ISOPHOTAL CONTOUR MAPS OF SUNSPOTS

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[*Manuscript received August 6, 1962*]

Summary

Maps are presented showing the complex intensity distribution in the umbrae and penumbrae of two large spots. The umbral isophotes show several points of minimum intensity, in one of which the temperature is some 500 °K below the average for the umbra. This extra-dark region, or " core ", is only a few seconds of arc in diameter and is located near one end of the umbra.

The possible relationship between the detailed intensity distribution and the detailed magnetic field distribution is discussed. In particular, it is suggested that the core represents the region of greatest field strength. On this basis a new model of the magnetic field configuration inside a sunspot umbra is proposed.

I. Introduction

A knowledge of the detailed intensity distribution in sunspots is fundamental to an understanding of their physical mechanism. The intensity data hitherto published are based on low-resolution observations, and consist either of isolated measurements made near the centre of the umbra or, at best, of a series of measurements made along a single line through the spot. On the other hand, photographs showing a resolution of 1–2″ of arc published by the authors (Bray and Loughhead 1959 ; Loughhead and Bray 1960) have shown that, quite apart from the umbral granulation, the intensity distribution in both umbra and penumbra is so complex that isolated photometric tracings give a quite inadequate idea of the distribution throughout the spot as a whole. Different regions of the umbra often exhibit large differences in intensity, and a large umbra may possess two, three, or more points of minimum intensity. Even an apparently regular sunspot *pore* can show a marked intensity difference from one side to the other (Loughhead and Bray 1961 : Plate 3). Consequently, only a complete *two-dimensional, photometric map* can fully reveal the detailed intensity distribution.

Such photometric maps for two sunspots are presented in this paper. The observations and the photometric procedure are described in Section II, while the various features of the umbral and penumbral intensity distributions are described in Section III. The most interesting result is the demonstration of the existence of a dark " core " in the umbra, the temperature there being some 500 °K below the average for the umbra. The core is only a few seconds of arc in diameter and in each case is located not at the centre of the umbra but near one end. The possible relationship between the detailed intensity distribution and the detailed magnetic field distribution is discussed in Section IV. In

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particular, it is suggested that the core represents the region of greatest field strength. On the basis of this hypothesis, a new model of the magnetic field configuration inside a sunspot umbra is proposed.

II. Observations and Microphotometry

The observational material consists of films of two large spots near the centre of the disk (mean umbral diameters 45 and 24″ of arc), taken on January 12 and May 11, 1959 respectively. Photographs of these spots are reproduced in Plate 3 of Bray and Loughhead (1959) and Plate 1 of Loughhead and Bray (1960). The film of May 11 contains, in addition to normal exposures of the spot, sequences of twofold, threefold, and fivefold overexposures. The latter two sequences, which served to bring up the detail in the umbra, were taken through a small prime-focus diaphragm (described in the above papers) in order to limit scattered light from the spot surroundings. In the film of January 12, diaphragmed exposures of up to sevenfold normal were obtained.

For the purpose of photometric calibration, the film of May 11 contains a sequence of step-wedge photographs, each taken with the same exposure time, as well as a number of exposures for checking the uniformity of illumination across the step-wedge.* A separate investigation showed that the characteristic curve of the film did not vary significantly with exposure time over the range used in the sunspot photographs, so that a single curve could be employed throughout.

On the film of January 12 the step-wedge was greatly overexposed, so in analysing this film the characteristic curve for the film of May 11 had to be used. In addition, the photosphere was overexposed on the " normal " exposures on the film of January 12. The measured intensities were therefore initially expressed in terms of the intensity at the centre of the penumbra; they were then converted to photospheric units, using the value 0·76 for the mean penumbra/photosphere intensity ratio given by the spot of May 11.† In view of these difficulties, not too much reliance can be placed on the numerical values of the intensities for the spot of January 12, although the morphological information is reliable.

Microphotometry was carried out with a circular scanning aperture of effective diameter 2″ of arc. This value was deliberately chosen so as to wash out the fine detail present on the negatives: with a smaller scanning aperture, the photometric traces would have been impossibly confused in both umbra and penumbra (the umbral granulation, for example, has a mean cell size of 2″·3), making the subsequent drawing of the isophotes very difficult. The level of the photospheric intensity was established by making traces both near to and well away from the spot; no significant variation with distance from the spot was detected. The sunspot on each of the selected exposures was then micro-

* The step-wedge was calibrated in a Hardy spectrophotometer.

