THE LIFETIME AND CELL SIZE OF THE GRANULATION IN SUNSPOT UMBRAE

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Summary

High quality photographs extending over a period of 2 hr 11 min have been obtained of the granulation in the umbra of a large sunspot. In agreement with earlier work, the mean cell size of the umbral granulation is found to be significantly less, and the lifetime considerably greater, than that of the photospheric granulation. Ten per cent. of the umbral granules last for over 2 hr.

The majority of the umbral granules, like the photospheric granules, show no detectable change in brightness, size, or shape during the periods over which they are observed to persist as identifiable structures. Some information is obtained about the modes of formation and dissolution of individual granules.

The similarity between the photospheric and umbral granulation is pointed out, and the possible role played by convective processes in sunspots is briefly discussed.

I. Introduction

Recent observations of the detail in sunspot umbrae (Bray and Loughhead 1959) have shown that the umbral granulation, while resembling the photospheric granulation in appearance, differs in lifetime and cell size. Measurement of a 32 min 42 sec sequence of photographs showed that some umbral granules last for at least this period ; the cell size, although derived from limited data, was found to be significantly less than that of the photospheric granulation. The present paper gives the results of the measurement of the lifetime and cell size of the granulation in the umbra of a large spot showing clear granular structure, based on a longer sequence showing a greater number of granules.

The mean cell size is found to be 2·3 sec of arc as compared with 2·9 sec for the photospheric granulation. Sixty-seven per cent. of the umbral granules last for more than 15 min, 27 per cent. for more than 45 min, and 10 per cent. for over 2 hr. Like the photospheric granules (Bray and Loughhead 1958*b*), most umbral granules showed no detectable change of brightness, size, or shape during the periods over which they were observed to persist as identifiable structures.

II. Observations

The observations of the granulation in the umbra of the spot were made with a 5-in. photoheliograph using techniques similar to those described previously (Bray and Loughhead 1959). Two consecutive sequences of photographs were obtained, each covering a period of nearly an hour. The umbral granules appear quite clearly on both sequences, taken with exposures three and five times greater than those required for the photosphere (cf. Plate 1). Together, the two sequences allowed the granules to be studied over a total period of 2 hr

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11 min. Some of the brighter granules are also visible on a 10 min sequence of twofold exposures taken shortly before.

The film, which was taken under good seeing conditions, contains nearly 40 umbral photographs whose quality approaches the theoretical performance of the telescope. Plate 1 shows the detail present in the umbra of the spot. Plate 1 (*a*) is a normal photograph of the spot and the surrounding photospheric granulation. Plate 1 (*b*) shows, on twice the scale, a photograph taken through a 0·22 mm diaphragm at the prime focus with three times the exposure of Plate 1 (*a*). Granulation appears over a large part of the umbra though none is visible in the left-hand portion, which is considerably darker than the rest.

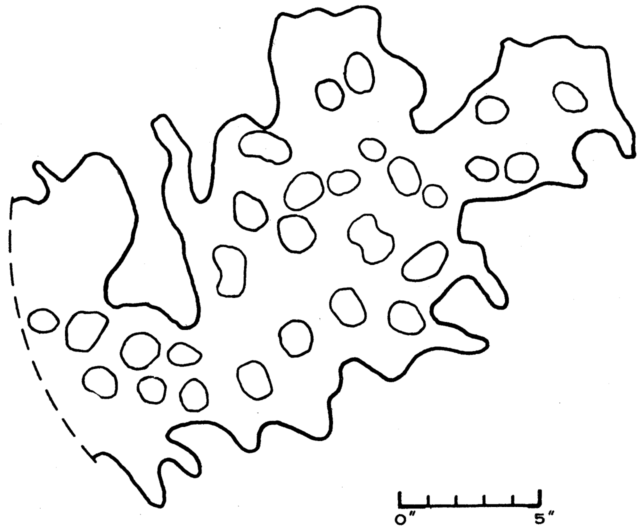


Fig. 1.—Umbral granulation pattern at $1^h\,2^m\,36^s$. The heavy line represents the apparent outline of the umbra. The lower histogram in Figure 2 was derived with the aid of this map.

