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Distribution of Radiation Flux across a Sunspot.

By

A. K. Das and A. S. Ramanathan, Kodaikanal Observatory, India.

With 15 figures in the text.

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Intensity variation curves for a large sunspot under very good observing conditions have been obtained for discrete wavelengths in the continuous spectrum in the 4000 Å region. The intensity ratio spot/photosphere is found to decrease with decreasing wavelength varying from 38% to 34% in the region under consideration. Another fairly large spot photographed earlier is found to give about the same value in the continuous spectrum.

Intensity variation curves along selected absorption lines in the same region have also been obtained for the same spot; from these curves a quantitative estimate of the decrease of contrast between the spot and the background with increase of height above the photosphere is obtained.

The intensity of the bright ring around the penumbra has been measured. It is found to be about 2% to 3% greater than that of the background at the lowest level, but increases at higher levels. The brightness of Secchi's bright ring around the umbra has also been estimated; it does not appear to vary with height in the same way as the outer ring.

The above may be regarded as preliminary conclusions; the investigation is being continued.

Introduction.

It has been known for a long time that the flux of radiation through the umbra of a sunspot is considerably less than the photospheric flux. Observational data on the intensity of umbral radiation are however not sufficiently definitive for the formulation of a really satisfactory theory of sunspots. This is of course largely due to the inherent difficulties of making quantitative measurements of the umbral light free from the effects of scattered radiation originating from a variety of sources. In some of the comparatively recent observations, such as those of Pettit and Nicholson [1], Wanders [2] and Wormell [3], an attempt has been made to make corrections for the effect of light scattered by the sky and instruments. How satisfactory these corrections are it is not easy to decide. At any rate the importance of such observations for the understanding of the nature of sunspots is evident, and further quantitative measures made under as perfect conditions as possible seem very desirable. From the foregoing investigations two features of sunspots appear to be reliably established, namely, (a) that the intensity ratio umbra/photosphere is independent of the position of the spot on the disc and (b) that this ratio varies linearly with the wavelength in the spectral range from λ 3000 to λ 17000. Another interesting conclusion which appears to emerge from PETTIT and NICHOLSON's observations and which has been tacitly assumed by MILNE [4] and UNSÖLD [5] is that the intensity ratio, umbra to photosphere, is about the same for all spots. This conclusion is however not confirmed by the later measurements of WANDERS and WORMELL. The principal cause of this discrepancy is probably that the measures of umbral intensity so far available are not entirely satisfactory. For the determination of the intensity ratio it seems preferable, in some respects, to rely upon a few large stable spots measured under really good conditions by a satisfactory photometric technique than upon measures made on a number of spots under indifferent conditions.

The primary aim of the present enquiry is to determine by careful photographic photometry the distribution of the radiation flux across a well-defined single spot under excellent observing conditions. As the experimental arrangements used in these observations were intended for an altogether different problem it was not possible to use as large a solar image as one could have wished. The choice of the spot was naturally determined by a combination of circumstances; nevertheless, in spite of their incidental nature, the observations were made under such good atmospheric conditions that they seem worth reporting on while awaiting further chances. The spot actually selected was a large one (KKL. 9825) which traversed the disc between the 9th and the 22nd January 1952. The observations were made between 11th January and 14th January when the spot was not more than four days away from central meridian passage. During this period the spot reached a stable state; the photoheliograms (on a scale of 8 inches to the sun's diameter) taken at this observatory during the same period showed a clear separation between the umbra and the penumbra as also a bright ring[1] around the penumbra separating it from the photosphere. As measured on the photoheliograms the diameter of the umbra and the outer diameters of the penumbra and the bright ring were respectively about 20″, 52″ and 68″. Unlike RICHARDSON [6] and WALDMEIER [7] we have not used the photoheliograms for photometry; our photometric measures are based entirely on spectrograms taken with the slit of the spectrograph sensibly bisecting the spot and extending well across the photosphere on either side of the spot area. In this respect our method is

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[1] This bright ring around penumbrae of spots was first noticed by HALE [Astrophysic. J., **23**, 54 (1906)] on spectroheliograms taken with the H_δ line; this observation was later confirmed by Dr. ROYDS at Kodaikanal from H_α spectroheliograms [M. N. R. A. S., **85**, 464 (1925)]. WALDMEIER (Astr. Mitt. Zürich 1939) however appears to be the first to make a photometric measurement of the bright ring as recorded on photoheliograms taken in light of wavelength of about 4000 Å.

similar to that of WANDERS [8] although there are some minor differences in the details of the photometric procedure.

Experimental Details.

