RECENT PROGRESS IN ASTROPHYSICS

M. WALDMEIER'S WORK ON THE CORONA

1. *Introduction.*—A comprehensive program of coronal observations was initiated in 1938 by M. Waldmeier, of the Zürich Observatory. Waldmeier's results are given in a series of papers[1] published since 1939 in the *Zeitschrift für Astrophysik*. Since the papers are not generally available in this country, the present review of some of those which have recently been received by the Committee for the Distribution of Astronomical Literature is published with the object of summarizing certain of Waldmeier's important results.

All but one of the papers to be reviewed concern observations made at the coronagraph which Waldmeier designed and constructed in 1938 with the assistance of B. Lyot. The instrument is installed at Arosa, Switzerland, at an altitude of 2050 m. The optical train of the Arosa coronagraph is schematically represented in Figure 4, *e*. The objective, by Couder, is designated by O_1; it is plano-convex, 12 cm in diameter, and 150 cm in focal length. S is a round, plane mirror in the focal plane of the objective, with a diameter about 0.3 mm, or 40″, greater than that of the sun's image; it reflects the photospheric light out of the tube at F. The 11-cm aperture B reduces the diffraction of light at the edge of the objective. Light scattered by the objective is focused by O_2 in the plane of the aperture I; diffraction at B causes this image to be brightest at the edge, where the light is stopped by I. O_3 is an achromatic doublet of 35-mm diameter and 114-mm focal length; it reproduces the coronal image to scale in the focal plane E.

In the (detachable) spectrograph, K is the collimator, P_1 and P_2 are totally reflecting prisms, and O_4 is the telescope objective. Three sets of dispersing prisms are available. One set, of three prisms, transmits the green line λ 5303 undeviated and is usable between λ 4800 and λ 6000; it gives a dispersion of 27 A/mm at λ 5303 in the focal plane of O_4. A second set of three prisms transmits λ 6500 undeviated and gives a dispersion of 68 A/mm at λ 6374. The third set comprises a single prism which gives a dispersion of only 230 A/mm and permits the whole visible spectrum to be viewed. The camera lens magnifies three times, so that, with the first prism set, the dispersion on the plate is 9 A/mm at λ 5303. The solar image is 45 mm in diameter. The eyepiece E is used as an aid in focusing; during an exposure the totally reflecting prism P_3 is withdrawn.

Figure 1, *a*, shows the coronagraph with spectroscope attached. Properly to eliminate the photospheric light, the coronagraph axis must always be directed at the center of the sun. The slit is brought to any point of the focal plane by rotation of the spectrograph around the axis of the coronagraph, together with radial movement of the spectrograph relative to the axis of the coronagraph. The orientation of the slit is effected by rotating the spectrograph around the axis of the collimator. The slit itself is 15 mm long, and its width is adjustable to ± 0.002 mm. The slit jaws reflect the coronal image to the guiding eyepiece shown on the left; the guiding must be very accurate to prevent the photospheric light from striking the plate.

The coronagraph requires fine skies. During the winter of 1938–1939, 40 out of 100 days were usable in part, the average usable period being 1.4 hours daily. During about half of this time, "second-class conditions" are said to have prevailed, meaning that the brightness of the sky next the limb was less than 40×10^{-6} times the brightness of the photosphere. In such conditions all prominences are visible, as are also the brighter coronal lines, and even the weaker lines can be photographed. During the entire 100-day

[1] *Zs. f. Ap.*, **19**, 21, 1939; **20**, 246, 323, 1941; **21**, 85, 1941; **21**, 109, 120, 181, 275, 1942; **22**, 1, 18, 1942.