Some of the granules are so close together that they can barely be distinguished. Note the bright forked structure in the left-hand portion of the umbra.* Plate 1 (*c*) shows a photograph with five times the exposure of Plate 1 (*a*), also taken through the diaphragm. The umbral granules now appear brighter, but the exposure is still insufficient to reveal any detail in the left-hand portion. (There are often large differences in intensity between different regions of an umbra, several intensity minima usually being present (Bray and Loughhead 1959)). Note the detachment of the left-hand tip of the fork to form a granule during the interval between Plates 1 (*b*) and 1 (*c*) (80 min).

III. Cell Size

Direct measurements of the diameters of individual umbral granules provide at best only a rough guide to the true dimensions owing to their dependence on photographic contrast and on the combined instrumental profile of telescope and

* Such forks or loops are characteristic features of sunspot umbrae ; with the correct exposure they, too, often show a granular appearance.

atmosphere. However, measurements of the mean cell size of the pattern, defined as the average distance between the centres of adjacent granules, are independent of these effects, provided individual granules are actually resolved. This quantity therefore provides a reliable and convenient parameter for characterizing the scale of the pattern. A similar parameter is often used in the theory of convective motion.

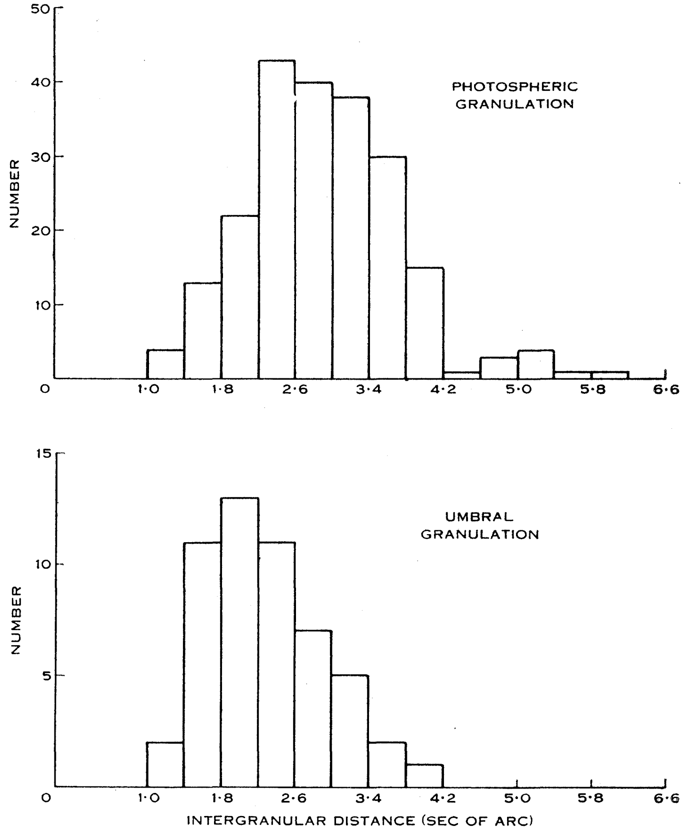


Fig. 2.—Cell size of the umbral and photospheric granulation patterns: the histograms give the distributions of the distances between the centres of adjacent granules (corrected for foreshortening), measured for groups of 28 umbral and 92 photospheric granules. The *mean* cell sizes are 2·3 and 2·9 sec of arc respectively.

The cell size measurements were derived from a very good photograph taken with an exposure factor of five. A map of the 28 umbral granules visible on this photograph is shown in Figure 1. Some of the granules near the edge of the umbra cannot be distinguished on Plate 1 owing to the difficulty of recording objects of different brightness with high contrast on a single reproduction.

The distribution of the 52 intergranular distances measured is given in Figure 2, which also shows the cell size distribution of the photospheric granulation, derived from a good-quality photograph (Bray and Loughhead 1958*b*: cf. Plate 1) taken with the same instrument. It is evident that the cell size of the umbral granulation is significantly less than that of the photospheric granulation, the *mean* cell sizes being 2·3 and 2·9 sec of arc respectively.* Observations of higher resolving power might be expected to yield somewhat more symmetrical distributions, with some separations of less than 1 sec of arc.

