A STUDY OF THE SOLAR CORONA AND PROMINENCES WITHOUT ECLIPSES

(*George Darwin Lecture, delivered by M. Bernard Lyot, Assoc.R.A.S., on* 1939 *May* 12)

The rareness of total eclipses of the Sun, their short duration and the distances one has to travel to observe them, have, for more than half a century, led astronomers and physicists to seek for a method which enables them to study the corona at any time.

The first attempts made to reveal the corona without an eclipse date from 1878. It would take too long to enumerate all those that have since been made. Most of the observers simply photographed that part of the sky where the Sun was, either direct or through coloured filters. An opaque disc, somewhat larger than the image of the Sun, was placed at the focus of the instrument to screen off the direct rays of the Sun and so avoid the photographic halo. At first, only blue, violet and ultra-violet rays were used; but, later on, from 1904, the progress of sensitising allowed the use of red and infra-red radiations, which are not so scattered by our atmosphere. A great number of plates have thus been obtained, generally from high places, sometimes at an altitude of more than 4000 m., and in a very pure atmosphere. They show halos, often irregular, surrounding the Sun, and resembling the corona. Unfortunately, these halos have been obtained with exposures much too short to register the corona itself; they do not show the prominences which are more brilliant than the corona, and, during partial eclipses of the Sun, they even spread on the disc of the Moon without showing the limb of our satellite, which should have been outlined by the light of the corona. These halos were due principally to the light of the Sun scattered by the lens or the mirror of the telescope.

Other observers applied indirect means. In 1893, Deslandres, and after him Hale and Ricco on Mount Etna, tried, but without success, to photograph the corona by isolating the dark K line of the solar spectrum with the spectroheliograph. The inner corona, which has no absorption lines, thus should have appeared relatively more brilliant.

I might mention also: (1) The thermo-electrical procedures tried in 1900 by Hale, then by Deslandres, to detect the infra-red radiations of the corona; (2) the polariscope of Savart used in vain by Wood, to recognise the polarised light of the corona; (3) the spectroscope used by Millochau, in 1906, to look for the green line of the corona close to the limb of the Sun. In consequence of these numerous failures, the problem had long been considered impossible.

In October 1929 I had the pleasure of speaking with the late Professor Henry Osmund Barnard, former Director of the Observatory at Colombo, Ceylon, and giving him the results I had obtained on the planets with my

polarimeter, sensitive to a proportion of polarised light of one-thousandth. Professor Barnard advised me to renew the attempts of Wood with this polarimeter.

The measurements made during eclipses showed that the brightness of the corona, at 2′ from the Sun's edge, is about a million times less strong than that of the solar disc. To succeed, it therefore appeared necessary, above all, considerably to reduce the diffusion of the light by the telescope. This is clearly shown by the following experiment :—

Diffusion by a Lens.—Let us take, for example, a single lens, 8 cm. in diameter and 2 m. in focal length. At a distance of 10 m. let us place a very intense source of light having the same apparent diameter as the Sun, and, with the lens, form a picture of the source on an opaque disc somewhat larger than this image. If we place the eye behind the edge of the disc we see that the lens is not black.

Two photographs of the lens are seen in fig. 1. Its edge is very brilliant, principally on the side of the source and on the opposite side. This illumination is due to the diffraction of the waves round the edge of the aperture. It fades rapidly when the observer removes his eye from the image of the artificial sun, thus producing around the disc a halo fading towards the exterior. This halo is very strong ; according to a more recent calculation of Nagaoka, at 2′ from the edge of the image, its brightness is 3000 times less strong than the Sun's—that is to say, about 350 times stronger than the corona's. At any distance the halo is more than 200 times stronger than the corona, which renders observations impossible.

A small bright disc is seen in front of the centre of the lens ; it is an image of the artificial sun reflected by the two faces of the lens. The lens appears studded with bright points due to the light diffracted by small bubbles in the glass, small hollows on the surfaces, and particles of dust deposited on them. If the eye follows the circumference of the disc, trails are seen lighting up and fading away twice in every turn. The shortest of these are scratches on the surfaces; the longest are veins in the glass. Some veins are very faint and not otherwise visible. The background of the lens is generally not black, but covered with a slight mist, due to an imperfect polish. The veins can be stereoscopically localised by using these two photographs taken by inclining the lens in two opposite directions. This lens was cut from plate glass. In another photograph showing a lens 15 cm. in diameter cut from a disc of borosilicate crown glass, the veins have a less regular form. During the last few years the firm Parra-Mantois has succeeded in producing discs in which not a single vein is seen.

This experiment shows the necessity of making a lens as flawless as possible. It is necessary to grind it from a thick disc, choosing the most homogeneous part, and to polish the surfaces for a very long time, without making scratches.

Coronagraph.—The principal defect, that is to say, the light diffracted by the edge of the lens, still had to be overcome. With this object I have made several coronagraphs, of which the plan is seen in fig. 2 (Plate 11).