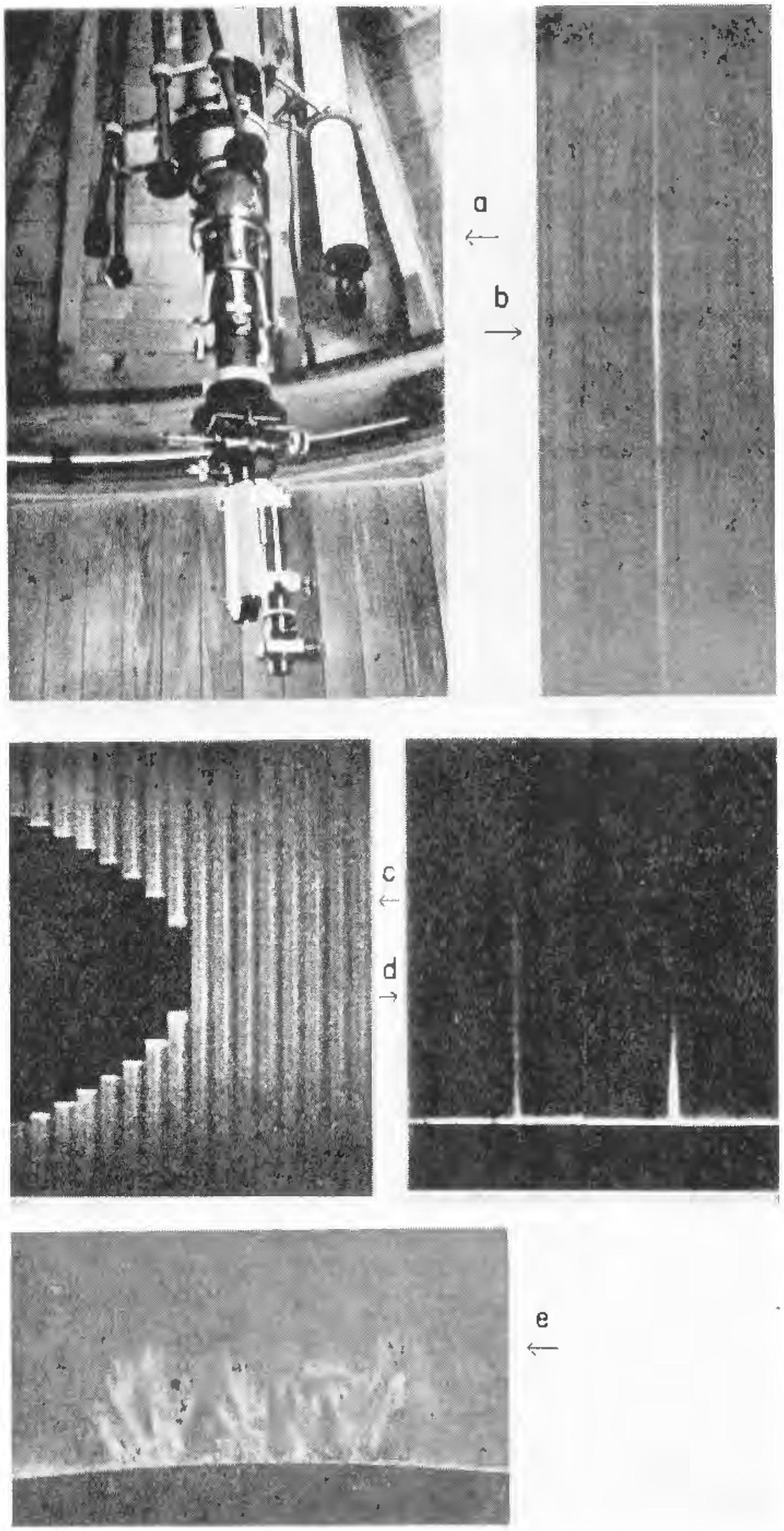

FIG. 1.—(*a*) The Arosa coronagraph with spectroscope attached. (*b*) The coronal line λ 5303 in a C-region on October 3, 1940. (*c*) Spectrocoronagram of east limb of sun, λ 5303, 7:35 U.T., March 24, 1942. (*d*) λ 5303 on September 21, 1941; *left,* position angle 110° at 9:09 U.T.; *right,* position angle 286° at 8:59 U.T. (*e*) Structure of the corona near position angle 286° in monochromatic light of λ 5303. Sketched at the *Spektrokoronaskop,* 6:25 U.T., September 21, 1941. Instrument not described.

period, there were only about 5 hours of "first-class conditions" (brightness of sky $<10 \times 10^{-6}$ ☉); then, all features of the innermost corona are visible and can be photographed.

2. *Photometry of the inner corona in white light.*—Most plates taken at total eclipse are badly overexposed in the region of the inner corona, and on many plates the limb of the moon obscures much of this region. For these reasons, among others, there has been accomplished little reliable photometry of that part of the corona which lies at a distance, h, of less than 3′ from the limb of the sun.

To obtain the isophotes in this region, Waldmeier has used a plate secured by Wolfer[2] 15 seconds after the beginning of totality of the eclipse of August 30, 1905. Wolfer's telescope was an 11-cm refractor, of 2.3-m focal length. Because he was unable to take a driving clock to the Algerian observing station, the exposure was only 0.1 second, and tbe photographic densities in the inner corona lie on the linear part of the characteristic curve. Since the edges of the plate and the area of the moon's disk are very clear, the influence of terrestrially scattered light is probably slight. Moreover, since the entire radial extension of the coronal image is only about 7 mm and is near the axis, distance effects are unlikely.

Using the Koch-Goos photoelectric photometer, Waldmeier has read the electrometer deflections at 432 places in the inner corona, 12 readings being taken at regular intervals along each of 36 radii, spaced 10° apart and starting from the polar radius. The plate contains no calibration; the electrometer deflections are calibrated by reference to a simultaneous determination by Schwarzschild,[3] from spectrograms, of the intensity gradient along two diameters. Figure 2, *a*, gives the isophotes which Waldmeier derives. The intensity at $h = 10\overset{'}{.}15$ is the arbitrary unit; the isophotes connect points of intensity 2, 5, 10, 20, 40, 50, 60, and 70, respectively.

For the ellipticities of the isophotes, defined essentially as

$$\epsilon = \frac{r_e - r_p}{r_p},$$

where r_e and r_p are the equatorial and polar radii, respectively, Waldmeier finds 0.047 at the limb and somewhat smaller values as h increases. In the interval $1' < h < 5'$, the intensity appears to fall off nearly exponentially, the mean value of the gradient, $a = -\Delta \log I/\Delta h$, being about 0.23. There is some variation in a with position angle, the larger values occurring in the fainter regions, i.e., where the isophotes bend toward the limb, and the smaller values occurring along the rays, i.e., where the isophotes bend outward. On the average, a appears to reach a maximum near $h = 2'$.

At the epoch of this eclipse the spot zones were at about $\pm 20°$ heliographic latitude. Figure 2, *a*, indicates intensity maxima near these zones. There appear to be secondary maxima between latitudes 50° and 60°. At a given distance from the limb the ratio of the intensity at the spot zones to the intensity at the equator is about 1.2; the intensity ratio, spot zones : poles, is about 2.

3. *Intensity distribution of the coronal emission at the limb of the sun.*—The strongest emission line in the coronal spectrum is λ 5303.86; according to Edlén,[4] it is produced by the forbidden transition $^2P^o_{1\frac{1}{2}} - {}^2P^o_{\frac{1}{2}}$ within the ground configuration $3s^23p$ of *Fe* XIV. In order to obtain the isophotes of a portion of the corona in the monochromatic light of this line, Waldmeier employed the Arosa coronagraph to secure 10 spectrograms off the west limb of the sun on March 9, 1942; 7 off the east limb on March 24, 1942; and 6 more off the east limb on the following day. The exposure was 7 minutes for each plate.

[2] *Astr. Mitt. Zürich*, No. 97, p. 236, 1906.

[3] *Astr. Mitt. Göttingen*, No. 13, 1906.

[4] *Arkiv f. Mat., Astr. och Fys.*, B, **28**, No. 1, 1941; *Zs. f. Ap.*, **22**, 30, 1942. See also P. Swings, *Ap. J.* **98**, 116, 1943.

