OBSERVATIONS OF CHANGES IN THE PHOTOSPHERIC GRANULES

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Summary

Using a sequence of 29 good-quality photographs extending over a period of 10 min, an attempt is made to detect changes in the brightness, size, and shape of individual granules. Of the 125 granules for which there is sufficient data, 57 per cent. show no detectable change during their observed periods of persistence, an additional 14 per cent. showing only minor changes of shape. Although there is some tendency among granules showing change for size increases to predominate over decreases, brightness increases and decreases occur with equal frequency. There is no correlation between the two types of change, nor is there any tendency for brightness or size variations to occur during any particular part of the life cycle. Observations with higher resolving power are required to elucidate the changes occurring during the formation and dissolution of individual granules.

In agreement with Macris, earlier estimates of the lifetimes of the granules are found to be too low. It seems likely that the true value for the most probable lifetime exceeds 7–8 min.

I. Introduction

Although the question of the mean lifetime of the photospheric granulation pattern has been investigated by a number of workers (for references see Macris 1953 ; Waldmeier 1955), no attempts have hitherto been made to detect changes in the brightness and size of the individual granules during their lifetimes, or to observe the details of their modes of formation and dissolution. Such observations, however, could give valuable information about the physical processes responsible for the granulation.

The reason for the lack of observations is the difficulty of photographing detail of the order of 1 sec of arc under conditions of day-time seeing. Moreover, while a few isolated photographs of moderate quality may suffice for estimating the mean lifetime of the pattern, a sequence of high-quality photographs extending over a period of at least 10 min is required if possible changes in the individual granules are to be detected.

In recent times the problem has been revolutionized by the application of time-lapse cinematography, and high-quality sequences of the granulation have been obtained by Lyot (in 1943) at the Pic-du-Midi (Macris 1953), by Blackwell, Dewhirst, and Dollfus (1957*a*, 1957*b*) from a manned balloon, and by Schwarzschild and his co-workers from a high-altitude unmanned balloon (Rogerson 1958). The results of the analyses of the balloon observations are awaited with interest.

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In the present paper an account is given of an attempt to detect changes in the brightness, size, and shape of the individual granules during the periods over which they were observed to persist. The photographs have been selected from a 10 min sequence obtained with a ground-level photoheliograph specifically designed for high-resolution photography. They are of sufficient quality to enable the granules to be classified according to brightness, size, and shape. It is found that the majority of the granules undergo no detectable change over the periods during which they were observed to persist. Although there is some tendency among granules showing change for size increases to predominate over decreases, brightness increases and decreases occur with equal frequency; there is no correlation between brightness and size variations. Finally, in agreement with Macris's results, the granules are found to remain identifiable over periods much greater than earlier estimates of their lifetimes would indicate.

II. Observations

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 diameter of the solar image is 20 cm and the effective wavelength 5400 Å. At this wavelength the theoretical limit of resolution is $0 \cdot 8$ sec of arc.

The present work is based on a sequence of the granulation in the neighbourhood of a spot group near the centre of the disk ($\cos \theta = 0 \cdot 9$) photographed during the afternoon of February 4, 1958. The sequence contains 29 photographs of good but variable quality well distributed over a period of 10 min 21 sec. A portion of one of these photographs is reproduced in Plate 1. It will be noticed that the fundamental elements in the granulation pattern appear to be the bright ones, the dark material separating the bright areas being of no particular size or shape (cf. de Jager 1955; Leighton 1957). In this paper the term "granule" refers to the bright elements.

It is also apparent from Plate 1 that there is a considerable diversity in the brightness, size, and shape of individual granules. It might be argued that this diversity is illusory, being due simply to chance differences in the effect of atmospheric seeing on different regions of the photograph. However, while such differences do indeed occur, the fact that the diversity is real is readily shown by comparing the appearance of individual granules on several photographs taken within a minute, a period very much longer than the duration of any particular distortion due to seeing. It is then found that a given granule which on one of the photographs appears, for example, particularly large or perhaps elongated in a certain direction, in general appears similar on adjacent photographs (cf. Figs. 1–8). This fact, which is convincingly demonstrated when a large number of granules are examined on several photographs, shows that the photographs do to some extent reveal the true form and brightness of the granules and do not, as some writers have suggested, merely reproduce the instrumental profile of the telescope and atmosphere.

