposure that the observer has just made. A tube and an eyepiece are also provided for checking or setting-up purposes, and these may be inserted in the hole which normally carries the electric light.

The camera is attached to the light-tight box *T*, Plate 10, by a flexible felt and rubber bag of an elastic-bellows construction, and this permits the observer to slip the light-tight box off the ways in order to clean and oil the main slit ways. In use during the past summer, this scout camera has proved not only a great convenience, but an absolutely necessary accessory as well. As a matter of routine, several scout plates of active areas, both on the limb and the disk, are ordinarily taken in advance. The position angle of each plate is recorded as read on the divided circle on the spectroheliograph head, seen at *DC* in Plate 11. After development and inspection in the dark room, it is an easy matter to select the area to be photographed and to make such minor changes in the position angle setting as the scout plates may indicate. After the start of the run, scout plates are taken regularly at intervals varying from two to fifteen minutes, depending upon the activity of the phenomenon under observation. Upon at least two occasions the valuable scout pictures have shown the necessity for changing from a long to a shorter focal length in order to include all the prominence in the motion picture frame. The scout plates are also a valuable photographic check on the main picture frame, confirming in the H picture any detail in the K picture whose reality may be in doubt. On several occasions they have furnished needed confirmatory evidence as to the timing of the main sequence.

In the balance of this paper we shall describe a number of accessory mechanisms which, while vital to the observational technique, are less definitely a part of the actual tower structure. Some of the subjects remaining to be treated are the McMath-Hulbert electrical drive and frequency control as applied to the right ascension and declination drives of the tower coelostat, the camera timing gear and drive mechanism, the electrical circuit diagrams, and the underground control room. As noted earlier, nearly all these accessories and mechanisms were already in existence and in a sense ready for use, having been developed as necessities in the earlier motion picture programs of the observatory.

Frequency Control and Right Ascension Drive

The necessity of careful guiding, or rather of unusually precise following, and this for long periods of time, was evident from the very beginning of motion picture celestial photography at this observatory. The exposures for lunar and planetary photography were relatively short, varying from a few seconds to half or three-quarters of a minute, and consequently any displacement of the image, even though slight and momentary, would be recorded on the film. The registration of the exposures on the negative must be uniformly exact, and it was accordingly imperative that any actual shift of the image between exposures due to guiding be reduced to the absolute minimum. A rather long series of experiments has resulted from this endeavor to make guiding, in the ordinary sense, the exception rather than the rule. These successive mechanisms will be briefly mentioned below in their chronological order.

1. The first step toward a more uniform driving rate was the construction of an electric drive using two telechron motors.* This replaced the double spring driving clock of the 4-inch Bausch & Lomb telescope, then in use by the author.

Both telechron motors, each having a 30-tooth pinion, meshed in a gear of 365 teeth. Mounted on the same shaft with the latter was a gear of 366 teeth which drove a 30-tooth pinion attached to the telescope drive. This gear train gave a ratio of 366/365 or 1.00273973 : 1. This, applied to the mean time rate, approximates very closely to the sidereal rate. Since the more correct rate is $\frac{366.242}{365.242}$, or 1.00273910 : 1, the error was about 1 part in 500,000. A change gear was also provided which gave a reasonably close approximation to the mean lunar rate. When the 10.5-inch reflector was erected at Lake Angelus, a more powerful telechron clock drive was constructed, using the principle of the one just described.

These mechanical refinements in the new installation produced a driving rate which was more uniform than the earlier drive, but there still remained an undesirable amount of slow motion guiding. The change of the rates of the apparent motions of celestial objects due to the effects of parallax and refraction were sufficient to account for most of these departures from a uniform driving rate. The

* Pop Astr *38*, p. 460, 1930

values of these changes in the case of the moon were computed by Dr. Maxwell, and means were devised to vary the drive rate to correspond to the changing apparent rate. The table of lunar rate changes due to parallax and refraction (IV, p. 70, 1931) shows that for a declination of $-24°$ the correction to be applied to the geocentric rate in right ascension varies from -0.746 min. per hour on the meridian to $+1.33$ min. per hour at 4 hours west. In order to vary the speed of the telechron motors a proportional amount it would be necessary to vary the frequency of the power supplied by a total of 2.076 cycles per second.

2. To secure this variation, a frequency changer was installed in 1931. This device was a two-phase frequency changer, similar in construction to a two-phase induction motor. A single-phase current was added, differing in phase from the power supply by 90°, and obtained from an additional motor generator. The resulting two-phase current produced a true rotating field in the stator of the frequency changer. When the rotor remained stationary, this field acted as a mechanically rotated field would act, and generated a 60-cycle alternating current in the single-phase winding of the rotor. When the rotor was turned in the same direction as the rotating field, one cycle was dropped per revolution, and when turned against the field, one cycle was gained per revolution. Thus the number of cycles gained or lost per second was determined by the revolution rate of the rotor, which was driven by a reversible series wound 110 V AC motor through a worm reduction. The speed of this motor and consequently the change in rate was controlled by an adjustable series reactance. The actual manipulation of this apparatus was performed at the observer's chair by means of push buttons that controlled the motor driven adjustment of the reactance.

3. At this point in the development, attention was again given to the mechanical elements of the design, and an entirely new drive was built. A single phase synchronous 1/75 HP motor was substituted for the telechron motors, and the spur and bevel gears of the telescope drive were replaced by two worm gear reductions. The normal motor speed was 1800 RPM and the total reduction to the polar axis is $1/90 \times 1/57 \times 1/504 = \frac{1}{2,585,520}$, while the reduction to secure the sidereal rate should be $1/1800 \times 1/60 \times 1/24 \times \frac{366.242}{365.242} = \frac{1}{2,584,919.6}$. To obtain this correct rate it is then necessary to increase the theoretical input frequency to 60.103936 cycles, which can be accomplished by the frequency changer.

With the elimination of the spur and bevel gears, and the substitution of the worm gear reductions constructed to close tolerances, it became possible to estimate the maximum mechanical error. At times, however, there were observed deviations from the desired rate that were greater than could be caused by the known possible mechanical deviations. These variations in rate were particularly noticeable at certain periods in the daytime solar work, and investigation revealed the fact that they were coincident with the load fluctuations of the primary power system. The frequency control of the local power company was perfectly integrated over any given twenty-four hour period, but the large industrial load variations caused temporary frequency changes great enough to affect the telescope rate. The requirements for the frequency control of a current driving a telescope proved to be far more exacting than is necessary for any ordinary application of an industrial power supply. The Detroit Edison Company then undertook the problem of supplying the observatory with a current, the frequency of which would be independent of their commercial lines.

4. Accordingly, in the summer of 1933, the Detroit Edison Company installed a source of direct current to drive a tuning fork controlled rotary converter which, in turn, supplied a 60 cycle 110 V AC current to the frequency changer. This scheme gave satisfaction except for the constant care that was required to preserve the adjustments and temperature conditions of the fork. The physical maintenance of the tuning fork presented so many serious difficulties that it was finally decided to redesign the entire frequency control system. No abandonment of the general principle of frequency control was contemplated. Experience had abundantly proved the beauty, adequacy and infinite flexibility of this method of controlling a telescope driving rate, and it was realized that future improvement could come only through a more workable method of creating a frequency input entirely independent of commercial sources of supply.

5. The writer suggested the use of vacuum tubes for this frequency control, and Walter A. Grieg of the Detroit Edison Laboratory adapted a resistance stabilized thermionic tube oscillating circuit to control the rotary converter, thus eliminating the necessity for the former frequency changers and resulting in a very considerable mechanical simplification.

No changes whatever have been found necessary in this, our final method of frequency control, after over three years of use in a program with unusually exacting requirements. It fulfills perfectly all the prerequisites we had set,—it is infinitely flexible, and at the same time stable; it may be manipulated with the greatest convenience, and yet does not require constant supervision or exacting adjustment. It possesses, moreover, one marked advantage over all other methods of driving a telescope through the control of the electrical frequency in that the method employed is entirely independent of the usual commercial power networks. It creates its own frequency in a manner that has no connection with the frequency of the source of the input power, and is consequently unaffected by any variations in the frequency of such source. It is quite possible for an observatory in an isolated location to engender its own electrical power through a gas or oil engine attached to a generator producing either AC or DC current, and to secure from this

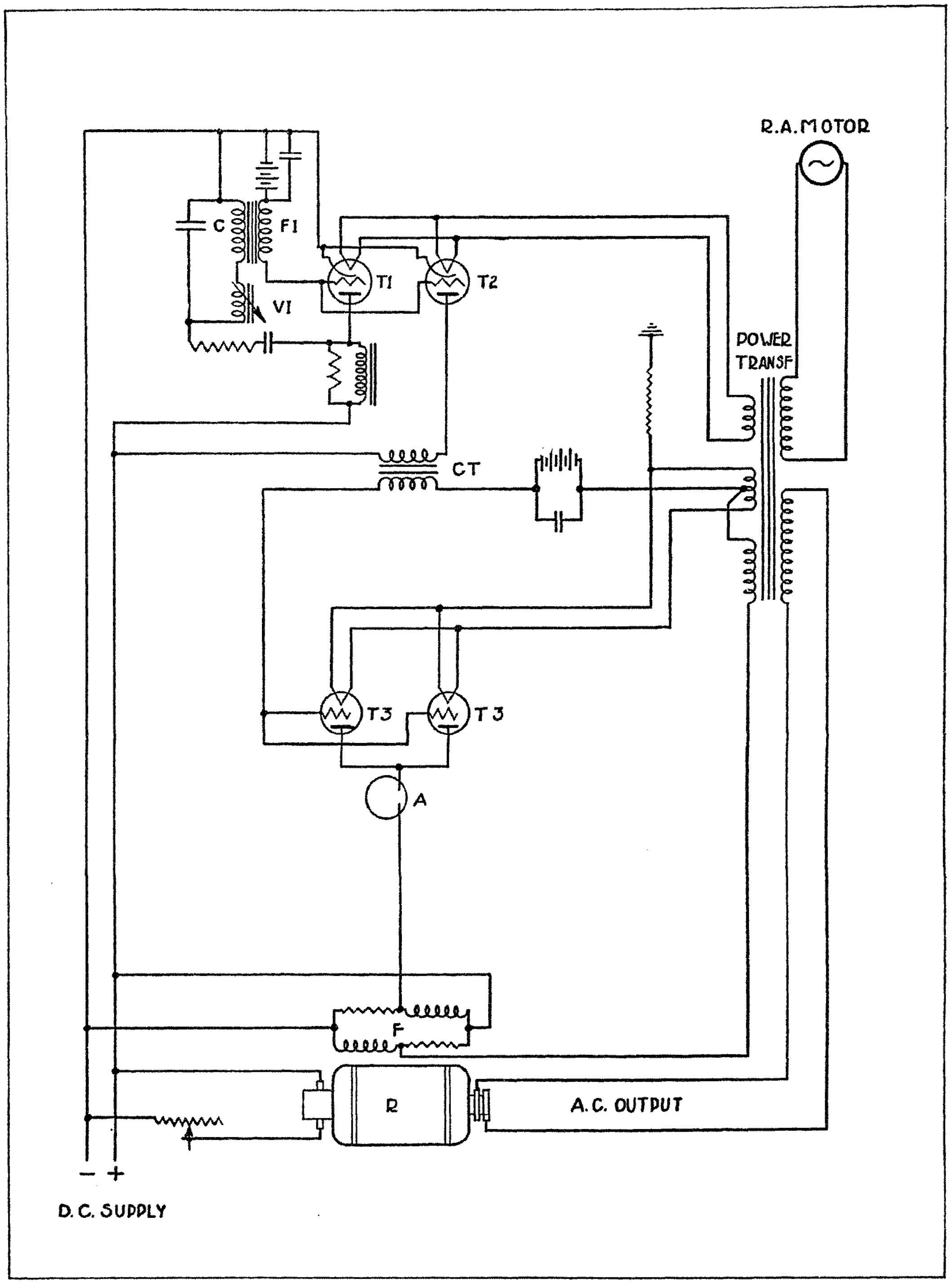

FIGURE 8. The Thermionic Tube Frequency Control Circuit.

a current with any frequency modulation desired—a frequency, moreover, that may be varied as needed in steps of approximately 0.002 cycle giving a practically continuous mode of change.

The principal elements of this circuit and the controlled converter circuit are shown in Figure 8; and certain of the generators and other elements will be seen in the view of the control room, Plate 14. The source of alternating current is the converter *R;* its input is 120 V DC and its output 110 V AC, 60 cycles per second, at 1,800 RPM. The RPM of the converter and consequently the number of cycles per second of the AC output is determined by the frequency of a resistance stabilized oscillating circuit, which may be varied at will between 57 and 60.5 cycles per second.

The oscillating circuit includes the condenser *C* in Figure 6, the variable inductance *VI* and the fixed inductance *FI;* the latter being also the transformer for the oscillator tube *T1*. *T2* is an amplifying tube with its plate output coupled, through the coupling transformer *CT*, to the grids of the parallel connected control tubes *T3*, *T3*. The frequency of the oscillator is adjusted by means of the variable inductance *VI*. These are not special thermionic tubes; they are the ordinary commercial variety with a total cost, at present rates, of approximately $3.00. The oscillator tube *T1* is Type 56; the amplifying tube *T2* is also Type No. 56; and the two control tubes *T3* are Type No. 45.

The grid voltage of the control tubes, coupled in this manner with the amplifier, has the same variation as the fundamental oscillator. The plate potential of these tubes is supplied by the power transformer and has, therefore, the same variation as the AC output of the converter. The value of the plate current, at any instant, is determined by the relative values of these two voltages. The plate current is a maximum when the grid and plate voltages have their maximum values at the same instant of time, and is a minimum when the maximum platè potential corresponds to a minimum grid potential and vice versa. In other words, the average plate current of the control tubes is at its maximum when the phase difference between the oscillator and converter voltages is zero, and is a minimum when the phase difference is 180°. This control tube output current is applied to the field of the converter, through the bridged field circuit *F*, regulating the field strength and consequently the RPM and the output frequency.

In operation, the converter is thrown on to the DC line and brought up to synchronous speed by adjusting the armature resistance. This resistance is next further adjusted until the control tube current, as shown by the milliammeter mounted on the main control panel, is about thirty milliamperes, which is a median value and corresponds to a phase lag of about 90° between the oscillator and converter voltages. Any increase in the converter speed will decrease this phase difference, which will increase the control tube output and hence the field strength, and will act to decrease the speed of the converter; similarly, any decrease in speed will decrease the field strength and act to produce an increase in speed. These speed corrections are, of course, very slight, and take place in a period of time obviously less than 1/120 second in length, so this method of speed control will exhibit no jumps or sudden deviations.

In order to eliminate variations caused by temperature changes in the oscillating circuit, the tubes, inductances, and condensers are installed in the constant temperature cabinet shown in Plate 13. In the upper left is the continuously running fan motor *M*, the thermostatically controlled heater *B*, and the mercury thermostat *C* which operates the heater element switch through a relay. The oscillator *T1*, the amplifier *T2*, the control tubes *T3*, and the transformer *D* are grouped in a unit. The fixed inductance *FI* and the condenser *C*, shown in Figure 6, are magnetically shielded in the case *E*, Plate 13; and the case *G* encloses the variable inductance. This variable inductance is a cylindrical coil having a movable iron core attached to the threaded rod *H*. The worm gear *I*, driven by the reversible DC motor *J*, is attached to a nut and raises or lowers the core of the inductance coil through the rod *H*; *LL* are the limit switches for this rate-changing motor *J*. The inverted converter *R* is shown in Plate 14 adjacent to the constant temperature cabinet *CT*. The thermostat tube relay and the heater switch are enclosed in the small metal cabinet *A*. A general view of this constant temperature cabinet is shown in Plate 17. Here is illustrated the cabinet *CT* (for convenience, an ordinary ice-box), showing how all circuits are cabled and brought out at one point. *IC* in this plate is the inverted rotary converter, the speed of which is controlled by the oscillating circuit inside *CT*. *SM* is the synchronous telescope drive motor, 1/20 HP and ball bearing; and *G* is the guard normally fastened over the terminal block on *IC*.

The performance of this device for rate control has proved extremely satisfactory, as any unadjusted variations are too slight for detection at the telescope, while the response to any changes of adjustment is immediate and precise. The starting operations have been described above, and the correct rate can be found in a few minutes at the telescope, or computed in terms of frequency, and adjusted in advance by the frequency meter. The rate control buttons are located adjacent to the right ascension slow motion buttons on the observer's control box. The repeated use of one or another slow motion button indicates the necessity for a change of rate, which is made by pressing the rate button adjacent to the particular slow motion button that is being used unduly.

It is the custom of our observers *to change the rate at once* when a slow motion button is used *more than once in two minutes*. This statement of our current observational practice has been purposely italicized. It will serve to indicate more clearly than would any longer description two salient features of our rate control mechanism. First, this method of precision telescope drive is not a device of occasional or sporadic application in our observational program, but rather a method found so efficient and valuable that our observers use it as constantly and automatically as a worker with older types of telescope drive would use his slow motion controls. Secondly, the observer, almost in his first half-hour of use of this infinitely flexible rate, ceases to regard good guiding as a matter involving unremitting attention and eyestrain in repeated adjustment of the cross-hairs to the guiding point, but changes unconsciously to the conviction that if he brings the telescope to the correct rate all guiding of the older conventional sort will be unnecessary. For the constant close attention and the innumerable slow motions of the older guiding, he substitutes delicate rate changes at very much longer intervals, with only occasional and rarely needed slow motion adjustments; he does very little actual *guiding* as the telescope does that for him, once he has provided the telescope with the correct *following* rate. Only those who have done a great deal of careful guiding by the older methods and then learned this substitute method can fully appreciate the amount of labor and strain from which the observer is freed by this change from slow motion guiding to driving rate guiding.

A very high degree of dependability and great ease of maintenance has been found to result from the mechanical simplicity of the entire drive system. Since its installation here, in addition to the large reflectors mentioned in the introduction for which this drive will be used, the writer has recently constructed a drive for the one-tenth scale model of the 200-inch telescope planned for the California Institute of Technology.

The Declination Drive

The original 10.5-inch reflector of this observatory and the new solar tower are believed to be the first instruments that have ever been provided with a sensitive and delicately variable drive in declination.* Astronomers have occasionally expressed surprise that we find such a drive in declination desirable, yet it is, in the larger sense, merely the logical continuation of our plan to make these instruments perfectly following instruments in every way, rather than of the type which requires constant attention to guiding. We find it indispensable and use it constantly in all our observational work, whether on the moon, sun, planets, or on stars moving geocentrically at the sidereal rate.

The principal requirement of a drive in declination is a wide range of rates. Including the effect of refraction, the rates for solar and stellar guiding are only a few seconds of arc per hour, while those for lunar work are to be measured in seconds of arc per minute. The lunar rate in declination, due to parallax and refraction

* A drive in declination was incorporated in the mounting of the McDonald telescope in Texas, which will soon be in operation.

alone, may vary from zero on the meridian to 9″.8 per minute at 3.5 hours west and 25° south declination.

As in the case of the drive in right ascension, that in declination is an evolution. The first design built to provide the necessary wide speed range consisted of a pair of friction disks, driven by a constant speed motor, and driving the telescope in declination through a flexible shaft carried up to the hand slow motion worm. This arrangement proved to have too much slippage, and the disks were replaced with a bevel gear and pinion. A planetary slow motion was introduced which was controlled by push buttons at the observer's station, and a set of change gears was then employed to obtain 52 fixed rates of drive varying from 0′.803 to 20′.0 per hour for lunar rates. For solar rates a removable reduction was employed which gave 52 rates from 6″.0 to 120″.0 per hour. This "stepped" form of rate change necessitated many changes of gears during a run of a few hours, and produced rates that at best were only momentarily correct. Accordingly, in order to secure the ability to vary the rates between the gear change steps, a frequency changer, similar to that used in the right ascension drive, was put in the line supplying the synchronous driving motor.

At the time of the installation of the tuning fork frequency control, the present Ward-Leonard system was installed on the declination drive. The outstanding feature of this design is the ease of speed control of the driving motor, from 400 to 2,200 RPM. This broad range renders the necessity of gear changes during a day or night's run a rare occurrence.

This device for speed control includes a motor driven DC generator and a motor. The field of the motor is connected directly across a 120 V DC line, and the armature is directly connected to the armature circuit of the generator. The generator field has one side connected to the negative 120 V DC line, and the other side to the slide of a potentiometer, which in turn is connected across the 120 V DC line. The field voltage of the generator may therefore be regulated to any value between 0 and 120 volts; this in turn regulates the potential across the generator armature circuit. The current through this armature circuit is largely determined by the difference between the generator potential and the back EMF of the motor. Since the motor field has a practically constant value, the back EMF is, within limits, very closely a function of the motor speed. Thus at any generator potential the motor speed will have a corresponding maximum value at which the back EMF is nearly equal to the generator potential. The effect of a load on the motor is to decrease the speed and the back EMF, and consequently to increase the current in the armature and to increase the torque of the motor.

Within the range of the equipment, this speed-torque relationship tends to maintain a uniform motor speed for any setting of the generator voltage, and the value of this uniform speed is therefore determined by the potentiometer setting.

The motor and worm reduction for regulating the potentiometer are shown at *D* in Plate 14. The buttons controlling this reversible motor are located on the observer's control box, adjacent to the declination slow motion buttons. When this equipment was moved to the control room from its original position near the telescope, the former flexible shaft connection to the telescope was replaced by a pair of Selsyn motors. In Plate 15 are shown the tachometer, the motor, the drive motor worm reduction *A*, the solar reduction train *B*, and the change gears *C*.

The Camera Drive

It was necessary to provide an automatic camera drive mechanism that could provide for and accurately time two independent time intervals;—one the length of exposure, and the other the length of time between exposures,—both intervals to possess a rather large range of variation. The length of exposure depends on the constants of the lens or mirror system and the intensity of the object, while the length of time between exposures is determined by the total amount of footage needed or the ratio of time compression desired. The length of the exposure itself manifestly plays a large part also in determining the maximum possible footage and the minimum amount of compression permitted in the time factor. To illustrate,—in lunar photography it is desirable to obtain about 40 feet of negative for a picture intended primarily for projection; the focal length will be governed by the type of formation under observation and perhaps also by seeing conditions. Thus, for a six-hour run, yielding a footage of 6⅔ feet an hour, it would be possible to plan for exposures of $20^s.0$ at f:54, or $2^s.2$ at f:18, or $48^s.0$ at f:85. A much greater amount of time compression would be required in the case of the satellites of Jupiter in order to show their motion adequately on the screen.

Because of the relatively rapid changes in the phenomena under observation, the time compression factor must be as small as possible in solar photography by the motion picture method. To fulfill this requirement a constant interval timer, to be described in detail later, has been added to the camera drive mechanism. The proper exposure time for lunar or planetary work is determined by means of a comparison photometer, and the variations to be expected and allowed for during the run are taken from an atmospheric extinction table. For solar exposures a Weston photronic cell with proper filter is used for K_2. Readings are taken with this cell every 30 minutes at a minimum, and the exposures varied accordingly. It is evident, from all the foregoing considerations, that it is necessary to have a camera drive and timer capable of a very considerable range of variation in the durations of both the exposure time and the "dark time"; and also capable of a very fine adjustment of exposure length during operation to compensate for the varying atmospheric transmission.

The first camera drive built in the effort to satisfy all these requirements was driven by a synchronous motor, and a set of change gears furnished the means for changing the exposure times used. The regulation of the ratio between exposure and dark time was accomplished by means of partial gears; these are 100-tooth change gears with the teeth removed over a suitable section of the circumference, and with each partial gear there was provided a set of change gears of such ratio that the number of revolutions imparted by the teeth of the partial gear to its meshing pinion will, through this secondary gear train, turn the camera through one complete cycle, i. e., from open shutter to open shutter, or from closed shutter to closed shutter. Four partial gears were provided which, with the ability to drive continuously if needed, offered a selection of five different ratios of light time to dark time. The mechanism can be set up in such a manner that the shutter is open at the end of the cycle when the pinion has entered the blank sector of the partial gear, or it may instead be arranged to have the shutter closed at this point. In the first case, the exposure is long relative to the dark time, and in the second the exposure is short and the time compression is greater.

While this first drive mechanism provided for a selection of exposure times and of light and dark time ratios, there was no possibility of securing intervals intermediate between those furnished by the change gears. There was the added disadvantage that this method of changing exposures was inconvenient and required considerable time.

Accordingly, when the Ward-Leonard system was applied to the declination drive as described previously, it was also installed on the camera drive, and an electric tachometer was attached to the camera motor permitting the observer to regulate the exposures from his station at the telescope. In 1934 a constant interval timer was added to the camera drive in order to increase the footage and to decrease the time compression in solar work. The present camera drive and declination drive are both shown in Plate 15. The interval timer is shown ready for operation, and *E* is the constant speed shaft which carries the partial gear when that form of drive is used. In the arrangement illustrated, *E* is driving the partial gear pinion shaft through a one to one gearing. The timing drum *H* carries a contacting bar which, in passing under the brushes *I*, completes the circuit to release the brake *L* and start the motor *K*. *K* drives the shaft *N* through the reduction *M* and the change gears shown. *O* is a brass drum carrying a narrow insulating bar, and is mounted together with the bakelite drum *P* on the shaft *N*. The contact of *H* with the brushes *I* causes *N* to turn and, before the bar *H* has moved out of contact, the insulating bar of the drum *O* has moved from under the brushes which are connected in parallel with the brushes *I*, and *N* continues to rotate until the insulating bar returns to its original position and breaks the circuits.

One revolution of the shaft is one complete camera cycle and requires about 3 seconds. The intermediate shaft *G* drives the camera Selsyn transmitter through the gearing shown. The bakelite drum *P* carries a contacting bar mounted at 180° from the bar on drum *O*. The brushes which contact drum *P* are in series with the closed shutter switch on the control box and also with a normally closed multiple relay which in turn is in the circuits for the camera drive motor and interval timer motor *K*. If the closed shutter switch is thrown, the relay will act to stop both motors when the shaft has turned 180° and brings the contactor on drum *P* under its brushes; thus it is possible to stop the camera with the shutter closed.

The Chronograph

Our solar prominence films, as they stand, will be of value as the only continuous record possible of processes and changes occurring on the sun. There would be the danger of limiting their value as scientific documents were they not provided with every possible adjunct of accurate recording. Accurate and uninterrupted automatic timing covering many hours is therefore a necessary and indispensable prerequisite, and prompted the construction of the special chronograph here described.

A time record of each exposure frame is made on an electrically driven chronograph located in the underground control room, shown in Plate 16; the switch for this chronograph motor is located in the solar tower office adjacent to the chronometers and to the short-wave and 113 kilocycle radio receivers. This instrument was designed to use the standard record paper supplied for Westinghouse recording frequency meters, and can therefore furnish an uninterrupted time chart covering many hours.

The clock mechanism for driving the chronograph is a 24-watt 1 RPM telechron motor *A* with spur and worm gear reductions *B* that drive the main drum *C* through a cone clutch *D;* the diameter of this drum is such that the peripheral speed is 1 inch per minute. The recording paper *E* is perforated along both edges, and small bullet-nosed pins *F* on the drum engage in these perforations, thus preventing slippage and consequent time error in the record. The paper is driven in this manner under a capillary pen *G* mounted on a rod *H* attached to the armature of a six-volt solenoid *J*. This solenoid, by means of a contactor on the camera (see Plate 15, *A*) is energized when the camera shutter is closed, thus the line is displaced to the left for closed shutter and, by means of a spring, to the right for open shutter. The movement of the pen is 0.1 inch.

The chronograph is prepared for starting by placing an hour line that is printed on the record paper beneath the pen point *G;* the chronograph is then started on an even minute and the starting time noted as a record for future reference. The correct time is taken from a chronometer and corrections are applied as derived from the U. S. Naval Observatory time signals. At the end of the run the clutch *D* is disengaged and the paper *E* wound back onto the supply reel *K* by means of the geared-up crank *L* provided for the purpose. The pen is then moved to a new position on its drive rod *H* by removing the taper pin *M* and inserting it again when the pen is in its new position. The drum is turned forward until the original hour line is again under the pen; then the clutch is engaged and the chronograph is ready to start the next record, ten recordings being obtainable on one length of paper.

The toggle switch shown at *N* connects the telechron motor directly across the AC line, and is used to bring the hour line in place under the pen. This makes it a simple matter to secure a very accurate setting of the line. The base *O* is the receptacle in which the record collects during the day's run.

Tabulations are made from these records by first measuring and indicating the mid-points of each exposure and then measuring the time of these points from the starting line in hours, minutes, and hundredths of a minute.

The chronograph was designed by the writer, and was made in the shops of the Motors Metal Manufacturing Company of Detroit.

The Underground Control Room.

This convenient and highly useful feature is to the northeast of the 10.5-inch reflector, from which it is reached by a flight of stairs. It houses most of the motors, master Selsyns, and other mechanisms described in this paper, and not only gives these a more constant temperature, but also relieves the working spaces of both the tower telescope and the reflector dome of a great deal of apparatus. The control room is shown in the general view of Plate 14. The camera Ward-Leonard generator *H* is shown coupled to the main DC generator *G*, both being driven by the 220 V AC motor *M*. At *B* is the declination Ward-Leonard generator, and at *C* are the camera and declination drive potentiometers. *K* is a small motor generator set that supplies direct current to the rate control motors and direct current relays. The rack *I* holds the camera drive change gears and partial gears.

Circuits and Controls.

All the equipment in the control room described previously can be made to serve either the 10.5-inch telescope or the tower telescope, a feature which saved a large expense in constructing the new tower. All the controls for this equipment which are used after the throwing of the main starting switches, are duplicated.

Circuits to the camera and the telescope motors and the various controls for the 10.5-inch dome are carried from the control room to a multiple disconnecting plug mounted on the main switch panel in this dome; and this multiple plug can be connected either to the mechanisms of the 10.5-inch dome or to those of the lower telescope. There is also another multiple plug which parallels enough circuits to permit the simultaneous operation of both cameras and both telescope drives. The rate controls for the cameras and for right ascension and declination are not paralleled, and can be used from one station only as determined by the position of the main disconnecting plug.

The control boxes, which hold all the controls used by the observer after the work of the day has been started, have identical arrangements for all controls that are common to both instruments (these control boxes are shown lying on the spectroheliograph head in Plate 11). The tower telescope control box has buttons for right ascension slow motions and the corresponding rate changes, buttons for declination slow motions and rates; camera rate buttons regulating exposures, and east and west dome control buttons. There is a reversing switch for the declination slow motions, a camera switch, a camera closed shutter switch, and switches for other incidental circuits.

The set-up box for the solar tower (not the "guiding" control box just mentioned) holds the Selsyn motor energizing switch and the following push buttons,—

- 2 for the right ascension setting motion.
- 2 for the declination setting motion.
- *6 third flat adjustments to include focusing, tilting on a N-S axis, and tilting on the E-W axis.
- *6 for the grating mounting, providing for focusing, for tilting grating axis, and for rotation of the grating about a vertical axis.
- *4 for collimating the 4-inch guiding lens.

The starred buttons are protected by covers against accidental contact.

The circuits from the various control boxes and switches on the spectroheliograph and the circuits from all the capacitor motors, are carried directly to a junction panel located in the main distributing cabinet in the tower telescope workroom. The lines from the control room and from the multiple plug on the main switch panel are carried in conduit from the 10.5-inch dome to this cabinet in the tower. All the meters, tachometers, and resistance controls are mounted on the front of this cabinet and the condensers for the capacitor motors are mounted inside. Every line is carried to the junction panel in order to facilitate testing or changes.

Tower Telescope Performance: a Summary.

With all the manifest advantages of the motion picture technique in recording the continuous changes of solar phenomena, for which no other equivalent method exists, there is one point in which the method is at a disadvantage. It is impossible to provide for the actual "publication" and consequent wide circulation of our motion picture results save through the purchase or rental of these films by those interested, and the subsequent display of these films by means of a suitable motion picture projector. This disadvantage, real or apparent, comes strongly to the fore as the need arises in this article to show some form of plate which will indicate with sufficient clearness and in a form sufficiently compact, the precise character of our actual results; and so, while we realize that any attempt to exhibit our results must be fragmentary and incomplete, we have made a combination photograph, Plate 19, as a rough indication of the changes observed, even though this is very far short of the continuous record of the original film.

This illustration of the performance of the tower telescope (Plate 19) is from a negative prepared by Harold Sawyer. Six strips have been cut from a film run of 5 hours and 24 minutes made on a prominence photographed on September 15, 1936. Each vertical column is formed by one of these strips and contains nine consecutive frames; the G. C. T. of mid-exposure is entered at the left of each frame. The focal length employed was 40 feet, and the emulsion was Eastman Par Speed; the spectroheliograms were made in the light of calcium K_2.

The seeing was rated as 3 on a scale of 5; occasional thin clouds were noted. For this reason, and because allowance is always made for increase of atmospheric extinction with increasing zenith distance, the lengths of the individual exposures increase in the later columns. The interval between exposures, or "dark time," was 2.5 seconds throughout. The exposure times varied form 33.5 to 71 seconds, as may be derived from the tabulated G. C. T., but are given here also for convenience. For the frames of columns 1 and 2, the exposures ranged from 33.5 to 37 seconds; for columns 3, 4, and the first five frames of column 5 it was 33.5 or 34 seconds. At 20h 00m 00s G. C. T., during the exposure of the sixth frame of column 5, it was lengthened to 40 seconds, and further lengthened to 71 seconds for the frames in column 6.

As one reads down the consecutive frames of a column, small changes can be made out in the practically continuous record. Reading across the columns, however, very striking changes of form will be noted; such changes, seen much more effectively during the projection of the continuous film record, are often of inspiring grandeur. The intervals between the first frames of successive columns of this combination plate are, reading from left to right,—

1h	1m	40s
1	6	2
0	56	41
0	47	42
1	22	15

This is the seventh tower telescope to be built in the historical sense; it is also the newest. We may perhaps be pardoned for stating our conviction, concurred in by experts in this field, that it is definitely the most convenient and efficient installation of the sort now in existence; and that is it easily first as regards shortness of exposure time, a factor so vital for a record which strives for entire continuity in recording celestial phenomena.

New features of the tower, in so far as we have had the opportunity to inspect similar installations or to study their descriptions, are as follows:

The circular all-steel tower construction is not only a new departure, but provides great rigidity. The tower possesses the first flexible all-mirror optical projection system; the first vibrating slits of this particular type; the first scout camera as a check on the main camera function; and is the first to employ spectroscopic guiding methods for controlling the accurate slit setting of the chosen line. The automatic mechanisms for timing the individual exposures by remote Selsyn control and for furnishing an adequately accurate time record for the middle of each exposure, and the completely rotatable spectroheliograph are also new.

In convenience of manipulation, it is believed to mark a distinct advance over earlier instruments of this type. Every possible motion, function, or change is secured through electric motors, which relieves the observers of undue strain. It may be noted here that, if we include the necessary electrical accessories of the control room, a total of 39 electric motors or Selsyn controls are used in the tower, and that 61 separate circuits were extended from the control room to these new mechanisms. Some thirty or more push buttons control every necessary manipulation or adjustment. So far as we know, the spectrum drifter device and the angstrom dial, the quartz mercury and neon arc spectrum line position control, and the concurrent scout pictures in calcium H have never been employed before, and have proved to be of the utmost practical value. Furthermore, due to the necessity of combining the tower with the existing circuits from the underground control room of the 10.5-inch telescope, we have the advantage of being able to operate both the spectroheliokinematograph and the tower with parallel circuits, thereby securing simultaneous exposures in K_2 and $H\alpha$ which is also a new departure in chromospheric observations, the advantages of which were demonstrated during the past season's work.

To sum up:—the new mechanisms have functioned well from the start, and only very minor features would be changed in any degree were we now starting construction of another tower telescope.

THE McMATH-HULBERT OBSERVATORY
OF THE UNIVERSITY OF MICHIGAN,
LAKE ANGELUS, MICHIGAN.
January, 1937.

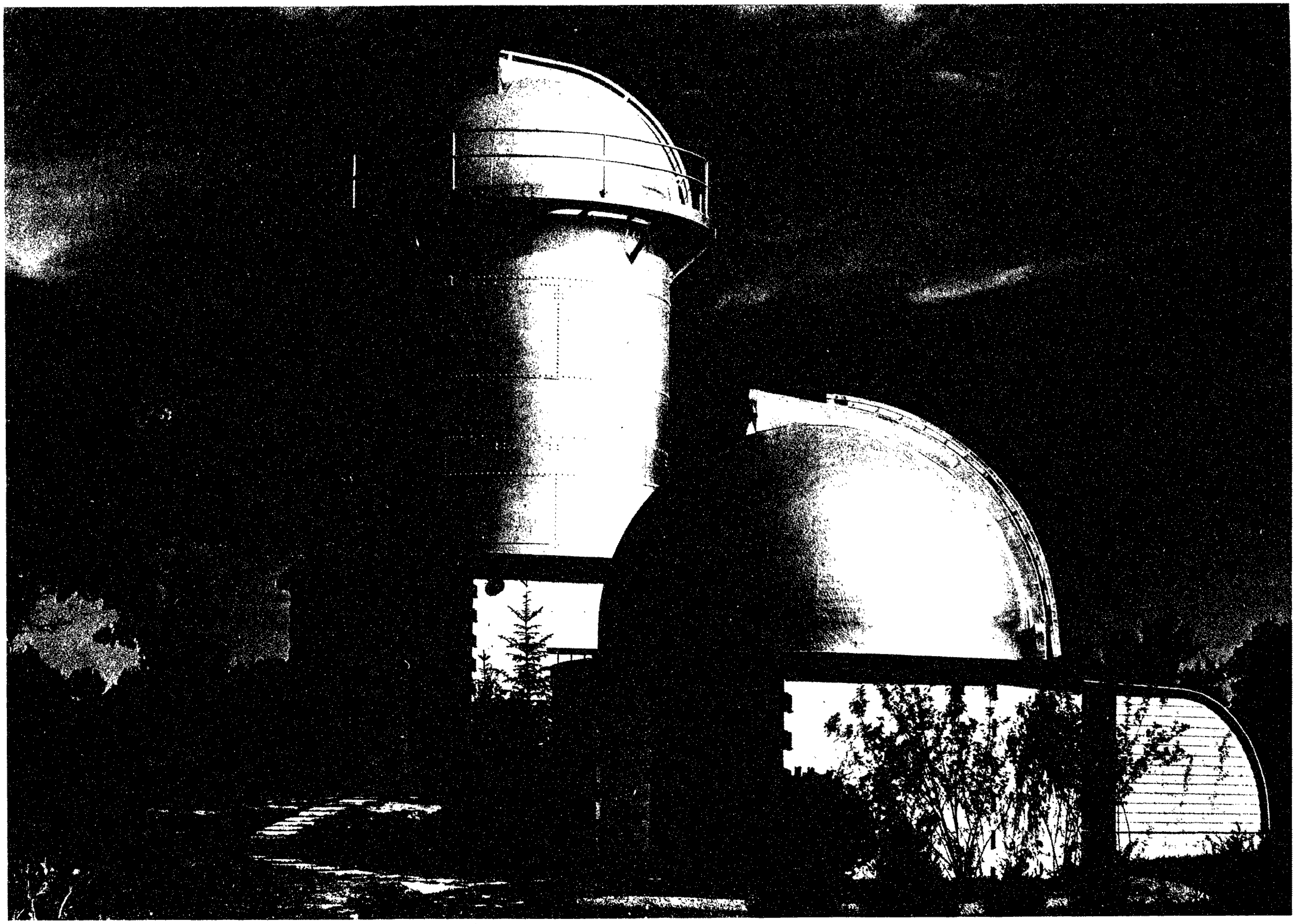

Plate 1. General View of the McMath-Hulbert Observatory, from a Photograph by Colonel Sidney D. Waldon.

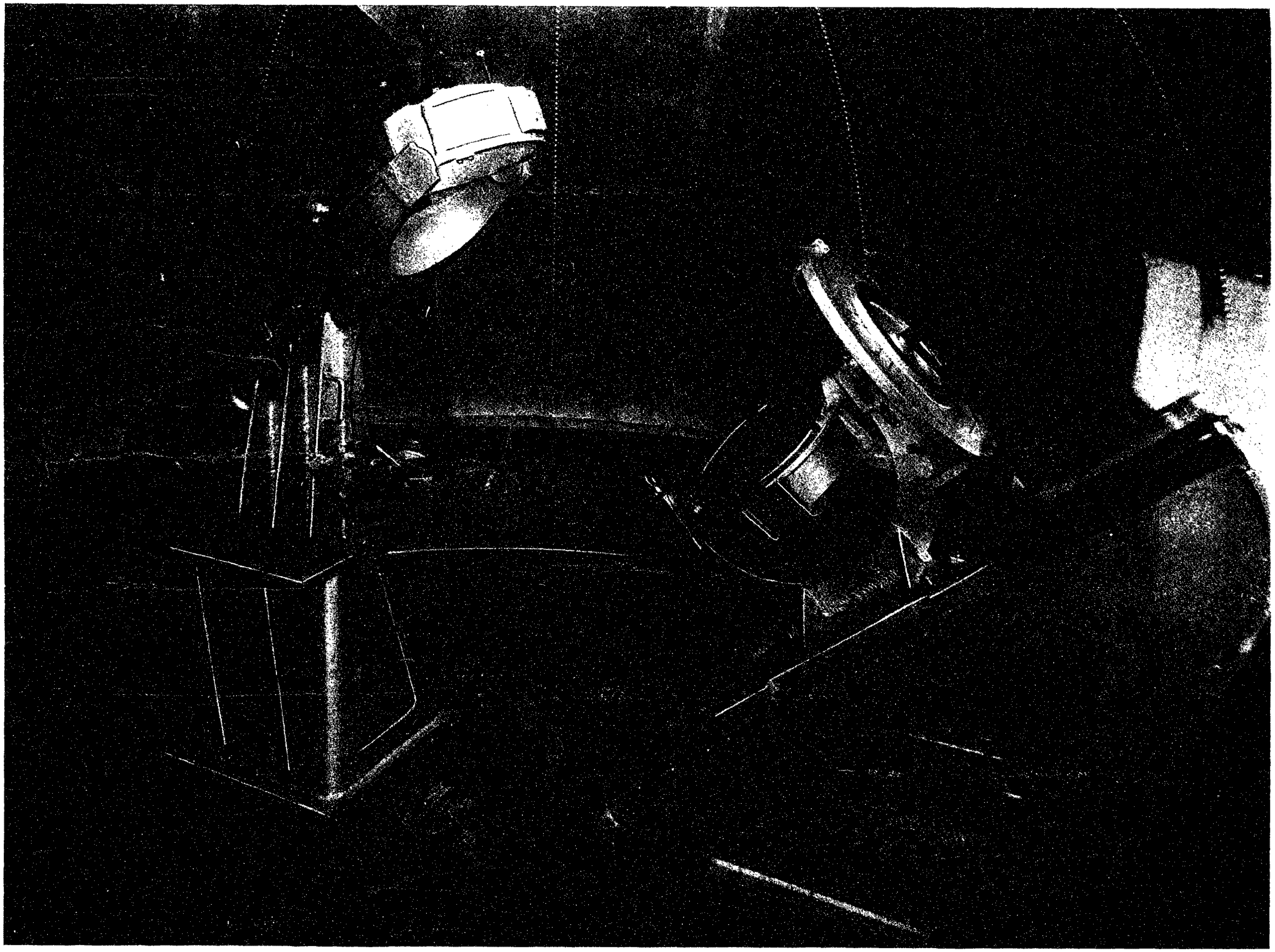

Plate 2. General View of the Coelostat and the Second Flat.