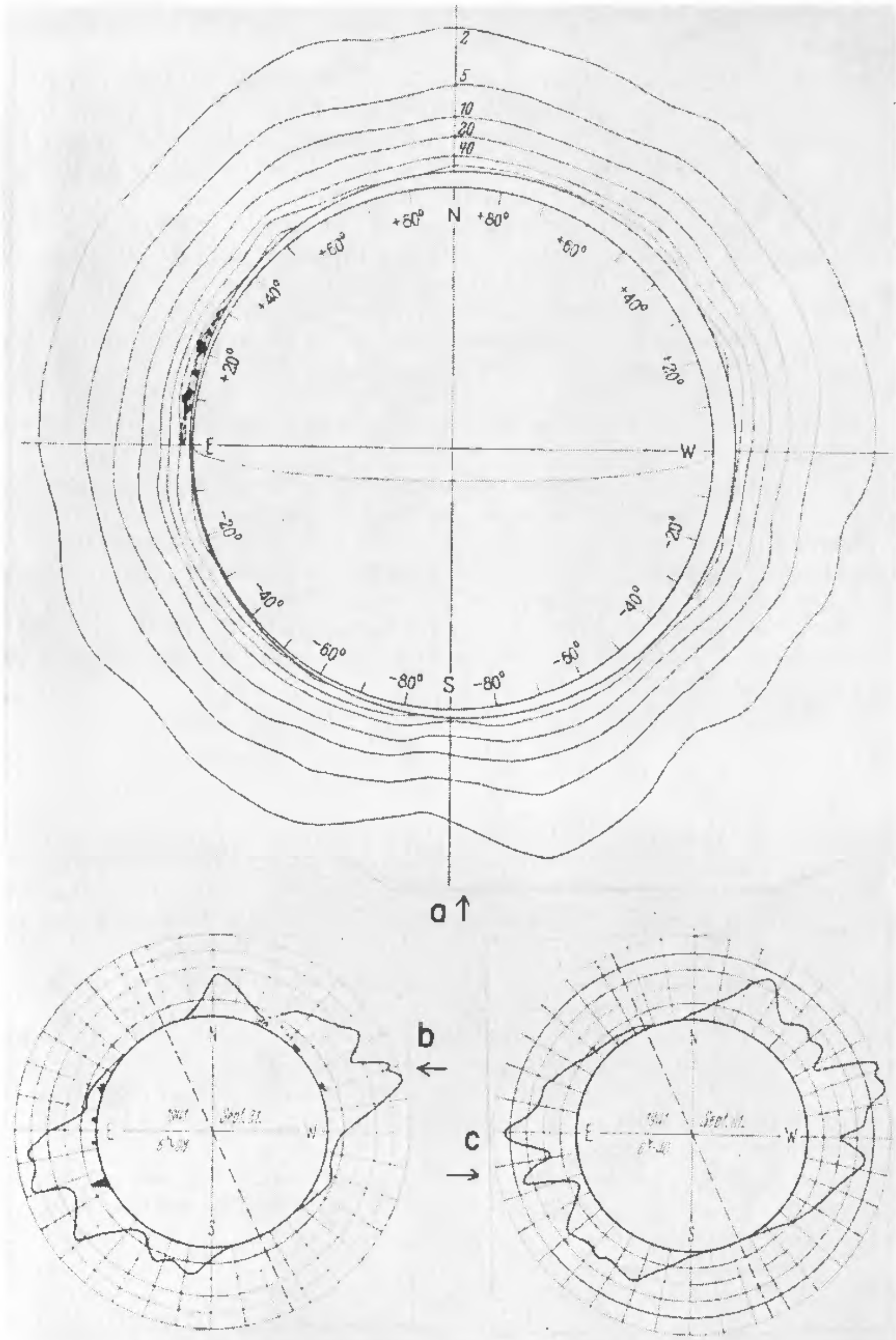

FIG. 2.—(*a*) Isophotes in the coronal continuum on August 30, 1905. (*b*) Corona-contour in the light of λ 5303. (*c*) Corona-contour in the light of λ 6374.

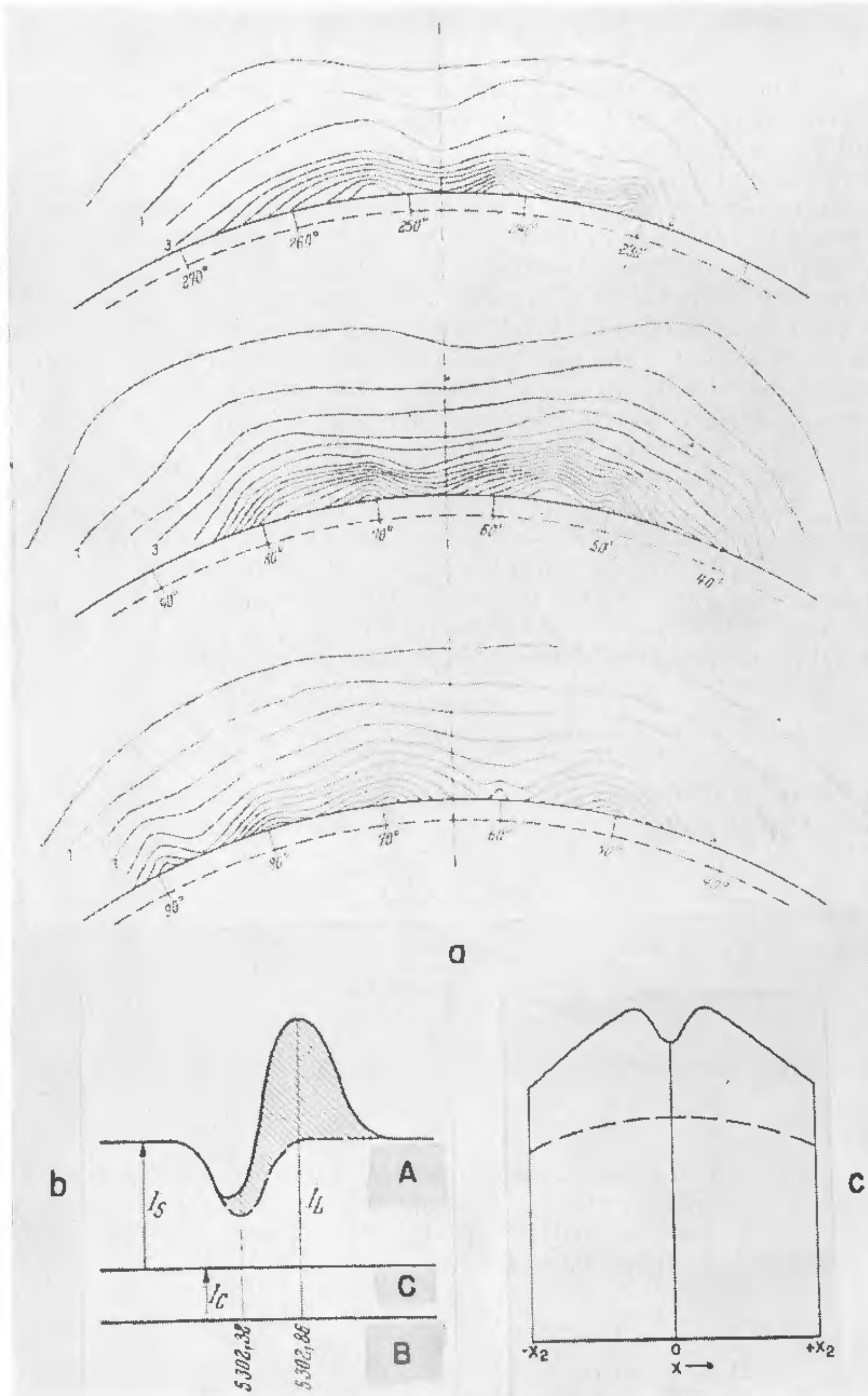

FIG. 3.—(*a*) Monochromatic corona-isophotes in the light of λ 5303; *top*, March 9; *middle*, March 24; *bottom*, March 25, 1942. (*b*) Contours of λ 5303 and λ 5302. (*c*) Variation in intensity of continuum alongside λ 5303.