The single lens, plano-convex, is shown at A ; it forms an image of the

Sun on a blackened brass disc at B projecting beyond the Sun by 15″ to 20″. A field lens C, placed behind the disc, produces an image of the lens A on the diaphragm D in the shadow. The edge of the diaphragm cuts off the light diffracted by the edge of the first lens. A small screen placed in the centre of the diaphragm cuts off the light of the solar image produced by reflection on the surfaces of the lens A. Behind the diaphragm and the screen, protected from the diffused light, a carefully corrected objective E forms an achromatic image of the corona on the plate. The whole apparatus is contained in a tube F, open only during the observations, and coated with thick oil in the interior, to collect the particles of dust. The first lens must be wiped frequently, and with particular care.

Atmospheric Diffusion.—To give good results, the coronagraph must be in a high place, because the dust, which is always present in the lower layers of the atmosphere, produces a whitish aureole of diffracted light around the Sun. This varying aureole is generally more than a hundred times brighter than the corona. The distance to which this aureole spreads varies in inverse ratio to the diameter of the particles producing it; a few degrees for dust, 5′ to 10′ for the ice crystals of cirrus. When the sky is perfectly clear, the aureole completely disappears, and the brightness of the atmosphere, in red light, diminishes to half a millionth of that of the Sun—that is to say, becomes fainter than that of the corona.

From observations made in the mountains, it appears that the particles of dust are carried by rising currents of air due to the heating of the ground by the Sun's rays; a layer of air, relatively warmer, suffices to stop them, and they then spread out widely, forming a horizontal sheet of a brownish colour. The height to which the dust rises increases during the period of fine weather and decreases when it rains or snows; it is greater in summer than in winter, greater towards the equator than towards the pole. In France, during the summer, the highest level of dust is often between 2500 m. and 3000 m. This fact has led me to set up my apparatus in the Observatory of the Pic du Midi, situated in the Pyrenees at an altitude of 2870 m. above sea-level.

The Observatory of the Pic du Midi.—This observatory offers advantages not found anywhere else for studying the corona: on the one hand, a sky, the pureness of which is often perfect, chiefly at the end of spring and the beginning of summer; and, on the other hand, a dome containing a very firm equatorial, 6 metres in length, on which heavy and cumbersome apparatus can be fixed.

Fig. 3 (Plate 12) shows a view of the observatory taken on 1937 June 29. It is built on a small terrace surrounded with very steep slopes, 15 m. below the summit of the Pic du Midi, separated by 30 km. from the axis of the chain of the Pyrenees. Snowfalls, frequent in spring, purify the air, whilst the sea of clouds remains a long time below the terraces and prevents the dust from rising. The rooms in which we live, seen in the middle of the photograph, are provided with central heating, running water and electricity. The dome opens and revolves electrically. During August and September the observatory is generally free from snow; in winter and spring, on the

contrary, the buildings disappear under the snow sometimes more than 5 metres deep. The snow on the roof slides, in part, to the outside, by the action of the Sun, forming ice-grottoes which sometimes remain till June. The dome is provided with a special apparatus protecting the rail from snow and allowing it to turn throughout the winter. During August and September the observatory is quickly reached by a road rising to 2600 m.; it takes a month to clear it of snow. In winter and spring the road completely disappears under the snow and one must go on foot.

Figs. 4 and 5 show some views of the ascent taken on 1936 June 5. One must leave the road at a height of 1100 m. and follow a higher valley, seen in fig. 4, leading to the foot of the Pic du Midi, visible at the end. The carriers leave their mules there, take the apparatus on their backs, and climb towards the left. At a height of 1800 m. (fig. 5) they reach an upper valley, in which they have to take to their skis. In the centre of the picture is the tube of the last coronagraph, closed like a telescope. At 2500 m. the carriers reach a ridge, not exposed to avalanches, by which they climb to the summit, in some places holding on to an iron cable. The observers follow the same route. The ascent takes seven to ten hours, according to the state of the snow.

My work on the corona so far has been made in two stages: the first one from 1930 to 1934, during which I sought to test the new method to obtain the principal results found during eclipses; the second stage, since 1934, during which I tried to obtain new results.

Observations made in 1930.—The first coronagraph was built in the Observatory of the Pic du Midi, and fixed on the equatorial on 1930 July 25. This very primitive apparatus contained the lens 8 cm. in diameter an 2 m. in focal length, the defects of which have been seen in fig. 1. This lens was placed in a tube built with planks found on the spot. An eye-piece, a polarimeter or a direct vision spectrograph could be fixed at the end of the tube. After reducing the aperture to 3 cm. to hide the principal defects of the lens, prominences with a violet-pink tint were seen. The use of a red glass greatly increased the contrasts and allowed of good observations.

The Sun was surrounded by a slight halo without details. The polarimeter showed that this halo was polarised in a radial plane like the corona, but more faintly. The polarisation appeared at 6′ from the limb; it increased rapidly towards the Sun and then remained almost constant under 3′. The more transparent the sky, the stronger it was.