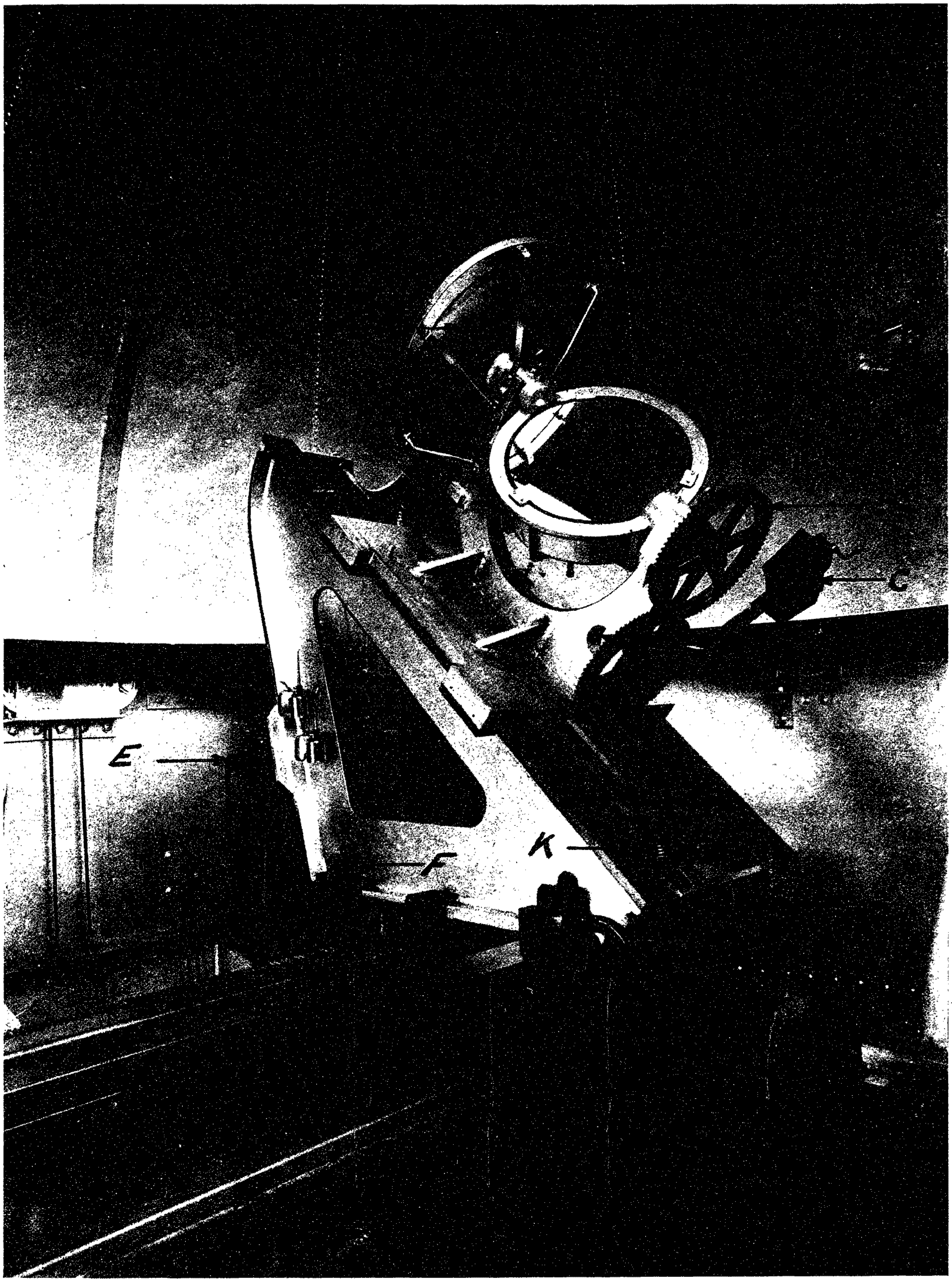

PLATE 3. The Coelostat.

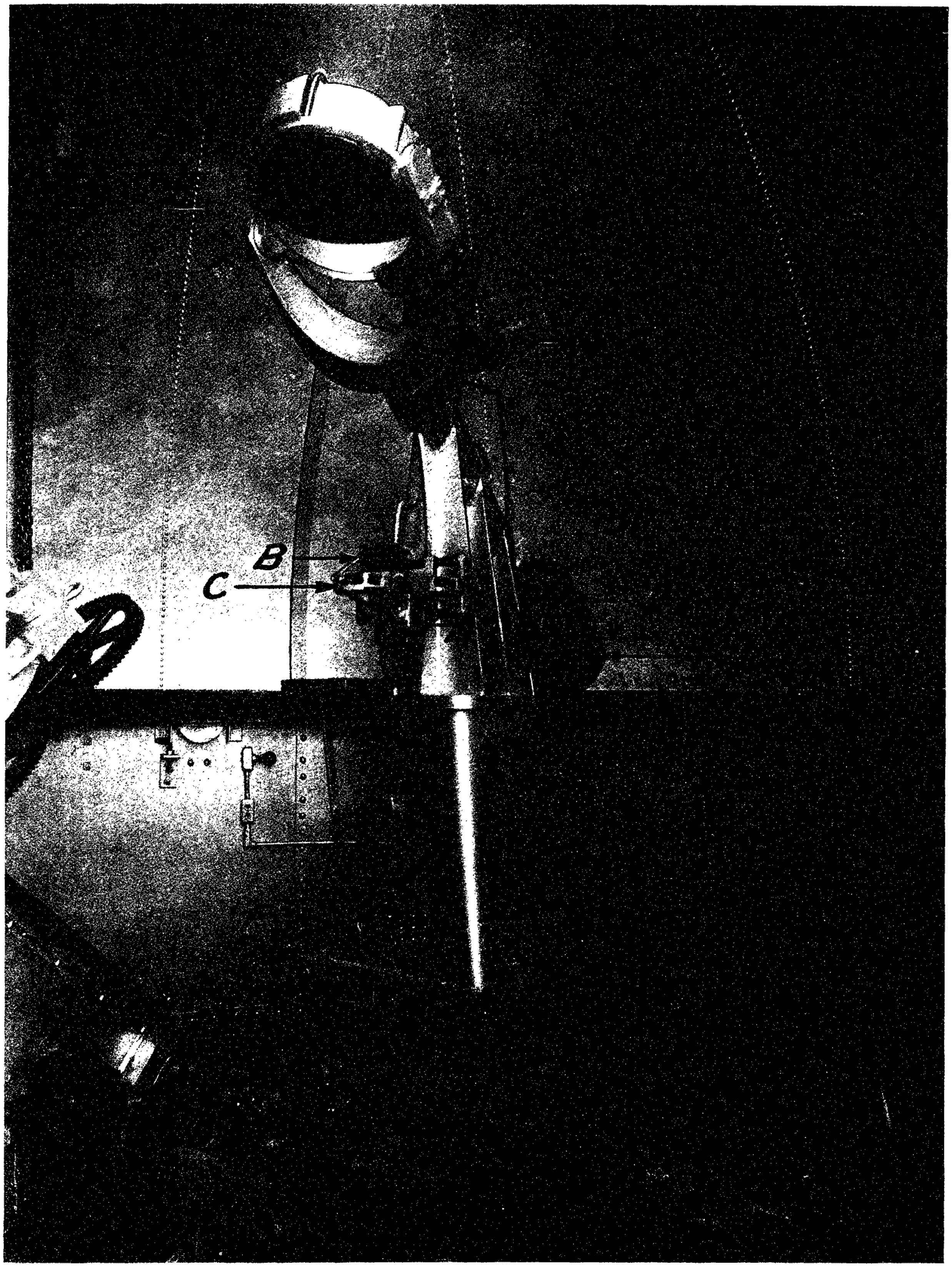

PLATE 4. The Mounting of the Second Flat.

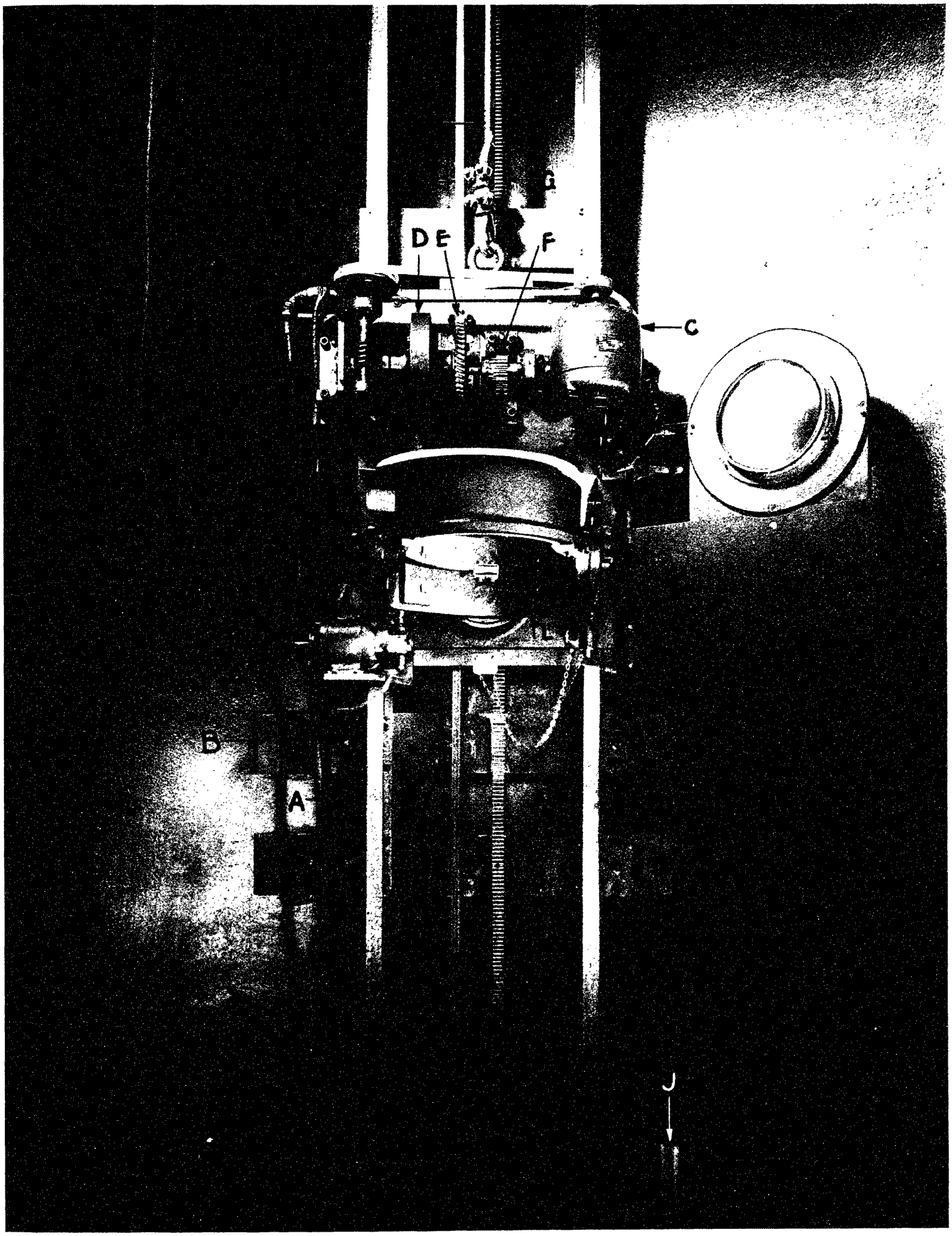

Plate 5. The Carriage of the Third Flat, with Mirror in Position.

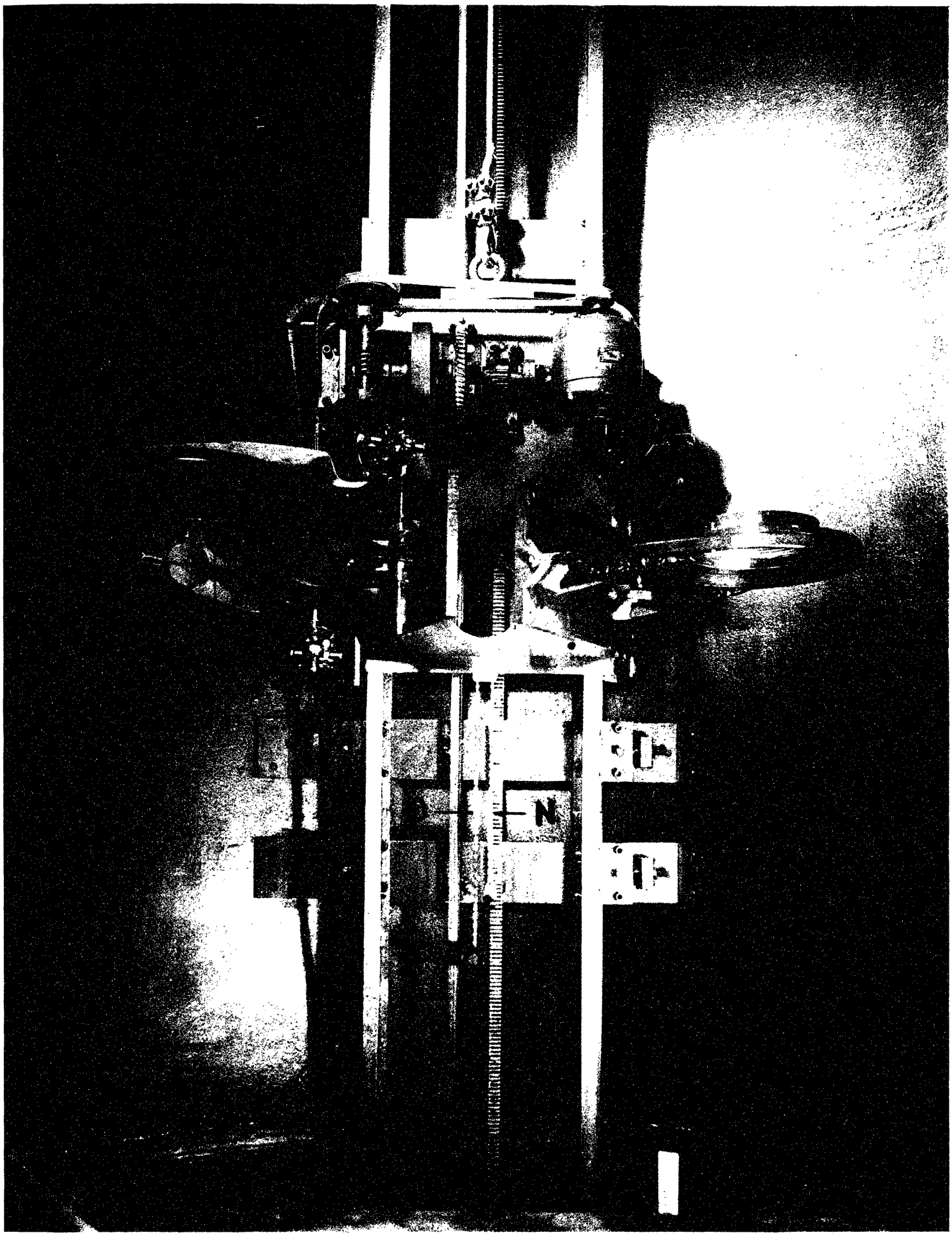

PLATE 6. The Third Flat and the Objective Lens.

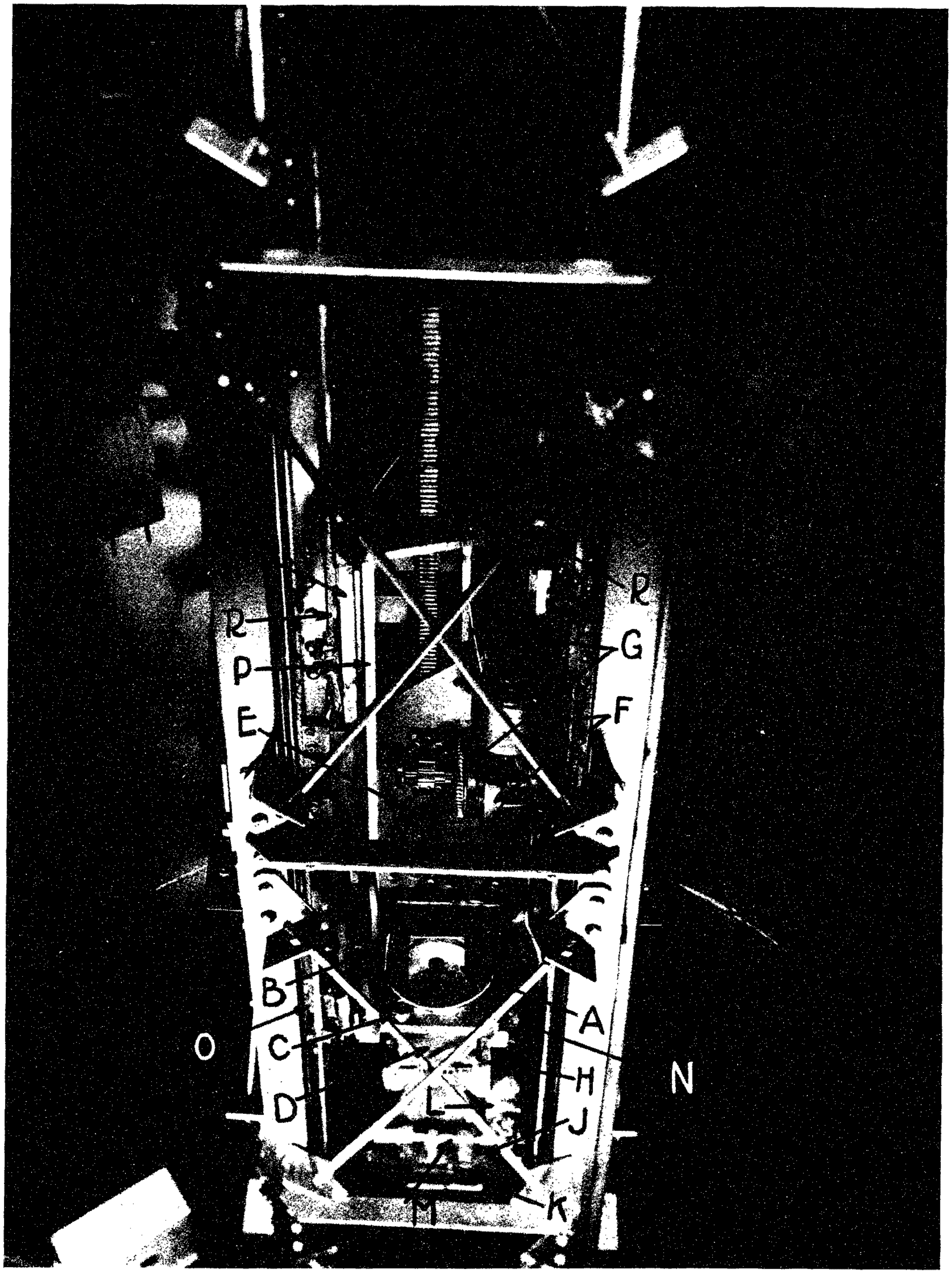

PLATE 7. The Spectroheliograph Cage, with Lens and Grating Carriage.

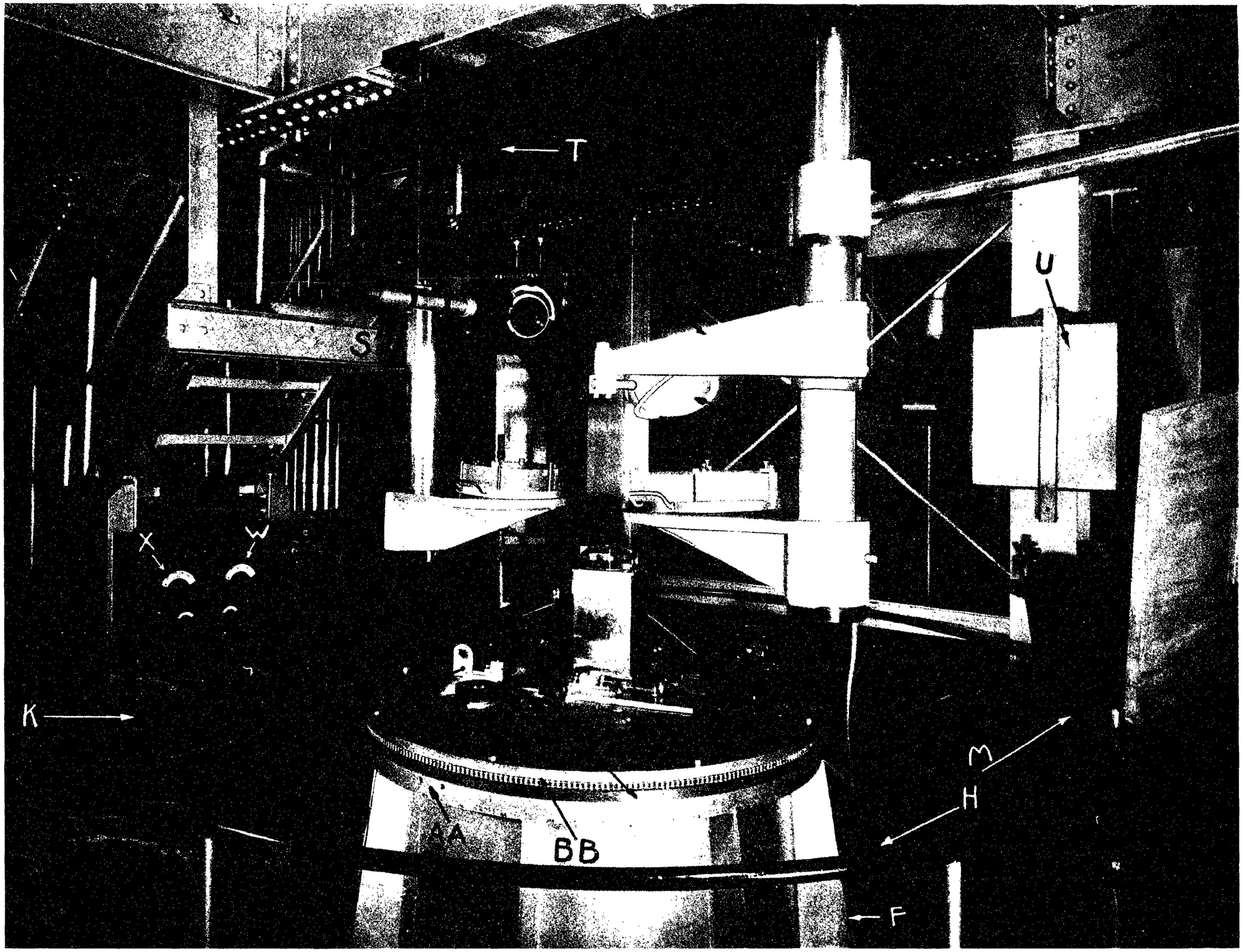

PLATE 8. The Spectroheliograph Head and Workroom, from the South.

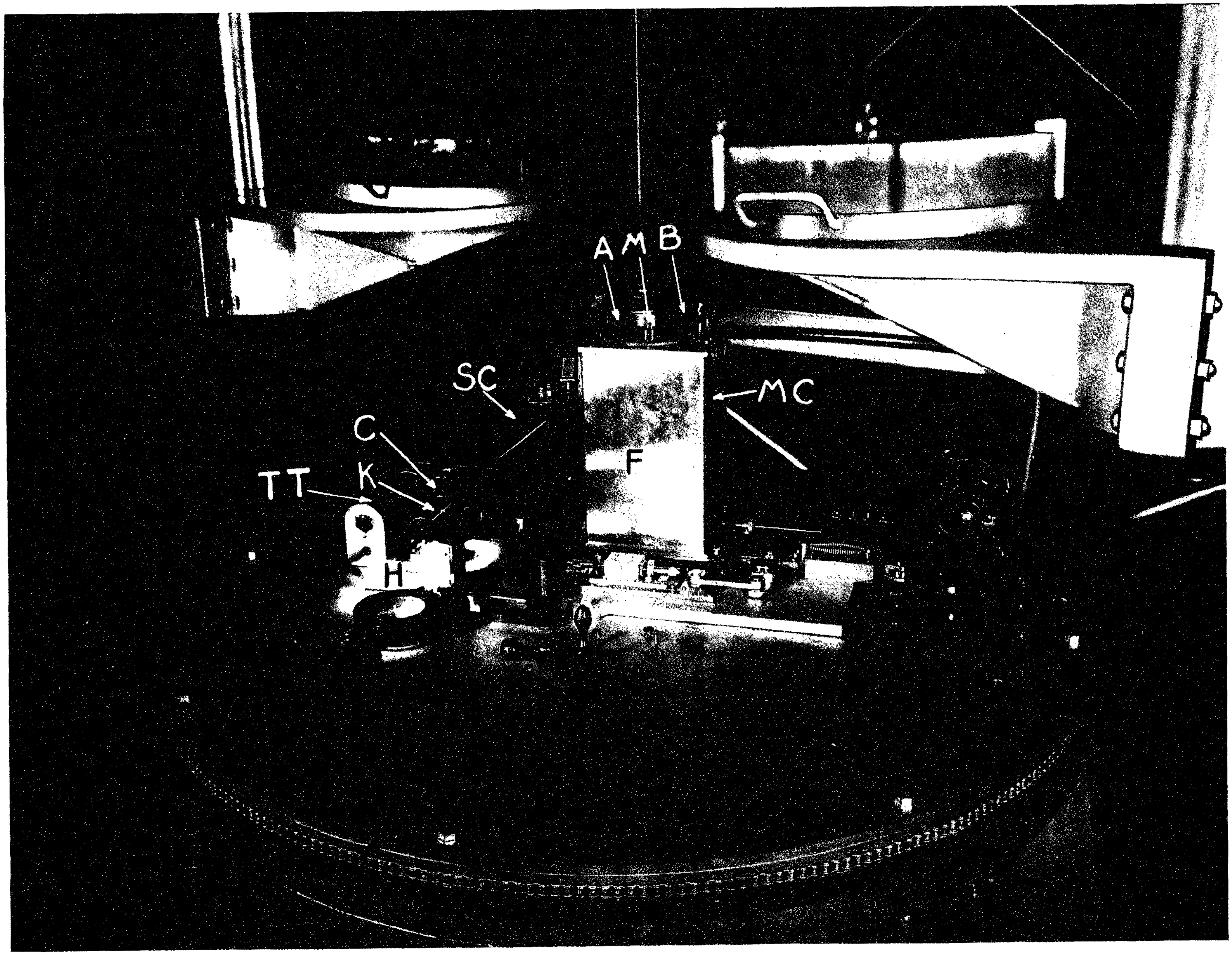

PLATE 9. The Spectroheliograph Head, with Camera in Place.

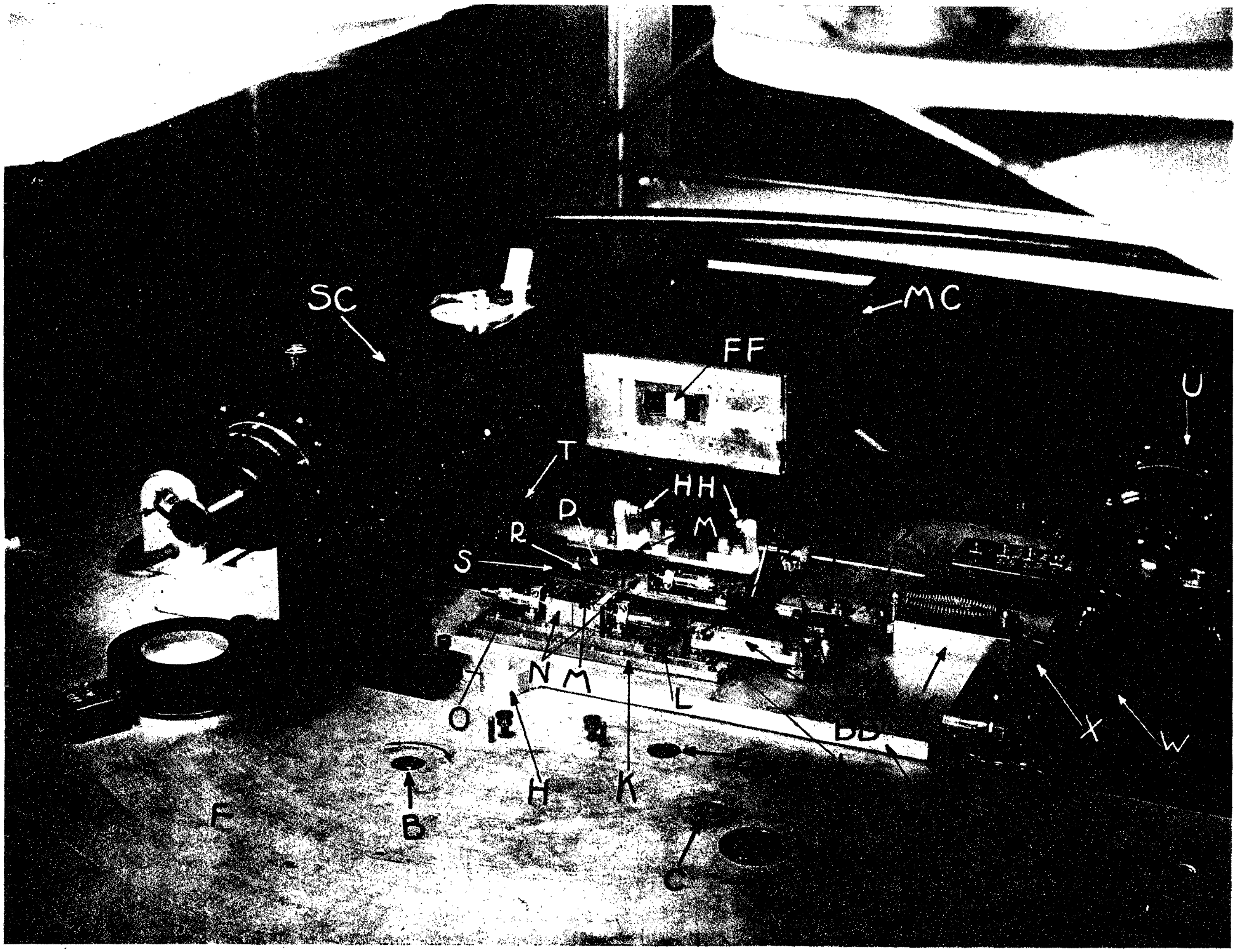

Plate 10. The Spectroheliograph Head; Detail View from the South.

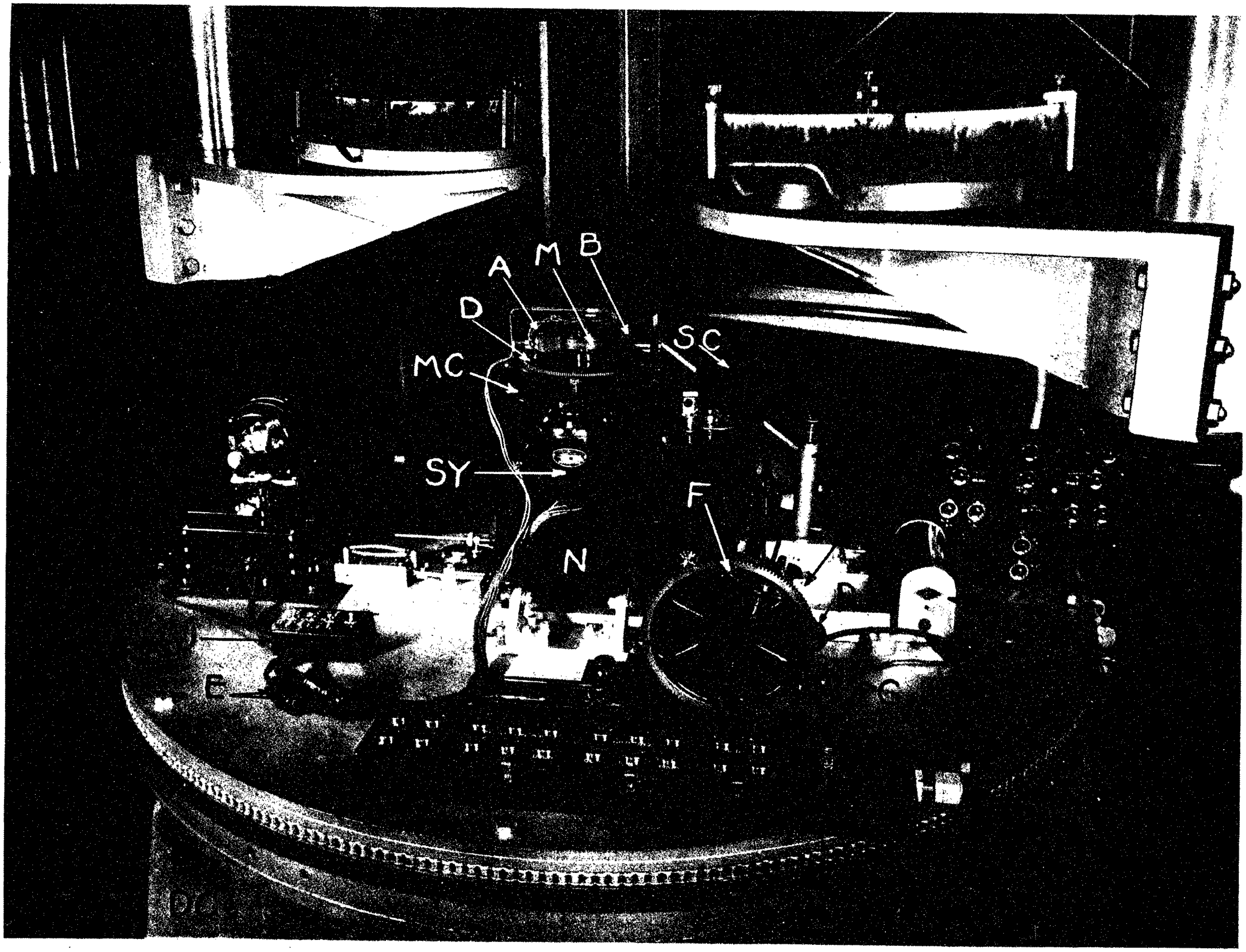

Plate 11. The Spectroheliograph Head; Detail View from the North.

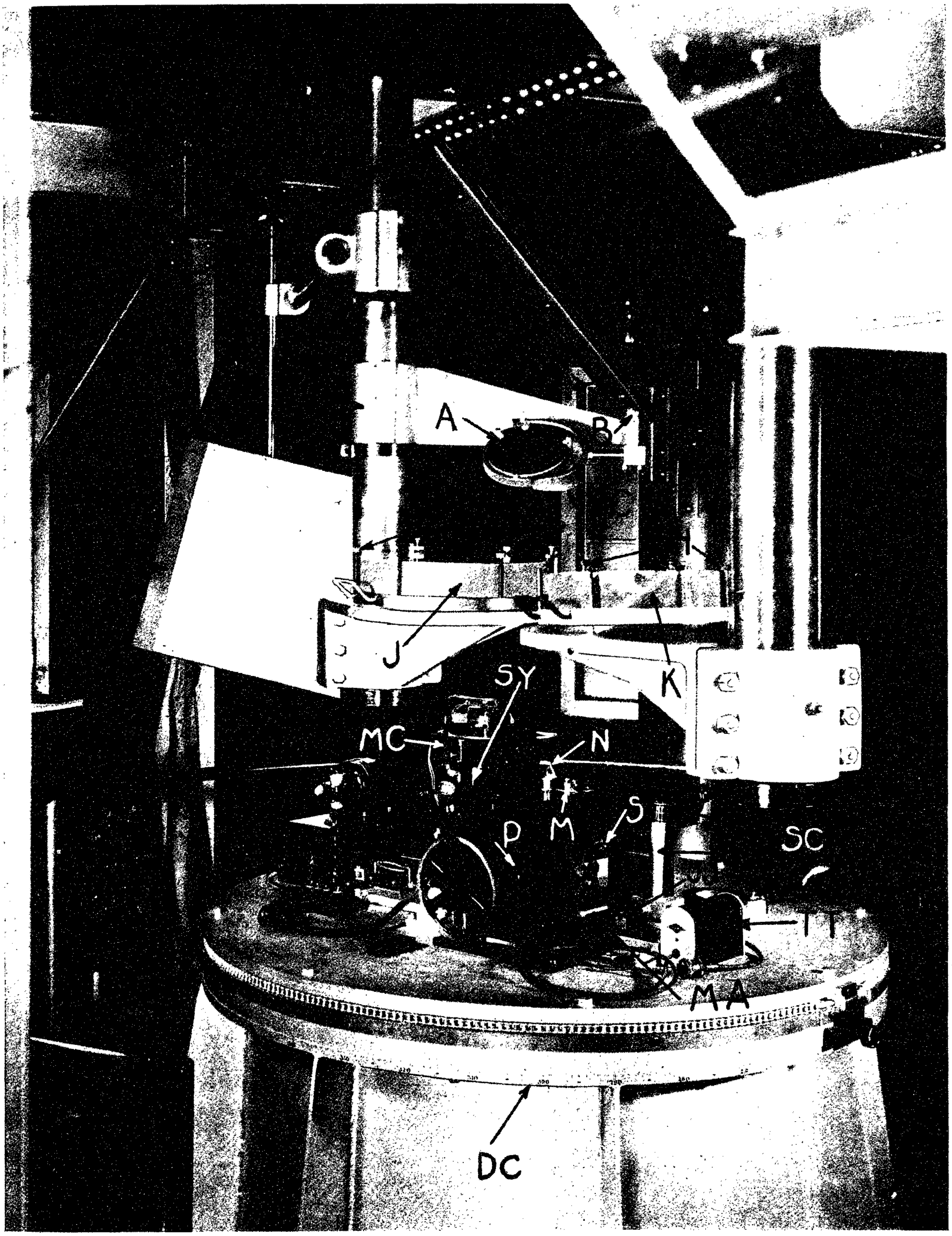

PLATE 12. Off-Axis Mirrors, Brackets, and Spectroheliograph Head.

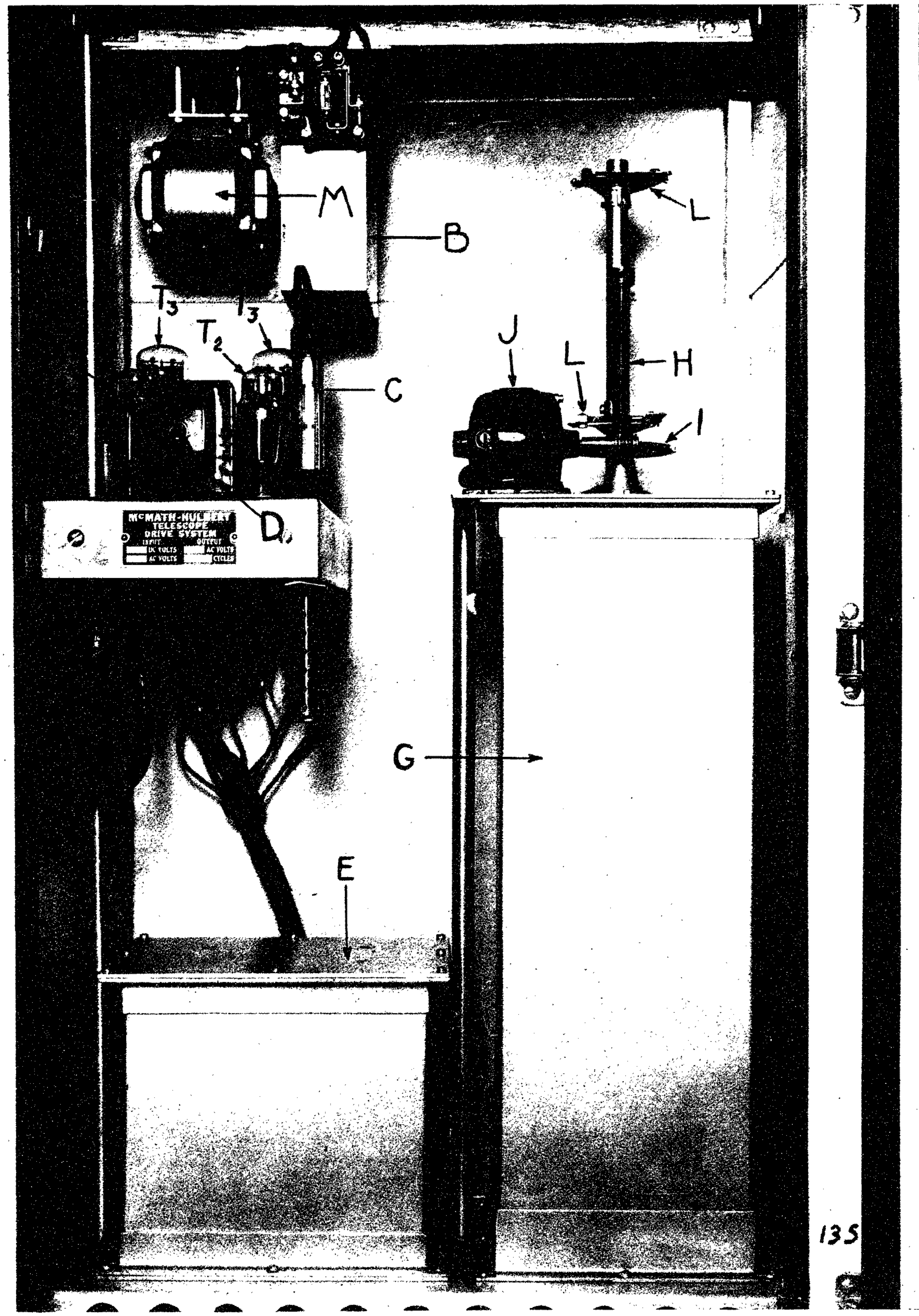

PLATE 13. Interior View of the Constant Temperature Cabinet.