All the plates were exposed with the slit bisected by and perpendicular to the equatorial radius of the limb. The first 4 plates were secured with the slit at $h = 0'.62$; in order to provide a calibration of all subsequent plates, they were exposed through graduated gray filters of known transmission characteristics. Between subsequent plates the slit was moved outward from the limb in increments averaging about $0'.5$.

At about five points along λ 5303 on each plate, a tracing was made across the line, all the points selected lying within $4'.1$ of the limb. Each tracing was then calibrated to give an intensity-curve A, as shown in Figure 3, b, above a base line B of zero intensity. On a few plates, densities occurred which were greater than any on the densest calibration plate, so that a slight extrapolation of the calibration-curve was necessary. Before the total intensity of the emission line could be ascertained, it was necessary to find the contour of the Fraunhofer line λ 5302.32 of *Fe* I, which does not appear over the coronal continuum but is evident in the photospheric light scattered by the earth's atmosphere. Once the position of the line C of zero intensity of the terrestrially scattered light I_s was found, it was possible to sketch the Fraunhofer line by reference to the Utrecht atlas and with consideration for the instrumental broadening.

To discover the relative contributions of the coronal continuum and the scattered photospheric continuum, Waldmeier then made a tracing of the continuum alongside the emission line on the outermost plate for each of the three observing days. After correction for a slight convergence of the slit jaws, each of the three tracings, when calibrated, looked like Figure 3, c. Let the measured intensity at $x = 0$ be Y_1 and at $\pm x_2$, Y_2; also, let $I_s(x)$ be the intensity of the scattered light at x, and i_1 and i_2 the intensities of the coronal continuum at $x = 0$ and $\pm x_2$, respectively. Then

$$\frac{i_1}{i_2} = \frac{Y_1 - I_s(0)}{Y_2 - I_s(\pm x_2)} .$$

Now, as h increases, $I_s(0)$ and $I_s(\pm x_2)$ must decrease toward a common minimal value $I_s^{\min}$, so that, at great distances from the limb, we have the approximation

$$\frac{i_1}{i_2} = \frac{Y_1 - I_s^{\min}}{Y_2 - I_s^{\min}} ,$$

and therefore

$$I_s^{\min} = \frac{i_1 Y_2 - i_2 Y_1}{i_1 - i_2} .$$

On the other hand, the maximum values of I_s compatible with the measurements are

$$I_s^{\max}(0) = Y_1 , \qquad I_s^{\max}(\pm x_2) = Y_2 .$$

Moreover, it is known that the intensity I_c of the coronal continuum falls off with increasing h much more rapidly than I_s. Consequently, I_s must simultaneously approach $I_s^{\min}$ and $I_s^{\max}$ as h increases, so that $I_s^{\min}$ and $I_s^{\max}$ must converge at large distances from the limb. Waldmeier therefore takes I_s as the mean of $I_s^{\min}$ and $I_s^{\max}$ on the outermost plates:

$$\begin{cases} I_s(0) = \dfrac{i_1(Y_2 + Y_1) - 2 i_2 Y_1}{2(i_1 - i_2)} , \\[2ex] I_s(\pm x_2) = \dfrac{2 i_1 Y_2 - i_2(Y_2 + Y_1)}{2(i_1 - i_2)} . \end{cases}$$

The circular arc through these three points, shown in dashes in Figure 3, c, was then taken as the run of I_s along the line, and the difference $Y - I_s$ was taken as I_c.

In a critical discussion of the intensity measures of a large number of investigators, Baumbach[5] has shown that the intensity i of the coronal continuum can be well represented by the empirical expression

$$i(\rho)=\frac{0.0532}{\rho^{2.5}}+\frac{1.425}{\rho^{7}}+\frac{2.565}{\rho^{17}}, \qquad (1<\rho<10),$$

where ρ is the projected distance from the sun's center in solar radii, and where the unit of intensity is 10^{-6} times the intensity at the center of the sun's disk. Waldmeier has used this relation to find I_c on all but the three outermost plates. The difference $Y - I_c$ was then taken as I_s, and the Fraunhofer line was drawn in as described above. Next, the shaded area was measured with a planimeter, and the area, in arbitrary units, was taken as the total intensity of the emission line. By this method the total intensity was found at 76 points in all. Through the points on each plate, and with consideration for the appearance of the line, the intensity distribution along the line was sketched. These drawings were converted to graphs of the intensity distribution along radii separated by 2° of position angle, and from these graphs the isophotes were constructed. The isophotes are shown in Figure 3, *a*.

The dashed arc represents the limb of the sun; the full arc, the limb of the "artificial moon." The vertical line lies in the plane of the sun's equator; the angular co-ordinates are position angles counted from north. The indicated intensity scale is arbitrary, one unit corresponding to an equivalent width of the order of 4×10^{-6} A in the photospheric continuum at the center of the sun's disk. The isophotes are seen to approach the limb quite sharply with increasing latitude, indicating a considerably greater ellipticity than in the corresponding isophotes for the coronal continuum. All three maps exhibit a pronounced equatorial minimum, and maxima near latitudes $\pm 10°$, which are those of the spot zones. Certain secondary maxima are also indicated. Waldmeier designates the maxima "rays" (*Koronastrahlen*). Near the limb, the isophotes are seen to be much more irregular than those in white light.

From the isophotes Waldmeier has found the radial intensity gradient a at a number of position angles. Along each radius, the gradient is very nearly constant, with some indication of a maximum near $h = 2'$. The average gradient exceeds by about 50 per cent the average gradient of the continuum in the same region; along the rays the gradient is approximately 30 per cent greater than the average.

