THE OBSERVATION OF SOLAR GRANULATION
FROM A MANNED BALLOON

I. OBSERVATIONAL DATA AND MEASUREMENT OF CONTRAST

D. E. Blackwell, D. W. Dewhirst and A. Dollfus

(Received 1959 February 25)

Summary

There appears to be a practical limit to the resolution attainable in solar photography from a ground station. In an attempt to obtain greatly improved resolution, photographs have been made with a 29 cm refracting telescope mounted underneath the nacelle of a manned balloon at a height of 18 000 ft. Two flights were made; during the second flight on 1957 April 1, 480 frames were exposed. Although the ground seeing during the flight was very poor, the photographs taken with the balloon-borne telescope during this second flight are superior to the best that have been secured at any ground station.

The complex structure of the photosphere is illustrated by photographs. Autocorrelation curves for two scans across the best photograph are given. The contrast transmission functions for the complete telescope (objective, eyepiece, photographic emulsion) have been measured using sinusoidal gratings, and the results used to correct microphotometric measurements of contrast. The corrected mean contrast between granules and intergranular regions is 40 per cent at a wave-length of 5300 A.

1. Introduction.—The fine structure of the solar photosphere, known as granulation, has received a great deal of attention during the last hundred years, but progress towards an understanding of its nature has been slow. Observations are greatly hindered by the daytime seeing, which is usually of poor quality: while some of this poor seeing has its origin in the upper atmosphere, much of the trouble is due to local heating near the ground or around the observing slit of a dome. Also, unless the telescope is carefully designed, instrumental imperfections arise, chiefly from the disturbing effects of the large flux of solar radiation through the apparatus. This is especially true of local heating near the prime focus.

In the past, good photographs have been taken by paying particular attention to the design of the telescope and to the selection of an observing site. We should mention here the early pioneering work of Janssen (1) and of Hansky (2). The well-known photograph taken by Janssen on 1885 July 5 has scarcely ever been improved upon, but it is not often mentioned that it has been selected as the best of an extensive collection of photographs taken at Meudon over a period of 20 years with a telescope of only 13·5 cm aperture. Better photographs, taken by Lyot at the Pic du Midi, were investigated by Macris (3); Lyot's techniques have been still further improved by Rösch (4, 5) using a refactor of 25 cm aperture. A smaller telescope, of 13 cm aperture only, has recently been designed and used by Bray, Loughhead and Burgess (6, 7) with good results. Other investigations of solar granulation will be referred to later.
Even under the best observing conditions at a good site the proportion of first-rate photographs has always been disappointingly small. In all of the work described above the theoretical resolution of a 25 cm objective has never been realized. As some of the bad seeing originates close to the ground we may reasonably expect that if photographs could be taken from a balloon at a height of a few thousand feet above the ground, better definition would result. The present experiments using a manned balloon were made to test this supposition and obtain photographs of still higher resolution. More recently, Schwarzschild and Rogerson have taken photographs from an unmanned balloon at heights of up to 80 000 ft (8, 9).

The expected scale of the fine structure is very close to the resolution limit of a telescope of about 25 cm aperture. If quantitative deductions about granulation are to be made from the photographs, the least that we can do is to test the laboratory performance of the telescope and use this information to correct the observed data as well as possible. This also has been done in the present investigation. The photometric measurement of granulation is closely analogous to the investigation of Fraunhofer line profiles with a spectrograph of rather low resolving power. It would be unwise to attempt to measure a line profile knowing almost nothing of the instrumental profile of the spectrograph; and almost as unwise to assume that the instrumental profile is that corresponding to simple diffraction, without aberration or scattering in the photographic emulsion. Similarly, it is unwise to deduce the photometric properties of granulation knowing that the resolution is only just sufficient to show the granulation, but not knowing the precise properties of the telescope.

