

CHARACTERISTIC FEATURES OF SOLAR PROMINENCES¹

By EDISON PETTIT

ABSTRACT

Spectra of prominences.—An objective-grating spectrogram taken at the eclipse of June 8, 1918, by Anderson and Babcock shows the prominences without the overlapping flash spectrum. The results of measures on this spectrogram are given in a table of wave-lengths and intensities. These data show that, with two exceptions, all the lines in the flash spectrum brighter than 30 on S. A. Mitchell's scale are found in prominences; 14 lines fainter than intensity 30 are also found, all of temperature classes III–V. "Metallic" prominences show all the lines in Mitchell's table brighter than 15, except those of ionized barium. Save in brilliancy there is probably no real difference between the spectra of common and metallic prominences.

Forms of prominences.—Prominences may be divided into five classes: (1) active, (2) eruptive, (3) spot, (4) tornado, and (5) quiescent, each of which is illustrated. An examination of prominences of classes 1, 2, and 5 in projection on the disk, combined with their appearance at the limb, shows them to be in form like sheets of flame standing on edge. The larger prominences are connected with the chromosphere only at intervals along the lower edge through columns like the roots of a tree.

Dimensions.—The thickness of prominences varies from 6000 to 12,000 km. The length as projected on the disk is seldom less than 60,000 km or greater than 600,000 km. A height of 50,000 km is quite common, and eruptive prominences have been known to reach a height of two-thirds of a solar diameter. The volume of a prominence is often of the order one hundred times that of the earth.

Masses of prominences.—After suitable correction of the observational material, the work of Pannekoek and Doorn shows that an ordinary prominence has a hydrogen content of 2×10^{23} atoms per cubic centimeter. The calcium content is negligible. On this basis a representative prominence 10,000 km thick, 200,000 km long, and 50,000 km high would have the mass of a cube of water 15 km on an edge. The mass of the largest prominence on record, that of May 29, 1919, would be about four times as much.

Distribution of the elements.—Comparison of both *H α* spectroheliograms and drawings made at the spectrohelioscope in *H α* with spectroheliograms in *K $_2$* shows that the forms of prominences in these two lines are essentially the same. An examination of the eclipse spectrum extends this conclusion to other lines. The absence of certain streamers and faint clouds from the *H α* observations may be due to instrumental conditions. There is, however, some reason to suppose that the effect may be real, since an electrical field would produce just this result. Disturbances in the corona about prominences are perhaps evidence that the *Ca⁺* atoms attract the electron streams in the corona.

Motions in eruptive prominences.—The principle of uniform motion modified by sudden increases in velocity already found was tested (1) by a review of the best examples already given, (2) by an examination of new material published by other observers, (3) by new material obtained for the purpose, and (4) by examining the impartiality of the measurements. The conclusion is that this principle of motion in eruptive prominences is real.

Light-pressure.—If light-pressure is operative in producing the motion, the Doppler effect which separates the absorption lines of the prominence from the corresponding absorption lines of the photosphere should also produce a separation of the hydrogen and calcium atoms. No separation of this kind was observed, however, in the eruptive prominence of August 6, 1931.

Expansion of eruptive prominences and the coronal density-gradient.—It is shown that the density of the prominence of August 6, 1931, followed the law $d \approx R^{-6}$, and also that

¹ Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington, No. 451.

the density of the corona follows the same law. The expansion of the prominence therefore keeps its density in step with that of the corona.

Tornado prominences.—These small objects are of the order 5600–22,000 km in diameter and 25,000–97,000 km in height. A case is reported in which the angular velocity became so high that the vortex exploded. No lateral motion over the solar surface has been observed.

Quiescent prominences.—Detailed measures of condensations appearing in a quiescent prominence revealed a continuous internal turbulence with velocities ranging up to 15 km/sec.

Height of the chromosphere in H α .—The height of the chromosphere was measured with the spectrohelioscope on several days of good definition and found to be 5500 km. This value is a little less than that found visually with the spectroscope.

Previous papers¹ describe an attempt made at the Yerkes Observatory to determine the characteristics of the forms and motions of the prominences. The present paper, which may be considered an extension of these early studies, is based on data obtained in part at Mount Wilson and in part at the Yerkes Observatory. The equipment available for this work has been the Rumford spectroheliograph attached to the 40-inch telescope at Yerkes, made available through the kind invitation of Professor E. B. Frost, the 13-foot spectroheliograph and spectrographs at Mount Wilson, and the spectrohelioscope recently invented by Dr. G. E. Hale.

SPECTRA OF PROMINENCES

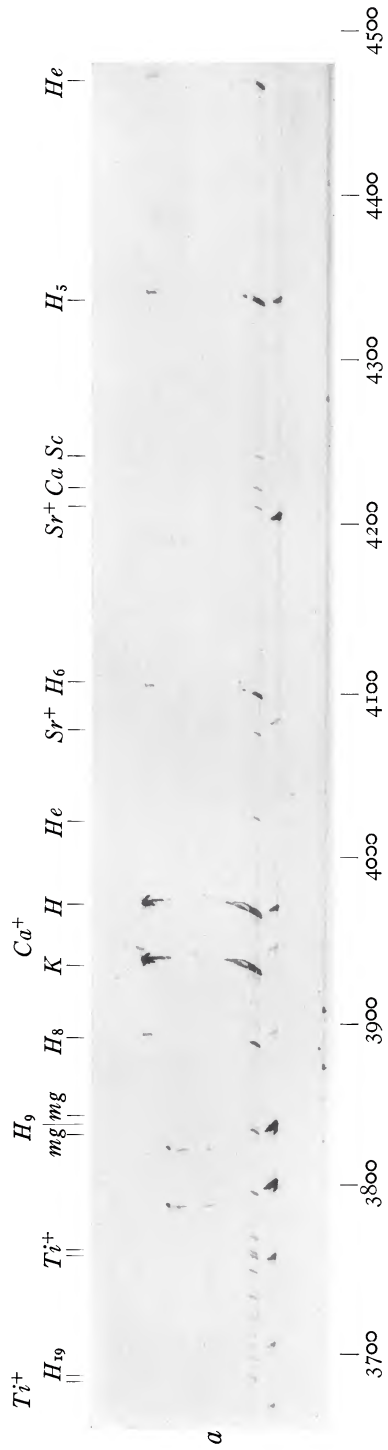
There are, in general, two spectral classes of prominences corresponding to (1) the prominences most commonly seen, and (2) the "metallic" prominences, usually brilliant spikes, often found in sunspots. The spectra of common prominences as seen without an eclipse consist of the Balmer series of hydrogen, the H and K lines of calcium, and the helium line D₃. The helium lines λ 6562 and λ 7065 appear faintly, and the Ca⁺ triplet $\lambda\lambda$ 8498, 8542, and 8662 can be photographed.² It is possible that the hydrogen line λ 10049 (H₆ of the Paschen series), observed by H. D. Babcock³ in the spectrum of the photosphere, occurs in prominences, but thus far it has not been found.

¹ Pettit, *Astrophysical Journal*, 50, 206, 1919; *Publications of the Yerkes Observatory*, 3, Part IV, 1925.

² K. Burns, *Lick Observatory Bulletin*, 10, 67, 1920; see also L. d'Azambuja, *Annales de l'Observatoire de Paris, Section d'Astrophysique à Meudon*, 8, Fasc. II, p. 100, 1930.

³ Revision of Rowland's Preliminary Table of Solar Spectrum Wave-Lengths, *Carnegie Institution of Washington Publication*, No. 396; *Papers of the Mount Wilson Observatory*, 3, 223, 1928.

PLATE I



a) Objective-grating spectrum (part only, original dimensions) of prominences, eclipse of June 8, 1918, by Anderson and Babcock.
b) Eruptive prominence (No. 31) of June 18, 1929. G.C.T. of exposures: (a) 16^h56^m; (b) 17^h35^m; (c) 17^h54^m; (d) 18^h50^m; (e) 19^h32^m; (f) 19^h50^m; (g) 20^h10^m; (h) 20^h23^m; (i) 20^h32^m; (j) 20^h46^m; (k) 20^h56^m; (l) 21^h04^m.

The spectra of prominences may be studied most conveniently at a solar eclipse. An objective-grating spectrogram taken between second and third contacts shows the spectrum as a series of images of the prominences corresponding to the various lines. Such a photograph was made by J. A. Anderson and Babcock¹ at the eclipse of June 8, 1918, in the first-order spectrum produced by a 6-inch grating of 21-foot radius, with ordinary photographic film in a plate-holder curved to fit the focal surface of the spectrum. An exposure of a few seconds made near mid-totally shows only the prominences without chromospheric spectrum (Pl. Ia).

The scale of this plate is 5.24 Å per millimeter and is very nearly uniform over the region $\lambda\lambda$ 4861–3341. Three prominences appear, furnishing three spectra which were measured by Miss L. M. Ware and the writer. These lines and their measured wave-lengths, together with those observed by S. A. Mitchell² in the flash spectrum, are given in Table I. The table also gives the intensity I_p estimated on an arbitrary scale made to fit Mitchell's for the prominent lines, the intensity in the flash spectrum I_F , the height of the chromosphere in the flash spectrum, the element, excitation potential (E.P.), and the temperature classification. The intensities I_p' are taken from the work of Pannekoek and Doorn.³ For the sake of completeness, the well-known lines in the visible spectrum and those observed by Burns⁴ in the infra-red have been added. The magnesium doublet λ 5172 and λ 5183 is beyond the sensitive limit of the 1918 film, but shows weakly in the reproduction of Davidson and Stratton's plate⁵ taken at the eclipse of January 14, 1926.

Table I includes all the lines of Mitchell's table having an intensity greater than 30, with the exception of λ 3234.49 Ti^+ (class IIIr) and λ 5316.67 Fe^+ , both of intensity 30. No trace of λ 3234 can be found on the 1918 film, and λ 5316 does not seem to show as a prominence image on Davidson and Stratton's plate.

¹ *Annual Report of the Director, Mount Wilson Observatory*, 1918.

² *Astrophysical Journal*, 71, 1, 1930.

³ *Verhandelingen der Koninklijke Akademie van Wetenschappen te Amsterdam, Afdeling Natuurkunde*, Sec. I, 14, No. 2, 1930.

⁴ *Lick Observatory Bulletin*, 10, 67, 1920.

⁵ *Memoirs of the Royal Astronomical Society*, 64, 105, Plate 5, 1929.

TABLE I
LINES IN THE PROMINENCE SPECTRUM

λ		I_P	I'_P	I_F	HEIGHT FLASH	ELEMENT	E.P.	TEMP. CLASS
Prominence	Flash							
8662.170	.....	.....	.....	.....	.....	Ca ⁺	1.7	V
8542.132	.....	.....	.....	.....	.....	Ca ⁺	1.7	V
8498.060	.....	.....	.....	.....	.....	Ca ⁺	1.7	V
7065.185	5.20	.....	.....	6	1000	He	20.9	Cr
6678.149	8.10	.....	.....	20	2200	He	21.1	Cr
6562.816	2.80	.....	1890	200	12,000	H ₃	10.2	Cr
5875.650	5.64	.....	138	80	7500	He	20.9	Cr
5183.....	3.58	.....	.....	40	2500	Mg	2.7	II
5172.....	2.65	.....	.....	30	2000	Mg	2.7	II
4861.344	1.50	200	512	200	8500	H ₂	10.2	Cr
4713.20	3.15	2	.....	5	5000	He	20.9	Cr
4571.80	2.00	I	.....	35	2500	Ti ⁺	1.6	V
4554.....	4.11	0	.....	50	2000	Ba ⁺	0.0	II
4549.61	9.63	I	.....	50	2500	Ti ⁺ -Fe ⁺	1.6	V
4541.71?	1.50	I	.....	6d	700	Fe ⁺ -Cr	2.8	III
4533.90	4.03	I	.....	30	2500	Ti ⁺ -Fe ⁺	1.2	V, III
4501.43	1.28	I	.....	25	2500	Ti ⁺	1.1	V
4471.60	1.54	30	40	80	7500	He	20.9	Cr
4468.46	8.48	I	.....	40	2500	Ti ⁺	1.1	V
4443.79	3.85	I	.....	30	2500	Ti ⁺	1.1	V
4395.02	5.13	I	.....	40	2500	Ti ⁺ -V	1.1	II
4388.44	8.39	0	.....	2	400	Fe	3.6	IV
4340.49	0.63	175	126	160	8000	H ₅	10.2	Cr
4334.78*	4.84	I	.....	2	500	La ⁺	V
4246.85	6.90	I	.....	50	5000	Sc ⁺	0.3	III
4233.....	3.22	0	.....	30	2200	Fe ⁺	2.6	.....
4226.46	6.74	I	.....	40	5000	Ca	0.0	I
4215.45	5.70	4	3	60	6000	Sr ⁺ -CN	0.0	II
4101.77	1.85	100	115	140	8000	H ₆	10.2	Cr
4077.80	7.83	7	7	80	6000	Sr ⁺	0.0	II
4045.32	5.84	I	.....	30	1800	Fe	1.5	II
4026.16	6.28	4	7	30	5000	He	20.9	Cr
3989.37	9.77	I	.....	6	600	Ti-Fe	0.0	V
3970.08	0.25	.....	.....	120	8500	H ₇	10.2	Cr
3968.48	8.70	1000	3310	175	14,000	Ca ⁺	0.0	II
3961.....	1.51	I	.....	35	2000	Al	0.0	Cr
3953.47	3.03	I	.....	4	600	Fe-Co-	3.0	IV
3947.59	7.66	I	.....	6	600	Fe-Ti	2.8	IV
3933.61	3.90	1200	2720	200	14,000	Ca ⁺	0.0	II
3913.02	3.55	I	.....	40	2500	Ti ⁺ -Fe	1.1	V, III
3900.38	0.54	I	.....	40	2000	Ti ⁺	1.1	V
3888.79	9.20	50	19	120	8500	H ₈	10.2	Cr
3859.48	9.87	I	.....	35	2500	Fe	0.0	I
3838.40	8.30	3	.....	60	7000	Mg	2.7	II
3835.47	5.54	15	.....	100	7000	H ₉	10.2	Cr
3832.34	2.34	2	.....	50	6000	Mg	2.7	II
3819.66	9.63	I	.....	10	5000	He	20.9	Cr
3797.92	8.02	12	.....	90	6000	H ₁₀	10.2	Cr
3770.70	0.72	9	.....	80	6000	H ₁₁	10.2	Cr

* Possibly ghost of H₅.