Within a few hours of the exposure of the plates used for this investigation, Waldmeier, on each of the three days, made a visual survey of the brightness of the green line λ 5303 around the limb. With the slit 40″ from the limb and parallel to the tangent, the brightness of λ 5303 was estimated on a scale of 0–50 at 5° intervals in position angle. A complete survey (72 settings) of this kind takes Waldmeier less than 20 minutes. He mentions that the green line, at the brightest places, is so strong that the room need not be darkened, or the eye shaded, to see it even through thin clouds! Figure 4, *a*, exhibits the good agreement of these visual surveys with the photographic results. I are the measured intensities, as derived from Figure 3, *a*, and S are the estimated intensities.

Waldmeier has completed a large number of these visual surveys. He commonly publishes his results in the form of a polar diagram like that in Figure 2, *b*, where the estimated intensities are plotted radially with respect to position angle. Such a diagram he calls a "corona-contour." Incidentally, the observations for the contour of Figure 2, *b*, were made at a time when the sun was totally eclipsed in another part of the world. Conspicuous prominences are usually indicated, as is the position of the sun's axis. These corona-contours usually exhibit the equatorial minima and the principal maxima at or near the spot zones. Occasionally, however, some of these typical features may be missing. More often than not, secondary maxima are observed near latitudes $\pm 60°$, and additional maxima are frequently found. The contours do not change rapidly; features

[5] *A.N.*, **263**, 121, 1937.

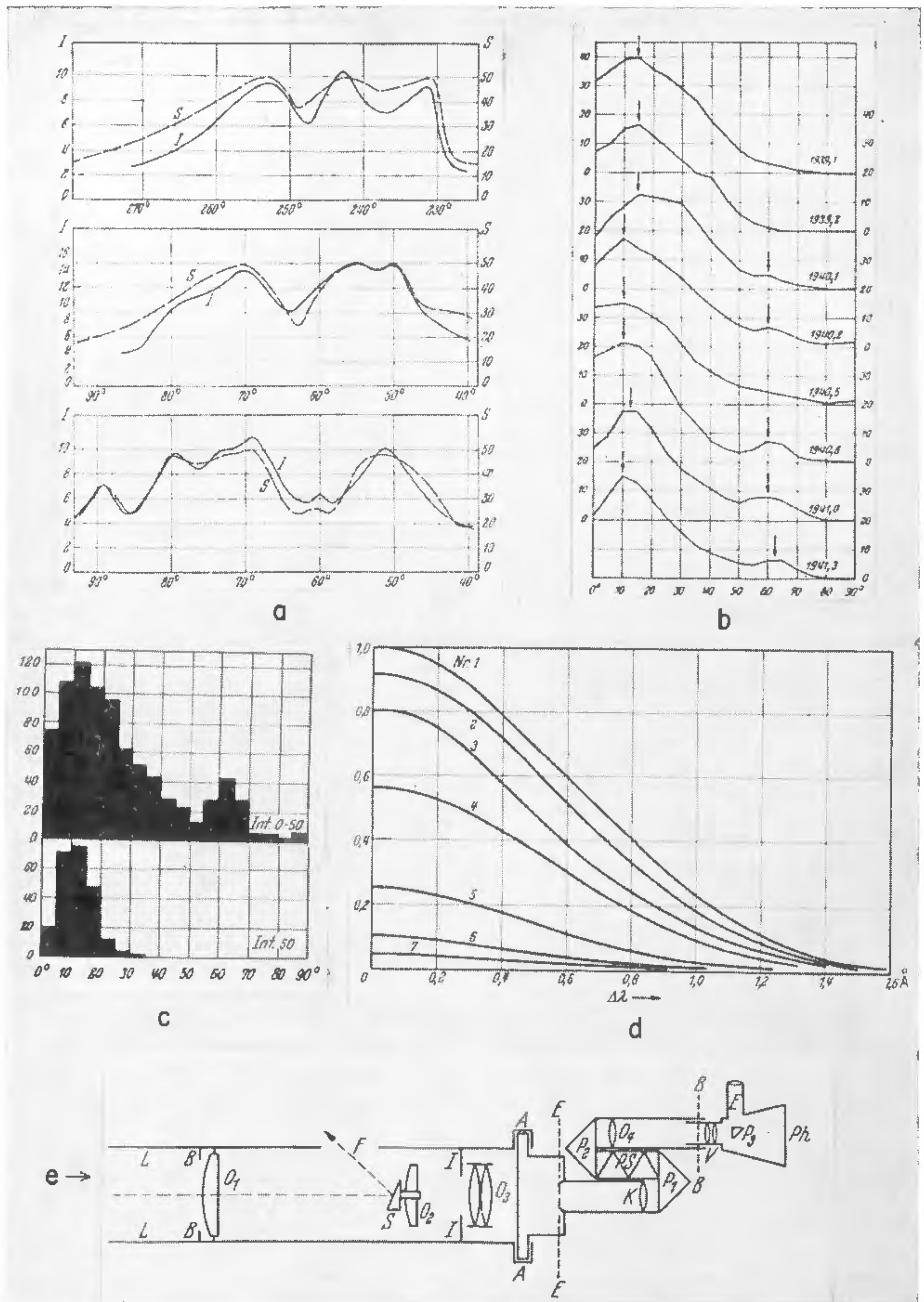

FIG. 4.—(*a*) Measured (*I*) and estimated (*S*) intensities of λ 5303 along the sun's limb. *Top*, March 9; *middle*, March 24; *bottom*, March 25, 1942. (*b*) Latitude distribution of intensity of λ 5303. (*c*) Latitude distribution of rays in λ 5303. (*d*) Observed intensity distribution in red wing of λ 5303 at different distances from the sun's limb. (*e*) Optical system (schematic) of the Arosa coronagraph with spectrograph attached.

observed in the morning are usually still present in the afternoon and may persist for several days. Figure 1, *c*, clearly illustrates the pronounced zonal structure which characterizes the inner corona in the light of the green line. On this spectrocoronagram, the equator is parallel to the dispersion; the spectra are separated by 0.′3. The equatorial minimum is most pronounced.

The second-strongest emission line in the coronal spectrum is λ 6374, which Edlén identifies with the forbidden transition $^2P^\circ_{1/2} - {}^2P^\circ_{1\frac{1}{2}}$ in the ground configuration $3s^23p^5$ of *Fe* X. Contours in the light of this red line commonly exhibit most of the features of the green contours. Thus, the red contour in Figure 2, *c*, is characterized by the equatorial minima, maxima over the spot zones, etc. The red line is typically about one-tenth as strong as the green, but occasional large deviations from this ratio are observed. For example, while the green contour in Figure 2, *b*, exhibits a minimum near position angle 260°, the red contour in Figure 2, *c*, obtained only a half-hour later, exhibits a strong maximum there. Waldmeier calls this a "red region," and places where the green line is relatively enhanced are called "green regions." In comparing the two contours one might note that the red line is faintly visible at the north pole; more often than the green line, the red can occasionally be seen throughout the polar region.

