HIGH RESOLUTION OBSERVATIONS OF THE GRANULAR STRUCTURE OF SUNSPOT UMBRAE

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Summary

High resolution photographs of sunspot umbrae have confirmed the existence of an umbral granulation, resembling the photospheric granulation but differing in regard to lifetime and cell size. Bright structures in the form of " loops " are also seen. Quite apart from the granulation, the intensity contours of spot umbrae show a detailed and complex structure.

I. Introduction

Apart from occasional " light-bridges " (Waldmeier 1955), sunspot umbrae usually appear in published photographs as uniformly dark areas. However, Chevalier (1916) reported the existence in spot umbrae of a bright granular structure, and this was later confirmed visually by Thiessen (1950). More recently, Rösch (1957) has published photographs showing evidence of this structure and has drawn attention to the need for further observations.

In the present paper an account is given of a systematic attempt to photograph detail in sunspot umbrae and, in particular, to obtain better observations of the umbral granules. The results are based on photographs selected from eleven films of six different spots. In agreement with Rösch's observations, these photographs reveal the existence of granules in spot umbrae (Plates 1 (*b*), 2 (*c*)). Measurements, although based on only a small number of granules, indicate that the " cell size " of the umbral granulation is less than that of the photospheric granulation ; moreover, the lifetime is found to be greater. In addition to granulation, " loop " structures are sometimes seen (Plate 3 (*c*)). Finally, in agreement with the observations of Das and Ramanathan (1953), it is found that the (smoothed) intensity profile of a spot umbra is not rectangular ; large spots often contain several intensity minima, each pair being separated by a " saddle ".

II. Instrument

The observations were made with the 5-in. photoheliograph (Loughhead and Burgess 1958) of the C.S.I.R.O. Division of Physics Solar Observatory. This instrument is designed to photograph any selected region of the solar disk on 35 mm film at 5-sec intervals, the 16 mm image formed by the objective being magnified by a second lens to a diameter of 20 cm. The effective wavelength is 5400 Å and the theoretical limit of resolution is 0·8 sec of arc.

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In order to photograph detail in the umbra of a spot it is necessary to give an exposure greater than that required for the penumbra or surrounding photospheric granulation. The necessary increase in exposure depends both on the size of the spot and on position in the umbra. Exposure factors ranging from two to seven were used; the latter value is normally sufficient for recording detail in the darkest region of the umbra of a very large spot. Apart from the removal of a 50 per cent. neutral filter normally present in the light path, the increases in exposure were achieved by using longer exposure times.

In the absence of any precautions, the contrast of the faint umbral detail would be reduced by scattered light from the penumbra and surrounding photosphere. To eliminate scattered light from the magnifying lens and two auxiliary prisms which divert the beam to the camera, prime-focus diaphragms were constructed, with diameters ranging from 0·06 to 0·22 mm. This range is adequate for the larger umbrae encountered on the 16 mm primary solar image. The diaphragms were made of thin aluminium foil, the holes being pierced with a fine, burnished needle. Any selected diaphragm could be mounted in a small metal box containing a central aperture. This box was carried on a Hilger micrometer microscope stage, which provided fine motions in two directions at right angles to the optical axis, thus permitting the diaphragm to be positioned on any part of a spot umbra. In addition, motion of the box along the optical axis allowed the diaphragm to be brought into the focal plane; to reduce heating, air was sucked through perforations in the front surface of the box (cf. Loughhead and Burgess 1958).

Any remaining scattered light is due to scattering in the Earth's atmosphere and at the 5-in. objective. Atmospheric scattering is usually low at the site of the Solar Observatory, some 30 miles south-west of Sydney. In addition, the objective is a cemented doublet—a type of lens inherently free from scattered light; it was cleaned regularly during the course of this work.

III. Observational Technique

The diaphragm selected for any given spot depended on the size and shape of the umbra. If this was circular, a diaphragm was usually selected which just included the inner edge of the penumbra, as seen in the telescope eyepiece (the umbra appears somewhat smaller on a visual image than on normal photographs such as Plates 1 (*a*), 2 (*a*), and 3 (*a*)). However, a smaller diaphragm was used when only the detail at the darkest point was required. If the spot was elliptical, a diaphragm was selected which just included the inner edge of the penumbra at the ends of the minor axis.