TABLE I—Continued

λ		I_P	I'_P	I_F	HEIGHT FLASH	ELEMENT	E.P.	TEMP. CLASS
Prominence	Flash							
3761.56	{ 1.33 1.88 }	9	.....	70	6000	Ti^+	{ 0.6 2.6 }	IV
3759.43	9.33	9	.....	70	6000	Ti^+	0.6	IV
3749.81	50.25	5	.....	70	6000	H_{12}	10.2	Cr
3746	5.78	0	.....	30	2000	Fe	0.1	IA
3737	7.00	0	.....	40	2000	{ Ca^+-Ni Fe }	{ 3.1 0.1 }	II, V I
3734.49	4.45	3	.....	70	5600	H_{13}	10.2	Cr
3721.98	2.00	2	.....	55	5600	H_{14}	10.2	Cr
3719.60	9.94	1	.....	35	2000	Fe	0.0	I
3711.73	2.06	2	.....	50	5000	H_{15}	10.2	Cr
3704.10	3.89	1	.....	45	4000	H_{16}	10.2	Cr
3697.24	7.21	1	.....	40	3500	H_{17}	10.2	Cr
3691.62	1.62	1	.....	35	3000	H_{18}	10.2	Cr
3686.99	6.83	1	.....	30	3000	H_{19}	10.2	Cr
3685.42	5.25	9	.....	80	6000	Ti^+	0.6	IV
3383.76	3.84	2	.....	25	2500	Ti^+-Fe	0.0	III, IV
3372.90	2.84	2	.....	30	2500	Ti^+	0.0	III
3361.28	1.24	2	.....	25	2500	Ti^+-Sc^+	0.0	I, III
3349.27	9.41	3	.....	35	2500	Ti^+	0.0	II
3341.40	1.88	1	.....	25	2000	Ti^+-Fe	0.6	II, IIIA

The lines fainter than 30 on Mitchell's scale that appear in Table I are shown in Table II. It will be noted that these are all spark lines of classes III–V (medium to highest energy-levels) or chromo-

TABLE II

LINES FAINTER THAN 30 IN THE FLASH SPECTRUM WHICH APPEAR IN PROMINENCES

Wave- Length	I_P	I_F	Element	E.P.	Temp. Class	Wave- Length	I_P	I_F	Element	E.P.	Temp. Class
7065.20	...	6	He	20.9	Cr	3989.77	1	6	Ti-Fe	0.0	V
6678.10	...	20	He	21.1	Cr	3953.03	1	4	Fe-Co	3.0	IV
4713.15	2	5	He	20.9	Cr	3947.66	1	6	Fe-Ti	2.8	IV
4541.50	1	60	Fe^+-Cr	2.8	III	3819.63	1	10	He	20.9	Cr
4501.28	1	25	Ti^+	1.1	V	3383.84	2	25	Ti^+-Fe	0.0	III, IV
4388.39	0	2	Fe	3.6	IV	3361.24	2	25	Ti^+-Sc^+	0.0	I, III
4334.84	1	2	La^+	....	V	3341.88	1	25	Ti^+-Fe	0.6	II, IIIA

spheric helium. Generally speaking, the brighter lines in the prominences are also those which are the brighter in the chromosphere. Possibly λ 4334.84 is a ghost. It is peculiar that λ 4388.39 Fe shows when λ 4387.86 He does not, since the height of the latter line is

2000 km at the chromosphere; but repeated measurement fails to change the value given here.

The spectrum of the metallic prominences is not so well known as that of the ordinary kind. The lines which, in addition to those in Table I, commonly appear in the visual region are given by the Kodaikanal observers in their daily visual inspection of prominence spectra.¹

Table III contains all the lines in the visual region of the flash spectrum brighter than 15 in Mitchell's table, except the three lines $\lambda\lambda$ 4934.08, 6141.77, and 6496.88, all belonging to ionized barium,

TABLE III
ADDITIONAL LINES WHICH APPEAR IN METALLIC PROMINENCES

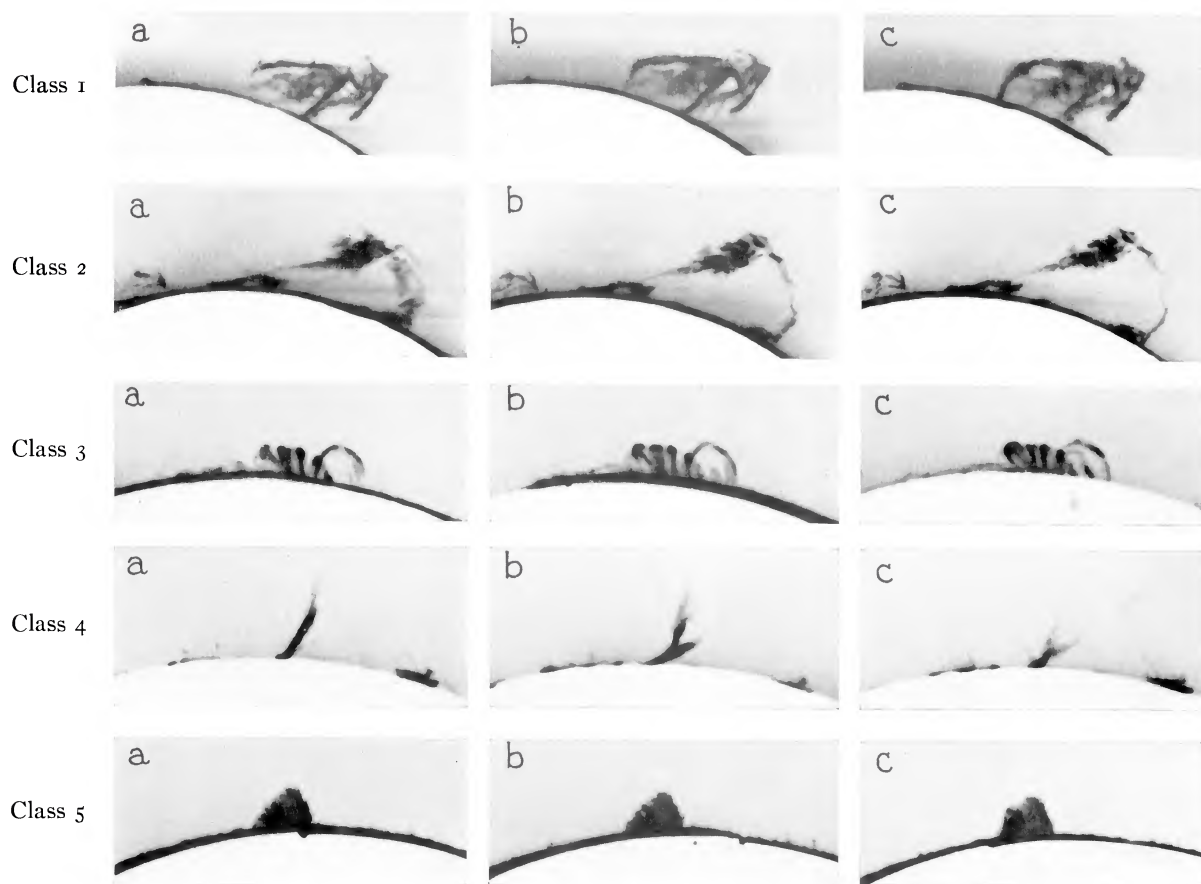
Wave-Length	I_F	Element	Wave-Length	I_F	Element
4923.96.....	30	<i>Fe</i> ⁺	5275.99.....	20	<i>Fe</i> ⁺ - <i>Cr</i>
5015.68.....	2	<i>He</i>	5316.67.....	30	<i>Fe</i> ⁺
5018.44.....	25	<i>Fe</i> ⁺	5362.86.....	15	<i>Fe</i> ⁺
5167.35.....	18	<i>Mg</i>	5889.98.....	25	<i>Na</i>
5168.99.....	25	<i>Fe</i> ⁺ - <i>Fe</i>	5895.99.....	20	<i>Na</i>
5172.65.....	30	<i>Mg</i>	6678.10.....	20	<i>He-Fe</i>
5183.58.....	40	<i>Mg</i>	7065.20.....	6	<i>He</i>
5234.63.....	15	<i>Fe</i> ⁺			

of intensity 25, 20, and 20, respectively. The lines of barium seem to be suppressed in the prominences; for example, the line λ 4554, of intensity 50 in the flash, is of intensity 0 in the prominences and just visible on the 1918 eclipse film. Helium, like hydrogen, seems to be present even in the lines that are very faint in the flash. In conclusion we may say that the spectrum of the prominences consists of the brighter lines of the flash spectrum and that metallic prominences are probably more brilliant only because the fainter lines are brought up by higher temperature, or greater density, or both. The occasional appearance of continuous spectrum² in these prominences is an indication of abnormal pressure. There is, then, no real spectral difference between the common and metallic prominences. Probably, if sufficiently long exposures could be given,

¹ Kodaikanal Observatory Bulletins, semiannual summary.

² C. A. Young, *The Sun* (1910), p. 225. This also shows in Davidson and Stratton's eclipse plate (*Memoirs of the Royal Astronomical Society*, 64, 105, Plate 5, 1929).

PLATE II



TYPES OF PROMINENCES, SHOWING STRUCTURAL CHANGES AT INTERVALS
OF A FEW MINUTES (G.C.T.)

Class 1, active type, February 28, 1929:

(a) 19^h15^m; (b) 19^h34^m; (c) 19^h45^m

Class 2, eruptive type, April 5, 1930:

(a) 17^h08^m; (b) 17^h13^m; (c) 17^h19^m

Class 3, spot type, August 19, 1927:

(a) 17^h43^m; (b) 17^h47^m; (c) 17^h51^m

Class 4, tornado type, July 5, 1928:

(a) 17^h11^m; (b) 17^h17^m; (c) 17^h24^m

Class 5, quiescent type, August 21, 1930:

(a) 16^h45^m; (b) 17^h00^m; (c) 17^h06^m

the spectrum of the prominences would be much like the flash, except that some of the lines, like those of helium, would be brighter, while those of elements like barium would be relatively fainter. This behavior suggests that the forces which expel prominences from the chromosphere sift out the heavier elements such as barium.

FORMS OF PROMINENCES

The forms of prominences as they appear at the limb of the sun may be divided in order of their approximate frequency into five classes: (1) *active* prominences, which appear to be torn apart by an area of attraction or by a neighboring sun-spot; (2) *eruptive* prominences, which ascend in a more or less vertical direction; (3) *spot* prominences, which often have the appearance of closed loops of a fountain or of spikes with external wings—generally their appearance is best described by the word “splash”; (4) *tornado* prominences, which appear like vertical spirals or tightly twisted ropes; (5) *quiescent* prominences, which show only minor changes from minute to minute.

Plate II illustrates the five prominence types, showing their development during approximately the same intervals of time.

In general we may regard all prominences as “active,” the distinction among the five classes outlined here being in the degree and kind of activity. In the strict sense of the word there seems to be no such thing as a “quiescent” prominence. Those which appear to be the best examples of this class show structural changes easily observable with the blink comparator in spectroheliograms taken at intervals of 4 or 5 minutes, provided the atmospheric definition was sufficiently good.

Classes 1 and 2 are closely associated; a single individual often exhibits both phases simultaneously or passes from the active into the eruptive state. Although a spot may or may not be connected with classes 1 and 2, both these forms may be associated individually or collectively with class 3. We shall consider these generalizations in what follows.

