Kodaikanal Observatory

BULLETIN No. CXXVI.

SOME OBSERVATIONS ON THE H AND K LINES IN THE SOLAR SPECTRUM

BY

A. K. DAS AND N. RAJESWARA RAO

Abstract

Centre-to-limb displacements of the chromospheric lines H_3, K_3 and H_2, K_2 have been measured on high-dispersion spectrograms secured during the years 1947-49. These measures show that the absorbing vapour producing the H_3 and K_3 lines has a descending motion of approximately 1·5 km./sec., while the vapour responsible for the emission lines H_2 and K_2 has a very slight ascending motion of the order of 0·3 km./sec. These results are contrasted with the results of St. John's observations of 1910 and the bearing of these results on theories of the cause of the higher radiative power of the H_2 K_2 layer is discussed; it is suggested that the emission of the H_2 and K_2 lines is unlikely to be due to high temperature.

The width, of the H_2, K_2, H_3 and K_3 lines have been measured at different points of the disk, both over the undisturbed photosphere and over faculae. It is found that although there is a marked increase from the centre to the limb in each case, the relative widths for any given position on the disk irrespective of the presence or absence of faculae are constant, *i.e.*, $K_3/K_2 = H_3/H_2 =$ constant and $K_3/H_3, K_2/H_2 =$ constant.

Introduction

The H and K lines of ionised calcium being by far the strongest lines in the solar spectrum have naturally attracted the most attention from solar physicists. These exceptionally broad lines are remarkable for certain peculiarities of structure, which are not easily noticeable in other strong solar lines. As early as 1872 Young visually observed them "to be regularly reversed on the body of the sun itself, in the penumbra and the immediate neighbourhood of every important spot". But the double reversals in these lines, so clearly seen in high-dispersion spectrograms, appear to have been observed photographically by Deslandres first in 1892 and confirmed immediately after by Hale. From the pioneer works of Hale and Deslandres with the spectroheliograph and the *Spectroenregistreur des vitesses* it became evident that the central absorption component (H_3 or K_3) of these lines is formed in the highest levels of the solar atmosphere, the emission components (H_2V, H_{2R}, K_{2V}, K_{2R}) have their origin at a lower level, while the broad shadings denoted by H_{IV}, H_{IR} and K_{IV}, K_{IR} are formed in the deepest levels of the solar atmosphere.

In his earliest observations of the K line Deslandres (¹) had noticed, among other peculiarities, a dissymmetry between K_2V and K_2R at the centre of the disk with the violet component the stronger, the inequality disappearing at the limb. This he had interpreted, though not with sufficient justification, as being due to a descending motion of the gases producing the K_3 component and an ascending motion of the gases emitting the K_2 component. However, this conclusion was established with greater certainty by Jewell (²), who was able to observe a progressive decrease in dissymmetry from the centre of the disk to the limb and could measure a descending motion of 'about a mile a second' in the H_3 and K_3 layers; he also found "some indications that the emission line might be slightly displaced towards the violet". On the other hand, Adams (³) working on the same problem a few years later found dissymmetry to be the exception and could measure an upward velocity of 0·41 km/sec. for the absorbing vapour and a slight displacement of the emission component toward the violet. In 1910 a very detailed study of the wave-lengths of the different components of the H and K lines over different parts of the undisturbed disk, over faculae and spots was made by St. John (⁴), whose measurements not only confirmed the conclusions reached by Deslandres and Jewell, but also showed that the variation of the displacement of K_3 from centre to limb was in remarkable agreement with the cosine law demanded by the hypothesis of vertical movements. According to St. John's measure-

(1) Comptes Rendus, 119, P. 458, 1894.
(2) Ap. J., 3, P. 103, 1896; Ap. J., 11, P. 237, 1900.
(3) Ap. J., 23, P. 45, 1906.
(4) Ap. J., 32, P. 36, 1910.