† The adopted value 0·76 is in good agreement with the values 0·78, 0·72, and 0·73 found by Michard (1953), Stepanov (1957), and Makita and Morimoto (1960) respectively at similar wavelengths.

photometered, the line of scan being displaced vertically 2″ after each run, so that every point of the spot was ultimately measured. (In all, 790 measurements were made for the spot of May 11, and 1440 for the spot of January 12.)

On the overexposures the photosphere is of course " burnt out ", so in order to express the umbral intensities in terms of the photospheric intensity, a step-by-step procedure had to be adopted. This consisted of matching, by virtue of their size and shape, isophotes derived from negatives with different degrees of overexposure, the lightest giving intensities directly in photospheric units. The isophotes occasionally showed significant changes in the interval between successive sequences of exposures, which sometimes extended for an hour or more, but no real difficulty was experienced in applying this procedure.

No corrections were applied for parasitic light due either to finite instrumental resolution or to scattering. The effective resolution of the intensity measurements is 2″ of arc, the diameter of the scanning aperture used in the microphotometry. This figure is smaller than the scale of the intensity variations under consideration, rendering corrections for instrumental smearing unnecessary. The use of a focal-plane diaphragm eliminated scattered light from all sources except the objective lens and the Earth's atmosphere (cf. Bray and Loughhead 1959). Test exposures of the solar limb showed that under good atmospheric conditions the parasitic light from all sources is very small.

III. The Isophotal Contour Maps

The resulting isophotal maps for the spot of May 11 are shown in Figures 1 (*a*) (penumbra and outer umbra) and 1 (*b*) (umbra). With regard to the penumbra the following points are noteworthy :

(1) the isophotes are very irregular and reflect the presence of both bright and dark regions, which are also evident on a photograph of the spot (see Loughhead and Bray 1960 : Plate 1 (*a*)) ;

(2) there is a gradual decrease in intensity from the photosphere (1·00) to the inner edge of the penumbra ($\simeq$0·70), although this is not readily apparent on the photograph. However, over quite a large part of the penumbra the intensity lies in the range 0·72–0·80 ;

(3) the umbra-penumbra boundary is characterized by a sharp increase in the intensity gradient and a marked simplification in the shapes of the isophotes.

The intensity distribution within the umbra has the following noteworthy features :

(1) the sharp gradient at the boundary continues for a short distance into the umbra, after which the intensity becomes more uniform ; over a large part of the inner umbra the intensity lies in the range 0·24–0·28 ;*

(2) the isophotes are still irregular in shape ;

(3) there are *three* intensity minima, one of which has an intensity of only 0·15 ;

* For spots whose umbral diameters exceed 19″ of arc, and at a wavelength similar to that of the present observations (5400 Å), Michard (1953) gives the figure 0·26.

(a)

(b)