DIMENSIONS OF PROMINENCES

The three-dimensional forms of prominences may be studied by comparing their outlines as they pass over the sun’s disk and ap-

pear in projection at the limb. Prominences show on the disk as the well-known absorption markings, or, in the case of metallic prominences, as bright markings. They generally appear as long streaks, usually somewhat curved, and, when radial or near the center of the disk, we see them in plan and may measure their thickness. A considerable number of such cases was selected from the routine series of spectroheliograms taken with the 13-foot spectroheliograph during the last sun-spot cycle and measured with a microscope having a simple scale in the field. The range in thickness is surprisingly small, generally from 6000 to 12,000 km, although some examples may measure 15,000 km. The length is quite variable. Very few prominences are shorter than 60,000 km, and a length of 600,000 km is unusual, although cases have been found where a broken line of prominences extended over more than one-fourth the circumference of the sun. D'Azambuja,¹ in charting the prominences in projection on the sun, found several instances of this kind. The height is also quite variable, 75,000–100,000 km being not uncommon. The highest yet recorded was a fragment of a class 2 prominence 929,000 km above the chromosphere, observed by T. Royds² on November 19, 1928.

We may regard the three-dimensional form of a prominence, then, as much like that of a thin sheet of flame issuing from the familiar fish-tail burner of the laboratory. The sheet of incandescent gas stands on one edge, usually not in contact with the chromosphere throughout its entire length, but raised above it a few thousand kilometers and connected with it by columns, like the roots of a tree. These columns are frequently staggered along the line beneath the prominence and generally spread out at the surface of the chromosphere. This description is drawn from an examination of the larger prominences; the smaller ones often seem to be without the connecting columns and simply stand on edge upon the chromosphere or above it. The atmospheric definition is seldom good enough to make an examination of the smaller objects satisfactory.

Representative dimensions are perhaps a thickness of 10,000 km, a length of 200,000 km, and a height of 50,000 km, which imply a vol-

¹ *Op. cit.*, 6, Fascs. 1–4, 1928–1930; see rotations Nos. 900 and 920, for example.

² *Monthly Notices of the Royal Astronomical Society*, 89, 255, 1928.

ume ninety-three times that of the earth. The largest prominence known to the author is that of class 2 observed¹ on May 29, 1919. We have no value of the thickness later than about three weeks preceding the eruption (which took place on the east limb), when it averaged about 8000 km. The supposition that at the time of the eruption the thickness did not exceed 12,000 km would give a volume four hundred times that of the earth.

MASSES OF PROMINENCES

The mass of a prominence is difficult to estimate largely because of the uncertainty as to the fraction of the atoms which are radiating. The density of the radiating atoms per cubic centimeter was determined for three prominences at the eclipse of June 29, 1927, by Pannekoek and Doorn.² To obtain the volume of the prominence, they assumed the thickness to be the same as the tangential extent. While this estimate is presumably valid for the small prominence *b*, it is probably twenty fold too great for prominence *a* (200,000 km reduced to 10,000 km). This makes the density of prominence *a*, 3.8 atoms in the H_5 state, or 32×10^{11} atoms of hydrogen per cubic centimeter at large, almost the same as the density for prominence *b*. For Ca^+ , Pannekoek and Doorn obtained for each prominence, with the foregoing correction, 2.6 and 1.6 atoms, respectively, in the $2S-2P_1$ and $2S-2P_2$ states. As all the Ca^+ atoms are supposed to take part in the radiating process, the admixture of calcium in the prominence is insignificant. We know little about helium, therefore we must, for the present, consider the prominence to be made of hydrogen of atomic density comparable with that computed above. Both *a* and *b* were very weak prominences, while *c*, which was outside their photometric range, was more nearly representative, and, judged from their estimates of intensities in the strontium lines, the ratio is about 6. This would indicate a density of 2×10^{13} atoms of hydrogen per cubic centimeter in a prominence of ordinary kind. This figure is, of course, controlled by the large factor of proportionality 1.2×10^{-12} between the excited H_5 atoms and the total number at 5500° K, which is to a great extent uncertain. Using, however, the foregoing density and the mass of a hydrogen atom, 1.7×10^{-24}

¹ *Loc. cit.*

² *Loc. cit.*

gm, we find the mass of the representative prominence 10,000 km thick, 200,000 km long, and 50,000 km high to be 3.4×10^{18} gm, about the mass of a cube of water 15 km on an edge. The mass of the largest prominence on record, that of May 29, 1919, would be about four times as much.

DISTRIBUTION OF THE ELEMENTS IN PROMINENCES

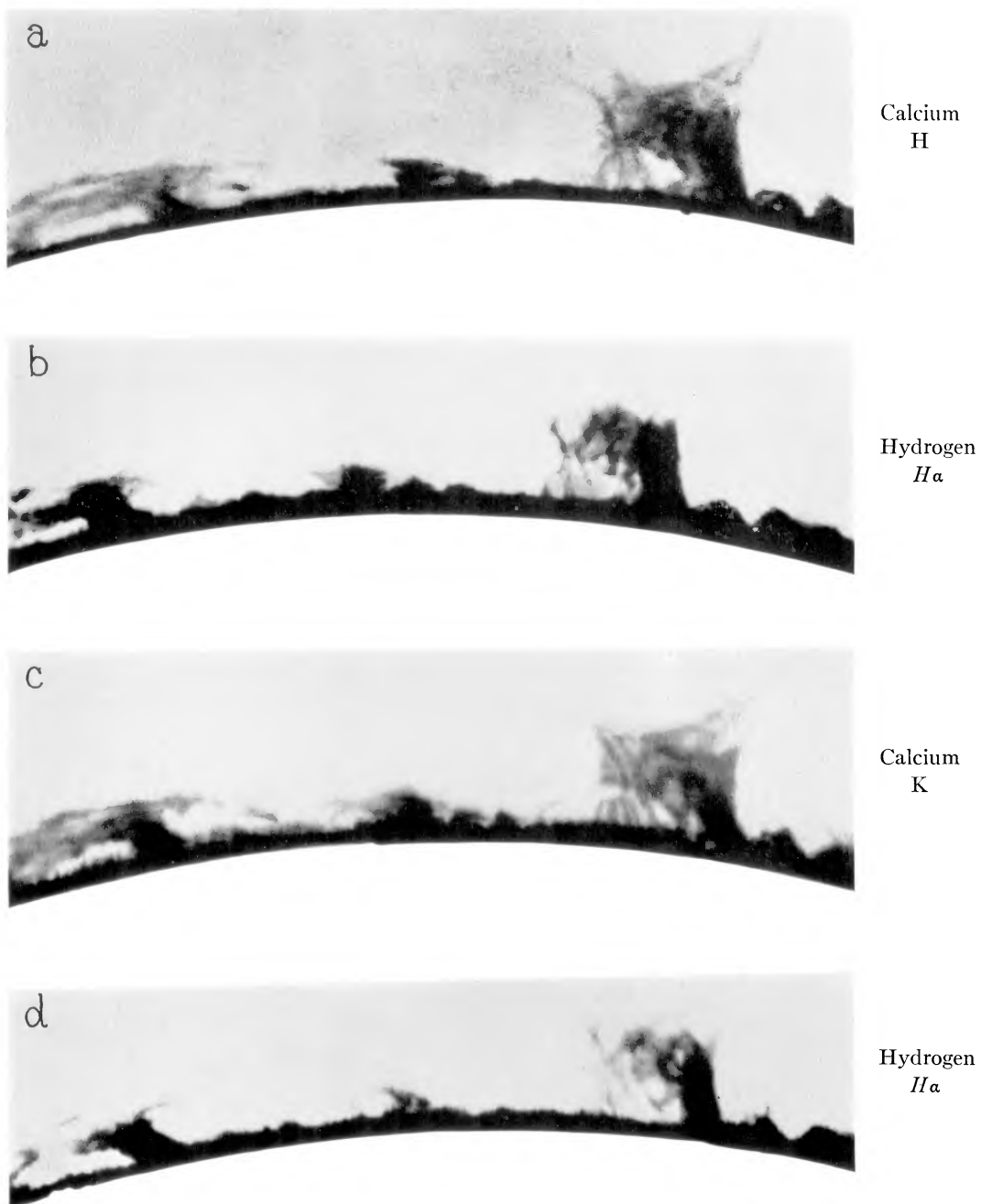
The ideal method of studying the distribution of the elements in prominences would be by means of objective-grating spectra taken at an eclipse, as shown in Plate Ia. As indicated in Table I, the range of intensity covered by the H and K lines of calcium, the first few lines of the Balmer series of hydrogen, and the lines of the other elements is so great that several widely differing exposures would be necessary. The film of Plate Ia indicates, however, that the principal features of the prominences shown in the lines measured which were brighter than about 5 (column headed I_p , Table I) were substantially the same. The other lines were too faint to be sure of the form. This statement applies to the general outline of the prominence, and not to the streamers or other fainter details.

Without an eclipse we are confined to a comparison of calcium with hydrogen and possibly helium. The writer has used both photographic and visual methods. Plate III shows four spectroheliograms taken alternately in the $H\alpha$ line of hydrogen and the H and K lines of calcium, which confirm the testimony of the eclipse film in Plate Ia. They are of the prominence of August 6, 1931, in the active stage just before the eruption began. The first exposure was made by the author at the Yerkes Observatory in the H line of calcium; the others were made a few minutes later at Mount Wilson by S. B. Nicholson in $H\alpha$ and K_2 . It will be noted that the streamers in the active prominences shown here are not so numerous or so intense in hydrogen as in calcium. Since this difference may be a matter of photographic contrast, it was thought advisable to study the question by comparing drawings made in $H\alpha$ with spectroheliograms made simultaneously in K_2 .

For this purpose the spectrohelioscope¹ was used with Anderson's rotating prisms. This instrument includes a 6-inch bright first-order

¹ Hale, *Mt. Wilson Contr.*, No. 388, Pl. XIX; *Astrophysical Journal*, 70, 265, Pl. XIV, 1929.

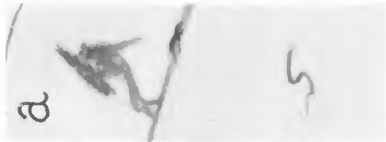
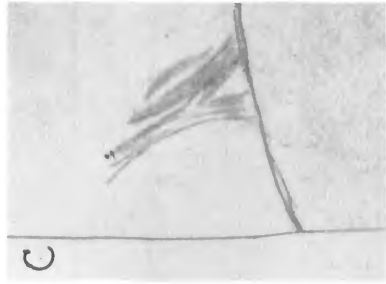
PLATE III



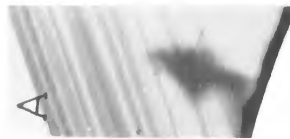
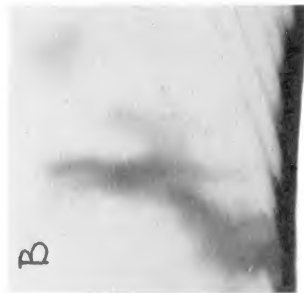
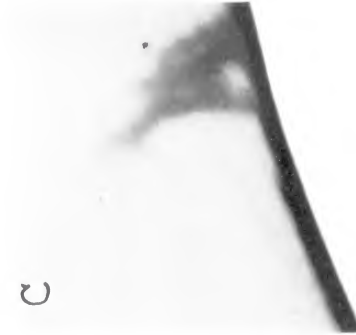
PHOTOGRAPHS OF PROMINENCE (No. 35) OF AUGUST 6, 1931, MADE BEFORE THE
ERUPTION BEGAN, ALTERNATELY IN THE LIGHT OF CALCIUM AND HYDROGEN

(a) Yerkes Observatory at $14^{\text{h}}22^{\text{m}}7$, (b) Mount Wilson at $14^{\text{h}}27^{\text{m}}$, (c) Mount Wilson
at $14^{\text{h}}37^{\text{m}}$, (d) Mount Wilson at $14^{\text{h}}44^{\text{m}}$, G.C.T.

PLATE IV



Hydrogen
 H_{α}



Calcium
K

DRAWINGS OF PROMINENCES (*a,b,c,d*) AS SEEN WITH THE H_{α} LINE OF HYDROGEN COMPARED WITH
PHOTOGRAPHS (*A,B,C,D*) MADE IN THE K LINE OF CALCIUM

(*aA*) Dec. 16, 1930; (*bB*) Dec. 19, 1930; (*cC*) Jan. 12, 1931; (*dD*) Jan. 26, 1931

plane-grating spectrograph, mounted Littrow fashion with a collimator-camera lens of 18-foot focal length. A line-shifter¹ consisting of a plate of glass 2 cm thick was placed behind the second slit. An 8-inch objective of 30-foot focal length formed the solar image on the first slit. A red color screen and a plane-parallel glass plate 1 cm thick, arranged to rotate about an axis in its own plane for fine guiding in right ascension, were placed close in front of the first slit. This equipment was mounted in the Pasadena Laboratory, where drawings of prominences in $H\alpha$ were made at a definite time, prearranged by telephone with Mount Wilson in order that photographs in K_2 might be taken simultaneously with the 13-foot spectroheliograph. Plate IV shows four of the $H\alpha$ drawings and the accompanying K_2 spectroheliograms. It will be noted that these prominences are essentially the same in both $H\alpha$ drawings and K_2 photographs, but that the streamers in $H\alpha$ are entirely absent or lightly indicated, whereas in exposure D , for example, they appear in K_2 as broad ribbons.