165 S. P.obs K. Kanal

Price annas 8 or 9 d.

ments, which are so far the best available on the subject, the mean displacement of K_3 relative to K_2 at the centre of the disk is 0·04 A° towards the red, which corresponds to a relative velocity of descent of approximately 3 km./sec. for the absorbing vapour. In fact, St. John deduces from his measurements a mean *descending motion* of 1·14 km/sec. for the K_3 vapour and a mean *ascending motion* of 1·97 km/sec. for the K_2 vapour over the general surface of the sun. In spite of the great importance of these observations and their bearing on the conception of turbulence in the solar atmosphere no further measurements of the vertical movements of the K_3 and K_2 layers appear to have been reported in later literature. Numerous spectrograms in the H and K region have recently been taken at the Kodaikanal Observatory in connection with the investigation of another problem ; as a number of these spectrograms are quite suitable for the measurement of vertical movements we have thought it desirable to examine them from this point of view as well. Incidentally, we have utilised these plates also for a study of the widths of the H_2, K_2, H_3 and K_3 lines over different parts of the undisturbed disk and over faculae. The plates selected for definitive measurements are those secured in blue sky and under conditions of best possible definition ; the results of the measurements are given in the present paper.

Apparatus and Observational Procedure

The spectrograms were obtained with a prism spectrograph of the Littrow design constructed some years ago by the first named of the present writers for obtaining maximum photographic resolution combined with high-dispersion in the region of spectrum under consideration. The dispersive system consists of three equilateral glass Prisms and a half-prism and the Collimator-Camera lens has a focal length of approximately 14 feet, so that a seven-prism dispersion amounting to 0·45 A°/mm. on the average is obtained in the H and K region with excellent definition and short exposure times. The spectrograph is remarkably free from stray light and the spectra obtained with it show no signs of astigmatism.

The spectrograph was fed by means of a 12-inch Foucault siderostat through an 8-inch visual telescope objective of about 10-foot focal length and an enlarging lens, so that the diameter of the solar image on the slit plate was approximately 4½ inches. The spectra were taken at nine definite points of the undisturbed disk, namely E, W, N and S points, points half-way between them and the centre (which, for brevity, we shall call ½E, ½W, ½N and ½S) as well as the centre itself. Facular spectra were taken at E, ½E, centre, ½W and W and the faculae chosen were those which were away from the centres of spots. On some of the spectrograms taken over the centre and the limbs iron arc comparison spectra were also impressed for calculating the absolute values of the wavelengths of K_3 and H_3.

Measurements of displacements and widths of the absorption and emission components

Our measurements of wavelengths have been made normally with a Hilger wavelength comparator. For the measurements of the displacements of the components from centre to limb plates with iron arc comparison spectra have been used. For the H_3 and K_3 lines the cross-hair has always been placed on the minimum of intensity as estimated by the eye. Although these lines are fairly narrow they are broad enough to make the physiological effect of contrast ([5]) unimportant ; and it is believed that the wavelengths measured represent the real minima of the lines The wavelengths of the centres of the emission lines H_2 and K_2 have been computed by making measures over both the outer edges of each line and taking the average ; this procedure naturally implies the assumption that the distribution of intensity in the bright lines is symmetrical about their centres.

([5]) A. Kuhl, Phy. Zeit., 29, P. 1, 1928.

The wavelengths obtained in accordance with the above procedure have been corrected for orbital motion and diurnal rotation of the earth using the usual formula

$V = 0 \cdot 464 \sin T \cos \delta \cos \varphi$, where T = hour angle of sun, δ = declinatson and φ = latitude of place of observation. The wavelengths for the limb spectra have been further corrected for the rotation of the sun. In order to eliminate uncertainties arising from the variation of the rotational velocity with height and latitude the means of the wavelengths of the respective components at points 1 mm. from the east and west points of the limb have been taken, so that the influence of solar rotation on the limb wavelengths is effectively eliminated. The values of limb wavelengths thus obtained and of the centre wavelengths for the absorption and emission components of H and K are collected in Table I. It is to be noted that the edges of the emission components of the H and K lines are often diffuse and irregular and therefore individual measurements on them may be subject to considerable uncertainties. The values of wavelengths given in the table are, however, means of several measurements made at different points of the edges and can therefore be regarded as representative of average conditions and free from errors arising out of local peculiarities.