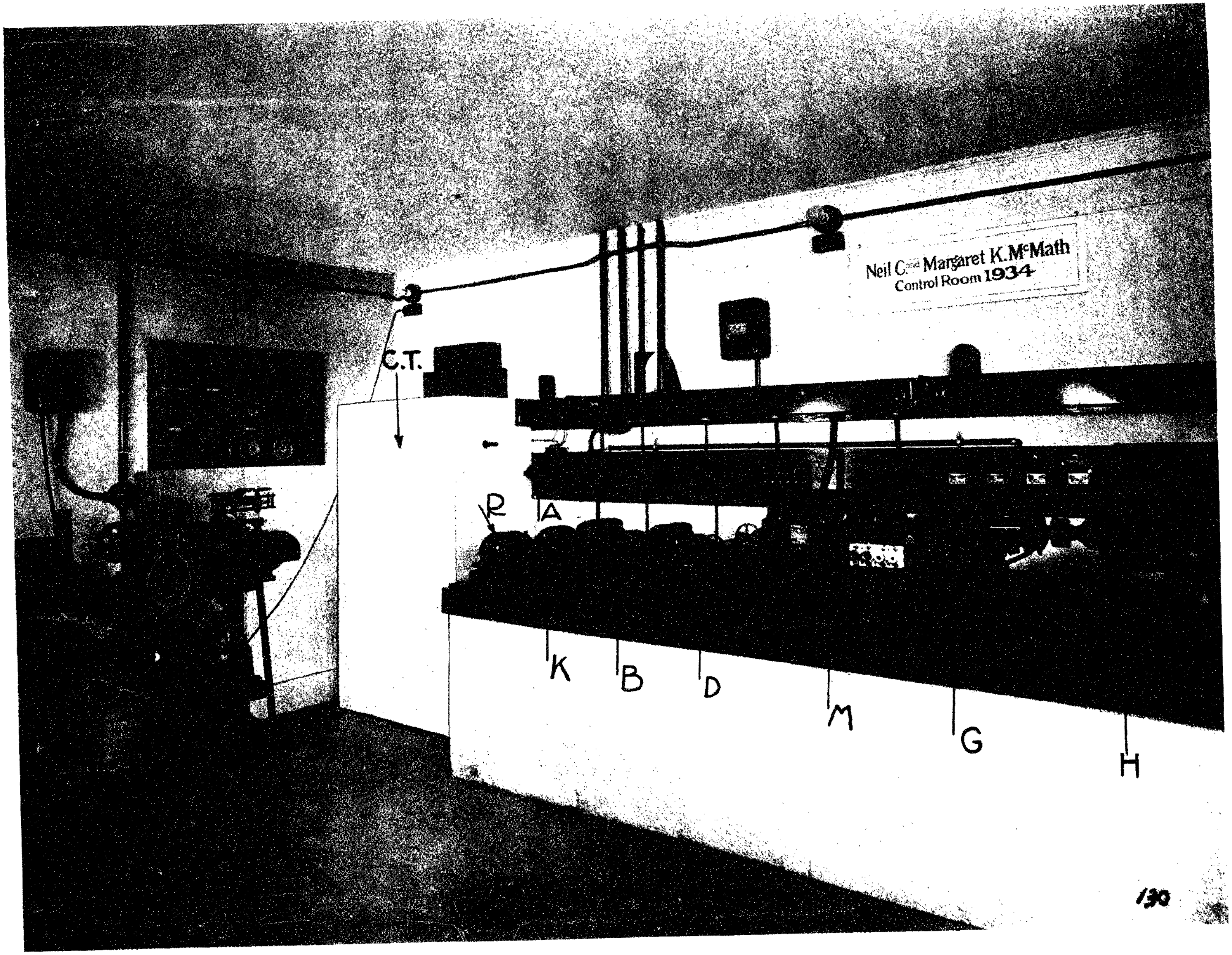

Plate 14. Interior View of the Main Control Room.

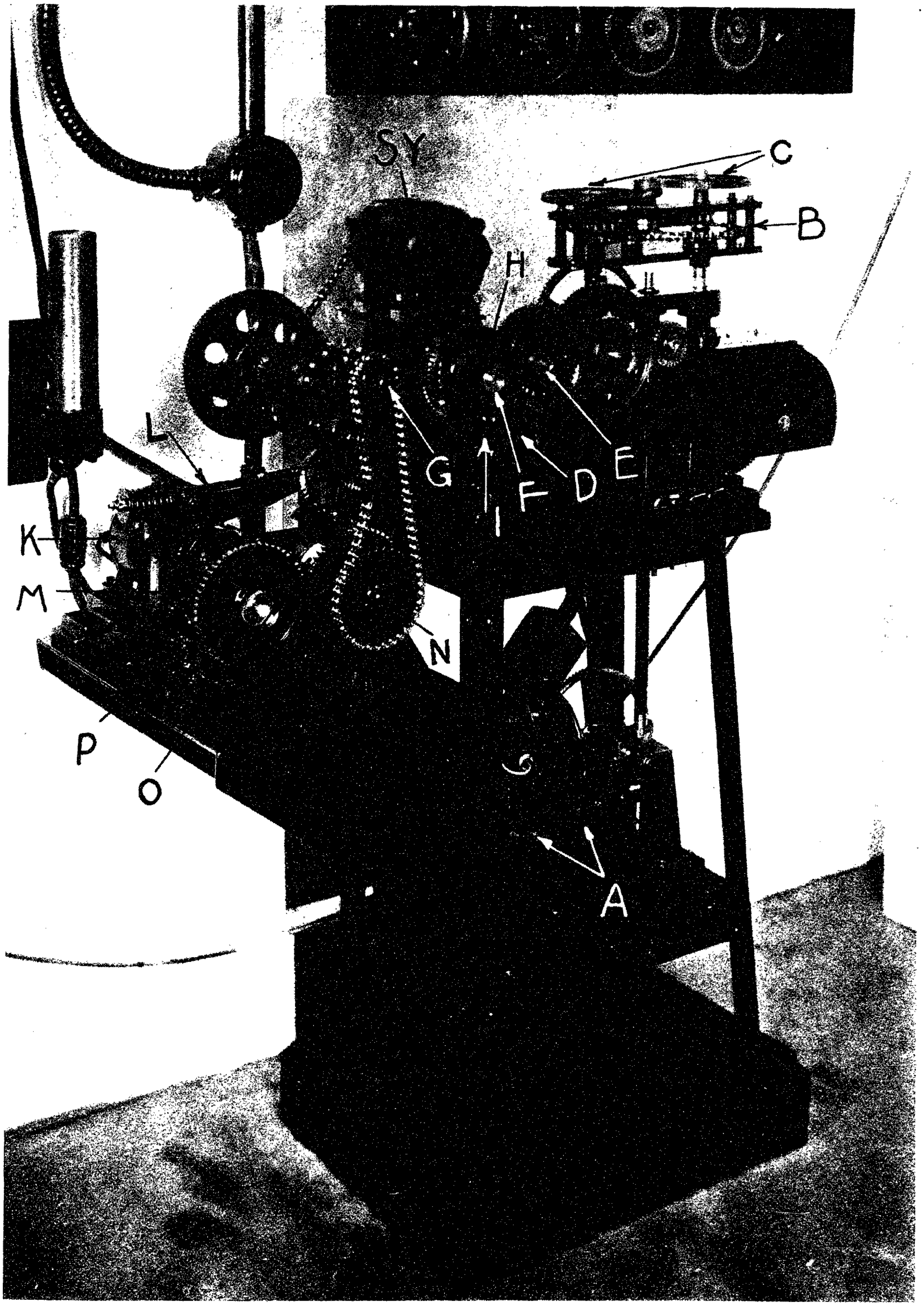

PLATE 15. Camera Timer and Declination Drive.

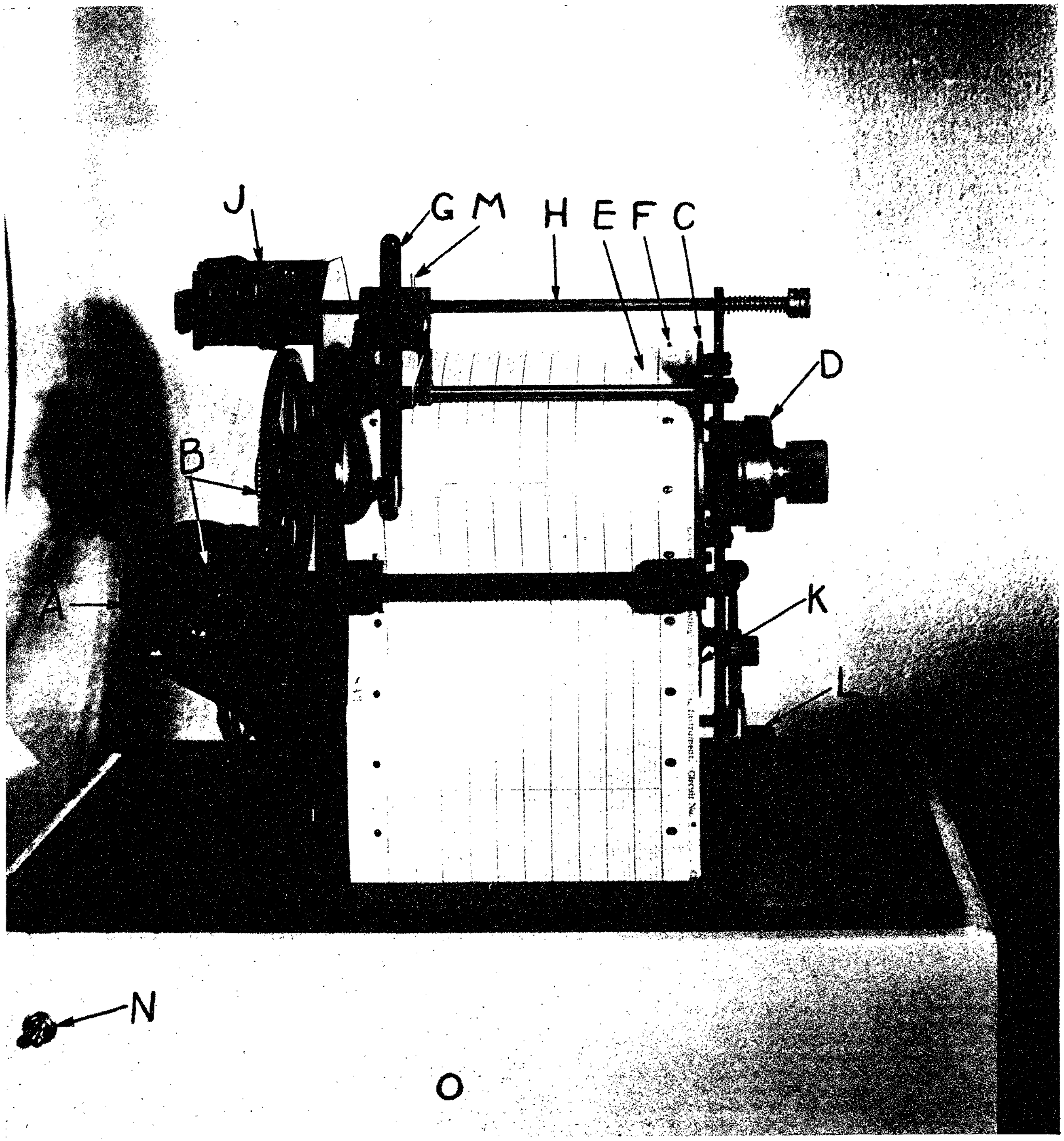

Plate 16. The Chronograph.

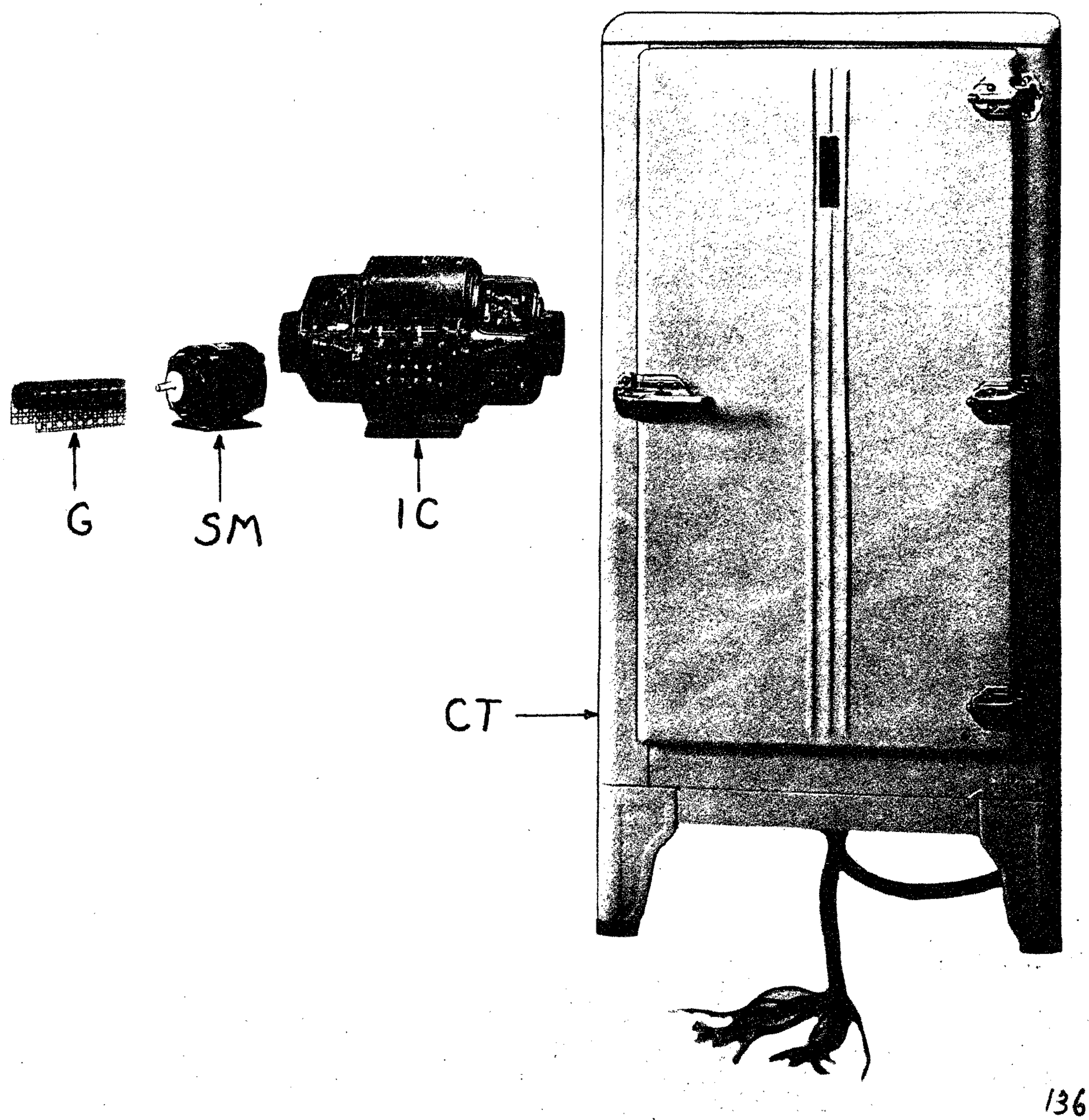

PLATE 17. Exterior View of the Constant Temperature Cabinet.

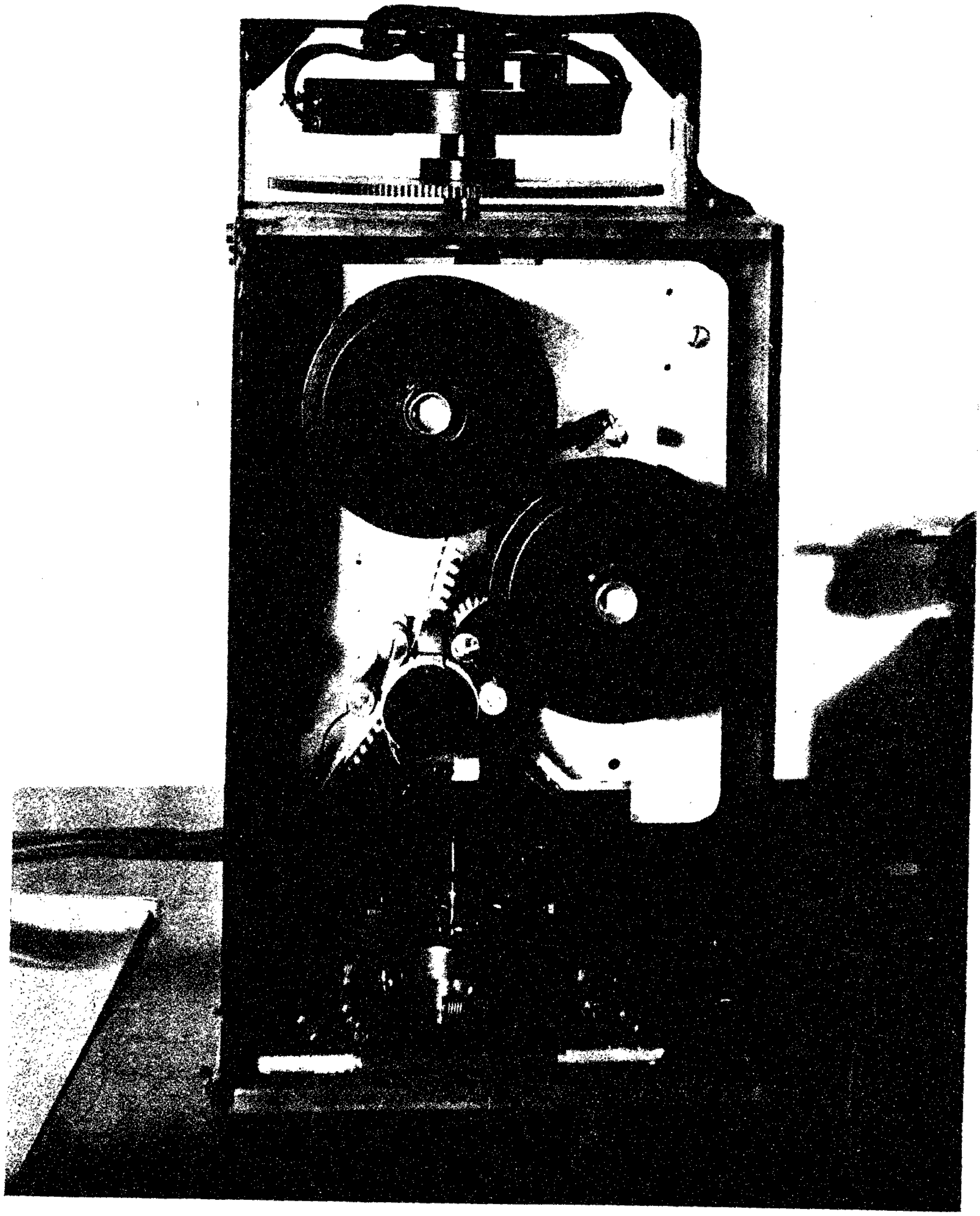

PLATE 18. Motion Picture Camera with Dark Slide Removed, Showing the Bell & Howell Super-speed Check-Pawl Mechanism.

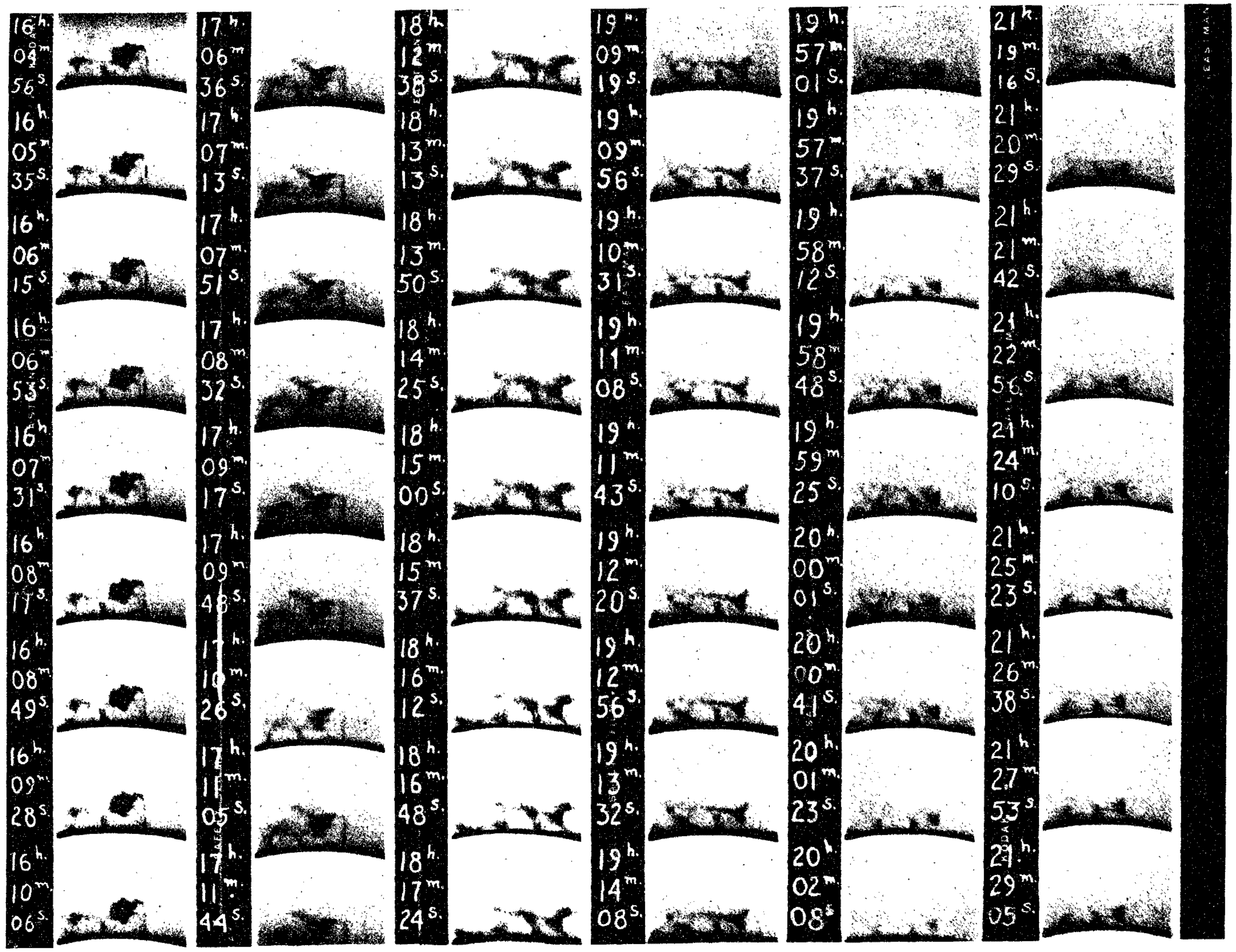

Plate 19. Illustration of the Performance of the Solar Tower.

Six short sections are shown, averaging about one hour apart, cut from a film run of 5 hours and 24 minutes made of a spot-type (Class IIIb) prominence on September 15, 1936. The G. C. T. of mid-exposure is written at the left of each frame. Reading down the set in each column, small changes can be made out in the nearly continuous record, while notable changes of form are seen when reading across the columns. See text for more precise numerical data. Negative prepared by Sawyer.

The New McGregor Building and 70-foot Tower Telescope of the McMath-Hulbert Observatory

By HEBER D. CURTIS

The new McGregor Building and attached 70-foot tower telescope of the McMath-Hulbert Observatory of the University of Michigan was dedicated on May 25. Judge Henry S. Hulbert, President of McGregor Fund Trustees, formally presented this powerful new tool for solar research to the University of Michigan, and the gift was accepted by President Alexander G. Ruthven for the University. Short addresses were also made by Dr. Robert R. McMath, Director of the McMath-Hulbert Observatory; by Dr. Heber D. Curtis, Director of the Observatories of the University of Michigan; and by Dr. Charles F. Kettering, Vice-President in Charge of Research, General Motors Corporation. Dr. Kettering, in discussing the importance of work in solar research, alluded to our sun as a star upon which depends every manifestation of life and energy on this our earth, but stated that, in the final analysis, the sun does just two things,—"It pumps water, and it grows vegetables!" Another of his characteristically happy and concise extemporaneous definitions, which will strike a responsive chord in every research laboratory, was,—"To do the best research you must not have all the money you would like to have; you must instead have a little less money than is really needed for the research."

The McGregor Building is so named in memory of the late Tracy W. McGregor, of Detroit, founder of McGregor Fund, whose interest in this and other fields of astronomical research had always been keen. McGregor Fund not only gave $100,000 to cover the cost of the building, tower telescope, and apparatus, but has also made a grant for a part of the support of the work in solar research for the coming five-year period.

The new building is located to the north of the other buildings of the McMath-Hulbert Observatory, and is shown at the right in Figure 1, a view taken from the southeast. The building in the center is the 50-foot tower telescope, with which Dr. McMath and his associates have secured their remarkable motion picture studies of the prominences and other solar phenomena (over 400,000 individual pictures, or "frames," have been taken with this tower to date!). The lowest dome to the left represents the original observatory, and at first housed the 10½-inch pyrex reflector with attached motion picture mechanisms which was used for the earlier work of the observatory on lunar changes and the motions of planets and satellites; the spectroheliokinematograph was later added to this telescope and has been of great service in securing concurrent motion pictures in Hα while the 50-foot tower was making its records in the K line of calcium. The spectroheliokinematograph, working with a telescope of only 10½ inches aperture, may be regarded as the starting point of the solar work at the McMath-Hulbert Observatory, and gave the stimulus to the erection of the 50-foot tower telescope and the latest 70-foot tower. For the spectroheliokinematograph showed the existence of many short-lived solar phenomena whose existence had not previously been suspected. The first motion picture of a solar prominence with this instrument was secured in early August, 1932; these films, while now regarded as rather crude in comparison with later results, were shown before numerous societies or organizations and some of the re-

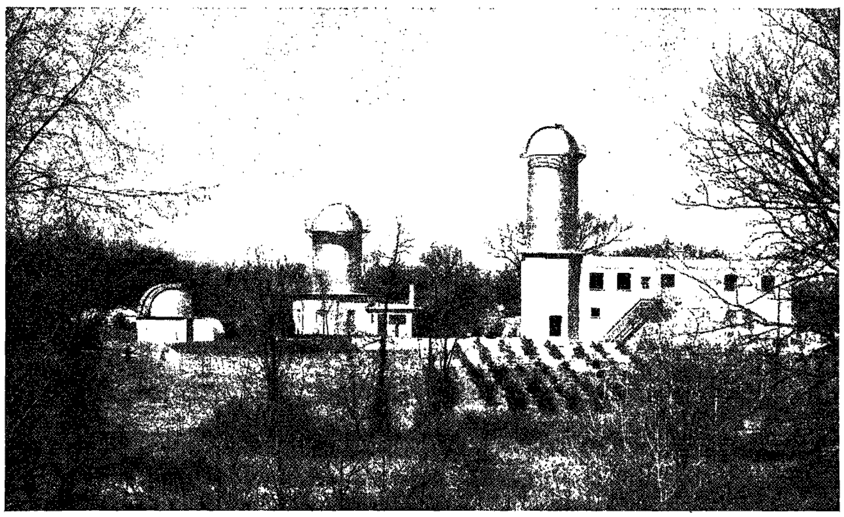

FIGURE 1
THE MCMATH-HULBERT OBSERVATORY FROM THE SOUTHEAST

sults were published in 1934. As a consequence, the 50-foot tower telescope was completed on July 1, 1936, and the first successful prominence film with the new tower was secured on the following day, July 2, 1936. The 10½-inch reflector is now being completely remounted with a 24-inch pyrex mirror, and will be a memorial to the late Francis C. McMath, one of the three original founders of the observatory.

The new McGregor Building is two stories in height, and covers an area of 5,600 square feet, with the 70-foot tower which is a part of the building at the south. On the first floor is a drafting room, a beautifully equipped modern machine and instrument shop, smaller film storage, cutting, and dark rooms, and a long laboratory room. On the second floor are the offices for the staff, a measuring room, a large dark room with unusually complete equipment for enlarging and other photographic work, a second long laboratory room, the library, and a projection booth which serves to project the films of solar phenomena for study, or for examination by visiting scientists.

The tower telescope and its foundations are throughout of unusually massive construction to obviate any risk from vibrations. The tower is double; the outer tower carries the dome, the floors and other structural elements, the ladders giving access to the various levels, as well as an electrically driven steel elevator, which rises in the space between the walls of the outer and inner towers and will serve to carry apparatus, etc., to the dome level nearly 70 feet above.

The inner tower, on the other hand, carries only the coelostat mechanism, now under construction, and the other optical parts of the tower telescope proper, through which the light from the sun collected by the mirrors of the coelostat will pass vertically downward. There is no well beneath the 70-foot tower, as is the case with the 50-foot tower. Instead, the light may be sent out laterally through openings in the walls of both towers and into instruments placed within either of the two long laboratory and observing rooms mentioned above.

The previous work of the McMath-Hulbert Observatory has been greatly impeded by lack of adequate working space, so that most of the work of design and measurement has had to be carried out in the basement of Dr. McMath's residence. The greater convenience and efficiency that will be secured through adequate working spaces for offices, measuring rooms, laboratories, and dark rooms is, of course, self-evident, and there is no piece of delicate mechanism, large or small, that can not be very quickly constructed in the unusually complete machine shop. But these advantages, while highly desirable, in no way represent the real purpose of the new McGregor Building. Thus a brief statement may be in place with regard to the work that is being planned for this new solar tower, and why this added method of attack is essential for the study of the sun.

Dr. McMath's remarkable films of solar phenomena in motion have aroused the interest and admiration of astronomers the world over, and have given us a vast amount of data for measurement of the velocities of matter in motion upon the surface of a star, which must form the working basis for all future theories of the sun. The motion pictures have given us the projections of these motions upon a plane (very nearly) that passes through the sun's center and is perpendicular to the radius vector of the earth. These measures thus give us the X and Y coördinates of the motions on the plane of projection. It has long been felt that these velocities in the X and Y coördinates only were insufficient to make a decision possible between theories of actual matter in motion, or certain theories of traveling luminescence suggested by some. To meet this need, velocities in a third, or Z, coördinate (radial velocities in the line of sight) have been secured during the past year, concurrently with the values of the X and Y coördinates, by the aid of auxiliary apparatus of unusual ingenuity.

A worker in other fields of the exact sciences might well feel that concurrent records of the phenomena of motion in three rectangular coördinates, plus records in different wave-lengths (as Hα and K), should be enough to satisfy any reasonable theorist. But a moment's reflection will bring home the fact that, for the sun at least, these velocities in three coördinate directions tell only part of the story, and perhaps far less than half. For a mere knowledge of velocities and directions of motion leaves many questions still unanswered, whose importance to our knowledge of the sun we can at present glimpse but faintly.

Some of these as yet unanswered questions are,—what are the actual temperatures of the streamer knots, or other phenomena such as explosions seen on the solar disk, that are traveling at speeds of 10 to 50 or more miles per second? Even more important, because of its possible connection with such familiar terrestrial phenomena as aurorae, magnetic storms, and radio reception, is an accurate knowledge of the electrical and magnetic conditions accompanying these solar storms. Are there, for example, increases in the output of ultra-violet light, whose pulses may well affect our radios? How much heat change, or how much change in electrical or magnetic forces is involved? This fourth parameter that we wish to know is thus not spatial like the other three. But we might term it an energy, or E, coördinate, and say that it has everything to do with the actual nature and the cause of these solar phenomena; it is an energy coördinate in that it will measure the energy relations on the sun itself and the possible terrestrial effects of these moving forms that so fascinate us when thrown on the screen.

The work of the new 70-foot tower telescope will thus be, by far, more of a physical than of a purely astronomical nature. The apparatus and attachments that are planned for use with the new tower telescope will be largely those of the physical laboratory,—bolometers, photometers, instruments for evaluating the electrical or magnetic characteristics of solar streamers, etc. By no means are all the paths of research with the new McGregor Building as yet clearly mapped; there may be many difficulties and pitfalls; much apparatus may have to be devised as the work progresses and the need for new instrumental adjuncts arises.

For the study of such energy relations through the most advanced techniques of modern physics and astronomy, it is our belief that the new McGregor equipment will form a tool of great power; an instrument and a new method of attack which will place the McMath-Hulbert Observatory in the front rank of the world's solar observatories. We do not know as yet just what will be found; if we did know, there would be no need for the new tower telescope and laboratory. But we feel sure that the results will be of great imporance for a more nearly complete knowledge of our particular star, and that possible results of great scientific interest and value may eventually have important terrestrial relationships or application.

With the additions that have been made to make a better use of the

PUBLICATIONS OF THE OBSERVATORY

OF THE UNIVERSITY OF MICHIGAN

VOLUME VIII, NO. 11

PUBLISHED BY MCGREGOR FUND

THE JULIUS F. STONE SPECTROHELIOGRAPH FOR THE DETERMINATION OF SOLAR ATMOSPHERIC RADIAL VELOCITIES

BY ROBERT R. MCMATH

This paper is a description of a new instrument, the Stone Spectroheliograph, which was installed in the 50-foot tower at Lake Angelus late in the year 1939. The instrument is a gift to the McMath-Hulbert Observatory of the University of Michigan by Mr. Julius F. Stone, for the purpose of "increasing by observation our knowledge of solar chromospheric phenomena." Motions of prominences as they appear projected on the plane of the sky were already being studied with the 50-foot tower spectroheliograph;[1] by his gift, Mr. Stone made it possible to design and build a new and complete instrument for the observation of motions along the line of sight.

The general purpose of the new instrument is to record the Doppler shift of an emission line (usually Hα) in any prominence with respect to the same absorption line in the sky spectrum. Such displacements had been checked visually at the spectrohelioscope as part of the regular observing program, and their estimated values recorded with the observing notes at various times. Additional attempts to estimate prominence radial velocities had been made photographically at the main tower spectroheliograph, with the No. 2 slit slightly displaced with respect to the center of the emission line. These observations are of slight scientific value, however, since they were obtained only at irregular intervals, and also because their accuracy depends almost entirely upon the judgment of the observer. To meet these objections, the Stone instrument is designed to record the prominence emission line displacements photographically and continuously throughout the observing day.

The design of the Stone Spectroheliograph evolved directly from experiments that began near the end of the summer of 1937, under the direction of the writer. Experimental observations were carried out by Mr. H. E. Sawyer, assisted by Mr.

[1] *Cf.* papers by McMath and Pettit, ApJ *85*, 279, 1937; *88*, 244, 1938.

G. H. Malesky, with a modified form of the spectroheliokinematograph (attached to the 10½-inch reflector). Observations during 1938 culminated in the production of a simultaneous record of radial velocities (from the modified spectroheliograph) and cross-motions (from the 50-foot tower spectroheliograph) in the eruptive prominence of August 12. This record demonstrated the feasibility of continuous, concurrent recording of radial velocities and of motions in the plane of the sky, and the modifications required in the spectroheliograph pointed the way to the design of a permanent radial-velocity spectroheliograph.

Deslandres,[2] Hale,[3] Keenan[4] and Waldmeier[5] have previously published methods of observing three orthogonal components of motion in the solar atmosphere, but the Stone Spectroheliograph, operating simultaneously with the 50-foot tower spectroheliograph, realizes advantages (to be described later) that are not available in the earlier schemes. Reports based upon observations made with the Stone spectroheliograph will be found elsewhere;[6] the present paper is confined to a description of the design and construction of the instrument.

General

The plan provided for as complete an instrument as could be installed in the existing 50-foot tower. The mirror counterweighting assembly on the coelostat was slightly modified to permit the mounting of a new 14-inch diameter first flat on the south end of the polar axis. A 12-inch diameter second plane mirror, with its own mounting, was then installed to direct the light beam from the No. 1 flat vertically down the tower to the imaging lens, 10 inches in diameter and 25 feet in focal length, which was placed just below the top floor of the inner tower. Since a second pit in the 50-foot tower was not feasible, a horizontal cage design was adopted for the spectrograph, necessitating the interposition of an 8-inch diameter third flat mirror in the path of the converging light beam. The installation of the new instrument also required a few slight alterations in the structural steel work supporting the towers. The spectrograph was placed on the north side of the tower work room, with the head above the platform that circles the large vertical spectrograph (see Plate I). This particular location was chosen to enable one observer to operate both instruments from one position under normal conditions.

Coelostat and Second Flat

The first and second flat mirrors of the new instrument, shown at *A* and *B*, respectively, in Plate II, are of optical pyrex. These mirrors, together with the

[2] Obs Paris Ann, Meudon *4*, No. 1, 1910.
[3] Proc NAS Wash *10*, 361, 1924.
[4] ApJ *83*, 55, 1936.
[5] Z f Astroph *15*, 299, 1938; *18*, 241, 1939.
[6] *Cf.* McMath, Sawyer and Mohler, The Measurement of Space Motions of Solar Prominences, *8*, 123, 1941.

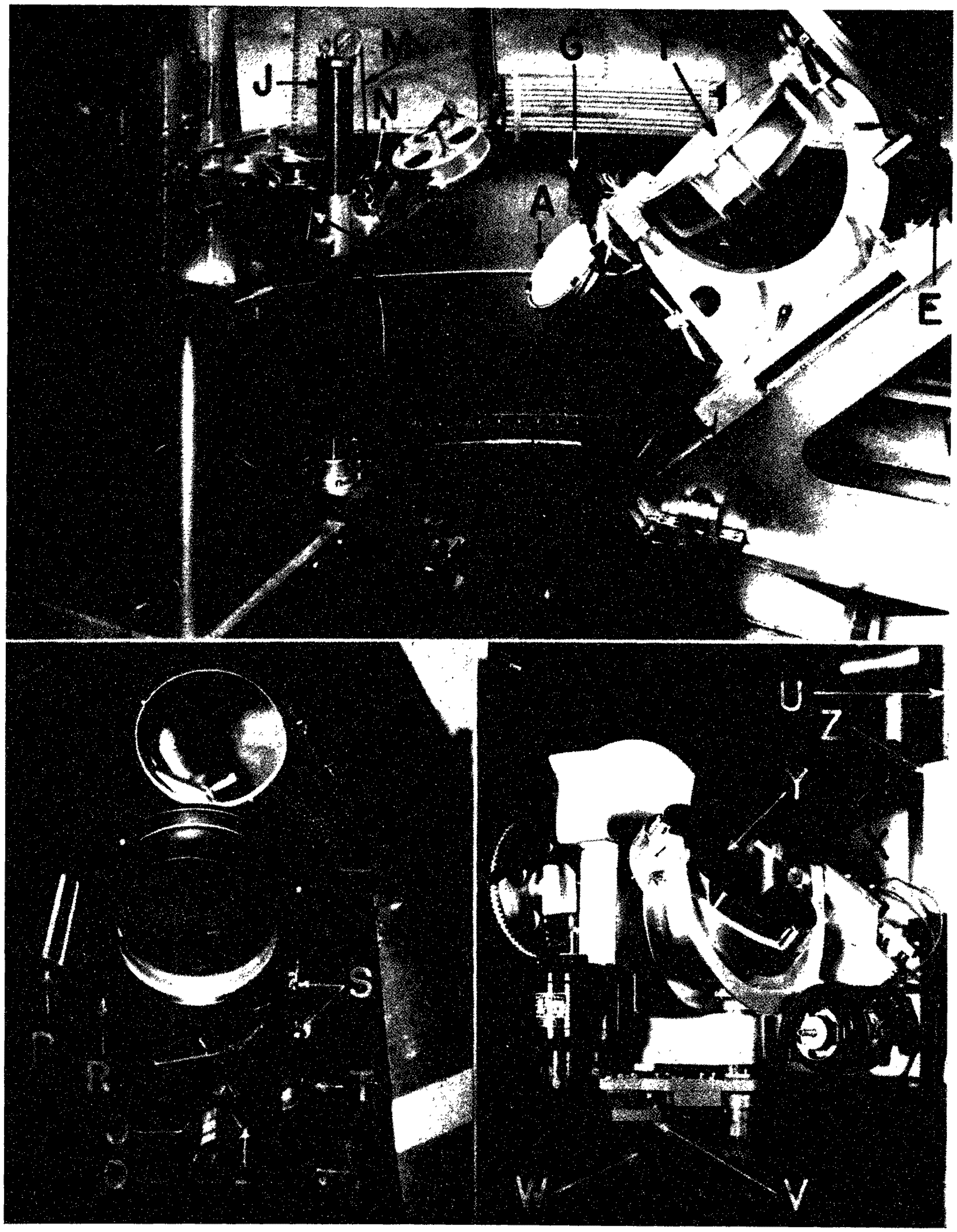

PLATE II. *Top.* Coelostat and No. 2 flat. *Lower left.* 10-Inch Objective Lens. *Lower right.* Third Flat Assembly.

8-inch third flat, 25-foot lens and spectrograph collimating lens, were figured by the Perkin-Elmer Corporation, of New York City. The three mirrors possess surfaces of unusual optical perfection.

The position selected for the No. 1 flat made a new right ascension drive unnecessary. Because of the rigidity of the larger coelostat and the cell design of the smaller flat, very little differential deflection between the two flats was anticipated. This expectation has since been verified by actual operation of the instrument. To correct for the effect of any small differences in flexure between the two optical systems, however, a motor-driven guiding motion in right ascension was installed on the south end of the No. 2 flat polar axis. For fast setting of the No. 1 flat, the clamp screws *C*, on the back side of the modified counterweight gear sector *D*, are released, and the mirror rotated in hour angle until its beam just fills the second flat. The existing right ascension drive is shown at *E*, with the 22-inch coelostat at *F*, the 14-inch mirror cell counterweight at *G* and the new coelostat counterweight at *H*.

The second flat mounting, a new and independent unit, was placed on the west side of the larger No. 2 flat. Its general design is similar to that of the larger No. 2 flat with one exception. To compensate for the changing elevation of the first flat throughout the year, the entire polar axis assembly is mounted on the 4½-inch diameter vertical tube *J*. The second flat may be shifted to any desired height by means of the balanced handle *K*, and locked into position by the clamp handle shown at *L*. To balance the weight of the polar axis assembly, a large counterweight is suspended inside the vertical tube from the flexible cable *M*.

The No. 2 flat assembly is provided with guiding and hand-setting motions in right ascension and declination, and, as previously mentioned, with a hand-setting vertical motion and a motor-driven guiding motion in right ascension. Of these, only the drive Selsyn, shown at *N*, is visible in the photograph (Plate II).

