CHROMOSPHERIC HEIGHTS IN ACTIVE REGIONS*

M. K. V. BAPPU and K. R. SIVARAMAN
(Kodaikanal Observatory, India)

ABSTRACT

Spectra, with a radial slit in the K and Hα lines, of a sunspot close to the limb are used to determine chromospheric heights in an active region. Equidensity contours obtained with the Sabattier effect are used to measure the values of h^* for different positions in the line core and wings. The spectra have also been utilized to determine similar heights in two very restricted regions of Ca^+ emission which show an arched emission structure in K_{232} with bright continuum emission. At the K-line centre, unit tangential optical depth in the umbra, umbra-penumbra interface, and penumbra are at 1310, 1610, and 2330 km respectively. The corresponding value for the umbra in the Hα-line centre is 1080 km. The arches have a value of $h = 3000$ km at $\Delta\lambda = 0$ for the K line.

The extension of a sunspot into the chromosphere can be detected by two procedures normally available to the non-eclipse observer. One is by the detection of magnetic fields of sufficient intensity with the aid of lines that have a sizeable chromospheric emission contribution. Severny and Bumba (1958) showed that such magnetic fields have high values out to at least 2000 km. The variations of the high and low values with location indicate the retention of the characteristics of the group seen at lower levels. A second approach, first demonstrated effectively by Mattig (1958), is the shift that the core of a strong line experiences towards the limb when the spot is very close to the limb and is examined with a radial slit. This is an extremely simple and effective way of studying the properties of the spot region at normal chromospheric heights. It has been used by Mattig (1962) and by White and Wilson (1966) for the Balmer series, more especially the Hα line. We report in this study measures made in the Ca II K line of a spot near the limb observed with the McMath solar telescope of the Kitt Peak National Observatory.

Our observations pertain to sunspot number Kodaikanal 12399 which on May 25·7 had the heliographic co-ordinates 7°N, 81°24′W. The spot had an area of roughly 280 millionths of the visible hemisphere with a well-defined umbra of nearly 80 millionths. Both umbra and penumbra were of identical polarity. Figure 1 depicts the spatial variations of the longitudinal component of the magnetic field as derived at Kodaikanal from observations of May 23·2, just 60 hours before the K spectra were obtained at Kitt Peak.

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* Presented by M.K.V. Bappu.

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The K-line spectra were obtained in the 6th order with a dispersion of 0·134 Å/mm. These were taken with a radial slit and with three different settings across the spot. Since the image scale in the focal plane of the McMath telescope is 2·29″/mm, 1 mm on the spectrogram in a direction perpendicular to the solar surface represents 1654 km on the solar surface. The single Hα spectrum taken of this spot had the radial slit pass directly through the umbra of the spot. The dispersion used is 0·174 Å/mm in the 4th-order spectrum. The spectra were exposed during spells of good seeing. An estimate of the halfwidth of the seeing function from the shape of the solar limb profiles is 1000 km. A wire stretched across the slit provided a convenient reference mark on the spectra as well as the drawings made immediately after an exposure of the location of the slit on the spot.

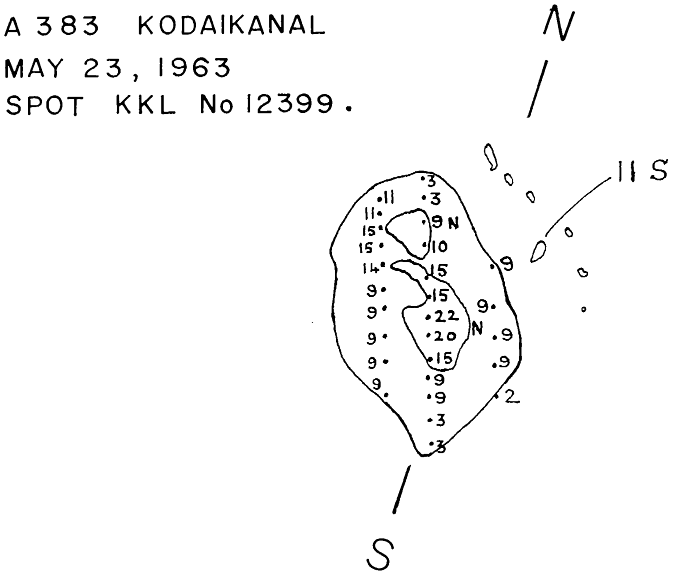

FIG. 1. *The spatial longitudinal magnetic-field values of the spot of May 23, 1963.*