Since the relativity effect should be the same at the centre and at the limb, the difference between the centre and the limb wavelengths as given in Table I can be attributed to vertical movement, which is at present the only known cause of the centre-to-limb displacements of solar lines. The vertical velocities calculated on this basis from the wave lengths in Table I are also incorporated in the same table. The + sign before the value for velocity denotes radial motion towards the sun or *descending* movement, while the — sign represents *ascending* motion. The velocities have been computed on the assumption that the "limb" spectra correspond to longitude 80°.

As is well known, the measurement of the widths of spectrum lines presents great difficulties. The difficulties are particularly great when the widths to be measured are those of reversals superposed upon broad absorption and emission lines as in the case of the H and K lines. The visual measurement of the edges of the H_2, K_2, H_3 and K_3 lines is largely influenced by the effect of contrast and is therefore greatly dependent upon the density distribution in the region of the negative used. It is probable that measurements of widths of lines made on negatives of widely varying densities would differ very considerably. It therefore appears very desirable that the width measurements should be made by an objective method. Our measurements have been made both by the visual method using a wavelength comparator and by an objective method using the tracings made by a recording photoelectric microphotometer of the Cambridge type. The measures as obtained by both methods are given separately in Table II. The spectrum plates utilised in these measurements do not happen to differ greatly in density from each other with the result that the widths obtained by the visual method from the different plates are concordant, and so also are the values obtained by the microphotometer method. But the mean values given by the microphotometer method are consistently higher than those given by the visual method. The values of widths collected in Table II are the means of several measures made on a number of plates and can therefore be regarded as representative of fairly average conditions.

Results and conclusions

A comparison of the radial velocities in Table I with those obtained by St. John shows that our value for the velocity of descent of the K_2 layer is slightly higher than that measured by St. John; but our measurements show nothing like the high velocity of ascent of the order of 2 km/sec. of the K_3 layer found by St. John, although they indicate an upward movement of about 0·3 km/sec. on the average. On St. John's plates the mean difference in wavelengths between K_2 and K_3 at the centre of the disk is of the order of 0·04°A, while on our plates the difference is only 0·02°A. This discrepancy we have further verified by making measurements on microphotometer tracings of well-exposed spectrograms secured under excellent observing conditions on two days; these measurements are also included in Table I. It may be noted that the scale of our spectra is considerably larger—at least double—than that of the spectrograms measured by St. John; and it does not seem possible to attribute the discrepancy to any uncertainty in our measurements, which extend over a number of spectra photographed on different occasions. It is however worth mentioning that we have also measured a few of the spectrograms taken by Mr. Evershed in 1911 (St. John's observations were made about 1910) and still available at Kodaikanal Observatory; these do show a difference of the order of 0·04 A° just as found by St. John. The observations on which the present paper is based were made during 1947-49.

An examination of the widths of the H_2, H_3, K_2 and K_3 as given in Table II shows that there is a marked increase in each case from the centre to the limb.* But, for a given position on the disk, be it centre or limb, there is no systematic change in width of any given line irrespective of whether the line is photographed over a facula or the undisturbed photosphere. The widths of H_2 and H_3 are systematically less than those of K_2 and K_3 respectively for a given position on the disk. The relative widths of the emission and the absorption components of both H and K are sensibly constant over the whole disk, irrespective of the presence of faculae; in other words

$$K_3/K_2 = H_3/H_2 = \text{constant.}$$
$$K_3/H_3 = K_2/H_2 = \text{constant.}$$

* The spectra were actually taken at about ½ mm. inside the limb which for the size of the image used means at a point about 80° from the centre of the disk.