The spectrograms were obtained with the help of a large plane grating spectrograph in angular mounting fed by an 18-inch Foucault siderostat and an 18-inch parabolic mirror giving a solar image of about 30 mm. diameter. The dispersing member of the spectrograph is a Rowland grating having 15.028 rulings per inch over a ruled surface $3^1/_4$ inches long. The collimator lens is a visual achromatic of about 7 feet focal length, while the camera objective is a single plano-convex of about 14 feet focal length for D. The whole spectrograph[1] is of all-metal construction and is firmly mounted on massive stone masonry piers; it is surrounded on all sides by rooms or heavy walls and gives excellent definition of spectrum lines. Due to the limitations of available space the axes of the collimator and of the parabolic mirror are placed at right angles to each other, so that the slit is illuminated by the mirror through a Cassegrain arrangement. The spectra obtained with this spectrograph are completely free from astigmatism, but because of the approximately 1:2 ratio between the focal lengths of the collimating and camera lenses the length of the spectrum lines on the photographic plate is about double the length of slit used. The interior of the spectrograph is very carefully blackened and diaphragmed in order to reduce stray light to a minimum.

Our observations were made in the neighbourhood of the H and K lines using the second order of the grating, the linear dispersion being about 2 Å per mm. The slit width used was quite narrow, about 0.04 mm. Very slow Kodak B 20 process plates sensitive to the blue-violet region of the spectrum were used and were developed for 5 minutes in M-Q developer at about 65° F taking the usual precautions to eliminate Eberhard effects. Six spot spectra were photographed on each plate (5 × 4 in.) which also had a series of density marks for determining its characteristic curve. The procedure for obtaining the density marks was as follows: The slit of the spectrograph was opened to its fullest extent of about 2.5 mm. and a step-slit was placed immediately in front of it. The step-slit consisted of a thin brass plate with a number of parallel slots separated by solid pieces. The slots were each 1 mm. high, but of breadths varying between 2.5 mm. and less than 0.25 mm.; they were cut parallel to each other with their breadths horizontal, so

[1] The optical components of the spectrograph are the same as those used in the spectrograph built originally by Mr. J. EVERSHED while he was at Kodaikanal. The instrument has recently been reconstructed (with some modification) and mounted for greater stability by one of the present writers (A.K.D.).

that when they were illuminated uniformly by a suitable source of continuous white light a series of strips of blackening of different densities was impressed on the photographic plate covering the whole spectral range for which the spectrograph was adjusted. The step-slit was illuminated by a Philips tungsten ribbon lamp fed by a 6-volt accumulator, the image of the ribbon being projected with suitable magnification on the slots by means of a lens; special care was taken to ensure that the step-slit was perfectly uniformly illuminated by the image of the ribbon. The step-slit was previously calibrated with the utmost care by comparing with the help of a recording microphotometer the photographic densities obtained with the step-slit in position and the photographic densities obtained with the slit of the spectrograph adjusted to a suitable constant width (after removing the step-slit) but with diaphragms of accurately measured rectangular apertures placed in front of the collimator lens. Both the series of densities were of course made on the same photographic plate giving exactly the same exposure time and using the same Philips ribbon lamp fed by the same constant current between 15 and 16 amps. With the arrangements used it was found that an exposure time of 25 secs. gave optimum densities for photometry so far as the densitiy marks made on Kodak B 20 process plates with the step-slit were concerned. Accordingly this exposure time was adhered to for making density marks on all plates on which the spot spectra were photographed. The spot spectra were however photographed with exposure times varying between 1 and 8 secs[1]. During these short exposures it was perfectly easy to keep the spot steady on the slit of the spectrograph, as is evident from the fact that most of our spot spectra are of very fine quality showing, on visual examination, the umbra, the penumbra, and the photosphere clearly demarcated and often the bright ring separating the penumbra from the photosphere; in some cases even the faint SECCHI's ring separating the umbra from the penumbra is noticeable on microphotometer tracings. The dimensions of the umbra, penumbra and the bright ring as measured on the spectrum plates (which were taken on slightly more than onefourth of the scale of the photoheliograms) were in good agreement with those obtained from the photoheliograms. Out of the many good spot spectra photographed we have however used for quantitative measurements only the best ones which had the correct kind of densities for photometry. All our density curves were traced with the Cambridge recording photoelectric microphometer of this

[1] Although the exposure time for the density marks was different from the exposure times for the spot spectra the difference was not excessively large. For differences of this order the Schwarzschild exponent, particularly in the case of slow, non-colour-sensitive plates, can safely be taken to be constant.

observatory and the reduction of the densities into intensities was made in the usual manner.