Diagrams drawn from the observations * show the proportion of polarised light found in different directions at 80″ from the edge of the Sun, on 1930 July 29 and July 31. The axis of the Sun was inclined 10° to N.E.; all the diagrams show minima at the poles and maxima above the zones of the sunspots. The proportion of polarised light attained, in some parts, 20- to 25-thousandths, about one-fifth of that of the corona. We can conclude that, in these parts, one-fifth of the light of the halo belonged to the corona, the rest being due to diffusion. On July 30 and the following days the

* *L'Astronomie*, **45**, 248, 1931.

spectroscope showed, in the light of the halo, among the solar lines due to diffused light, an emission line, with a wave-length equal to that of the green line of the corona within 1 angstrom.

The first photograph of the spectrum of the corona without an eclipse * was taken on 1930 August 8, with the slit of the spectrograph tangential to the eastern edge of the Sun. When the slit of the spectrograph was moved, the green line underwent great changes in intensity, agreeing with the indications of the polarimeter. By covering the head with a black cloth the red line was seen, but fainter, and with variations of intensity different from those of the green line.

Observations made in 1931.—On 1931 June 12 I again ascended the Pic du Midi with a more elaborate apparatus which had been prepared during the winter in the Meudon Observatory. This apparatus consisted principally of a larger lens, 13 cm. in diameter and 3·15 m. in focal length, ground

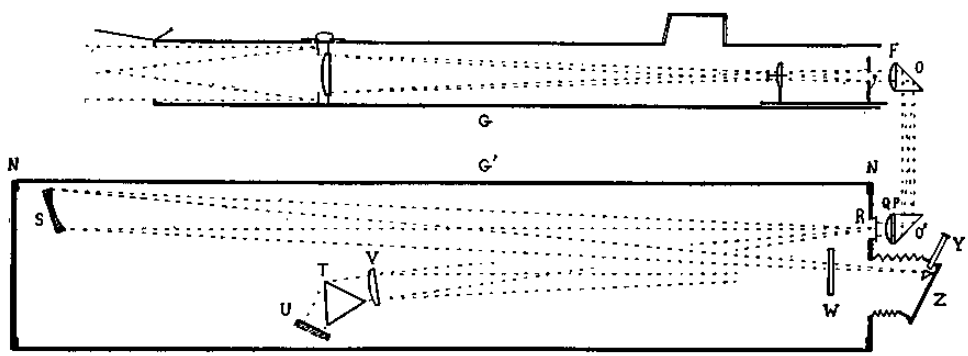

FIG. 6.—*Plan of the coronagraph and the spectrographs used in 1931.*

in the Institut d'Optique de Paris, as well as the chief parts of two large spectrographs and of a spectroheliograph.

Fig. 6 shows the general plan of the installation set up on the Pic du Midi during June and the beginning of July; G is the coronagraph; a lens F, followed by two totally reflecting prisms O and O′, casts a picture of the corona on the slit R of the spectrograph. The second prism is followed by a coloured filter P and a field lens Q concentrating the rays on the grating S. This 6-inch grating is concave with a radius of 7 m.; it forms the spectrum on plate Z. A cylindrical lens W corrects the astigmatism, narrows the spectrum, and increases its brightness. By turning the prism O′ the rays can be thrown on to a prism T with a side of 16 cm., working with a Littrow setting between a plane mirror U and a lens V, 3·60 m. in focus. The pieces of both spectrographs are set up in the tube G′ of the telescope and regulated from the eyepiece by means of seven controlling tubes. Both spectrographs underwent considerable flexures, displacing the lines on the plate more than half a centimetre. To correct these flexures, the plate-holder was furnished with correcting screws and with a microscope Y, in which the observer followed a monochromatic picture of a hole lighted up by an iron arc. The first totally reflecting prism could be turned a little at a time by means of an electro-magnet and a ratchet wheel; this rotation constituted

* *Loc. cit.*

the first movement of the spectroheliograph. The frame could be moved in its slide little by little by means of a second electro-magnet; this constituted the second movement of the spectroheliograph. Both electro-magnets were fed simultaneously by a contact wheel turned by the driving clock.

The prism spectrograph gave a dispersion of 5 A. per mm. in the green, and 11 A. per mm. in the red. A photograph showed the solar line $H\alpha$ and the red line of the corona 6374 A., visible to a height of 4′·5. The panchromatic plates were not yet sensitive enough; it was necessary to hypersensitise them and make exposures of at least 30 minutes. Another plate was taken on 1931 August 7 by isolating, with the second slit of the spectroheliograph, a portion of the spectrum, 10 A. in width, containing