The absence of streamers may be due, in part, to the relatively faint image in the spectrohelioscope caused by the broadening of the illuminated slit by the rotating prisms, but it was also observed with the 12-inch telescope and spectroscope at the Yerkes Observatory last summer. In the Yerkes observations the lack of streamers may perhaps be traced to the strong field-light of the instrument. All the cases so far cited are prominences of class 1. An instance of class 2 will be seen in Plate VI. It must be concluded, therefore, that the elements composing a prominence are very thoroughly mixed, with possibly some difference in the streamers, although this may be an instrumental effect.

These streamers appear usually to extend into the chromosphere in a definite small area or center of attraction,² into a sun-spot, or into another prominence. If this be due to electrical forces, we know no reason why they should act on the neutral hydrogen atom, which has no external electrical field, although they would act on the ionized calcium atom.

It has already been pointed out³ that the coronal streamers of the

¹ *Ibid.* ² *Publications of the Yerkes Observatory*, 3, Part IV, 229, 1925.

³ *Ibid.*, p. 231.

eclipse of June 8, 1918, radiating from a center of attraction between the two active prominences on the western limb of the sun, strongly suggest lines of force about the pole of a magnet. A close examination of a photograph of that eclipse taken by Miss M. R. Calvert and Professor E. E. Barnard with a 60-foot focus lens shows that the coronal streamers near the stronger prominence (see the H and K images of Plate Ia) have exactly the same curvature as the prominence streamers, which were moving into the center of attraction at a rate of 100 km/sec., a velocity obtained by measuring two of these eclipse plates in the blink comparator. The characteristic curving of coronal streamers about prominences of all types to form the well-known arches is also an argument for a field of force about a prominence. Such a coronal disturbance¹ appeared above the great prominence of May 29, 1919, where the streamers arranged themselves in an arch whose shape conformed closely to that of the prominence. If the corona is, indeed, composed largely of electrons, the ionized calcium atoms of large prominences must certainly disturb it.

HEIGHT OF THE CHROMOSPHERE IN $H\alpha$

The height of the chromosphere in $H\alpha$ was measured with the spectrohelioscope on several occasions in February and March, 1931. The method depended on the following phenomenon: if we observe the sun with the spectrohelioscope set for $H\alpha$ and then shift the line off the second slit with the line-shifter so that we see the sun in the continuous spectrum of a near-by wave-length, the radius of the image is decreased by the thickness of the $H\alpha$ chromospheric layer. With the instrument just described the effect is very striking.

The measurements were made with a filar micrometer and projecting doublet, which transferred the image to an accessible position. The line-shifter was adjusted to give minimum light, indicating that the $H\alpha$ line was centered on the second slit. The position of the limb in the field was then adjusted by rotating the plane-parallel glass plate which operates as a fine motion in right ascension until the limb came in contact with the wire of the micrometer. The continuous spectrum was then brought on the second slit by quickly

¹ Drawings of the corona from photographs, communicated by the Astronomer Royal, *Memoirs of the Royal Astronomical Society*, 64, Appendix, 1929.

moving the line-shifter, a neutral-tint shade glass was thrown over the eyepiece to reduce the intensity to that previously observed, and the micrometer wire was again set on the limb. The difference in readings was the thickness of the chromosphere, expressed in revolutions of the screw. The experiment was repeated on the other limb to eliminate the systematic error of image drift. This was small, however, as the whole measurement required only a few seconds. The instrument was calibrated by observing with a chronograph the time required for the limb to drift over the micrometer wires, the coelostat clock having been stopped. The value of 1 revolution of the screw was thus found to be 4".44.

Observations were made on days of good definition only—February 25 and March 6, 7, and 9, 1931. The mean value of the thickness of the chromosphere in $H\alpha$ was 7".6, which is equivalent to 5500 km. This value is less than half that found by Mitchell¹ from flash spectra, but only about 19 per cent less than that observed by G. Abetti² with a visual spectroscope. The spectrohelioscope probably gives a minimum value, since the wire is set at the base of the rough outline of the chromosphere.

ERUPTIVE PROMINENCES (CLASS 2)

A study of all the available data on eruptive prominences on which four or more measurements were made has been published in a previous paper.³ Of this collection of 24 eruptive prominences, 11 were spectroheliographic results in Ca^+ , either H or K, and 13 were visual measurements, usually by the method of transits, in the $H\alpha$ line of hydrogen. The principal results were: (1) eruptive prominences move with uniform motion, the velocity increasing suddenly at intervals, and (2) the maximum velocity observed was 400 km/sec.

The principle of uniform motion expressed by (1) has always been a stumbling-block to those seeking to explain the motions of eruptive prominences on the theory of light-pressure⁴ or otherwise.⁵

¹ *Loc. cit.*

² *Handbuch der Astrophysik*, 4, 139, 1929; see also *Osservazioni e memorie del R. Osservatorio Astrofisico di Arcetri*, 1922 ff.

³ *Publications of the Yerkes Observatory*, 4, Part III, 1925.

⁴ S. R. Pike, *Monthly Notices of the Royal Astronomical Society*, 88, 3 and 635, 1927–1928.

⁵ N. T. Bobrovnikoff, *Astrophysical Journal*, 74, 157, 1931.

After allowing the matter to rest about ten years, I began to wonder if the observations themselves might be at fault, as suggested by Pike,¹ for example. To get at the facts in the case, we may (1) review the best examples already given (i.e., those best observed in respect to the character of the motion), (2) examine the results published by other observers, (3) obtain new material for this purpose, and (4) test the impartial character of the measurements by having them checked by other investigators. We shall consider these points in the order named.

1. *Examples already given.*—For simplicity, the numbering previously used in identifying the various examples is retained. The examples showing the uniform character of motion in the most indisputable manner are illustrated in Figure 1. Of these, Nos. 1, 2, and 3 are spectroheliographic results in the H line of calcium obtained by the author; Nos. 16 and 18 are visual measurements made by J. Fényi at the Haynald Observatory; and No. 23 is by J. B. Coit, of Boston University—all in the *H α* line of hydrogen.

Number 1, the prominence of May 29, 1919, is that in which the phenomenon of uniform motion accelerated at intervals was first observed by the author. The curve represents the motion of the center of the prominence, i.e., the march of the average of the heights of the top and bottom above the chromosphere. It seems to make little difference in the result whether the top, center, bottom, or some particular feature which endures long enough is used as an origin of measurement of the height; the same kind of curve is always obtained, although the velocity may differ a little, as might be expected on account of the motions of parts of the prominence relative to one another during the eruption, generally an expansion with ascent.

Number 2 is the prominence of July 15, 1919, the measurements being made on the middle of the expanding crest. This prominence had the form of an expanding arch, and the center of the crest was easily measured and followed from exposure to exposure.

Number 3 is an interesting case. This prominence had the form of a cloud of smoke shot from a gun, at an angle of 50° to the vertical. The measurements were made on the end of the column in the direc-

¹ *Op. cit.*, pp. 21-22.

tion of motion. On coming to Mount Wilson, I found that two spectroheliograms had been taken with the 13-foot spectroheli-

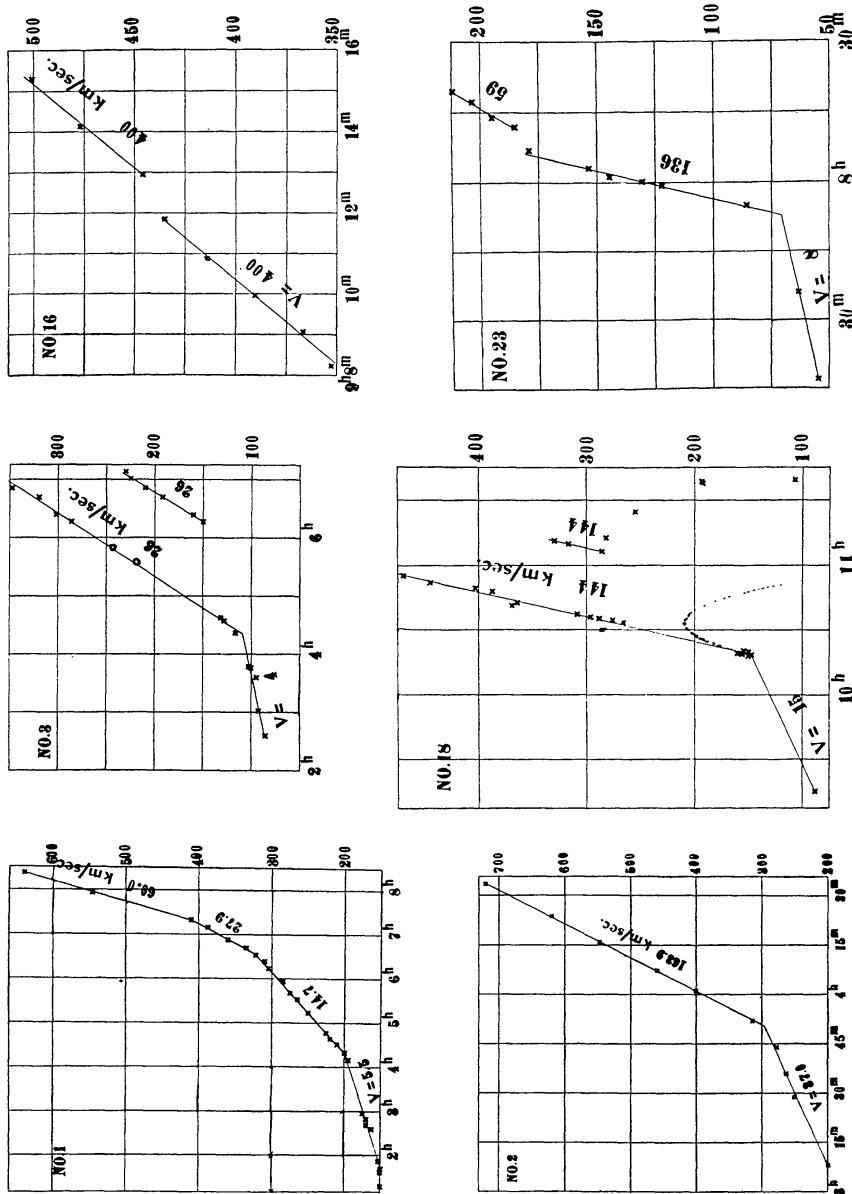


FIG. 1.—Motions of eruptive prominences (No. 1) May 29, 1919; (No. 2) July 15, 1919; (No. 3) September 8, 1919; (No. 16) September 20, 1893; (No. 18) December 24, 1894; (No. 23) June 11, 1895. Abscissae are times of observation (G.M.T.); ordinates, height of prominence; unit = 1000 km.

graph, which, upon measurement, gave the two points, indicated by the circles in the plot, close to the straight line already obtained at the Yerkes Observatory.

All these motions are so large that a simple millimeter scale is sufficient to measure them. On the plates made with the Rumford

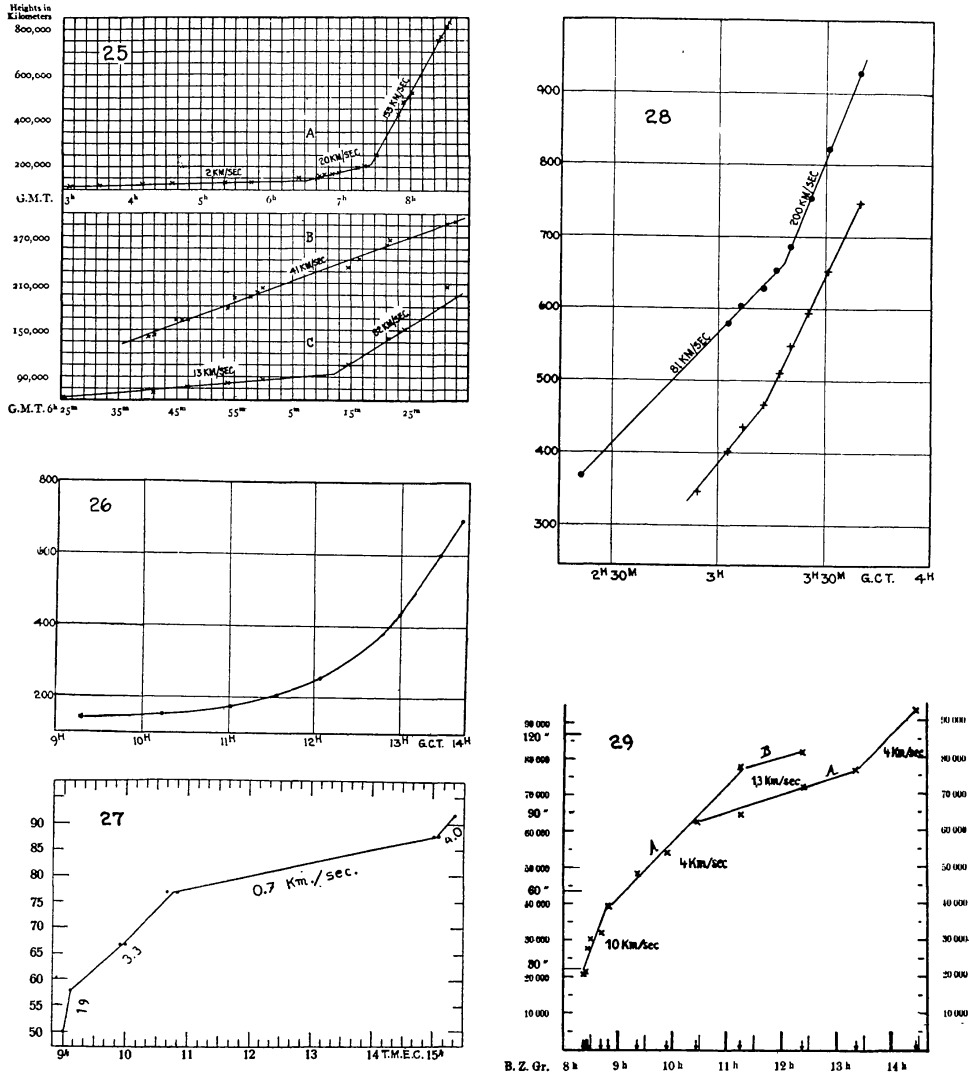


FIG. 2.—Motions of eruptive prominences (No. 25) October 8, 1920; (No. 26) May 14, 1925; (No. 27) May 14, 1928; (No. 28) November 19, 1928; (No. 29) March 18, 1929. Abscissae are times of observation (G.C.T. except No. 25, which is G.M.T., and No. 27, which is European Central Time); ordinates, heights of prominence; unit = 1000 km.

