FACULAR GRANULE LIFETIMES DETERMINED WITH A SEEING-MONITORED PHOTOHELIOGRAPH

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[*Manuscript received November* 9, 1960]

Summary

A telescope designed to take exposures automatically at moments of good seeing has been used to obtain a $5\frac{1}{2}$ hr sequence of high quality photographs of a facular region near the east limb of the Sun. Individual facular granules are found to be much longer lived than the photospheric granules, a result which agrees with the work of ten Bruggencate (1940) and Waldmeier (1940) but disagrees with the more recent observations of Macris (1953) and of Krat and Goldberg-Rogosinskaja (1956). Fifty per cent. of the facular granules last for over 2 hr, and 10% last for over 5 hr. In some cases, a facular granule, only 750–1500 km in diameter, occurs as an isolated bright structure, surrounded by normal photosphere and well removed from neighbouring sunspots or faculae. Apart from their greater brightness and much longer lifetimes, the facular granules differ from the photospheric granules in that they do not form a well-defined cellular pattern; these differences suggest different modes of origin.

A description is given of the method of triggering the exposures by means of a seeing monitor.

I. Introduction

Sunspot groups are invariably accompanied by white-light faculae, though sometimes faculae may be observed without attendant spots. Faculae are visible only near the limb and are composed of individual granules mostly 1–2 sec of arc in diameter. The facular granules are brighter than the surrounding photosphere and may occur singly or in clusters. High-resolution photographs (e.g. Loughhead and Bray 1960*b* : Plate 1 (*a*)) show that the facular granules are superimposed on a background of normal photospheric brightness.† In some cases isolated granules occur, well removed from neighbouring spots or faculae and surrounded by normal photosphere.

ten Bruggencate (1940) estimated the lifetimes of the individual facular granules to be of the order of 1 hr, while Waldmeier (1940) found that many facular granules last for more than 2 hr. These estimates were based on comparisons of pairs of photographs taken 1 hr and 2 hr apart. However, these results were later contradicted by Macris (1953) and by Krat and Goldberg-Rogosinskaja (1956), who found lifetimes comparable with those of the photospheric granules. The mean lifetimes of 6–7 min and 2 min found by these authors have since been quoted by Mustel (1958) and de Jager (1959) in recent monographs as representing the true values. However, the lifetimes determined

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† This result contradicts ten Bruggencate's conclusion that the facular granules are superimposed on a bright background (ten Bruggencate 1942).

by Macris refer, in fact, to the ordinary *photospheric* granules in the neighbourhood of a spot group near the centre of the disk ; any faculae in the neighbourhood would be invisible, since white-light faculae are visible only near the limb. Moreover, the poor quality of the photographs published by Krat and Goldberg-Rogosinskaja (1956 : cf. Plates 1 and 2) casts some doubt on the reliability of their results ; experience shows that poor seeing invariably leads to an under-estimate of the lifetime of any 1–2 sec of arc photospheric detail.

The determination of the lifetimes of the facular granules described in the present paper is based on a sequence of good-quality photographs covering a period of $5\frac{1}{2}$ hr. The observations were made with a 5-in. photoheliograph (Loughhead and Burgess 1958), the exposures being triggered automatically by a solar seeing monitor at the moments of best seeing. The results confirm the work of ten Bruggencate and Waldmeier in showing that individual facular granules are much longer lived than the photospheric granules : some 80% have lifetimes exceeding 1 hr, 50% exceeding 2 hr, 25% exceeding 4 hr, and 10% exceeding 5 hr. Some information has also been obtained about the modes of formation and dissolution of individual granules (Section IV).

II. Observations

In order to study the lifetime and evolution of the facular granules, a sequence of photographs fairly uniformly distributed over a period of several hours and consistently showing a resolution of 1 sec of arc is required. This poses an observational problem of considerable difficulty, since the seeing seldom remains at such a good level over so long a period. In fact, our experience indicates that it might take a year or more to obtain a sequence of sufficient quality and duration by the normal method of time-lapse cinematography. However, the chances of obtaining a useful sequence are considerably improved if, instead of photographing at fixed intervals, exposures are triggered off only during moments of good seeing. These moments do occur, even during long periods of otherwise mediocre seeing ; they usually last for a few seconds, occasionally for as long as a minute.