It may be noted that the spot studied by us was one of the large ones characteristic of the present solar cycle; the umbral area of this spot was about 575 sq.secs. of arc and therefore larger than that of any of the spots to which the measurements of WANDERS and of WORMELL relate. Furthermore, our spectrograms were secured under very good seeing conditions and consequently our measures of umbral intensity may reasonably be expected to require only very small corrections for scattered light. However, an estimate of the correction for radiation scattered into the spot umbra from the surrounding areas was made by employing a procedure originally worked out by WANDERS [9] but simplified by WORMELL [10]; this procedure depends upon the availability of the apparent distribution of the intensity of radiation from points in the vicinity of the solar limb, both inside and outside the true position of the limb: We assume that the true distribution of intensity near the limb of the solar image is such that there is a sudden discontinuous jump [11] from zero to a finite value I as the limb is crossed, the intensity thereafter remaining constant at the value I inside the image. Then if $i\,(x)$ be the apparent intensity at a distance x seconds outside the limb,

$$i\,(x) = \mathrm{I} \cdot \frac{1}{\sqrt{\pi}} \int_{x\sqrt{a}}^{\infty} e^{-u^2}\,d\,u = \frac{1}{2}\,\mathrm{I}\left\{1 - Erf\left(x\sqrt{a}\right)\right\} \tag{1}$$

where $'a'$ is WANDERS' scattering parameter. WANDERS has given calculated curves of intensity variation with distance from the solar limb for various values of the scattering parameter; from these curves it is apparent, as WORMELL has pointed out, that the observed value of $i\,(x)$ at a distance of 5 secs. of arc within the limb gives a sufficient approximation to the true value of I. It is also clear from (1) that when $x = 0$, $i\,(x) = {}^1/_2\,\mathrm{I}$. Consequently on a curve giving the apparent distribution of radiation in the neighbourhood of the solar limb, there will exist two points 5 secs. of arc apart such that the intensity at one will be I and the intensity at the other will be ${}^1/_2\,\mathrm{I}$; the latter point (with intensity ${}^1/_2\,\mathrm{I}$) will correspond to the true limb. The intensity at a point 5 secs. outwards from the point representing the true limb is then read off from the intensity distribution curve and dividing this by I we obtain $\frac{i\,(5'')}{\mathrm{I}}$. In order to determine the required value of the scattering parameter $'a'$ which corresponds to this observed value of $\frac{i\,(5'')}{\mathrm{I}}$ we require a curve of $\frac{i\,(5'')}{\mathrm{I}}$ against $'a'$. This curve can be prepared from equation (1) or more readily by reading off the ordinates for $x = 5$ secs. outside the limb from the intensity-distance curves for different values of $'a'$ given by WANDERS and plotting them against the corresponding values of 'a'; from this curve the value of 'a' corresponding to the observed value of $\frac{i\,(5'')}{\mathrm{I}}$ is read off. Once the scattering parameter 'a' is determined for any given observing condition the scattering into a spot umbra can readily be estimated by taking into consideration the shape of the spot and the fact that most of the scattered light at the centre of the umbra comes from the inner edge of the penumbra.

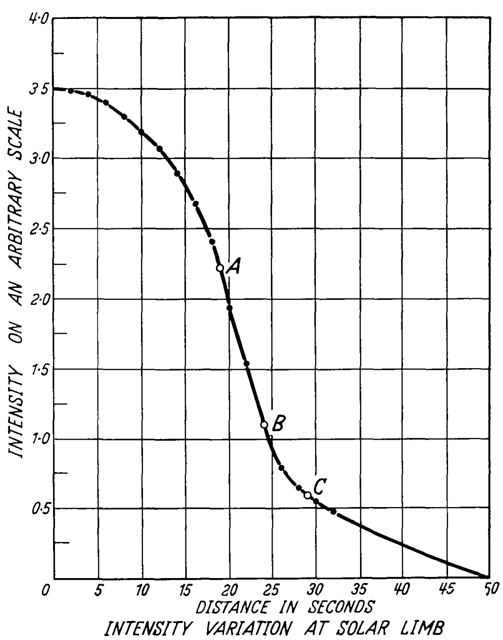


Fig. 1.

On all the days on which our spot spectra were photographed the seeing conditions were uniformly good and it seems quite sufficient to estimate scattering correction for the day (12th January) on which most of the plates actually measured were taken. For determining the intensity variation in the vicinity of the solar limb we used the K spectroheliogram taken in the morning at 4 h. 00 m. G.M.T. on a Kodak B 20 process plate (the spot spectra were photographed around midday, i.e. 6 h. 30 m. G.M.T.). No density marks were unfortunately available on the spectroheliogram; another plate of the same kind was therefore used for obtaining the density marks with the arrangement described above and the plate was developed in exactly the same developer and under the same conditions as the spectroheliogram. The density marks available on the spectrum plates could not be utilised owing to the fact that the developer used for the spectroheliogram was different from that used for the spectrograms. The curve giving the variation of intensity in the neighbourhood of the solar limb thus obtained is reproduced in Fig. 1. The points A and B on the curve are 5 secs. of arc apart and the intensities at these two points are I and $^1/_2$I respectively; B corresponds to the true position of the limb. The point C on the curve gives $i\,(5'')$ outside the limb, so that $\frac{i\,(5'')}{\mathrm{I}} = \frac{0.6}{2.224} = 0.027$. The value of the scattering parameter obtained from this is: $a = 0.073$, which corresponds to very good observing conditions. The spot under study was approximately circular in shape with a mean umbral diameter of about 20″. Therefore the scattered light in the centre of the umbra works out as

