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SPECTROGRAPHIC OBSERVATIONS AT THE TOTAL SOLAR ECLIPSE OF 1940 OCTOBER 1

II. CONCERNING THE FLASH SPECTRUM AND ATOMIC VELOCITIES IN THE CHROMOSPHERE

R. O. Redman

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The amount of observational material obtained at the 1940 eclipse as a result of the work described in the preceding paper is rather large, and there remains still a great deal not yet measured or discussed. Owing to present-day conditions and the uncertainty of being able to finish the work without delay, it has been decided to publish the results in stages, as they reach completion. The present paper deals with some matters relating to the chromospheric spectrum. It is hoped to examine the question of the extreme limb spectrum in a later publication.

Wave-lengths and Identifications.—The first task in dealing with these spectrograms was to measure wave-lengths and identify as many lines as possible. Unless cut, the plates are too large for the only measuring machine at present available at the Radcliffe Observatory, so that all wave-lengths have been obtained from measurements of microphotometer tracings at magnification 100 : 1. Details of the microphotometer, a photoelectric machine completed for the observatory by Messrs. Casella in 1939, have never been published, as it is thought that a quite sufficient number of similar instruments have already been described in astronomical and physical literature. It may, however, be mentioned here that the machine was intended to give as much positional accuracy as possible on its 100 : 1 tracing-plate ratio, and that tests showed that with this, the largest of its four magnifications, plate positions could in favourable circumstances be measured with an average error about 0·8 μ, which is equivalent to between 0·002 and 0·005 A. on our spectra. While it cannot be claimed that the procedure of measuring on microphotometer tracings is as accurate as the best work an ordinary micrometer machine can produce in experienced hands, it appears entirely adequate for our present purposes, and errors arising from the microphotometer itself are undoubtedly of less importance than those from such factors as line blends or plate grain.

The chromospheric spectrum at low levels appears to be rather more complicated than the normal Fraunhofer spectrum of the Sun's disc, so that the number of lines which can be measured and identified on a properly exposed photograph at present depends solely on the resolving power of the spectrograph. The difficulty of measurement is much enhanced by the fact that the lines vary considerably in their structure, not only from line to line, but also from height to height in the chromosphere. There are many strong Fraunhofer lines in the normal solar spectrum whose counterparts in the low chromosphere are almost unrecognizable because of intense self-reversal. This reversal, which is extremely common among the stronger lines, becomes weaker with increasing height. Blends also vary with height. The well-known line λ 4471, *He*I, is heavily blended in the lower chromosphere, and is only seen clearly and unmistakably because it persists in considerable strength to heights at which the other lines have all faded away.

Using the first exposure on each plate, but relying chiefly on plate 2, exposure 1 (referred to as 2/1), 3994 emission lines have been measured and 2968 identified. On account of the difficulties just mentioned, we cannot be sure that all the fainter lines are real. About 1500 lines are relatively strong and give reliable measures and identifications, except where blending is unusually severe. For standard wave-lengths the M.I.T. tables * have been used, together with the Revised Rowland Catalogue, and for the rare earths the classifications given by King in his well-known series of papers in the *Astrophysical Journal.* The wave-lengths covered are $\lambda\lambda$ 4023–4928. We have ignored the question of errors in the M.I.T. wave-lengths, except in a few cases where there appear to be definite misprints.

Since there was no terrestrial spectrum on the plates, well-known and easily identified lines in the chromosphere have been used for comparison. For identification a measured wave-length had in general to be within 0·05 A. of the laboratory value. This tolerance was narrowed slightly for the shorter wave-lengths and stretched a little for a few lines of longer wave-lengths where the instrumental dispersion had become smaller. Occasionally, where the Rowland and M.I.T. wave-lengths differed by an unusually great amount, and where our measure agreed better with Rowland, the latter was taken as standard.

The following spectra are certainly present in emission: *H*I, *He*I, *Na*I, *Mg*I, *Ca*I, *Ca*II, *Sc*I, *Sc*II, *Ti*I, *Ti*II, *V*I, *V*II, *Cr*I, *Cr*II, *Mn*I, *Fe*I, *Fe*II, *Co*I, *Ni*I, *Zn*I, *Sr*II, *Y*I, *Y*II, *Zr*I, *Zr*II, *Ba*II, *La*II, *Ce*II, *Pr*II, *Nd*II, *Sm*II, *Eu*II, *Gd*II, *Dy*II, and also *CH*, *CN*. A number of the stronger unidentified lines in Rowland were also found. A further 25 atomic sources, neutral or singly ionized, have been classed as "probably" or "possibly" present. They need not be mentioned here, for the list is bound to be incomplete, owing to our restricted wave-length range. The evidence for *Na*I, *Mg*I and *Ca*II on our plates is rather weak, as none of their strong lines is in our region, but they have been included in the above list as the *D*, *b*, and H and K lines are all well-known features of the flash spectrum. A rather striking feature of our spectrograms is the abundance and strength of the rare earth lines, the overwhelming majority from singly ionized atoms.

Similar measures and identifications have been made on plate 2, exposure 2 (2/2), which shows both emission and absorption lines. It is not intended to discuss these now, but one result which concerns the chromosphere may be included here. In his well-known work on the chromospheric spectrum, Menzel † remarked on an asymmetry of the emission lines relative to the corresponding absorption, and Thackeray ‡, using the spectrograms obtained in 1936, found a systematic shift in wave-length between emission and absorption amounting to 0·021 ± 0·010 A. (24 lines), emission being of shorter wave-length.