III. Reduction

The analysis of the enlargements of the 29 photographs (reproduced with normal contrast on such a scale that 1 mm corresponds to 0·6 sec of arc) was carried out in two stages. Firstly, 298 granules were selected from a " key " photograph occurring near the middle of the sequence. Each granule was given a number and its presence or absence on each of the remaining photographs was

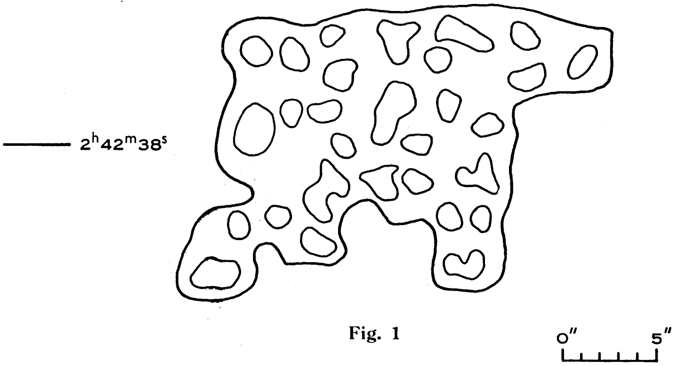

Fig. 1

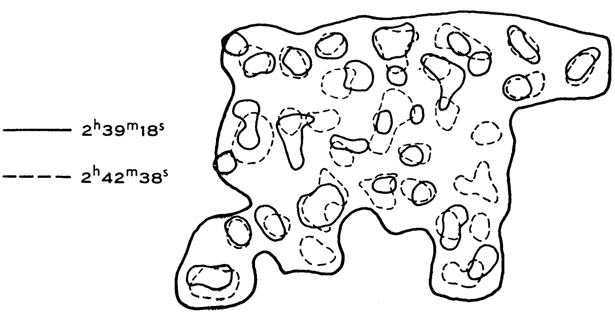

Fig. 2

Fig. 1.—Granulation pattern at $2^h\ 42^m\ 38^s$. This figure is the " key " map for one of the eight selected regions (see text). In Figures 2–8 the pattern at $2^h\ 42^m\ 38^s$ (shown dotted) is compared with the pattern at earlier and later times. The pattern is easy to follow from map to map and it will be noticed that a number of granules persist throughout the sequence—a period of 9 min 6 sec. Despite apparent differences due to seeing, the sizes and shapes of individual granules are fairly well reproduced from figure to figure. For example, note how the elongation of the granule in the top right-hand corner persists from map to map.

recorded. Secondly, the granules were classified on the basis of their appearance at the time of the key photograph, and then an attempt was made to detect changes using good-quality photographs occurring before and after the time of the key.

A very good-quality photograph near the middle of the sequence was chosen as the key. On this photograph the 298 granules are distributed over eight regions selected as being particularly free from the effects of seeing. In order to simplify the problem of identifying the same granules on successive photographs, it was decided to make maps of the granulation pattern in the eight regions on each of the 29 photographs (cf. Bray and Loughhead 1958). All maps were drawn independently, without reference to the key map or to one another. In tracing out the granules care was taken to draw outlines for only those bright features which were surrounded by dark material. No attempt was made to delineate the granules in any area seriously affected by seeing.