An instrument has been constructed to monitor the seeing continuously and to trigger the exposures automatically at the moments of good seeing. The principle of operation of the device is to measure photoelectrically the magnitude of the fluctuations in light intensity—due to seeing—of two narrow segments of the solar limb. The seeing monitor, which is carried on the same mounting as the 5-in. photoheliograph, has been described in detail elsewhere (Bray, Loughhead, and Norton 1959). The method used to trigger the exposures is described in Appendix I.*

The present work is based on a film taken on June 7, 1960, between 10.00 a.m. and 4.00 p.m. local time. The film shows an extended facular region surrounding a small group of sunspots near the east limb. The triggering level was set at

* *Note added in Proof.*—It has recently come to our attention that Siedentopf (*Die Sterne* **19** : 145 (1939)) had earlier published an account of a device to provide a quantitative measure of the solar seeing. Like the monitor described by the present authors, this device measured the distortion of the solar limb, but used a single radial slit instead of two tangential ones.

0·8 V (cf. Appendix I) throughout the film except for a period at the beginning when 92 exposures were obtained at the 0·5 V level. Out of the 800-odd photographs taken in all, 20 show a resolution of 1 sec of arc over substantially the whole frame; many others show 1–2 sec of arc resolution over more limited areas. The 20 best photographs are very uniform in quality and constitute a good sequence, fairly uniformly distributed over a period of 5 hr 33 min, for determining the lifetimes of the facular granules.

The appearance on the photographs of the faculae surrounding the spot group is typical of facular regions near the limb (cf. Waldmeier 1955). Except for the occasional appearance of bright facular streaks closely bordering small umbral areas on the *limb* side of the spot (Loughhead and Bray 1959), faculae show no close association with their attendant spots. In fact, they are distributed over a very large area in the neighbourhood of a spot group, each facular region consisting of a loose conglomeration of individual granules 1–2 sec of arc in diameter. In most cases the facular granules are not sufficiently compacted to form a pattern; even in big clusters composed of, say, 20 or more individual granules, they are often spread out along intersecting lines. For this reason it is not possible to define a mean "cell size", or average distance between the centres of adjacent granules, similar to that measured for the photospheric and umbral granulation (cf. Loughhead and Bray 1960*a*). Not all facular granules occur in clusters: many occur as completely isolated structures, surrounded by photospheric granules of normal brightness.