To examine this shift, 328 emission lines and 159 absorption lines were selected on 2/2 in the region $\lambda\lambda$ 4200–4600, freedom from blends and certainty of identification being the principal criteria. The whole region was covered by four long microphotometer tracings (the instrument records on a roll of bromide paper, not sheets, so that this is possible), and the mean relative shift found was

$$\text{absorption} - \text{emission} = -0{\cdot}0007 \pm 0{\cdot}002 \text{ A.}$$

In other words, the shift was zero to within ·001 or ·002 A. The average residual for an individual emission line was 0·016 A. and for absorption 0·014 A. The bad seeing during totality was a help in this particular work, for it ensured that the centre of the spectrograph slit was uniformly illuminated with both emission and absorption spectra, so that both appear on the same tracings covering only 0·6 mm. slit length. A correction for the curvature of the slit image becomes unnecessary in these circumstances. The emission lines may be regarded as chromospheric, the absorption lines as coming from within $0''{\cdot}35$ of the limb ($\theta > 88^\circ{\cdot}5$).

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* *M.I.T. Wave-length Tables,* Wiley & Sons, 1939.

† *Lick Obs. Publ.,* 17, 299, 1931.

‡ *M.N.,* 97, 678, 1937.

It may be objected that what should be measured is the shift of the self-absorption within a line relative to the emission part of the same line, and not absorption lines relative to independent emission lines. This is a much more difficult task and has not been attempted. There is, however, no obvious systematic asymmetry on our microphotometer tracings, for example in the sense that the emission is always stronger on the violet side of the self-reversal than on the red. Such differences as show appear to be of a random nature and due simply to irregularities in the plate emulsion, and more especially to numerous blends. In any case, whatever may be concluded on this point, there seems no reason to believe that there is at the Sun's limb a general systematic wave-length displacement between absorption and emission lines.

Instrumental Profile.—Before considering the profiles of the chromospheric lines, it was necessary to find the instrumental profile. As explained in the preceding paper, this was determined by exposures made with a krypton discharge tube, which gives lines so narrow that their profiles measured on the plate may be regarded as entirely instrumental. The question of errors of measurement will be discussed later. Examination of Table I, where the result of these measures is to be found, shows that the total width of the instrumental profile where the intensity has fallen to half the maximum value (the half-width, abbreviated to h.w. in the rest of this paper) *, is only 0·038 mm. It is clear that the optical performance was limited more by the slit width, 0·04 mm., and by the plate grain, than by any shortcomings of the prisms or lenses. The theoretical h.w. cannot be given accurately, since the spectrograph had 3-inch prisms and 3½-inch lenses, and the illuminated aperture was neither circular nor square, but for an infinitely narrow slit and at the centre of the plate it should be near 0·030 mm.

Table I

Instrumental Profile for Eclipse Spectrograph

Distance from Centre	Intensity	Distance from Centre	Intensity
0·000	1·00	0·06	0·026
·005	0·98	·07	·016
·010	·85	·08	·0107
·015	·66	·09	·0078
·020	·45	·10	·0059
·025	·30	·12	·0038
·030	·195	·14	·0024
·035	·130	·16	·0018
·040	·087	·18	·0014
·045	·065	·20	·0011
0·050	0·045	·25	·0008
		0·30	0·0005

The measured krypton lines were near the centre of the plate and it has been assumed that the instrumental profile is constant (in mm., not A.) throughout. Except for the extreme wings, which differ by something of the order of 10 per cent. from each other, the profile is symmetrical. These differences have been neglected, as they are not thought to be significant, and in any case have no appreciable effect on the present work.

Since it is often more convenient to refer to the linear width of the lines on the plate, rather than to their widths in A., the dispersion of the spectrograph at various wave-lengths is given in Table II.

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* We use the h.w. extensively in what follows, as a convenient summary description of the shapes of the emission lines. Its usefulness is enhanced by the fact that the centres of these lines, contrary to the case of strong absorption lines, are the parts where our measures are most reliable, and also the parts where the effect of velocity in the line of sight shows itself most quickly. The h.w., however, is not a complete substitute for the measured profile, to which we return when necessary.

TABLE II

Spectrograph Dispersion in Relation to Wave-length

λ	A./mm.	λ	A./mm.
4100	2·71	4600	4·78
4200	3·09	4700	5·25
4300	3·48	4800	5·75
4400	3·89	4900	6·27
4500	4·32	5000	6·81

Some Narrow Chromospheric Lines.—The first line profile to be measured on 2/1 was λ 4333, *La*II, chosen because it is a fairly strong line near the centre of the plate and is at the same time very sharp. The continuous spectrum was measured and subtracted, as has been done whenever it is of sufficient strength to appear on our exposures. The h.w. of λ 4333 was then 0·043 mm., the same value being later obtained from the other plate 1/1 (fig. 1). We can come to two important conclusions immediately: (1) The spectrograph performance at the eclipse, with the moving back in action, must have been little, if at all, inferior to what it was when we photographed the krypton spectrum with the back stationary; and (2) two independent regions of the chromosphere, on opposite sides of the Sun, had very little turbulent motion, since the average velocity of the lanthanum atoms in the line of sight, parallel to the solar surface, could not have exceeded a value in the neighbourhood of ±2 km./sec. More precisely, if we assume a Gaussian distribution of velocities, the average velocity in the line of sight required to combine with the instrumental distortion to give the observed profile would be ±1·6 km./sec.