Lens Mount

The image-forming unit of the optical train is a very good 10-inch diameter achromatic lens of 25-foot focal length, figured by the Perkin-Elmer Co. The lens mounting is positioned on the west side of the inner tower, approximately two feet below the top floor (Plate II, lower left-hand photograph). Focusing is facilitated by a fine pitch screw and nut on the back of the nickel-iron base plate *O*, and by a scale at *P*. For convenience in operation, the focusing screw is extended to the observing pedestal below by means of the rod *Q*. The lens is carried on the welded steel bracket *R*, which is hinged at one side on tapered pins, *S*, to permit, if necessary, its easy removal from the system. The lens mount support bracket at *T* is of welded steel.

Third Flat Mounting

The No. 3 flat mirror assembly (Plate II, lower right-hand photograph) is mounted on the 6-inch diameter tube, *U*, which was originally installed on the west side of the work room to carry the 12-inch diameter off-axis parabolic mirror. Subsequent operations, however, proved the desirability of reducing to an absolute minimum the time required to change from one mirror combination to another, especially in eruptive-prominence photography. Accordingly, the original plan was changed, and both the 12 and 16-inch diameter off-axis mirrors are now carried on a single plate mounted on the east support tube. This arrangement leaves the west tube free to provide a very rigid support for the new mirror mounting.

It was considered advisable to allow for the possibility that the new tower optics might also be used for direct solar photography, or in conjunction with the old spectroheliokinematograph. Consequently, to facilitate rapid changes in the collimation of the No. 3 flat, fast and slow setting motions were installed, employing a fine pitch tangent screw (not shown in the photograph) and arm, and motors *W* and *X*. Also shown in the photograph are the 8-inch mirror at *Y* and the large welded steel bracket, *Z*, that carries the mirror assembly.

Spectrograph

The spectrograph is of the Littrow type. The new spectrograph cage, shown in Plate I, is similar to the vertical cage of the larger instrument in its welded structural steel construction and rigid cross-bracing throughout its entire length. The cage was fabricated by the Whitehead and Kales Corporation, of Detroit, heat-treated to relieve welding strains, and then machined at the head and grating ends to insure proper alignment. The cage is carried on two precision SKF bearings, *A* (Plate I), on the head end, and on a single self-aligning SKF bearing on the grating end, which makes it impossible for the supporting bearings to cramp the cage. Also, the bearing design and accurate counterweighting of the cage assembly permit the instrument to be easily rotated by hand, without the use of an auxiliary gear or chain drive. The grating mount and head plate are carried very near the supporting bearings, in order to minimize bending stresses in the cage. The head plate is graduated along its edge to permit the radial velocity spectroheliograph to be set to the same position angle as the main tower telescope spectroheliograph. The cage is then locked into position by the clamp *B*.

Since the space available for the new cage is limited by the size of the tower work room, it was necessary to restrict the focal length of the collimating lens to 8 feet. Both the lens and the 6-inch grating are mounted on the back plate of the cage. Lens focus, grating tilt and grating drift are controlled from the head end of the instrument by the knobs *A*, *B* and *C*, respectively (see Plate III).

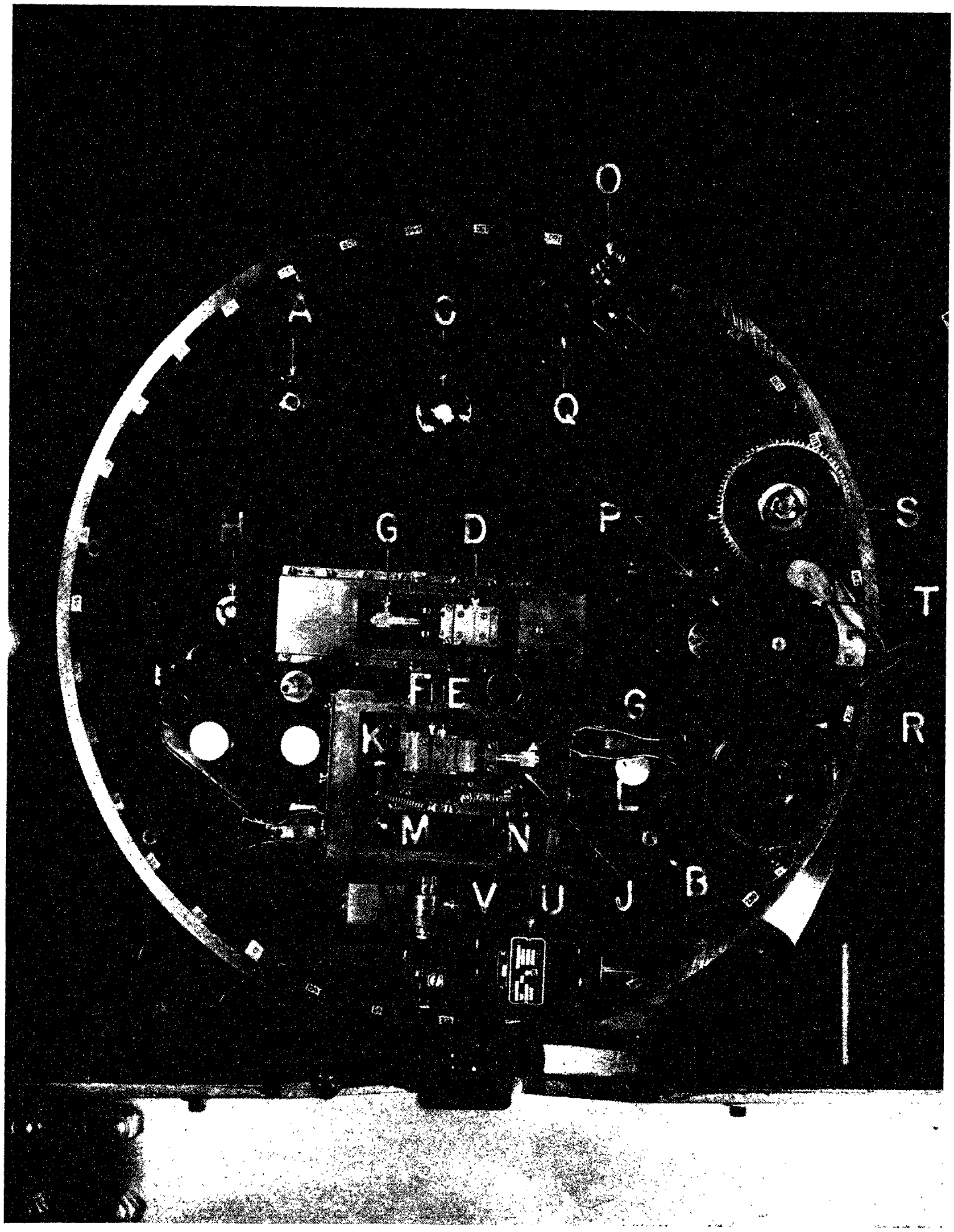

Plate III. Head Plate of the Stone Spectroheliograph.

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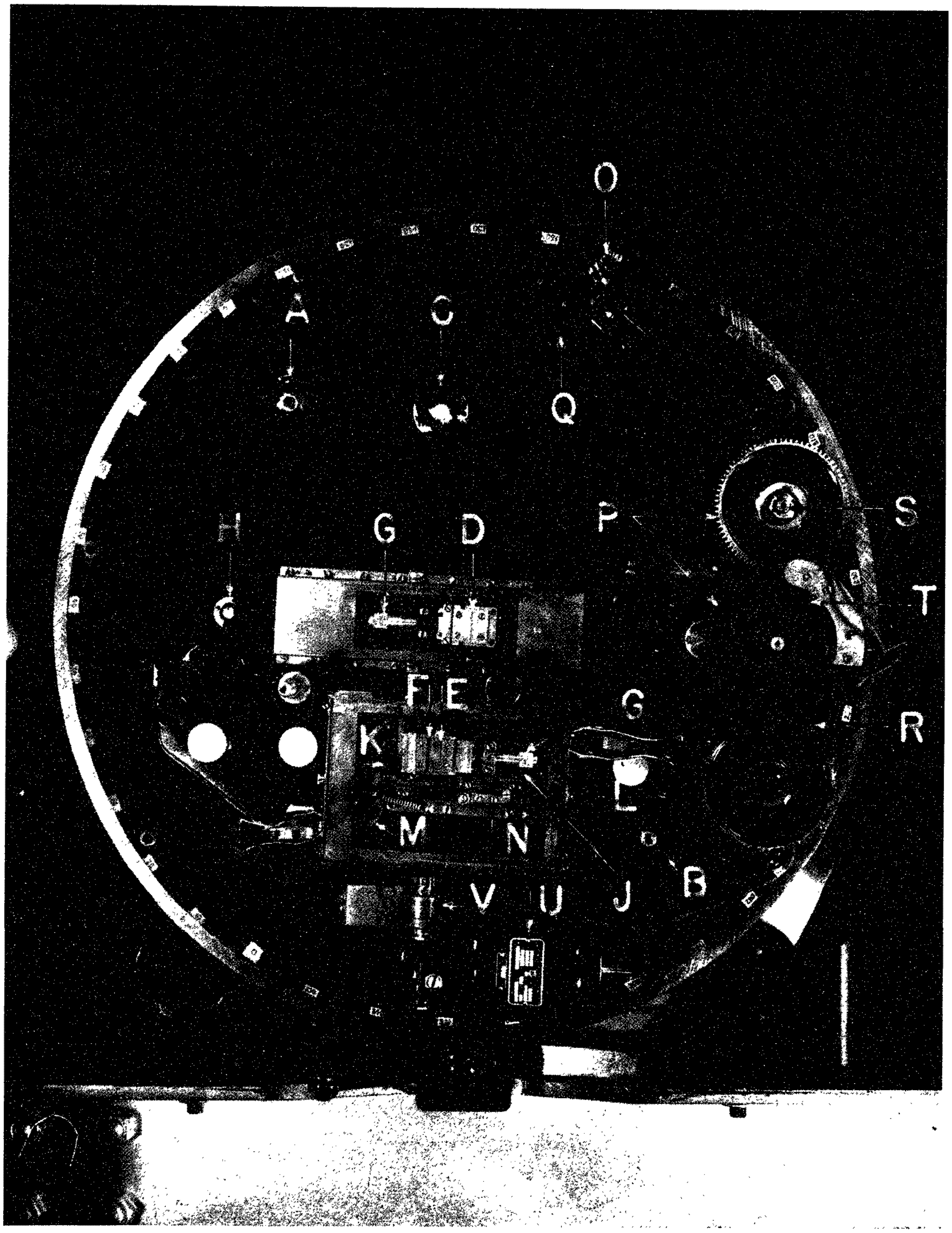

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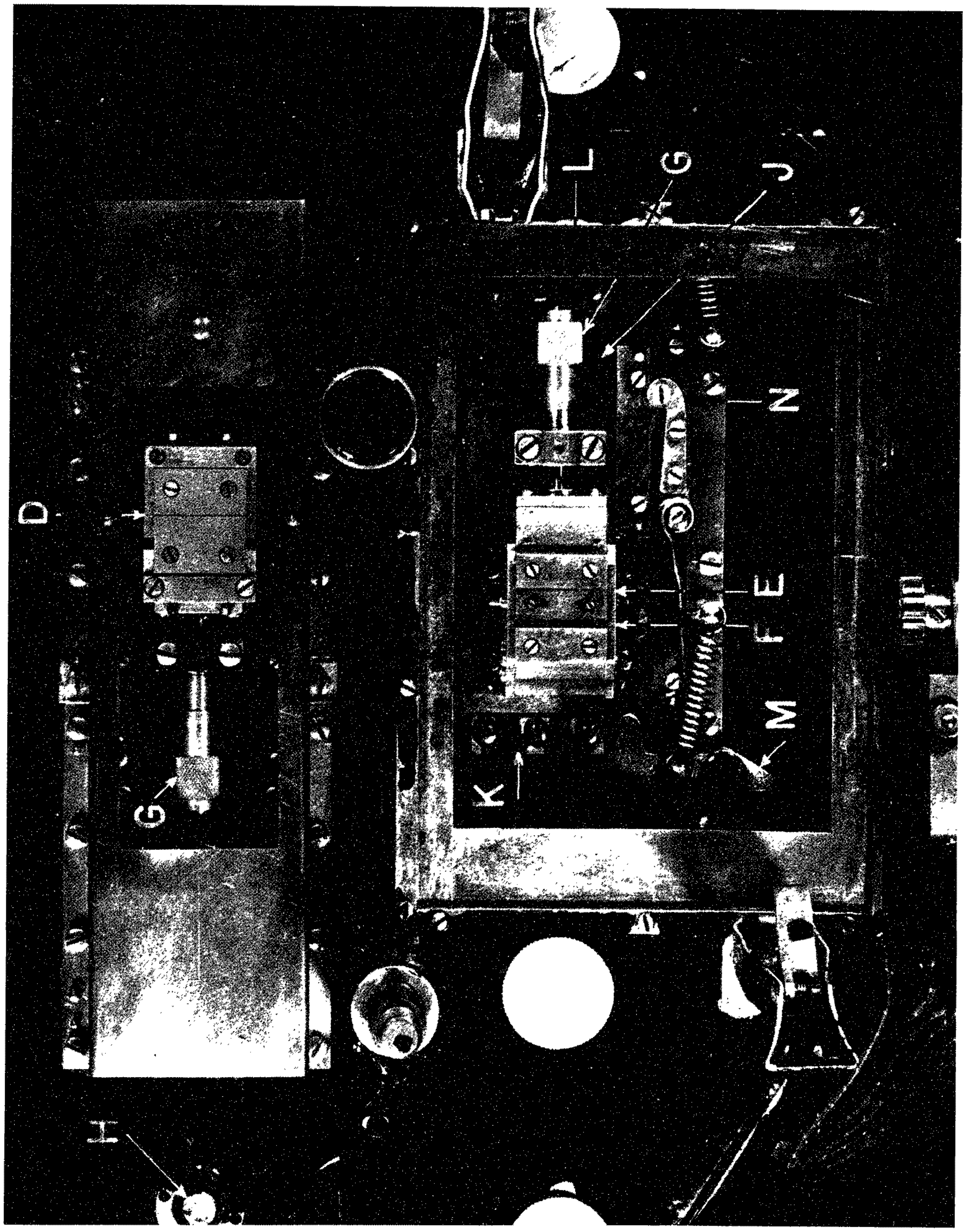

Plate IV. Details of the Slit Assembly.

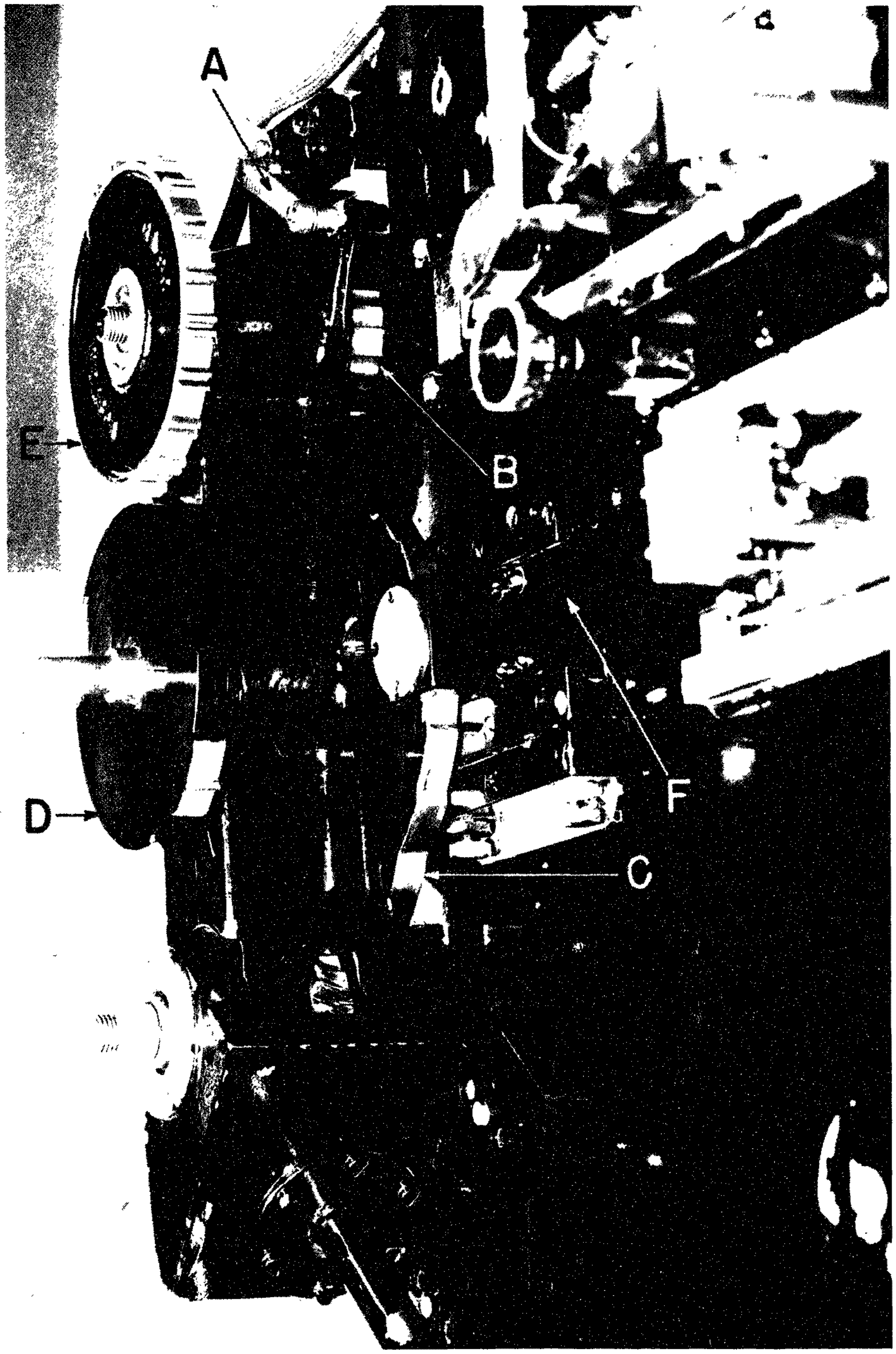

PLATE V. Details of the Cam Assembly.

Operation of the Spectroheliograph

The Stone Spectroheliograph is designed to register a series of photographs of the Hα line, with a narrow No. 1 slit (0.1 mm), and a No. 2 slit of sufficient opening (2 mm) to photograph a portion of the spectrum approximately 13 A wide. The width of the No. 2 slit corresponds to a radial-velocity range of ± 240 km/sec. The slits are provided with an intermittent cam-driven motion, which moves them forward at regular intervals by an amount just equal to the width of the second slit. In this way the Hα line, with the adjacent continuous sky spectrum, may be photographed at nine different elevations above the chromosphere on a single 35 mm frame. At the beginning of the next frame, a second, or slit-positioning cam, shifts the entire slit assembly forward by an amount equal to the width of the No. 1 slit, and nine different elevations, bordering those on the previous frame, are photographed. Twenty repetitions of this operation serve to cover the entire area under observation (including the prominences), since the spacing between successive lines on any one frame is 2 mm. At the end of twenty frames, or every 170 seconds, the slit-positioning cam returns the slit assembly to its original position, and the procedure is repeated. The interval between successive records of the same portion of a prominence is thus less than three minutes. Finally, to establish the location of each emission line in the prominence, an underexposed, conventional spectroheliogram is impressed on each frame through a narrow No. 2 slit, on the return stroke of the slit-driving cam.

The performance of the radial-velocity spectroheliograph is illustrated in Plate VI. The upper photograph reproduces a prominence spectroheliogram in Hα obtained with the main spectroheliograph. The lower photograph is an enlargement of one frame of the radial velocity record of the same prominence. Superposed on the "grid" of sky absorption lines are the Hα emission lines of the prominence. The light lines are overexposed areas which are due to a small difference between the displacement of the cam and the width of the wide No. 2 slit. The series of photographs at the right illustrates the action of the slit-positioning cam. Beginning at the top, the absorption-line grid is displaced progressively downward with respect to the prominence at the rate of 0.1 mm per frame.

The details of the slit and camera driving assemblies are shown in Plates III, IV and V. The No. 1 slit jaws (*D*, Plates III and IV) are made of Carboloy[7] and those of the No. 2 narrow slit *E* and the No. 2 wide slit *F* of oil-hardened tool steel. The widths of both narrow slits are regulated by Starrett micrometer barrels, *G*. The slit-driving link, *H*, is a duplicate of the main spectroheliograph linkage.

Plates III and IV show the slits in position nearing the end of the return

[7] *These Publications*, 7, 33, 1937.

stroke of the slit-driving cam. The slit plate, *J*, may rest against either of the two stops, *K* and *L*, depending upon which of the two No. 2 slits is in operation. In the photograph, the finger, or trip, *M*, is just beginning to shift the wide slit into photographing position by moving the slit plate over against the right-hand stop. At the opposite end of the cam stroke, a second trip, not shown on either photograph, returns the slit plate to the left stop. The latch mechanism, *N*, holds the slit plate in position against both stops.

The slit-driving motion is transmitted from a synchronous motor (*C*, Plate I) through two worm and worm gear combinations, one of which is shown at *O*, Plate III, to the cam-driving gears, *P*. The knob, *Q*, may be employed for manual adjustment of the slits. The driving gears and cam assembly are carried on the cast aluminum lever arm, *R*, which is pivoted in SKF ball bearings at *S*, Plate III. In Plate V, the driving gears have been removed to show the cam assembly more clearly. The slit driving arm, *F*, is held against the cam, *C*, by heavy springs mounted behind the spectrograph head plate. The lever arm is held in position by the spring shown at *A*, which keeps the slit-positioning cam, *B*, riding against a stationary cam follower. At the end of each revolution of the slit-driving cam, *C*, the single-tooth gear, *D*, engages the partial gear, *E*, to rotate the slit-positioning cam by one step. This cam is so cut that the engagement of successive grooves with the cam follower moves the end of the lever arm to the right, 0.2 mm per step. Since the distance between the pivot and the slit-positioning cam is just twice that between the pivot and the slit-driving cam, the driving cam, and hence the entire slit assembly, is moved 0.1 mm to the left. Also, while the slit assembly is being shifted, the contactor and brushes, *T* (Plate III) set the camera drive motor, *U*, in motion. Commutator *V*, mounted on the output shaft of the camera drive motor, is timed to break the motor circuit after the camera drive has moved the film ahead in the camera gate. The 35 mm camera designed and built for this instrument is shown at *D* in Plate I.

Disk Radial Velocities

The Stone Spectroheliograph, although primarily intended for prominence work, has also been successfully applied to the solar disk. For this purpose, the sequence of operations may be so timed that alternate continuous and intermittent scans are registered on separate frames of the photographic film. In addition, suitable filters must be installed to equalize the photographic densities produced by the two scans. Plate VII shows an excerpt from a record of a bright eruption on the disk of the sun on July 26, 1941. Corresponding points in the two successive frames are labelled: (*A*) is a sunspot; (*B*) is a bright eruption; and (*C*) is a rapidly moving dark flocculus. The dark gap in the spectrum at (*A*) is due to the relative

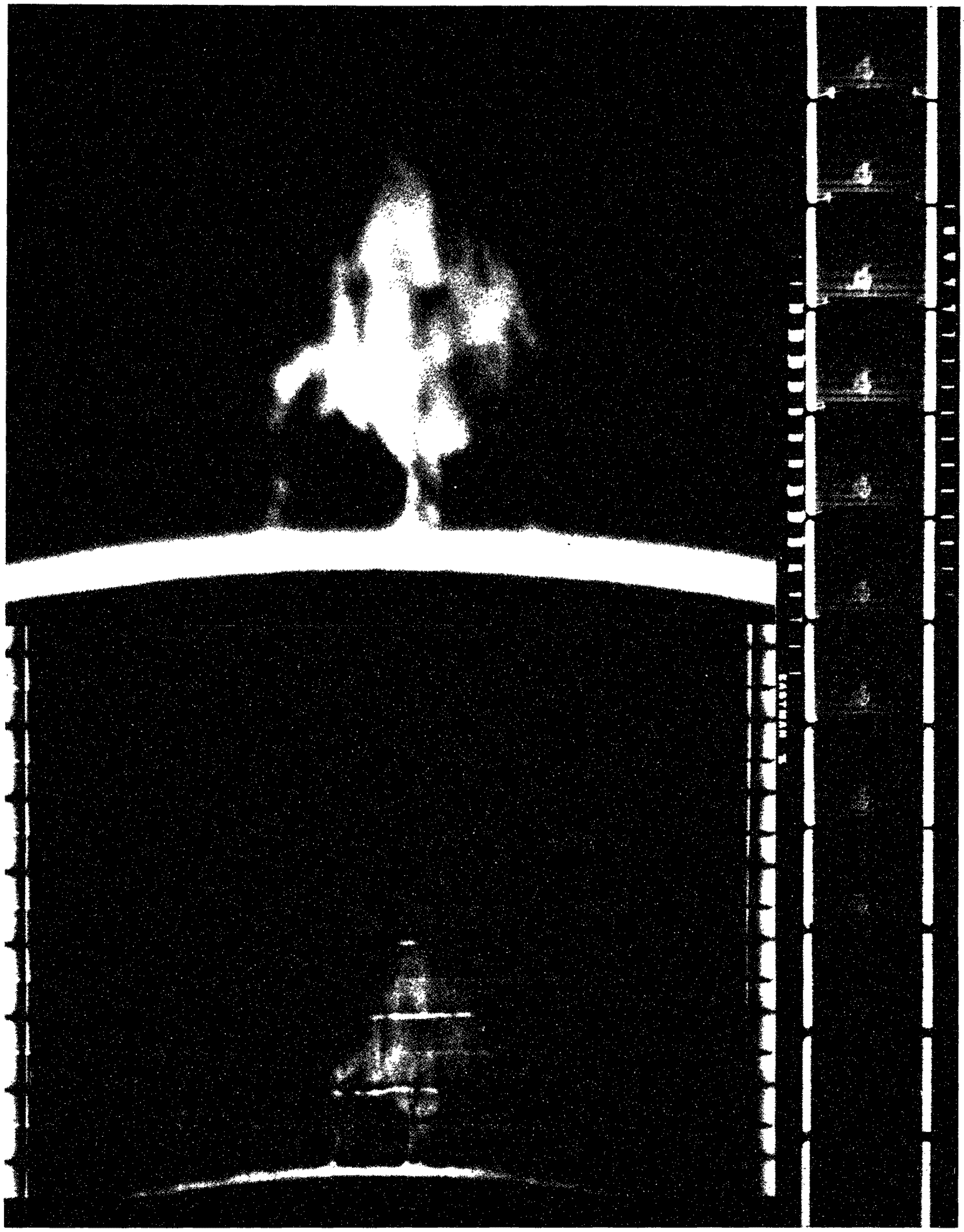

Plate VI. *Top.* Prominence Spectrogram in Hα Obtained with Fifty-Foot Tower Spectroheliograph. *Bottom.* One Frame of the Radial-Velocity Record of the Same Prominence, Obtained with the Stone Spectroheliograph. *Right.* Twelve Successive Frames Illustrating Action of Slit-positioning Cam.

faintness of the spot spectrum, as compared with the disk. At (*B*), the hydrogen emission of the bright eruption reaches and surpasses the brightness of the neighboring continuous spectrum. The dark flocculus (*C*) is an object of the class reported by McMath and Petrie;[8] the large displacement of the $H\alpha$ absorption indicates a radial velocity of + 60 km/sec.

A few minor changes in the new instrument have been made since it was first installed; plans for the future include a change-gear box on the head plate to make possible changes in the timing of each complete cycle. On the whole, however, the performance of the Stone Spectroheliograph has been splendid, and the resulting radial-velocity records have exceeded all expectations.

The entire staff of the McMath-Hulbert Observatory joins me in an attempt to express our gratitude to Mr. Stone for making possible this great addition to our facilities. Director McMath is responsible for the general design while Mr. George H. Malesky made all of the drawings in connection with the construction of the instrument. Instrument-Maker Charles W. Guenther constructed the complicated slit-driving mechanism, assisted by William Witkowski. Messrs. Sawyer and Mohler, of the staff, are responsible for the installation and conditioning of the new instrument. Dr. Leo Goldberg of our staff has been of great assistance in the preparation of the manuscript of this paper.

THE McMATH-HULBERT OBSERVATORY
OF THE UNIVERSITY OF MICHIGAN.
LAKE ANGELUS, PONTIAC, MICHIGAN,
October, 1941

[8] *These Publications* 6, 43, 1937.

PUBLICATIONS OF THE OBSERVATORY
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VOLUME VIII, NO. 6

PUBLISHED FROM THE WHEELER FUND

THE FRANCIS C. McMATH MEMORIAL 24-INCH REFLECTING TELESCOPE OF THE McMATH-HULBERT OBSERVATORY

By Robert R. McMath

Foreword

In the fall of the year 1936, the three founders of the McMath-Hulbert Observatory—the late Francis C. McMath, the writer's father; Judge Henry S. Hulbert; and the writer—started plans for a 24-inch reflecting telescope. By that time it had become apparent that the new 50-foot tower telescope was successful. It was thought that ultimately the original 10½-inch reflector[1] would be relieved of its share in the solar program, and that it was desirable to return to the earlier lunar and planetary program of the observatory with a more powerful instrument. This was made possible by the fact that the mounting for the 10½-inch had been originally designed to carry a twenty-inch mirror.

Francis C. McMath and Judge Hulbert had been present during the pouring of the second 200-inch mirror and were much interested in the low coefficient of expansion pyrex which the Corning Glass Company had succeeded in obtaining for that great mirror. Accordingly, Mr. McMath suggested that we ascertain from the Corning Company the availability of their special pyrex for our proposed new telescope. This inquiry resulted in the purchase of a ribbed 24½-inch primary mirror blank, together with the two secondaries and a plug for the optician's use when figuring the primary.

During the years 1937–38, the 10½-inch and its spectroheliokinematograph were in use making simultaneous records with the solar tower; and, in 1938 especially, Sawyer and Malesky employed the instrument in exploring the methods and techniques of the prominence radial velocity program. A generous gift by Julius F. Stone in July, 1938, made possible a new spectroheliograph in the solar tower for the radial velocity program, and plans for this instrument were started the following September. This combination of circumstances made it possible for the writer at this time to suggest to his associates the idea of a memorial telescope to Francis C.

[1] *These Publications*, *4*, 53–73, 1931.

McMath, who had died February 13, 1938. The new telescope was to make use of the pyrex mirror blanks purchased by the three founders during Mr. McMath's lifetime. The names of the donors are shown on Plate 1, which is a photograph of the bronze plaque attached to the west side of the pier of the telescope.

It was found, upon investigation, that the dome needed almost no alteration in order to house the new telescope. Telescope clearances were carefully laid out and, except for a rearrangement of the shutter operating cables, were found to be close but adequate. Floor clearances also were carefully studied, and, as a result, the observing floor was raised about two feet, giving the observer easy access to the guiding eyepiece. A tunnel was excavated and lined with masonry in order to provide access to the hollow part of the pier, and the electrical circuits between the control room, observer's control box, and telescope were rearranged and somewhat simplified. Practically all of the electrical equipment used for the 10½-inch was also used for the new 24-inch telescope.

General

Plate 2 is a general view of the telescope, taken through the open shutter of the dome. The old pier, declination axis housing, declination axis, and polar axis were retained in the new instrument design, and the original declination and hour circles were again mounted as before. The remainder of the telescope is new. It was decided to provide three motions in right ascension as follows: First, a fast-setting motion of 45 degrees per minute of time; second, a slow-setting motion of 90 minutes of arc per minute; and, third, a guiding motion of 45 seconds of arc per minute. The first two of these motions, together with the slow-setting motion in declination, are controlled by push buttons located on the auxiliary control box. The 4½-inch refractor which originally was employed as a guide telescope is now mounted on the 24-inch as a finder.

The tube center section and mirror cell were built up of 3/16-inch rolled steel, reinforced with ring flanges. This entire assembly was welded together and thrice annealed before machining, resulting in a very light but stiff structure. Special attention was paid to the securing of adequate mirror ventilation. To this end, the mirror cell was provided with large ventilating holes, through which the mirror can be seen in the photograph.

In order to avoid "dead air" in the tube, the open or skeleton type of design was chosen. The longitudinal struts were made of 13-gauge steel formed into box sections which extend the full length of the tube. These boxes were completely welded together and then welded to the center steel section and stiffening rings. The center circular strut, also of box section, was made in six pieces which, after individual welding, were welded between the longitudinal struts. The adjustable

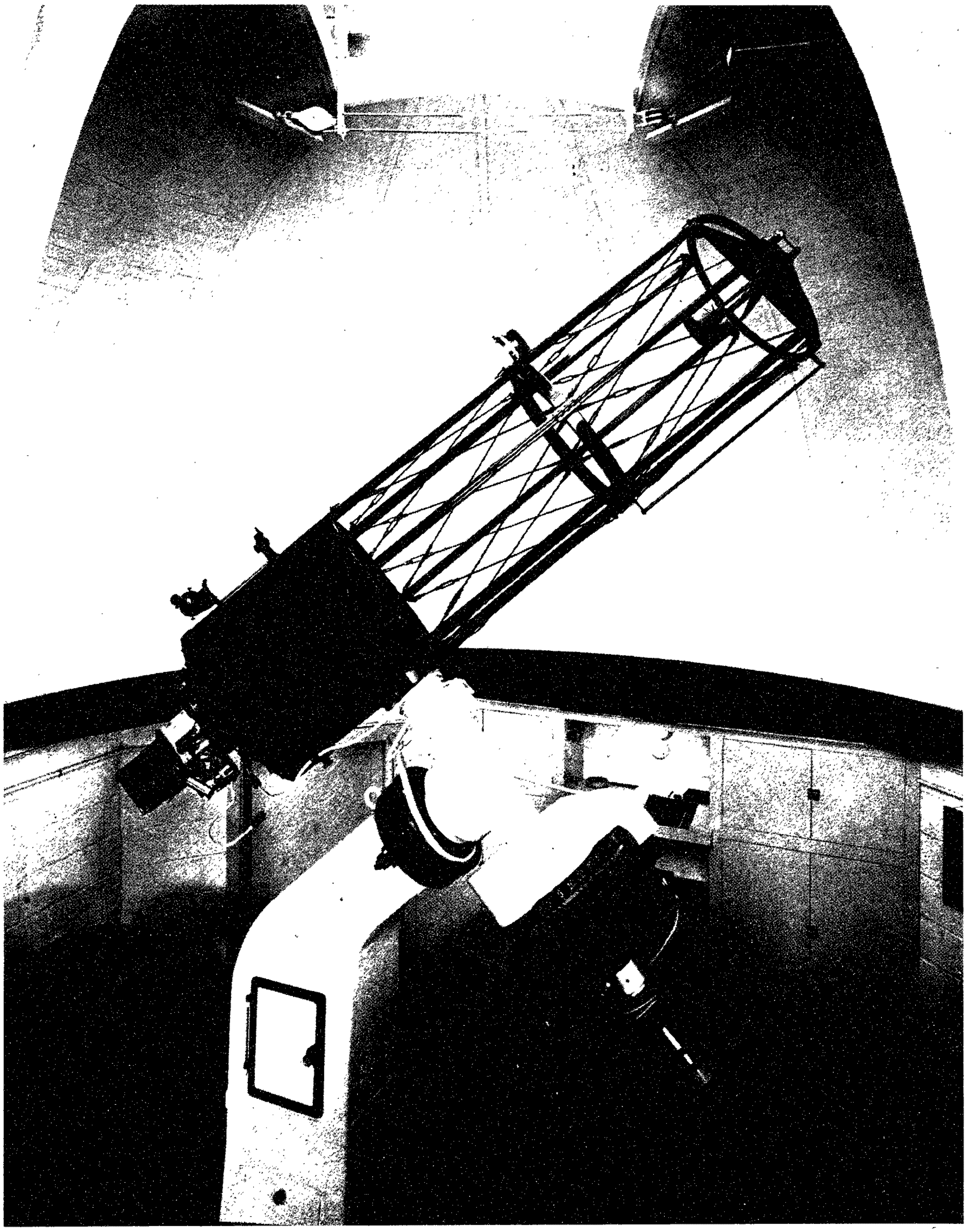

PLATE 2. General view of the 24-inch Francis C. McMath Memorial Telescope taken through the open dome shutters from the east side.

tie rods were added last. Altogether, the assembly is unusually rigid. It may be of interest to note here that a very large lathe was used as a welding jig and that, after welding, the tie rods were adjusted while the assembly was in the same lathe. Next, the entire tube assembly was swung "on centers" in the lathe and both ends of the tube turned at right angles to the optical axis.

The secondary mirror is supported by four 3/32-inch steel webs. The end ring, webs, and secondary center tube were assembled in a heavy jig, welded together, and then annealed. After annealing, the assembly was placed in the big lathe, the center tube was bored, and all faces made true and concentric. The outer ring was fitted into a recess in the telescope tube end ring in order to locate accurately the secondary assembly. The resulting tube assembly has proven very accurate and rigid, and has given entire satisfaction.

The mirrors were entrusted to the Perkin-Elmer Corporation of New York City for figuring. Our specifications were exacting, as no part of any surface could depart from the theoretical surface by more than one-tenth of a standard wavelength. Three mirrors were ordered to be made from the optical pyrex furnished by us: First, the 24-inch primary, focal length to be 96 inches plus or minus one-quarter of an inch, or F : 4; the diameter of the central hole to be not less than 4 nor more than 5 inches. Second, two secondaries, one to give a combined focal length of 50 feet, or F : 25, and the other mirror a combined focal length of 100 feet, or F : 50.

Perkin-Elmer Corporation completed the primary mirror by conventional methods, and it was tested at their shop by Dr. Heber D. Curtis, who pronounced it well within the specifications, reported that it was an unusually fine surface, and recommended its acceptance. The two high magnification secondaries, however, presented real difficulties. McCarthy, of Perkin-Elmer, felt that conventional methods of testing were inadequate and proposed a new method, which he has recently described.[2] The Perkin-Elmer Corporation made up the necessary auxiliary optical equipment, and our two secondaries were figured by the new method, which eliminates the combined testing of primary and secondary. These two mirrors have been an unqualified success, both focal lengths being well within specifications, while the figuring is superb. Exposures for the disk of Jupiter are shorter by a factor of at least twelve when compared with our old 10½-inch telescope.

Right Ascension Drive

We were particularly desirous of building a fine drive for the 24-inch telescope because we planned to use the 100-foot focal length combination a large portion of the observing time. Fortunately, the thermionic tube control[3] apparatus was

[2] JOSA, *31*, 107, 1941.
[3] *These Publications*, *5*, 123–31, 1934.

available, and after due consideration, it was decided to drive the telescope directly with the inverted converter in order to secure DC motor starting characteristics in winter.

The converter can be seen at *A*, Plate 3, which is a photograph of the new right ascension drive assembly. At *B* is shown the 46-inch diameter, 720-tooth, 5-pitch LH wormwheel. The blank for this gear was made by shrinking a bronze ring over a welded and double-annealed steel built up wheel and hub. This construction was rather expensive, but the wheel will not change shape with aging; consequently, the method was thought to be economical in the end. The firm of Hanson-Whitney furnished the worm and thrust bearing assembly, and the combined performance of these is practical perfection. The worm is of nickel steel, hardened and heat treated after preliminary machining, and finally ground to a mirror finish. The end thrust plug is glass hard high speed steel, lapped and ground, while the wearing part is soft machine steel. This type of construction has been used several times at this observatory, and was suggested to the writer by Curtis several years ago. *C* is the 1 to 90 ball bearing worm and wormwheel first reducing gear, and its output shaft is at *D*. Shaft *D* is split inside of the aluminum cup *E*, permitting the slow-setting motor *G* and the guiding motor *F* to superimpose their motions on the normal motion of shaft *H*. It should be emphasized that the gearing attached to these two motors, *F* and *G*, is not a part of the telescope drive as such and is not normally in motion.

At *I* is seen the end of the main worm which carries the 1 to 57 worm and wormwheel reducer *K*. Worm *I* drives wormwheel *B*, thus completing the all worm and wormwheel drive from motor *A* to polar axis *M*. At *N* can be seen a few teeth of the fast-setting gear, but the motor, being mounted on the under side of *B*, cannot be seen. The commutator supplying electrical current to the fast-setting motor is seen at upper *D*. A 50-pound weight is attached to cable *R* underneath the floor and is fastened to the polar axis by means of pulley wheel *P*. Unfortunately, due to construction considerations, the connection between the wormwheel *B* and the original polar axis could not be made as large as desired. This has resulted in some elasticity of the telescope as a whole, but has not affected the right ascension driving qualities of the telescope.

Declination Drive

The declination drive motions are, in a sense, somewhat similar to those of the right ascension drive, since they again include coarse- and fine-setting and guiding motions, together with the straight declination drive. Fast or rough setting of the telescope is made by releasing a friction clamp, the back of which is shown at *D*, Plate 4, and moving the drive arm *E* to the desired declination angle. This angle is easily read on the declination circle *H*.

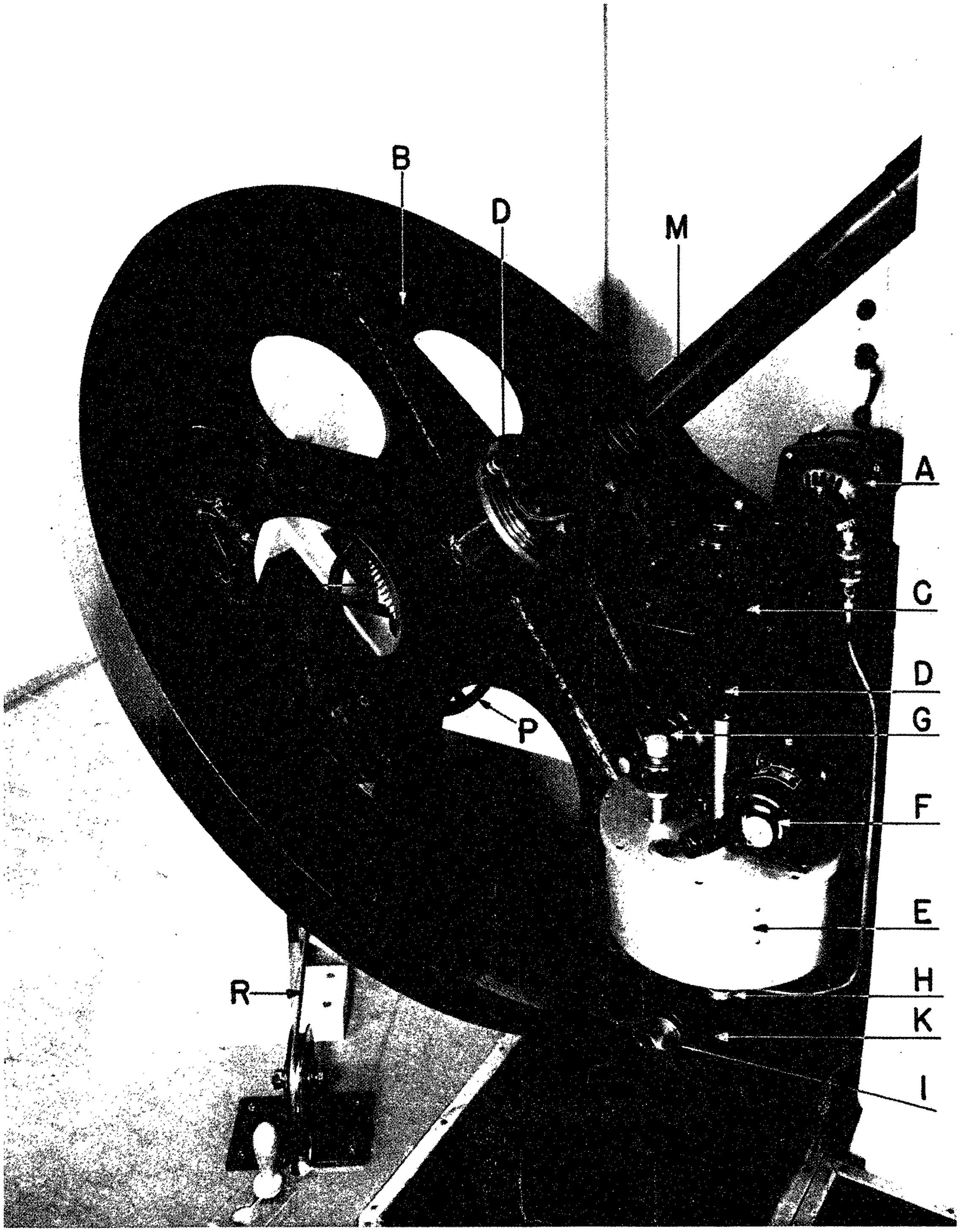

PLATE 3. View of the New Right Ascension Drive.