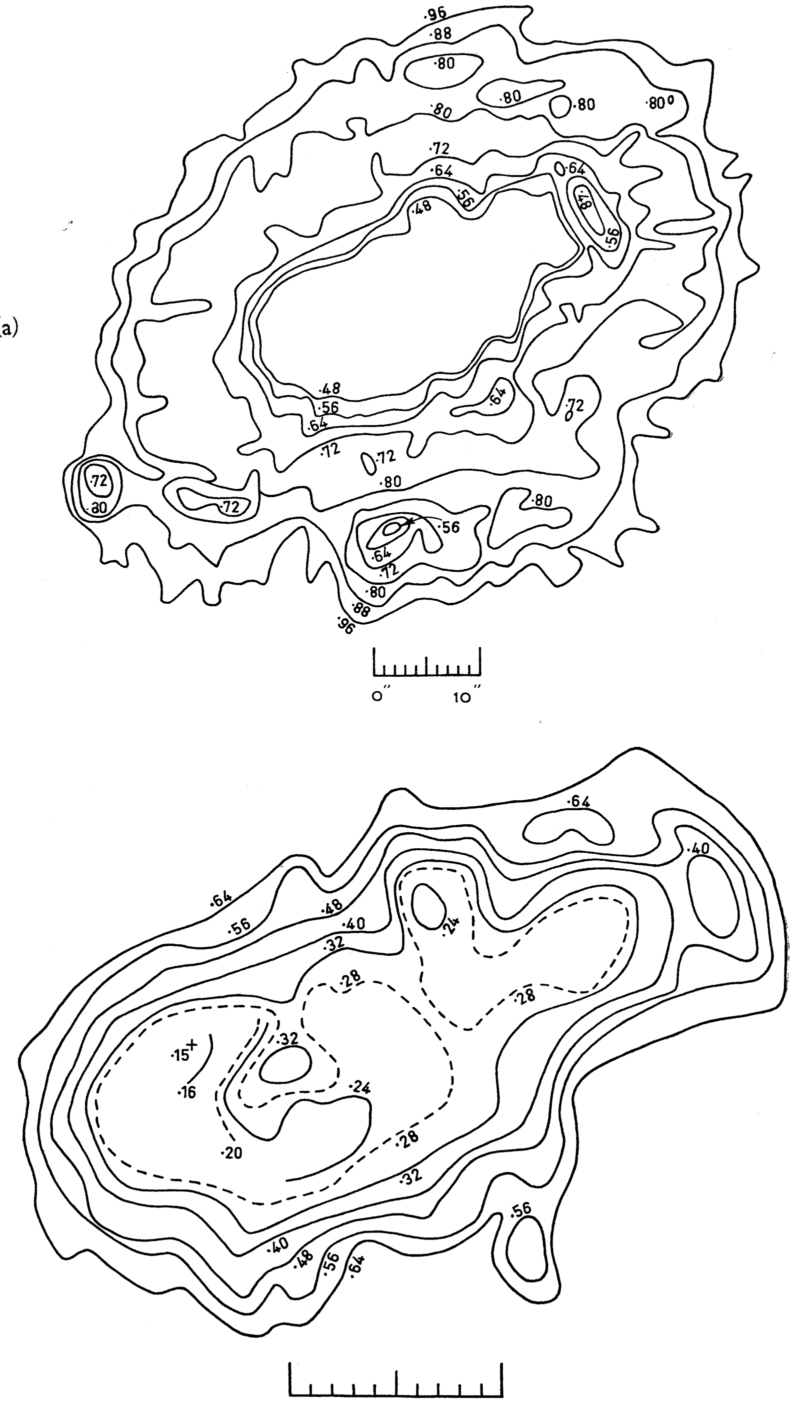

Fig. 1.—Isophotal contour maps (spot of May 11, 1959). (*a*) Penumbra and outer umbra. (*b*) Umbra. The darkest region is located well towards the left-hand end of the umbra; its temperature is some 500 °K below that of the rest of the umbra. For other noteworthy features, see text. Note: some of the isophotes are incomplete, owing to truncation by the focal-plane diaphragm used in taking the original photographs.

(4) this extra-dark region, which we shall call the " core " of the umbra, is only a few seconds of arc in diameter *and is located not at the centre of the umbra but near one end.*

Similar conclusions apply to the larger spot of Figures 2 (*a*) and 2 (*b*). The only significant difference is that there is no extensive region of more or less constant intensity in the umbra (the spot of Figure 1 is not typical in this regard).

The most interesting feature of the isophotal maps is the umbral core. The core appears to be only a few seconds of arc in diameter, and calculation shows that for the spot of May 11 the intensity corresponds to a temperature some 500 °K below the average for the umbra. It is probable that some of the early visual observers, and also Chevalier (1916), noticed the presence of an umbral core.

IV. A Possible Model of the Magnetic Field Configuration

The general relationship between magnetic field strength and light intensity in the photosphere is very well known. The dark regions that we call sunspots are invariably accompanied by magnetic fields whose strengths range from several hundred to several thousand gauss ; the larger and darker the spot, the more intense the associated field. Moreover, although weak fields are often found at places where the photosphere shows no visible disturbance (Babcock and Babcock 1958), the larger fields are always associated with spots. Von Klüber (1948) has compared photometric and magnetic measurements made along lines crossing a number of spots. His paper gives a number of cross sections which clearly reveal a significant correlation between large-scale variations in field strength and intensity, points of maximum field strength roughly coinciding with those of minimum intensity.

How far is this large-scale correlation between field strength and intensity paralleled by a correlation on the smaller scale of the detailed intensity variations shown in Figures 1 and 2 ? If such a correlation does indeed exist, then we must expect the magnetic field distribution in a spot to show a complexity comparable to that of the intensity distribution. And, in fact, despite the great difficulty of obtaining magnetic observations having the necessary high spatial resolution, Severny (1959) has been able to show that the field (or, more strictly, its longitudinal component) does possess a detailed structure.

The existence of this structure clearly contradicts the classical picture of the magnetic field distribution. According to this picture, the magnetic field inside a sunspot is axially symmetrical, the strength decreasing steadily from the centre to the edge of the spot (Hale and Nicholson 1938). The lines of force at the centre of the spot are perpendicular to the solar surface (longitudinal field) but, away from the centre, they become more and more inclined to the vertical, an inclination of about 70° being attained at the outer border of the penumbra.