On the spectrogram the spot spectrum is confined to a limited region in the form of an absorption band that traverses the entire spectrum parallel to the dispersion and which, while crossing the K or Hα line, experiences a deviation towards the limb that is a maximum in the line core. Other features of the spectrum display a similar tendency. On one of our spectrograms are two well-defined bright chromospheric arches that have a bright continuum emission. References in what follows to chromospheric arches pertain to these two features.

The measurements, in the line core and wings, of the deviation from a straight line parallel to the dispersion, indicate the different geometrical heights of unit tangential optical depth. Since the boundaries of the umbra and penumbra as seen on the

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spectrogram are seldom sharp enough to yield measures of precision, considerable care is necessary to derive these heights with some measure of accuracy. We have utilized the technique of equidensitometry exemplified by the use of the Sabattier effect. This method has been extensively utilized in astronomical research by Richter and his colleagues at Tautenburg. It was first employed in astronomy by Schröter (1958) when he successfully utilized it for studying the structure in the Balmer lines of chromospheric origin.

Our measuring technique has been to use twice Sabattiered prints of each spectrum (Figure 2) of the sunspot and the arches. The double contours of wire shadow and spectrum of the spot or inhomogeneity facilitate greatly the easy measurement with a two-co-ordinate measuring engine of the shifts in line wings and core towards the limb. The errors in measurement of the equidensity contours amount to about ± 25 km while the photographic reproducibility of the contours is within 75–100 km. Hence, we believe that our values of the shifts to limb are accurate to within 100 km on the solar surface.

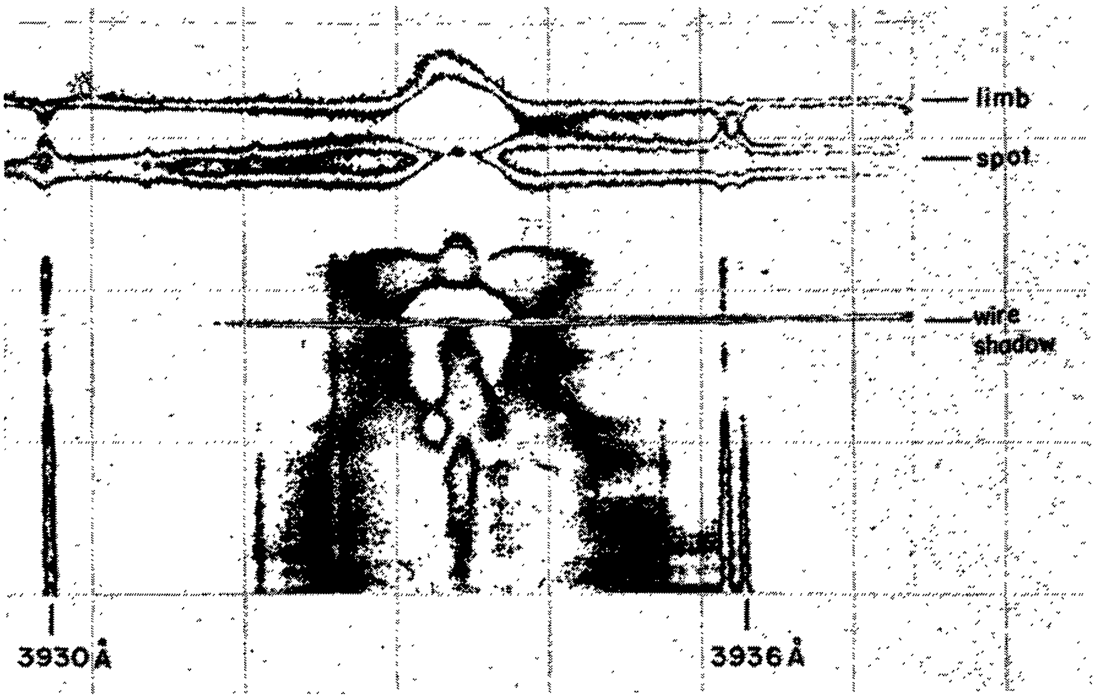

FIG. 2. *A twice Sabattiered print of the K-line spectrogram with radial slit through the spot umbra (Position B).*