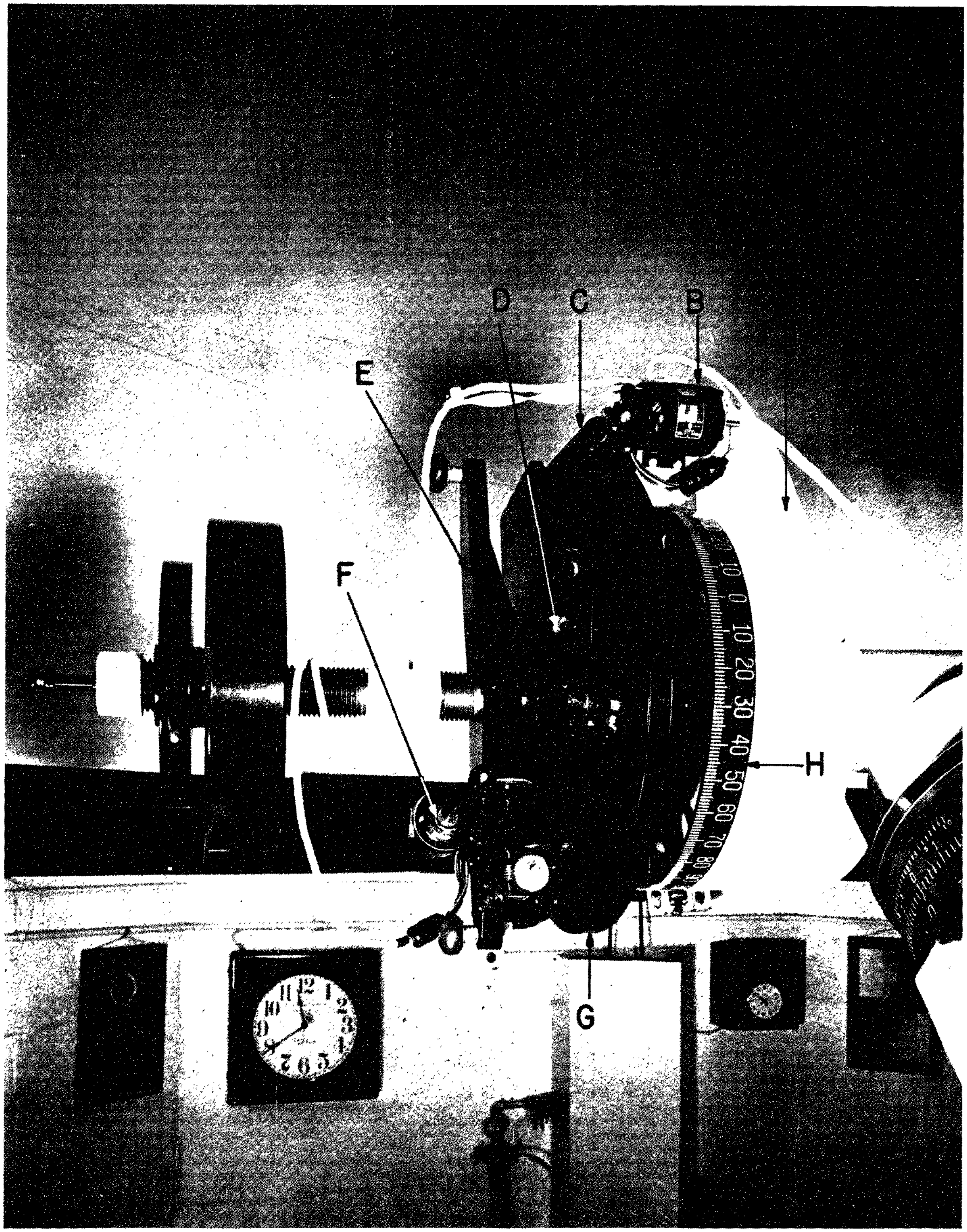

PLATE 4. View of the Declination Drive Assembly.

The slow or fine-setting motion of 50 minutes of arc per minute of time is obtained through the drive motor *B*, 9-pitch worm *C*, and 680-tooth wormwheel *G*. Worm *C* was made in two pieces and has a special spring adjustment in order to eliminate all lost motion at this point in the assembly. The slow motion motor support bracket *A* purposely is a very heavy casting to act as a counterweight about the polar axis. This was done to avoid adding to the already heavy stress imposed upon the declination axis by the new tube loading.

The slave Selsyn *F* transmits the guiding and drive motions from the Ward-Leonard system and gear carriage in the control room. This same system was used on the 10½-inch reflector and on the second flat mirror in the solar tower, and has been fully described and illustrated.[4]

Special attention was paid to the very important problem of eliminating lost motion in the entire declination drive assembly. Precision thrust and radial ball bearings were used throughout, and some form of take-up adjustment was provided at each point where normal wear might occur.

Camera and Guiding Eye Piece Assembly

The camera end of the new 24-inch reflector, Plate 5, represents a rather unique departure from standard telescope design. Since this instrument was intended primarily for work on the lunar and planetary programs of the observatory, the 35 mm camera was used as the nucleus about which the driving and guiding accessories were constructed. This general design procedure has produced a dual guiding system which embodies all the features deemed most desirable by the observing staff, based on several years' experience with our particular photographic problem. The lower guiding assembly, intended for lunar or planetary work, guides directly on the central cone of light being photographed. This is accomplished by use of the rotating shutter and mirror combination shown in the enlarged print of the camera support casting (*N*, Plate 6). *S* is the shutter disk carrying a semi-circular plane mirror *R* and the easily interchanged shutter plate *T*. *U* is the last step in the Selsyn driven gear train which operates the camera and shutter.[5] At *V* is shown the small counterweight balancing the entire shutter shaft assembly.

During the guiding period the light beam from the secondary is reflected through 90° by the shutter mirror *R* and comes to a focus on the illuminated reticule *J*, Plate 5. The optical center of this reticule can easily be shifted by means of the adjusting screws *M* to any chosen guiding point in the field. The reticule can then be rotated so that the guide point will follow the wires in both right ascension and declination. Extension tube *G* includes a 65 mm lens set for approximately conjugate foci to transfer the image from the reticule through the rotatable right angle prism *F* to the guiding eye piece *E*.

[4] *These Publications*, 7, 42–56, 1937.
[5] *Ibid.*, 50.

Throughout the open-shutter or photographing period, the mirror lies outside of the central light cone and therefore reflects no image through to the guiding eye piece. This important feature prevents the observer from shifting the telescope while a photograph is being taken. Also, since the reticule-to-mirror and camera-focal-plane-to-mirror distances were set accurately in our shop, the telescope can be focused at the guiding eye piece through use of this guiding system.

By shifting plate *K* against the stop plate *O*, the low power composition eye piece *H* is brought into the optical axis position. Here, by means of a focal plane diaphragm which is a duplicate of the camera aperture, the observer is able to view the exact field which will be photographed at the camera. This same setting can also be obtained on a ground glass placed at the camera focal plane, but this latter procedure requires the removal of the camera from its mounting.

The second guiding system is intended primarily for lunar and stellar work. The guiding eye piece assembly—made up of the illuminated reticule, transfer lens, right angle prism, and guiding eye piece previously described—is slipped out of its bayonet lock on the plate *K* and moved to a new position at *D*. Flange *D* is part of an adjustable tube which carries a small reflecting prism at its opposite end. This prism, together with the eye piece assembly, can be moved radially, by means of the adjusting screw, from the outer edge of the cone of light coming through the central hole in the primary, to the edge of the inner central cone being photographed. The entire assembly can also be revolved about the optical axis, by use of coarse and fine setting motions, through 360° to insure a large field from which to choose a guiding point. Obviously, because of this optical set-up, the stellar images near the outer edge of the light cone are not perfectly sharp, but are of sufficiently high quality to permit their use as guiding reference points.

The new 35 mm camera is shown at *L*, along with camera driving Selsyn at *P*, primary mirror edge support at *B*, primary mirror back support at *C*, and secondary mirror focusing handle at *A*.

An electrical contactor to record exposure times on the chronograph in the control room is mounted on the camera support casting back plate, and cannot be seen in this photograph. One additional new accessory, a comparison type photometer to be used as an exposure meter, is not complete at the present time.

Conclusion

In conclusion, it may be well to add a few words in regard to the program ahead of the new instrument. We had long discussed amongst ourselves the desirability of doing over the original lunar and planetary educational motion picture films with an instrument with more resolution and better mechanical adjuncts. The first few months' use of the new telescope convinces us that we can do very much better work with this new instrument than with the old.

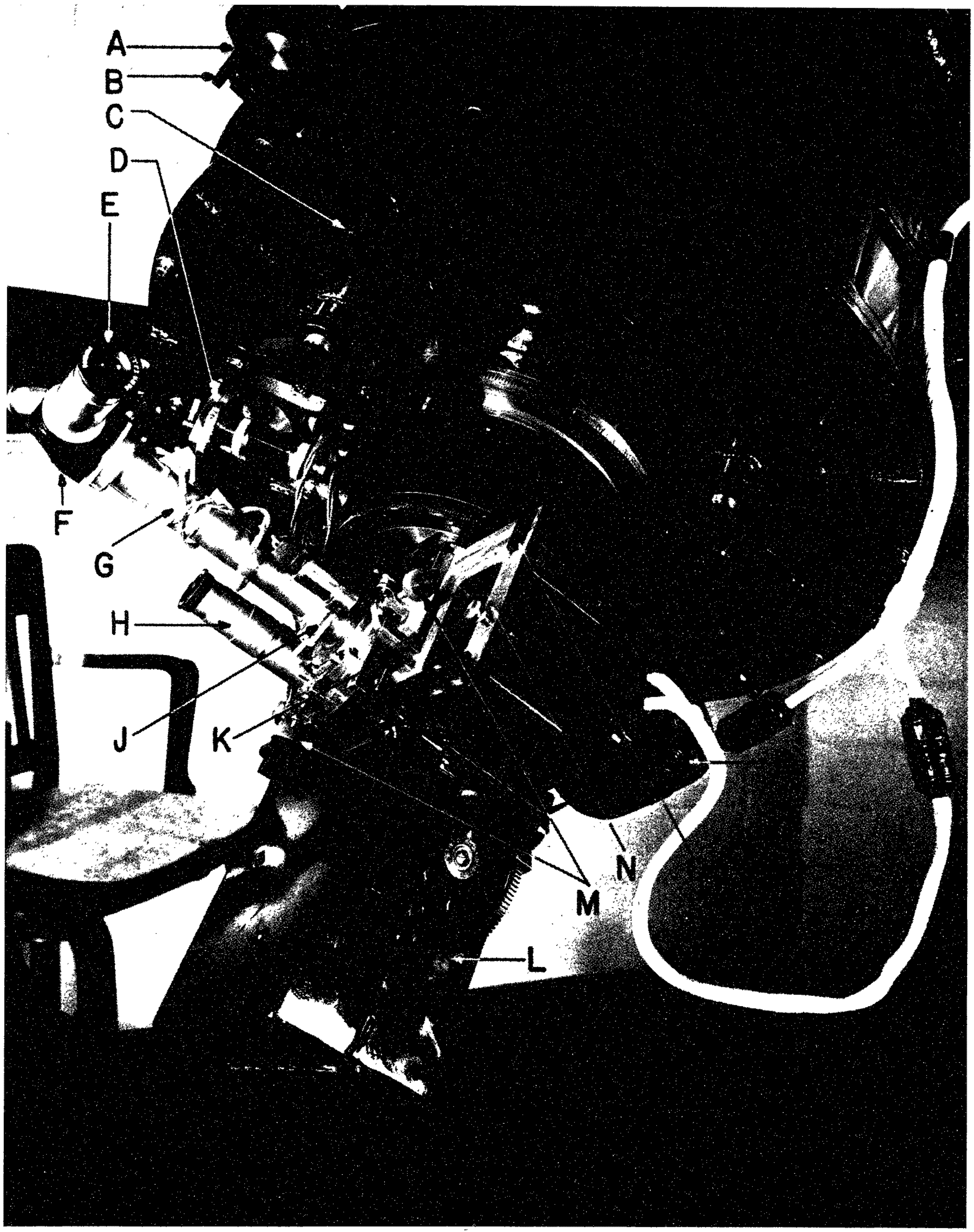

PLATE 5. Camera End Assembly.

We have already secured several hundred feet of 35 mm motion picture negative of the disk of Jupiter. Using the 100-foot E F L combination, the disk of Jupiter is approximately 7 mm in diameter, and a shadow transit of one of the satellites has been clearly observed on one of the above films. We have been hoping for a blue-sensitive emulsion with sufficient speed and lack of grain so that enlarged pictures of Jupiter on the screen will not be too grainy. Just recently Dr. C. J. Staud of the Eastman Research Laboratories has sent us some very promising material for this purpose. After our early experiments with Jupiter, we plan to photograph Saturn in the same way and hope to record some activity on the disk of the planet.

Our experimental lunar pictures showing the sunrise and sunset are very promising, and it is our expectation that within a year or so we can make up educational reels for distribution to institutions desiring them.

Mr. George H. Malesky of our staff collaborated with the writer in the design of this new instrument, and all drawings were made by Malesky. To our instrument maker, Mr. C. W. Guenther, we owe thanks for successfully making the difficult shutter assembly. Dr. Heber D. Curtis gave us valuable suggestions in regard to the mounting of the primary mirror. And we are greatly indebted to Messrs. Sawyer, Mohler, and Brodie of the staff for their work in the installation and adjustment of the telescope.

The entire staff of the McMath-Hulbert Observatory of the University of Michigan is very grateful to the donors for making possible the acquisition of this new addition to the instrumentation of the observatory.

THE McMATH-HULBERT OBSERVATORY
OF THE UNIVERSITY OF MICHIGAN,
LAKE ANGELUS, PONTIAC, MICHIGAN
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TELLURIC BANDS OF CH_4 IN THE SOLAR SPECTRUM

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ABSTRACT

An all-reflecting telescope and spectrometer have been employed in conjunction with a Cashman *PbS* cell to secure a direct-intensity map of the solar spectrum in the region of 0.8–2.5 μ with a resolution of about 50,000. Four molecular-band systems at 1.66, 2.20, 2.32, and 2.37 μ have been identified as the $2\nu_3$, $\nu_1 + \nu_4$, $\nu_3 + \nu_4$ and $\nu_2 + \nu_3$ transitions of CH_4 in the earth's atmosphere.

A preliminary analysis of the wave numbers of the $2\nu_3$ rotational components indicates second-order deviations from theory. The average half-spacing B_0 is found to be 5.163, as compared with the value $B_0 = 5.252$ obtained by Childs.

A comparison of the $2\nu_3$ telluric line intensities with those produced by a measured quantity of methane at room temperature leads to a calculated methane abundance in the earth's atmosphere of 1.2 parts in a million by mass, and a temperature of $-37°$ C.

INTRODUCTION

Since June, 1947, the writers have been engaged in mapping the solar spectrum beyond the infrared limit of the photographic plate, employing a lead sulphide photoconductive cell as an energy detector. The first observations[1] were made on an experimental basis, the *PbS* cell being driven on a lead screw along the focal plane of the McGregor spectrograph. The original optical system was inefficient because of absorption by the lenses in the McGregor tower and spectrograph. Nevertheless, preliminary experiments resulted in the extension of the solar spectrum with high resolution to about 2μ.

THE ALL-REFLECTING SPECTROMETER

Late in 1947 an all-reflecting spectrometer of the Pfund type, especially designed and constructed for the infrared application, was installed inside the existing McGregor spectrograph. The new spectrometer employs a 15,000-line, plane-reflection grating, together with two parabolic and two plane mirrors. The focal length of each of the parabolic mirrors is approximately $23\frac{1}{2}$ feet. The grating, which was ruled at the Mount Wilson Observatory, produces a high concentration of energy in the first order at λ 20,000. We are indebted to Dr. I. S. Bowen for the loan of this grating. The imaging lens in the tower will soon be replaced by a 12-inch by 50-foot off-axis parabola. In the interim we have been utilizing a $10\frac{1}{2}$-inch Cassegrain reflector, which was originally employed at Lake Angelus in conjunction with the so-called "spectroheliokinematograph" for motion-picture photography of the solar disk and prominences.

The observations were carried out in the first order of the grating spectrum. A predispersing unit, consisting of a low-dispersion spectroscope, eliminates interference from overlapping orders of the grating. The entrance slit of the monochromator is located in the focal plane of the solar imaging telescope, the exit slit being also the entrance slit of the spectrometer. The optical components of the monochromator are a calcium fluoride prism and four mirrors, two plane and two parabolic. Rotation of one of the parabolic mirrors makes possible the selection of any portion of the spectrum. The construction of all mechanical parts of the spectrometer and accessories was carried out in the McMath-Hulbert Observatory shop. The optical components, with the exception of the grating, were figured by Mr. Lloyd Sprinkle, of Detroit. The *PbS* cell and amplifier were furnished

[1] McMath and Mohler, *Pub. A.S.P.*, **59**, 267, 1947.

through the kindness, respectively, of Dr. R. J. Cashman and Mr. Wallace Wilson, of the Northwestern Technological Institute.[2]

THE INFRARED SOLAR MAP

During the past fall and winter, several maps of the solar spectrum have been obtained throughout the entire region 0.80–2.5 μ. The records are in the form of pen-and-ink tracings on a direct-intensity scale. Various dispersions have been employed, ranging from 2.50 to 4.85 mm/A. It is well known from low-resolution observations that the near infrared solar spectrum is masked by heavy telluric absorption bands of H_2O between 1.35 and 1.50 μ and also between 1.75 and 1.95 μ. The intervening regions are clear of molecular absorption, however, except for systems of lines and bands, which, though numerous, are sufficiently weak and isolated to be admirably suited for identification and study.

The clear regions of the spectrum are also rich in solar atomic lines, of which approximately two hundred and fifty have been discovered from a comparison between tracings made with high and low sun. A systematic program of measurement, identification, and analysis of the solar and telluric lines in the infrared is in progress and will be reported in this *Journal* from time to time. The present contribution deals with the identification of telluric bands of methane, centered at 1.66, 2.20, 2.32, and 2.37 μ, and with the preliminary analysis of the 1.66 μ band.

THE DETERMINATION OF WAVE LENGTHS

The problem of the determination of wave lengths and the identifications of both atomic and molecular lines is a difficult one, inasmuch as no high-resolution observations in the lead sulphide region have been made in the laboratory. Two independent methods have been employed to establish the infrared wave-length scale. The first makes use of the well-known property of diffraction gratings that gives a precise superposition[3] in the spectrum of lines in different grating orders with wave lengths λ/n, where n is the order of the spectrum. The wave lengths of infrared Fraunhofer lines may thus be derived from those tabulated with high precision in the *Revised Rowland Tables*.[4] The probable errors of wave lengths determined in this way are of the order of ± 0.1 A, which should be entirely adequate for line identifications in the infrared.

A second and complementary procedure for establishing a wave-length calibration is based on the identifications of solar lines for which wave lengths have been computed from the known term values of atomic-energy levels. This procedure can be applied with certainty only when complete or nearly complete multiplets occur in the spectrum, the identifications being guided by the theoretical intensity relationships for lines in multiplets. Thus the initial wave-length calibration in the 1.6 μ region was achieved via the identification of the triad of *Fe* I multiplets that result from transitions between the term e^5D and the three higher-lying terms u^5F°, t^5D°, and u^5P°.[5] The computed wave lengths for these multiplet lines extend from λ 14,255 to λ 16,590. Since most of the term values on which they are based are known to within 0.05 cm^{-1}, they provide a firm basis for calibration over a wide region of the spectrum. Additional multiplets of *Si* I, *Al* I, *Mg* I, and *C* I permit an extension of the calibration to about λ 17,500.

It should be emphasized that the first method described above yields wave lengths in air, the second *in vacuo*. The results obtained by the two methods are in satisfactory agreement, considering the uncertainties in the infrared refractivity of air and in the

[2] For a more complete description of the instrumentation, see McMath and Mohler, *Sky and Telescope*, **7**, 143, 1948.

[3] Except for a small correction due to the variation with wave length of the refractivity of air.

[4] *Pub. Carnegie Inst. Washington*, No. 396, 1928.

[5] McMath, Adel, Mohler, and Goldberg, *Phys. Rev.*, **72**, 644, 1947.

atomic term values. For example, the computed air wave length of the $4p^3D_2 - 4d^3D_2^0$ line of *Si* I is 16,681.4 A, as compared with the measured value of 16,681.2 A.

THE CH_4 BAND AT 1.666 μ

One of the outstanding features of the infrared solar map is a molecular-band system centered at 1.666 μ, consisting of positive, negative, and zero branches, as shown in Figure 1. The *R* branch contains eleven regularly spaced components, and the *P* branch eight, while the almost completely resolved *Q* branch shows ten members. This band and three others at 2.20, 2.32, and 2.37 μ have recently been identified by the writers[6] as arising from the CH_4 molecule, on the basis of comparisons with published laboratory observations of the methane spectrum. We have now established the identification beyond any doubt by inserting in the solar beam a 25-cm-long absorption cell filled with methane at atmospheric pressure. All the bands identified as CH_4 are enormously enhanced, as may be seen in Figure 2.

The observational and other data relating to the 1.666 μ band of CH_4 are contained in Table 1. The first column gives the rotational quantum numbers associated with each transition, the second column the measured wave length in I.A., and the third column the equivalent widths in A, measured for a solar altitude of 14°34′. The fourth column gives the line frequencies in wave numbers, calculated for an index of refraction of air equal to 1.000274. The colons signify uncertainties in wave length, occasioned by apparent blending with other solar or telluric lines or by possible multiple structure of the high members of the positive and negative branches. It is interesting to note that W. H. J. Childs,[7] in a study of the 9047 cm^{-1} band, found a multiple splitting in the *R* branch that "increases in magnitude and complexity with the rotational quantum number."[8] This band is the second overtone, $3\nu_3$, and the 1.666 μ band the first overtone, $2\nu_3$, of the fundamental band at 3020 cm^{-1}. Fourteen lines of the ν_3 band have been found by Migeotte[9] in the solar spectrum.

The line spacings are given in the fifth column of Table 1. The spacings in the *P* and *R* branches increase regularly toward the long wave lengths, from 8.96 to 11.73 cm^{-1}, the average being 10.56 cm^{-1}. The 1–0 component of the *P* branch, which is absent or very weak in the solar spectrum, was likewise not found in the laboratory studies of Moorhead[10] and of Norris and Unger.[11] The wave numbers determined by the latter authors, after correction to vacuum, are given in the sixth column of Table 1. The laboratory values are systematically higher, on the average, by nearly 4 cm^{-1} than are those of the present investigation. In view of the high order of agreement between the solar wave lengths measured from overlapping grating orders and those computed from atomic-energy-level differences, we are inclined to favor the solar values.

ANALYSIS OF THE $2\nu_3$ BAND

Dennison[12] has given the following expressions for the excited rotational energy levels of the CH_4 molecule:

$$\frac{W}{hc} = \nu_0 + B_i J(J+1) - 2J\zeta B_i\,, \tag{1a}$$

$$\frac{W}{hc} = \nu_0 + B_i J(J+1)\,, \tag{1b}$$

$$\frac{W}{hc} = \nu_0 + B_i J(J+1) + 2(J+1)\zeta B_i\,. \tag{1c}$$

[6] *Phys. Rev.*, **73**, 1203, 1948. Spectroscopic evidence for the presence of CH_4 in the earth's atmosphere was first reported by M. Migeotte (see n. 9).

[7] *Proc. R. Soc., London, A*, **153**, 555, 1936.

[8] *Ibid.*, p. 565.

[9] *Phys. Rev.*, **73**, 519, 1948; *Ap. J.* **107**, 400, 1948.

[10] *Phys. Rev.*, **39**, 83, 1932.

[11] *Phys. Rev.*, **43**, 467, 1933.

[12] *Rev. Mod. Phys.*, **12**, 175, 1940.

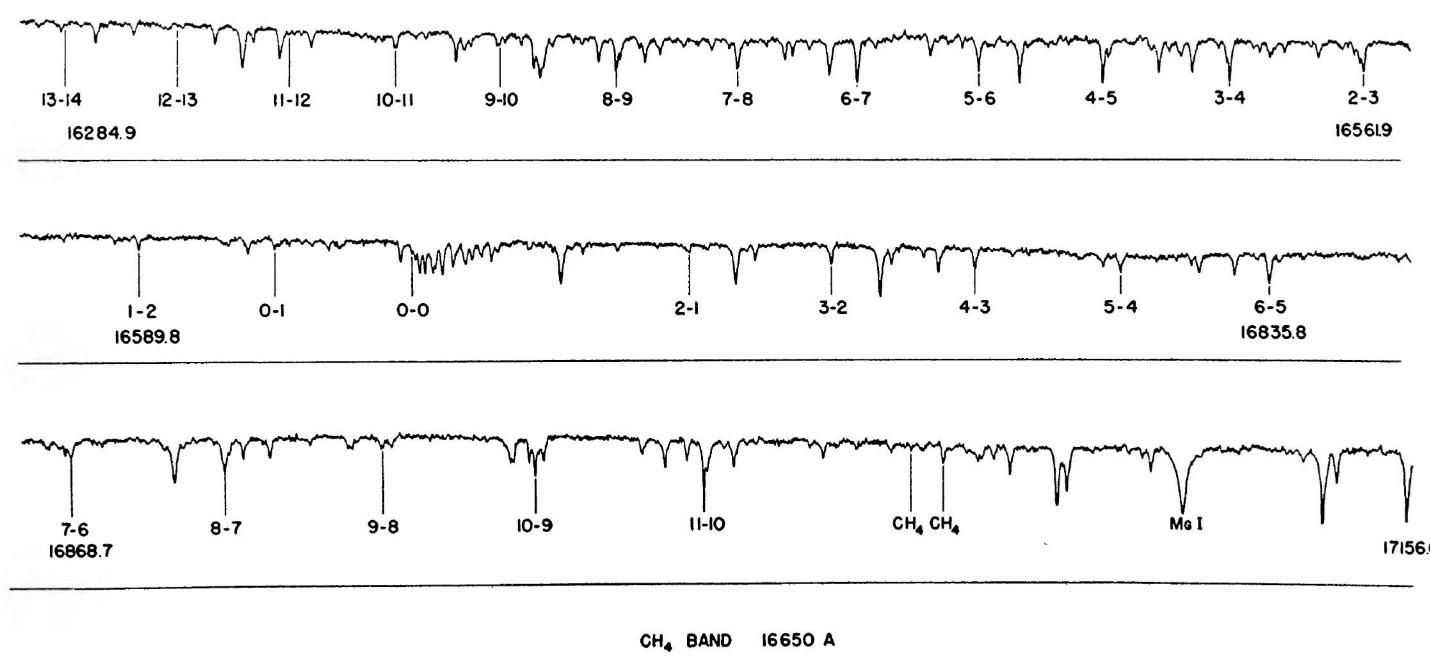

FIG. 1.—The $2\nu_3$ overtone band of CH_4 at 1.665 μ in the solar spectrum. Zero intensity is represented by the horizontal line at the bottom of the tracing.

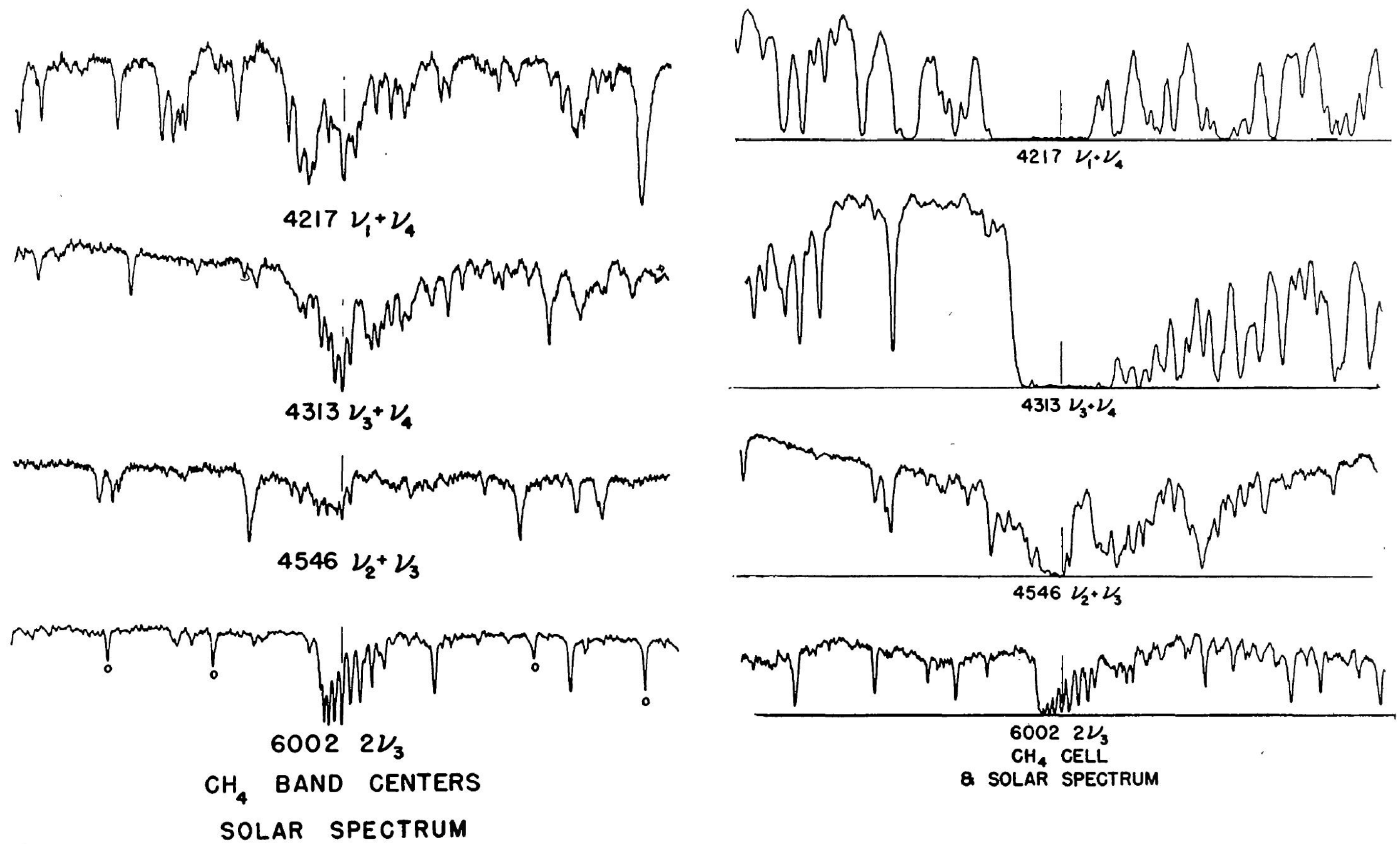

FIG. 2.—Four Q branches of CH_4 are shown to the left as they appear in the solar spectrum, and to the right as they are enhanced by a methane absorption cell. The horizontal line at the bottom of each tracing to the right represents zero intensity.

TABLE 1

1.666 μ BAND OF CH_4 IN THE SOLAR SPECTRUM

Designation	λ (Obs.)	W	ν (Obs.)	Δν	ν (Lab.)	Lab.−Sun	ν (Calc.)
0–1	16619.2	0.18	6015.49	....	6018.3	2.8	6015.57
				10.66			
1–2	16589.8	.13	6026.15		6029.7	3.5	6026.16
				10.37			
2–3	16561.3	.43	6036.52		6040.5	3.9	6036.60
				10.37			
3–4	16532.9	.49	6046.89		6051.7	4.8	6046.92
				10.18			
4–5	16505.1	.51	6057.07		6059.5	2.4	6057.09
				10.00			
5–6	16477.9	.42	6067.07		6070.1	3.0	6067.10
				10.00			
6–7	16450.8	.54	6077.07		6080.5	3.5	6076.98
				9.62			
7–8	16424.8	.46	6086.69		6090.5	3.8	6086.69
				9.61			
8–9	16398.9:	.57	6096.30		6100.3	4.1	6096.24
				9.42			
9–10	16373.6:	.45	6105.72		6109.9	4.3	6105.62
				8.96			
10–11	16349.6	.19	6114.68		6117.3	3.5	6114.83
2–1	16709.2	.15	5983.09		5989.0	5.9	5983.07
				11.01			
3–2	16740.0	.29	5972.08		5975.8	3.8	5972.00
				11.25			
4–3	16771.6	.34	5960.83		5964.8	4.0	5960.82
				11.28			
5–4	16803.4	.28	5949.55		5952.3	2.8	5949.54
				11.38			
6–5	16835.6	.48	5938.17		5942.8	4.6	5938.15
				11.55			
7–6	16868.4:	.40	5926.62		5930.8	4.1	5926.67
				11.47			
8–7	16901.1:	.58	5915.15		5920.2	5.1	5915.10
				11.73			
9–8	16934.7	....	5903.42		5706.0	2.5	5903.45
0–0	....	....	....	....	....	....	6004.86
1–1	16648.8	.18:	6004.79		....	....	....
				0.21			
2–2	16649.4	.27:	6004.58		....	....	....
				0.33			
3–3	16650.3	.50:	6004.25		....	....	....
				0.43			
4–4	16651.5	.52	6003.82		....	....	....
				0.61			
5–5	16653.2	.50	6003.21		....	....	....
				0.72			
6–6	16655.2	.52	6002.49		....	....	....
				0.87			
7–7	16657.6	.39	6001.62		....	....	....
				1.01			
8–8	16660.4	.36	6000.61		....	....	....
				1.22			
9–9	16663.8	.26	5999.39		....	....	....
				1.24			
10–10	16671.5	.16	5998.15		....	....	....

In equations (1), $B_i = h/8\pi^2 cI_i$, where I_i is the effective moment of inertia for vibrational state i, and ν_0 is the wave number of the 0–0 rotational component. An additive constant equal to $(\zeta^2 - 2\zeta)B_i$ has been omitted from all three terms.

The parameter ζ was introduced by Teller[13] to explain the anomalous fine structure of the infrared bands of symmetrical molecules. Under certain conditions the vibratory motion of the atoms may introduce a small component of angular momentum of magnitude $\zeta(h/2\pi)$. This momentum may orient itself parallel, perpendicular, or antiparallel to the ordinary rotational angular momentum, to produce the splitting given by equations (1). The quantity ζ has the order of magnitude -0.05 for the $2\nu_3$ overtone band.[14]

For the ground state, $\zeta = 0$, and $W/hc = B_0 J(J+1)$. The selection rules permit only transitions from the ground state to state (1*a*) above for $J \rightarrow J+1$ (positive branch), to state (1*b*) for $J \rightarrow J$, and to state (1*c*) for $J \rightarrow J-1$. Accordingly, the wave numbers of the rotational components of the P, Q, and R branches are given by the following expressions:

$$\nu_P(J) = \nu_0 + B_i(J^2 - J + 2J\zeta) - B_0(J^2 + J), \tag{2}$$

$$\nu_Q(J) = \nu_0 + B_i(J^2 + J) - B_0(J^2 + J), \tag{3}$$

$$\nu_R(J) = \nu_0 + B_i[(J+1)(J+2) - 2(J+1)\zeta] - B_0(J^2 + J), \tag{4}$$

where ν_0 is the wave number of the 0–0 line, $\nu_P(J)$ is the wave number of a line of the negative branch arising from ground level J, and similarly for $\nu_Q(J)$ and $\nu_R(J)$.

We then obtain the following combination relationships:

$$\nu_R(J) - \nu_Q(J) = B_i(1-\zeta)(2J+2), \tag{5}$$

$$\nu_R(J) - \nu_P(J) = B_i(1-\zeta)(4J+2), \tag{6}$$

$$\nu_Q(J) - \nu_P(J) = B_i(1-\zeta)\,2J, \tag{7}$$

$$\nu_R(J-1) - \nu_P(J+1) = (B_0 - B_i\zeta)(4J+2), \tag{8}$$

$$\nu_R(J) + \nu_P(J+1) - \nu_Q(J) - \nu_Q(J+1) = 0. \tag{9}$$

By taking appropriate wave-number differences as indicated above, we should be able to determine the constants $B_i(1-\zeta)$, $B_0 - B_i\zeta$, and hence $B_0 - B_i$. The first three columns of Table 2 list the values of $B_i(1-\zeta)$ as determined from equations (5), (6), and (7), respectively; the fourth column gives $B_0 - B_i\zeta$; and the last column the quantity on the left-hand side of equation (9). The values of $B_i(1-\zeta)$ calculated from equations (5), (6), and (7) are in reasonably good agreement with one another but, nevertheless, show a systematic increase from one column to the next. This effect, which is also shown by the residuals from equation (9) in the last column of Table 2, suggests that the Q-branch frequencies predicted from theory by equation (3) are too low relative to those of the P and R branches.

All the quantities in the first four columns of Table 2 decrease systematically with increasing J, which suggests that the frequency formulae (2), (3), and (4) should contain additional terms, probably in J^3. The expressions (2) and (4) for the wave numbers of the lines in the P and R branches may be represented by a single formula, of the well-known form,

$$\nu = \nu_0 + (B_i - 2\zeta B_i + B_0)\,m + (B_i - B_0)\,m^2, \tag{10}$$

[13] *Hand- und Jahrbuch der chemischen Physik*, **9**, 125, 1934.

[14] Johnston and Dennison, *Phys. Rev.*, **48**, 868, 1935.

where $m = J + 1$ for the R branch and $m = -J$ for the P branch. Equation (10) suggests an attempt to fit the observed wave numbers to a formula of the form,

$$\nu = \nu_0 + am + bm^2 + cm^3 \; . \tag{11}$$

The constants were determined by least squares, with the results shown in the first column of the accompanying tabulation, the second column containing the values obtained by Norris and Unger from a similar calculation. The constant c is small but appreciable. The wave numbers calculated from equation (11) are given in the eighth column of Table 1, under the heading "ν (Calc.)." The residuals, ν (Obs.) — ν (Calc.), are within the error of measurement, the average value being ± 0.05 cm^{-1}. The calculated value of ν_0 accords well with the assignment of quantum numbers given for the Q branch in Table 1. From a comparison of equations (10) and (11) we identify the constants a and b with $B_i - 2\zeta B_i + B_0$ and $B_i - B_0$, respectively. We have

	Lake Angelus	Norris and Unger
ν_0	6004.86	6008.0
a	10.775	11.131
b	−0.06194	−0.0449
c	−0.000794	−0.00341

TABLE 2

CH_4 CONSTANTS CALCULATED FROM EQUATIONS (5), (6), (7), (8), AND (9)

J	$B_i(1-\zeta)$			$B_0 - B_i\zeta$	
	Eq. (5)	Eq. (6)	Eq. (7)	Eq. (8)	Eq. (9)
1	5.340	....	....	5.400	−0.13
2	5.323	5.343	5.372	5.407	− .23
3	5.330	5.344	5.362	5.406	− .35
4	5.325	5.347	5.374	5.408	− .41
5	5.322	5.342	5.366	5.404	− .46
6	5.327	5.342	5.360	5.402	− .42
7	5.317	5.336	5.357	5.397	− .39
8	5.316	5.328	5.341	5.390	−0.28
9	5.316	5.324	5.332	....	....
10	5.297	....	....	....	....

$$\begin{aligned} a + b &= 2B_i(1-\zeta) \\ &= 10.713 \; . \end{aligned} \tag{12}$$

According to Johnston and Dennison,[14] the correct value of ζ to be employed for the $2\nu_3$ band is $-\zeta_f$, where ζ_f is the appropriate value for the fundamental ν_3 band. Childs[15] finds $\zeta_f = 0.050$, from which we obtain $B_i = 5.101$ and $B_0 = 5.163$, since $B_i - B_0 = -0.0619$. Childs obtained $B_0 = 5.252$ from an analysis of Cooley's[16] measures of the ν_3 and ν_4 bands at 3020 and 1306 cm^{-1}.

[15] *Op. cit.*

[16] *Ap. J.*, **62**, 73, 1925.

TEMPERATURE AND ABUNDANCE OF CH_4

The equivalent widths of individual lines in the P, Q, and R branches of the $2\nu_3$ band are given in the third column of Table 1. The intensities were measured on a tracing obtained on March 28, 1948, between 22^h05^m and 22^h53^m U.T. The tabulated equivalent widths have been corrected to correspond with a solar altitude of 14°34′ at the midpoint of the tracing. The equivalent widths of the P and R lines were determined directly from areas measured on the tracing. Those of the overlapping Q lines were estimated from the central intensities with the aid of a calibration between central intensity and equivalent width established from measurements of the P and R lines.

We have employed the equivalent widths in the positive and negative branches in an attempt to determine both the abundance of methane and the average temperature of the absorbing column. For either an absorbing or a scattering atmosphere, the equivalent width of an absorption line is given by[17]

$$\frac{W}{\lambda}=C\cdot N\cdot S_{JJ'}e^{-E_J/kT}, \tag{13}$$

where S_{JJ}' is the strength (square of the matrix element) for a transition from lower level J to upper level J'; E_J is the energy of the lower level; T is the absolute temperature; N is the total number of atoms or molecules per square centimeter along the absorbing column; and C is a known constant. If E_J is given in wave numbers, the Boltzmann constant, k, has the value 0.695. The expression (13) is valid only if the line is unsaturated, an assumption which we adopt on the basis of the actual appearance of the CH_4 lines on the tracings. For the CH_4 molecule, the energies (in cm^{-1}) of the rotational levels in the lowest vibrational state are given by

$$E_J=B_0J(J+1), \tag{14}$$

where B_0 has been found above to have the value 5.16 cm^{-1}.