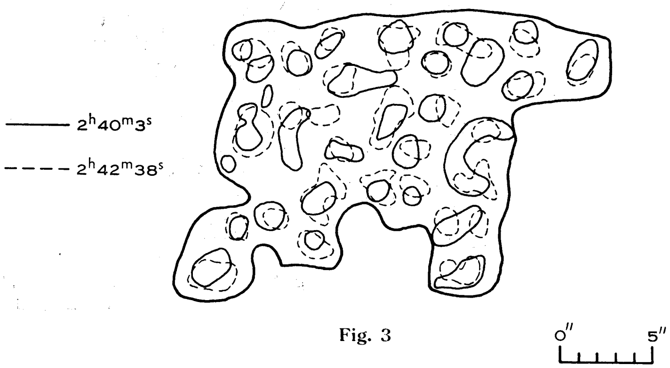

Fig. 3

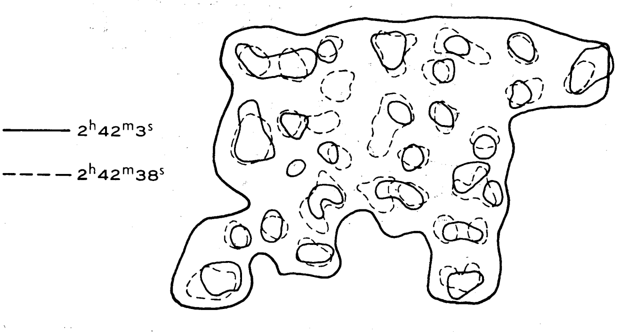

Fig. 4

The outlines of a few small adjacent sunspots were included on each map. The purpose of this was twofold, firstly as an aid in locating the eight selected regions on any given photograph, and secondly as an aid in comparing any given map with the key map. However, owing to small random displacements (~1 sec of arc) due to seeing, the final matching of the two maps could be made only by displacing one of them slightly until the best fit was obtained for the granulation pattern in the neighbourhood of the granules under study. The pattern is in fact quite easy to follow from photograph to photograph (cf. Figs. 1–8), so that the use of the auxiliary spots could have been avoided at the expense of additional labour.

Each of the remaining 28 maps was compared in turn with the key map and the presence or absence at the corresponding time of each of the 298 granules was recorded. A positive identification for a given granule was allowed only if at least 50 per cent. of its area overlapped a granule on the key. In order to allow for the effect of seeing on the apparent size of a granule, or for any possible growth or decay, a positive identification was allowed when the areas were substantially different, provided the granules coincided in position.

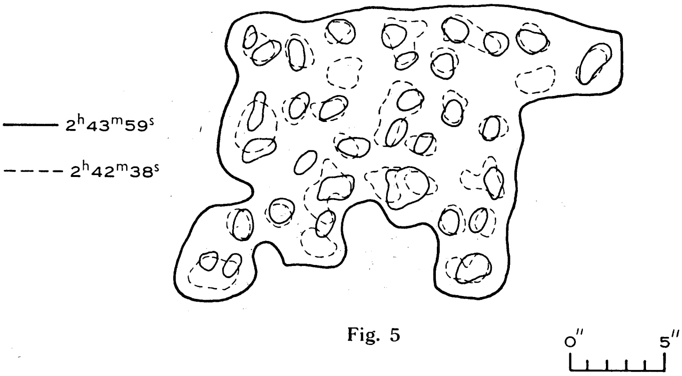

Fig. 5

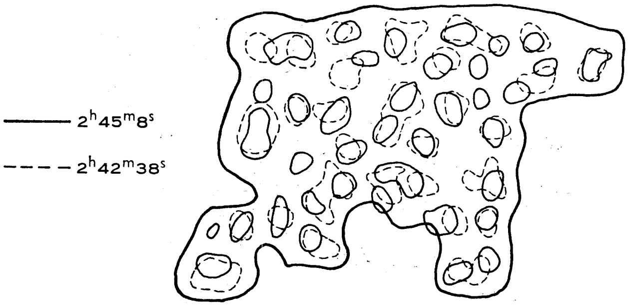

Fig. 6

The above method of procedure is illustrated in Figures 1–8. The key map for one of the eight selected regions is shown in Figure 1 and in Figures 2–4 and 5–8 it is shown compared with maps corresponding to earlier and later times respectively. It will be noticed that a number of the granules persist throughout the sequence—a period of 9 min 6 sec. A discussion of the observed periods of persistence of the granules is given in Appendix I.