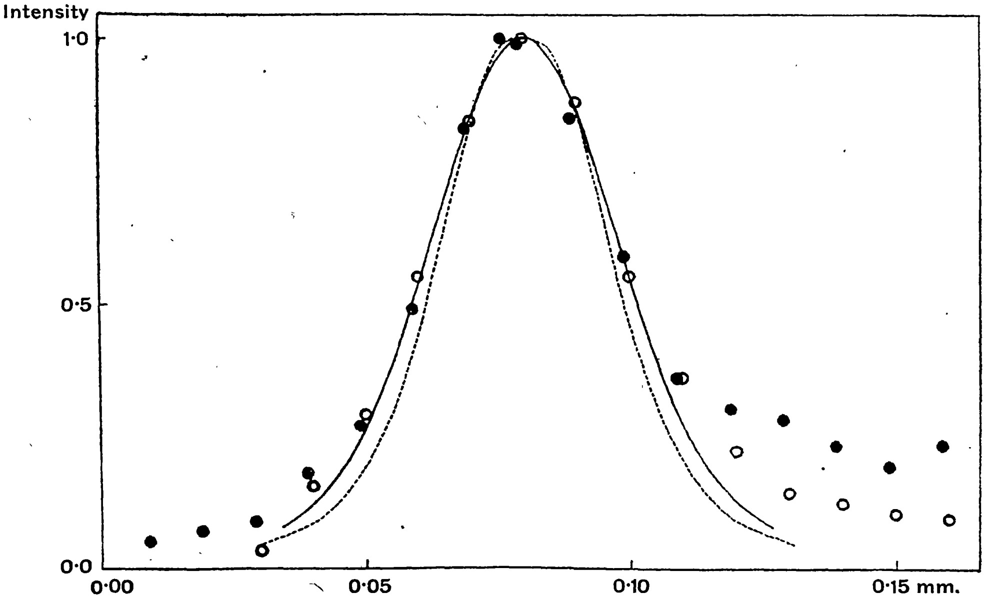

FIG. 1.—*Observations of* λ 4333, *LaII. Filled circles are from Plate* 1, *open circles from Plate* 2. *The broken curve is the instrumental profile, the continuous curve is computed for* $\bar{v} = \pm 1{\cdot}6$ *km./sec. The scale is* 1 *mm.* = 3·6 *A. The wing to the right is affected by blends with* $\lambda\lambda$ 4333·913 *PrII,* 34·030 *CH,* 34·149 *SmII.*

It appears unlikely, as we shall see later, that a line from the low chromosphere is ever very sharp if the corresponding line in the Fraunhofer spectrum is strong. Hence a list was made of lines in the region $\lambda\lambda$ 4200–4600, whose Rowland numbers do not exceed unity, and which in the chromosphere are reasonably strong and free from blends. They were measured on 2/1, what we use being, as before, the profile after the continuous spectrum has been subtracted. For the results see Table III. λ 4333 has been included; it is the strongest of these lines and also the most favourable for measurement. For all the 30 lines the average h.w. is 0·043 mm., the average wave-length 4430 A. If we confine attention to the 19 rare earth lines only, the average h.w. is 0·042 mm.; if we consider only the 22 lines whose Fraunhofer equivalent widths as measured by Allen are less than 0·040 A., the average h.w. is 0·0425 mm. Restricting the choice of lines makes no essential difference to the results. It is impracticable under present conditions to publish a graph of each line separately, so that the 30 measured profiles have been reduced to a common ordinate scale, by making the maximum unity, and superposed in fig. 2. (The abscissa scale remains unaltered.)

TABLE III

Measured Half-widths of Chromospheric Lines

		Fraunhofer Line					Fraunhofer Line		
λ	Source	Rowland No.	Equivalent Width (Allen)	Chromospheric h.w.	λ	Source	Rowland No.	Equivalent Width (Allen)	Chromospheric h.w.
			A.	mm.				A.	mm.
4208·983	*Zr*II	1	0·043	0·050	4434·321	*Sm*II	−1	0·013	0·050
4222·599	*Ce*II	0	·018	·043	4446·387	*Nd*II	−1	·008	·034
4256·396	*Sm*II	−1		·043	4453·706	*Ti*I	1	·044	·033
4316·801	*Ti*II	1	·042	·040	4462·985	*Nd*II	−1	·012	·036
4318·935	*Sm*II	−1	·009	·042	4467·341	*Sm*II	−1	·011	·041
4322·503	*La*II	0N	·008	·049	4470·861	*Ti*II	1	·029	·039
4333·734	*La*II	1N	·030	·043	4500·295	*Cr*I	0	·029	·055
4349·789	*Ce*II	−1	·005	·037	4560·280	*Ce*II	−1	·012	·046
4358·169	*Nd*II	0	·018	·040	4562·361	*Ce*II	0	·019	·037
4382·167	*Ce*II	−1	·012	·039	4568·312	*Ti*II	0	·019	·046
4384·294	*Sm*II	1	·045	·043	4577·174	*V*I	0	·029	·040
4398·011	*Y*II	1	·049	·044	4577·687	*Sm*II	−1		·046
4399·203	*Ce*II	−1	0·006	·042	4582·835	*Fe*II	1	·048	·049
4424·342	*Sm*II	−1		0·048	4592·058	*Cr*II	1	0·041	0·057