For a large umbra, such as that illustrated in Plate 3, the observing procedure was as follows: the spot was photographed without a diaphragm every 5 sec for a period of 5 min, using an overexposure factor of three. This sequence served to reveal the structure in the neighbourhood of the umbra-penumbra boundary and, in the subsequent examination of photographs taken through a diaphragm, helped to locate the position of the diaphragm relative to the spot. The appropriate diaphragm was then inserted and a 20 min sequence with an overexposure factor of five was obtained in order to show the structure of the outer umbra. Retaining the diaphragm, a further 20 min sequence was obtained, using an overexposure factor of seven ; this sequence served to reveal the structure of the core of the umbra. Finally, a repetition of the first sequence was followed by a 15 min sequence of normal photographs and a photometric calibration.

A similar procedure was used for smaller umbrae, such as that illustrated in Plate 1, except that overexposure factors ranging from 2 to 5 instead of from 3 to 7 were employed.

During the period September 1958 to February 1959, 11 films were obtained of six different sunspots of various sizes. Although photography was confined to days of exceptionally good seeing, examination of the films reveals less than 40 umbral photographs whose quality approaches the theoretical performance of the telescope. However, many others provide useful supporting data. The umbral granulation was found to be more difficult to photograph successfully than the photospheric granulation ; our experience shows that this can be attributed partly to the greater exposure times required.

IV. The Detail in Sunspot Umbrae

Plates 1–3 illustrate the typical detail to be seen in sunspot umbrae.

Plate 1 (*a*) is a normal photograph of a fairly large spot and the surrounding photospheric granulation. The umbra is divided into two parts by a light-bridge, which itself shows some granular structure. Plate 1 (*b*) shows, on twice the scale, a fourfold overexposure taken through a diaphragm centred on the upper part of the umbra. A number of umbral granules can be distinguished, including three faint ones at the dark core of the umbra. They are more closely packed than the photospheric granules (Section VI).

Plate 2 (*a*) is a normal photograph of a somewhat larger spot ; on the original negative a faint light-bridge can be seen across the centre of the umbra. Plates 2 (*b*) and 2 (*c*) show twofold and threefold overexposures respectively, roughly centred on the light-bridge ; the scale of these photographs is twice that of Plate 2 (*a*).

As shown in Plate 2 (*b*), the light-bridge consists of bright segments, an elongated portion near the middle being particularly prominent. On the right-hand border of the umbra there are several bright granules ; these granules are apparently detached from the penumbral filaments and are much brighter than those within the umbra proper. Examination of other films has shown them to be a characteristic feature of the umbra-penumbra boundary* (cf. Secchi 1875).

In Plate 2 (*c*) the centre of the light-bridge is overexposed, but its " wings " begin to appear. Above the light-bridge a number of umbral granules are now visible. The exposure is insufficient to show any granulation in the lower portion of the umbra (which the negative shows to be darker than the upper) or in the central region of the upper part ; overexposures greater than threefold

* They are not to be confused with the bright regions sometimes found on the *penumbra* side of the umbra-penumbra boundary (Bray and Loughhead 1957 ; Loughhead and Bray 1958 : cf. Plate 1).

are not available for this spot. It is clear that there are two points of minimum intensity separated by a saddle which, on an overexposure, appears as a light-bridge. Note the small variation in brightness of the granules in its neighbourhood.

Finally, Plate 3 (*a*) shows the main spot* of the largest group which has appeared to date during the current sunspot maximum. On the same scale Plate 3 (*b*) shows a threefold overexposure made without a diaphragm. The outline is essentially an *isophote* of the umbra; it differs considerably from the outline of the umbra shown on the normal exposure. In addition, the left-hand region of the umbra is now seen to be brighter than the rest; it shows several umbral granules, whereas only one particularly bright granule is visible in the main portion.

Plate 3 (*c*) is a sevenfold overexposure taken through a diaphragm roughly centred on one of the points of minimum intensity; it is reproduced on twice the scale of Plate 3 (*a*) and (*b*). The umbral granulation is only faintly visible on the negative, probably owing to mediocre seeing, and fails to appear on the print. However, there is one striking feature, a bright loop which appears to consist of four elongated granules. Similar loops have been seen in other umbrae. This photograph shows clearly that the umbral intensity profile is far from rectangular.

The nature of the umbral detail shown by Plates 1–3 is in general confirmed by the rest of the observational material. In particular, umbral granules similar to those illustrated have been seen on all the films except one. Often the granules appear faint or indistinct, but this can usually be attributed to incorrect exposure or poor seeing. One fairly large spot failed to show more than one or two granules, although the exposure was correct and the seeing, judged by other criteria, appeared fair. In this case it is possible that the quality of the seeing has been wrongly assessed. Granulation has also been observed in the umbrae of small spots and in pores only a few seconds of arc in diameter. In such cases the granulation often appears on negatives taken with a normal exposure.