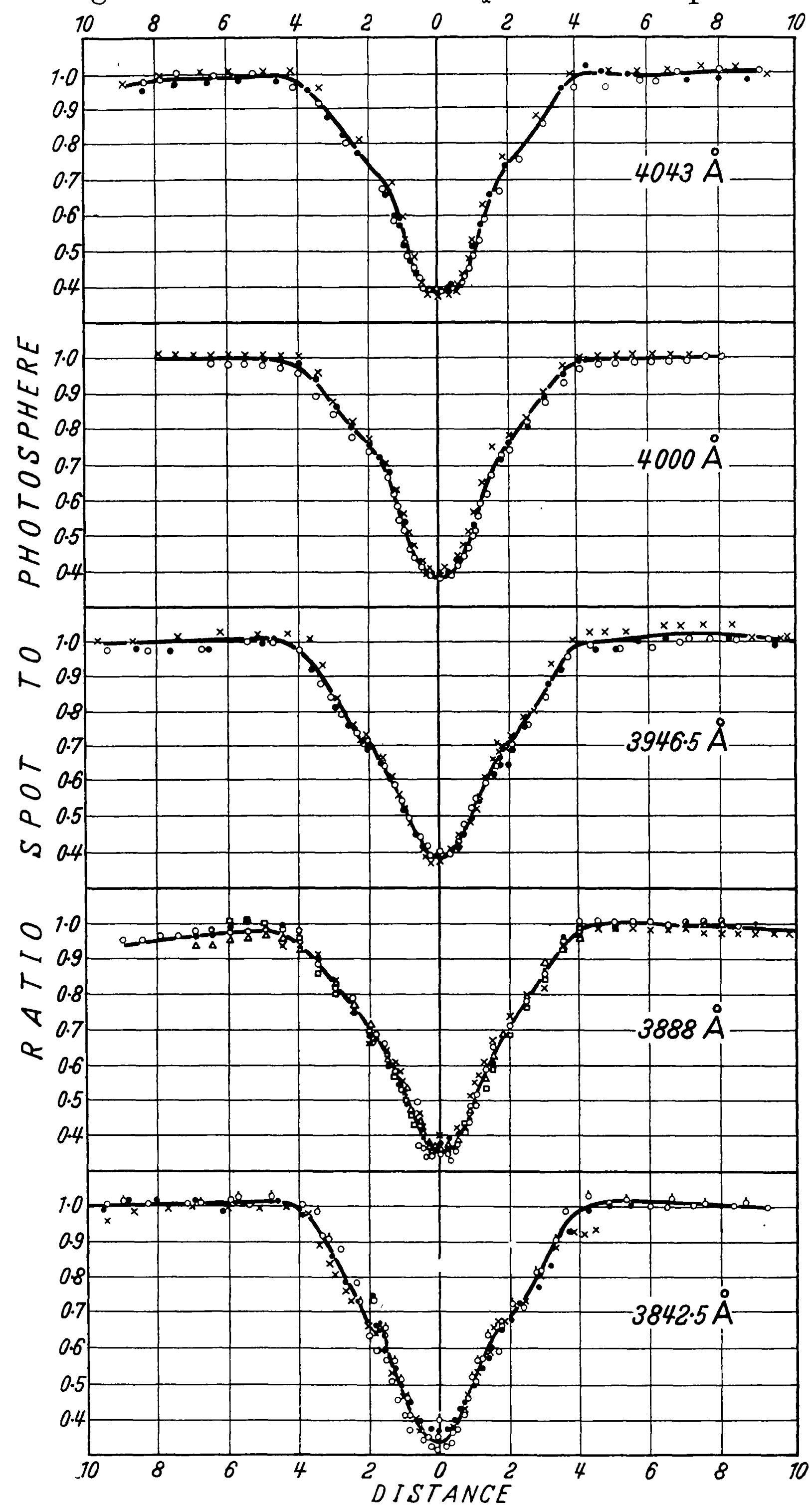
$$\mathrm{I}\,e^{-ab^2} = 30 \cdot e^{-0.073 \cdot 100} = 0.02\,,$$

where I is the difference of intensity between the penumbra and the umbra and b is the radius of the umbra. This estimate, though admittedly rough, shows that the amount of scattered light in the spot umbra under the actual conditions of our measurements must be quite small.