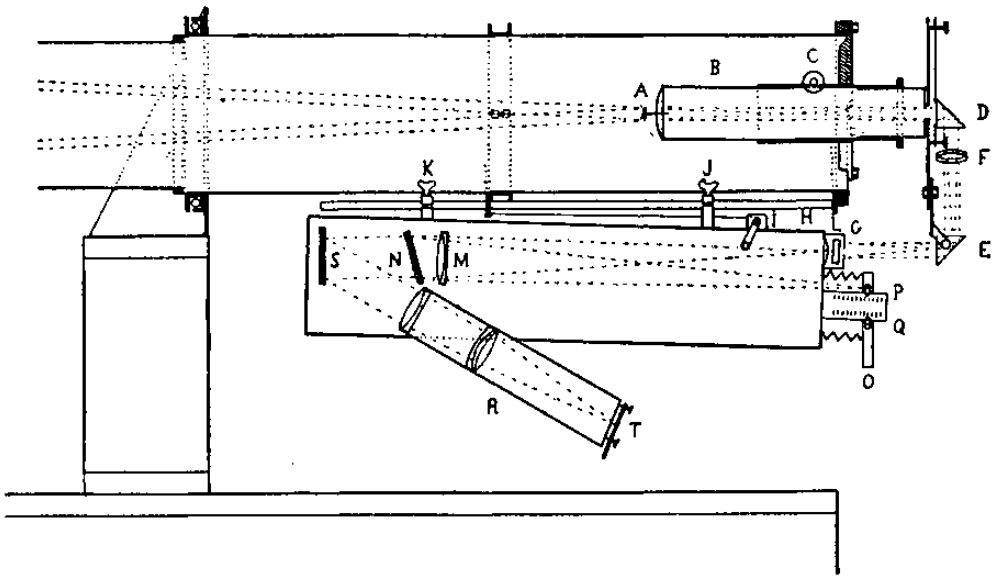

FIG. 7.—*Plan of the final coronagraph and the spectrograph used since 1935.*

the green line λ 5303.* It shows the aspect of this line, section by section, all around the Sun. The length and intensity of the line vary greatly; it has only one maximum in the west, on the equator. A large group of spots and flocculi, the only one then existing on the Sun, passed the limb in this region. An enlargement of the west side of the preceding plate shows the great width of the coronal line as compared with the solar lines. This width can be seen still better on a spectrum taken with the 7-m. concave grating in the second order, with a dispersion of 1·3 A. per mm.* The coronal line has an average width of 0·8 A., and extends to 1·2 A., ten times more than the neighbouring solar lines.

In 1932, the solar activity was approaching its minimum and the coronal lines were faint. I preferred to cease observations for a time and study new apparatus in view of the forthcoming increase in solar activity. This apparatus consisted chiefly of a more powerful coronagraph than the earlier one, connected with a spectrograph easier to manage, very luminous in the infra-red, and with very slight flexure.

The Final Coronagraph.—The chief lens of the coronagraph is plano-

* *Zeitschrift für Astrophysik*, 5, pt. 2, 73, 1932.

convex, with a diameter of 20 cm. and a focal length of 4 m. It was ground at the Paris Observatory, by M. Couder, from a disc of excellent borosilicate crown glass, kindly presented by the firm of Parra-Mantois. The tube is no longer of wood, but of duralumin. It is 6 m. long and weighs only 22 kg. It consists of four parts, which can be put one inside the other to facilitate transport. The eyepiece-holder is provided with a joint allowing the observer to bring any point of the field to the centre of the eyepiece without moving the coronagraph. The latter is carried on two large ball-bearing pedestals and can be turned on its axis. To the coronagraph is joined a single spectrograph (fig. 7) with a plane Rowland grating of 4 inches, reflecting, in the second order, 10 per cent. of the visible and next infra-red rays, and, in the first order, 35 per cent. beyond 9000 A. The grating can be placed at N to reflect the rays back through the objective M of focal length 1 m.; the spectrum is formed in the frame-holder O. The grating can also be placed at N, to form the spectrum in the camera R of 35 cm. focal length. The spectrograph, carried on two steel tubes H, by means of two jaws J and K, can slide in a direction parallel to the axis of the coronagraph to focus the corona on the slit. It is counter-balanced and turns with the coronagraph, permitting the observer to set the slit in any direction.

Fig. 8 (Plate 13) shows the whole of the installation, the tube of the coronagraph A and the ball-bearing pedestals B and C. The chief lens is at D; it is held in its cell by a groove and can be taken out to be cleaned, by means of a handle. Also shown are the spectrograph E, the frame-holder F for the objective and the camera G. This apparatus was set up in 1935 and has been used each year since. It has given the following results :—

Direct Photography of the Corona.—When the sky is very pure, by adapting an orange filter and a weak eyepiece to the coronagraph, the strongest parts of the inner corona are sometimes seen. More often, on the contrary, the coronal forms have slight contrasts and the diffused light makes them disappear in the eyepiece. They can, however, still be well photographed if a red filter and highly contrasting panchromatic plates are used. The photographs you are about to see have been obtained through a filter transmitting wave-lengths of more than 6200 A., on slow panchromatic Guilleminot plates multiplying the contrasts by $3\frac{1}{2}$, for these radiations.

The first direct photograph of the corona without an eclipse was obtained at 16^h on 1931 July 21.* Twelve exposures were taken; after each one, the coronagraph was turned through 30 degrees on its axis. This proceeding enables us to distinguish with certainty the coronal features from the defects due to the instrument, chiefly the spots produced by particles of dust deposited on the second lens of the coronagraph. One positive has been made by printing successively, on the same plate, the six best negatives placed in such a manner as to obtain the coincidence of the images of the prominences; this diminishes the spots which do not coincide, as well as the irregularity of the grain of the negative.

* *L'Astronomie*, 46, 272, 1932.