The small size of the granules, coupled with the limited resolving power, permits the granules to be described only in a rather crude and qualitative way; even this is only possible on less than one-half of the photographs. In fact, the description of the granules demands photographs much better than those required for mere identification. The classification of the granules was carried out on the basis of brightness, size, and shape. With regard to brightness the categories were restricted to " bright ", " medium ", and " faint ", and with regard to size, to " large ", " average ", and " small ".*

Average-sized granules were classified as either " circular " or " elongated ", whereas large granules were permitted an additional category, namely, " irregular ". No shape classification was made for small granules. The direction of elongation, where applicable, was also recorded.

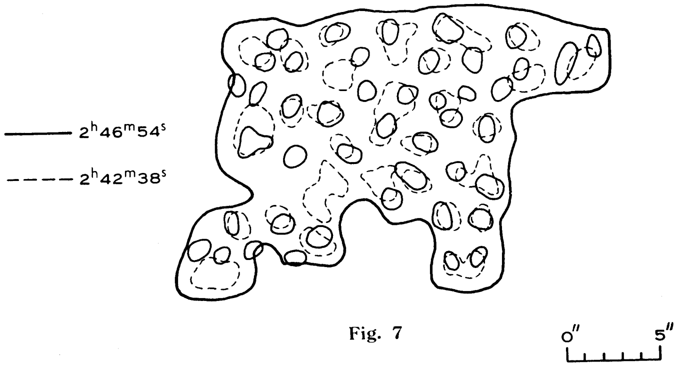

Fig. 7

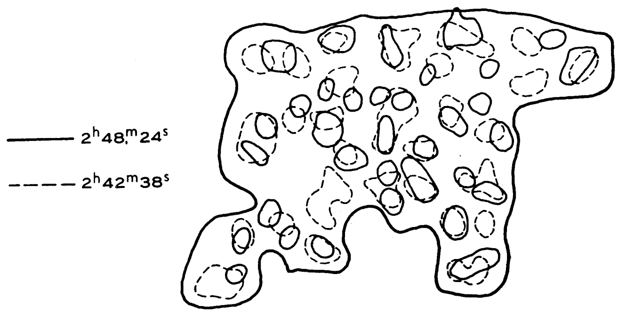

Fig. 8

The granules were initially classified according to their appearance at the time of the key photograph, using as supporting evidence three good photographs occurring within 35 sec. If a given granule either failed to appear on two or more of these photographs, or alternatively was too affected by seeing to be described, it was deleted. This procedure eliminated 158 of the original 298 granules. The remaining 140 were then described according to their appearance on each of a number of other selected photographs occurring before and after the key. This selection, which was varied with the region under study, contained

* The average measured diameters of the granules corresponding to these three classes are 1·8, 1·3, and 1·1 sec of arc respectively. However, these values should be regarded only as rough guides to the true dimensions since they depend to some extent on the contrast of the original negative and the positive print and on the combined instrumental profile of telescope and atmosphere.

on the average seven photographs, the remaining ones being of insufficient quality. On a given photograph, no attempt was made to describe a granule if it appeared to be appreciably affected by seeing.

IV. Results

Table 1 gives the results of the classification of the granules at the time of the key, while Table 2 gives the results of the attempt to detect changes.

Table 1

CLASSIFICATION OF GRANULES*

Brightness	Size			
	Large	Average	Small	Total
Bright	12	23	2	37
Medium	23	50	19	92
Faint	1	6	4	11
Total ..	36	79	25	140

* The classification refers to the time of the key photograph.

Table 2

CHANGES IN GRANULES

Type of Change		No. of Granules
No change		71
Brightness	increase	12
	decrease	12
	increase and decrease*	4
Size	increase	16
	decrease	7
Change of shape		17
Total		125

* These granules showed both an increase and a decrease in brightness during the period of observation.

Considering large and average-sized granules together, Table 1 indicates that bright granules are about one-half as numerous as those of medium brightness and five times as numerous as faint granules. Particularly noteworthy is the almost complete absence of large, faint granules. With regard to small granules, the distribution appears to be quite different, bright granules being very rare and less numerous than faint ones. However, if the true size of these granules is substantially smaller than the resolving limit of the telescope, the photographs would not reveal their true brightness, so this apparent distribution may well be erroneous. Observations with higher resolution may be expected to throw light on this question.