When several contours are averaged together, the transient rays are smoothed out in the averaging, and the result is a fairly smooth contour, symmetrical about the equator and axis but usually exhibiting the equatorial minimum, the primary maxima at the spot zones, and the secondary maxima near ±60°. In Figure 4, *b*, the abscissa is the heliographic latitude, and the ordinate for each curve is the intensity of λ 5303 averaged over about 10 contours observed near the epoch indicated at the right. There is some indication that the primary maximum is moving toward the equator with the spot zones.

Figure 4, *c*, gives the latitude distribution of all the rays observed in λ 5303 during 28 months beginning in January, 1939. The principal and secondary maxima are especially marked. In the lower graph, where only the most intense rays are considered, the concentration toward the spot zones is most conspicuous.

By way of comparison with the figures pertaining to the continuum, Waldmeier notes that in the light of the green line the intensity ratio, spot zones : equator, is about 2; the ratio, spot zones : poles, is at least 20.

4. *Red regions, green regions, and C-regions.*—It would seem to be well established that the regions of greatest coronal activity are the spot zones. Waldmeier has inquired whether the rays in these zones can be associated with individual spots or with other photospheric or chromospheric phenomena. The problem is complicated by the fact that the corona can he observed only at the limb, of course, where other features are usually invisible.

In Figure 5, *a*, the heliographic maps of the corona are based on corona-contours observed by Waldmeier at the epochs indicated along the time scale at the bottom. The maps span the longitude range that was carried by the sun's rotation past the west limb during the period January 7–14, 1941. The map on the left depicts the intensity distribution in the light of the green line; the one on the right, the red. On each of the corona maps, the clear areas are those where the line was invisible; the light shading marks areas where the intensity lay between 1 and 15; the heavier shading, areas of intensity 16–30; crosshatching, intensities 31–45; and black, intensities 45–50. The middle map depicts the photosphere in the same longitude span and during the same period; it is an adaptation of the photosphere map regularly published at Zürich.[6] The shaded areas represent facula groups; the black areas, spot groups.

Comparison of each of the corona maps with that of the photosphere again discloses that the coronal emission is generally most intense over the spot zones. Moreover, each individual spot underlies a region of maximum coronal intensity. However, some of the brightest regions lie over unspotted areas: notably, the secondary maxima near ±60°,

[6] "Heliographische Übersichtskarten der Flecken- und Fackelherde," *Publ. Eidgen. Sternwarte Zürich.*

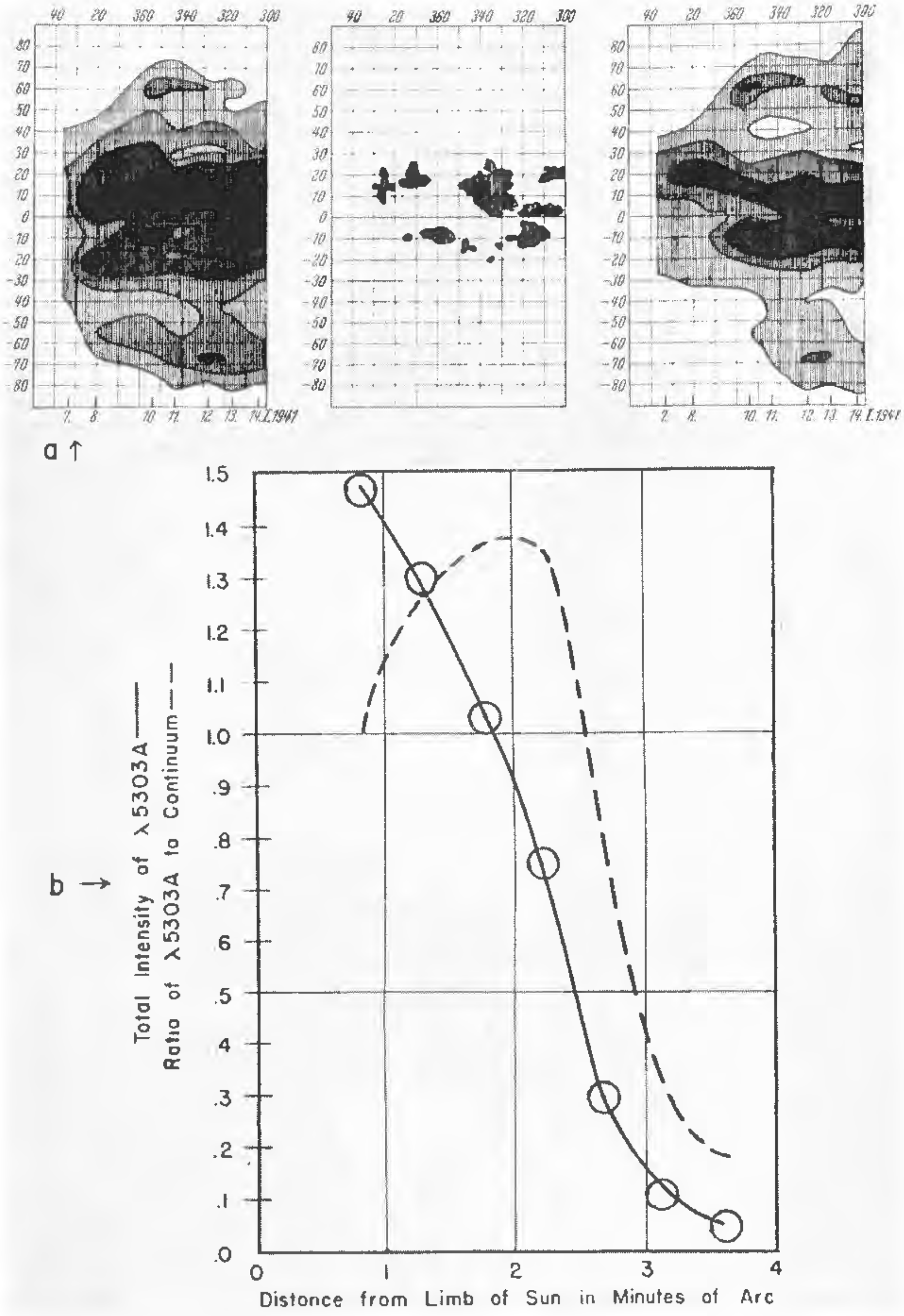

FIG. 5.—(*a*) Heliographic maps of the photosphere (*center*) and the corona in λ 5303 (*left*) and in λ 6374 (*right*). (*b*) Full curve: total intensity of λ 5303 at different distances from the sun's limb; dashed curve: ratio of total intensity of λ 5303 to brightness of continuum according to Baumbach.

where the photosphere manifests no disturbance whatever. In interpreting the maps it must be remembered that interpolation between the epochs of coronal observation has been necessary. Waldmeier suggests that international co-operation among observers could eliminate the lacunae.