Central Intensity of Umbra.

The variation of the intensity of radiation across the umbra and the penumbra of the spot (KKL. No. 9825) was measured in the continuous spectrum in the neighbourhood of the H and K lines. Windows at 4043 Å, 4000 Å, 3946.5 Å, 3888 Å and 3842.5 Å in the continuous spectrum as nearly free from absorption lines as possible were chosen for this purpose; the microphotometer runs were made across the spectral band (i. e. parallel to the Fraunhofer lines) at these wavelengths so that the tracings represented the continuous variation of the photographic densities across the umbra, the penumbra and the photosphere. The density curves were then converted into intensity curves. Five different plates were selected for photometry and from these at least three independent measures could be made for each of the wavelengths chosen. The mean intensity curves thus obtained are represented in Figs. 2, 3, 4, 5 and 6. These mean curves show that the average central intensity of the umbra for λ 4043, λ 4000 and λ 3946.5 is practically the same, namely 38% of the photospheric intensity, while for λ 3888 and λ 3842.5 it is 35% and 34% respectively. These values appear to fit fairly well into the umbral intensity-wavelength curve given in PETTIT and NICHOLSON'S [12] paper. Although our measures cover a narrow range of wavelengths, they show that the umbral intensity increases with the wavelength; this is particularly clear when we compare the umbral intensities for the five different wavelengths obtained from any single plate. It is hoped that it will be possible to extend our measures to a wider spectral range during the coming winter months. It may be worthwhile to note in this context that a fairly large spot (KKL. No. 9776, umbral diameter about 14″) observed under good conditions in October 1951 gave a central intensity of about 38% (see Fig. 13) measured in the continuous spectrum at λ 3842.5. This spot had a rather pronounced SECCHI's bright ring separating the umbra from the penumbra which probably made an appreciable contribution to the scattering into the umbra; moreover, this spot was smaller in size and its spectrum was photographed when it was about 20° farther away from central meridian than KKL. 9825 which would also increase the amount of scattered light in its umbra. If allowance is made for scattered light, the umbral intensity of this spot also becomes very nearly the same as that of KKL. 9825.

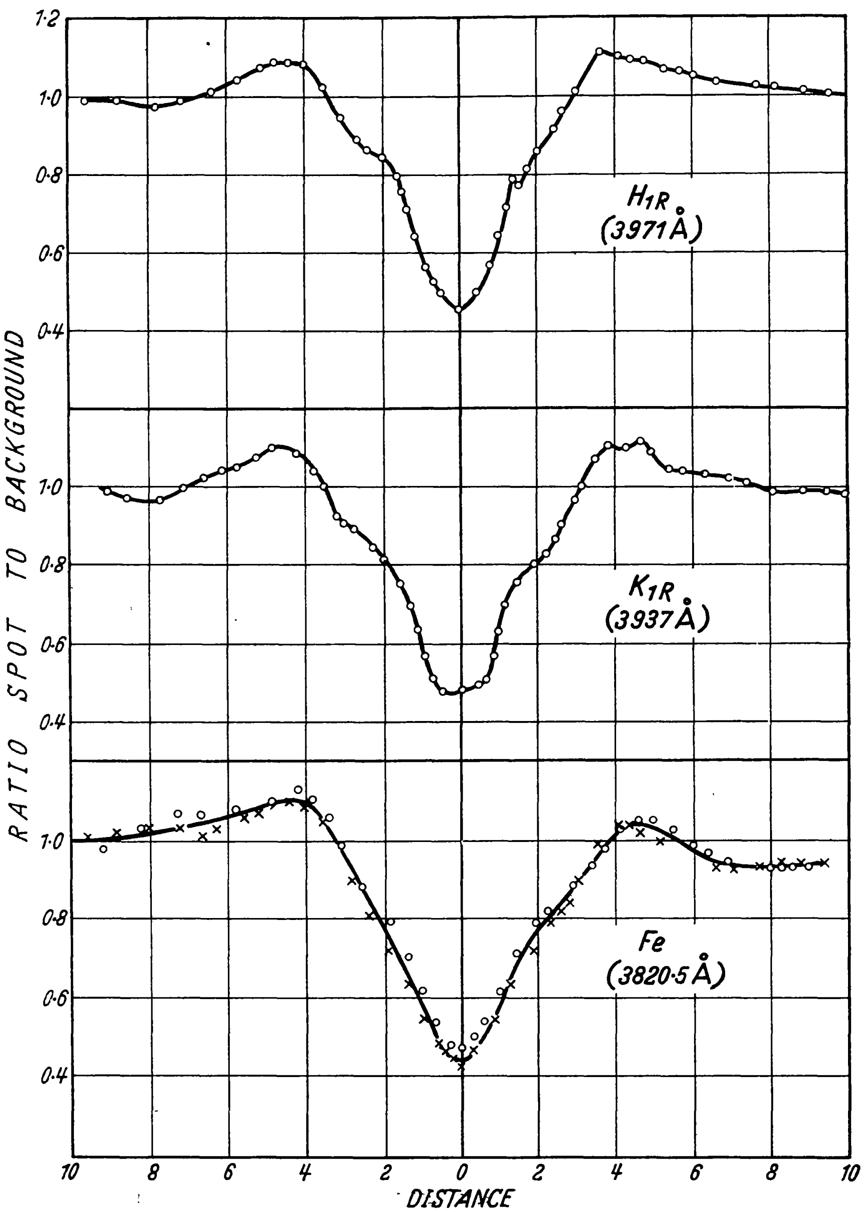
It is common experience that spots generally appear less pronounced on spectroheliograms taken in the K and H_α lines than on photoheliograms