spectroheliograph at the Yerkes Observatory, the motions in Nos. 1 and 2 covered about 88 mm, and those in No. 3 about half as much. Numbers 16 and 18 are plots of the measures as published by

Fényi. For No. 23, Coit gave the heights obtained by using the mean apparent solar diameter. These have been corrected by applying the constant factor necessary to reduce them to the actual apparent diameter. I think it must be admitted that for none of these cases could a smooth curve other than a straight line be drawn which would do justice to the observations. Perhaps the most questionable case is No. 1, but even here there would have to be a straight section between 4^h and 6^h30^m G.M.T., since in this part the observations give a well-determined line.

2. *Observations published since 1920.*—The instances cited under (1) are from the list of all available data up to 1920. Results published since that time are numbered in continuation of the series already given. They consist of No. 25, the eruptive prominence of October 8, 1920, observed by O. J. Lee¹ with the Rumford spectroheliograph at the Yerkes Observatory; No. 26, on May 14, 1925, by D'Azambuja² at Meudon; No. 27, on May 14, 1928, by Abetti³ at Arcetri; No. 28, on November 19, 1928, by Royds⁴ at Kodaikanal; and No. 29 on March 18, 1929, by W. Brunner⁵ at Zurich. The observed heights of the prominences and the times of observation as given by the observers are collected in Table IV; the plots are shown in Figure 2. A plot of No. 25 was given by Lee, but no table of times and heights. To supply these, I have read them from the plot, the times being checked from the observing book at the Yerkes Observatory. For No. 26 a table was published but no plot; and for No. 28, by Royds, only the half-tone prints and three stated heights were given. Dr. Royds has kindly furnished me with contact copies of the original negatives and data giving the exact times of exposure. The plot in Figure 2 shows the heights of the crest and of the base of the moving cloudlike prominence which I have measured.

In Lee's prominence, No. 25, there can be no question that the

¹ *Astrophysical Journal*, 53, 310, 1921.

² *L'Astronomie*, 40, 64, 1926.

³ *Osservazioni e memorie del R. Osservatorio Astrofisico di Arcetri*, No. 45, 36, 1928.

⁴ *Loc. cit.*

⁵ *Astronomische Mitteilungen der Eidgenössischen Sternwarte in Zürich*, No. 121, 7, 1929.

TABLE IV
COLLECTED DATA ON ALL OBSERVATIONS OF ERUPTIVE
PROMINENCES* OBTAINED SINCE 1920

Identity and Remarks	G.C.T. of Observation	Height in Thousand Kilometers
25. October 8, 1920. Observed by Lee at the Yerkes Observatory. Spectroheliograph in H line of Ca^+ . Lat. 24° S. on the east limb. No sun-spot near. <i>Astrophysical Journal</i> , 53, 310, 1921. No table given. Heights and times read from Lee's plot. The times of observation have been checked against the observing book to obtain the decimal of minutes. Top of the prominence was measured by Lee. For detailed analysis of other points see reference. $V = 2, 20,$ and 155 km/sec.	15 ^h 04 ^m 5	110
	32.0	115
	16 08.0	125
	35.6	125
	17 22.8	130
	42.5	135
	18 23.8	150
	40.8	150
	44.7	160
	45.8	170
	53.6	170
	59.7	175
	19 14.2	199
	21.0	201
	31.0	250
	49.3	425
	53.0	480
	57.9	500
	20 01.8	520
	25.2	750
26.5	770	
31.5	810	
33.2	831	
26. May 14, 1925. Observed by D'Azambuja at Meudon. Spectroheliograph in K line of Ca^+ . Lat. 35° - 48° S. on the west limb. No sun-spot near. <i>L'Astronomie</i> , 40, 64, 1926; see table, p. 65. Accelerated motion. V varies from 4 to 122 km/sec.	9 18	140
	10 13	152.5
	11 01	175
	34	205
	12 05	253
	58	435
	13 27	600
	43	695
27. May 14, 1928. Observed by Abetti at Arcetri. Spectroheliograph in K line of Ca^+ . Typical sun-spot prominence connected with the large spot leading the group, Mt. Wilson, No. 3346. Lat. 14° S. on the west limb. <i>Osservazioni e memorie del R. Osservatorio Astrofisico di Arcetri</i> , No. 45, 36, 1928. $V = 19, 3.3, 0.7,$ and 4.0 km/sec.	8 00	50
	07	58
	30	
	55	66.7
	9 00	66.7
	40	76.7
	50	76.7
	10 04	
	14 00	87.6
	05	87.6
10		
20	91.7	

* For data previous to this date see *Publications of the Yerkes Observatory*, 3, Part IV, 210, 1925.

SOLAR PROMINENCES

TABLE IV—Continued

Identity and Remarks	G.C.T. of Observation	Height in Thousand Kilometers
28. November 19, 1928. Observed by Royds at Kodaikanal. Spectroheliograph in K line of Ca^+ . Lat. 71° – 72° S. on the west limb. No spot near. Only three measurements given. Others obtained by measuring copies of the original plates furnished by Royds. <i>Monthly Notices of the Royal Astronomical Society</i> , 89 , 255, 1929. $V = 81$ and 200 km/sec.	$2^h 21^m 4$	364
	54.6	348
	57.8	371
	$3^h 02.8$	580, 404
	06.8	603, 436
	12.7	626, 464
	16.7	650, 510
	20.7	684, 545
	25.8	754, 592
	31.3	812, 650
	39.6	928, 742
29. March 18, 1929. Observed by Brunner at Zurich. Visual in $H\alpha$ line of hydrogen. Lat. 10° S. on the east limb. No sun-spot. Times are given, heights read from Brunner's plot. <i>Astronomische Mitteilungen der Eidgenössischen Sternwarte in Zurich</i> , No. 121, 7, 1929. $V = 10, 4, 1.3$, and 4 km/sec.	8 22	20.5
	25	21
	27	27.5
	30	30
	42	31
	50	39
	9 22	48
	54	53.5
	10 27	62
	11 15	77.5, 64
	12 23	81, 71
	13 21	76
	14 27	92.5
	30. June 23, 1924. Observed by Lewis Humason. 13-foot spectroheliograph at Mount Wilson. Not published. Measures by the author. K line of Ca^+ . Lat. 58° N. on the east limb. No spot. $V = 43$ and 73 km/sec.	15 40.0	222
45.0		222
51.0		222
16 47.0		181
51.5		195
58.1		200
17 03.2		222
08.6		228
13.1		250
18.0		261
18 01.3		395, 195
03.7		417, 222
06.5		434, 245
16.0		453, 289
20.0		473, 306
31. June 18, 1929. Observed by J. Hickox. 13-foot spectroheliograph at Mount Wilson. Not published. Measures by the author. K line of Ca^+ . Appeared over large spot, leader of group, Mt. Wilson, No. 3726. Lat. 10° S. on the east limb. Arose at a point 12° S., sending streamers over the spot to a point on the solar equator. $V = 3, 19$, and 37 km/sec.	16 35	68.2
	46	68.2
	56	68.2
	17 35	76.4
	54	81.9
	18 50	90.1
	19 32	109.2
	50	133.8
	20 10	155.6
	23	169.3

TABLE IV—*Continued*

Identity and Remarks	G. C. T. of Observation	Height in Thousand Kilometers
31.— <i>Continued</i>	20 ^h 32 ^m 46 56 21 04 27	185.6 221.1 240.2 245.7 300.3
32. February 6, 1930. Observed by Hickox. 13-foot spectroheliograph at Mount Wilson. Not published. Measures by the author. K line of Ca^+ . Appeared in Lat. 29° N. on the east limb. No spot near prominence. $V = 21$ km/sec.	17 44 50 56 18 18 19 20	122 125 139 158 236
33. April 10, 1931. Observed by Hickox. 13-foot spectroheliograph at Mount Wilson. Not published. Measures by the author. K line of Ca^+ . Appeared in Lat. 35° N. on the west limb. No spot near. Measures of both crest and base are given. $V = 86$ km/sec.	17 11 18 21.5 41.4 47.8 18 11	189, 111 197, 125 217, 131 295, 206 320, 242 420, 330
34. August 22, 1930. Observed by Pettit with the Rumford spectroheliograph attached to the 40-inch telescope at the Yerkes Observatory. H line of Ca^+ . Appeared in Lat. 24° N. on the west limb. No spot near. Measures made on a small floating cloud which became detached from the head. $V = 4$ and 25 km/sec.	18 55.5 19 11.4 14.0 19.3 23.8 26.7 29.8 34.3 36.5 39.7 41.8 49.3 54.3 20 00.1 02.5 11.9 16.3 19.0 21.3	53.6 57.5 58.9 59.4 60.9 66.2 68.2 76.9 79.4 85.2 87.7 93.5 98.4 108.6 110.1 114.4 117.9 122.2 124.7
35. August 6, 1931. Observed by Pettit with the Rumford spectroheliograph with the assistance of H. S. Pettit and P. C. Keenan at the Yerkes Observatory. Measures by L. M. Ware, S. B. Nicholson, E. Hubble, and the author. The means of the measurements by all four observers are given in the table. Prominence appeared in Lat. 6° S. on the west limb. No spot or prominent surface marking near. $V = 5, 19, 74, 126,$ and 105 km/sec.	14 22.7 49.2 54.3 59.6 15 07.4 12.7 16.9 31.5 36.0 40.0 44.7 48.9	49.2 47.4 47.9 47.4 47.9 48.4 50.8 60.2 63.3 63.3 63.3 66.7

TABLE IV—*Continued*

Identity and Remarks	G.C.T. of Observation	Height in Thousand Kilometers
35.— <i>Continued</i>	15 ^h 52 ^m 8	67.9
	58.5	65.4
	16 03.9	70.0
	07.8	70.5
	11.8	71.5
	18.5	77.1
	23.3	82.3
	29.0	89.2
	32.8	94.8
	37.6	100.8
	42.5	103.1
	46.2	108.4
	50.6	113.3
	56.8	120.0
	17 00.7	124.6
	04.7	129.5
	07.6	135.1
	13.0	139.2
	16.8	145.8
	25.5	171.2
	30.4	180.5
	34.3	193.5
	38.8	212.3
	42.5	232.0
	46.3	247.4
	52.8	287.2
	56.0	312.5
	58.9	336.3
	18 05.7	387.2
	08.9	410.5
	11.7	427.1
	16.3	462.7
	19.1	480.6
	21.7	497.5
	30.1	530.6
	33.6	554.2
	36.4	570.0
	40.5	596.0
	43.0	605.0
	45.7	620.4

motion (*a*) was uniform with two sudden increases. Lee's detailed analysis of other parts of the prominence shows the same feature (*B, C, D, E, F*), *E* and *F* (see reference) evidently being affected by fading. Prominences Nos. 27, 28, and 29 also show uniform motion. Number 27 probably had more of the features of a class 3 prominence of the fountain type, and through the later stage of the eruption may have been moving nearly parallel to the solar surface.