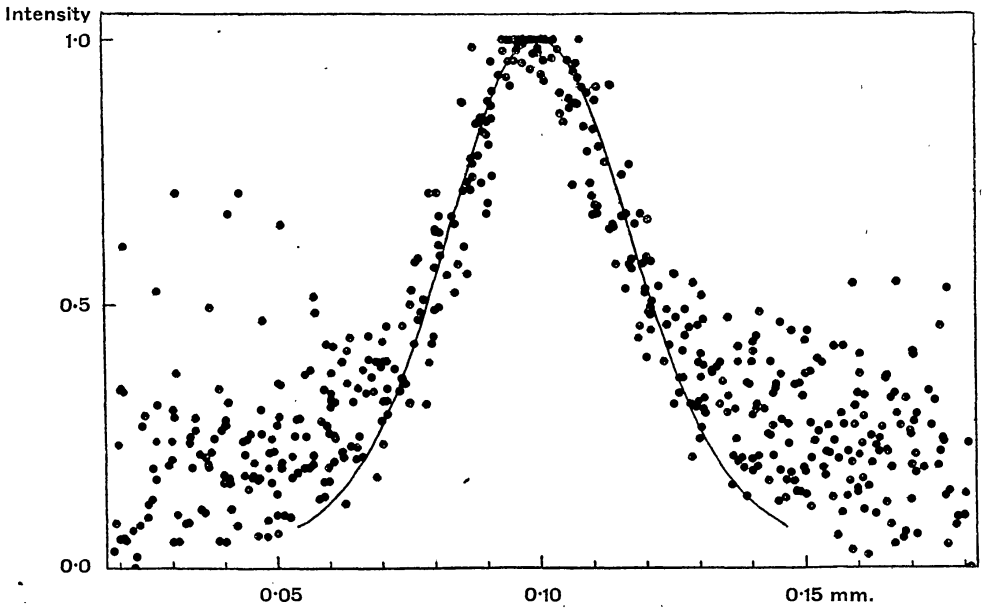

FIG. 2.—*Observed points from thirty narrow chromospheric lines, superposed on the profile computed for* $\bar{v} = \pm 1\frac{3}{4}$ *km./sec.*

The curve there is computed for the average wave-length λ 4430 A. by assuming an originally monochromatic radiation, modified by a Gaussian distribution of atomic velocities in the line of sight, with $\bar{v} = \pm 1{\cdot}75$ km./sec. and distorted by the spectrograph in accordance with the instrumental profile of Table I. This gives 0·043 mm. for the h.w., agreeing with the average from the 30 lines, and it can be seen that the upper part of the curve agrees very satisfactorily with observation. The growing tendency of the measured points to lie above the curve as one goes below intensity 0·5 is believed to be almost entirely due to other lines adjacent to those measured.

The Neutral Helium Line λ 4471.—The only helium line on our exposures which is favourable for measurement is λ 4471, and even this cannot be used at low levels, on account of very heavy blends, the effect of which is accentuated by a weakening of the helium line itself in the very low chromosphere. The measured h.w. at five different settings along the slit on 2/1, above the level at which blends are troublesome, were 0·077, ·088, ·089, ·096, ·096 mm., the mean being 0·091 mm. Owing to the use of a slow spectrograph the line cannot be followed to any very high chromospheric level, and the circumstances under which the spectrograms were obtained make it impossible to estimate heights except extremely roughly. As far as we can tell, these measures refer to a height about 1500 km., using the word "height" in the conventional manner. Computing the average line of sight velocity in the same manner as before we find $\bar{v} = \pm 7{\cdot}5$ km./sec. On the other plate six measures, two on 1/1, the others on 1/2, 1/3, 1/4 and 1/5, gave values for the h.w. 0·96, 1·22, 1·07, 1·05, 0·90 and 0·81 mm. respectively, with a mean value 1·00 mm. This gives $\bar{v} = \pm 8{\cdot}5$ km./sec.

For two independent reasons these helium profiles are probably a little too wide: (1) We have taken no account of the fainter component of λ 4471, apart from very slight smoothing of the curves; and (2) to avoid blends we had to measure at heights where the continuous spectrum is relatively weak, in some cases too weak to be recorded on the plate, although possibly still present in sufficient strength to affect the line profile. Inspection of the characteristic curves of the plates showed that the continuous spectrum would be almost impossible to measure when its intensity is less than one-tenth of the maximum intensity in the helium line. The effect of an unmeasured continuous spectrum is to flatten the profile. The rather large scatter between the individual values given above for the line width may in part be due to this cause.

Our measures may be compared with those Unsöld * made on the *He*I line λ 5876, the first of the series of which λ 4471 is the second member. His measures were not reduced in quite the same way as ours; he used the mean square and not the average velocity, while the 16·1 km./sec. of his paper is a space velocity, not the component in the line of sight. It is best to go back to the original measures, from which we find $\bar{v} = \pm 9{\cdot}1$ km./sec. Considering that Unsöld made no correction for instrumental distortion, while his measures were made in full daylight, and not at an eclipse, the agreement with our velocity (8 km./sec., using both plates) is not wholly unsatisfactory.