Modern magnetic observations also contradict the classical picture. In particular, they clearly indicate the presence of *transverse* fields in the umbra where, according to the classical picture, the field should be longitudinal. This is shown by the frequent occurrence of the central π component in the Zeeman patterns of simple triplet lines in the umbral spectrum (see, for example, Evershed

(a)

(b)

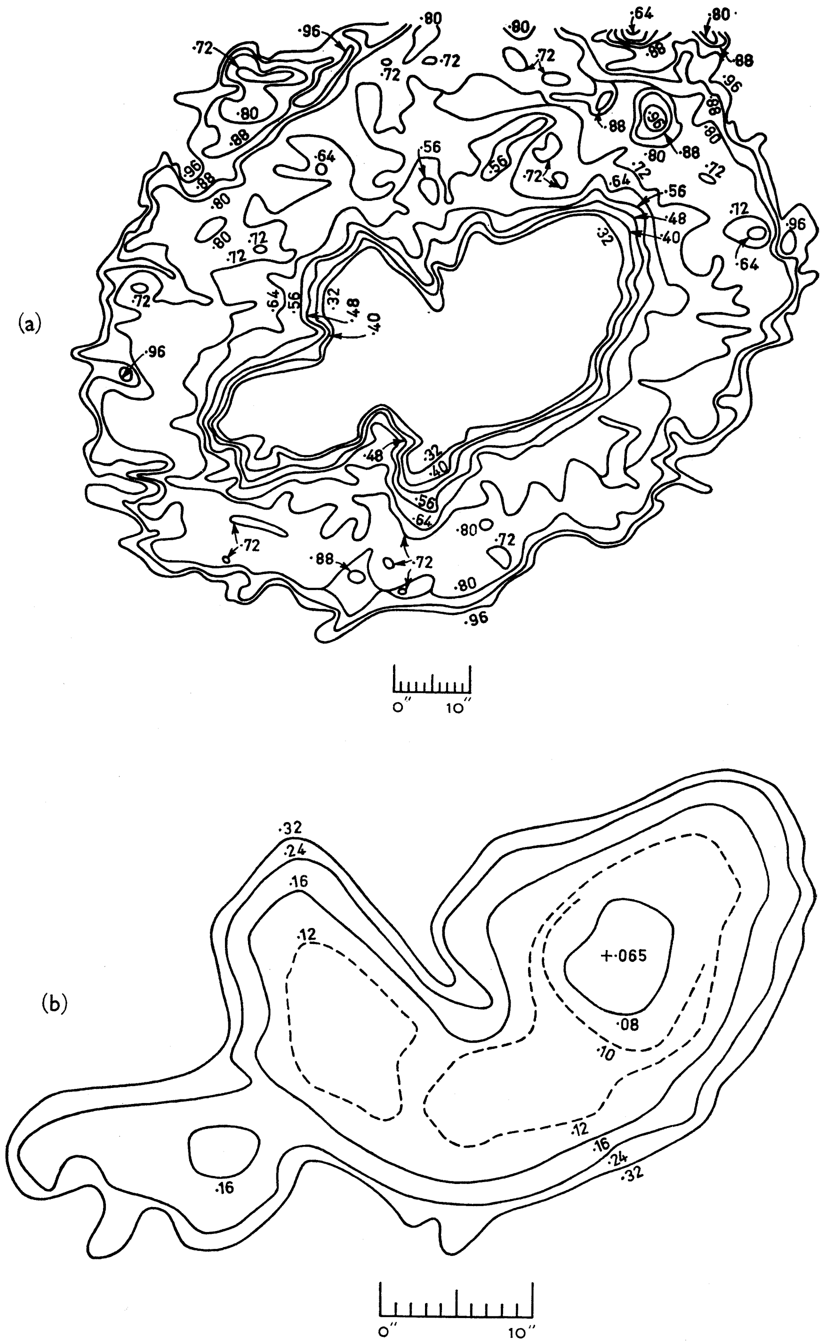

Fig. 2.—Isophotal contour maps (spot of January 12, 1959). (*a*) Penumbra and outer umbra. (*b*) Umbra. In this spot the dark umbral core is located somewhat more centrally than in the spot of Figure 1.