IV. Lifetimes

The lifetimes of the umbral granules were determined by a method similar to that used in determining the lifetimes of the photospheric granules (Bray and Loughhead 1958*b*). The results of the measurements, which refer to 48 granules in all, are as follows : 67 per cent. of the granules had lifetimes exceeding 15 min, 38 per cent. exceeded 30 min, 27 per cent. exceeded 45 min, and 10 per cent. exceeded 2 hr. Three particularly bright granules are visible on the short sequence of twofold overexposures as well as on the two long sequences ; these granules lasted for at least $2\frac{1}{2}$ hr.† Umbral granules are therefore considerably longer-lived than photospheric granules, whose lifetimes, according to the best available estimates, are of the order of 10 min (Macris 1953 ; Bray and Loughhead 1958*b*).

V. Changes in Umbral Granules

The umbral granules exhibit a diversity in brightness, size, and shape similar to that shown by the photospheric granules. By examining their appearances on each photograph in the sequences, an attempt was made to detect changes in the individual granules during the periods over which they were observed to persist as identifiable objects. The results are given in Table 1.

Table 1

CHANGES IN UMBRAL GRANULES

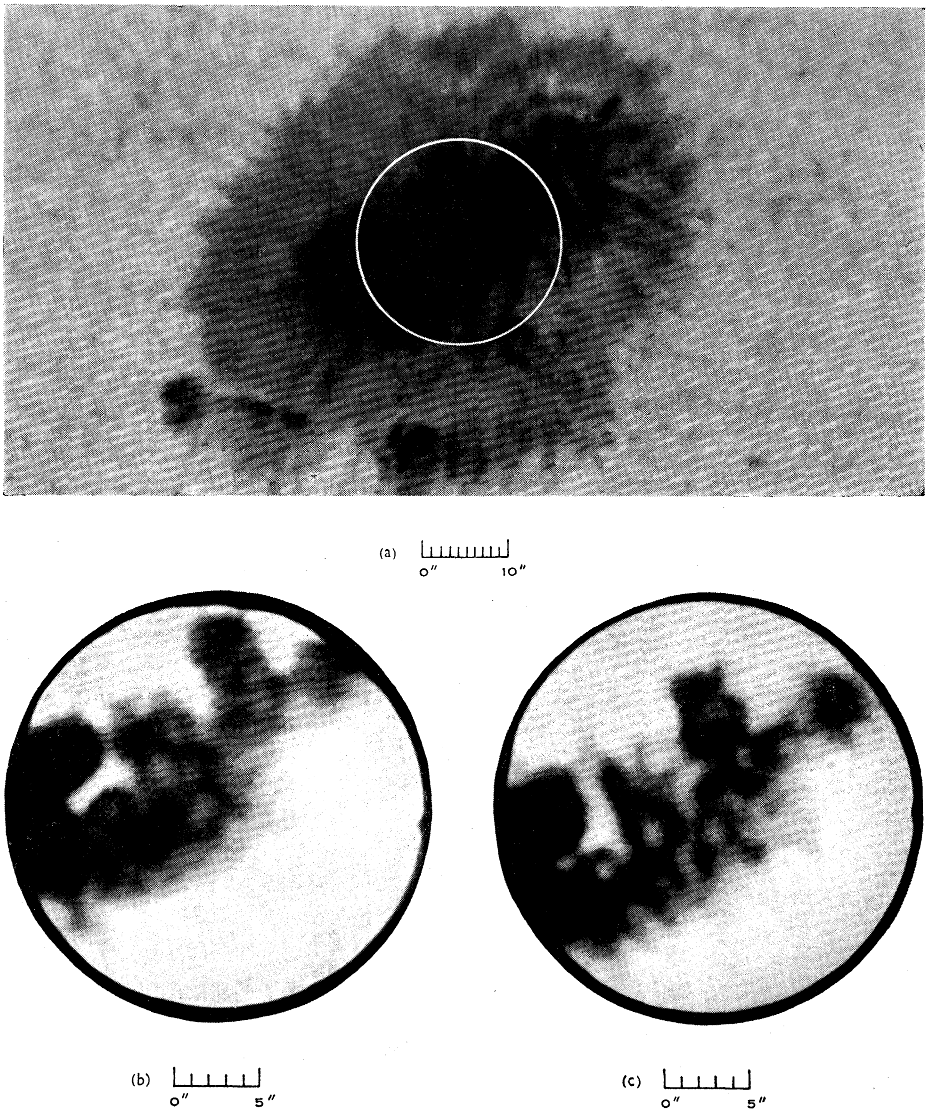
Type of Change		No. of Granules
No change		34
Brightness	increase	4
	decrease	4
Size	increase	1
	decrease	4
Change of shape		5

Comparison of Table 1 with the corresponding results for the photospheric granulation (Bray and Loughhead 1958*b* : cf. Table 2) suggests that rather more umbral than photospheric granules undergo no detectable change (71 per cent. as opposed to 57 per cent.). However, this may be an observational effect, since

* The significance of this result is established by the fact that the observed difference between the mean cell sizes, 0·6 sec, is six times greater than the standard error of the difference of the means, which is $\sqrt{\{(0\cdot09)^2+(0\cdot06)^2\}}=0\cdot1$ sec, 0·09 and 0·06 sec being the standard errors of the means of the two distributions.