With regard to shape, 63 granules were found to be circular, 36 elongated, and 16 irregular. A considerable proportion are therefore non-circular (cf. Figs. 1–8). No preferred direction was found in the case of elongated granules.

Of the 125 granules for which there were sufficient data, 71 or 57 per cent. showed no detectable changes, an additional 14 per cent. showing only minor changes of shape (Table 2). The average period of observation was $6\frac{3}{4}$ min. Moreover, while there is some tendency among granules showing change for size increases to predominate over decreases, brightness increases and decreases occur with equal frequency. There is no correlation between the two types of change, nor was any tendency found for brightness or size variations to occur during any particular part of the life cycle.

The stability of the granulation pattern over a period of 10 min is illustrated in Plate 2. Although there are apparent differences from one photograph to another due to seeing, several features can be followed without difficulty over almost the entire sequence.

V. Conclusion

The observations show that the majority of the granules last considerably longer than earlier estimates would indicate (see Appendix I) and display little change during their observed periods of persistence. The observations refer only to granules in the neighbourhood of a sunspot group near the centre of the disk ;* it is not known whether the results are applicable to granules in regions remote from spots.

The observations provide little information about the modes of formation and dissolution of individual granules. Only 26 cases of well-defined births or deaths were recorded ; from these the impression was gained that in general a granule develops from a vague patch of diffuse, bright material which originates in a hitherto dark area. These diffuse patches are usually larger than the granules subsequently formed and are very difficult to distinguish from granules smeared by poor seeing. The dissolution of a granule appears to occur by the reverse process, although occasionally a granule loses its identity by coalescing with another granule. However, these remarks are only tentative and observations with much higher resolving power are required to make further progress in elucidating these aspects. Such observations may prove of decisive importance in choosing between rival theories of the mode of origin of the granulation.

VI. Acknowledgment

The authors wish to thank Mr. H. R. Gillett for processing the film and making the enlargements.

* The results refer, of course, to the true photospheric granulation and not to the " facular " granulation, since any faculae surrounding the spots would be transparent at the heliocentric angle of the group ($\cos\theta = 0\cdot 9$).

VII. References

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Appendix I

Remarks on the Lifetimes of the Granules

Using a 22 min sequence of the granulation obtained by Lyot in 1943, Macris has derived values for the lifetimes of the granules considerably in excess of earlier estimates. He finds that the maximum of the lifetime distribution curve occurs for a value of 7–8 min. However, although individual lifetimes as high as 15–16 min were recorded,* the curve is weighted towards values less than 7 min, so that the mean value is 6–7 min.

The results of the present work are in broad agreement with those obtained by Macris and, in particular, indicate that earlier estimates are too low. Table 3

TABLE 3

OBSERVED TIMES OF PERSISTENCE OF GRANULES*

Time (min)	No. of Granules	Time (min)	No. of Granules
$0<t<1$	14	$6\leqslant t<7$	41
$1\leqslant t<2$	3	$7\leqslant t<8$	25
$2\leqslant t<3$	8	$8\leqslant t<9$	47
$3\leqslant t<4$	26	$9\leqslant t<10$	26
$4\leqslant t<5$	19	$t>10$	23
$5\leqslant t<6$	17		
		Total ..	249

* These represent only *lower limits* to the true lifetimes (see text).