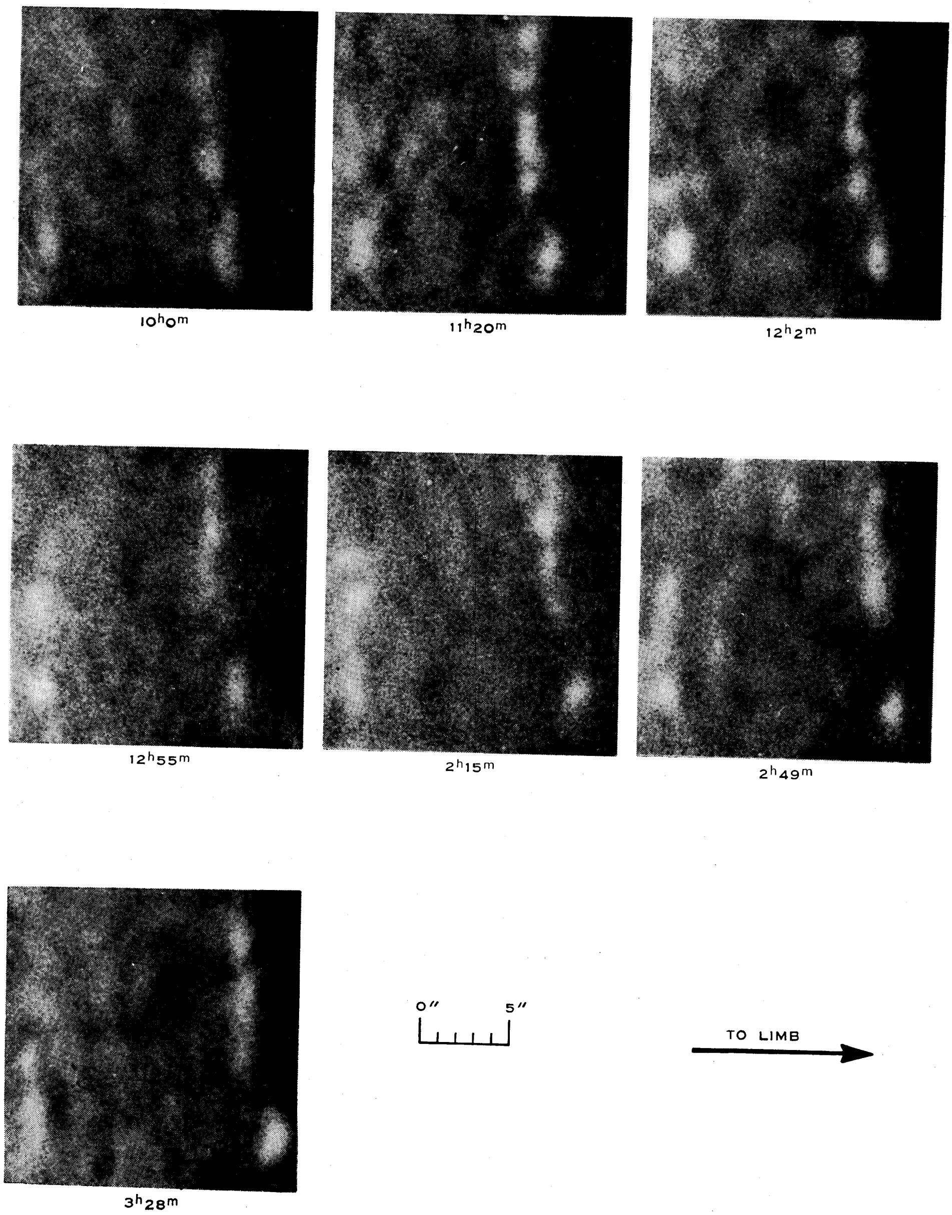
An examination of a large number of limb films taken with the 5-in. photoheliograph has revealed that individual facular granules are often clearly visible only 1–2 sec of arc from the limb. On the other hand, the photospheric granules are visible only up to 4 or 5 sec from the limb (Rösch 1957; Loughhead and Bray 1960*b*). This is evidence that the facular granules extend to a greater height than the photospheric granules.

III. Lifetimes

The lifetimes of 118 individual facular granules have been determined by a method similar to that used in determining the lifetimes of other fine structures in the photosphere (see, for example, Bray and Loughhead 1958*b*). The granules selected for study were well distributed over the entire facular region, at distances from the limb ranging from 4 to 70 sec of arc. Most of the granules were members of clusters; some, however, were isolated ones. Two of the features selected—which appeared to be facular granules—were located in the penumbra of one of the associated sunspots; however, in the course of time they elongated and then merged together to form a bridge across the penumbra, so their identification as facular granules is uncertain.

In comparing maps of the facular region made from photographs taken some hours apart, some allowance must be made for the effect of solar rotation. Not only does the distance of a given facular granule from the (east) limb increase but, in addition, foreshortening causes faculae at different distances from the limb to move at different apparent rates (cf. Plate 1). However, this effect did not lead to any difficulty in following individual granules from photograph

FACULAR GRANULE LIFETIMES



Sequence illustrating stability of individual facular granules in a small region near the east limb over a period of $5\frac{1}{2}$ hr. There are some changes due to the growth of new granules, but two granules situated in the lower corners of the photographs persist throughout the sequence. The apparent increase in the separation of these granules is due to solar rotation, the heliocentric angle of the centre of the region changing from 78° at $10^{h}\,0^{m}$ to 75° at $3^{h}\,28^{m}$.

to photograph. Nevertheless, in many cases it was not possible to specify the exact times of beginning and end of a given granule ; one reason is the somewhat irregular spacing of the photographs in the sequence. In addition, the identification of a granule on maps corresponding to photographs taken several hours apart is sometimes made difficult by the growth and decay of neighbouring granules. Only in 38 out of 118 cases was it established with certainty that the granule in question both began and ended during the $5\frac{1}{2}$ hr sequence. Consequently, the values obtained represent *lower limits* to the true lifetimes.