This positive shows, but faintly, a wide streamer to the north-east, a narrower one to the south-east and a luminous edge to the west. Only the general shape of the corona appears, because the diameter of the Sun on the negatives is only 12·5 mm., and, on the other hand, for very slightly contrasted details, the photographic plates have a very bad resolving power, equal to several tenths of a millimeter. Therefore the size of the negatives had to be increased.

A series of photographs was obtained in 1936, in the same way *, but with a solar diameter of 30 mm.; they show much more detail, wide streamers, dark gaps and luminous arches surrounding the brightest prominences. This method shows only the inner corona up to 7′ from the Sun's edge; but, in return, it enables us to study its variations.

For example, a picture taken at 8^h on 1936 July 6 shows the south pole very dark; to the south-east, several luminous arches; to the south-west, narrow jets followed by a dark gap; to the west, a dark space above a prominence. On a plate of the next day the dark gap is still seen to the south-west, but the other details have changed very considerably. To the west, the dark space has disappeared; to the south-east, the luminous arches are no longer visible, but another arch has formed towards the equator.

Two other photographs show the corona on 1936 July 19 with two prominences detached from the Sun's edge, and the corona on 1936 August 5.

In 1938, the coronagraph was supplied with a mechanism which turns the second lens and the disc on their common axis during the exposures. The particles of dust, describing circles around the Sun, disappear. This proceeding completely eliminates the spots, and a single negative is sufficient to give a good picture.

Many photographs have been thus taken, each one with a single negative much larger than the preceding ones, on which the Sun measures 65 mm. in diameter. Some parts of the photographs are reproduced in actual size in Plate 14 (figs. 9–17). All the details they show have been confirmed on several negatives taken successively. The north pole of the Sun is at the top. The black disc of the coronagraph appears more regular than that of the Moon on eclipse plates; it is surrounded by a fringe of light due to diffraction which is sometimes increased by bad seeing.

On 1938 July 6, at 9^h (fig. 9), to the north-east, a spot of light surrounded by a luminous ring is seen, and to the south-east, a bright dome. On the same day, at 15^h (fig. 10), to the north-east, the spot and the ring have disappeared; to the south-east, fine arches are substituted for the dome. On the same day, at $17^h\ 55^m$ (fig. 11), one-half of the arches, on the side of the equator, is covered with a new dome. At $10^h\ 30^m$ on July 9 (fig. 12) notice, for example, the entangled arches to the south-west. On the same day, at $15^h\ 2^m$ (fig. 13), these arches are modified and small clouds have formed on the south side. On the same day, at $18^h\ 40^m$ (fig. 14), the clouds are in the same place, but fainter. It would be interesting to study these rapid changes by means of cinema films.

* *L'Astronomie*, **52**, 193, 1938.

On the following day, July 10, at $6^h\ 39^m$ (fig. 15), a bright streamer is seen in place of the arches, throwing a curved jet on the equator and containing a dark arch. On the same day, at $12^h\ 10^m$ (fig. 16), the dark arch has risen. Three days later, July 13, at $9^h\ 50^m$ (fig. 17), the corona has completely changed. It shows numerous fine jets to the east and a dark space connected with a prominence to the west. The north pole is very dark, the south pole is provided with fine jets. The reproductions do not show all the details visible on the negatives.

A photograph on July 18 shows a very bright fan-like streamer, to the west. Another photograph taken on July 19 at $12^h\ 09^m$ shows brilliant trails due to the passing of large particles, which are probably thistle-down, crossing the Sun at an altitude of about 5000 m. These seeds generally precede the particles of dust.

On 1937 May 11, at 9^h, the planet Mercury passed in front of the corona tangentially to the Sun, near the south pole. The sky was completely covered during the first part of the transit across the corona. It became clear at $10^h\ 10^m$, which allowed Mercury to be seen and 16 photographs to be taken.

On the first one, at $10^h\ 22^m$, the planet is $1'\ 10''$ distant from the edge of the Sun; it passes in front of a prominence. Ten minutes later, Mercury leaves the prominence and is outlined against the corona. The sky was not perfectly clear, as there were very slight cirrus clouds, the ice crystals of which produced streaks. On the last photograph, taken at $11^h\ 14^m$, Mercury is $2'\ 37''$ distant from the Sun, and is still visible due to the coronal light on which it is outlined. Immediately afterwards, the sky became overcast.

On these photographs, neither a line nor a point of light, appears on the edge of the disc of Mercury. We may conclude that the atmosphere of Mercury diffuses light very feebly, and that it produces, on the surface of the planet, a refraction less than one-thirtieth of that of the Earth.

The Spectrum of the Corona.—I have used the spectrograph, last described, to explore the spectrum of the corona, part by part, from 3350 A., the limit of the transparency of the coronagraph, up to 12000 A., the limit of the sensitiveness of the plates. Most of the plates have been taken with the camera of 1 m. focus which gives a dispersion of 5 A. per mm. with the third order of the grating, in the ultra-violet, and a dispersion of 7·5 A. per mm. with the second order, in the visible and the beginning of the infra-red up to 8300 A. Two shorter cameras, of 35 cm. and $8\frac{1}{2}$ cm. in focus, enabled me to continue the registration of the spectrum up to 11300 and 12000 A. It was necessary to use seven different kinds of plates and make exposures from 10 minutes in the visible spectrum up to 4 hours in the infra-red.