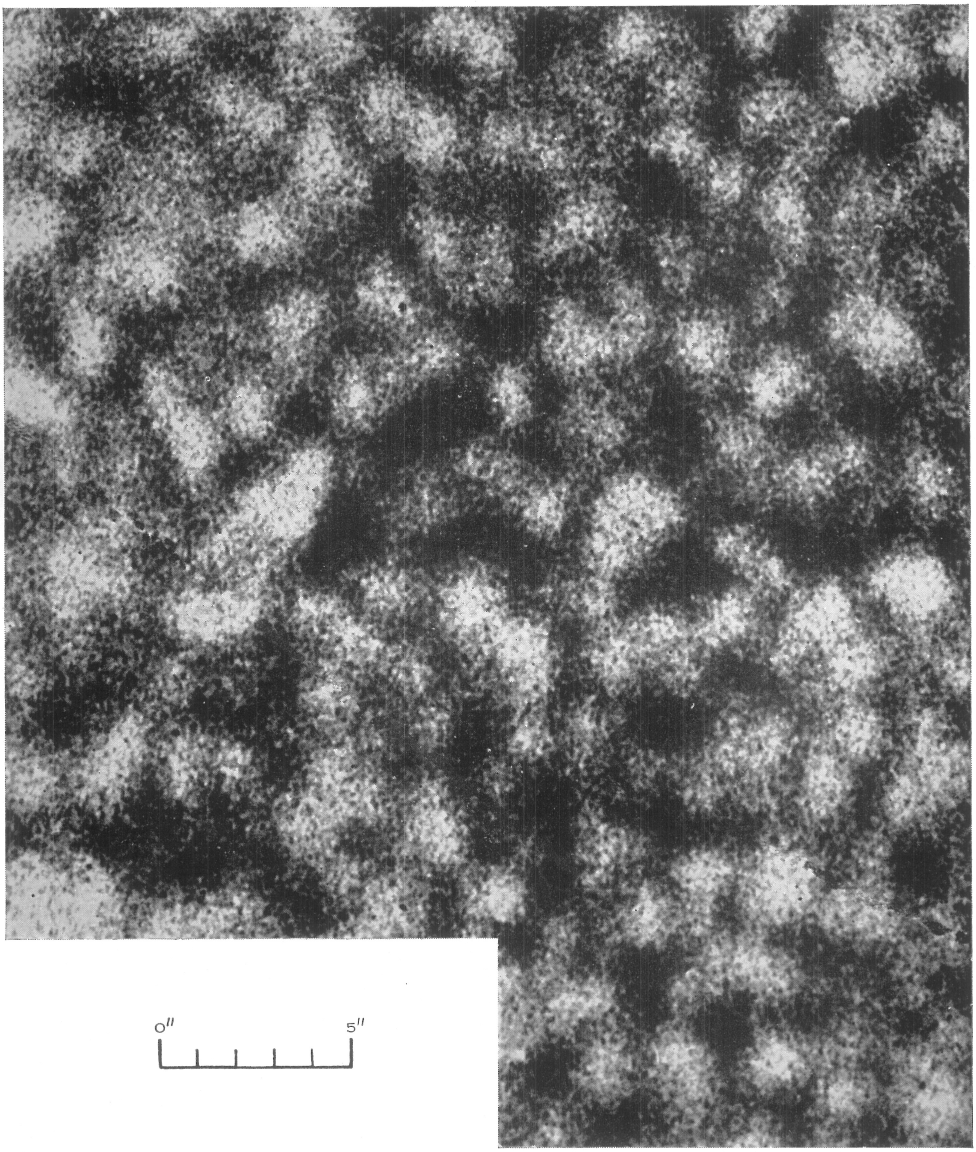
gives the periods during which the individual granules were observed to persist; it is based on measurements of 249 of the original 298 granules. (Forty-nine were rejected on the basis of their non-appearance on two or more of the three photographs occurring within 35 sec of the key.) The reliability of these values can be gauged from the fact that, for those granules which remained identifiable

* Macris finds that long lifetimes occur only for *clumps* of granules and concludes that individual granules have lifetimes of less than 8–9 min. This is not confirmed by the present work.

for 7 min or longer (nearly 50 per cent. of the total), positive identifications were recorded on the average for 20 photographs out of an average possible number of 22.

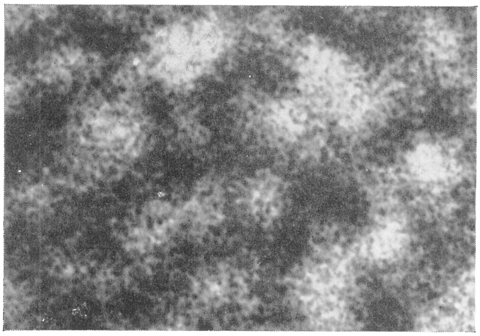
Owing to the relatively short duration of the sequence (10 min 21 sec), the starting and ending times of many of the granules fell outside the period of observation. Consequently the times given in Table 3 represent only *lower limits* to the true lifetimes. Therefore, although Table 3 appears to confirm Macris's value of 7–8 min for the most probable lifetime, it seems likely that a longer sequence (say 20 min or more) of equally good photographs would yield a higher value. Future observations alone can settle this question.