The measures we make pertain to the displacement of the features caused by a

Table 1

Values of h*

$\Delta\lambda$ (Å)	h^* (km) K line					Hα line $\theta = 84°54'$ Radial slit over spot umbra
	Position of radial slit on sunspot			Chromospheric arch 1	Chromospheric arch 2	
		$\theta = 81°54'$		$\theta = 74°34'$	$\theta = 72°18'$	
	A	B	C			
0·0	1790	1490	2510	3410	3440	1230
0·1R	1400	1250	1950	2510	3520	1200
0·1V	1620	1390	2120	3380	3540	1010
0·2R	1150	1070	1490	2400	2920	860
0.2V	1100	940	1370	3500	2990	750
0·25R	1050	940	1390	1390	1940	500
0·25V	1040	840	1090	2730	2430	580
0·3R	940	850	1320	–	–	440
0·3V	970	750	680	–	–	510
0·4R	750	670	1200	–	–	380
0·4V	900	600	370	–	–	420
0·5R	560	510	1000	170	–	330
0·5V	830	530	280	240	240	340
1·0R	300	530	230	90	–	150
1·0V	600	420	320	–	–	120
1·5R	–	250	100	–	–	70
1·5V	120	170	90	–	–	50
2·0R	0	170	50	–	–	–
2·0V	0	0	80	–	–	–
δh (km)	180	180	180	220	220	150

Radial slit positions A, B, C of the spot refer to locations of the slit over the penumbra-umbra interface, umbra and penumbra respectively.

projected geometrical difference Δh in the heights between the positions of unit optical depth (τ_{tang}) in the continuum and for any wavelength in the line. Hence, the actual chromospheric height difference is $h^* = \Delta h/\sin\theta$, where θ is the heliocentric angle of the inhomogeneity. This is a measure of the actual height difference between $\tau(\lambda) = \cos\theta$ in the line and $\tau_{5000} = \cos\theta$. We have measured these displacements for different values of $\Delta\lambda$ in the K line. We believe that such data would be of help in the future elaboration of inhomogeneous chromospheric models, especially those involving the absorption and source function in an active-region chromosphere. Table 1 gives the values of h^* for different values of $\Delta\lambda$ for the three slit positions on the spot and the chromospheric arches.

Two corrections have to be incorporated to these values of h^* in order to deduce the true heights of unit tangential optical depth in the chromosphere. One must first subtract the geometrical distance between $\tau_{5000} = \cos\theta$ and $\tau_{5000} = 0{\cdot}004$. The values of this correction δh obtained from Allen's (1963) table are also indicated in Table 1. A second correction factor needed for the sunspot chromosphere observations is the relationship between τ_{5000} in the spot and in the normal photosphere. This necessitates the use of data from a reliable model of a sunspot. Since our present knowledge of sunspots is inadequate to provide this information, we have refrained from making the required correction. This factor is, however, likely to be within 200 km, and needs to be subtracted from h^* if we assume that the spot umbra is more transparent than the neighbouring photosphere.

We plot in Figure 3 the values of h^* measured in the K line for the three positions