If the theoretical line strengths, S_{JJ}', were accurately known, equation (13) would permit the calculation from the observed equivalent widths of both T and N. Since the strengths have not been calculated with sufficient accuracy, we adopted the following procedure. An auxiliary tracing of the 1.666 μ band was obtained, utilizing an incandescent lamp, together with a methane absorption cell 25 cm long, which was furnished through the kindness of Professor E. F. Barker, of the University of Michigan Physics Department. The cell was first evacuated and then filled with methane at 25-cm pressure. Since both the temperature and the abundance of the laboratory methane could be determined with precision, a comparison between the laboratory and the solar intensities leads to the evaluation of these parameters for the earth's atmosphere.

From equation (13), the ratio of equivalent widths between sun and laboratory is

$$\frac{W_s}{W_l}=\frac{N_a}{N_l}e^{-(B_0/k)J(J+1)(1/T_a-1/T_l)}, \tag{15}$$

where N_a is the number of molecules per square centimeter along the line of sight in the earth's atmosphere, N_l is the number per square centimeter in the absorption cell, and T_a and T_l are the atmospheric and laboratory temperatures, respectively. Taking logarithms, and inserting numerical values for B_0 and k, we obtain

$$\log\frac{W_s}{W_l}=\log\frac{N_a}{N_l}-3.224J(J+1)\left(\frac{1}{T_a}-\frac{1}{T_l}\right). \tag{16}$$

In Figure 3, we have plotted log (W_s/W_l) against $J(J+1)$. The points are well represented by a straight line, fitted by least squares, with slope -0.00267 and intercept

[17] Menzel, *Ap. J.*, **84**, 462, 1936.

-0.0492. By comparison with equation (16) and with $T_l = 293°$ K, we find $T_a = 236°$ K and $N_l/N_a = 1.120$. At a temperature of 293° and pressure equal to 25 cm *Hg*, the number of CH_4 molecules per square centimeter along a 25-cm path is 2.05×10^{20}. Hence the number N_a along a square-centimeter column of the earth's atmosphere toward altitude 14°34′ is 1.83×10^{20} molecules, or 4.87×10^{-3} gm. The total mass of a square-centimeter column of the earth's atmosphere in this same direction is 4.09×10^3 gm. Hence the relative mass abundance of methane is 1.18×10^{-6}, or about one part in a million.

The calculated temperature of $-37°$ C. is a reasonable value, being that normally found at a height of about 8 km.[18] Pending further study, nothing definite can be stated as to the lateral and vertical distribution of the methane in the earth's atmosphere. The indicated average height of 8 km is reasonable for the relatively light CH_4 molecule.

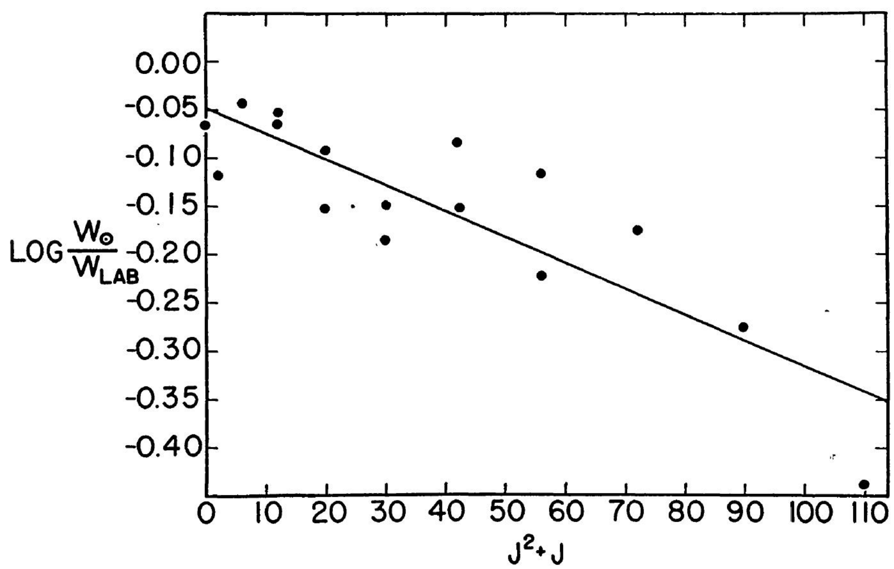

FIG. 3.—The determination of temperature and abundance of CH_4 in the earth's atmosphere

Analysis of tracings made with the sun at various altitudes may provide further information on the vertical distribution.

THE CH_4 BANDS AT 2.3 μ

Cooley,[19] Moorhead,[20] Vedder and Mecke,[21] and Nielsen and Nielsen[22] have observed the methane spectrum in the 2.3 μ region with varying degrees of resolution. The most prominent bands, with well-defined *Q* branches, are three combination bands—$\nu_1 + \nu_4$ at 4216.3 cm^{-1}; $\nu_3 + \nu_4$ at 4313.2 cm^{-1}; and $\nu_2 + \nu_3$ at 4546 cm^{-1}. The quoted wave numbers, *in vacuo*, are from Herzberg's[23] compilation. The appearance of the three *Q* branches on the Lake Angelus tracings is shown in Figure 2, which also shows the enhancement of the bands by a methane absorption cell. The vertical lines near the band centers represent the positions measured in the laboratory.

[18] *Smithsonian Physical Tables* (1934), p. 559.

[19] *Op. cit.*

[20] *Op. cit.*

[21] *Zs. f. Phys.*, **86**, 137, 1933.

[22] *Phys. Rev.*, **48**, 864, 1935.

[23] *Infra-red and Raman Spectra* (New York: D. Van Nostrand Co., 1945), p. 308.

Unlike the zero branch of the $2\nu_3$ bands, for which the intensities and spacings vary regularly with serial number, the 2.3 μ Q branches appear highly complex. It is possible that their mutilated appearance may be due to intensity anomalies rather than to irregularities in the spacing of the components.

Since the above investigation was carried out, we have secured a new set of tracings of the methane spectrum in the 1.6 and 2.3 μ regions, employing an incandescent lamp as a source in place of the sun. In view of the blended nature of the solar spectrum, the laboratory tracings are much more suitable for the measurement and analysis of molecular bands. A more precise study of the CH_4 spectrum is therefore being carried out and will be reported in the near future.

We are indebted to Professors E. F. Barker and D. M. Dennison, of the University of Michigan, for helpful advice and discussion and to Mr. Robert M. Page for computational assistance. This investigation would not have been possible without the continuing grants-in-aid by McGregor Fund.

THE OBSERVATORIES OF THE UNIVERSITY

To the President of the University:

SIR—We submit herewith the report of the Observatories of the University for the year 1950-51.

THE OBSERVATORY
Ann Arbor, Michigan

INSTRUMENTAL

Tests made in the spring of 1950 of the optical components of the Curtis-Schmidt-type telescope indicated that the performance of the correcting plate was not adequate. The Perkin-Elmer Corporation decided that the quality of the glass itself would not justify further work on the plate, and they made an entirely new one during the months of February, March, and April, 1951, during which time the telescope was dismantled. The performance of the new correcting plate has proved excellent, and the optical system more than meets the original specifications. During the winter the right-ascension clutch of the telescope was redesigned and rebuilt by the Warner and Swasey Company.

An Eichner iris-diaphragm astrophotometer was purchased in the fall of 1950. The instrument has proved highly satisfactory in principle, but regular use has been delayed until Mr. Frank A. Ferris carries out a number of necessary mechanical modifications. Miller is constructing a photoelectric photometer after a basic design provided by Whitford. Testing on the 12-inch visual refractor has begun, and the photometer will also be used at the Newtonian focus of the Curtis telescope. Boggess and Dennison have improved and modernized the Williams-Hiltner direct intensity microphotometer under the guidance of Dr. Orren C. Mohler. Weston has completed the construction of a tube sensitometer for the calibration of objective prism plates obtained with the Curtis telescope.

SUMMARY OF RESEARCH WORK

Stellar and nebular spectroscopy.—Under Dr. Dean B. McLaughlin's supervision a total of 457 spectrograms were obtained with the 37½-inch reflector. The plates were distributed among different classes of objects as follows:

Be stars	113
Composite spectra	42
Peculiar spectra	68
T Tauri and related variables	46
Novae	20
Gaseous nebulae	17
VV Cephei	22
Upsilon Sagittarii	32
Binaries, type stars, miscellaneous	97

McLaughlin has continued his long-range studies of the spectra of Be stars, composite stars, novae, and other peculiar stars. The discussion of a twenty-two year series of spectrograms of Beta[1] Monocerotis was completed, and the results published in abstract. A large number of spectrograms of the Be spectrum variable HD 20336 have been measured as part of a complete study of the changes of displacement of absorption and emission and the V/R variations of the emission. The record extends over nearly forty years. Under McLaughlin's direction a number of students measured plates of the triple star HD 157978-9. A general study of the spectral variations of VV Cephei outside eclipse was completed, and a description by McLaughlin is in press in the *Astrophysical Journal.* Potter measured a number of spectrograms of VV Cephei. The Michigan record of the spectrum of this star now extends over nearly a complete orbital period of twenty years. A large number of plates of Upsilon Sagittarii have been measured, with special attention to the variable "violet satellites" of the hydrogen lines. Michigan spectra of Nova Puppis 1942 during the early postmaximum stages have been measured. These were supplemented by extensive measures of Mount Wilson spectrograms and by some Lick spectrograms. While on sabbatical leave at Lick and Mount Wilson during the second semester, McLaughlin made numerous measures of the spectra of novae. Detailed measurement of Mount Wilson spectra of Nova Herculis 1934 resulted in a revised interpretation of the absorption systems of Nova Herculis and showed that some supposed large changes of velocity were due to appearances and disappearances of absorption components during interruptions in the Michigan observations. Special attention was given to the development of the absorption systems in novae. Those studied most extensively were: v356 Aquilae (Lick plates); Nova Aquilae 1945 (Mount Wilson and Lick plates as well as a series obtained at McDonald Observatory by Edmondson and Aller); T Coronae Borealis (Mount Wilson plates). Shorter series were studied of v368 Aquilae (Lick); Nova Cygni 1942 (Mount Wilson); and Nova Cygni 1948 (Mount Wilson), as well as one or two plates each of several other novae. A systematic search for the coronal lines resulted in identification of the red line, $\lambda 6374$, in Nova Puppis 1942. It is suspected in three other novae, but final decision must await completion of reductions of measures. The green line, $\lambda 5303$, was not found or suspected, except in novae in which it was already known.

In collaboration with Dr. O. C. Wilson of the Mount Wilson and Palomar observatories, Dr. Aller has carried out a study of the structure of the planetary nebula IC 418. The distribution of the radiating gases has been derived on the assumption of radial symmetry. Aller is engaged in spectrophotometric studies of a small number of representative planetary nebulae in collaboration with Dr. R. Minkowski. The reductions are well advanced, particularly for NGC 7662, for which intensities are being studied at five different points in the inner and outer rings. Final completion of the program requires the determination of certain vignetting corrections in the spectrograph. This part of the problem is now being investigated by Minkowski. Aller has obtained the spectra of a large number of emission objects in M33 with the Curtis telescope and objective prism. Most of the objects were discovered by Haro, but a few additional ones have been found. The brightness of these objects in the light of Hα have been measured by comparison with stars in the nearby selected area 45, and electron densities have been estimated. Typical patches appear to have electron densities on the order of 10-40 particles/cm^3. Aller has obtained a series of spectrograms of T Tauri. Most of the observations have been secured with the two-prism spectrograph and the six-inch camera at the 37½-inch reflector. This star occasionally shows rapid variations in the intensity and character of the emission lines which are superimposed on a dwarf G absorption spectrum. Other stars of this type such as RY Tauri and R Monocerotis are also being observed when possible on a continuing basis. Aller and students have also secured spectrograms of CI Cygni, BF Cygni, and Z Andromedae whenever possible during the summer, fall, and late spring of the past year. BF Cygni shows rapid night-to-night fluctuations in the intensities of the emission lines. Z Andromedae and CI Cygni show somewhat slower changes. Observations with the Curtis telescope and objective prism have been taken to supply data on the background continuum. Aller and Weston have continued observations of the spectrum of AE Aurigae with the 37½-inch reflector.

Chamberlain is making a study of the network nebula in Cygnus from direct photographs taken with the Curtis telescope. Various plate-filter combinations are being used to isolate Hα, N_1 and N_2, and λ3727 [OII]. The intensity variations in the light of Hα have been investigated in an effort to obtain the turbulence spectrum. Photometric comparisons with M32 are also being made to obtain the absolute emission in several of the nebula filaments.

PHOTOMETRY

Yoss is investigating the application of objective grating methods to the establishment of photo-red magnitude sequences with the Curtis telescope. The wave-lengths range of this magnitude system is so limited that the first-order grating images show no perceptible elongation. The plates are intended for measurement with the Eichner astrophotometer. When completed by Miller, the photoelectric photometer will be employed for the photometry of extended objects, for the establishment of magnitude standards in support of photographic programs, and for other special programs.

GALACTIC STRUCTURE

A study of the utility of photo-red general star counts as a supplement to and check on the analyses of photographic counts was completed by Miller. The plates, taken with the Curtis telescope, were centered on the North Polar Sequence. The value of such counts is apparent, but further application depends on the progress of the photometric programs described above. Sets of long-exposure Schmidt plates have been taken on selected, very opaque, and apparently sharply defined dark nebulae. These plates provide the material for a study by Miller of the possible existence of low-absorption extensions of these objects. The exceptional power of the Schmidt-type telescope for objective prism classification is to be applied by Miller to the problem of providing giant-dwarf or luminosity classifications for stars with determined proper motions. The programs are three in number:

1. The stars of the Leander-McCormick proper-motion catalogues.

2. A sufficient number of the Yale zone stars in the neighborhood of each of the centers of program (1) to furnish adequate data for statistical analysis.

3. Hitherto unclassified stars of the Radcliffe Selected Area proper-motion catalogue.

Yoss is investigating classification by means of unwidened spectra. His objective is to reach the faintest possible magnitude limit, using filters to reduce sky fog and overlap by unwanted spectral regions.

EXTRAGALACTIC STUDIES

Clements and Miller completed measurement and discussion of the outer photo-red isophotes of the edge-on spiral NGC 891 photographed with the Curtis telescope. This study was undertaken as a test of the combination of the Schmidt plates and the new microdensitometer of the McMath-Hulbert Observatory, prior to initiation of a similar analysis of the larger irregular galaxies visible in our latitude. An extension of this investigation is being undertaken by Boggess and Dennison with the improved Hiltner-Williams microphotometer. In particular, they will compare the isophotes derived from the usual cross-sectional tracings, with those obtained by using the instrument as an isophotometer according to the scheme devised by Williams and Hiltner. The future development of this program will be under the direction of Dr. Wyatt.

Wyatt is initiating a study, with the Curtis telescope, of blue and red isophotes in bright elliptical galaxies, with the intention of finding the dependence of projected shape and color on distance from center, and of developing diameter and shape parameters that are freer of instrumental selection than previous data. The results will be analyzed statistically with the aim of finding a more precise distribution function than has been possible previously for the three-dimensional shapes of the elliptical galaxies. Wyatt is photographing a high-latitude galaxy field in the Cetus region with the Curtis telescope. F. G. Brown, in England, will determine the position angles of galaxies on these plates and analyze the results statistically, in an attempt to discover whether the highly selective orientation effects found by him in 1938 for a Harvard field in Horologium apply over more extended regions of the sky.

THEORETICAL ASTROPHYSICS

Dr. Pierce and Dr. Aller have obtained the variation of the absorption coefficient with wave length and the temperature distribution in the solar atmosphere from analysis of limb-darkening measures between wave lengths 0.5μ and 2.5μ made at the McMath-Hulbert Observatory. They have computed model solar atmospheres for different ratios of hydrogen to the metals. The theoretical absorption coefficient calculated on the assumption that the negative hydrogen ion is responsible for the opacity is too small by a factor of 1.35 to account for the observed flux of energy from the sun. Dr. Goldberg and Dr. Aller are investigating various possible mechanisms for the formation of the infra-red helium absorption line at $\lambda 10830$ in the solar spectrum in an attempt to explain its remarkable variations in intensity over the solar disc. The population of the metastable 2^3S level appears to be much larger than can be accounted for on the assumption that the level is excited by collisions in the chromosphere. Photo-ionization from the ground level, followed by recapture in higher triplet terms, must be invoked to explain the high population of this level. Kung has carried out calculations of the center-limb variation of the profile of the third member of the Brackett series at $\lambda 21655$ in the solar spectrum. His computations demonstrate the importance of the Stark broadening and suggest that the excitation temperature for the fourth level of hydrogen is slightly lower than the local temperature.

An investigation has been undertaken by Aller to determine whether the proton-proton reaction is important in the red dwarf stars. Previous studies (1949) had suggested that the model stars would tend to be too bright. Accordingly, new calculations were carried out in which it was no longer assumed that the energy generation took place only in the convective core. Instead, the energy generation was taken into account throughout the entire star. Detailed computations were carried through for Krueger 60A. It was found that the observed luminosity could not be explained with any reasonable choice of the hydrogen, helium, and metallic contents. The model stars were always too bright.

METEORITE RESEARCH

Bauer continued work, during the first semester, on the problems of the age and origin of meteorites. His new calculations, based on more recent observations by physicists, indicate that cosmic radiation is about eight times more effective in producing helium in meteorites than indicated by previous observations; and that, therefore, the maximum age, evaluated in this direct way, of any of the metallic meteorites for which helium measures are available is less than about 400 million years. It is still not possible to take into account some factors that would make the actual rate of helium production in meteorites by cosmic radiation still larger. Bauer has continued work on ONR contract N8onr-582 which was extended for another year. The continuation of the program was made possible by a grant from the J. Lawrence Smith Fund, which enabled Bauer to devote full time to the program during the first semester. The apparatus for measuring the helium contents of metallic meteorites is very near completion. All of the technical problems of the apparatus have been solved.

MISCELLANEOUS

Yoss completed a study of Comet Minkowski, using direct and 6° objective prism plates taken with the Curtis Schmidt in photographic and photo-red light.

LAMONT-HUSSEY OBSERVATORY

Bloemfontein, South Africa

27½-inch refractor.—During the past year the double star work at the Lamont-Hussey Observatory has been carried on solely by Professor Rossiter, Astronomer-in-Charge, and has consisted chiefly of the measurement of very close pairs, namely, those with separations under 2/10 of a second, and especially such pairs with suspected short periods. Approximately 850 such measures were made. The average time for such a measure is 20 minutes or more, compared to the 5 to 10 minutes for the measure of a wider, easier pair. Six hundred and thirty visitors in groups averaging ten to a group had the use of the telescope for 72 hours during the year. The total number now exceeds 17,000. The final year of Professor Rossiter's work with the Lamont telescope will be a continuation of the measurement of the closer pairs and especially those pairs which show suspected rapid motion. The total number of measures is approaching 30,000, a number far short of that which is needed and desired, because the major effort was concentrated on the search program.

Hα survey.—During the past year Mr. Henize has nearly completed the Hα survey of the southern sky with the Mount Wilson 10½-inch refractor and 15° objective prism. It is anticipated that the observing program will be terminated by August 15, 1951, after which the telescope will be dismantled and returned to the Mount Wilson and Palomar observatories. Henize has taken new Hα photographs of the large Magellanic Cloud for a detailed study of the properties of the emission nebulae whose discovery was reported at the Michigan symposium by Henize and Miller. The discussion of this material will be carried on by Henize and Aller. Henize has also obtained objective prism spectra of Nova Pictoris 1925, the three novae in Scorpius in 1950, and RR Telescopii. Descriptions of these objects have been published by Henize and McLaughlin. Henize has been given the opportunity to make spectrographic observations on four nights with the Radcliffe reflector at Pretoria. The program consisted of stars which the Hα survey plates indicated to be of potential interest. A preliminary discussion of the observations has been prepared for publication.

Respectfully submitted,

LEO GOLDBERG, *Director*

McMATH-HULBERT OBSERVATORY

Lake Angelus, Pontiac, Michigan

OBSERVING AND INSTRUMENTAL

McGregor Tower.—Two new instruments were added by purchase for use in the McGregor Tower. These are a birefringent filter manufactured by Baird Associates and an échelle grating manufactured by the Bausch and Lomb Company. A large concave mirror of 18¾ inches, required for the all-reflecting échelle grating spectrograph, was figured by Mr. Lloyd Sprinkle of Detroit. A new microdensitometer, employing direct pen and ink recording, was completed and installed in the measuring room of the McGregor building. The instrument has been in use for approximately 500 hours and has been very satisfactory. The McGregor Tower was repainted both inside and out during the course of the year.

Solar observations were made in the McGregor Tower on 108 days. The spectrographic equipment of the Tower was used on an additional 130 days for laboratory work of various sorts. The observational programs for which one or more days of solar observing were required are listed below:

1. Solar and laboratory runs for use in determinations of the abundance and distribution of methane, carbon dioxide, and nitrous oxide in the earth's atmosphere.

2. Solar observations for determining a wave-length scale in the lead-sulfide region.

3. Solar observations of the variation in profile of Brackett gamma with position on the sun by Mr. Kung.

4. Spectroheliographic observations of Ca II, λ8542.

5. Photographs with the McGregor Littrow spectrograph of the spectra of prominences over the wave-length region from λ7000 through λ3850. In connection with this work, the Baird birefringent filter was used for guiding on particular prominence features.

6. An experimental spectrograph using an échelle grating and a prism for dispersing elements was set up to explore possibilities of these instruments for prominence spectroscopy.

7. Some échelle spectrograms were obtained with an all-mirror instrument installed in the spectrograph room of the McGregor Tower.

8. A rather large number of days were required for testing relative sensitivity of lead-sulfide and lead-telluride photocells supplied from several sources.

9. The absorption lines in the solar spectrum at λ10830, λ10124, and λ20582 were recorded at various points of the solar disc with the lead-sulfide cell.

Fifty-foot Tower.—The Fifty-foot Tower was repainted on the outside, and a new asphalt tile floor was laid in the observing room. New timing controls were installed to make the Fifty-foot Tower self-contained and independent of other units of the Observatory. In this connection the wiring between the 24-inch telescope and the Fifty-foot Tower has been completely renewed and modified. A new public address system connecting the Fifty-foot Tower, the McGregor Tower, and the administrative offices makes possible rapid dissemination of information on solar activity and close co-operative programs for the two solar towers.

During the year ended June 30, 1951, the Fifty-foot Tower telescope was in operation 193 days. In this period 67,000 spectroheliograms were secured—47,000 with the spectrograph of the Tower telescope and 20,000 with the Stone radial velocity instrument. The spectroheliograms covered the following observational programs:

1. Records of flares and active dark flocculi within sunspot groups. Series of spectroheliograms taken at known wave-length displacements from Hα permit a study of the location and velocity of the moving gases.

2. Studies of prominences with respect to surrounding disc features.

3. Form and activity of prominences for which spectra were secured in the McGregor Tower.

4. Variations in position and width of the Hα line in the spectra of active prominences.

24-inch reflector.—An improved mounting for the Perkin-Elmer low-dispersion prismatic spectrometer used in conjunction with the infrared solar intensity measures was constructed and installed. A special carbon arc for use as an intensity standard was also built for the 24-inch installation. The reflector was used full time from June 15 to September 15, 1950, and again in June, 1951, by Mr. Edward M. Lewis for the determination in absolute units of the spectral energy distribution of the sun in the infrared.

Snow telescope.—The co-operative program between the Mount Wilson and Palomar observatories and the McMath-Hulbert Observatory has been continued throughout the year. Mr. Dale Vrabec of the McMath-Hulbert Observatory was in residence under the direct supervision of Dr. Orren C. Mohler. Dr. Mohler visited the project for a month and carried out a series of observations. Observations were made on 143 days between July 1, 1950, and July 1, 1951. More than 1,500 tracings were made during the course of the year's work, requiring 500 observing hours. On August 1, 1950, a refrigerated lead-sulfide cell was installed, and the solar spectrum was mapped to a long wave-length limit of 3.6 microns. During May, 1951, a new Cashman PbS cell in quartz envelope, adapted for cooling, was tested and found to give better results than any hitherto attained. With this new cell, more than 80 per cent of the theoretical resolving power of the grating in the infrared spectrometer can be attained.

Upon the attainment of this additional resolving power, it became evident that a complete new map of the solar spectrum between 1.4 and 3.6μ should be made, and observations leading toward this end were started. An important part of this program was a set of observations for establishing the wave-length scale to a higher degree of accuracy.

A great many "east-west" solar limb tracings were made for the purpose of identifying solar lines.

Early in 1951 the University of Michigan Press published a *Photometric Atlas of the Near Infra-red Solar Spectrum, λ8465 to λ25,242.* All of the tracings reproduced in this atlas were made on Mount Wilson as part of the co-operative program mentioned before.

An exploratory series of tracings of the helium λ10830 line were made by Vrabec at the suggestion of Dr. Mohler. These tracings were made in plage areas as well as at the center and limb of the sun. Vrabec also made a series of tracings showing the change in Brackett gamma from the center to the edge of the sun for use by Kung in his thesis.

Summary of Research Work

Infrared solar spectrum.—The long and laborious job of establishing a wave-length scale as correct as possible with regard to both scale and zero point is being continued on the basis of tracings from the McGregor Tower and the Snow telescope on Mount Wilson. A reasonably satisfactory scale, with errors of the order of ± 0.1A, has been established to a long wave-length limit of 36,000A, but increases in sensitivity and refinements of instrumental operation have continued to make the wave-length scales obsolete almost as fast as they have been completed. Work has been started on what it is supposed will be the best wave-length scale possible with present equipment. The equivalent widths of the solar absorption lines in the lead-sulfide region have been measured. A supplement to the infrared atlas, consisting of wave lengths and identifications of solar and telluric lines in the atlas, together with equivalent widths of the solar lines is nearing completion. Laboratory measurements of the absolute f-values of lines in the $2\nu_3$ band of CH_4 have been completed and the results submitted for publication in the *Journal of the Optical Society of America.* Similar measures are being made for CO_2 and N_2O and will be employed for the determination of the abundances and vertical distribution of these gases in the earth's atmosphere.

Prominence spectra.—Preliminary prominence spectrograms obtained in the autumn of 1950 with the Littrow spectrograph of the McGregor Tower have been reduced. The spectrograms cover the spectral region from Hα to K.

Helium 10830.—Intensity tracings of the 10830 line of He I are in the process of reduction. These measures will provide information about the limb darkening of the sun at λ10830 and the remarkable changes in intensity of this helium line in various solar features.

Infrared intensity of the sun.—The 24-inch reflector and Perkin-Elmer spectrometer are employed full time on the measurement, in absolute units, of the intensity of selected infrared regions of the solar spectrum.

Solar prominences.—The velocities and accelerations in the eruptive prominence of August 7, 1950, were studied in detail. The prominence was shown to be associated with an active sunspot region that crossed the disc several days prior to the onset of a great geomagnetic storm. A series of solar radio noise bursts at 200 Mc/s took place when the eruptive prominence reached a height of 285,000 km. The forms and motions of eight prominence fields were analyzed for comparison with the prominence spectra taken with the McGregor spectrograph.

Solar flares.—Intensity measures of flares have been continued. Light curves for twenty-one flares photographed in 1949 showed intensities at maximum that ranged from 1.6 to 5 times the intensity of the undisturbed Hα disc. Relationships between intensity, area, location on solar disc, and terrestrial effects were investigated.

The development of a flare at the limb of the sun was recorded on May 8, 1951. During the first minute of the activity the brilliant prominence rose with a velocity of the order of 700 km/sec and reached a height of 60,000 km. Hα spectra taken during this period showed Doppler shifts indicating motion tangential to the sun's surface greater than 300 km/sec. Hα was 8A to 10A wide. The flarelike prominence reached a maximum intensity four times that of the undisturbed Hα disc. The occurrence of this bright limb object coincided with the onset of a burst of 200 Mc/s solar radio noise and a sudden ionospheric disturbance on the earth.

A solar flare was observed on May 19, 1951, in both the Fifty-foot Tower and in the McGregor Tower, using the lead-sulfide cell. A complete record of this disturbance in the 10830 line of He I was obtained to accompany the Hα spectroheliograms of the Fifty-foot Tower.

Solar radio noise.—The comparison of 200 Mc/s solar radio noise records secured at Cornell with optical solar activity photographed at Lake Angelus continues. The relationships between the two aspects of solar activity have proved to be both interesting and complex, and the results are being put in shape for publication.

Solar and geomagnetic data.—A compilation has been made of solar features and events from 1948 to the present for comparison with concomitant ionospheric disturbances and geomagnetic effects.

Small scale features of the solar chromosphere.—Studies have been and are being made of the smallest observable features in the solar chromosphere. Some of the data obtained from eclipse plates are being published.

Respectfully submitted,

ROBERT R. MCMATH, *Director*

THE UNIVERSITY MUSEUMS

To the President of the University:

SIR—The work of the University Museums during the year 1950-51 is presented in the annual reports of the directors of the Museum of Anthropology, the Museum of Paleontology, the Museum of Zoology, and the University Herbarium, and of the Chairman of the Operating Committee. The report of the Operating Committee deals with the area of joint responsibility and co-operation of the four museum units. This includes the exhibits program, courses in museum methods, special educational programs sponsored by the University Museums, and the operation of the building. The Operating Committee is composed of the directors of the three museums

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SOLAR SPECTROSCOPY WITH A VACUUM SPECTROGRAPH*

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Received August 23, 1955

One of the first attempts to use solar spectrum observations in a quantitative way was made by a distinguished member of the staff of the Princeton University Observatory, Professor Henry Norris Russell. On the basis of estimated line intensities in the *Revised Rowland* tables, Professor Russell (1929) determined the relative chemical composition of the sun. In the succeeding twenty-five years his results have been refined but not greatly modified. Professor Russell's great work demonstrated the inherent power in quantitative studies of line intensities and stimulated attempts at more precise intensity measurements. Studies of the chemical composition of the sun were followed by analyses that derived the parameters of the physical state of an average solar atmosphere. Curve-of-growth methods provided information on states of excitation, kinetic temperatures, and pressures. Such methods are based on the measurement of a kind of average, the equivalent width, and, as is often the case, much important information is lost in the use of an average.

Today improvement in knowledge of the sun depends largely upon securing measurements of intensities in the solar spectrum that are sufficiently precise for the determination of accurate line profiles. At the present time, profiles of varying degrees of reliability have been determined for a total of about fifty *strong* lines in the solar spectrum (Pierce 1954). These refer to ten chemical elements. However, fewer than one-quarter of these measurements are precise enough to be useful in critical comparisons of theory and observation. The profiles of *faint* lines are almost unknown.

The reasons for this unsatisfactory state of our knowledge are not hard to find. Most of them originate in various imperfections in the spectroscopes that have been used in solar spectroscopy. The majority of solar spectroscopes in use today were designed originally for the measurement of accurate wave lengths rather than reliable intensities. Although these instruments show more than adequate resolution of close lines for position work, in all but a few cases stray light in the spectrum has not been controlled.

These considerations point toward the need for a large-grating instrument, designed especially to eliminate scattered light. With the successful ruling, in recent years, of

* Address of the retiring president of the American Astronomical Society at Princeton, N.J., April 5, 1955. The work described here was supported in part by Contract N6-onr-232V with the Office of Naval Research.

highly perfected gratings, there are no optical defects that will interfere with the precise measurement of intensity. There are, however, many other problems that must be overcome before the full performance of the practically perfect gratings, such as those produced by the Babcocks (1951), actually can be obtained.

For example, soon after the installation of one of the new Babcock gratings in our monochromator in the Snow telescope on Mount Wilson, it became evident that convection currents within the spectroscope limited the performance of the grating. The difficulty first appeared during the measurement of wave lengths of spectrum lines on direct intensity tracings. Air currents caused the spectrum lines to move in random fashion through a range of 0.06 A when conditions were good, and as much as 0.2 A when conditions were poor.

Elimination of bad seeing that is caused by motion of air within the instrument is the strongest argument for the construction of a vacuum spectroscope. There are, however, other considerations that favor a large vacuum instrument. Such a spectroscope is insensitive to changes in air pressure and temperature and thus makes possible closer

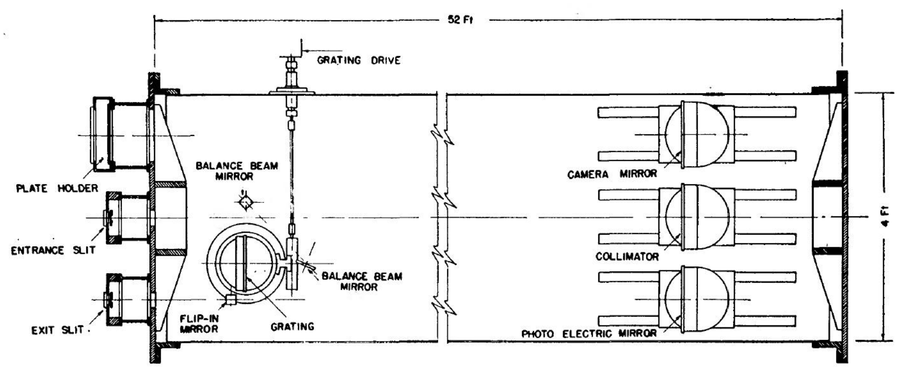

FIG 1.—Schematic plan of the McMath-Hulbert 50-foot focal length vacuum spectroscope

control and repetition of observing conditions. A high-dispersion spectroscope operating in air must include compensation for pressure changes as small as 3 mm of mercury. Changes in temperature not only initiate air currents in air-filled spectrographs but also effect changes in the collimator, the image-forming elements, the mounting, and the grating. In a 15000-groove/inch grating on a Pyrex blank, a temperature change of 1° C will shift a spectrum line by one part in 300000 of its wave length. In a vacuum instrument, all these temperature effects are either eliminated or greatly reduced. When the spectrograph is evacuated, heat is transferred chiefly by radiation or by conduction along poor thermal paths, and the rate of contraction or expansion of any optical part must therefore be very small indeed. Nevertheless, the change in length of the instrument may be appreciable during a long period of observation, and it must be possible to control continuously the position of the focal point.

Several new inconveniences arise when a large spectroscope must be confined within a vacuum tank. All controls for the adjustment of the optical parts must be brought outside the tank through airtight seals. At least one window must be provided to let light into the instrument, and often a second is needed to let the light out. Unless windows are carefully selected and placed in the optical path, they can be troublesome sources of dust lines and interference fringes.

With these considerations in mind, preliminary designs for a large-scale vacuum spectroscope were begun at the McMath-Hulbert Observatory in November, 1953. The McGregor tower telescope, with its solar images, 6 and 12 inches in diameter, is so located that it can send light to several positions suitable for a large spectroscope. The best of these sites, lying to the east of the tower, was selected for the new instrument.

FIG. 2.—Working head of vacuum spectroscope. *From left to right:* air lock for photographic plates; entrance slit; and exit slit with E.M.I. photomultiplier in place.

No changes in the telescope were required. A focal length of at least 50 feet was needed for the new spectroscope, in order to illuminate completely the large gratings now available for use in solar spectroscopy. The choice of a 50-foot focal length also provided a correct matching of the resolving power of the 6 × 8-inch Babcock grating with the resolving power of existing photographic plates. In order to avoid chromatic aberration, it was decided to use an all-mirror optical system.

Figure 1 is a schematic drawing of the plan finally adopted. It shows the relative positions of the single collimator mirror, the grating mounting that can be rotated to move the spectrum, and two image-forming mirrors, one for use in a spectrographic arrangement, the other for a monochromator. It was decided that special temperature regulation other than that provided by evacuation would not be required. It was also thought that deep concrete piers, based in sand, would provide a sufficiently stable foundation for the instrument without additional antivibration mounting.

The general features of the large spectroscope began to materialize with the delivery to the observatory of a cylindrical tube, 52 feet long and 4 feet in diameter. The tube was delivered on April 13, 1954; but, before its arrival, underground concrete footings had

TABLE 1

COINCIDENT WAVE LENGTHS AND DISPERSION FOR DIFFRACTION ANGLE 55°68

Wave Length	Order	Dispersion (mm/A)	Wave Length	Order	Dispersion (mm/A)	Wave Length	Order	Dispersion (mm/A)
27531	I	1 62	6883	IV	6 48	3933	VII	11 34
13766	II	3 24	5506	V	8 10	3441	VIII	12 96
9177	III	4 86	4588	VI	9 72	3059	IX	14 58

been prepared. Two-inch-thick, heavily ribbed steel plates for closing the ends of the tube had been machined at the observatory. The tube was manufactured by the Whitehead and Kales Company, of River Rouge, Michigan. Two sections of $\frac{1}{4}$-inch-thick steel plate were rolled and welded into two tubes, each 26 feet long. After delivery to the observatory, the two sections were welded together to form one continuous tube. The two end-plates are demountable. In addition, two portholes provide access to the inside of the tube. The steel end-plates are attached by bolts to two rings, machined at the observatory, and welded to the cylinder.

The air seal for the two end-plates is provided by a rubber gasket that is cemented into a groove in the end-plate and seals by pressure against the bolt ring on the end of the tube. Individual features of the spectroscope become clear if the path of a beam of light is traced through the instrument. In normal operation the telescope projects an image of the sun on the entrance slit of a small-prism spectroscope. This predisperser, in turn, images a spectrum on the entrance slit of the vacuum spectroscope (Fig. 1). The purpose of the predisperser is to exclude from the main instrument all sunlight except the narrow band of wave lengths under investigation. The dispersion of the predispersing spectroscope is such that a slit opening of 0.1 mm will admit only 69 A of the spectrum near Hα to the collimator of the vacuum spectrograph.

This use of a small-prism spectroscope not only reduces the intensity of stray light but also eliminates overlapping orders and permits selection of wave length and order desired. Table 1 shows as an example, in the seventh-order K region, the mixture of radiation emergent from the exit slit of the vacuum spectroscope if the prism spectroscope is not used. Table 1 also shows the variation of dispersion with wave length for a constant angle of diffraction, 55°68. The change of dispersion with angle of diffraction is large. The wave length 5000 A appears at the angles of diffraction and dispersions listed in Table 2. The rapid change of dispersion with angle of diffraction produces a linear dispersion of 26 mm/A for fifth-order Hα at an angle of 79°88!

A field lens that images the telescope objective on the collimator is placed just in front of the entrance slit of the grating instrument. This lens provides part of the vacuum seal and, at the same time, admits light to a cylindrical air lock surrounding the slit mechanism. The air lock makes it possible to adjust the slit jaws without destroying the vacuum in the main tank. With the slits in vacuum, a small electric motor is used to open and close the slit jaws. The slits are 2 inches long, are made of optically polished chromium carbide, and are tilted so that light reflected from them can be used for guiding.

TABLE 2

ANGLES OF DIFFRACTION AND DISPERSIONS FOR λ 5000 A

Order	Angle of Diffraction	Dispersion (mm/A)	Order	Angle of Diffraction	Dispersion (mm/A)	Order	Angle of Diffraction	Dispersion (mm/A)
I.	8°63	0 92	III	26°74	3 07	V	48°59	6 91
II	17 46	1 92	IV	36 87	4 57	VI	64 16	12 59

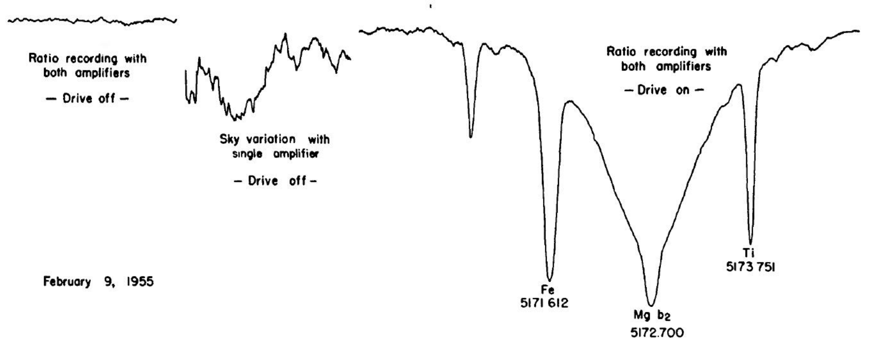

FIG 3 —Sample tracings to illustrate ratio recording

The light proceeds from the entrance slit (Fig. 1) along the axis of the large vacuum tank to a 12-inch collimating mirror. All the final adjustments of this and all mirrors in the tank must be made after the air has been pumped out. The necessary motions are provided by electric motors, controlled from the observer's station. The collimator returns a parallel beam along the tube to the grating near the entrance slit (Fig. 1). All final grating adjustments and means for changing the wave-length region under observation are brought outside the vacuum tank either mechanically or electrically. The angle of rotation of the grating can be read with a periscope.