The analysis shows that the majority of the facular granules are very long-lived compared with the photospheric granules: 81% had lifetimes exceeding 1 hr, 53% exceeding 2 hr, 27% exceeding 3 hr, 25% exceeding 4 hr, and 10% exceeding 5 hr.* These figures confirm Waldmeier's conclusion that the majority of the facular granules last for at least 2 hr.

TABLE 1

LIFETIMES OF SUNSPOT AND PHOTOSPHERIC FINE STRUCTURES

Feature	Lifetime	Reference
Facular granules	2 hr	Waldmeier (1940)
	2 hr	Bray and Loughhead (this paper)
Penumbral filaments ..	~2 hr	Bray and Loughhead (1958*a*)
Umbral granules*	15–30 min	Bray and Loughhead (1959)
		Loughhead and Bray (1960*a*)
Photospheric granules ..	7–8 min	Macris (1953)
	~10 min	Bray and Loughhead (1958*b*)
	10 min	Rösch and Hugon (1959)

* Some umbral granules are much longer lived: 10% last for more than 2 hr.

No significant tendency has been found for short-lived granules, on the one hand, or long-lived granules, on the other, to cluster together. Isolated facular granules have lifetimes similar to those of members of clusters.

Plate 1 illustrates the stability of the facular granules in a small selected region over a period of $5\frac{1}{2}$ hr. Although there are some changes due to the growth of new granules, two granules persist over the entire sequence ; these are located in the lower corners of the photographs. The apparent increase in the separation of these granules is a consequence of solar rotation (see above). The region is nearer the limb at the start of the sequence.

Reliable determinations have now been made of the lifetimes of all the basic photospheric and sunspot fine structures, namely, the photospheric and facular granules, sunspot penumbra filaments, and sunspot umbra granules.

* The apparent deficiency in the number of granules lasting between 3 and 4 hr is due to a gap of $1^h\ 17^m$ between two neighbouring photographs occurring $2^h\ 55^m$ and $4^h\ 12^m$ after the beginning of the sequence. If there had been another good photograph during this interval, some of the 15 granules recorded as having a lifetime of just less than 3 hr would probably have been recorded as persisting for over 3 hr, thus smoothing the distribution curve.

These data are summarized in Table 1. It is evident that the facular granules, in common with the fine structure of sunspots, are much longer lived than the photospheric granules.

IV. Changes in the Facular Granules

In the case of the photospheric granulation, it was possible to make a systematic study of changes in the brightness, size, and shape of individual granules during their observed lifetimes (Bray and Loughhead 1958*b*). However, this is not possible for the facular granules. In the first place, since the facular granules are close to the limb, their apparent sizes and shapes depend on the degree of foreshortening which, because of solar rotation, changes during the life of a granule. Secondly, any intrinsic variations in the brightness of a granule are masked by changes due to its varying heliocentric angle. The most that can be said is that no systematic changes in brightness have been established; faint granules appear to remain faint throughout their lifetimes and, similarly, bright granules appear to remain bright.

On the other hand, some information has been obtained about the process of growth and decay of individual granules. In nine cases the spacing and quality of the photographs were such that the process of formation could be studied in detail; from these it appears that a granule develops quite suddenly in a region of hitherto normal photospheric brightness, being preceded—at least occasionally—by a patch of diffuse material of intermediate brightness some 3–4 sec of arc in diameter. The transition from a region of normal photospheric brightness to a recognizable facular granule takes place in a period short compared with the average lifetime. Twelve cases of well-defined deaths have been studied; a facular granule appears to lose its identity either by fading and being replaced by material of photospheric brightness, or by coalescing with another granule. The final fading takes place in a time short compared with the lifetime. In two cases an interesting variant was noticed: the original granule disappeared and was replaced by two facular granules on either side of its former position. These in turn were quickly replaced by ordinary photospheric material.