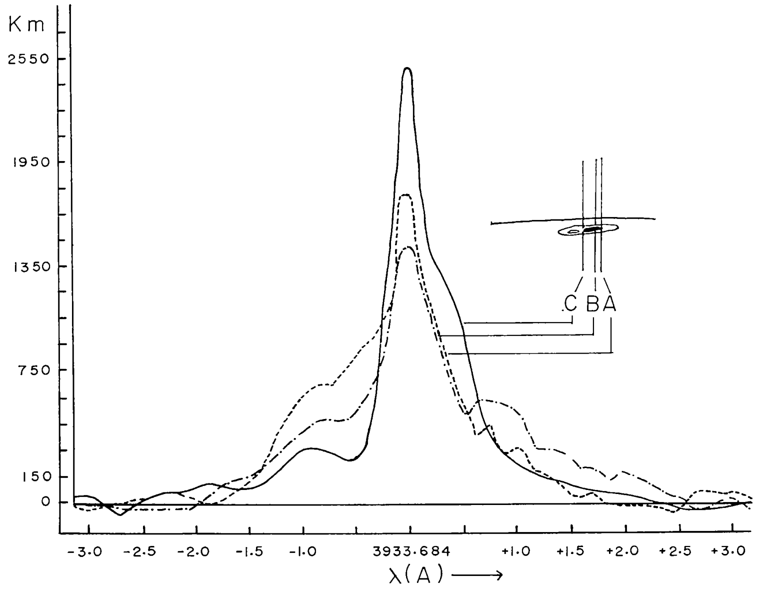

FIG. 3. *The variation with $\Delta\lambda$ of the values of h^* of the sunspot in the K line. The dashed curve, dot and dashed curve and the continuous curve represent the variations for positions, A, B, C respectively.*

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of the radial slit shown in the inset. A striking feature of this plot is the change in h^* for different locations of the slit. We see farther down in the chromosphere in the centre of the K line in the sequence: penumbra, penumbra-umbra interface, and the umbra. This is indicative of a spatial opacity variation in a sunspot with the umbra being more transparent than the penumbra. Figure 4 is a plot of the h^* values for the two chromospheric arches. Also plotted herein is the $\Delta\lambda$ variation of h^* for the slit setting on the spot through the umbra. The arches have h^* values for $\Delta\lambda = 0$ near 3000 km. The $\Delta\lambda$ variation for these arches is exceedingly steep unlike the slow changes seen over the spot. In an active region one still encounters $\tau_{\mathrm{tang}} = 1$ at chromospheric heights even for values of $\Delta\lambda$ exceeding ± 1·5 Å. This agrees with our findings from Kodaikanal spectroheliograms where we can identify floccular outlines even as far away as 10 Å from the K_3 core.

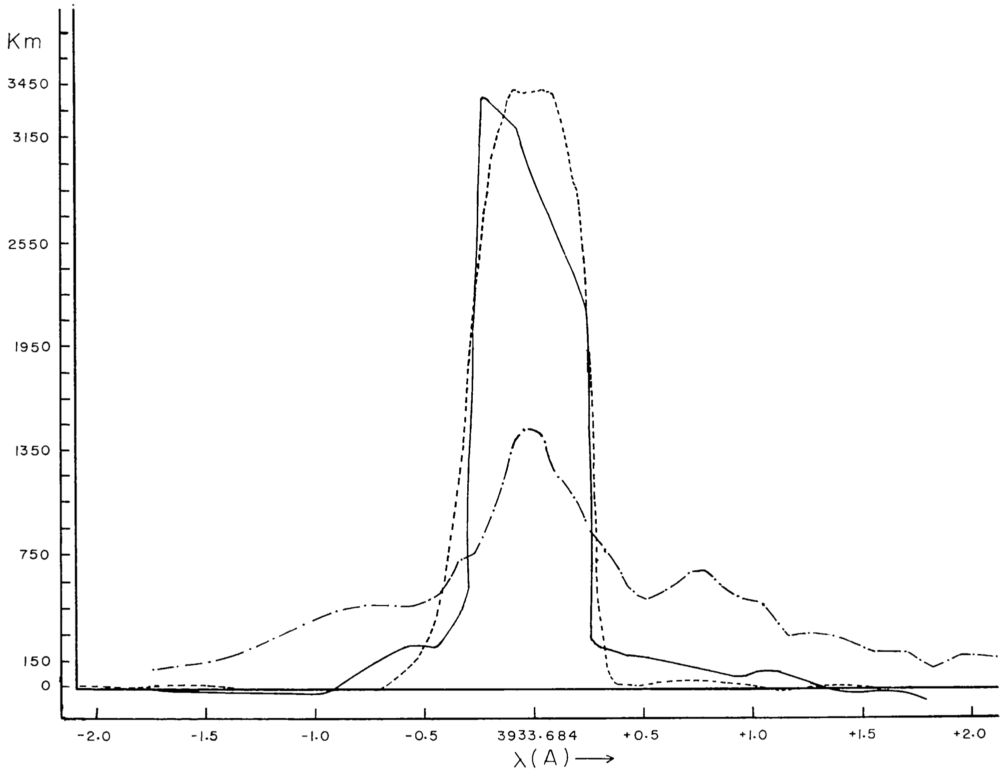

FIG. 4. *The variation with $\Delta\lambda$ of the K-line values of h^* for the chromospheric arches. The continuous curve is for arch 1 and the dashed curve for arch 2. The dot and dashed curve represents values of position B over the sunspot, plotted for comparison.*