CHANGES IN THE PHOTOSPHERIC GRANULES

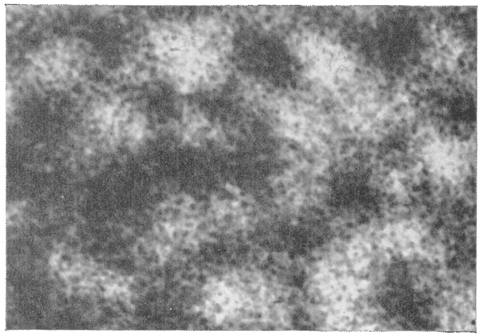


An enlargement from one of the 29 granulation photographs used in the present study. It will be noticed that the fundamental elements in the granulation pattern appear to be the bright ones, the dark material separating the bright areas being of no particular size or shape. There is a considerable diversity in the brightness, size, and shape of individual granules.

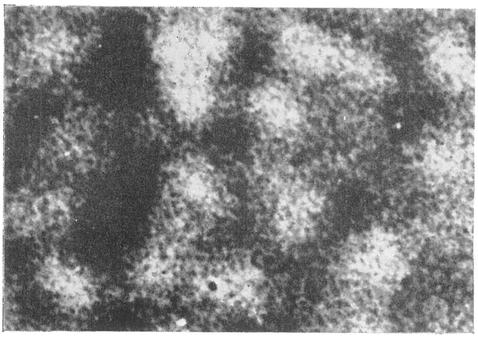
CHANGES IN THE PHOTOSPHERIC GRANULES



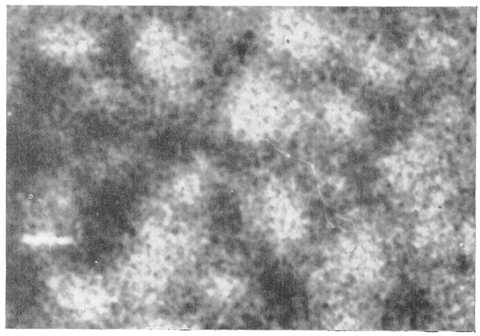
$2^h 38^m 13^s$



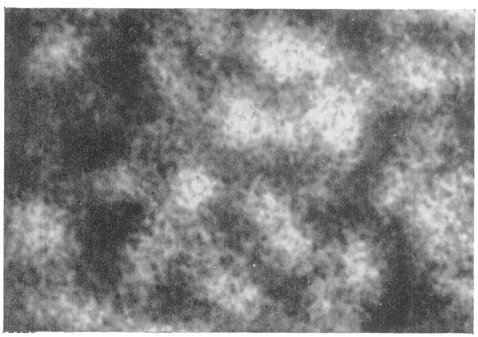
$2^h 39^m 18^s$



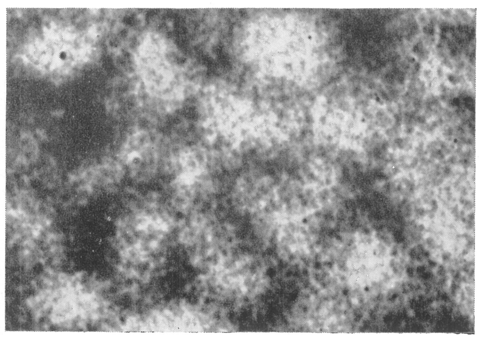
$2^h 42^m 38^s$



$2^h 45^m 33^s$



$2^h 46^m 54^s$



$2^h 48^m 19^s$

$0''$ $5''$

A sequence of photographs showing the stability of the granulation pattern over a period of 10 min 6 sec. Despite apparent changes due to seeing, several features can be followed without difficulty over almost the entire sequence.