V. Discussion

Apart from their greater brightness, the facular granules differ from the photospheric granules in at least two important respects. Firstly, in most cases the facular granules are not sufficiently compacted to form a well-defined cellular pattern. Secondly, their lifetimes are an order of magnitude greater than those of the photospheric granules. Hence, in spite of a superficial resemblance, it is likely that the two types of granules owe their origins to different physical mechanisms. It is not yet known how the physical conditions within a facular granule differ from those of its surroundings; it is not safe to assume, for example, that the observed enhanced emission of a facular granule is due solely to a temperature excess over its surroundings.

As ten Bruggencate (1940) has pointed out, a remarkable feature of the facular granules is the extraordinary stability shown by the individual granule: a single granule, only 750–1500 km in diameter, can persist as an isolated structure—in some cases well removed from sunspots and neighbouring faculae—for a period of several hours. It is tempting to speculate that both the enhanced emission and the stability are due in some way to the influence of the magnetic field pervading the facular region. If so, the observations imply that the influence of the field is concentrated within regions no larger—and possibly much smaller—than a single facular granule.

VI. Acknowledgments

The authors wish to thank Dr. C. H. B. Priestley, of the C.S.I.R.O. Division of Meteorological Physics, for correspondence concerning the interpretation of the intermittency in the solar seeing. The benefit of discussions of this paper with Dr. R. G. Giovanelli is gratefully acknowledged. The conversion of the 5-in. photoheliograph to seeing monitor control was carried out in collaboration with Mr. D. G. Norton, to whom we are also indebted for assistance in securing the observations. We are grateful to Mr. H. R. Gillett for processing the films and making the enlargements.

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Appendix I

*Triggering of Exposures at Moments of Best Seeing**

The principle of operation of the seeing monitor (Bray, Loughhead, and Norton 1959) is described in Section II. Figure 1 explains how the " seeing signal " is made to trigger the exposures. The vacuum-tube voltmeter is set to indicate the peak-to-peak voltage of the fluctuating signal from the amplifier-adder unit, averaged over a period comparable with the time constant of the meter. This voltage is a direct measure of the quality of the seeing on a quantitative (though arbitrary) scale. Its value fluctuates between wide limits; on the high side, very poor seeing values of 10 V or more do occur, but are fairly exceptional; on the low side, seeing better than 0·3 V has not yet been observed.