In the case of Hα the measures given may be compared with those of Mattig (1962) or White and Wilson (1966). The former finds a mean value of h^* equal to 2160 km

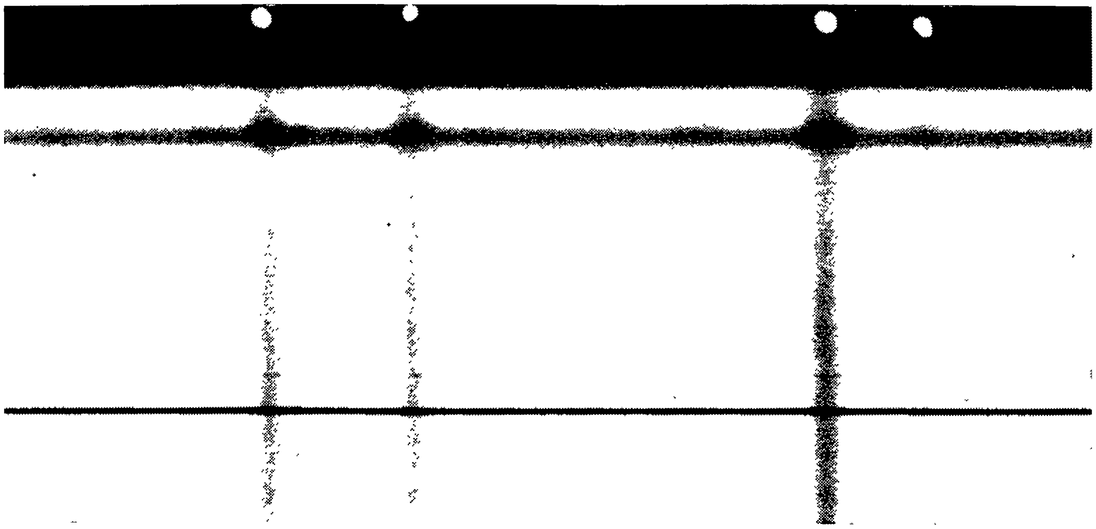

FIG. 5. *This spectrum with the spot very close to the Sun's limb shows the displacement of the spot position in the three Ti lines near λ 5260 Å relative to the spot's continuum (Fraunhofer Institut, Anacapri station).*

which with the appropriate δh correction reduces to 2000 km. The Sacramento Peak investigators obtain 1560 km for this corrected value while we obtain a figure of 1080 km. This is perhaps indicative of the variations from spot to spot and emphasizes the need for determining as many different parameters for a few well-studied spots than a mean value for a large number of spots. Our studies of the $\Delta\lambda$ variation of h^* for K relate, therefore, to conditions in the spot which yield a value of $h^* - 150$ equal to 1080 km in the Hα-line core.

The chromospheric arches form the nearest approximation we have to the applicability of such a study to the quiet chromosphere. More specifically, in the current case we have studied the characteristics of a small-sized inhomogeneity and compared it with the corresponding case of an active-region chromosphere. However, we realize that the parameters from the arches form a lower limit to such values in the quiet chromosphere. The intense brightening in Ca^+ is indicative of a highly localized region that possesses a longitudinal magnetic field, which, while weak, may still be greater than in its immediate surroundings. Hence, while yet insignificant from the standards of an active region, it is by no means typically representative of the quiet chromosphere.

Acknowledgments

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DISCUSSION

Mattig: In the last year I have observed the same effect in 60 weak and middle-strong lines to determine the height of line formation in sunspots. The height differences between the formation of the line center and the continuum is always smaller than 1″=725 km. There is a well-pronounced correlation between the height of line formation and the Rowland intensity; for stronger lines the heights are larger than for weaker lines.

Some further observations in the umbra and penumbra are in agreement with your observations. In the Na-D lines I found nearly the same heights in the umbra and penumbra. (See Figure 5.)