Comparison of the two corona maps reveals regions where one of the lines is abnormally strong relative to the other. Thus, there is a green region at 5°, −55°, and a red region at 310°, +55°. Waldmeier has also compared such corona maps with the chromosphere maps published at Paris-Meudon.[7] He finds that there is a strong positive correlation between the more intense chromospheric faculae and the coronal maxima, and a strong negative correlation between the filaments and the coronal maxima. These relations reflect the well-known circumstance that the same correlations exist between the brighter chromospheric faculae, the filaments, and the spots. Like the photosphere, the chromosphere exhibits no disturbance under the secondary maxima of coronal activity near ±60°.

Occasionally, Waldmeier observes regions where the green line is abnormally strong. Figure 1, *d*, shows, on the left, the normal appearance of the green line when the slit lies along the radius. The spectrogram on the right, taken at about the same time but at a different position angle, shows the line abnormally strong near the limb and the intensity gradient abnormally steep. One of the most puzzling features of this spectrogram is the sharp central absorption: a forbidden line cannot appear in absorption. Perhaps the central absorption could be an instrumental or photographic effect?

Waldmeier calls regions of abnormally strong line emission the "C-regions." Figure 1, *b*, shows λ 5303 in a C-region; here the slit lies parallel to the tangent. The central absorption is again apparent. In the papers available here, Waldmeier gives no tracings of lines in the C-regions, but he states that the width is about 3 A and that the central absorption is approximately 0.4 A wide.

Between February, 1939, and March, 1940, Waldmeier observed 15 C-regions in all. They are rather long lived: one region was distinguishable on three successive days, another persisted throughout one rotation. Apparently without exception, they occur in the spot zones. They commonly extend about 20° in longitude and 3°–6° in latitude—about the dimensions of a large spot group. Approximately 20 per cent of the C-regions observed appeared to be associated with large, active spot groups. More often than not, however, the C-regions appear over parts of the photosphere which manifest no disturbance.

Waldmeier noticed that the two most intense C-regions observed at the east limb during the 3 months beginning in February, 1939, were both followed almost exactly 8 days later by the most intense magnetic storms of the quarter-year, both storms being marked by brilliant auroras. In neither case were unusual spot groups apparent.

Figure 6 illustrates the magnetic effects associated with the 15 C-regions observed in 1939–1940. The ordinate is an arbitrary index of terrestrial magnetic activity. It is apparent that the magnetic activity was near maximum about 8 days after the observation of at least 4 of the 7 C-regions seen at the east limb. The mean of the 7 curves, at the bottom, indicates the same effect. On the right, the mean of the 8 curves for C-regions observed at the west limb exhibits a maximum between 6 and 7 days before the C-regions reached the west limb. From the mean curves Waldmeier concludes that magnetic disturbances occur approximately 7.4 days after a C-region is at the east limb, and about 6.2 days before one is at the west limb. Since one-quarter of the solar period is 6.8 days, this leaves 0.6 day for the transit time of the indicated corpuscular emission.

Waldmeier concludes that of the 15 C-regions observed, 10 are associated with magnetic disturbances. He uses this ratio, 10:15, to derive 24 days as the approximate mean lifetime of a C-region. Because the corona cannot yet be observed daily, it is not possible to find what proportion of all intense magnetic storms are associated with C-

[7] "Cartes synoptique des couches supérieures de l'atmosphère solaire," *Ann. Obs. Paris-Meudon.*

regions. However, of the 20 most intense storms during the 21 months beginning in January, 1939, 10 occurred at times such that the associated C-regions might have been observed. Of these 10 C-regions, 7 were in fact observed. This result is in close agreement with the two-thirds ratio derived above.

It is well known that most magnetic disturbances tend to repeat themselves at 27-day intervals, and that terrestrial magnetic activity is characterized by an 11-year period. These facts have led to the hypothesis that the sun is directly responsible for the magnetic disturbances. However, the identification of the regions responsible for the

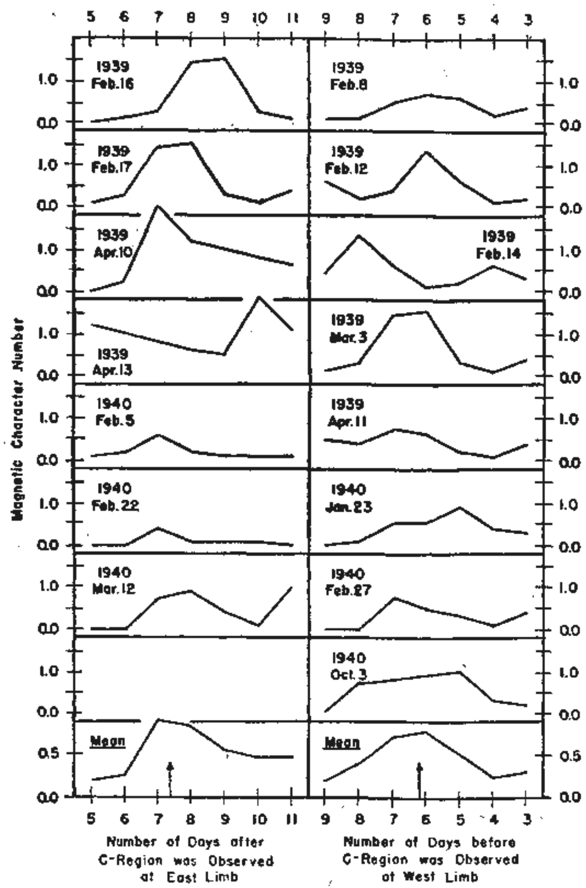

FIG. 6.—Magnetic effects of C-regions

magnetic effects has been difficult. Thus, for example, the responsible regions seem to be generally indifferent to the spots themselves. Only the most intense magnetic storms usually appear to be directly associated with spots, and many of these with short-lived chromospheric eruptions above active spots. Ordinarily, these intense storms do not recur after the sun has completed one rotation. In some cases, however, an intense storm apparently associated with an eruption will recur after 27 days, although the eruption itself is long since dissipated.