SPOT PROFILE (KKL.9825.) IN CONTINUOUS SPECTRUM

Figs. 2 to 6.

which are usually taken in the continuous spectrum. No quantitative measurements on spot structure at the different levels represented by the spectroheliograms appear however to be available. It is



SPOT PROFILE (KKL. 9825.) AT DIFFERENT LEVELS

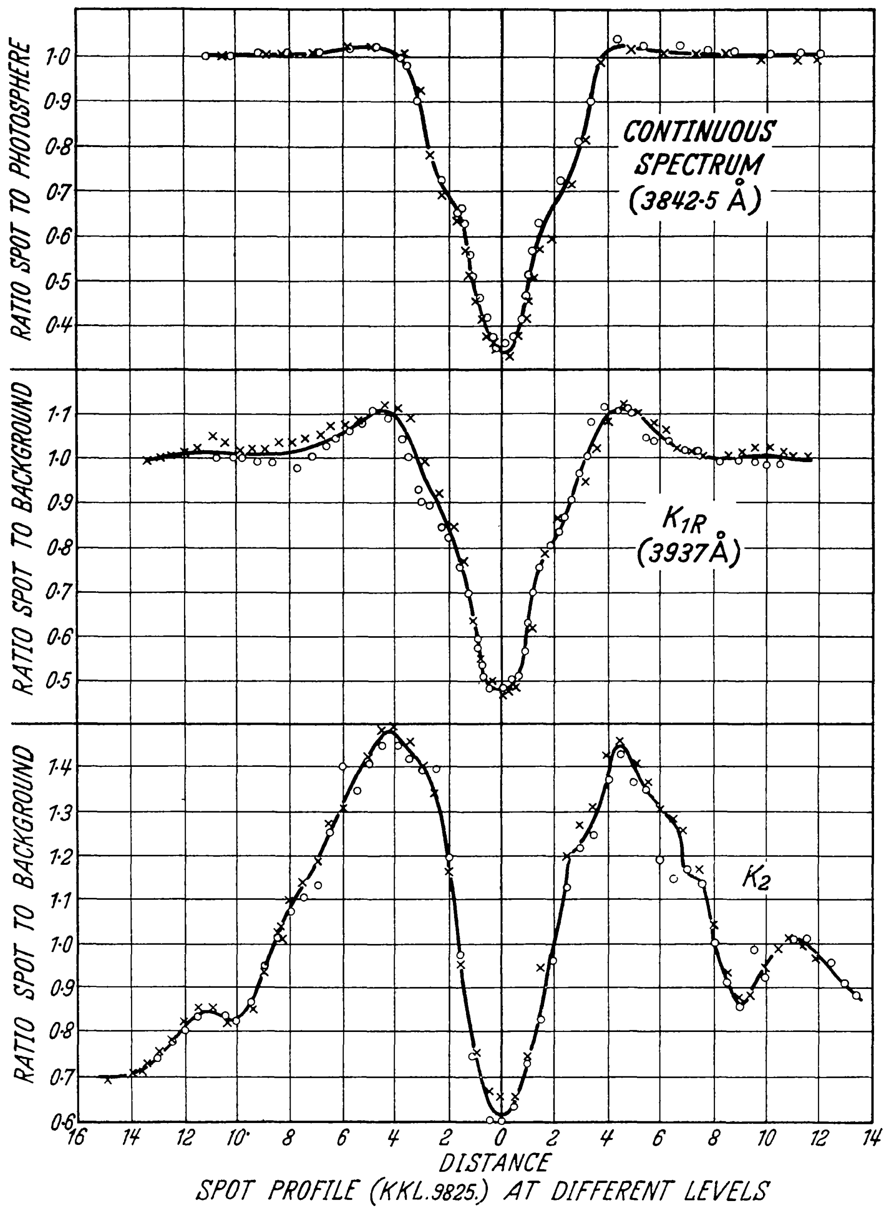
Figs. 7 to 9.