Satisfactory performance of the spectroscope as a direct recording monochromator is dependent upon the precision motion of the grating. Fortunately, a well-tested unit for providing the desired slow rotational motion of the grating was available in the McGregor infrared spectroscope. Its transfer to the vacuum spectroscope greatly expedited the construction of the new instrument. The rate of continuous rotation of the grating can be varied from 0°01 per hour to a maximum rate of 0°5 per hour. The rota-

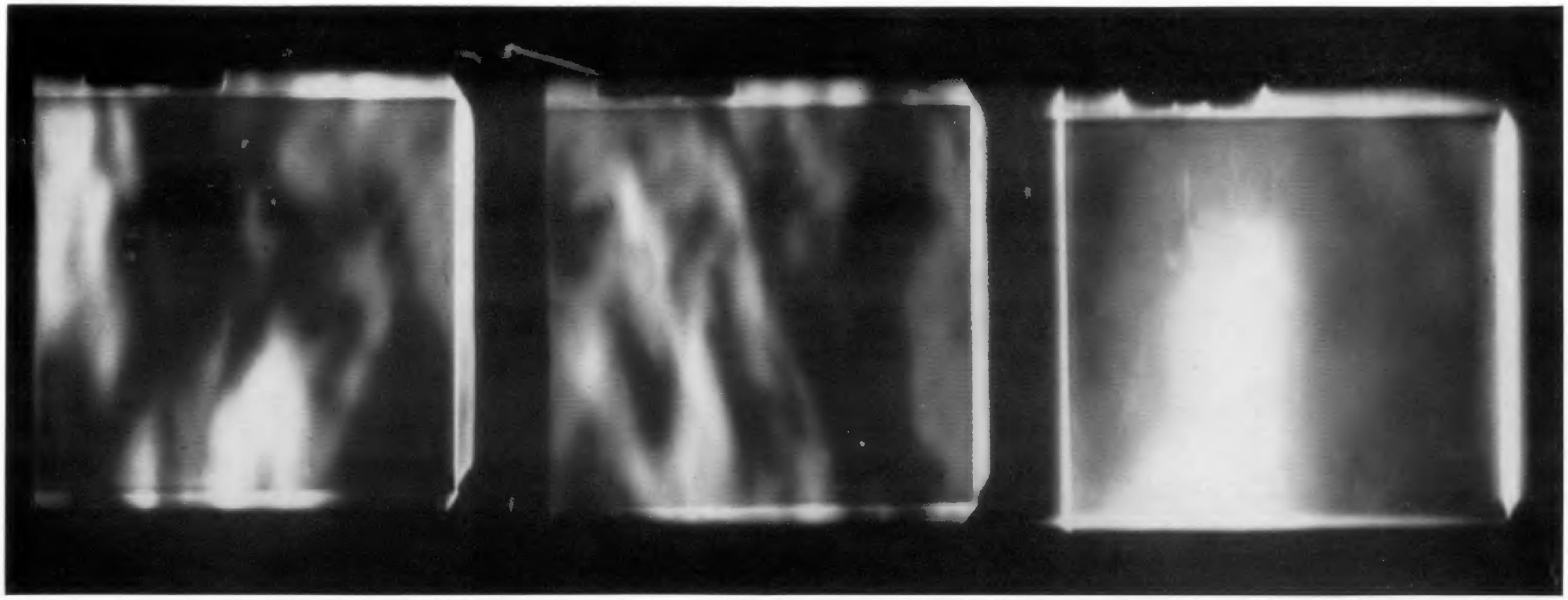

FIG. 4.—Foucault knife-edge tests to show disturbances by air currents in the spectrograph. *Left*, spectrograph at normal air pressure; *center*, spectrograph at half normal air pressure; *right*, spectrograph at 50 μ air pressure.

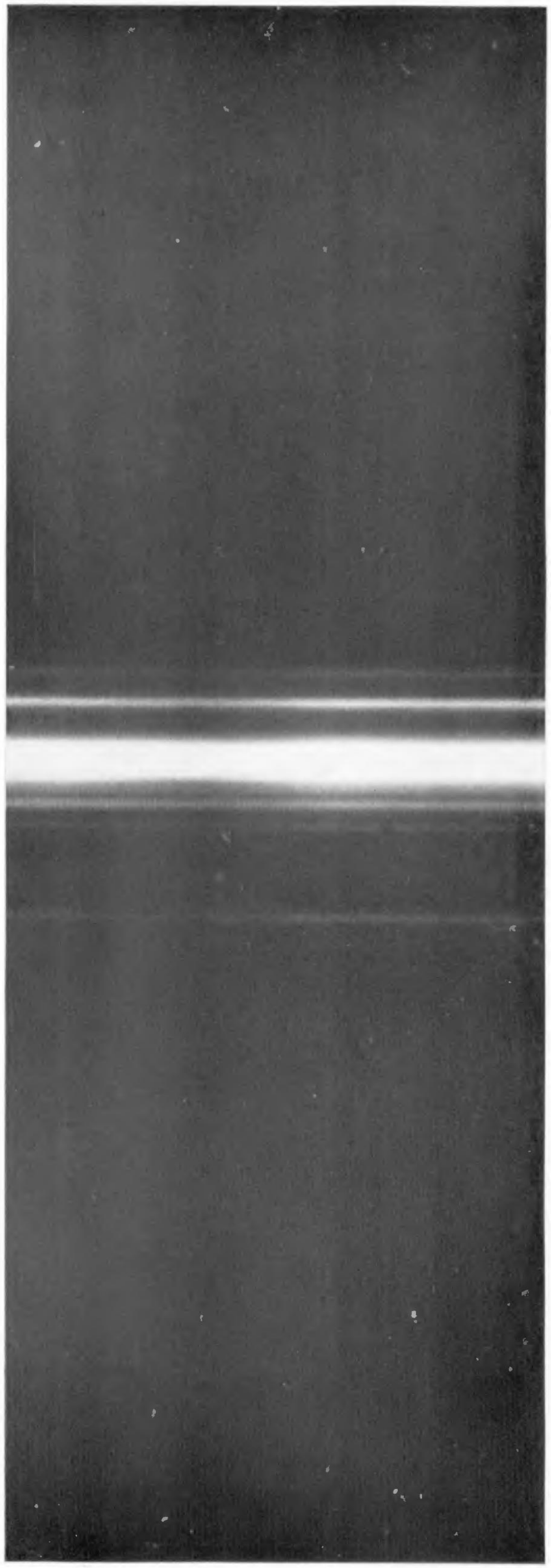

FIG. 5.—Photograph of 5461 A line of natural mercury

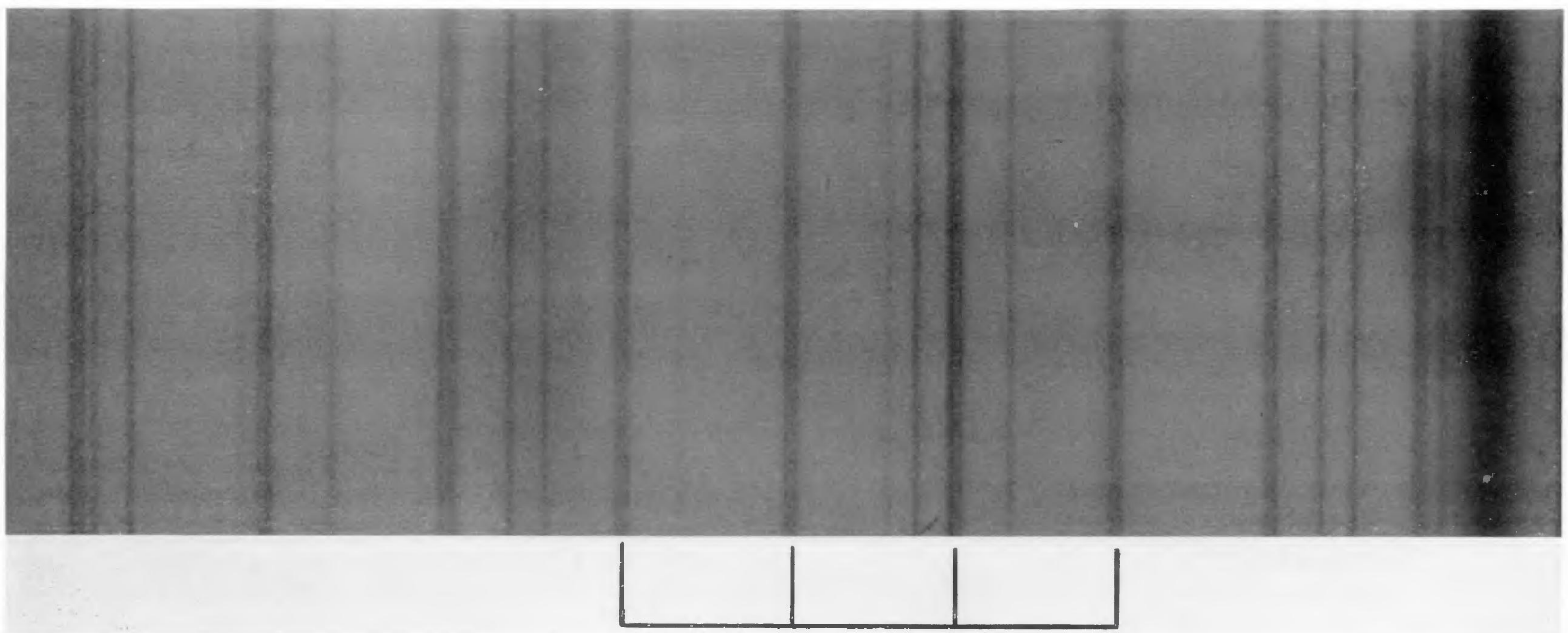

Fig. 6.—Photograph of iodine lines superposed on the solar spectrum at 5331 A. The four labeled pairs of lines have an average separation of 0.009 A

tion of the grating and the consequent variation in wave length of the emergent radiation are controlled by the frequency of the current driving the synchronous motors of the spectrograph. The same current is used to drive the recording chart, and in this way precise proportionality between grating rotation and linear distance on photometric tracings can be maintained.

The grating disperses the light and diffracts it back along the vacuum tank to either of two image-forming mirrors placed symmetrically on either side of the collimator (Fig. 1). One of the mirrors images a spectrum on an area to the left of the entrance slit, where it can be used for spectrum photography. The other mirror images a spectrum on an exit slit to the right of the entrance slit, thus forming a powerful grating monochromator which can be used for direct photoelectric recording. A small flip-in mirror (Fig. 1) can be tilted in to the beam to send light to a periscope for direct visual check of the wave-length region on the exit slit. Light baffles and traps have been installed throughout the tank to absorb stray light and keep it from reaching either the photographic plate or the exit slit. The camera mirror and photoelectric mirror may be covered by an absorbing shutter to eliminate reflection of unused light. The radiation that emerges from the exit slit can be used for various nonphotographic methods of detecting and recording intensities. With the grating set to provide a high-order spectrum, the energy that emerges from the exit slit is an almost monochromatic band that has a width of only 0.008–0.010 A.

The photographic plate and its holder are located in an air lock to make possible the changing of plates without loss of the spectroscope vacuum (Fig. 2). The single plateholder is supplemented by a magazine plateholder that permits the exposure of a dozen plates in rapid succession.

In principle, any detector can be used to measure the energy of the emergent beam. Up to the present time only E.M.I. No. 6262 photomultipliers have been tried. These have performed well. The output of the photomultiplier has been amplified by a Kron-type amplifier and the output recorded on a Leeds and Northrup G Speedomax.

Ratio recording will be attempted with most of the electrical detectors, to minimize effects of changes in sky transparency. A reference signal is obtained by reflecting a part of the collimated beam of sunlight from just in front of the grating to an auxiliary photomultiplier (see "Balance Beam Mirror," Fig. 1). A change in sky transmission will change both spectrum and reference beams by the same factor, but their recorded ratio will be unchanged. Figure 3 shows the effectiveness of ratio recording during an interval of variable sky transparency. The ratio of the outputs of the two cells is very nearly constant, even though the variation in output of one cell is large. Under these conditions, with the aid of ratio recording, the tracing (Fig. 3) of the magnesium line at 5173 was made.

Air was pumped out of the new spectroscope for the first time on May 21, 1954. The first photographs were made with a temporary camera on November 9, and the first tracings, with E.M.I. photomultipliers as detectors, were obtained on December 21. All these observations made use of some temporary equipment and can be improved as the instrument is completed. Nevertheless, they indicate that the initial performance of the spectroscope is good enough to permit profitable attack on solar problems.

The Foucault knife-edge test offers a way of observing the effect of pumping the air out of the tank (Fig. 4). The photographs made with air in the tank show the image badly distorted by air currents, but the photograph made with no air in the tank is free from this disturbance. The tank can be evacuated to the limiting pressure of the pump, 30 μ, but it is almost impossible to detect any convection currents after the pressure has been reduced to less than 3 or 4 mm.

The lines of natural mercury are sometimes used to test the performance of spectroscopes. Figure 5 is a photograph, taken with the vacuum spectrograph, of the 5461 line.

It was made in the fifth order of Babcock grating No. 96B, and it reveals most of the components of the hyperfine structure.

The lines of iodine provide another group of useful test objects for spectroscopes. The iodine spectrum contains many closely packed double lines in the green part of the spectrum. The four double lines shown near the center of Figure 6 have an average separation of 0.009 A. The ratio of the mean wave length of the lines to their average separation is 600000. The significance of a resolving power of 600000 can be made clearer by comparing a normal tracing of solar lines, as in the top line of Figure 7, with the much

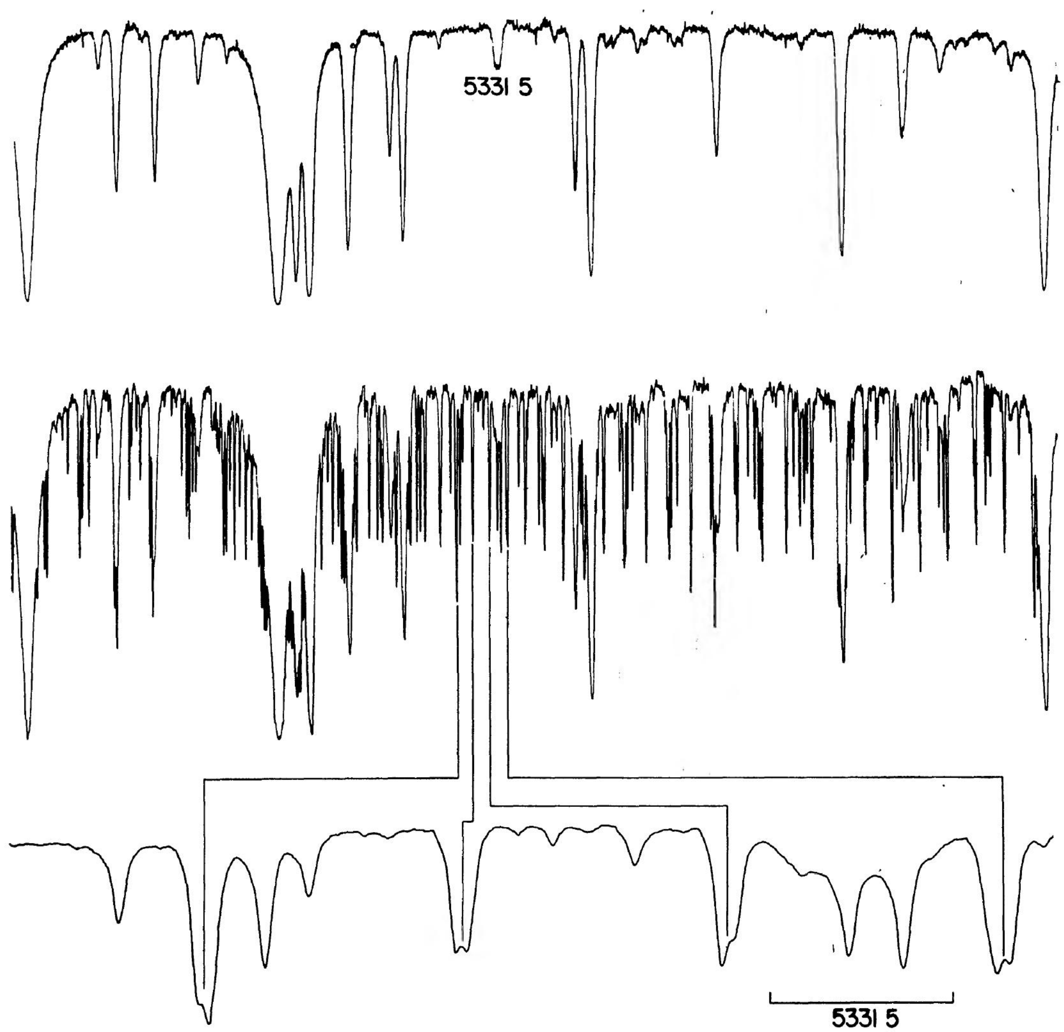

FIG 7.—Direct tracings of solar spectrum and superposed lines of iodine

sharper iodine lines. The second line of Figure 7 shows the same part of the solar spectrum with the absorption lines of iodine superposed. Lastly, on a greatly expanded scale, the resolution of the previously mentioned close double iodine lines is shown. The scale of the last tracing, necessary to show the effects of a resolving power of 600000, can be judged by comparing the 5331 A solar line in the top tracing with the broad depression in the lower right that is the same line.

Figure 8 is a sample photograph of the solar spectrum made with the vacuum spectroscope. The tracing of the photograph reveals the high resolving power in the depth

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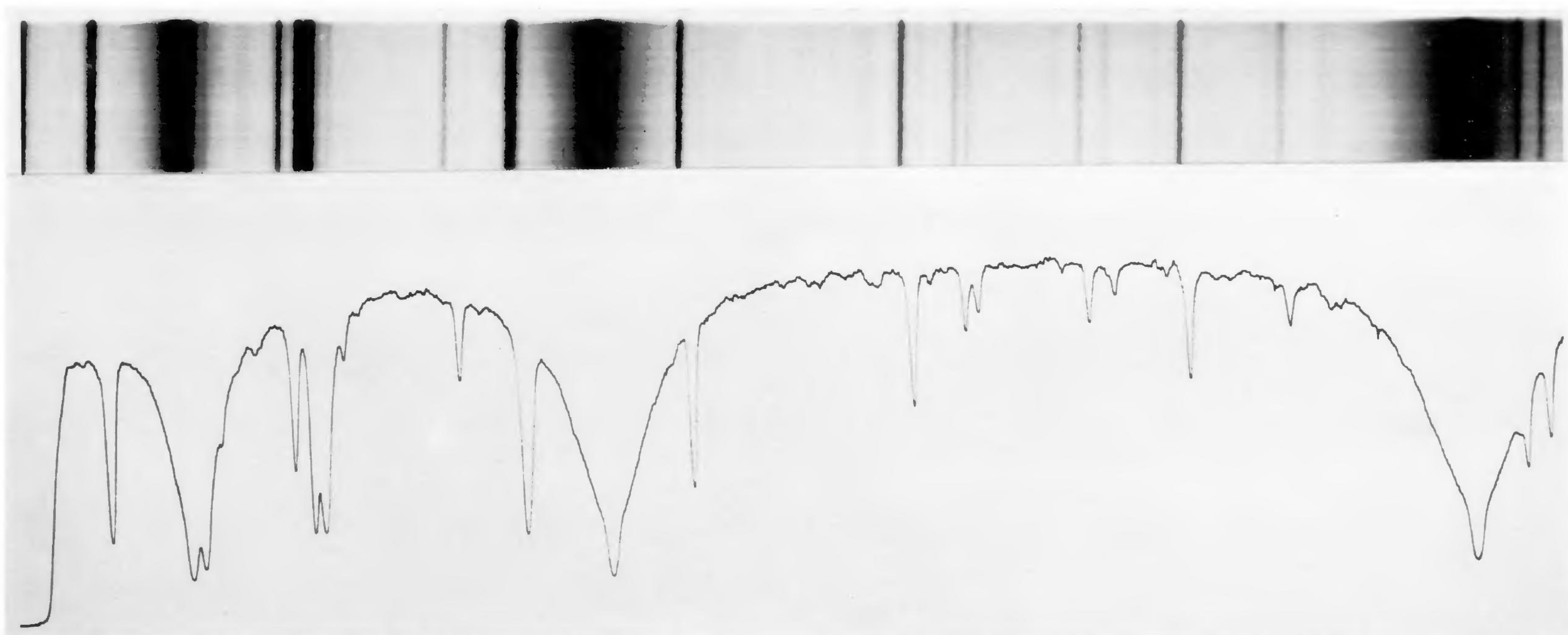

FIG. 8.—Photograph and tracing of magnesium b lines. The variations in the continuous background parallel to the dispersion and the displacements in the absorption lines are real solar features.

and sharpness of the lines of the heavy elements that flank the broad magnesium lines.

It is possible to compare some uncorrected direct photoelectric tracings from the vacuum spectroscope with results from the use of high-resolution instruments in line-profile work by Evans (1940) and Shane (1941). The greatest differences are in the central intensities, and even here the differences average less than 3 per cent (Fig. 9).

The K line of calcium is particularly interesting to all who use the results from spectroheliographs. New material for detailed study of this line can be obtained with the

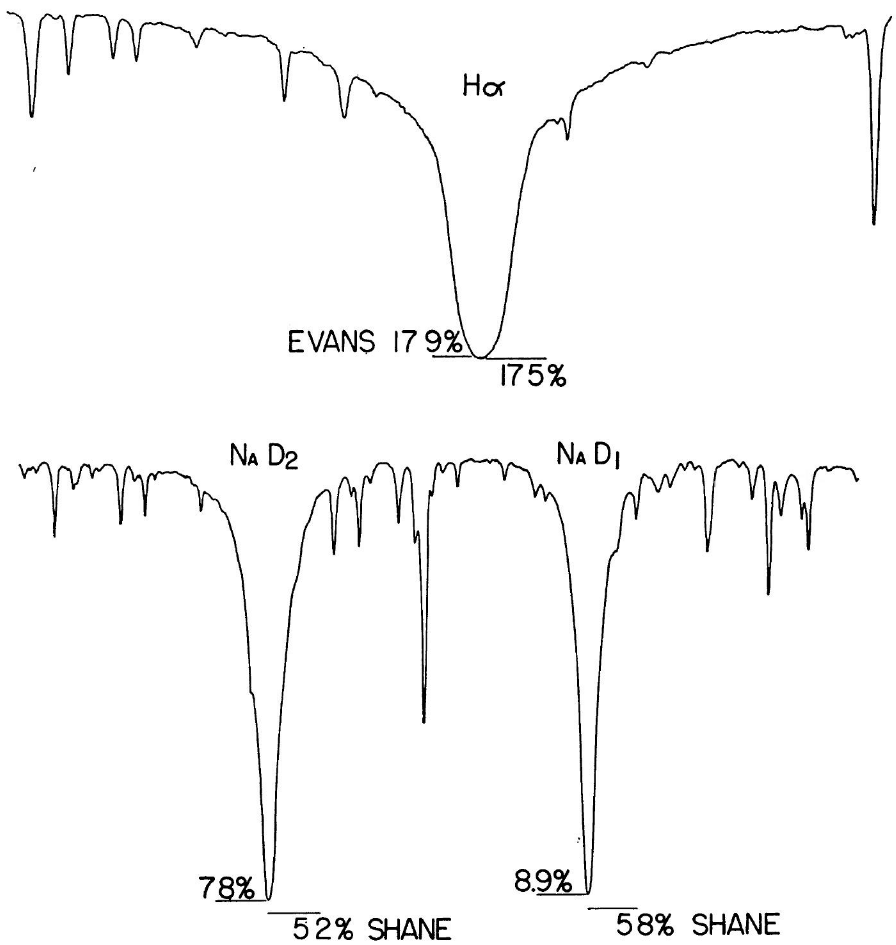

FIG 9 —Direct photoelectric tracings of Hα and the sodium D line

vacuum spectrograph. The complex structure in the center of the line is revealed on a scale that should make precision measurements more easily obtainable than before (Fig. 10).

The programs planned for the vacuum spectrograph are extensive, and our hopes are high. Precision measurements should lead to improvement in abundance determinations. The evaluation of large-scale motions, turbulence, and kinetic temperatures as a function of height can be attempted. Molecular lines and the central intensities of the very strong absorption lines will give clues to the values of these quantities in the outermost solar layers Lines with high excitation potential will be useful for the deeper layers.

Many of the programs for the new instrument will be connected with those of the spectroheliographs in the 50-foot tower. Provision has been made for placing monochromatic features of the sun on the slit of the vacuum spectroscope with the aid of a Lyot filter. Velocity and intensity changes in the spectra of spots, plages, and associated active phenomena will be intensively studied. The vacuum spectroscope will provide observations of higher precision than those previously recorded for large numbers of solar spectrum features. It is hoped that the number and quality of the observations that can be obtained will be of significant help in extending our knowledge of the sun.

The vacuum spectroscope has been a team project, and I could not overstate the contribution which has been made by my colleagues, Drs. Mohler and Pierce. Mr. John Brodie has made every drawing, and our instrument-maker, Mr. Sanderson, has converted the drawings into operating assemblies of steel and nonferrous metals. Everybody without exception in the group at Lake Angelus has helped when needed. The construction of this spectroscope was made possible by generous grants-in-aid by the Arthur Curtis James Foundation, The Detroit Edison Company, and McGregor Fund of Detroit, to whom I offer my grateful thanks.

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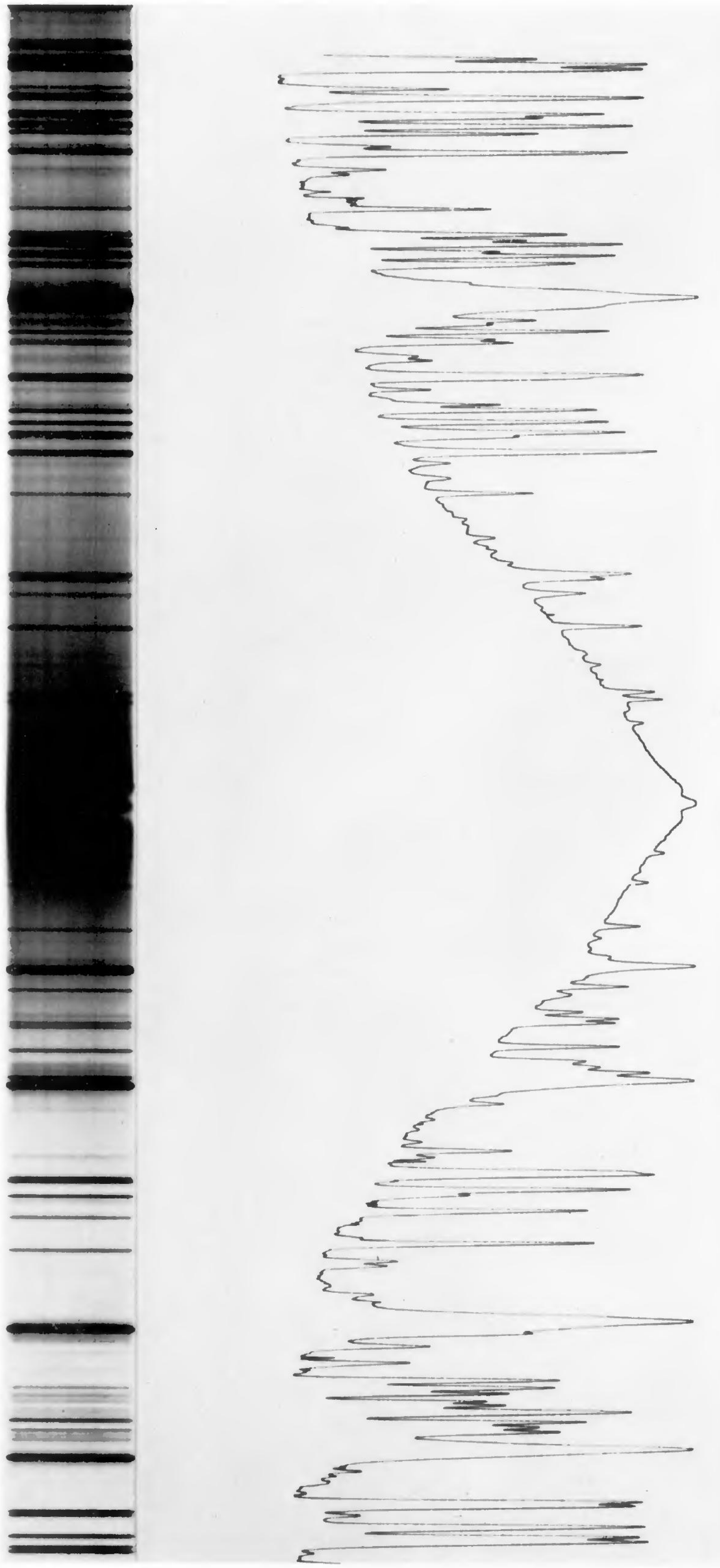


FIG. 10.—Photograph and tracings of the K line of calcium

Studies at the McMath-Hulbert Observatory of Radio Frequency Radiation at the Time of Solar Flares*

HELEN W. DODSON†

Summary—**The complex flare phenomenon is described in terms of its photographic aspect on $H\alpha$ spectroheliograms, associated prominence activity, terrestrial effects, and the general pattern of radio frequency emission. Flare-associated events at 2800 and 200 mc are reviewed, and the association between flares and the onset of 200-mc noise storms is discussed. Records of 2800 and 200-mc radiation at the time of 277 flares are compared. Flare-events at frequencies less than 200 mc are considered, and a study of 496 flares at 80 mc is summarized.**

An effort is made to compare reports of dynamic spectra at radio frequencies with flare data and single frequency records.

The apparently close association between flares with "major early bursts" at frequencies $\lessapprox$200 mc and geomagnetic disturbances is discussed.

Introduction

The long series of photographic records of solar activity at the McMath-Hulbert Observatory of the University of Michigan has made possible, throughout the past eight years, comparison of distinct solar events with concomitant solar emission at radio frequencies. Investigations into the relationships between optical features and radio frequency emissions have been, in large part, cooperative undertakings between staff members of the McMath-Hulbert Observatory, where the optical studies have been made, and staff members of the laboratories primarily devoted to radio frequency observations.

The work reported here stems from close cooperation with the School of Electrical Engineering of Cornell University whose excellent 200-mc solar records have been shared with us since 1950, and with the National Research Council of Canada at Ottawa, where for more than 10 years, A. E. Covington has recorded with great precision solar emission at 2800 mc. The daily 80-mc solar records of the Cavendish Laboratory, Cambridge, England, also have been made available to us and have been examined for the period January, 1949, to August, 1955.

Early in our investigations it became apparent that the complex solar event known as a *flare* was closely associated with many of the great enhancements at radio frequencies. Consequently, a large part of our work has been directed towards determining the general pattern of radio frequency emission at the time of solar flares. On the basis of both optical and radio frequency observations, a "flare" is a complex phenomenon and the interrelationships of its many aspects still are not clearly understood.

* Original manuscript received by the IRE, November 6, 1957.
† McMath-Hulbert Observatory, University of Michigan, Ann Arbor, Mich.

The Complex Flare Phenomenon

Hα and CaII Brightenings

The principal optical aspect of the "flare event," and the one that is both necessary and sufficient at the present time for the identification of the phenomenon, is a relatively sudden increase in intensity of $H\alpha$, CaII, and other monochromatic radiations, in portions of the sun covering 50 to more than 1000 millionths of the solar hemisphere, for time intervals of the order of tens of minutes to several hours. The sudden brightenings generally take place in the bright plages that accompany or surround sun spots. The optical flare may be confined to the region of original brightening or may spread with time to quite distant areas.

Prominence Activity at the Time of the Hα Brightening

Visual and photographic studies also show that flare brightenings frequently are accompanied by certain types of prominence activity. With a small number of flares, a rapidly rising prominence is ejected from a region near the flare during the very early stages of the brightening.[1] These ejections, with velocities of the order if 1000 km are most easily observed as prominences when the associated flares are near the limb of the sun.

A much more usual type of flare-associated prominence is that indicated by the appearance on the disk of active dark flocculi in the postmaximum phase of flares. These primarily dark markings, exhibiting Doppler shifts of the order of a few hundreds of kilometers or less, probably are the disk counterparts of surge-type prominences seen at the limb. Visual and photographic records, made in the center of the $H\alpha$ line, show that many of these active flocculi, during the first minutes of their lifetime, are *brighter* than the undisturbed $H\alpha$ background.

In addition, certain flare-like events near the limb of the sun have shown that systems of very bright loops may develop and increase in size during the course of a flare. Finally, previously existing, relatively quiescent prominences, visible as "filaments" on the disk, may become active, show Doppler shifts, and be either partially or wholly dissipated during, or shortly after, flares in neighboring locations.

[1] H. W. Dodson, E. R. Hedeman, and J. Chamberlain, "Ejection of hydrogen and ionized calcium atoms with high velocity at the time of solar flares," *Astrophys. J.*, vol. 117, pp. 66–72; January, 1953.

Terrestrial Effects of Flares

Certain "terrestrial effects" provide evidence for additional aspects of the complex flare phenomenon. Ionospheric disturbances occur in close time association with a majority of flares and imply an increase in ultraviolet radiation or X rays at the time of the $H\alpha$ brightening. Relationships between certain flares and subsequent geomagnetic storms indicate that at least some flares are accompanied by the actual ejection of material particles which, hours or days later, may impinge upon the earth's atmosphere and cause a geomagnetic storm and an aurora. Finally, there have been great increases in cosmic rays received on the earth within minutes or hours after the occurrence of a small number of great solar flares.

General Pattern of Radio Frequency Radiation at the Time of Solar flares

Examination of daily 2800, 200, and 80-mc records for most of the 8-year interval, including 1949 and 1956, and records published in the literature for intermediate frequencies, has shown that the basic patterns of flare-associated radiation, within this frequency range, are fundamentally similar. At these frequencies, the fully developed flare event exhibits two parts, but either of the two parts may occur separately. With many flares there is no distinctive enhancement at radio frequencies. See Fig. 1.

The first or "early" part of the double pattern is a sudden burst that starts with the $H\alpha$ flare and usually is over by the time $H\alpha$ maximum has been attained. At 2800 and 200 mc, the second part is an enhancement that generally starts more gradually than the first part. At 200 and 80 mc the second part is definitely a "late" component, since it begins after $H\alpha$ flare maximum has been attained and reaches its maximum late in the course of the flare. It may continue long after the $H\alpha$ flare has faded.

Flare Event at 2800 MC[2]

At 2800 mc, the first or early part of the flare-associated event is a sudden single burst which may be either simple or complex in structure. (See Fig. 1.) In general, this burst starts with the onset of the flare and is over by the time maximum intensity has been attained by $H\alpha$ radiation in the flare. For the flares that we have studied, the maximum of the 2800-mc burst precedes $H\alpha$ maximum by an average of 3.4 minutes. Thus, the sudden burst type event at 2800 mc definitely is associated in time with the period of increasing $H\alpha$ intensity in the flare.

The second or late part of the "flare event" at this frequency is a gradual diminution of excess flux. When only the second part of the flare pattern occurs, the distinctive event is classified as a "gradual rise and fall." This type of event at 2800 mc appears to start with the $H\alpha$ flare but has its maximum either at the time of $H\alpha$ maximum, or later.

Our detailed study[2] in 1953 of 2800-mc solar radiation, as recorded at Ottawa, provided strong evidence that there is an outstanding event or disturbance in solar radiation at this frequency only when a flare or subflare is in progress. In recent years, the sensitivity of the Ottawa equipment has been increased, and less intense and more frequent events are reported. Spot checks continue to provide evidence for a very close

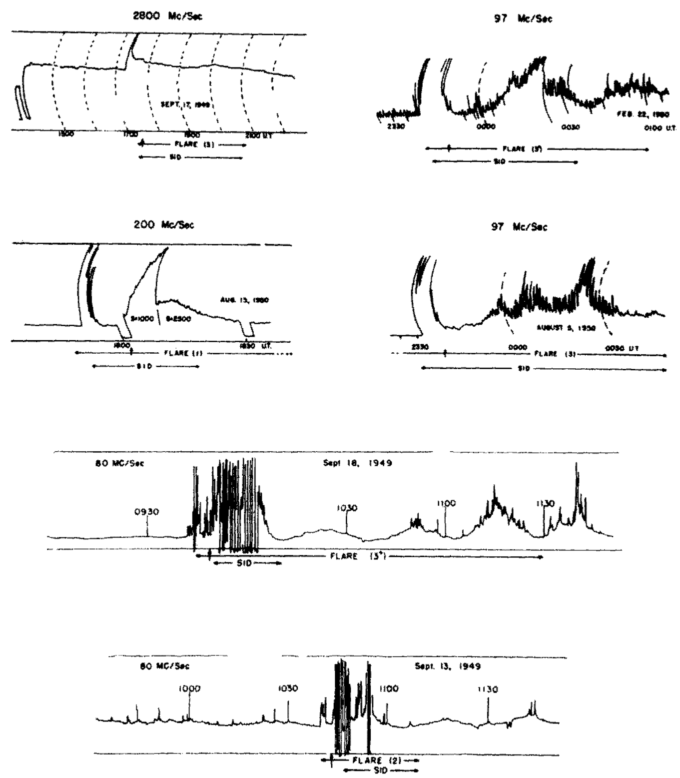


Fig. 1—Examples of 2800, 200, 97, and 80-mc radiation at the time of solar flares. Vertical arrows indicate times of flare maxima. The 80-mc records were made with an interferometer and show maxima and minima in the interference pattern as well as changes in solar emission.

association between 2800-mc events and optical phenomena. For example, on July 24, 1956, the report of 2800-mc outstanding events includes a "group of eight bursts," between $17^h51^m.2$ and 24^h30^m U.T. Even though our calcium spectroheliograms for this date monitored only the large active center in the southeastern part of the solar disk, they showed small temporary brightenings in very close time association with four of the 2800-mc bursts. Ionospheric records, after the close of our photographic program at 2141 U.T., indicated the occurrence of flares with two more of the 2800-mc events. The data are summarized in Table I and an example of the brightenings is shown in Fig. 2(a).

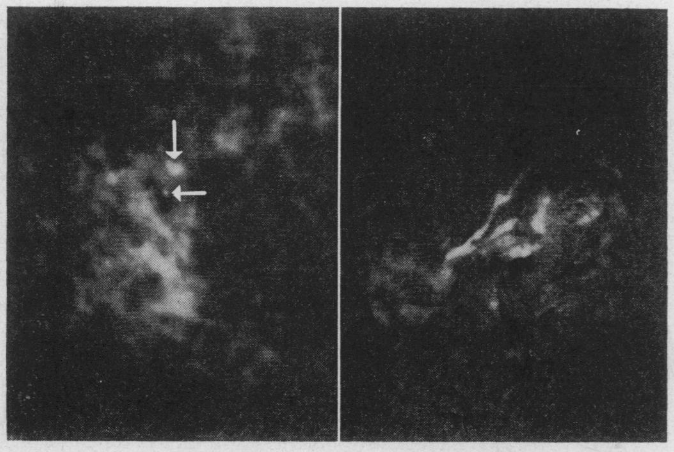
[2] H. W. Dodson, E. R. Hedeman, and A. E. Covington, "Solar flares and associated 2800 mc/sec (10.7 cm) radiation," *Astrophys. J.*, vol. 119, pp. 541–563; May, 1954.

TABLE I

COMPARISON OF A GROUP OF 8 BURSTS AT 2800 MC JULY 24, 1956, (REPORTED BY COVINGTON, OTTAWA, CANADA) WITH CONCOMITANT PHOTOGRAPHIC AND IONOSPHERIC DATA

2800-MC Event			Small Brightenings in Southeastern Plage (Calcium Spectroheliograms)	Flares, as Indicated by Sudden Short-Wave Fades
Type	Time U.T.	Peak Flux 10^{-22}wm^{-2}(cps)$^{-1}$		
Single	1751.2–1752	9	No event in plage photographed	—
Single	1811 –1812	12	1810.5–1814	—
Single-simple	1908.3–1910.8	19	During a small flare, 1854–1920, but probably not associated	—
Single-simple	1934.5–1937.5	24	1934.5–1940	—
Single-simple	2025.8–2027	19	2025.5–2029	—
Single-simple	2048.3–2049.8	15	2048 –2051	—
Single-simple	2156.5–2207.5	*350	No spectroheliograms at these times	2158–2218
Precursor	2230	11		
Single-simple	2233 –2245	200		2237–2303
Post Increase	2245 –>2430	15		

* Estimated.



(a) (b)

Fig. 2—Spectroheliograms showing solar phenomena at the time of certain distinctive events at radio frequencies. (a) Calcium spectroheliogram, 1956 July 24^{d}19^{h}34.^{m}5 showing small round dot over umbra of spot and larger region near it that brightened simultaneously with small 2800-mc burst (see Table I). (b) $H\alpha$ spectroheliogram 1951 June 16^{d}17^{h}27^m showing large flare associated with great increase in 200-mc noise storm.

According to all of our studies there is very close time association between 2800-mc bursts and temporary brightenings visible on $H\alpha$ and Ca$^+$ spectroheliograms.

FLARE EVENTS AT 200 MC[3]

Outburst-Type Phenomena

Starting times of the sudden burst-type features that constitute the early parts of flare events at this frequency cluster closely about the starting times of the flares. The "early burst" generally is over before, or close to the time of, $H\alpha$ maximum. It is unfortunate that the great, early bursts are off scale, and therefore unmeasurable, on almost all of the calibrated records at low frequencies.

The second part of the flare-associated outburst at this frequency often appears to be a great increase in the

[3] H. W. Dodson, E. R. Hedeman, and L. Owren, "Solar flares and associated 200 mc/sec radiation," *Astrophys. J.*, vol. 118, pp. 169–196; September, 1953.