Waldmeier proposes that the C-regions are to be identified with the areas of the sun responsible for the magnetic disturbances. "Different narrowly limited regions of the solar surface emit a corpuscular radiation over quite a long period," he suggests.

These so-called C-regions always lie in the spot zones, but usually in spot-free regions. The corpuscular radiation vanishes with the appearance of photospheric disturbances, possibly through the action of the magnetic field associated with spots. However, in large and quickly developing spot groups, possibly through rapid variations of the magnetic field-strength, chromospheric eruptions appear, which in turn lead to the emission of corpuscular streams through some mechanism as yet unknown.[8]

It is not clear to me whether Waldmeier proposes that these corpuscular emissions actually originate in the corona. More appealing, I think, is the view that they originate at greater depths, and that the C-regions are to be understood as indications of the effect of the corpuscles on the coronal matter. This interpretation suggests that high-speed ions ejected from the lower layers might somehow produce the coronal excitation. Thus, a proton which travels from sun to earth in half a day will have an average speed 1 per cent the speed of light and a kinetic energy of the order of 60,000 ev.

Incidentally, regions in which the other coronal lines are abnormally strong do not all behave the same as the C-regions. For example, λ 5694, which normally is less than 5 per cent of the intensity of the green line, becomes strong only over active spot groups. Waldmeier notes one case where, over a very large active spot group surmounted by prominences, λ 5694 was three times as strong as the green line! This line is tentatively identified by Edlén as due to *Ca* XV, which has the highest ionization potential of all the ions found in the corona—more than double the ionization potential of *Fe* XIV, for example.

5. *Contours of* λ *5303*.—For a discussion of the contours of the green line at different distances from the limb, Waldmeier secured 7 spectrograms on July 10, 1940. The slit was oriented in the direction of the tangent to the limb at position angle 260°, where there was a coronal ray. The first plate was exposed with the slit 51″ from the limb, and between subsequent plates the slit was moved outward from the limb in increments of 28″. For purposes of calibration, 7 additional plates were secured with the slit 51″ from the limb. These plates were taken through gray filters of known transmission characteristics. The density-curve at the center of λ 5303 was then found from tracings of these 7 plates. The photometer slit was 0.012 mm wide, corresponding to 0.11 A on the plates, and 1 mm long. On all plates, only the red half of the line was traced, in order to avoid the blend with the Fraunhofer line λ 5302.

After correction was made for differential extinction and for the effect of the scattered continuous light, the contours shown in Figure 4, *d*, were obtained. The intensities are given in arbitrary units; curve No. 1 refers to the plate exposed with the slit 51″ from the limb; curve No. 7 to that with the slit 3′38″ from the limb. The contours were measured with a planimeter, and the areas were expressed in units of the area of a strip of unit intensity 1 A in width. The resulting total intensities are given in Figure 5, *b*, along with the ratio of these intensities to the intensities of the coronal continuum according to Baumbach's relation. The ratio has been taken as unity at $h = 51''$. It appears here that the emission gains strength relative to the continuum out to about $h = 2'$ and thereafter falls sharply. At the greatest distance investigated, the emission has not yet become proportional to the continuum, although there is some indication that the two gradients converge at greater distances. In any case, the gradient found here for λ 5303 refers to a ray, and it is therefore steeper than the average gradient for the green line.

Waldmeier finds that the total intensity is proportional to $\rho^{-21.4}$ over the interval investigated. By the argument given in Unsöld's book,[9] this leads to a source function, F, given by

$$F(r) \propto r^{-22.4} ,$$

where r is the distance from the center of the sun in solar radii. Since the source function is proportional to the specific intensity averaged over all directions, J, we have

$$F(r) = \sigma(r) \cdot J(r) ,$$

[8] *Zs. f. Ap.*, **21**, 284, 1942.

[9] *Physik der Sternatmosphären*, pp. 439–442, Berlin: J. Springer, 1938.

where σ is the volume coefficient of emission; and since σ itself it proportional to the density D of the emitting material, we then have

$$D(r) \propto \frac{F(r)}{J(r)}.$$

However, J is very nearly constant in the interval considered ($1.05 \leq r \leq 1.23$); so Waldmeier takes the density proportional to the source function alone and writes

$$D \propto e^{-a(r-1)},$$

where

$$a = \frac{22.4 \ln r}{r-1} \backsim 21.0 .$$

By way of comparison, the density gradient a in an isothermal atmosphere of temperature $T = 4800°$ (the boundary temperature of the sun) and mean molecular weight $\bar{\mu} = 1$, is

$$a = \frac{\bar{\mu} g}{RT} = 4770 ,$$

where g is the acceleration of gravity at the solar surface and R is the gas constant. The coronal density gradient is seen to be less than one two-hundredth as steep.

The contours themselves are evidently characteristic of Doppler effect. After correction for instrumental broadening—Waldmeier finds the instrumental half-width to be 0.44 A—the true half-width of the line is found to decrease from 0.54 A at $h = 51''$ to 0.28 A at $3'38''$. Waldmeier estimates the probable error of his half-widths as about ± 0.06 A. The modal velocities ξ_0 corresponding to the measured half-widths run from 37 to 19 km/sec. Using the relation

$$T = \frac{\bar{\mu} \xi_0^2}{2R},$$

Waldmeier derives the kinetic temperature T corresponding to the average value of ξ_0, or 27 km/sec. Since only *Fe* x to *Fe* xiv appear to be abundant, he takes $\bar{\mu} = 5$. The result is $T = 219{,}000°$, which is, in fact, of the same order of magnitude as the temperature indicated by the ionization equation.

From the last two equations it follows that

$$a = \frac{2g}{\xi_0^2}.$$

McCrea[10] has shown that this expression is valid in a turbulent atmosphere if ξ_0 is the actual modal velocity, i.e., the mode taken without discrimination between thermal and turbulent velocities. Using this relation with $\xi_0 = 28$ km/sec, Waldmeier derives $a = 8.52$, which seems to agree rather well with the observed gradient, $a = 21.0$, when it is kept in mind that the latter value refers to a ray and is therefore likely to be two or three times the average gradient. However, I am unable to reproduce his result for the calculated value of a; with $\xi_0 = 28$ km/sec, I find $a = 486$ instead of 8.52. This value is less discordant than that for an isothermal atmosphere at 4800°, but it is still very much larger than the observed gradient.

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September 22, 1944

[10] *M.N.*, **89**, 718, 1929.