evident that such quantitative measures are of considerable importance for the understanding of the sunspot phenomenon, the origin of which still remains obscure. Some of our spectrograms of the January spot (KKL. 9825) have been photometered along an absorption line at λ 3820.5 due to iron, and in the K_{1R} and H_{1R} wings of the K and H lines at approximately λ 3937 and λ 3971 respectively. From two independent measures the average central intensity of the umbra in the λ 3820.5 line is found to be 44% of the background; the H_{1R} and K_{1R} lines give the central intensity of the umbra as 45% and 48% respectively (see Figs. 7, 8 and 9). Two independent measures made along the K_2 bright line give an average umbral central intensity as high as 62% of the background (see Fig. 12). For the October spot (KKL. 9776) the K_1 and K_2 lines yield umbral central intensities of 50% and 68% respectively; on making reasonable allowances for scattered light these values also become practically the same as in the case of the January spot (see Figs. 11 and 12). It is evident however that in the case of the K_2 line the background cannot be determined with as much confidence as for the other lines. Nevertheless the order of magnitude of the progressive decrease of contrast between the spot and the background with increase of height above the photosphere seems fairly well defined.

Bright Ring around Penumbra.

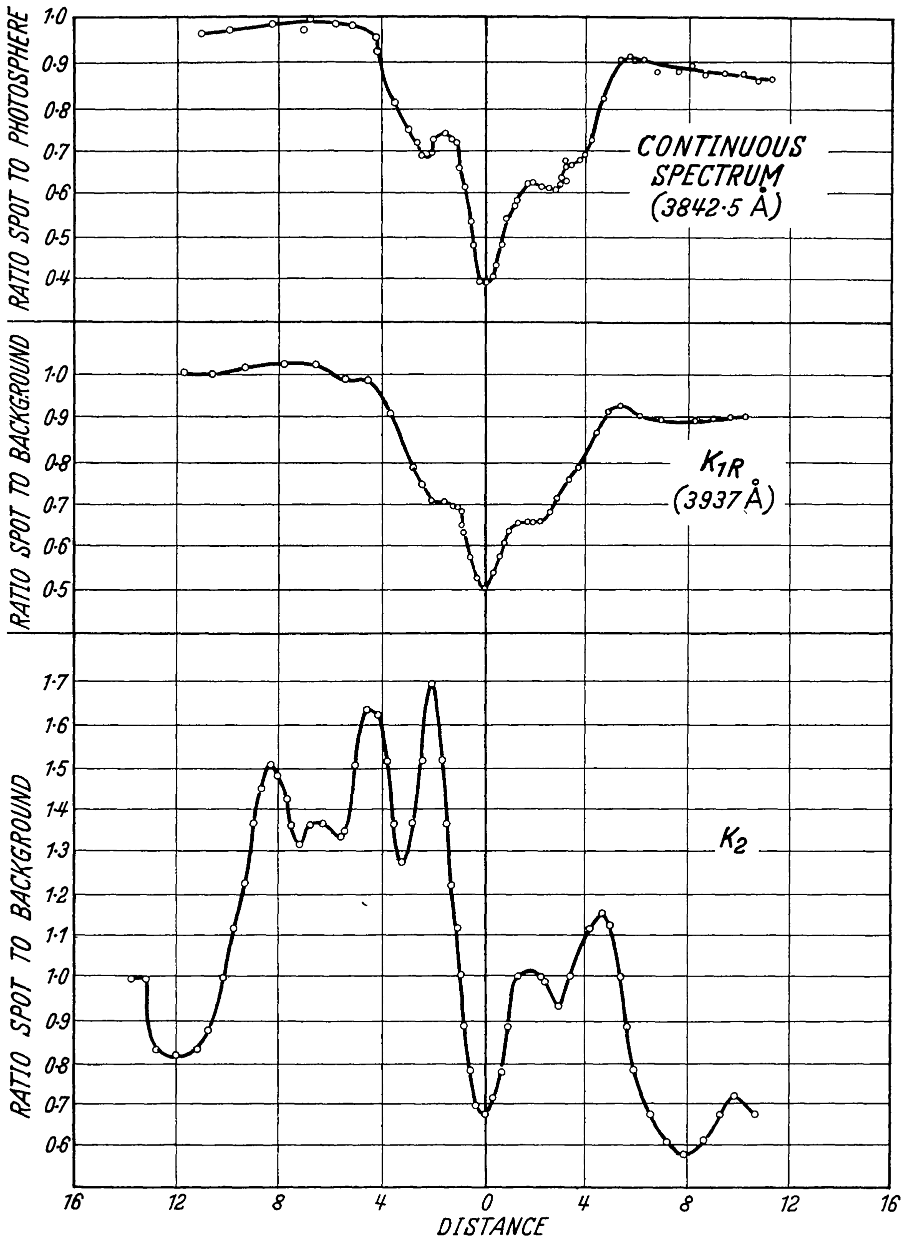
As has been mentioned by ROYDS [13] and later by WALDMEIER [14] a bright ring round the penumbra is a normal feature of the structure of nearly all spots of medium size. But there appear to be exceptions also. However, on a number of spectrograms of the large spot (KKL 9825) studied by us the bright ring appeared conspicuously as two narrow bands of greater-than-background photographic density, one on either side of the spot spectrum at the periphery of the penumbra. That these bands appear symmetrically on the outer edges of the penumbral spectrum and correspond in position to the bright ring visible immediately outside the penumbra on the corresponding photoheliograms is sufficient evidence that they are not due to the ordinary faculae which always accompany a spot and extend over an area many times that of the spot. The intensity curves prepared from these spectrograms clearly show that the bright ring is appreciably brighter than the background. We have prepared intensity curves both for the continuous spectrum at λ 3842.5, and for absorption lines at λ 3820.5, λ 3937 (K_{1R}) and λ 3971 (H_{1R}) as well as for the bright K_2 line. These are represented in Figs. 7, 8, 9, 10, 11 and 12. It is found that in the continuous spectrum (λ 3842.5) the ring is 2% to 3% brighter than the photosphere; this agrees with the result of WALDMEIER'S measurements from photoheliograms of the Zürich Observatory taken in light of wavelength 4000 ± 200 Å. But in the absorptionlines λ 3820.5, H_{1R} and K_{1R} the intensity of the ring is practically the same, namely about 10% brighter than the background. The brightness of the ring over the background however shows a remarkable increase when measured in the K_2 line; our measures indicate that the ring may be nearly 50% brighter than the background.