† The lifetimes of the longer-lived umbral granules are comparable with those of the penumbral filaments (Bray and Loughhead 1958*a*).

LIFETIME AND CELL SIZE OF SUNSPOT UMBRAL GRANULATION



(*a*) Sunspot photographed at $2^{h}\,13^{m}$ E.A.S.T. on May 11, 1959. Heliographic coordinates: 115° W., 11° N.; heliocentric angle, 17°.

(*b*) Threefold overexposure taken at $11^{h}\,46^{m}$ through a 0·22 mm diaphragm at the prime focus. Granulation appears over a large part of the umbra. With this exposure the penumbra and outer parts of the umbra are burnt out and appear white on the photograph. Note the bright forked structure at the left.

(*c*) Fivefold overexposure taken at $1^{h}\,6^{m}$. The umbral granules appear brighter with this exposure, which, however, is still insufficient to reveal detail in the left-hand portion. Note the detachment of the left-hand tip of the "fork" to form an umbral granule during the interval between (*b*) and (*c*).

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*).

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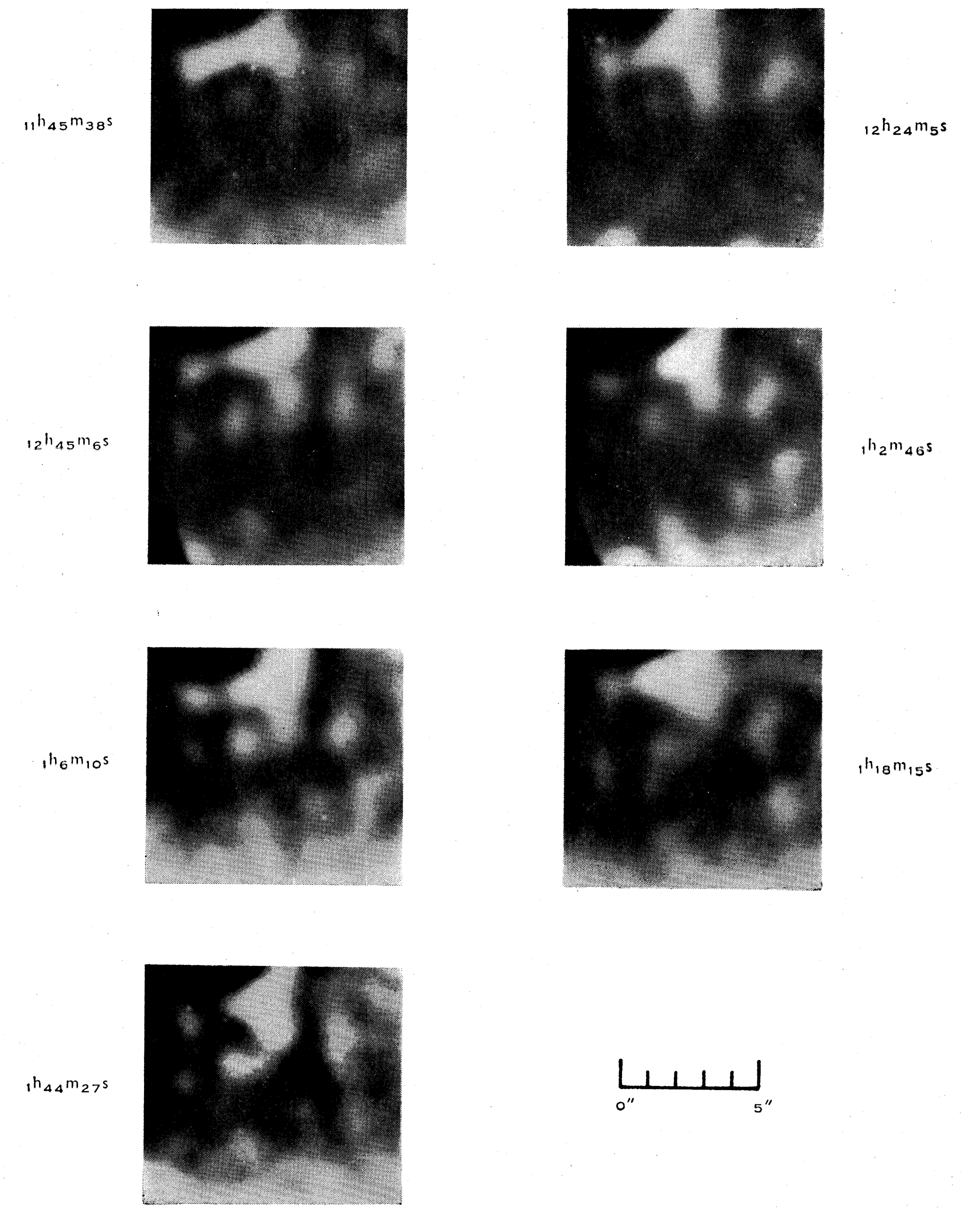