2. Apparatus.—Two flights have been made. Accounts of the apparatus used on the first flight from the Meudon Observatory on 1956 November 22 have already been published and only a few notes will be given here. The telescope and balloon are described in ref. (10). The telescope was a refractor, with a visual doublet of 29 cm aperture and 294 cm focal length which had been figured by Schaeer. The primary image was projected by an eyepiece of 2·5 cm focal length to give an image of diameter 46 cm in the second focal plane. This final image was photographed on Kodak Microfile Pan film through a Wratten No. 58 filter with a peak transmission of 5300 A and a bandwidth at half-peak transmission of 600 A. The shutter of a Contax camera was placed in the prime focus and set to a speed of $0.8 \times 10^{-3}$ sec. It was later discovered to have given an exposure of about $2 \times 10^{-3}$ sec because of the low temperature at altitude. The telescope was so supported on an altazimuth mounting underneath the balloon basket that it could be directed at the Sun by one of the two observers, whilst the second could control the mechanisms of the telescope (primary shutter, exposing shutter, camera wind, focusing, alteration of shutter speed) electrically from the basket. The automatic mechanism for operating the Contax is described in ref. (11). When the balloon is floating at equilibrium altitude and the observers in the basket are still, the telescope does not oscillate appreciably. The principal effect is an occasional slow rotation about the vertical axis. Under reasonably calm conditions it proved possible to keep the telescope directed at the Sun with an error not exceeding 20′−30′ for a few minutes at a time. On this first flight 390 photographs were taken at heights between 18 000 ft and 20 000 ft, but the photographs of granulation had a sheared structure caused by the movement of the telescope during the unexpectedly long exposure.
On 1957 April 1 a second flight was made from Meudon (12) with similar apparatus, but including a much improved shutter. This publication shows a photograph of the balloon and apparatus. The Contax shutter was replaced by a flying slit shutter of original design which gave a speed of about $2 \times 10^{-4}$ sec. This was sufficiently fast to prevent the appearance of shear on practically every photograph even though the balloon was less stable than during the first flight. An outline drawing of the shutter mechanism is shown in Fig. 1. An essential requirement of the shutter was that it should be as nearly inertia-free as possible, to minimize vibrations transverse to the optical axis of the telescope just at the moment when the photograph is taken. The shutter proper consists of the framework A pivoted and balanced about a horizontal axis and containing in its upper part the adjustable slit, S, which makes the exposure. The slit is set to a width of about 0.4 mm. In operation, we require this slit frame A to be accelerated to the required angular speed and then to be allowed to continue its motion at constant speed whilst the slit which it contains moves across that part of the primary image which is being photographed. At the end of its run it must be stopped positively without any rebound. These operations are performed by the mechanism shown. The spring loaded arm C can rotate freely about the same axis as the slit frame A. The sequence is initiated by the solenoid B which lifts the latch G and so releases the slit frame. The arm C is then accelerated by the spring and carries the slit frame A with it, until the

![Diagram of shutter mechanism](image_url)
slit is just before the area of prime focus to be photographed. Part C is then brought to rest by a cushioned stop, D, but the slit framework A continues in free motion at constant speed until it comes against the stop E. This stop is a small permanent magnet which, attracting a steel shoe on the slit frame A, prevents any rebound.

The shutter is reloaded by a solenoid at F, which pushes the whole shutter framework until it is caught by the latch G. The shutter is enclosed in a light-tight box which contains, however, an entrance aperture which is normally covered by a preliminary shutter. This shutter is moved out of the way by an electromagnet just before each 0.2 millisecond exposure is made.

In flight the speed of the shutter could be changed by altering the tension of the spring by means of the motor-driven wheel H. The speed was measured in the laboratory by illuminating the shutter with a neon lamp fed from a beat frequency oscillator. The light after passing through the shutter then shows a pattern of light and dark stripes, and the speed of the shutter can be calculated from a knowledge of the scale of this pattern and the width of the slit. There is a limit to the increase of speed that can be effected by diminishing the slit width. The reason for this is that during the flight the position of the shutter with respect to the primary focal plane is changed. The change in focus is very difficult to predict theoretically. It depends partly on the known change in refractive index of the air at altitude. But it depends also on thermal changes in the dimensions of the metal framework and the two components of the objective, and the temperature at which these attain thermal equilibrium with their surroundings is uncertain. It proved impossible to predict the position of focus with an accuracy better than ±2 mm. We must evidently be careful that the shutter slit is not displaced so much from the focal plane that the whole of the objective cannot be seen through it at once, and, as the focal ratio of the objective is f/16, the slit must not be less than 0.2 mm in width.