V. Lifetimes of the Umbral Granules

The film of the spot shown in Plate 2 provided nine photographs of sufficient quality to enable an estimate to be made of the lifetimes of the umbral granules; these photographs extend over a period of 32 min 42 sec. In estimating the lifetimes a method was employed similar to that used in determining the lifetimes of the photospheric granules (Bray and Loughhead 1958*b*).

Four of the granules were observed throughout the entire period (two of them failed to appear on one photograph) and therefore provide clear evidence that some granules last for at least half an hour. Four others were reliably identified for periods ranging from 4 to 10 min. However, for various reasons the non-appearance of these granules at other times cannot be taken as definite evidence of their non-existence. Hence all the above values represent only *lower limits* to the true lifetimes. A longer series of high quality photographs might well show that the true values are actually higher.

* The diffuse bright streak crossing the penumbra (top, left) is not a photographic defect but is a real feature of a type which has been noticed before.

Despite the small number of lifetimes estimated, it is clear that some umbral granules are longer lived than the photospheric granules, whose lifetimes according to the best available estimates are of the order of 10 min (Macris 1953 ; Bray and Loughhead 1958*b*).*

VI. "Cell Size" of the Umbral Granulation

Simple measurements of the diameters of individual umbral granules provide at best only a rough guide to the true sizes, owing to their dependence on photographic contrast and on the combined instrumental profile of telescope and atmosphere (cf. Bray and Loughhead 1958*b*). However, the mean "cell size" of the pattern, i.e. the average distance between the centres of adjacent granules, is independent of these effects, provided individual granules are actually resolved. This quantity therefore provides a more reliable parameter for characterizing the scale of the pattern.†

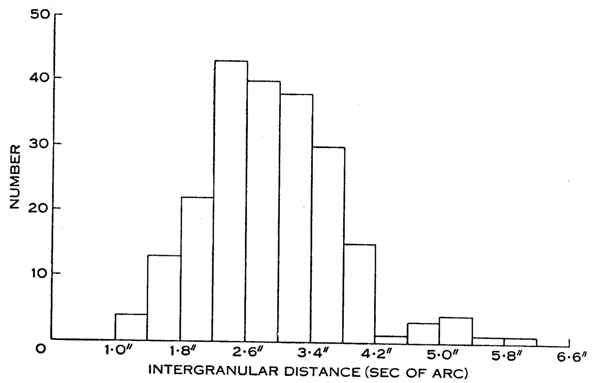

Fig. 1.—"Cell size" of the photospheric granulation : the histogram gives the distribution of the distances between the centres of adjacent granules, measured for a group of 92 granules. The most probable value is 2·6 sec of arc and the mean value 2·9 sec. The cell size of the umbral granulation is found to be 2·0 sec (see text).

To determine the mean cell size the distances between the centres of adjacent granules have been measured for the groups of granules in the umbrae of the spots illustrated in Plates 1 (*b*) and 2 (*c*) ; these are the only two spots for which sufficiently good photographs of the umbral granulation are available. The first group gave four values ranging from 1·7 to 2·0 sec of arc, with a mean of 1·9 sec. The second group gave 11 values ranging from 1·5 to 2·3 sec together with one value of 2·7 sec, giving a mean of 2·0 sec. Although based on small numbers of granules, the results for the two spots are concordant and give an overall mean of 2·0 sec of arc for the cell size of the umbral granulation.

* Penumbral filaments are also longer lived than the photospheric granules, having lifetimes of the order of several hours (Bray and Loughhead 1958*a*).

† Nakagawa (1959) has used a similar parameter in an experimental verification of Chandrasekhar's theory of convection in conducting liquids in the presence of a magnetic field.

It is interesting to compare this result with the mean cell size of the photospheric granulation, derived from measurements of a good-quality photograph (Bray and Loughhead 1958*b* : cf. Plate 1) taken with the same instrument. The results, which were derived from a group of 92 granules, are given in Figure 1. The mean value is 2·9 sec of arc, the most probable value being about 2·6 sec. The mean cell size of the umbral granulation in the two spots measured is therefore significantly less than that of the photospheric granulation.

All measurements were corrected for foreshortening.