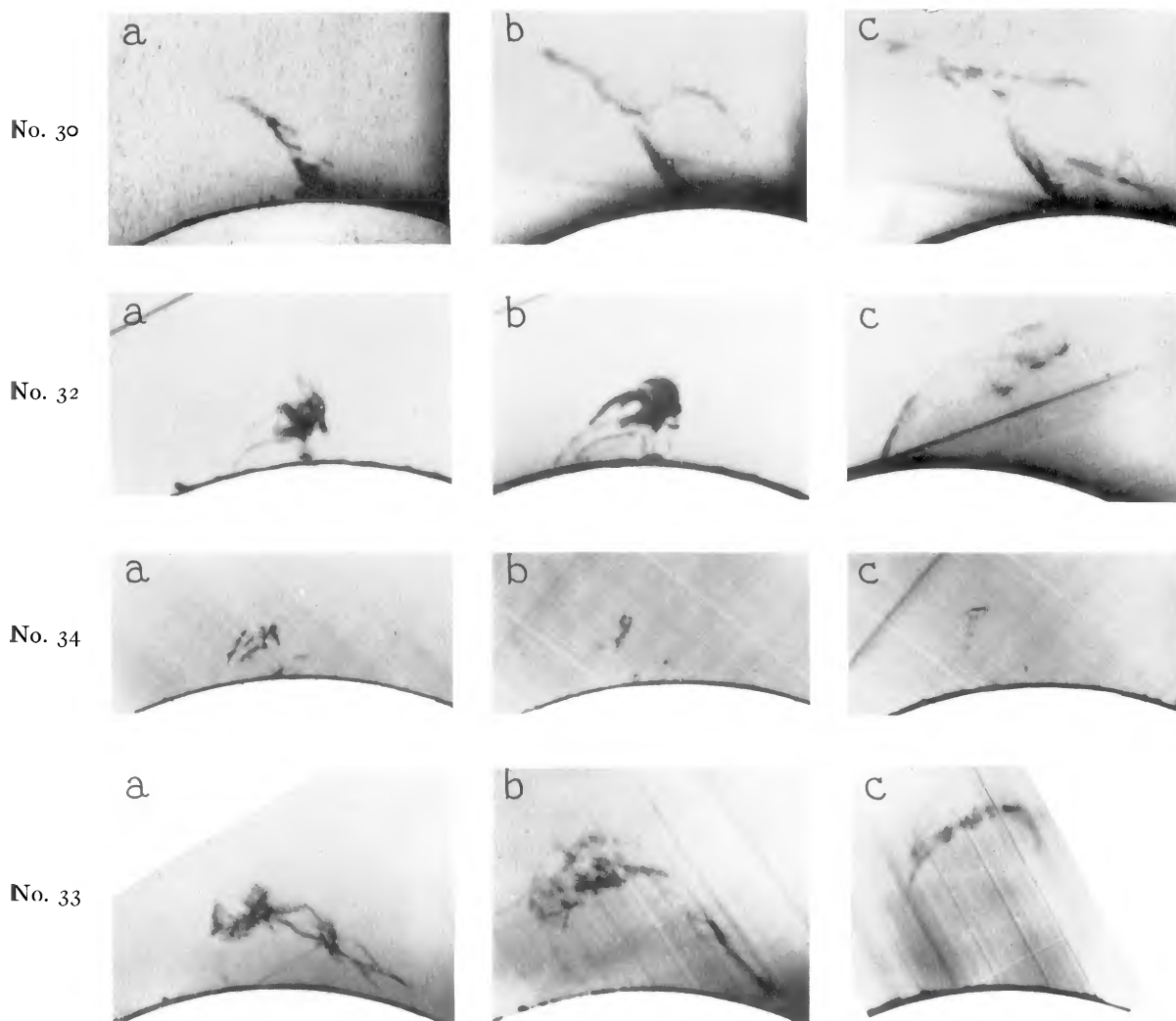
Number 29 in its last stages doubtless was affected by fading. Number 26 seems to be a clear case of accelerated motion, but the observations were made so far apart that we cannot be sure. The average interval between observations is 38 minutes, with one of nearly an hour. The frequency of the breaks in the well-observed curves is of this order.

3. *New material.*—This consists of No. 30, taken by Lewis Humason with the 13-foot spectroheliograph[†] at Mount Wilson, June 23, 1924; No. 31, June 18, 1929; No. 32, February 6, 1930; and No. 33, April 10, 1931—all taken with the same instrument by Joseph Hickox; No. 34, August 22, 1930, and No. 35, August 6, 1931, taken at the Yerkes Observatory with the Rumford spectroheliograph by the author, at the kind invitation of Professor Frost. The plots are shown in Figure 3. The 13-foot spectroheliograms themselves were on a scale of 27,800 km per millimeter, and those with the Rumford spectroheliograph, 7800 km per millimeter. Plate V shows three exposures each of Nos. 30, 32, 33, and 34, while Plate *Ib* shows twelve stages of No. 31; Plate VI shows seven stages of No. 35 taken in the H line of calcium and a comparative study of this prominence in the *H α* line of hydrogen with the spectrohelioscope. Plate III shows No. 35 in *H α* and in H and K just before the eruption began.

The measurements in nearly all cases refer to the highest point on the prominence. For Nos. 33 and, in part, 35 (Hubble's measures between 16^h7^m8 and 17^h7^m6), other points which could be identified in successive exposures have also been measured. The results are given in Table IV and in Figures 3 and 4. An unfortunate break in the series of exposures of No. 30 was due to an attempt to change objectives, which resulted in a change in orientation of the solar image, thus throwing the prominence out of the field. This leaves the curve somewhat doubtful in its middle part. The ends, however, are so well observed that there can be little question as to the character of the motion and velocity. Numbers 32 and 33 are represented by only a few points, but these are fairly well distributed, and, fortunately, no change in velocity occurred in either series.

[†] For a brief description of the 13-foot spectroheliograph see Hale, *Publications of the Astronomical Society of the Pacific*, 27, 233, 1915.

PLATE V



ERUPTIVE PROMINENCES

No. 30, Lewis Humason, June 23, 1924:

(a) 16^h47^m; (b) 18^h01^m3; (c) 18^h20^m

No. 32, Hickox, Feb. 6, 1930:

(a) 17^h50^m; (b) 18^h18^m; (c) 19^h20^m

No. 34, Pettit, Aug. 22, 1930:

(a) 18^h55^m5; (b) 19^h29^m8; (c) 19^h41^m8

No. 33, Hickox, Apr. 10, 1931:

(a) 17^h11^m; (b) 17^h41^m4; (c) 18^h11^m

Number 31 was fairly well observed, two breaks occurring in the velocity-curve.

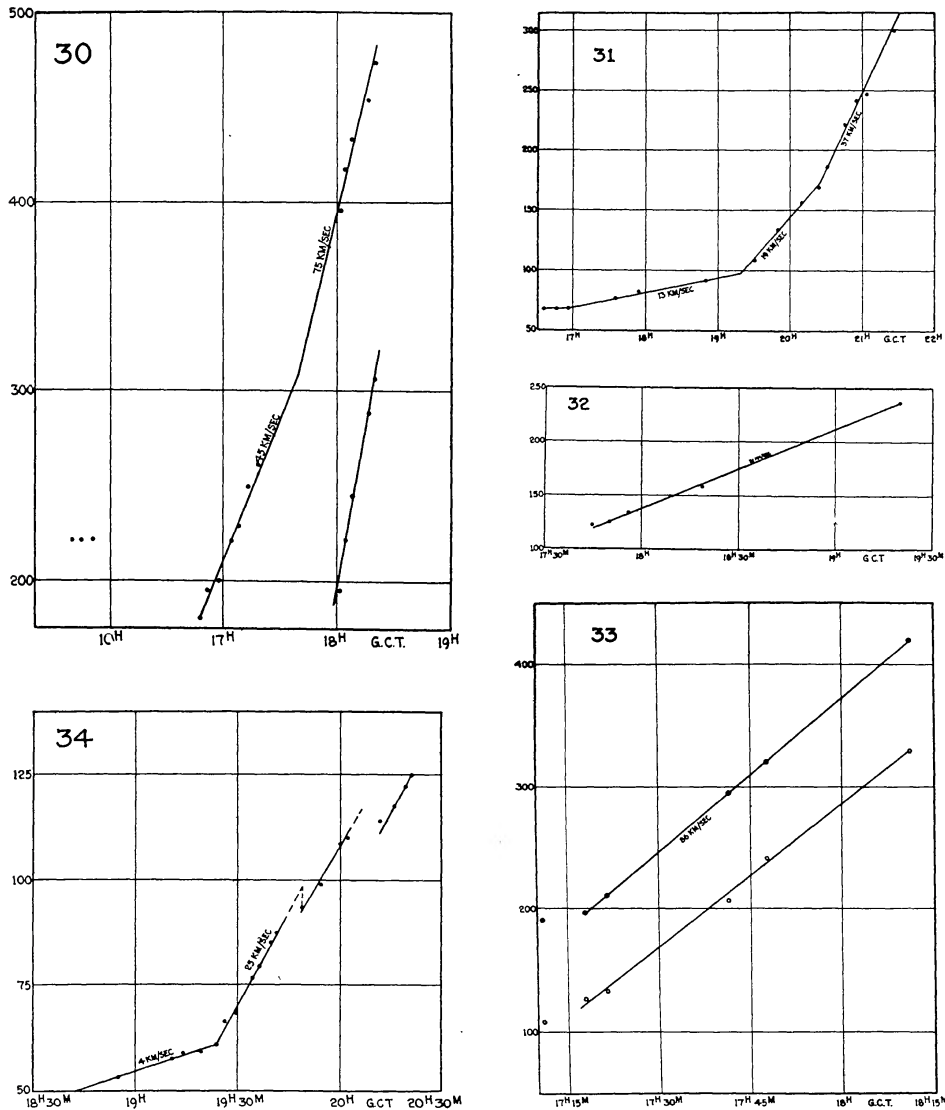


FIG. 3.—Motions of eruptive prominences (No. 30) June 23, 1924; (No. 31) June 18, 1929; (No. 32) February 6, 1930; (No. 33) April 10, 1931; (No. 34) August 22, 1930. The abscissae are times of observation (G.C.T.); ordinates, heights of prominence; unit=1000 km.

Number 34, observed by the author at the Yerkes Observatory, is a small prominence (Plate V) rising to only 125,000 km, but on the large scale of the 40-inch telescope it could be measured easily.

It appeared on the west limb of the sun in latitude 42° N. as an active prominence. In the late morning it finally developed into an expanding arch, the south end rising, and toward noon eruptive characteristics appeared. Plate V shows three stages of the prominence during the eruptive state. Exposures were made at the average rate of one for every 4.8 minutes.

The chief difficulty with most prominence observations is that only a few exposures are made, and those at intervals too great to be sure of the character of the changes taking place. If 15 or 20 minutes elapse between observations, a break in the velocity-curve may occur; and in an interval of an hour, two such breaks are possible; 5-minute intervals are about right, or better those of 3 minutes, if the instrument can be operated at such a speed. To accomplish this, an additional observer may be necessary, with an assistant to develop the plates, in order that the progress of the eruption may be known and suitable adjustments of the spectroheliograph be made.

Prominence No. 35, observed by the writer at the Yerkes Observatory with the Rumford spectroheliograph, presented an opportunity to obtain detailed information about the eruption over a considerable time. This prominence first appeared on the disk on July 29 as a faint absorption marking in $H\alpha$ on the central meridian. This would put it about one day, 13° , beyond the west limb at the time of the eruption on August 6. On July 30 it had developed strongly, and its thickness measured on the Mount Wilson plates was 8000 km. It then appeared as a hook-shaped marking 140,000 km long, the greater part making a small angle with a solar meridian, the south end bending off toward the west. On July 31 its angular distance from the center of the disk was sufficient to make possible a measurement of the height, which is equal to the measured height divided by the distance of the prominence from the center of the solar disk expressed in terms of the sun's radius. Table V shows the heights of this prominence at intervals during its life.

These measurements were made on the straight part of the prominence at a point where the eruption seemed to take place and, in general, represent the greatest apparent height. There was a steady growth over a period of four or five days, followed by a rapid decay

for two days preceding the eruption. The prominence may be seen on both $H\alpha$ and Ca^+ disk plates, and no special marking can be found in the flocculi within a radius of 30° . The nearest sun-spots were 350,000 km distant and of insignificant dimensions.