Hydrogen Lines.—When measuring the shapes of the hydrogen lines we encounter a difficulty it has been possible until now to ignore. In none of the lines considered so far is there appreciable self-reversal, although this statement is by no means true for chromospheric lines in general. The majority of strong lines, especially those corresponding to strong Fraunhofer lines, show some signs of self-reversal, which in particular cases, at low levels, may weaken and distort the line to an astonishing extent. There is a marked correlation of the strength of the reversal with the Fraunhofer intensity, and it is for this reason that for the measures described above we selected a list of lines with Rowland numbers not exceeding unity. Leaving for later consideration the question of how the self-reversal is produced, we need remark only on one fact, viz. that it has a tendency to diminish as one proceeds from lower to higher layers of the chromosphere. It is a race between a general weakening of the line and a falling off

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* *Z. f. Ap.*, 3, 77, 1931.

of the reversal; sometimes the latter wins, but in certain cases, fortunately including the hydrogen lines, we can get rid of practically all the reversal before the line becomes too faint to be recorded on our spectrograms. To reach chromospheric layers as high as possible, the microphotometer slit was shortened to 0·15 mm. (as projected on the plate) and widened to 0·02 mm., twice the standard setting, the lines being very broad. This arrangement minimizes the trouble that at the ends of the hydrogen lines, where we wish to measure, the intensity falls off rather rapidly, so that with a longer microphotometer slit one cannot avoid averaging over an undesirably large range of photographic density. As with helium, it is impossible to make anything but a very rough estimate of the "height," but it is again about 1500 km. The profiles from these tracings are given for $H\beta$, $H\gamma$ and $H\delta$ respectively in figs. 3, 4 and 5. Observed points are

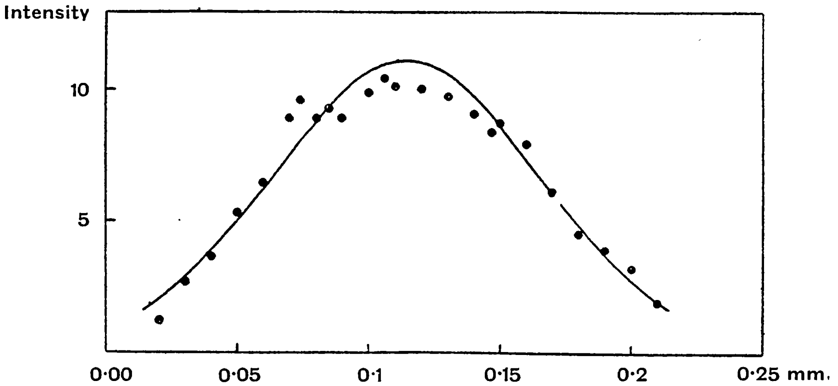

FIG. 3.—*Observed points on the profile of* $H\beta$, *with the curve computed for* $\bar{v} = \pm 14$ *km./sec.*

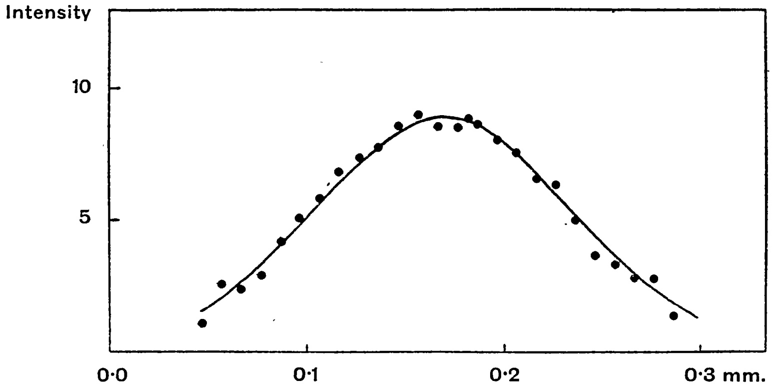

FIG. 4.—*Observed points on the profile of* $H\gamma$, *with the curve computed for* $\bar{v} = \pm 12\frac{1}{2}$ *km./sec.*

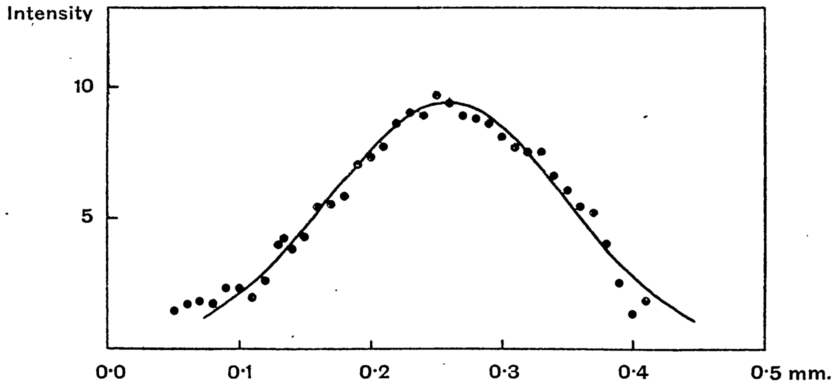

FIG. 5.—*Observed points on* $H\delta$ *profile, with curve computed for* $\bar{v} = \pm 14$ *km./sec.*

shown together with curves computed as before from a Gaussian distribution of line of sight velocities, plus instrumental distortion, the latter being relatively small for these lines. We find average velocities as follows:—

$H\beta$	$\bar{v} = \pm 14$ km./sec.
$H\gamma$	$12\frac{1}{2}$,,
$H\delta$	14 ,,

The fit with observation is satisfactory. There are indications of some self-reversal still remaining in the case of $H\beta$. (We expect the reversal to diminish from $H\beta$ to $H\delta$.) For the three lines together $\bar{v} = \pm 13{\cdot}5$ km./sec. It was found with $H\gamma$ and $H\delta$ that at slightly lower levels, with some self-reversal present, the outer part of the profile could still be fitted quite well to a curve computed for $\bar{v} = \pm 13\frac{1}{2}$ km./sec.