VII. Conclusion

The observations described in this paper have confirmed the existence of granulation in the umbrae of sunspots ; this resembles the photospheric granulation but differs in regard to lifetime and cell size. The intensity profile of a spot umbra is not rectangular (Das and Ramanathan 1953). A large umbra often possesses several intensity minima, each pair being separated by a " saddle ". Thus, quite apart from the granulation, the intensity contours of spot umbrae show a detailed and complex structure. What relationship, if any, does this structure bear to the umbral magnetic field distribution ? Recent progress in plotting magnetic fields (e.g. Nikulin, Severny, and Stepanov 1958) leads one to hope that with improved spatial resolution this question may soon be answered.

The similarity of the umbral granulation to the photospheric granulation raises the question of whether the umbral granules, like the photospheric granules (Loughhead and Bray 1959), are to be identified with convection cells. If so, it follows that even the strong magnetic fields present in large spots fail to suppress the convective motions. These questions will be discussed more fully in a later paper.

VIII. Acknowledgments

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IX. References

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Explanation of Plates 1–3

Plate 1

(*a*) Sunspot photographed at $1^{h}\ 36^{m}$ E.A.S.T. on September 1, 1958. Heliographic co-ordinates: 204° W., 6° S.; heliocentric angle, 23°.

(*b*) Fourfold overexposure taken at $11^{h}\ 44^{m}$ through a small diaphragm centred on the upper portion of the umbra. Several umbral granules are distinctly shown, including three faint ones at the core of the umbra. The scale of (*b*) is twice that of (*a*).

Plate 2

(*a*) Sunspot photographed at $12^{h}\ 25^{m}$ E.A.S.T. on September 19, 1958. Heliographic co-ordinates: 303° W., 19° S.; heliocentric angle, 28°.

(*b*) Twofold overexposure taken at $10^{h}\ 39^{m}$ through a diaphragm. Note the discrete structure of the light-bridge and the bright granules at the umbra-penumbra boundary.

(*c*) Threefold overexposure taken at $11^{h}\ 19^{m}$. The part of the umbra above the light-bridge is brighter than that below, and shows clear umbral granulation.

The approximate position of the diaphragm relative to the spot is shown by the white circle. The scale of (*b*) and (*c*) is twice that of (*a*).