The crest of the prominence appeared on the limb on August 3, and during the succeeding three days exposures were made at short intervals. Its form on August 4 strongly suggested eruptive characteristics, but by the following day it had subsided, and on the morning of August 6 it was reduced to half its maximum height. The

TABLE V
HEIGHTS OF THE ERUPTIVE PROMINENCE (NO. 35) OF AUGUST 6, 1931,
AT LONG-RANGE INTERVALS THROUGHOUT ITS ENTIRE LIFE

Date G.C.T.	Height in Thousand Kilometers	Date G.C.T.	Height in Thousand Kilometers
July 29.71.....	Birth	Aug. 5.79.....	75
31.70.....	64	6.60.....	48
Aug. 1.63.....	67	6.65.....	64
2.61.....	92	6.70.....	114
3.60.....	103	6.75.....	342
4.69.....	100	6.78.....	620

eruption began on the fourth exposure (six exposures were recorded on each plate during the earlier stages of the eruption), at $15^{\text{h}}07^{\text{m}}4$, but did not push above the mass of surrounding streamers until $15^{\text{h}}16^{\text{m}}9$ U.T. A delay of 15 minutes before the next exposure was caused by the development of the first two plates and the call for assistance. After this short break a fairly regular exposure program, at the rate of one exposure each 5 minutes, was kept up until the prominence disappeared 3 hours later. The sky was excellent until the end of the eruption, when clouds intervened for 20 minutes. By the time they had passed, the crest of the prominence had entirely vanished, and only the ropelike stem remained. Throughout most of the eruption this stem appears to have had a spiral structure which had become strongly developed when the stem faded away. Long streamers from the head descended to the base along a curved line nearly parallel to the stem, with velocities of about 125 km/sec. as they neared the chromosphere. Knots in the base of the prominence moved from the brighter part of the stem in streams into the chro-

mosphere at about 40 km/sec. during the last stages of the eruption. This streaming of the prominence into the chromosphere at the same time it is rising is characteristic of an eruption, at least of all those that the writer has witnessed. A considerable part of the fading of the prominence can be accounted for in this way.

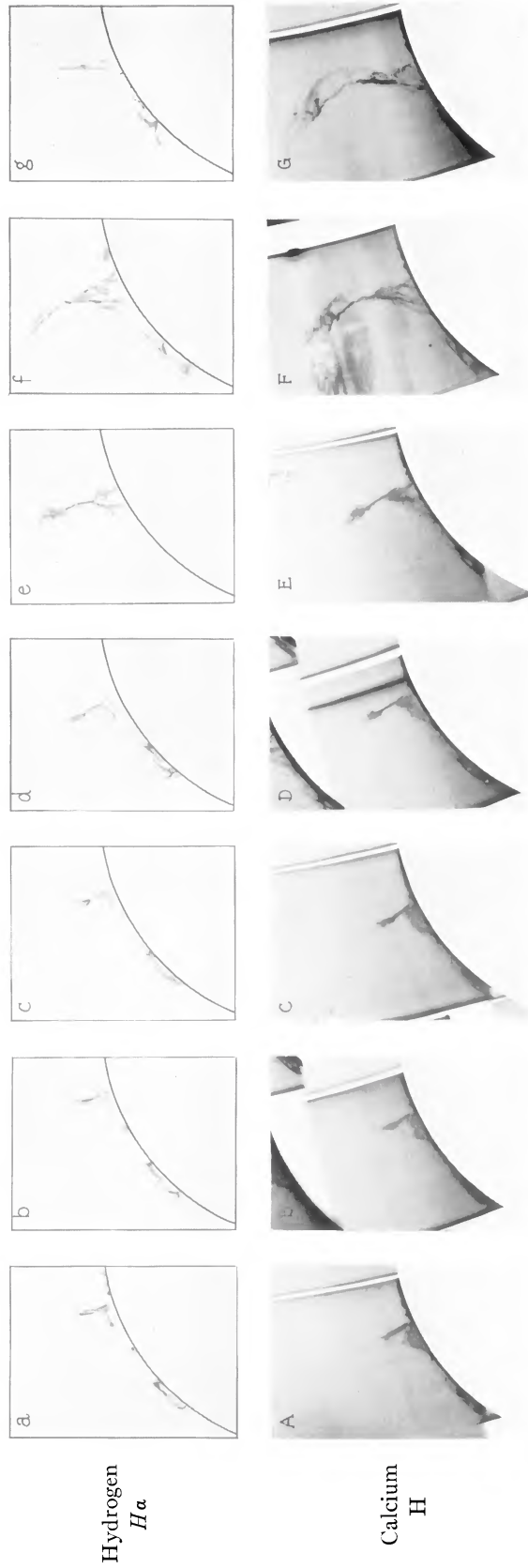
During the eruption, drawings of the prominence in $H\alpha$ were made with the spectrohelioscope[†] at Yerkes by Mr. P. C. Keenan, Miss Calvert, and Mr. W. W. Morgan. These are illustrated in Plate VI, together with the corresponding photographs in the H line of Ca^+ . A close general correspondence will be noticed. The evidence, therefore, is that in eruptive prominences, also, the hydrogen and calcium are rather thoroughly mixed. In (*f*) the crest and its streamers are entirely missing from the drawings, and in (*g*) only the brighter part of the stem appears. This lack of streamers and fainter clouds, as seen in $H\alpha$, is in keeping with the phenomena of other classes of prominences and is possibly an instrumental effect. Some evidence for this explanation is afforded by the report of Keenan and Morgan that at 18^h40^m the prominence had entirely disappeared in the spectrohelioscope, while the head could be seen on the calcium spectroheliograms faintly and the stem easily as late as 19^h10^m, a half-hour later.

The heights of the crest of this prominence are plotted in Figure 4. Measures of the radial velocity were made at Yerkes and Mount Wilson with spectrohelioscopes of the same construction. At 18^h U.T., Keenan reported, "The broad top of the prominence shows a shift to the red corresponding to about 38 km/sec.," and Morgan states, "There is a slight progressive shift as the distance from the sun increases." Nicholson and Hickox at Mount Wilson found "shifts to the red of 70 to 120 km/sec. at 15^h45^m U.T.," after the eruption had fairly begun and the prominence had an upward velocity of 5 km/sec.

The study of this prominence has involved 209 exposures at the Yerkes Observatory, of which 54 were made during the eruption on August 6; 53 exposures at Mount Wilson, made chiefly while the prominence was on the disk, of which only 2 showed it in the eruptive state; and 14 visual observations of form and velocity made at

[†] *Mt. Wilson Contr.*, No. 388; *Astrophysical Journal*, 70, 265, 1929.

PLATE VI



Hydrogen
 $H\alpha$

Calcium
H

DRAWINGS (*a, b, c, d, e, f, g*) OF THE ERUPTIVE PROMINENCE OF AUGUST 6, 1931, MADE IN THE $H\alpha$ LINE OF HYDROGEN COMPARED WITH PHOTOGRAPHS (*A, B, C, D, E, F, G*) MADE IN THE H LINE OF CALCIUM AT THE YERKES OBSERVATORY

(*aA*) 16^h50^m5; (*bB*) 17^h00^m7; (*cC*) 17^h13^m0; (*dD*) 17^h30^m4; (*eE*) 17^h46^m3; (*fF*) 18^h05^m7; (*gG*) 18^h10^m1.
 Drawings (*a*), (*b*), (*c*), (*d*), and (*g*) by Keenan; and (*e*) by Morgan; and (*f*) by Miss Calvert, copied from the spectrohelioscope notebook by Miss Calvert and checked by the other observers before she or they had seen the photographs. The cloudy marking to the left of the head of the prominence in exposure *F* is a plate defect.

Yerkes and Mount Wilson. Altogether this is perhaps the best-observed prominence so far recorded. An account of the prominence during the active stage will be reserved for a discussion of prominences of class 1.

4. *Measurements of heights by several individuals.*—To test the impartial character of the measurements of the heights of the prom-

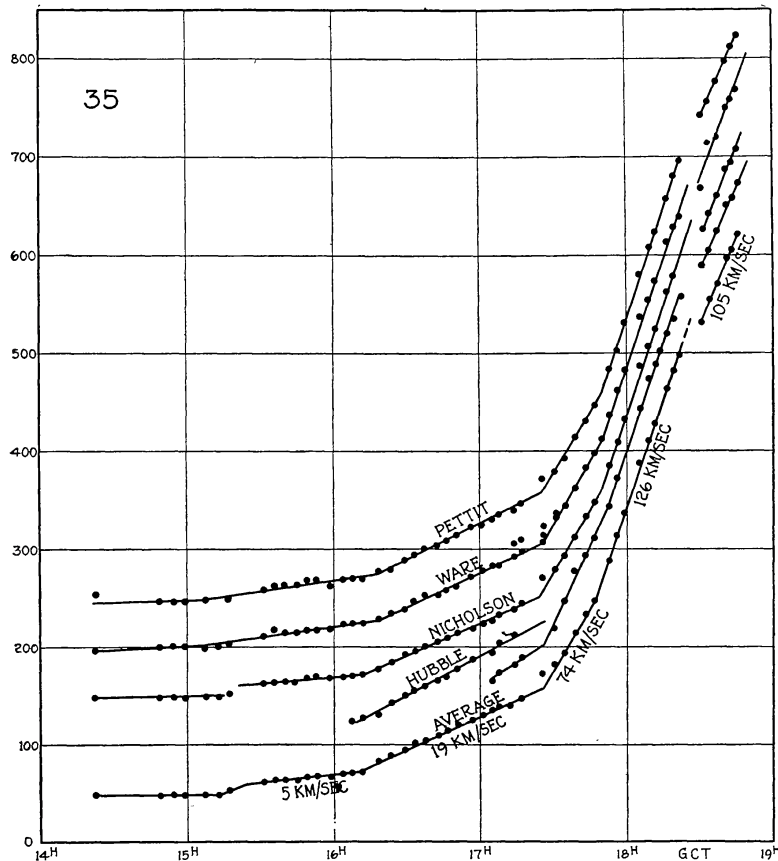


FIG. 4.—Motion of the eruptive prominence (No. 35) of August 6, 1931, as measured on the same plates by different individuals. The scale of ordinates (unit, 1000 km) refers to the "average" plot. The plot of Hubble's measures is raised 50,000 km, Nicholson's 100,000 km, Miss Ware's 150,000 km, and the author's 200,000 km, in order to separate the curves. Abscissae are the times of observation (G.C.T.)

inence of August 6, 1931, the author has asked several of his colleagues to measure the plates independently. The results are presented in Figure 4, where the plots have been separated in ordinate by an amount equal to 50,000 km. The scale to the left corresponds

to the "average" curve. Mr. Hubble's curve is raised 50,000 km; Mr. Nicholson's, 100,000 km, etc. The values in Table IV are the averages of all these measurements. Hubble, experienced in the study of faint nebulosity, has traced the faintest detail visible at the crest which appears to be continuous. Nicholson, Miss Ware, and the author have apparently measured about the same thing, the readily apparent crest. Miss Ware seems to have caught the faint detail seen by Hubble at the break in the curve near $17^{\text{h}}20^{\text{m}}$. Hubble's points are all a little higher than those of the other observers. The plot of the averages appears at the bottom of Figure 4. The result must be apparent to everyone, and there can be no escape from the conclusion that the motion was uniform, with three sudden increases in velocity. The decrease in velocity shown by the detached part of the curve is a phenomenon probably connected in many cases with fading, but scarcely in this prominence, as the object measured was a faint knot which became detached from the crest and floated away.

I think it must be granted that in none of the cases presented here, Nos. 30-35, is one warranted in describing the velocities of the prominences as other than uniform. For Nos. 25-30 uniform motion is also generally apparent, except in No. 26, which must be regarded as a doubtful case on account of the scarcity of the observations. If we pick out at random six or seven points along the curve of No. 35 and plot them, the conclusion would probably be the same as that for No. 26.

One is naturally led to inquire as to just what conditions may produce the upward motion of an eruptive prominence. E. A. Milne¹ states that the chromosphere is in any event held up by light-pressure and thereby calculates the average lifetime of an excited calcium atom. That his result is reasonable is an argument that light-pressure is responsible for the existence of the calcium chromosphere. He has suggested² that, once the prominence begins its vertical motion, the Doppler shift of the absorption line will expose the atom to the neighboring continuous spectrum and thus introduce an increasing acceleration.

¹ *Monthly Notices of the Royal Astronomical Society*, **84**, 354, 1924.

² *Ibid.*, **86**, 474, 1925.

It remains to be shown, however, why this effect would not lead to a separation of the hydrogen and calcium atoms. The prominences disappear as absorption markings on the disk in K spectroheliograms when the slit-width is greater than about 1 Å, and do not show strongly unless the slit is set to include only the doubly reversed center of the line, that is, about 0.2 Å. The effective width of the H and K absorption lines in the prominences is therefore 0.2 Å, while their width in the photospheric spectrum is 10 Å. It follows that with increasing velocity of ascent the absorption lines of Ca^+ in prominences will move gradually along the V-shaped absorption lines of the photosphere and reach fully unobstructed photospheric light only when the velocity of the prominence is 385 km/sec.

The $H\alpha$ absorption line has, on the other hand, about the same width, 1 Å, in both prominences and photosphere, for the prominences still show faintly as absorption markings when the spectroheliograph slit is set at the extreme edge of the $H\alpha$ line. Hence the $H\alpha$ line of the prominences would be fully exposed to the photospheric light at a velocity of 45 km/sec. At this velocity the absorption line of the Ca^+ atom has moved only about a half-angstrom from the center of the K line in the photosphere, and still has $4\frac{1}{2}$ Å to move before reaching the unabsorbed light. The velocity vector of Ca^+ due to light-pressure can therefore be but little disturbed when the $H\alpha$ line has received the full effect.

As already noted, eruptive prominences seem to show no separation of the atoms of neutral hydrogen and ionized calcium, and it therefore still remains to be shown that such an effect exists, if light-pressure is to be accepted as an explanation of the motions of eruptive prominences.