A sequence of photographs showing the stability of the umbral granulation pattern over a period of $1^h\ 59^m$; the first two photographs are threefold overexposures, the rest are fivefold overexposures. Despite apparent changes due to seeing (e.g. the tail-like projections seen on several granules at $1^h\ 18^m\ 15^s$), some umbral granules can readily be followed over the entire sequence. Note the granule which becomes detached from the upper prong of the fork structure, and also the bright granule which ultimately attaches itself to the lower prong.

the smaller scale of the umbral pattern renders changes more difficult to detect. For those granules showing change, variations in brightness and size are uncorrelated and have no tendency to occur during any particular part of the observed lifetime.

Plate 2 illustrates the general stability of the umbral granulation pattern over a period of nearly 2 hr. Although there are apparent differences from one photograph to another due to seeing, some granules can easily be followed over the entire sequence. The " tails " attached to some of the granules at 1 hr 18 min 15 sec have no real existence but are due to poor seeing on this photograph.

Changes in the umbral granules are difficult to detect during their periods of formation and decay, when the granules cannot easily be identified as such. However, a few cases of well-defined births and deaths were recorded. Some granules are preceded by a diffuse patch of bright material, which is difficult to distinguish from a granule smeared by seeing. Others originate by detachment from the inner ends of penumbral filaments or from the tip of a " fork " structure (cf. Plate 2). Dissolution sometimes occurs by a granule fading into diffuse bright material, which may then become dark. Sometimes a granule loses its identity by coalescing with a neighbouring granule, penumbral filament, or fork structure (cf. Plate 2).

VI. Discussion

The view that the photospheric granules are to be identified with convection cells is supported by two main lines of observational evidence : the cellular nature of the granulation pattern (Loughhead and Bray 1959 ; Schwarzschild and Schwarzschild 1959), and the observed correlation between brightness and line-of-sight velocity in the photosphere (Plaskett 1954 ; Stuart and Rush 1954). Although no measurements have yet been made of the velocities of umbral granules, the general similarity of the umbral granulation to the photospheric granulation suggests that it also may prove to have a convective origin. If so, the influence of the spot magnetic field on convection currents in its umbra may well be responsible for the smaller cell size actually observed (cf. Chandrasekhar 1952*a*), though it is not clear how the magnetic field would affect the lifetime. In addition, theory indicates that the retardation of the circulatory convection currents by the field would reduce—but not suppress—the transport of convective energy from the bottom of the hydrogen convection zone to the visible layers of the spot.

Biermann (1941) suggested that the upward transport of energy by convection in a spot would be completely suppressed by the field, while Hoyle (1949) pointed out that, assuming the material was constrained to follow the lines of force as they fan out near the surface, the convected energy would be distributed over a greater area than in the absence of a field. Chandrasekhar (1952*b*), on the other hand, has concluded that under solar conditions the onset of thermal instability in the presence of a magnetic field is characterized by oscillations of increasing amplitude rather than by cellular convection. Now that the existence of umbral granulation is firmly established and some information about its lifetime and cell size is known, further work on the behaviour of convection currents in a magnetic field under solar conditions is clearly desirable.

VII. Acknowledgments

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VIII. References

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