But in view of the uncertainty in determining the background intensity in this case this very large increase in contrast may prove to be an overestimate and the figure may have to be reduced to some extent.



Figs. 10 to 12.

The progressive increase in contrast between the bright ring and the background with elevation above the photosphere and its sudden enhancement at the K_2 level suggest that there may be a common cause underlying the formation of the bright spot ring and the bright K_2 component of the K line. It would have been interesting to examine the behaviour of the ring in the K_3 absorption line, but this was not possible due to the insufficient dispersion of the available spectrograms.



SPOT PROFILE (KKL. 9776.) AT DIFFERENT LEVELS

Figs. 13 to 15.

Incidentally it may be noted also that some of our intensity curves corresponding to absorption lines show a dip below the background immediately after the bright ring surrounding the penumbra. This may well be an indication of the existence of a "dark ring" encircling the bright ring; however, the matter requires a closer examination.

Secchi's Bright Ring around Umbra.

An examination of the large collection of routine photoheliograms of the Kodaikanal Observatory which are taken on plates sensitive only to the blue-violet shows that the bright ring encircling the penumbra is a very common feature of medium and large spots; but the bright ring first observed by Secchi between the umbra and the penumbra shows up much less frequently on our photoheliograms. In the case of the January spot the inner ring is quite unnoticeable visually both on the photoheliograms and on our spectrograms although the outer ring is quite conspicuous. Some of our microphotometer tracings however show small kinks indicating the presence of the inner ring with a brightness of 2.5% to 3% above the neighbouring penumbra when measured in the continuous spectrum in the neighbourhood of the H and K lines. In the H_{1R} wing of the H line the inner ring has a brightness of about 2% above the adjacent penumbra, but the ring does not appear at all in K_2. In the October spot, on the other hand, the inner ring appears to be somewhat stronger than the outer ring as measured in the continuous spectrum at λ 3842.5; but the outer ring has much the same brightness against the photosphere in both the spots.

From Figs. 13, 14 and 15 which give the intensity curves for the October spot it will be seen that the profile of the spot is very unsymmetrical. In the continuous spectrum the inner ring is 6.5% brighter than the penumbra on one side and only 2.5% brighter than the penumbra on the other side. In K_1 the inner ring is scarcely noticeable. In K_2 the brightness appears to be about 31% over the penumbra on one side and only 7.5% on the other. This excessive assymmetry makes unreliable any apparent variation of contrast of the inner ring with increase of height above the photosphere. On the whole the nature of the variation in the contrast of the inner ring with respect to the background appears to be different from that of the outer ring. We intend to study this question further when suitable spots become available.

Our thanks are due to Mr. K. Sethumadhavan of this observatory for considerable help in suitably preparing for the press the diagrams included in this paper.

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Dr. A. K. Das, Director, Solar Physics Observatory, Kodaikanal, S. India.