Most of the spectra were taken with a slit in the form of an arc of a circle, on the inside of which the image of the disc of the coronagraph was thrown. This image was adjusted in such a way that the slit crossed either the west or the east side of the corona, at about 40″ from the edge of the Sun, between latitudes $\pm 70°$.

Fig. 18 (Plate 15) shows the ultra-violet extremity of the spectrum of the west side, from 3330 A. on the left to 3480 A. on the right on 1937 July 19.

All the lines are in the form of an arc of a circle which is that of the slit. You see the Fraunhofer lines, due to diffused solar light, and, in the middle, the coronal line 3388 A. having maxima near the equator. The slit crossed a bright equatorial prominence of which you see the emission lines with a faint continuous spectrum.

In the ultra-violet, the violet and the blue, I could not photograph any other line of the corona. The other coronal radiations are fainter and are blotted out by atmospheric diffusion. In the green, the diffusion of the atmosphere is reduced and the conditions are more advantageous. For example, fig. 19 shows a part of the spectrum of the east edge, on 1937 July 18 at 14^h 20^m. We have the *b* group of magnesium and the double E line. The slit crossed 5 prominences, the lowest of which emitted numerous metallic lines and a strong continuous spectrum which produced a bright and narrow horizontal line. Nearer the equator, the slit also crossed a coronal streamer of which the continuous spectrum is visible. On the streamer we see, to the left, the coronal line λ 5116, and, to the right, the strong coronal line λ 5303 between 4 ghosts of the grating. On the continuation of the same plate, the coronal line λ 5536 ought to be seen, but is not visible. It does not appear on any of the plates I have taken in 1936, 1937 and 1938, under favourable conditions and a very strong solar activity. According to the rare observations which have been made of it, its intensity was one-half of that of λ 5116. We can conclude either that it has become much fainter or that it rises to less than 40″, contrary to the other known lines.

Fig. 20 shows the continuation of the same spectrum in the yellow. To the right, we have the bright helium line D_3, then the two solar lines D_1 and D_2 strongly emitted by the lower prominence. The continuous spectrum of the coronal streamer appears very bright. If these plates do not show the line λ 5536, in return they show a new line which has not been observed during eclipses. It appears to the left, on the coronal streamer, while the prominences do not emit it. Its wave-length is 5694·42 A., and its intensity is about half that of λ 5116. A spectrum of the east side taken on 1938 July 6 strongly shows λ 5303 to the left and λ 5694 to the right, but does not show λ 5536 situated between the two. Fig. 21 shows another part of the last spectrum but one, farther away, in the red. We have the coronal line λ 6374 and, in the middle, the line $H\alpha$ so highly exposed that it shows 40 ghosts. After the line $H\alpha$ we have the red helium line emitted by the prominence, and then the coronal line λ 6702.

The spectra do not show any of the new lines found by the Japanese in the eclipse of 1936. These lines were found, indeed, on small-scale spectra on which agglomerations of grains are to be feared.

The beginning of the infra-red is seen on a spectrum of the west side taken on 1937 June 10 from 14^h to 15^h (fig. 23, Plate 16). To the right is the telluric band *a*, and to the left the helium line λ 7065 emitted by the prominences. Slightly to the left of the latter we see a coronal line which had not been known when we found it. It has a wave-length of 7059·62 A. Later, Professor Menzel found this line on a plate taken by him during the

eclipse of 1936. To the right, the two strongest prominences emit a line of oxygen 7254 A. Farther on in the infra-red, fig. 24 shows a spectrum of the west side taken on 1937 May 28 with a three-hours' exposure. In the middle, the coronal line 7892 A.; to the right, a faint coronal line 8024 A., which has not been observed during eclipses. To the left, we see the triplet of oxygen emitted by four prominences. After an extensive tract of the spectrum without coronal radiation are two strong coronal lines, 10747 A. and 10798 A., never yet photographed during eclipses. They appear very bright on a spectrum of the east side, taken on 1936 August 5, from 9^h to 11^h (fig. 25). They are followed by the helium line 10830 A. emitted by a series of prominences, and to the right begins the telluric band Φ. Both coronal lines have an intensity about equal to that of the green line λ 5303. On a spectrum of the east side taken on 1936 July 23 (fig. 26), the helium line is very strong and followed with the line 10938 A. of hydrogen, the sixth term of the Paschen series. Both spectra were taken on Eastman Z plates hypersensitised with ammonia, and by reducing the dispersion to 45 A. per mm. with the camera of 35 cm. focus and the first order of the grating.

Two plates have been taken with the camera of $8\frac{1}{2}$ cm. focus and exposures of 5 minutes and of 3 hours. On the first, the two strong coronal lines are seen; on the second, the spectrum extends to 12000 A. without showing any other emission line.