For the second flight a smaller magnification was used, the image diameter being 14.4 cm and the scale 6.7 = 1 mm. During this flight 480 frames were exposed at an altitude of 18,000 ft. For the reasons just explained the position of focus is uncertain and the projection eyepiece was moved through 0.1 mm every ten photographs over a total range of ±2 mm. During both flights a photoelectric photometer was used to estimate the exposure. The film was processed in strips and developed in Kodak D.19b for 5 minutes at a temperature of 70 °F. Photographs of a standardized step wedge, previously made on portions of the same batch of film, were developed with each strip to provide a calibration. The emulsion gave a contrast of γ = 6.1.

3. Measurement of contrast transmission functions of complete apparatus

3.1. Introduction.—The photography of granulation is extremely difficult but the deduction of the photometric properties of granulation from calibrated photographs is even more difficult. Not only are we observing an extended object of low contrast, but we are also working near the resolution limit of a medium-sized objective. In visual tests with an eyepiece on a point object the objective may appear to perform well, showing clear and regular diffraction rings, but a test of this kind does not easily show how much spurious light there is in the outer parts of the image; such spurious light diminishes the contrast in the image of a complex object if the scale of its structure is of the
order of magnitude of the resolution. In all cameras there is the extra complication of scattering in the photographic emulsion and, in our apparatus particularly, the possible additional image defects introduced by an enlarging eyepiece. Although in our apparatus we should not expect these latter effects to be serious it seems desirable that such an optical system should be tested in its entirety on an extended low contrast object which has the same order of angular scale as solar granulation. To effect this we have measured the contrast transmission functions of the complete telescope—objective, eyepiece and photographic emulsion—and applied the results to the interpretation of the photographs.

3.2. The contrast transmission functions.—The contrast transmission function of an optical system, also known as the sine wave response factor, describes its response to various spatial frequencies in the object plane. It is a concept first suggested by Duffieux (13) and developed by Schade (14) and is now used increasingly to describe quantitatively the performance of an optical system in preference to the concept of resolution measured as lines/cm or as the "Rayleigh limit". Analytically, it is the Fourier transform of the distribution of light in the image of a line object. An equivalent definition is that it is the ratio of contrast in the image plane to that in the object plane for each spatial frequency separately. The numerical value of the transmission function varies with spatial frequency, reaching zero at the "cut-off" frequency of the system. The significance of the cut-off frequency is that no greater spatial frequencies are passed by the optical system; if such spatial frequencies exist in the object they are completely suppressed in its image and cannot be restored in any way. At wave-length $\lambda$ the cut-off frequency corresponds to an angular resolution limit of $\lambda/d$ radians, where $d$ is the linear diameter of the objective. If the optical system includes a photographic emulsion, it is necessary to include this as equivalent to an additional component.

3.3. Measurement of the contrast transmission functions.—The measurement of the transmission functions is not easy. It may be done directly by scanning the image of a line object and taking the Fourier transform afterwards, or by arranging a mechanical scanning device which will automatically measure the Fourier transform, as has been done by Ingelstam, Djurle and Sjogren (15). This method has the advantage of measuring the phase as well as the amplitude. Alternatively, an extended test object may be used. For many years a square wave test object has been popular, but although this has the advantage of ease of construction it has the disadvantage of introducing uncertainty in going from the square wave response factor to the sine wave response factor (16). The use of a sinusoidal test object has been developed by Schade; for this work he uses film sound track (17).

In our tests we have used sinusoidal test objects which have been prepared photographically, starting with an accurate transmission grating of spacing 12 lines/mm and of square wave form. This grating has been reduced in size by projecting it with a high quality camera lens and photographing the slightly defocussed image on a Kodak Maximum Resolution plate. For each of several reduction ratios this procedure is repeated using various exposures and different amounts of blurring, and the most suitable test object selected. Suitability is judged by two factors; contrast, or percentage modulation, and purity of waveform. These two characteristics are easily tested by viewing a distant
lamp through the grating; the amplitude of each modulation frequency is then proportional to the integrated brightness of the corresponding spectral order. Using this technique it is relatively easy to produce gratings of at least 170 lines/mm which attain such perfection of waveform that they show no trace of spectra above the first order. The brightness of the first order spectrum relative to the zero order depends upon the depth of modulation; this property provides a useful guide for the rapid selection of gratings suitable for further tests. This spacing of 170 lines/mm is near the cut-off frequency of an f/10 optical system.