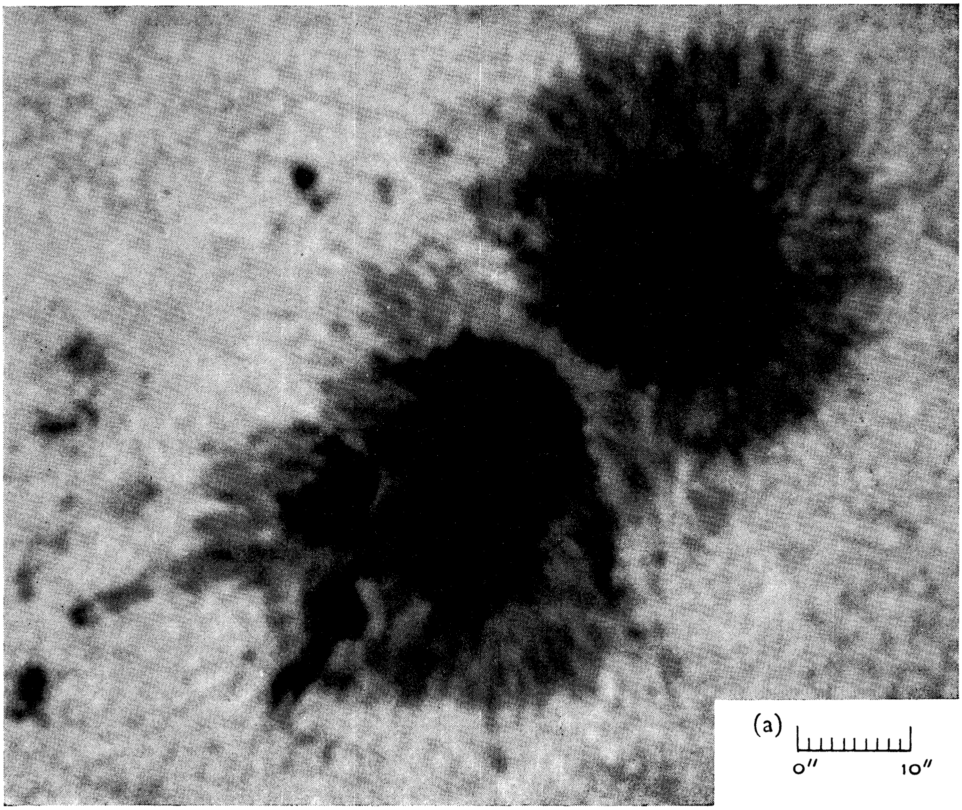
Plate 3

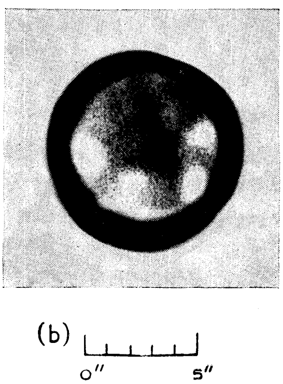
(*a*) Sunspot photographed at $2^{h}\ 40^{m}$ E.A.S.T. on January 12, 1959. Heliographic co-ordinates: 253° W., 11° N.; heliocentric angle, 25°.

(*b*) Threefold overexposure taken at $12^{h}\ 34^{m}$ without a diaphragm. Note that the apparent umbral outline differs from that in (*a*); a few umbral granules can be seen in the left-hand portion.

(*c*) Sevenfold overexposure taken at $2^{h}\ 10^{m}$ through a diaphragm, whose location is shown by the white circle in (*a*). Note the bright "loop" structure (lower, left) and the gradual decrease in intensity towards the core of the umbra. Granulation fails to appear owing to mediocre seeing. The scale of (*c*) is twice that of (*a*) and (*b*).

GRANULAR STRUCTURE OF SUNSPOT UMBRAE





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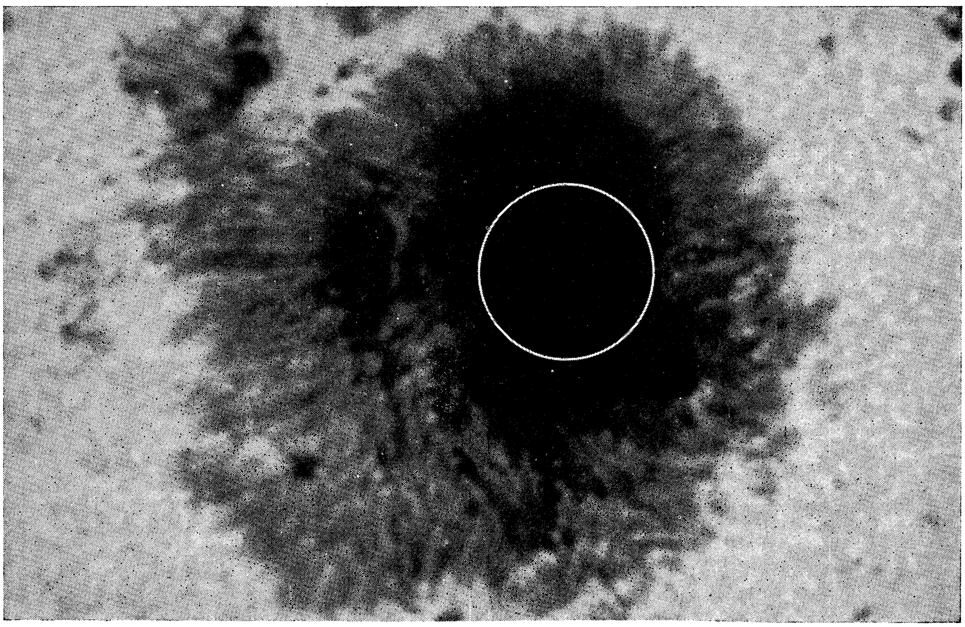

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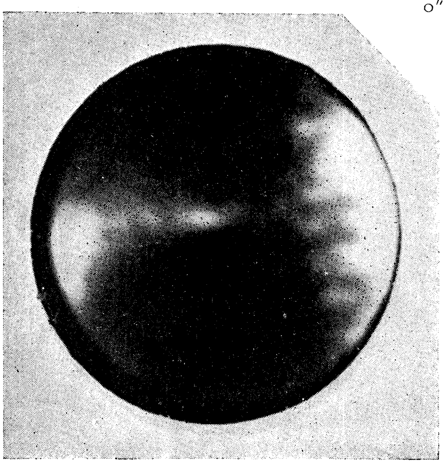