TABLE I

Date	K_3 Centre	K_3 Limb	K_3 Centre-Limb	K_3 Velocity in Km/Sec.	K_2 Centre	K_2 Limb	K_2 Centre-Limb	K_2 Velocity in Km/Sec.	H_3 Centre	H_3 Limb	H_3 Centre-Limb	H_3 Velocity in Km/Sec.	H_2 Centre	H_2 Limb	H_2 Centre-Limb	H_2 Velocity in Km/Sec.
12-3-48	3933·690	3933·668	+·022	+1·7	3933·653	3933·663	—·010	—0·8	3968·500	3968·479	+·021	+1·6	3968·465	3968·470	—·005	—0·4
18-3-48	3933·688	3933·663	+·025	+1·9	3933·670	3933·661	+·009	+0·7	3968·496	3968·477	+·019	+1·5	3968·470	3968·478	—·008	—0·2
21-3-48	3933·686	3933·665	+·021	+1·6	3933·658	3933·668	—·010	—0·8	3968·500	3968·477	+·023	+1·8	3968·470	3968·471	—·001	—0·1
Average .	..	..	..	+1·7	..	..	..	—0·8	..	..	..	+1·6	..	..	..	—0·2
8-1-47	3933·688	3933·670	+·018	+1·4	3933·666	3933·668	—·002	—0·2								
15-6-49	3933·684	3933·667	+·017	+1·3	3933·667	3933·667	·000	0	3968·495	3968·475	+·020	+1·6	3968·480	3968·485	—·005	—0·4
26-7-49	3933·686	3933·670	+·016	+1·3	3933·659	3933·668	—·009	—0·7								
Average . .				+1·3				—0·3				+1·6				—0·4
Mr. Evershed's Plates.																
4-8-1911	3933·684	3933·665	+·019	+1·5	3933·644	3933·668	—·024	—1·9								
23-6-1911	3933·685	3933·665	+·020	+1·6	3933·647	3933·668	—·021	—1·6	3968·495	3968·475	+·020	+1·6	3968·456	3968·475	—·019	—1·5

TABLE II

Cen.	Measurements with Micrometer K_2	K_3	K_3/K_2	H_2	H_3	H_3/H_2	K_2/H_2	K_3/H_3	Measurements on Microphotometer tracings K_2	K_3	K_3/K_2	H_2	H_3	K_3/H_2	K_2/H_2	K_3/H_3	St. John's values K_2	K_3	K_3/K_2	H_2	H_3	H_3/H_2	K_2/H_2	K_3/H_3
Centre	0·40	0·27	0·68	0·36	0·25	0·69	1·11	1·08	0·58	0·32	0·56	0·53	0·20	0·55	1·09	1·10	0·150			0·128			1·09	1·17
½E and ½W	0·46	0·31	0·67	0·42	0·28	0·67	1·11	1·11	0·60	0·33	0·55	0·55	0·30	0·55	1 09	1·10								
½N and ½S	0·47	0·31	0·67	0·43	0·29	0·68	1·10	1·19	0·61	0·33	0·54	0·55	0·31	0·56	1·10	1·09								
Faculae Centre . . .	0·44	0·29	0·66	0·41	0·27	0·67	1·07	1·06	0·60	0·32	0·53	0·55	0·29	0·55	1·10	1·09								
Faculae ½E and ½W . .	0·49	0·34	0·69	0·47	0·32	0·68	1·05	1·07	0·62	0·34	0·55	0·57	0·31	0·54	1·08	1·10								
E and W	0·59	0.40	0·69	0.52	0 36	0·69	1·13	1·11	0·87	0·49	0·56	0·79	0·44	0·56	1·11	1·11	0·759	0·345	0·45	0·710	0·306	0·43	1·07	1·18
N and S	0·58	0·41	0·70	0·54	0·37	0·69	1·09	1·11	0·85	0·49	0·58	0·76	0·45	0·58	1·11	1·11								
Faculae E and W . . .	0·64	0·42	0·66	0·58	0·39	0·67	1·09	1·09	0·85	0·49	0·58	0·77	0·44	0·57	1·10	1·11								

St. John (loc. cit.) has also measured the widths of H_3 and K_3 at the centre of the disk and the limb and of H_2 and K_2 at the limb. For comparison we have included his mean values in Table II. It is seen that St. John's values for the widths of H_3 and K_3, both for the centre of the disk and the limb, are considerably lower than our corresponding visual measures, while his widths for the H_2 and K_2 lines at the limb are much higher than the width measured by us by the same method. These discrepancies are probably due to the fact that St. John's plates were much denser than ours, as he seems to have found it necessary to resort to " careful timing of exposures and strong development " for making the H_2 and K_2 lines measurable. This appears also to be quite natural in view of the fact that his plates were taken with a grating spectrograph, which would give a great deal less contrasty spectrograms in this region of the spectrum than a prism spectrograph. Moreover, our prism spectra had more than double the dispersion of St. John's grating spectra. Our microphotometric measures of the widths of H_2 and K_2 at the limb are however higher than those obtained by St. John ; it is likely that microphotometric measures are more dependable than visual measures in a case like the present. It is worth noting that in spite of the marked divergence between St. John's absolute measures of the widths of the lines and ours the relative widths K_2/H_2 and K_3/H_3 are practically the same in both series of measures, although from our measurements we find K_3/H_3 more nearly equal to K_2/H_2.