1942; Severny 1959). The absence of the π component in the *penumbral* spectrum shows that its appearance in the umbra cannot be due merely to scattering from the spot surroundings but must be due to the presence of a transverse field (Bumba 1962*a*, 1962*b*). This conclusion is strongly supported by some magnetograph observations made by Severny (1959: cf. Fig. 2), which actually show a region of *zero longitudinal field* at the very centre of the umbra of a sunspot. Further confirmation is provided by the work of Dollfus (1958) and Leroy (1959), who have shown that the integrated radiation of sunspots is partially plane polarized as a result of the transverse Zeeman effect.

The magnetic observations described above make it clear that the classical picture of the magnetic field configuration requires major revision, but by themselves do not provide a new picture to replace the old. However, some further information is provided by von Klüber's (1948) observation of a strong transverse

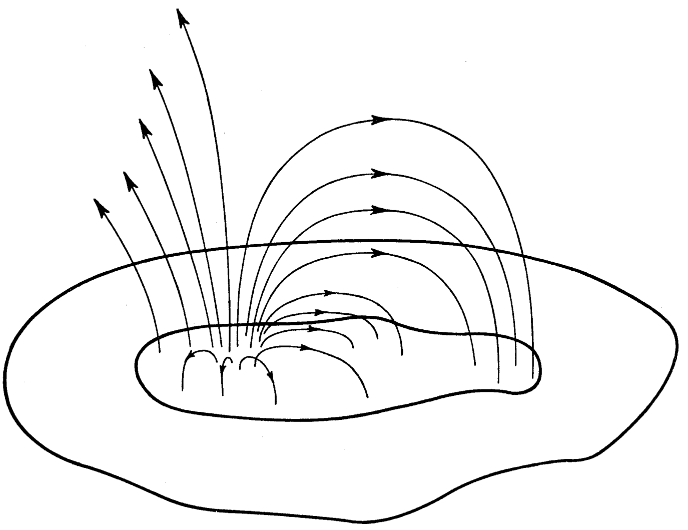

Fig. 3.—Schematic drawing of possible magnetic field configuration in the umbra.

field between *two regions of opposite polarity* in the umbra of a large spot. On a normal photograph (see von Klüber's Fig. 11) the umbra appears as a single structure with only an incomplete light-bridge separating the regions of opposite polarity. In a similar case, recorded by the Mt. Wilson observers, a spot umbra was divided into two parts of opposite polarity by a well-marked light-bridge; the published spectrogram clearly shows the presence of a transverse field in the neighbourhood of the bridge (Hale and Nicholson 1938: Plates 6*m*, *n*). The occurrence of large complicated sunspots containing several separate umbrae of different polarities within a single penumbra is fairly well known, but von Klüber, on the basis of his own observations, has suggested that regions of opposite polarity may frequently occur even within single isolated sunspots.

We believe that some further indication of the probable form of the magnetic field configuration can be obtained by considering some of the features of the isophotal maps presented in this paper. In particular, let us make the hypothesis that the umbral core represents the region of greatest field strength. We are then led to a picture of the field configuration whose main features are shown schematically in Figure 3. Since the core is located near one end of the umbra, we may suppose that some of the field lines emanating from it return to other parts of the umbra rather than to neighbouring spots or the photosphere. The area of these parts is much greater than that of the core, so the field strength there must be correspondingly weaker. It is evident that the umbra must possess *two* polarities, one concentrated in the core and the other scattered over the rest of the umbra, with perhaps some concentration in the regions of subsidiary intensity minima. Finally, it is clear that the field must be transverse over parts of the umbra separating regions of opposite polarity.*

It could, perhaps, be argued that although the new picture may be valid for large spots like those studied in this paper, the classical picture should be retained for small, simple spots of apparently regular appearance. However, it is our experience that all spots, ranging from sunspot pores only a few seconds of arc in diameter to the largest spots, have a complex intensity structure. If there is a close relationship between the magnetic field and intensity distributions, it follows that for all spots, irrespective of size, the classical picture of the field configuration has to be revised.

V. Acknowledgments

The authors wish to thank Miss M. J. Pilgrim for much assistance in reducing the photometric traces and Mr. J. E. Shaw for calibrating the step-wedge.

VI. References

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* Another picture of the field configuration in sunspot umbrae has recently been suggested by Bumba (1962*a*). In his model the lines of force in the umbra are twisted into spirals whose pitch increases rapidly with height (cf. Bumba 1962*b*: Fig. 12). Consequently, the field lines in the lower levels of the umbra form an almost horizontal ring, whereas in the upper levels they are directed more or less vertically.