The spectra, of which these are some examples, are very numerous—about 200. They show eleven coronal lines, five of which are new. These records establish that all the coronal lines are wide.* Taking into account the influence of the spectrograph, their average widths are 0·8 A. in the green, 0·9 to 1 A. in the red and greater in the infra-red.

The wave-lengths have been measured on the best and the most dispersed spectra. The intensities of the strongest lines have been drawn from a series of plates taken on 1936 August 5 with solar comparison spectra. The following list gives for each line: the wave-length, λ, a mean value for the east and west sides, in international angstroms; the probable error, $\Delta\lambda$; the number, N, of plates used for the wave-length measurements; the order, P, of the spectrum; the dispersion, D, in A. per mm.; the mean time, T, of

λ	$\Delta\lambda$	N	P	D	T	i
					h m	
3388·10	± 0·07	2	3	5·2	0 35	...
5116·03	± 0·02	3	2	7·5	0 18	2·6
5302·86	± 0·02	4	2	7·5	0 18	120
5694·42	± 0·05	3	2	7·5	0 10	1·5
6374·51	± 0·03	4	2	7·5	0 27	28
6701·83	± 0·03	4	2	7·5	0 33	3·3
7059·62	± 0·05	2	2	7·5	0 40	4
7891·94	± 0·07	3	2	7·5	1	29
8024·21	± 0·10	1	2	7·5	1	1·3
10746·80	± 0·15	1	1	15	4 10	240
10797·95	± 0·15	1	1	15	4 10	150

* *L'Astronomie*, 51, 211, 1937.

exposure; and the intensity maximum, *i*, of the line compared with the millionth of that of 1 angstrom of the neighbouring continuous solar spectrum.

Measurements of the wave-length of the green line, to the east and west edges, made on spectroheliograms by sections, show that the corona revolves in the same sense as the Sun and at the same rate to within 30 per cent.

The eleven lines of the corona visible on the plates are not all distributed in the same way around the Sun. It is easy to compare the distributions of these monochromatic radiations by placing side by side, on the same plate, the lines which are far away from one another in the spectrum. Fig. 27 (Plate 16) shows, for example, the coronal lines photographed on the west side on 1937 July 18. The north pole of the Sun points to the top. We see, from left to right, lines λλ 8024, 7892, 6702, 6374, 5694, 5303, 5116 and 3388. In the centre, λλ 6374, 5694 and 5303 have different distributions. In fact, (*a*) λ 6374 has, to the north-west, a strong double maximum not existing on the two following lines; (*b*) λ 5694 possesses, slightly above the equator, a maximum corresponding to a minimum of λ 6374; (*c*) on the other hand, under the equator, where λ 5303 is at its maximum, λ 5694 is invisible; (*d*) the line λ 7892 (the second one to the left) agrees with λ 6374 only, whilst the other lines tally with λ 5303.

According to a great number of spectra of this kind, too long to examine here, we can class, in three series, the eleven lines observed. The first series comprises line λ 5303, and lines λλ 3388, 5116, 6702, 7059, 8024, and probably also λ 10747 and λ 10798. The second series comprises only the new line λ 5694, different from all the others. The third series comprises lines λλ 6374 and 7892.

Spectra of the Prominences.—Some of the plates show spectra of prominences particularly rich in lines, the measurements of which are not finished. On the preceding plates you have seen some helium, oxygen and metallic lines of relative intensities very different from those existing in the chromosphere. We are now going to show you the spectrum of hydrogen represented by the series of Paschen and Balmer.

Fig. 28 (Plate 16) shows a spectrum of the north-east side taken on 1938 July 10 with the solar lines of ionised calcium 8498, 8542 and 8662 A. strongly emitted by a prominence, as well as numerous lines of the Paschen series. From right to left: terms 11, 12, 14, 16, 17, 18, . . . up to term 31. The terms 13 and 15 are hidden by lines of calcium. Between terms 17 and 18 we see a line of oxygen, 8446·7 A. From the limit of the series, the continuous spectrum of the prominence (probably due to the solar light diffused by it) is reinforced because a continuous spectrum of hydrogen is added to it. The continuous spectrum of hydrogen is better visible on a spectrum of the south-west side (fig. 29) taken on 1937 June 30 from $11^h\ 30^m$ to $12^h\ 30^m$.

In the same way, in the ultra-violet, figs. 30 and 31 show a spectrum of the north-west side, taken on 1938 July 12 at 8^h. On the right of fig. 30 are term 7 of the Balmer's series close to line H of calcium, then line K of calcium and terms 8, 9 and 10. On fig. 31 are terms 10, 11, . . . up to

term 31 and followed by the continuous spectrum of hydrogen. The lines of Paschen's series are much fainter than Balmer's; but the diffusion, greatly reduced in the infra-red, renders observation of both series equally easy.

Prominences through Coloured Filters.—The continuous spectrum of the prominences had been observed during eclipses, but the plates, generally taken with an objective prism, indicated that this spectrum was emitted only by some particular parts of the most intense prominences.