Errors of Measurement.—It is desirable at this stage to review our photometric procedure in order to obtain some idea of the reliability of the results just described. In skeleton, the method has been to measure lines on a plate calibrated with additional exposures taken through an optical wedge, and to correct the profiles so obtained by determining the instrumental distortion from krypton spectra photographed two or three days before the eclipse.

The first point to consider is our tacit assumption that the performance of the spectrograph at the eclipse was identical with that shown by the krypton photographs. As regards the temperature of the optical parts, or focus adjustments, we may be confident that there was no change which would lead to any detectable variation of the instrumental profile. On the other hand, the krypton exposures were taken with the camera mechanism stationary, the eclipse exposures with it working, and possibly setting up some small vibration in the instrument. There also may have been a slight change of slit width. As mentioned in the preceding paper, the slit had to be opened frequently for cleaning, on account of the dusty conditions at Calvinia, and unfortunately it did not have a very reliable zero reading. As much care as possible was given to keeping the width constant, but it is difficult to say to what degree of accuracy this aim was achieved. However, the width had been chosen on the basis of trials which showed that not much improvement in spectrum definition was obtained by using a narrower setting, so that the rate of change of instrumental profile with slit width was fairly small. In any case we can say that the eclipse performance was not far short of the krypton performance, since we have measured chromospheric lines with a h.w. exceeding the instrumental h.w. by only 5 μ. We can, moreover, set fairly narrow limits to the small velocities derived from these lines. In the case of λ 4333, *La*II, for example, we found $\bar{v} = \pm 1{\cdot}6$ km./sec. Now the spectrograph could never do more than give theoretical performance for an infinitely narrow slit, and for this limiting case $\bar{v} = \pm 2{\cdot}9$ km./sec. At the other limit the whole observed width of the line is instrumental, in which case $\bar{v} = 0$. (This neglects systematic photometric errors such as are considered below.) On the whole it seems more probable that the eclipse performance was slightly worse than krypton performance, than that it was better, *i.e.* $\bar{v} < 1{\cdot}6$ km./sec. is rather more likely than $\bar{v} > 1{\cdot}6$ km./sec. Before leaving this point it should be added that the instrumental profile includes distortion due to the photographic plate and to the microphotometer, as well as the spectrograph proper. Microphotometer adjustments have been kept as uniform as possible, and this contribution to the instrumental profile, as well as that of the plate, should have remained satisfactorily constant throughout.

The time-intervals between separate exposures on one plate, including calibrations, were kept small relative to the time elapsing between exposures and development, so as to minimize any effects due to latent image changes. Our plates were all brushed during development, to reduce Eberhard effect. If present, this should be of comparable amount in both eclipse and krypton exposures. Both chromospheric and instrumental profiles would then appear too narrow, but the errors should roughly cancel each other when the krypton and chromospheric lines are of the same order of sharpness.

There is also the question of errors arising from plate calibration procedure. For the calibration exposures the wedge was illuminated direct from the zenith sky. It was, of course, screened from direct sunlight; even so, more light than was necessary to fill the prisms was entering the slit, and a harmful amount might reach the plate by reflection or scattering within the instrument. As mentioned in the preceding paper, the interior of the spectrograph is well diaphragmed, and parts of the camera tube are lined with black velvet. The lenses are cemented doublets. These favourable constructional features appear to have been sufficient to suppress the false light, for if the quantity reaching the plate were at all serious, there would be a noticeable deviation from linearity in the (log I, h) relation, to be seen most at the more lightly exposed end of the wedge image. We have been unable to find more than very slight signs of this on the eclipse plates, so that errors from this source should be negligible. The wedge "constant" was determined at Pretoria after the eclipse, using the same spectrograph. Values were found at nine wave-lengths covering λλ 4100–4800. This is the fourth wedge the writer has had occasion to calibrate at various times, and it is believed that errors of the wedge constant are here sufficiently small to be disregarded.

Owing to the conditions in which this work was undertaken, insufficient time was available for experiment with the spectrograph prior to the eclipse, in order to devise a method whereby the wedge exposures could be made of the same duration as the eclipse exposures, while retaining such an essential condition as uniformity of illumination of the wedge. Relying on the known fact that a plate's characteristic curve changes slowly with exposure time, both the eclipse exposures, of average length 0·58 second, and the krypton exposures (10 seconds to 30 minutes) were calibrated with a pair of wedge exposures of duration 20 and 40 seconds respectively. In making tests on Ilford Zenith plates since the eclipse it has been found that between exposure times 30 seconds and 30 minutes the characteristic curves are identical to a fairly high degree of accuracy. Two such curves could, for instance, be fitted together between microphotometer readings 5 and 95 per cent. with a maximum difference 0·017 in log I and an average difference about 0·007. There is thus no difficulty as far as the krypton exposures are concerned.* Between exposure times 0·5 and 30 seconds, however, our tests revealed a greater change of characteristic curve. Duplicating as nearly as possible the contrast of the eclipse plates, it was found that the slope of the central part of the 30-second curve was of the order of 10 per cent. greater than that for 0·5 second, a greater difference than had been anticipated. Unfortunately it was impossible to make these tests with plates from the same batch as those used at the eclipse, but assuming that the latter had the same properties, our chromospheric line profiles contain a small systematic error, the exact amount depending on the part of the characteristic curve which has been used. Our $\bar{v}$, then, is systematically too great. If we apply the best corrections we can, $\bar{v}$ is reduced to about 12½ km./sec. for hydrogen, 7½ km./sec. for helium, and 1·3 km./sec. for lanthanum. Fortunately the error is not sufficiently great to alter the general significance of our results.