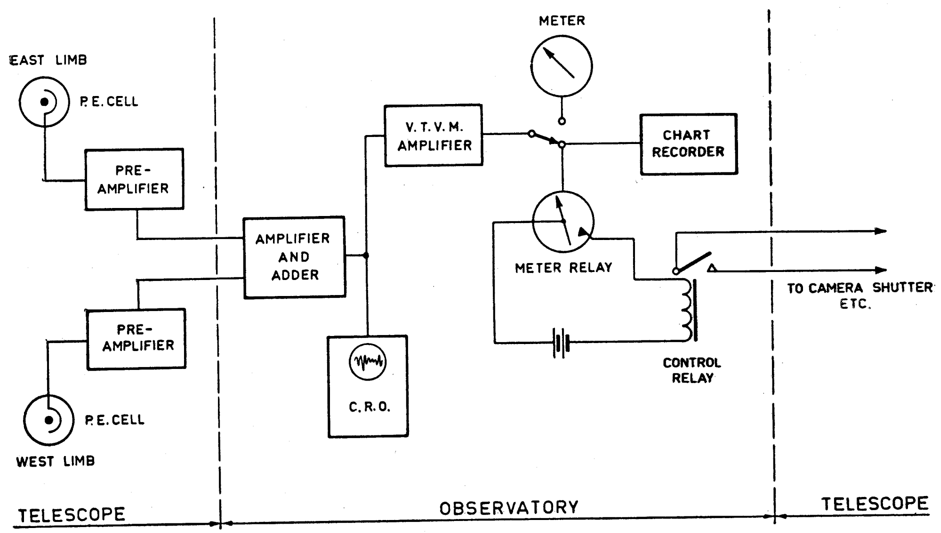

Fig. 1.—Block diagram of seeing monitor and telescope triggering system. The seeing signal from the vacuum-tube voltmeter is fed to a sensitive meter relay, whose pointer carries a contact at its lower end. This contact can close with a second contact attached to the case of the instrument. The latter can be manually adjusted so that the contacts close when the seeing signal falls to some predetermined value. This in turn closes a control relay which operates the shutters. Simultaneous tracings of the seeing signal can be obtained with a chart recorder.

There is a good correlation between the measured peak-to-peak voltage of the seeing signal and the quality of the solar image. For the purpose of obtaining direct photographs showing 1 sec of arc detail, the seeing does not become " promising " until the signal drops to 0·8 V or below. The limb of the solar image on the seeing monitor box then appears sharp and well defined, and a fairly close visual inspection is required to detect any waviness.

The actual triggering of the telescope shutters is carried out by a meter relay, which can be connected to the output of the vacuum-tube voltmeter (cf. Fig. 1). The meter relay is of the sensitive moving coil type and has a

* This work was carried out jointly with Mr. D. G. Norton.

full-scale deflection corresponding to a peak-to-peak voltage at the input to the V.T.V.M. of 4 V. The lower end of the meter pointer carries a contact, which can close with a second contact attached to the case of the instrument. The second contact can be manually adjusted so that the contacts close at any predetermined value of the seeing signal voltage. An exposure is made within a small fraction of a second of the contacts closing. Should the seeing remain at the chosen level, or even improve, exposures continue automatically at the rate of one every 2–3 s (the time required for the camera to wind on).

On a day of generally good seeing there are typically between 50 and 200 occasions when the seeing signal drops to 0·8 V or below. Such periods usually last for a few seconds, only occasionally for as long as a minute. When a quiet period occurs the seeing signal declines with great rapidity (e.g. it may drop from, say, 5 V to only 0·5 V in a few seconds or even in less than a second) and afterwards increases to a more average value equally quickly. On the occasions when the seeing signal falls much below 0·8 V, a fair percentage of the photographs obtained show the full theoretical performance of the 5-in. objective. Under normal observing conditions the triggering level is usually set at this value. However, should a period of exceptionally fine seeing occur, the triggering level is manually reset to a lower value in order to avoid film wastage.

Dr. C. H. B. Priestley, of the C.S.I.R.O. Division of Meteorological Physics, Melbourne, has suggested (personal communication) that the intermittency in the solar seeing described above may be correlated with a similar intermittency characteristic of the temperature fluctuations in the boundary layer of the atmosphere (the first few hundred feet). The temperature traces show alternating disturbed and quiet periods (Priestley 1959 : cf. Fig. 19), the intermittency being most marked on days of light wind ; during the disturbed periods the temperature fluctuations are of the order of 1 °C, whereas during the quiet periods any residual fluctuations still present seem to be less than 0·1 °C. The quiet periods can persist from several seconds to a minute, lasting on the average somewhat longer than the moments of good seeing described above. Simultaneous velocity measurements have shown that the disturbed periods are associated with ascending air and the quiet periods with descending air. Priestley has interpreted the meteorological data as implying the existence of a regime of *convective plumes* (i.e. ascending columns of heated air) in the boundary layer of the Earth's atmosphere. There seems little doubt that the sudden moments of good seeing occur when the line-of-sight from the telescope momentarily passes through the regions of nearly uniform temperature surrounding the plumes. If this explanation is correct it implies that the quality of solar seeing is largely determined by temperature inhomogeneities in the boundary layer. This conclusion is entirely consistent with the well-known fact that temperature inhomogeneities close to a telescope (within a few hundred feet) have a marked effect both on image motion and image degradation (cf., for example, Hosfeld 1954 ; Gifford, Johnson, and Wilson 1955 ; Rösch 1956 ; Smith, Saunders, and Vatsia 1957 ; Elsässer and Siedentopf 1959 ; Elsässer 1960).