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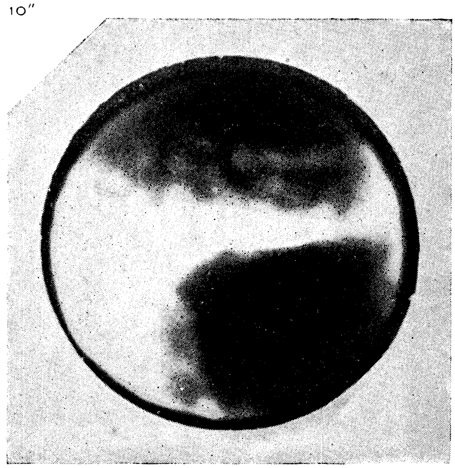
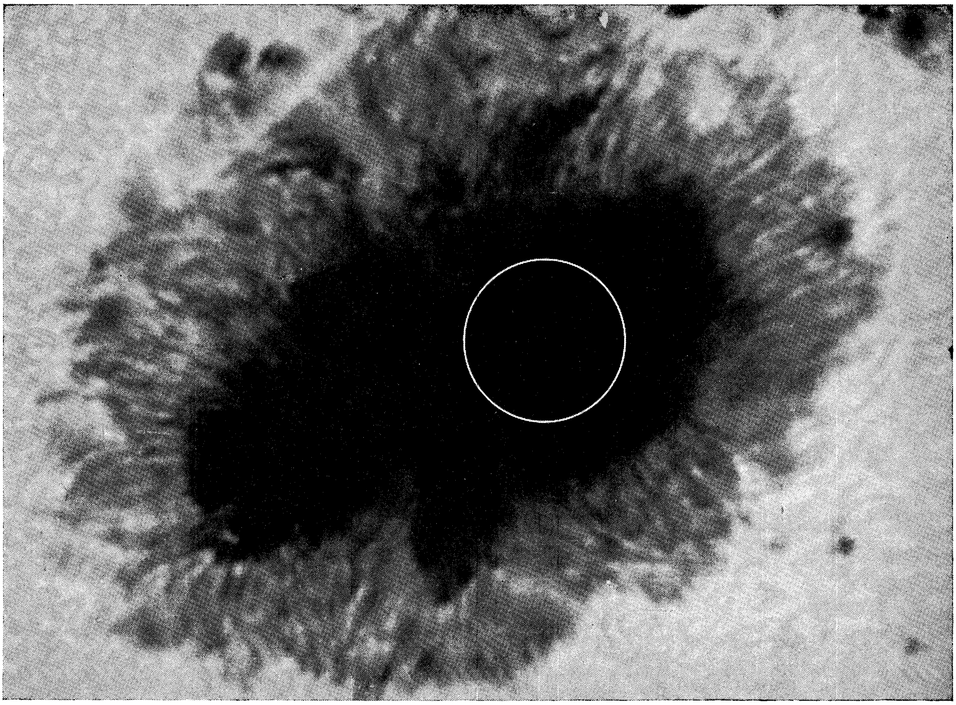


(c) 0″ 5″

GRANULAR STRUCTURE OF SUNSPOT UMBRAE



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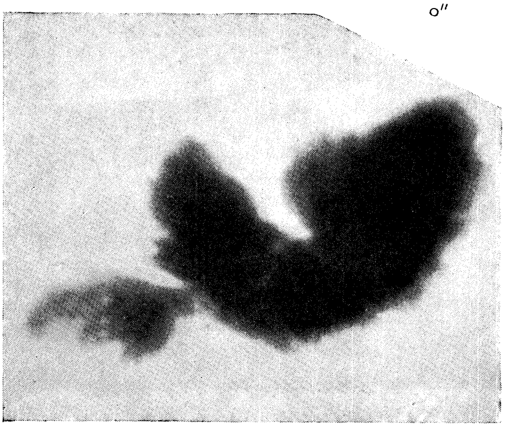

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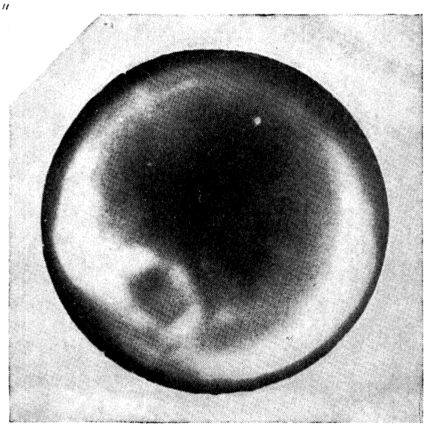

(c) 0″ 5″