Are the Velocities Thermal?—If the chromosphere were composed of gas in ordinary thermal equilibrium, the distribution of atomic velocities would be Maxwellian. In one dimension the distribution for any given element would be Gaussian, while the mean velocity would be inversely proportional to the square root of the atomic weight. Neglecting for the time being the systematic error for which evidence has just been discussed, the measured average line of sight velocities are as follows:—

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* We have neglected the fact that the krypton tube, being run off an induction coil, was a flickering and not a steady source. This should have little effect, since the period of light variation was very short relative to the total exposure time.

Hydrogen	13·5 km./sec.
Helium	8 ,,
Lanthanum	1·6 ,,
Various other heavy elements	1·75 ,,

while the hydrogen lines fit a Gaussian velocity distribution quite well. We have seen that for two reasons the measured helium velocity is probably a little too great, while for another reason the same is probably true of the elements giving small velocities, between 1 and 2 km./sec. If the velocities *were* thermal, with the average hydrogen velocity 13·5 km./sec., other average velocities would be:

He	6·8 km./sec.
Ti, *Cr*, *Fe*	1·9 ,,
La, *Ce*, *Nd*, *Sm*	1·1 ,,

Everything considered, the agreement with observation is quite good, without any allowance whatever being made for turbulence. It seems clear that any chromospheric turbulence distinguishable from thermal motions, *i.e.* of a kind which affects all atoms equally, irrespective of atomic weight, cannot exceed something of the order of 1 km./sec.

The measured velocities are in the line of sight. If we assume a Maxwellian distribution given by $e^{-hm(u^2+v^2+w^2)}du\,dv\,dw$, where u, v, w are velocities in rectangular co-ordinates, m is atomic weight and h is a parameter determining the scale of the motions and hence the temperature, the average one-dimensional velocity is $\bar{v}=\frac{1}{\sqrt{(\pi hm)}}$, which is the quantity we measure. The average *space velocity* is $\frac{2}{\sqrt{(\pi hm)}}$, the mean square space velocity is $C=\sqrt{\left(\frac{3}{2hm}\right)}$ and $\frac{1}{2}mC^2=\frac{3}{2}RT$, where R is Boltzmann's constant and T is the temperature.

Thus

$$T=\frac{1}{3}\frac{mC^2}{R}=\frac{1}{2hR}=\frac{\pi m\bar{v}^2}{2R}.$$

We have $R=1{\cdot}372\times10^{-16}$, while for hydrogen $\bar{v}=1{\cdot}35\times10^6$ and $m=1{\cdot}66\times10^{-24}$, so that $T=35{,}000°$ K.

If we apply the systematic correction mentioned at the end of the last section, the temperature reduces to 30,000°, while the distribution of average velocity with atomic weight continues to agree as well as before with the supposition that the velocities are thermal. The temperature itself is subject to a fairly large uncertainty, owing to the fact that it varies as the square of the velocity. Hence an error of the order of 10 per cent. in line width becomes an error of the order of 20 per cent. in temperature.

It will be clear that 30,000° is simply a kinetic temperature and that our observations do not demand the existence of black-body radiation for 30,000° or any approach to thermodynamical equilibrium for such a temperature. Even so, the result at first sight may seem incredible. Evidence in its favour is mentioned below, but let us first consider various difficulties. In the first place we have ignored a large number of chromospheric lines, possibly a majority, which do not fall readily into our velocity scheme. For instance, at the greatest height at which it is measurable, λ 4227, *Ca*I, shows a rather irregular structure, with h.w. = 0·086 mm. Similarly, for λ 4215, *Sr*II, the minimum h.w. is 0·105 mm., and for λ 4077, *Sr*II, 0·133 mm. All three lines are considerably broader than the temperature suggested above will explain. On the other hand, all three are resonance lines; in the Fraunhofer spectrum they are strong, with very low residual intensities for at least two of the three; in the low chromosphere they show intense self-reversal, and the line shape remains rather irregular and flattened at the greatest heights at which we can measure. It is legitimate to suppose that in these cases we never get rid of the self-reversal and that the lines are on that account unsuitable as a guide to atomic velocities.

Other lines behave in an intermediate manner; they are fairly wide in the low chromosphere, sometimes with clear signs of self-reversal, while although they become narrower at higher levels, the width often fails to reduce to a value which would fit our velocity scheme. Examples are shown in Table IV. With the exception of the calcium line, λ 4227, there is a fairly well-marked correlation between the Fraunhofer intensity and the minimum width, and for the two lines weakest in the ordinary solar spectrum the h.w. approaches the values of Table III, when measurements are made at as high a level as possible.