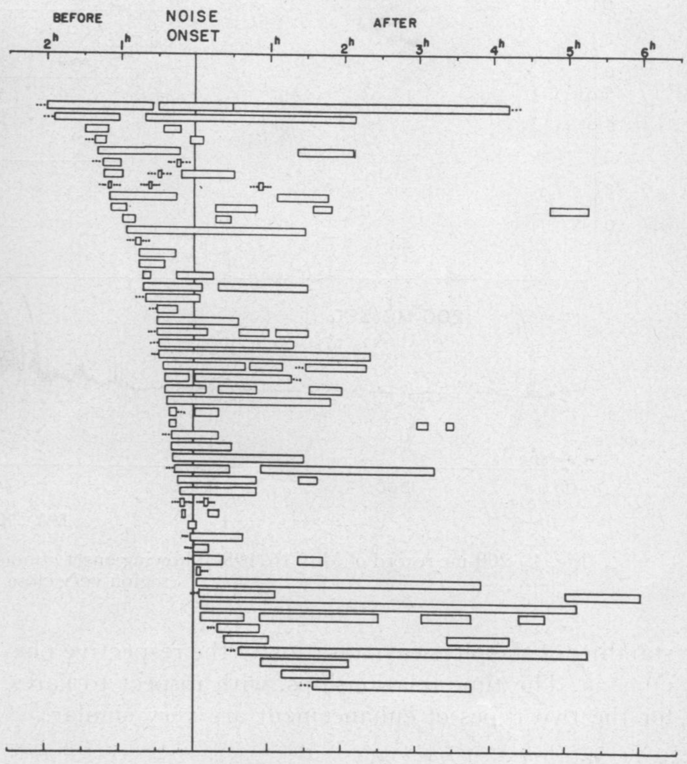


Fig. 3—Comparison of times of onset of 200-mc noise storms with occurrence and duration of $H\alpha$ flares. The vertical line represents the time of start of the noise storm, and each horizontal entry represents a different storm. Small rectangles give the starting times and durations of $H\alpha$ flares. Dots indicate that time of beginning or ending of a flare was not reported.

continuum or base level, without correspondingly great superposed bursts (see Fig. 1). The increase in flux generally starts as the $H\alpha$ flare begins to fade and often lasts long after the $H\alpha$ flare has ceased to be visible as a distinct solar feature. In some cases, the second part of the flare event at 200 mc is a noise storm of long duration with very great burst activity superposed on the increased base level. The relationship between these two types of enhanced 200-mc radiation during the post maximum phase of $H\alpha$ flares must await more information on polarization, dynamic spectra, and better under-

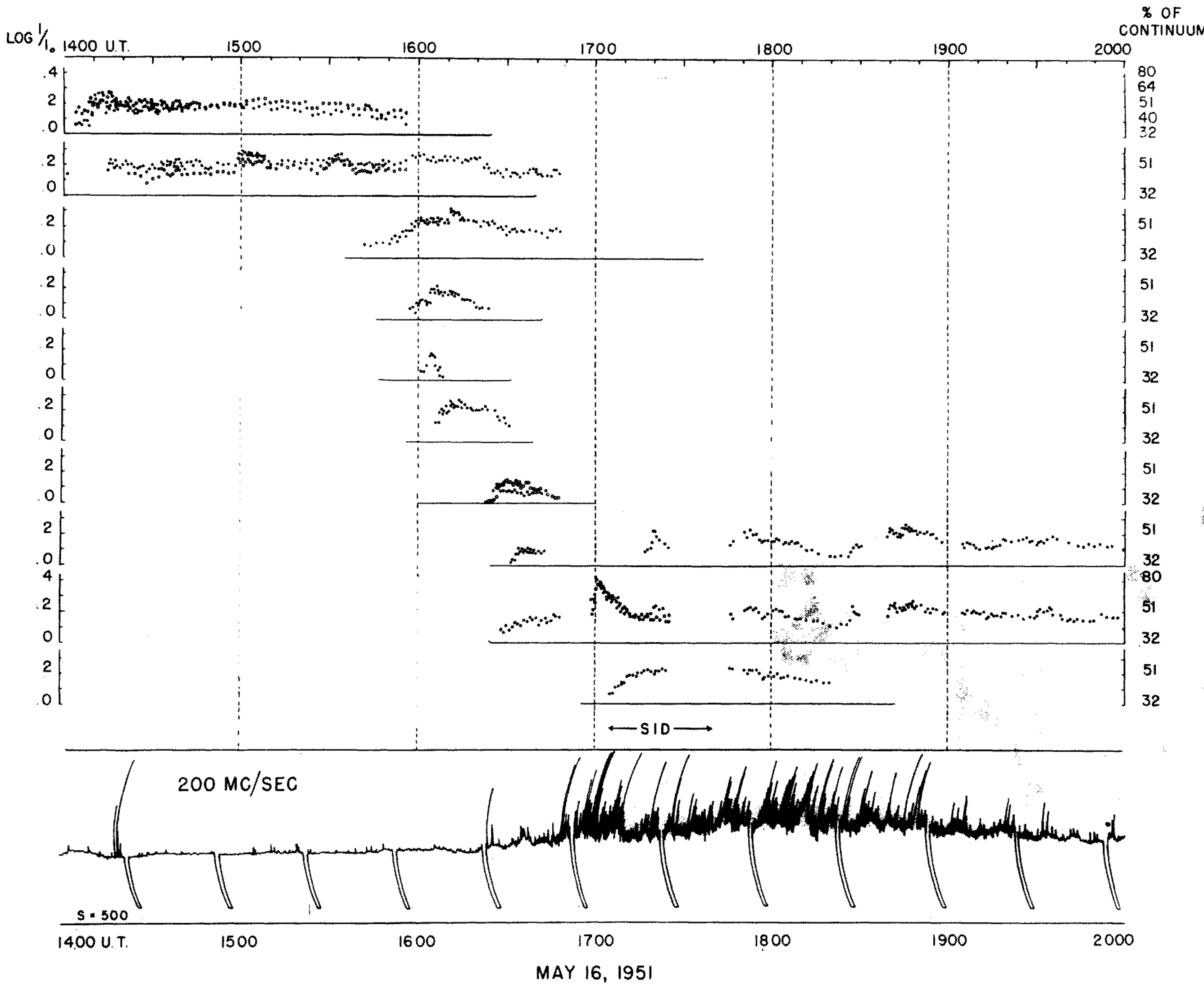


Fig. 4—200-mc record of May 16, 1951, showing onset of noise storm, and photometric light curves for concomitant flares in region very close to central meridian.

standing of the physical causation of the respective phenomena. The time relationships, with respect to flares, for the two types of enhancement are very similar.

Noise Storms

Frequency of Association between Flares and Onsets of Noise Storms: Association of very great bursts, or outbursts, with flares is well established, but the relationship between flares and noise storms at low radio frequencies is considerably less clear. Since this is the case, we have investigated the relationship between flares and *all* noise storms on the 200-mc Cornell records from April, 1950, when the daily 8-hour records were first made, to July, 1953. This study provides strong evidence for an association between flares and the well-defined *onsets* (or well-defined increases) of many noise storms. During this period, the Cornell records show 91 instances of the *beginning* of a protracted period of enhanced radiation of the type described as "noise storm." For 57 of the 91 cases, flares or subflares are known to have been in progress close to the starting times of the 200-mc enhancements. (See Fig. 3, p. 151, for a schematic representation of many of these cases.) In two additional cases, sudden ionospheric disturbances were reported, and for a third, brightenings (possibly of a flare-like nature) in a prominence accompanied the onset of the noise storm. For the times of 29 of the remaining 31 cases we have neither photographic nor visual observations and, therefore, cannot be certain of the solar circumstances. For the final 2 cases, intermittent visual observations were in progress at our observatory but flares were not reported. Thus, for 98 per cent of the recorded *onsets* of noise storms, there were either flares, SID's, or no observations.

The time relationships between the flares and the onsets of 200-mc "noise" in this investigation confirm the earlier study[3] in which "noise storms" were recognized as one of the "late" aspects of the flare-associated event at this frequency.

Characteristics of Flares Associated with Onsets of Noise Storms: Hα flares identified and selected on the basis of their time association with the onsets of 200-mc

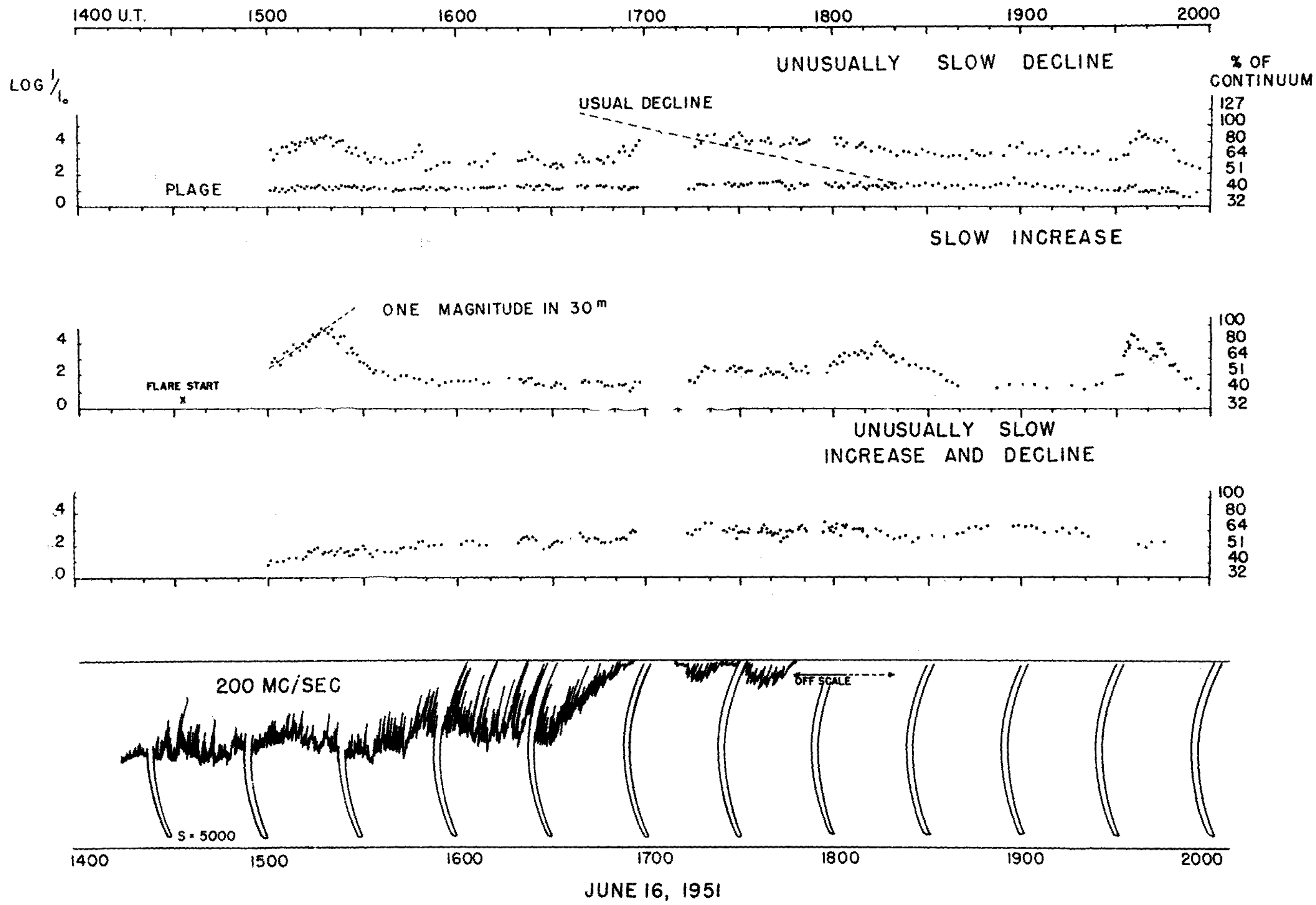


Fig. 5—200-mc record for June 16, 1951, showing a great increase in flux during a noise storm, and photometric light curves for concomitant flares in region 25 east of central meridian.

noise storms present a certain number of common characteristics. First of all, the group contains a high percentage of flares with such a complex structure and assorted brightenings that they do not lend themselves readily to representation by composite, representative light curves. More than half of the flare phenomena associated with the onset of noise storms were what might be termed "multiple flare events," in the sense that at the time of the noise storms several flares, in the same plage, followed each other in close succession. Our photographic records show that the flares were usually brightenings of different parts of the same plage rather than repeated brightenings of exactly the same region as so often happened. The 57 flare-associated noise storms involved a total of 98 separately reported flares. A number of these flares seemed to spread laterally with time, or to break out successively in a number of different regions within the plage. The photometric light curves shown in Fig. 4, for May 16, 1951, illustrate these complexities. The brightenings measured here were reported as 3 flares, each with multiple maxima, and each in a somewhat different part of the plage.

Many of the flares associated with the onsets of noise storms rose to maximum at a relatively gradual rate. The rate of increase of $H\alpha$ intensity was often the slowest of the three general rates of rise found in our photometric study of flares.[4] The rate of decline also was often very slow. The photometric light curves shown in Fig. 5, for the flares of June 16, 1951, illustrate these aspects. The flare at 1500 U.T. on this date was the only flare in our photometric program that reached a maximum intensity as great as that of the continuous spectrum at the slowest of the three rates of rise.

The $H\alpha$ spectroheliogram of the flare of June 16, 1951, shown in Fig. 2(b), illustrates another characteristic of the flares associated with the onsets of noise storms. Frequently the "noise storm flares" must be described by the words patchy, stringy, outlines a dark filament, rather than by the more usual terms compact, clearly outlined, round.

In our photometric study[4] of flares, we have reported that the ionospheric effects of some of the "noise storm flares" were less than the large size and brightness of the flares led us to expect.

Finally, the flares associated with the onset of noise storms showed a higher than average concentration toward the central part of the solar disk. Seventy-eight per cent of the individual flares associated with noise storms occurred within 40° of the central meridian.

[4] H. W. Dodson, E. R. Hedeman, and R. R. McMath, "Photometry of solar flares," *Astrophys. J. Suppl. Ser.*, vol. 2, suppl. no. 20, pp. 241–270; February, 1956.

However, our study[5] of 2295 flares in the *Quarterly Bulletin* has shown that, in general, only 53 per cent of reported flares are observed in this portion of the solar disk.

Center-To-Limb Effect in Noise Storms: If it be assumed that the positions of flares associated with the onsets of noise storms provide information about the location of the source of enhanced 200-mc radiation, then a center-to-limb effect can be found in the relative intensities of continuum and superposed bursts.[6] When the flares were within 25° of the central meridian, the amplitude of the superposed noise storm bursts generally was less than the intensity of the continuum. For flares between 25° and 50° CMD, there were as many cases with burst amplitude greater than the continuum as the reverse. When the flares were more than 50° from the central meridian, the amplitude of the bursts was greater than the intensity of the continuum for more than 90 per cent of the cases. This variation from center-to-limb in relative intensity of storm-base-level and burst amplitude suggests that the two aspects of a noise storm may originate at different levels in the solar atmosphere. It also should be pointed out that the identification of the noise-emitting regions by associated flares indicates that 200-mc "storm" radiation is received from active regions at all meridian distances, even from regions on the solar limb.

The foregoing investigations have shown that the great, well-defined *onsets* of noise storms often take place when flares are in progress, or just over. Furthermore, near solar minimum in 1954, enhanced 200-mc radiation of the noise storm type occurred during the transit across the solar disk, of all regions in which flares were observed, but not during the transit of all bright calcium plages, nor of all regions with strong green coronal emission.[7] In spite of this evidence for a close association between flares and 200-mc noise storms, we have also found that there were, during the interval studied, certain very long periods of greatly enhanced 200-mc radiation for which the concomitant flare occurrence was relatively low. These cases must be studied further.

Comparison of 2800-MC and 200-MC Radiation at the Time of 277 Flares

Morphology of the Events

In order to permit direct comparison of flare-associated emission at 2800 and 200 mc, we have brought together data for the 277 flares between August, 1948 and June, 1952 for which the two radio records were available to us for study.

For about 60 per cent of the flares, the general patterns of the radio frequency events at the two frequencies were basically similar, in the sense that flares that had "double" events at one frequency, had "double" events at the other, or only "early," or only "late" phenomena, respectively. Of the 163 flares for which there was no distinctive event at 2800 mc, 63 were also "null" at 200 mc and 52 more were associated with only very low energy or poorly defined events at the lower frequency. For the remaining 40 per cent of the flares, there were gross differences in the flare events at the two frequencies.

Time Relationships

For flares with "early," burst-like features at the two frequencies, the starting times of the bursts were very similar. The average difference was only 0.3 minute, and in the sense that the 2800-mc burst preceded the 200-mc burst. It should be remembered that, at best, we have been able to determine times only to the nearest tenth of a minute and that we are comparing records made at different institutions with different types of instruments.

The second or "late" parts of the flare events have a much greater difference in time of onset at the two frequencies than do the "early" parts. At 2800 mc, the second part apparently starts with the flare itself, or while the "early" burst is still in progress. At 200 mc the "second" part often is well separated from the first, and its onset usually does not occur until after flare maximum has been passed. In the second part of the flare event at radio frequencies, the longer wavelength radiation apparently lags behind the shorter.

Basically Similar Flare Events at the Two Frequencies

Direct comparison of flare-associated, distinctive events at the two frequencies is easiest when the events are the simplest. Often the single, and single-simple bursts at 2800 mc apparently mesh exactly with comparable events at 200 mc. There are even certain cases, though much rarer, when the "gradual rise and fall" at 2800 mc has a similar counterpart at 200 mc. See Fig. 6.

When the flare-associated bursts are more complex, even though the events may be similar in basic pattern at the two frequencies, they will often differ greatly in detail. To illustrate these complexities, we show in Fig. 7 the photometric $H\alpha$ light curves, and the 2800 and 200-mc records for three flares of importance 2. It is hoped that in the future information from dynamic spectra will permit us to identify, on records such as these, the various spectral types of radio bursts, and the harmonics of lower frequencies. This information may make possible a clearer understanding of the significance of radio frequency emission at the time of flares.

[5] L. Goldberg, H. W. Dodson, and E. A. Müller, "The width of $H\alpha$ in solar flares," *Astrophys. J.*, vol. 120, pp. 83–93; July, 1954.

[6] H. W. Dodson, "Relation between Optical Solar Features and Solar Radio Emission," IAU Symp. IV in "Radio Astronomy," ed. H. C. van de Hulst, Cambridge University Press, Cambridge, Eng., pp. 327–333; 1957.

[7] H. W. Dodson and E. R. Hedeman, "Resume of visually and photographically observed solar activity at time of 200 mc/sec noise storms near 1954 solar minimum," *Astrophys. J.*, vol. 125, pp. 827–830; May, 1957.

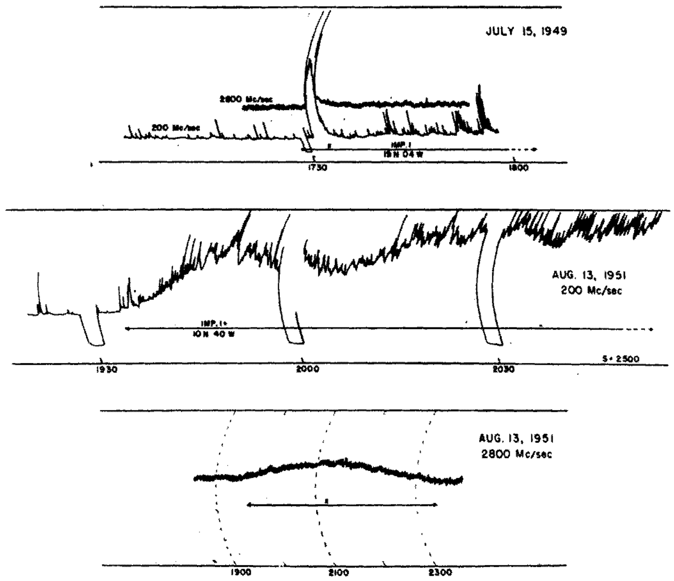


Fig. 6—Examples of "similar patterns" of flare-associated radiation at 2800 and 200 mc. Cross indicates time of flare maximum.

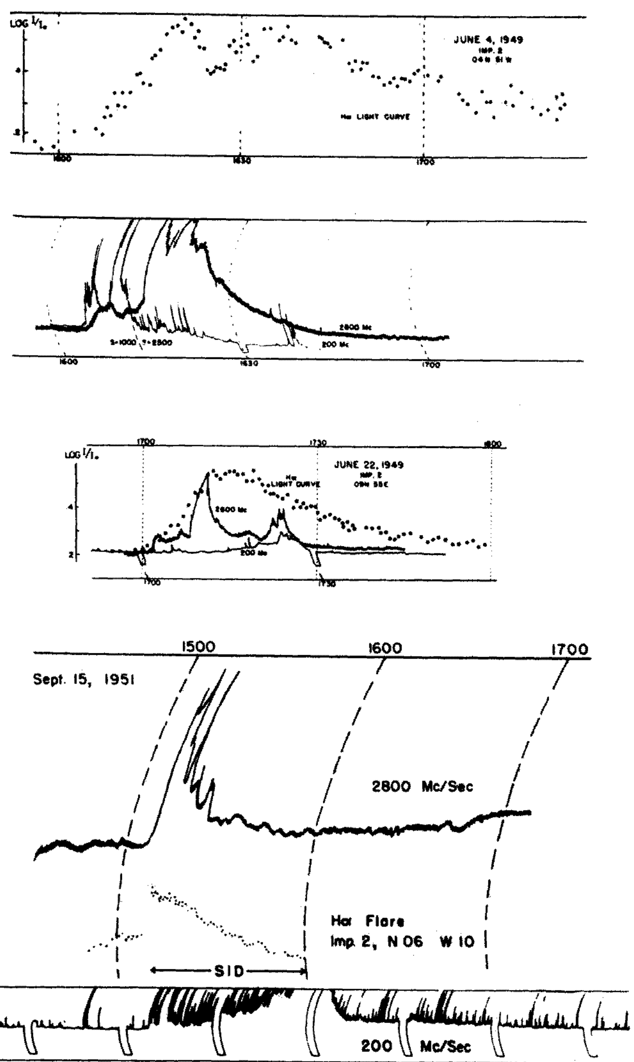


Fig. 7—Examples of complex flare events at 2800 and 200 mc and photometric light curves of concomitant *Hα* flares. Note change of sensitivity in 200-mc record for June 4, 1949.

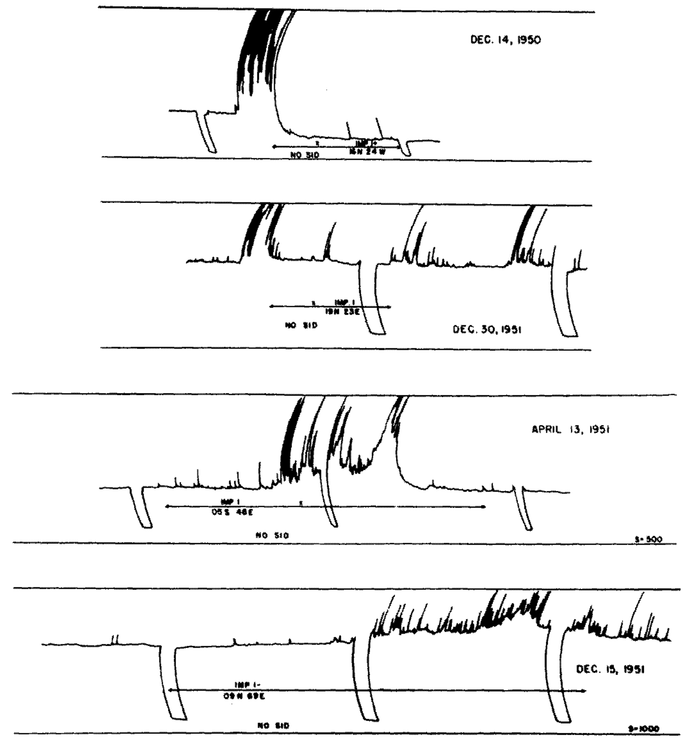


Fig. 8—Examples of 200-mc radiation at the time of flares for which there was no distinctive event at 2800 mc. The first two cases are premaximum events and the last two are primarily post-maximum. Crosses indicate time of flare maximum. Time scale is given by "dummy load" at 30-minute intervals.

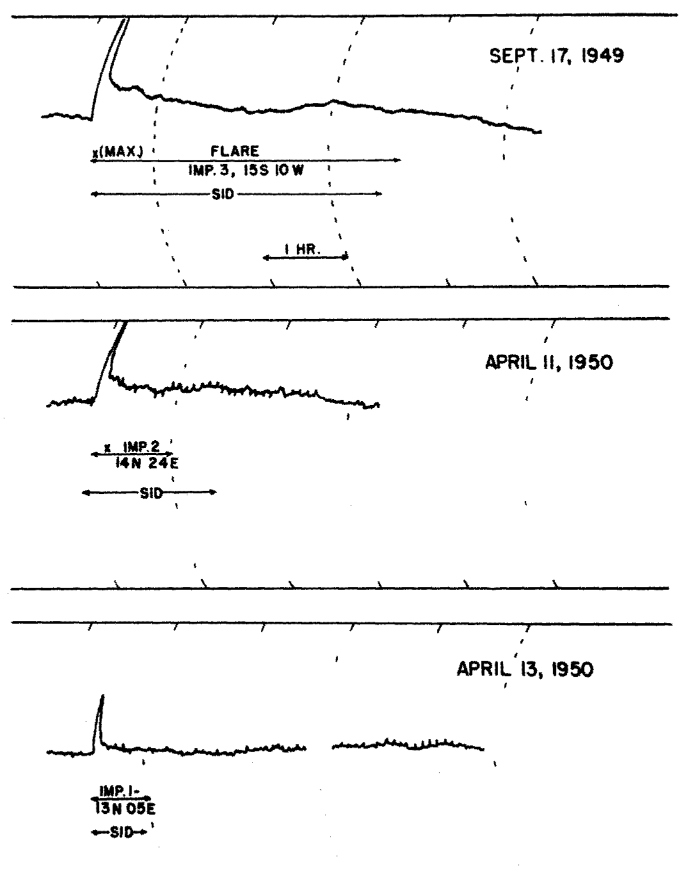


Fig. 9—Examples of 2800-mc radiation at the time of flares for which there was no distinctive event at 200 mc. Cross indicates time of flare maximum.

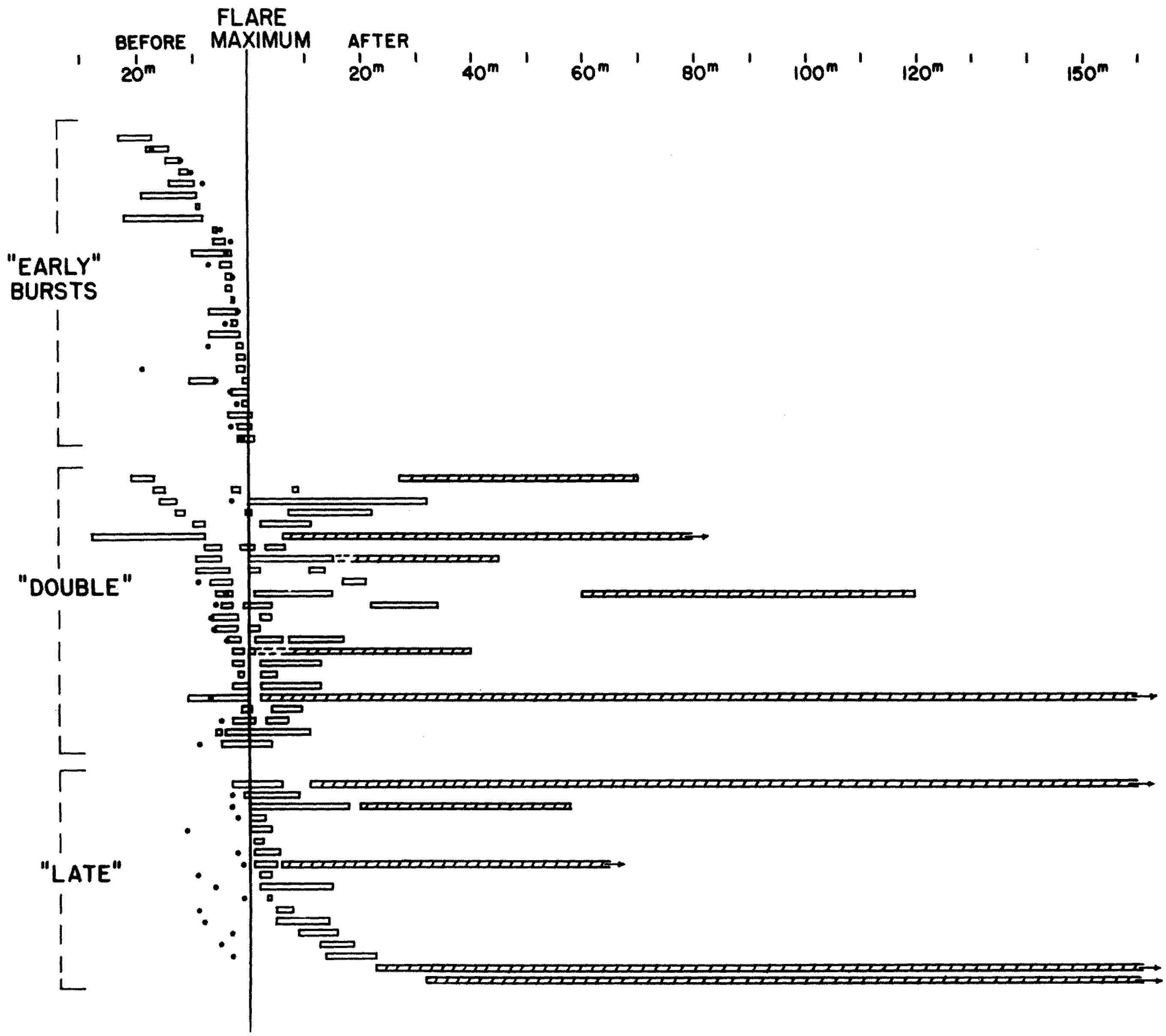


Fig. 10—Time relationships between 80-mc events and $H\alpha$ flares. The vertical line represents the time of flare maximum. A dot gives the time of start of the flare, if known. Each horizontal entry represents, schematically, distinctive events on the 80-mc interferometer records of the Cavendish Laboratory at the time of a flare. The open rectangles indicate "noise storms." All flares in our study for which time of maximum was reported are included in the diagram.

Basically Different Events at the Two Frequencies

Differences between the two frequencies perhaps can be seen most clearly if our attention is drawn to flares for which there was a well developed event at one frequency and no evidence for distinctive, flare-associated emission at the other.

Of the 277 flares in the study, there were 100 flares for which we found no enhancement at 2800 mc, but for which there was evidence of an event at 200 mc. Of these 100 flares only two were of importance greater than one, and only 11 were accompanied by reported ionospheric disturbances. At 2800 mc, a high percentage of important flares have distinctive events and many of the less important flares do not. At 200 mc, the occurrence of flare-associated emission correlates much less closely with the importance of the $H\alpha$ flare. Fig. 8, p 155, shows four examples of 200-mc emission at the time of flares for which there was no concomitant enhancement at 2800 mc.

The converse group, null at 200 mc but with distinctive events at 2800 mc, is small and includes only 15 flares from our set of 277. However, a high percentage of this 200-mc "null" group were important flares, with reported ionospheric disturbances. Fig. 9, p. 155, shows three examples of 2800-mc emission at the time of flares for which there was no enhancement at 200 mc.

Frequencies Lower than 200 MC

Double Pattern

Our direct information on flare-associated radiation at frequencies lower than 200 mc comes from examination of the 80-mc data, Cavendish Laboratory, for 1949–1955, from 18-mc bursts recorded July–October, 1957, on the IGY Indirect Flare Detector, McMath-Hulbert Observatory, and from inspection of occasional records published in the literature. At the lower end of the radio frequency spectrum, the "early" and "late" aspects of the flare-associated radiation apparently are still present. (See Fig. 1 and Fig. 10, pp. 150, 156.)

There is some indication that the "late," postmaximum, part of the event at low frequencies is relatively greater, in comparison with the "early" part, than is the case at higher frequencies.

Furthermore, the 80-mc records show that during the postmaximum phase of some flares there may be, at this frequency, two types of enhanced emission. At, or immediately following, $H\alpha$ maximum of certain flares there is a very great increase in flux, with duration of the order of tens of minutes. This great event, in turn, is followed by a protracted period of "storminess" with above average flux and many superposed bursts; see Fig. 1 and Fig. 10. This flare pattern, which perhaps should be called "triple" rather than double, is more obvious on the single-frequency traces at 80 mc than on comparable records at 200 mc. Fig. 10 shows schematically time relationships between 80-mc bursts and all $H\alpha$ flares in our study for which the time of flare maximum was reported.

TABLE II

PERCENTAGE OF FLARES IN DIFFERENT IMPORTANCE CATEGORIES WITH DISTINCTIVE EVENTS AT 80 MC

Flare Importance	Number of Flares		Percentage of Flares with 80-MC Event
	With 80-MC Event	"Null"	
1	145	176	45
1+	59	34	63
2	42	21	67
3	9	1	90
(?)	(6)	(3)	—
Total	261	235	53

TABLE III

PERCENTAGE OF FLARES AT DIFFERENT DISTANCES FROM THE CENTRAL MERIDIAN WITH DISTINCTIVE EVENTS AT 80 MC

CMD	Number of Flares		Percentage of Flares with 80-MC Event
	With 80-MC Event	"Null"	
0°–10°	40	26	61
11°–20°	31	27	53
21°–30°	40	18	69
31°–40°	38	45	46
41°–50°	32	32	50
51°–60°	29	28	51
61°–70°	21	22	49
71°–80°	13	21	38
81°–90°	13	16	45
(?)	(4)		
Total	261	235	53

80-MC Data

The 80-mc records at the Cavendish Laboratory were examined for the times of 791 flares. The equipment was not in use for the times of 260. The record was "confused" because of instrumental adjustments, calibration, or polarization measures at the time of 35 more. For the remaining 496 flares, there was evidence on the records for a distinctive event at the time of 261 flares, and no such event for 235. It should be pointed out that the 80-mc records were, in general, unmonitored interferometer records. Because they were unmonitored, a certain number of cases of terrestrial interference have undoubtedly been falsely identified as solar events. Because they are interferometer records, a certain number of flares have been designated incorrectly as "nulls" since their 80-mc emission may have occurred during the minimum in the interferometer pattern.

There were distinctive events on the 80-mc records at the times of flares in all importance categories and at all central meridian distances. Sometimes the events were very great and sometimes they were only small isolated bursts near the start of the flare. The percentage of flares with distinctive events *increased* with increasing flare importance, and *decreased* with increasing distance from the central meridian. See Table II and Table III.

It is questionable whether or not some of the lesser solar bursts here assigned to concomitant flares are, in truth, flare associated. However, until more is known about spectra, polarization, or location of source, they have been included as flare events on the "circumstantial" evidence of time association.

COMPARISON OF DYNAMIC SPECTRA WITH SINGLE-FREQUENCY DATA FOR FLARES

The writer has not yet been able to study in detail a large number of flares with both single-frequency records and dynamic spectra. Nevertheless, certain relationships are beginning to emerge from the available data. According to the 1955–1956 *Quarterly Bulletin*, the Type III burst, with its rapid drift from high to low frequencies, is a very usual event when the sun is active. Single bursts of this type, or groups of them, apparently occur very close to the starting times of certain flares. This statement is based on: 1) evidence made available to us by Haddock for a small number of cases recorded by the recently completed University of Michigan Solar Radio Spectrograph at the time of flares observed at the McMath-Hulbert Observatory, and 2) comparison of *Quarterly Bulletin* radio-frequency and flare data for January, 1955, to June, 1956. In the latter comparison, direct flare reports were supplemented by data from 3750-mc bursts, on the assumption that 3750 mc resembles 2800 mc in its close flare association.

Type II bursts, with their much slower drift from high to low frequencies, apparently are relatively rare. Wild reported to the *Quarterly Bulletin* only 20 cases of

Type II bursts during the same 18 months in which he reported more than 1000 Type III events. Type II bursts seem to be closely associated with $H\alpha$ flares. On the basis of evidence currently available to the writer, they tend to occur in the postmaximum, rather than in the premaximum stages of the flare.

Unfortunately, there are only very few flare or ionospheric observations available for comparison with the 20 cases of Type II bursts in the tables of the *Quarterly Bulletin.* However, by again assuming that a burst at 3750 mc provides indirect data on starting (and maximum) times for $H\alpha$ flares, we have prepared the diagram in Fig. 11. This graph gives data for the 13 cases for which direct or indirect flare information could be located. It shows that in each case, the Type II burst, within the frequency range 240–40 mc, began from 1 to 21 minutes after the flare and/or 3750-mc burst. For the two cases for which the time of maximum of the $H\alpha$ flare is known, the Type II burst definitely was a postmaximum event. These results are in agreement with our earlier study of Type II bursts.[6,8] Type III bursts also are shown in the diagram in Fig. 11 whenever they too occurred. Wild[9,10] already has pointed out that many of the radio-frequency bursts are flare associated and that Type II bursts frequently follow Type III bursts and, in turn, are sometimes followed by a long period of storminess (Type I). This apparently triple phenomenon is clearly shown in certain of the 80-mc records at the time of flares. See Fig. 1 and Fig. 10.

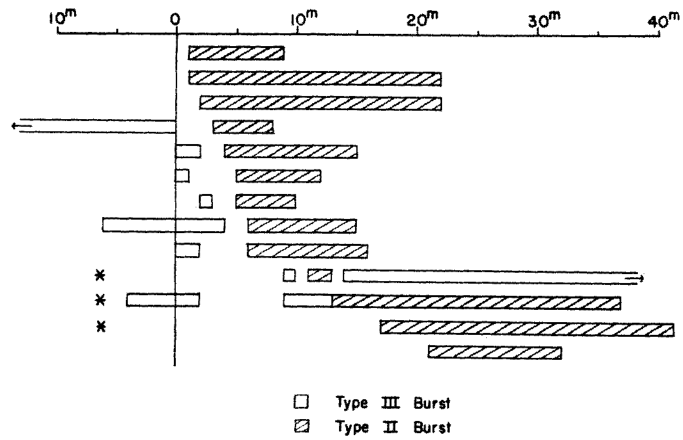


Fig. 11—Comparison of start of flares (or 3750-mc bursts) with Type II bursts reported in *Quarterly Bulletin,* January 1, 1955, to June 30, 1956. Type III bursts also are shown. The vertical line gives time of start of $H\alpha$ flare and/or 3750-mc burst. Asterisks show cases for which $H\alpha$ flare was observed. No data available for 7 of the 20 Type II bursts.

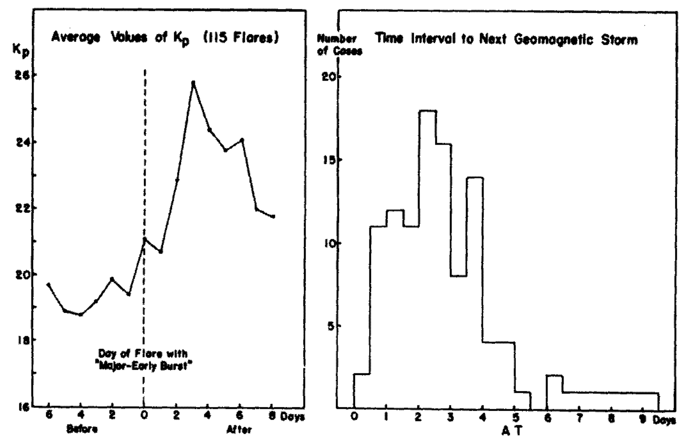


Fig. 12—Geomagnetic effects of flares with "major early early bursts" at frequencies $\lesssim$200 mc.

Geomagnetic Disturbances Following Flares with "Major Early Bursts" at Low Radio Frequencies

Radio frequency records at the time of solar flares not only provide new data that may lead to increased insight into the flare phenomenon, but they also give information that may help to identify the flares that are associated with geomagnetic storms. During our day by day examination of the Cornell 200-mc solar records, it was observed that flares with sudden bursts of great magnitude during the premaximum phase of the flare frequently were followed within one to four days by sudden-commencement geomagnetic storms. Conversely, certain important flares (importance 2+ or 3) without such "major early bursts" at 200 mc were not followed by geomagnetic disturbances.

In order to test these ideas, we have investigated the possible geomagnetic effects of all flares, using world-wide data, between January, 1949, and April, 1956, for which we had positive evidence of a "major early burst" at frequencies $\lesssim$200 mc. In this study, we tried to include only flares with premaximum bursts of duration $\gtrsim$2 minutes and for which the intensity was very great. The study showed that flares with these great, premaximum events are relatively rare (115 cases) and that flares with such radio frequency emission indeed are followed by geomagnetic storms in a high percentage of cases. (See Fig. 12.) According to this study, the average time interval between the occurrence of flares with "major early bursts" and onsets of the next geomagnetic storms is about two and a half days, a time interval considerably longer than that usually given in studies of solar-terrestrial relationships. It should be pointed out that the study exclusively referred to the declining branch of the sun spot cycle and included small as well as great storms. These factors may be playing a part in the above time relationships, but the evidence for such a situation is not strong within the study itself.

The average time of two and one-half days between flare and start of storm, as found by the foregoing study, makes it very tempting to try to identify the ejection of

[8] H. W. Dodson, "The relation between observed solar features and solar radio emission," *Proc. NEC,* vol. 11, pp. 498–505; October, 1955.
[9] J. P. Wild, "Radio Observations of Solar Flares," Trans. IAU, ed. P. Th. Oosterhoff, Cambridge University Press, Cambridge, Eng., pp. 661–663; 1957.
[10] J. P. Wild, "Spectral Observations of Solar Activity at Metre Wave-Lengths," IAU Symp. IV in "Radio Astronomy," ed. H. C. van de Hulst, Cambridge University Press, Cambridge, Eng., pp. 321–326; 1957.

the storm-producing particles with the occurrence of the slowly drifting, flare-associated Type II bursts at radio frequencies. For Type II bursts, the inferred particle velocity is ~300–700 km, corresponding to travel times from sun to earth of 2–5 days.[9,10] Future work may show that the above association is true. However, on the basis of present information, such an association is not yet justified. First, the 115 flares in the geomagnetic study[11] here considered were selected on the basis of a great *premaximum* burst, whereas Type II bursts, in the range 240 to 40 mc, as reported to date (through June, 1956, *Quarterly Bulletin*) are primarily postmaximum phenomena. It is true that many of the flares with major early bursts also had "late" components which indeed may have been Type II phenomena. Future studies should permit discrimination between the several parts of the flare event at radio frequencies and should provide clarification of these points. However, we do know that certain flares of importance 3, with only "late" components in their radio frequency emission, were not followed by geomagnetic storms within a small number of days.

Secondly, geomagnetic events following the 20 cases of Type II bursts reported through June, 1956, in the *Quarterly Bulletin* do not suggest an unusually close (or suitable) association between these phenomena and subsequent geomagnetic storms. The time interval between each reported Type II burst and the next geomagnetic storm is shown in Table IV. For certain bursts, a second time interval is also given, since particles moving with velocities of ~300–700 km per second do not readily lend themselves to association with geomagnetic storms that begin within less than two days after the time of the burst.

TABLE IV

TIME INTERVAL BETWEEN REPORTED TYPE II BURSTS AT RADIO FREQUENCIES AND START OF NEXT GEOMAGNETIC STORM. JANUARY 1, 1955–JUNE 30, 1956

Date and Time of Burst		Intensity	Δt*
1955			
February 24	0104–0124	strong	3^d21^h
June 9	0001–0033	weak	13 10
June 15	0400–0408	weak	7 6
June 21	2329–2354	strong	0 11 (10^d16^h)
July 5	0215–0224	strong	6 22
July 7	0206–0213	moderate	4 22
September 10	0509–0520	weak	1 20
September 19	0152–0202	weak	7 23
November 15	0441–0505	weak	0 01 (2 22)
November 15	2205–2208	moderate	2 04
November 18	0242–0252	moderate	1 11 (13 06)
November 24	0442–0513	moderate	7 05
November 30	0544–0549	moderate	1 03 (5 16)
1956			
January 16	0031–0049	moderate	1 22 (3 07)
January 19	0026–0031	strong	2 17
February 14	0555–0620	strong	4 20
March 8	0321–0342	strong	1 18 (12 08)
April 25	2348–2419	weak	0 21 (2 17)
May 16	0007–0039	moderate	4 06
May 30	{2331–2333 2351}	moderate weak	0 22 (14 20)

* When the time to the first succeeding storm is $\lessapprox 2^d$ the time to the next storm is given in parentheses.

CONCLUSION

Our studies have provided growing evidence that the flare mechanism is in some way intimately associated with much of the transient activity at radio frequencies. Either flares themselves or a stage of development of an active center such that flares can occur may be a necessary circumstance for the emission of greatly enhanced solar radiation at radio frequencies.

[11] H. W. Dodson and E. R. Hedeman, "Geomagnetic disturbances associated with solar flares with major premaximum bursts at radio frequencies $\lessapprox 200$ mc/s," *J. Geophys. Res.*, in press, March, 1958.

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