To check this fact, I have photographed the same prominence through three coloured filters successively. Four photographs were taken on August 27 at $12^h\ 15^m$, on a prominence to the north-west. The first and the last pictures (Plate 17, figs. 32 and 35) were taken through a filter cutting off the chromospheric radiations and allowing only the continuous spectrum between 6100 and 6400 A. to pass. The second picture (fig. 33) was taken with the helium line D_3 and the third one (fig. 34) with the line $H\alpha$ of hydrogen. The pictures obtained with the continuous spectrum are identical with that given by the helium line D_3, both with regard to form and relative intensities. This spectrum comes, therefore, from all parts of the prominence.

Measurements of polarisation made through these filters have given the following results :—

The continuous spectrum of the prominences, in the red and the orange, has about the same polarisation as the corona, in a radial plane.

The radiations $H\alpha$ and D_3 are, on the contrary, about 10 times less polarised, and their plane of polarisation is deviated from the radius, sometimes to more than 20°.

In the visible spectrum, the continuous spectrum of the prominences appears to be due to the diffusion of the solar light by the electrons they contain. It would be interesting to study, as well, the polarisation of the continuous spectrum emitted beyond the limits of the Paschen's and Balmer's series.

Movements of Prominences.—The coronagraph, supplied with a filter isolating line $H\alpha$, shows the prominences with great brilliancy against a very dark sky, and thus causes their faintest details to appear. Moreover, thanks to the highly favourable situation of the Pic du Midi, the seeing is often very good. Since the summer of 1935, I have taken advantage of these good conditions to register the movements of the prominences on cinema films that we shall presently see on the screen.

The cinematograph possesses a considerable advantage over direct observation; it enables us to vary, at will, the scale of time in order to give the phenomena the speed best adapted to our perception. We have thus been led to accelerate the movements 600 times. The views have been taken on panchromatic 35-mm. films at the rate of two per minute. The exposures were made, sometimes automatically, sometimes choosing, through an eyepiece, the moments of steadiness, which generally gave sharper pictures. The times of exposure were 2 or 3 tenths of a second. The scale of the pictures is such that the total height of the photographs represents

an average of about 380,000 km.; that is to say, the distance of the Earth from the Moon or 30 times the diameter of the Earth. The films are very short, and, in order to render the movements easier to catch, each one is thrown twice successively on to the screen. Eleven films are projected.

The first one was taken on 1935 September 11.* One branch of the prominence, situated to the north-east, consists of two parts placed one in front of the other. One part is stationary, the other moves upwards.

Another prominence † was filmed to the west, on 1936 August 8 from 8^h to 13^h. A whirling motion is seen in its head. Some filaments, coming from several parts of it, gain impetus in a very active part of the chromosphere surrounded with the most intense coronal dome and in which a bright eruption, 100″ in height, took place after the film was finished. Some filaments fade away in rising and light up again in falling. Near the Sun, they attain a speed of 180 km. per second.

The best film was obtained on 1937 June 12, from $8^h\ 30^m$ to $15^h\ 10^m$, on a prominence situated to the east. At the beginning, it consists of three clouds detached from the Sun's edge (Plate 17, fig. 36). The material flows for 2 hours in the form of very fine filaments, then the right part is blown upwards and falls again to its former level. Towards the fourth hour (of the taking of the film), the cloud on the right becomes very bright. A chromospheric eruption leaves the Sun at the rate of 700 km. per second and cuts the prominence into two parts. The luminous mass, the equilibrium of which is lost, flows on to the Sun; it seems to make the tour of a rounded invisible obstacle surrounding the place of the eruption.

A film taken on 1938 June 10 shows an arch, to the north, flying up slowly, then more and more rapidly (fig. 37). Unfortunately, the end of the phenomenon is veiled by cirrus.

The last prominence, cinematographed on 1938 July 19, to the west (fig. 38), is similar to those called "coronal" by Pettit. The material moves, on both sides of the arches, in opposite ways; in some places, it originates in invisible clouds.

In conclusion, it is of interest to compare the results obtained by the two methods—with and without eclipses.

Direct Photographs of the Corona.—The outer parts can be obtained only during eclipses. The method without eclipse shows only the inner corona, but, in return, it alone enables us to follow its variations.

Spectrum of the Corona.—In the ultra-violet, the violet and the blue, the atmospheric diffusion is very strong and the new method is very inferior to the old one. In the green, the diffusion is less strong; its effects can be diminished by increasing the dispersion and making longer exposures, if necessary. If, moreover, we choose days during which the corona is particularly intense, the faint coronal lines appear then as well as during eclipses. The plates, more numerous and on a larger scale, enable us to distinguish these lines from the agglomerations of grains; they give their wave-lengths with greater accuracy. In the infra-red, the plates not being

* *L'Astronomie*, **51**, 208, 1937.
† *L'Astronomie*, **52**, 204, 1938.

very sensitive, the method without an eclipse is much superior to the other.

Prominences.—Only the method without an eclipse enables us to wait for the appearance of very bright objects having the richest and most interesting spectra.

We must not conclude that observations without eclipses can replace the expeditions for the study of eclipses. The new and the old methods complete one another on numerous points, and their simultaneous use will increase our knowledge of the outer atmosphere of the Sun much more rapidly.