TABLE IV

Line	Fraunhofer Equivalent Width (Allen)	H.w. at Low Level	Minimum h.w. Measured
	A.		mm.
4077, *Sr*II	0·340	*	0·133
4215, *Sr*II	0·270	*	·105
4227, *Ca*I	1·230	*	·086
4246, *Sc*II	0·160	0·094	·077
4468, *Ti*II	0·141	·075	·057
4515, *Fe*II	0·103	·054	·047
4520, *Fe*II	0·080	·055	·043
4534, *Ti*II	0·150	0·090	0·058

* Heavy self-reversal.

A hard-and-fast demonstration on this point is at present impracticable, but the writer believes that such lines as those of Table IV are all more or less seriously distorted by self-reversal and that we cannot rely on them for obtaining line of sight velocities from their profiles. It is further believed that, if we can confine our attention to lines with small Fraunhofer intensities, and therefore with self-reversal likely to be small, or if we can measure lines at fairly high chromospheric levels, agreement with a kinetic temperature about 30,000° K. will be found.

Another difficulty is that the lines may be broadened by other causes, *e.g.* by Stark effect. We can estimate the Stark broadening of the hydrogen lines, using Verwey's formulæ, as quoted by Unsöld.* At the base of the chromosphere the electron and ion concentration according to Cillié and Menzel † is 4×10^{11}, while an independent estimate by Pannekoek ‡ gives 6×10^{11}. Taking the mean value 5×10^{11}, Unsöld's fig. 65 shows that the half-width for $H\gamma$ due to Stark effect must be about 0·016 A., or 1·1 km./sec. There must be some uncertainty in this estimate, but on the other hand we have measured the hydrogen lines at some distance above the bottom of the chromosphere, which would make the computed value smaller. With other elements quantitative estimates are apparently at present impossible, but it is known that for helium the effect is less than for hydrogen, and for heavier elements much less. Present ideas with regard to the densities in the reversing layer and the chromosphere indicate that Stark effect should be much weaker in the latter than in the former, where it is known that only the hydrogen lines are affected appreciably. We are entitled to conclude that, as far as available evidence goes, the Stark effect can produce only a negligible part of the observed line widths. That being the case, and since turbulence is ruled out by the narrow rare earth lines, the only natural explanation of the observed line widths appear to be that they are due to velocities of a thermal nature.

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* *Physik der Sternatmosphären*, p. 180, 1938.

† *Harvard Circular*, 410, 1935.

‡ *M.N.*, **98**, 709, 1938.

This view may become more plausible on consideration of the following points:—

(1) While our observations disprove the current theory which supposes that ordinary turbulence provides the velocities, and hence the gas pressure, to support the chromosphere *, the thermal (or pseudo-thermal) velocities we observe appear to be quite adequate for the support of hydrogen and helium, although the case of the heavier elements, particularly ionized calcium, needs further examination.

(2) A high kinetic temperature for the chromosphere may provide a clue to a long-standing puzzle, viz. why such high excitation lines as those of helium, particularly the ionized helium line λ 4686, should be observed in the chromospheric spectrum.

(3) Edlén's recent work (details of which are unfortunately still not available in this country on account of the war) calls for extremely high excitation conditions in the corona. In the photosphere, on the other hand, we have conditions corresponding more or less to a temperature of 6000° C. It would appear natural to expect that the chromosphere, lying geometrically between these two, would also be intermediate in physical properties, including atomic excitation and probably also atomic velocities. The fact that the helium line λ 4471 at first increases considerably in strength as one goes from the lowest levels of the chromosphere upwards †, reaching a maximum and then fading away gradually as still higher levels are reached, suggests strongly that there is an increase in excitation conditions from the photosphere upwards. This line is from the neutral atom, so that increase of ionization with height will work in the opposite direction and tend to reduce the intensity as one proceeds upwards. Other lines show increased intensity with height also, but on a smaller scale, and with them it is difficult to say to what extent there is a real increase, other than that caused by a decrease of self-reversal. The latter appears inadequate to explain the variation in λ 4471, particularly since the change is probably still greater than what is observed, on account of masking by blends.

The writer has had many encouraging and helpful discussions with Dr. H. Zanstra during the course of this work.

Summary

A first instalment is given of results relating to the chromospheric spectrum, from photographs obtained at the 1940 total solar eclipse.

(*a*) There is no detectable general wave-length displacement between emission and absorption lines near the Sun's limb. Comparison of 328 emission with 159 absorption lines gave a mean shift, absorption minus emission, of -0.0007 ± 0.002 A.

(*b*) The profiles of a selected number of chromospheric lines have been measured. Making allowance for instrumental distortion, which was measured by photographing the krypton spectrum, average atomic velocities in the line of sight were found which varied between 13·5 km./sec. for hydrogen and 1·6 km./sec. for lanthanum. The distribution of velocities with respect to atomic weight, and also the shapes of the hydrogen lines, are consistent with a kinetic temperature 35,000° K. Evidence is produced to show that there is probably a small systematic error in the widths of the measured profiles. Correction for this reduces the temperature to about 30,000° K.

(*c*) At the two places observed, on opposite sides of the Sun, there was no turbulent motion (other than motion of a thermal nature) exceeding about 1 km./sec. in the line of sight.

Radcliffe Observatory,
Pretoria.

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* See, for example, McCrea, *M.N.*, **89**, 483, 718, 1929.

† First noticed by Menzel (*Proc. Amer. Phil. Soc.*, **81**, 107, 1939) and quite conspicuous on our spectrograms, where the line intensity at maximum is of the order of three times the intensity at the lowest levels.