Discussion

The results of the present work show that the high-level calcium vapour (H_3-K_3 layer) has a descending motion of about 1·5 km/sec., while the lower H_2-K_2 layer has a slight upward velocity probably of the order of 0·3 km/sec. This agrees very closely with Jewell's measurement of the radial velocities of the K_3 and K_2 layers in 1900, but during the intervening years the only measurements available, namely those of Adams in 1905 and of St. John in 1910, gave divergent results. From these meagre data it is impossible to say whether the observed variations in radial velocities have any correlation with the cycle of solar activity ; but the fact that these variations do occur is significant. Jewell interpreted his results as an indication that the H_3 and K_3 lines were produced by meteoric matter falling into the solar atmosphere and that the emission components H_2 and K_2 were caused by the rise of temperature due to the impact between the down-rushing meteoric matter and the up-rushing chromospheric material. According to an estimate by H. N. Russell(6), however, the total quantity of meteoric matter falling into the sun is, at most, 60 tons per second and " the whole kinetic energy which this can carry in amounts to 2 ergs/cm² sec. as against $6 \cdot 2 \times 10^{10}$ ergs/cm² sec. of photospheric radiation ". Jewell's hypothesis does not therefore seem to be capable of producing the rise of temperature envisaged by him. On the other hand, Deslandres(7) already in his earliest work had attributed the brightness of K_2 to phenomena of ' electrical luminescence '. St. John, who like Jewell regarded the emission of K_2 and H_2 as probably due to the higher temperature of the concerned layer, suggested that the rise of temperature was caused by the conversion into heat of the mechanical energy lost by the up-going and down-rushing masses of calcium vapour through collision and internal friction. However, in the process imagined by him the rise of temperature should be expected to be most in the layer where the maximum conversion of mechanical energy into thermal energy would take place and this should also be the layer where the vertical movement would be the least. But St. John's own observations show a high upward velocity in the K_2-H_2 layer. On the other hand, our observations as well as the early observations by Jewell, which show little or no vertical velocity in the K_2-H_2 layer, are consistent with the idea of mechanical energy being converted into thermal energy and raising the temperature of the K_2-H_2 layer. But the fact that the K_2-H_2 layer has a higher radiative power regardless of whether the vertical velocity in the layer is high or practically nil argues against St. John's theory of higher temperature being responsible for the higher radiative power of the K_2-H_2 layer. We should then have to fall back on Deslandres' idea of electrical luminescence or on some other mechanism for explaining the emission of the K_2 and H_2 lines. There is a very attractive suggestion by Woolley(8) based on Rosseland's theory of cyclical transitions in a field of dilute temperature radiation according to which the emission of K_2 and H_2 may be a case of fluorescence. Although from observational materials so far available it is not possible to arrive at a decisive conclusion in favour of fluorescence or electrical luminescence as the cause of the emission of the K_2 and H_2 lines, fluorescence through Rosseland transitions is capable of explaining such a variety of solar and stellar phenomena that it appears to be the most likely cause of the triple structure of the H and K lines and indeed of Fraunhofer lines in general.

Kodaikanal Observatory,
December 1949.

A. K. DAS,
N. RAJESWARA RAO.

APPENDIX

In this connection, it may be mentioned that our microphotometer records show a faint absorption line at about 3933·920 which does not seem to have been observed by any of the previous workers. As this line falls on the red wing of K_2 near its edge, it might have affected the measurements of the previous workers.

(6) Ap. J., 69, P. 49, 1929.
(7) C. R., 117, P. 716, 1893.
(8) M.N.R.A.S., 94, P. 631, 1934.

GIPD—M—165 SP Obs K. Kl.—7-851—385