Pike,¹ starting with Milne's theory, discusses the effect of bright neighboring areas on the prominences already in equilibrium with radiation pressure and finds² that facular areas of the order 200,000 km square radiating in the region of H and K at an effective temperature of 7500° K would produce the average observed velocities of eruptive prominences. R. K. Sur³ has made calculations on the same lines. W. H. McCrea⁴ discusses the physical theory of light-

¹ *Ibid.*, 88, 3, 1927. ² *Ibid.*, p. 22, 1927. ³ *Astrophysical Journal*, 63, 111, 1926.

⁴ *Monthly Notices of the Royal Astronomical Society*, 89, 483, 1928.

pressure on excited atoms of hydrogen in the chromosphere and finds that radiation pressure can support only about one-tenth the gravitational pull of the sun, and later¹ introduces the idea of turbulence to account for the remainder. N. T. Bobrovnikoff² has computed the central force necessary to produce the observed motions in eruptive prominences whereby arcs of parabolas were made to approximate the observed straight lines of the motion diagrams.

In all these theoretical considerations a continuously accelerated motion is postulated, which is in contradiction to the principle of uniform motion found in these investigations. It would seem that any adequate explanation must account for the observed motions.

TABLE VI

L	B^2	R	Vol. = LB^2	$2R^6$
13.....	9	94	117	138
12.....	36	114	432	438
15.....	49	123	735	692
20.....	64	134	1280	1162

Our inability to understand how prominences can have uniform motion of ascent may be due, in part at least, to a neglect of the presence of the corona through which it moves. It is well known that bodies of gas lighter than air inclosed in rubber balloons ascend in our own atmosphere with uniform motion,³ the expansion of the gas keeping pace with the decreasing density of the atmosphere—this in spite of the constant accelerative force of levitation. That an analogous condition exists in prominences is suggested by the following argument.

If we suppose that the head of prominence No. 35 expanded in the line of sight at the same rate as in the other two dimensions, we can determine its volume for any moment in arbitrary units by multiplying the length L of the head by the square of its breadth B . The results are shown in Table VI. Here the dimensions of the prominence are in units of which the solar radius $R = 89$.

A comparison of the last two columns of Table VI indicates that

¹ *Ibid.*, p. 718, 1928. ² *Astrophysical Journal*, 74, 157, 1931.

³ Sir N. Shaw, *Manual of Meteorology*, 1, 222, 1926.

the volume of the prominence appears to vary nearly as the sixth power of the distance from the center of the sun, and that the inverse relation would hold for the density d , namely, $d \approx R^{-6}$.

Let us compare the variation in density of the prominence with that of the corona.

THE CORONAL DENSITY GRADIENT

We know that the apparent visual intensity of the corona¹ varies inversely with the seventh power of the distance from the center of

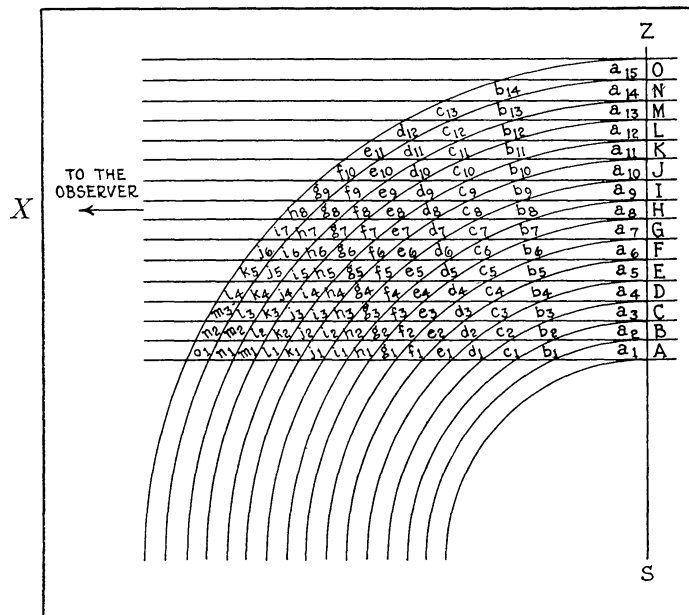


FIG. 5

the sun. To obtain from this an expression of density, let us first determine the actual variation of intensity of the light in a unit volume (the volumetric brightness) of concentric shells of equal width in the corona. It will be necessary to assume that the intensity in these shells varies according to various powers of R until one is found that yields a computed apparent coronal intensity which varies inversely with the seventh power of R .

Let Figure 5 represent a cross-section of the concentric shells in the plane of the observer (in the direction X), each shell of the thickness 0.1 radius of the sun. Since the figure is symmetrical about the

¹ *Mt. Wilson Contr.*, No. 299; *Astrophysical Journal*, 62, 202, 1925.

line SZ , we shall need to consider only that part of the corona to the left of this line. The intensity of the light directed to the observer by a shell of the corona is represented by that included in the equal tubes indicated by the spaces between the horizontal lines. The light contributed by each shell to any tube is given by the volume of the shell cut out by the tube (length may be used as a measure of volume), multiplied by the volumetric brightness of the shell (or zone). If we represent the volumetric brightness of each shell by A, B, C, \dots , etc., and the corresponding volumes of the portions of the shells intercepted by the tubes by $a_1, b_1, c_1, \dots, a_2, b_2, c_2, \dots, a_3, b_3, c_3, \dots$, etc., the total light L_1, L_2, L_3 , etc. entering the first, second, and third tubes in the direction of the observer is given by

$$\begin{aligned} L_1 &= Aa_1 + Bb_1 + Cc_1, \dots, \text{ etc.}, \\ L_2 &= Ba_2 + Cb_2 + Dc_2, \dots, \text{ etc.}, \\ L_3 &= Ca_3 + Db_3 + Ec_3, \dots, \text{ etc.}, \text{ etc.}, \end{aligned}$$

and the sequence can be extended to any shell. The results of the summations for values of A, B, C , etc., depending on the volumetric brightness \bar{B} varying according to R^{-7} and R^{-8} are given in Table VII.

The quantities in the fourth and fifth columns have been multiplied by factors which make the figures directly comparable with those in the third column. It will be noted at once that the third and fourth columns agree very well, while the third and fifth do not. It follows, then, that if the apparent brightness of the corona varies inversely with the seventh power of the distance from the center of the sun, the real intensity or volumetric brightness of the contributing shells varies inversely with the eighth power of their radii. This result is a little surprising since one would expect the greater optical path toward the limb of the sun to make the apparent brightness greater than the real. This, however, is counterbalanced by the very steep intensity gradient toward the limb.

If we assume that the coronal particles shine by reflected light, their intrinsic brightness will vary inversely with the square of R , making the outer corona too faint. Since we have found that the brightness actually varies inversely as the eighth power of R , it fol-

lows that if the particles were equally illuminated, the volumetric brightness of the corona would vary inversely with the sixth power of R , and therefore the actual density follows the same law, viz., $d \approx R^{-6}$.

We have already seen in Table VI that the density of the prominence of August 6, 1931, follows the law $d \approx R^{-6}$, and we may conclude that we have here a volume of gas that expands as it rises, keeping its density about in step with that of the corona.

TABLE VII

Shell No.	R	R^{-1}	L When $\bar{B} \approx R^{-8}$	L When $\bar{B} \approx R^{-7}$
1.....	1.05	0.714	0.679	0.500
2.....	1.15	.370	.381	.305
3.....	1.25	.208	.204	.176
4.....	1.35	.122	.123	.113
5.....	1.45	.074	.081	.078
6.....	1.55	.056	.052	.052
7.....	1.65	.030	.032	.034
8.....	1.75	.020	.020	.021
9.....	1.85	.014	.014	.015
10.....	1.95	.009	.009	.010
11.....	2.05	.007	.006	.007
12.....	2.15	.005	.004	.005
13.....	2.25	.003	.003	.004
14.....	2.35	.002	.003	.003
15.....	2.45	0.002	0.001	0.001

It is difficult to find any explanation for the sudden increases in velocity. The corona is about as non-homogeneous as possible, being made up almost entirely of streamers radiating from the sun in curved lines. Perhaps these streamers carry high-speed electrons which, passing through the prominence, give it the necessary impulse. As yet all this is speculative, for we know nothing of the actual working of this phenomenon, although its presence in terrestrial magnetic storms is fairly well established.

Another feature of eruptive prominences which finds its analogue in terrestrial meteorology is their tendency to become spiral. Number 35 showed this feature in the narrow stem in the later phases of the eruption. That of May 29, 1919, exhibited it on a gigantic scale in the last stages, when the whole prominence formed a spiral ribbon. In fact, all the eruptive prominences I have examined, with

the exception of No. 3, showed this tendency, particularly in the later stages of the eruption.

TORNADO PROMINENCES (CLASS 4)

The spiral form in a prominence sometimes gives it the appearance of a closely wound rope or screw. Plate II, class 4, shows an example photographed at intervals of about seven minutes. The phenomena remind us of the small desert dust storms which appear as whirling columns, the angular velocity finally becoming so high that the vortex explodes, as shown in the case of the prominence, by the third exposure. These objects are relatively small and require good atmospheric definition to show the spiral structure. Seventeen cases with three available exposures each were found among the photographs taken with the 13-foot spectroheliograph at Mount Wilson during the last sun-spot cycle. They average 12,000 km in diameter and 53,000 km in height, but vary from 5600 to 22,000 km in diameter and from 25,000 to 97,000 km in height. In every case a faint, diffuse, smokelike column issues from the top of the vortex, often bent over and, in some cases, touching the chromosphere.

In no case is any lateral motion of the whole spiral toward the north or south detectable, although in two cases the time interval between the first and third exposures was 1^h45^m and 2^h30^m, respectively. The customary interval was 12–24 minutes. Unfortunately, we have no direct method of detecting these objects on the disk unless it be from a spiral form in the surrounding flocculi, and we therefore do not know whether there is any proper motion in longitude.

QUIESCENT PROMINENCES (CLASS 5)

An example of class 5 is illustrated in Plate II. This prominence was photographed at the Yerkes Observatory on August 21, 1930. In all, 55 exposures were made between 14^h20^m and 19^h40^m U.T., most of the series being at intervals of 5 minutes. The plates were measured by Miss Ware with the blink comparator. Figure 6, a plot of the observed vectors, shows that the prominence is in a state of turbulence. Velocities of 5–10 km/sec. are common, but 15 km/sec. is rare. The form changed only slightly during the day, the three exposures in Plate II made by Hickox at Mount Wilson showing it

at a time of maximum change. It thus seems that the quiescent state is simply one in which the rate at which the prominence receives material from the chromosphere is the same as that at which

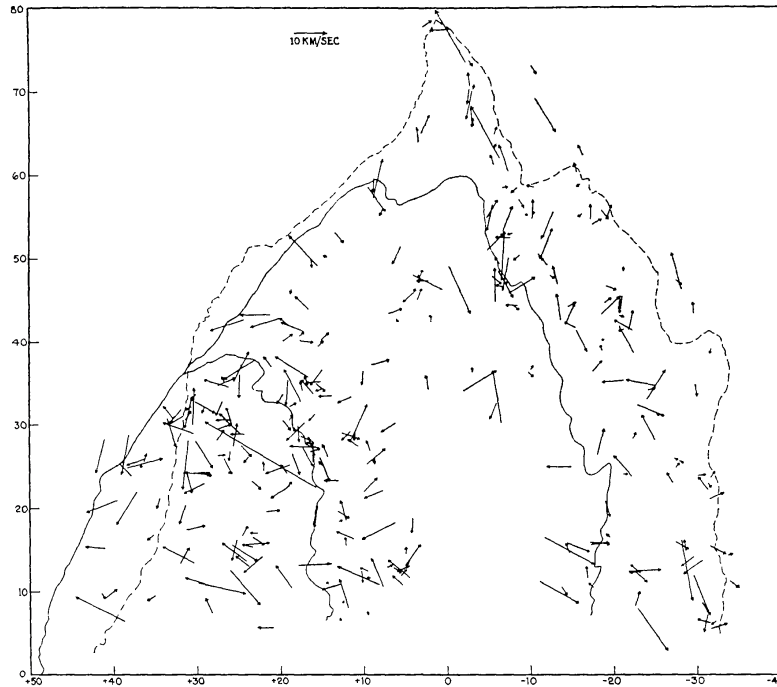


FIG. 6.—Internal motions of the quiescent prominence of August 21, 1930, during the interval 14^h20^m to 19^h40^m G.C.T. The co-ordinates are in units of 1000 km. The dotted line shows the outline at the end of observation.

it returns it. Additional data concerning this class and classes 1 and 3 will be reserved for a future discussion.

My thanks are due to Professor Frost for the use of the Rumford spectroheliograph at the Yerkes Observatory; to Mr. Keenan and Mrs. Pettit for assistance; to Mr. Hickox and Mr. Nicholson for assistance at Mount Wilson; and to Miss Ware and Miss Richmond for aid in the measurement and reduction of the observational material.

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