The modulation of each grating was measured by scanning in a microphotometer at very slow speed, using a microscope objective of numerical aperture 0.28. Such an objective has a Rayleigh resolution of 1250 lines/mm and may be expected to measure the modulation of a 68 lines/mm grating to within 5 per cent. The modulation used increased with the grating frequency, being of the order of 15 per cent at the lower frequencies and up to 50 per cent at the higher frequencies.

In our tests of the telescope we have been obliged to use a collimator, as a sufficiently distant source would have introduced poor seeing in a long light path near the ground.

The collimator used was a chemically silvered paraboloid of diameter 46 cm and focal length 640 cm. As there is a reduction of image size by a factor $\times 2.3$ it was necessary to use gratings of spacing up to 68 lines/mm only. The figure of the paraboloid was known to be of excellent quality. During the tests careful observations were made of the local seeing and a test was not made until the steadiness of the first diffraction ring of an artificial star source showed that the seeing was sufficiently good. Otherwise the identical optical system of the flight was used and the film was developed under exactly the same conditions as those of the flight film.

3.4. Results of measurements.—The results for the complete telescope are shown in Fig. 2. The curve for an aberration-free system in monochromatic light is also shown (18); the last point on this curve is the calculated cut-off limit of the telescope.

This is the first time that the contrast transmission functions have been measured for a complete photographic telescope. It is clear from the diagram that in spite of the apparently satisfactory results of conventional visual tests made on the objective before the flight, the performance of the whole telescope seems markedly inferior to that of an aberration-free system; the contrast transmission function at a spatial frequency corresponding to $1^\prime$, for example, being only about one-third of its value for an ideal telescope.

Although it is known from visual tests that its resolving power is good, as defined by the Rayleigh criterion, later examination in the light of the measured contrast transmission functions revealed spurious light in the outer parts of the image that had previously been thought unimportant. The only additional optical component is the chemically silvered paraboloid used as a collimator. It has been found by Lyot that such a mirror may form an image of a point object which contains excess light in its outer parts, the effect being ascribed to the variable thickness of the chemically deposited silver coating (19).

We attribute most of the fault to the objective. Other tests suggest that its defects are due partly to a rapid variation of spherical aberration with wave-length.
and partly to disturbances in the wavefront produced by local figuring of the surfaces. Separate tests of the eyepiece show that it is almost free from defects.

![Contrast transmission functions of complete telescope (objective, eyepiece, filter, photographic emulsion) as used on balloon flight (lower curve). The upper curve is the computed curve for an aberration-free optical system of the same size.](image)

4. Preliminary discussion of the appearance of the photographs

4.1. Image quality.—During the flight the focus setting was changed by 0.1 mm after every ten photographs. Two points now arise: first, that the ten photographs taken at the position of "best focus" are not all of equal quality, but one photograph in particular is somewhat superior to the others. Second, there is not a regular deterioration of image quality with change of focus: it sometimes happens that an isolated photograph taken as far as 0.3 mm from the "best focus" is of better quality than some taken nearer to this position. Even 2 mm from true focus there is an occasional photograph that shows a trace of fine structure of the order of size of the granulation. These observations show that the seeing is still not uniformly good even at 18 000 ft.

Whilst the flight was in progress, careful observations of the Sun were made at Meudon, the place of departure, by Mme d'Azambuja: the seeing throughout was of very poor quality. That we have obtained under these conditions photographs which are superior to the best previously secured from the ground confirms the supposition we set out to test, that there is undoubtedly a great improvement to be obtained by observing from a balloon at an altitude of about 18 000 ft.
4.2. **Shapes and dimensions of granules.**—Plate 1 shows enlargements of two parts of a good photograph taken near the centre of the solar disk. The resolution appears to be about 0''.5; it is clearly greater than the mean size of the granules so that the granules appear little altered in reproduction. The photograph clearly shows the individuality of each granule. Their mean size is about 1''.4. Few granules are larger than 2'' and few are smaller than 0''.8. When examined individually, the granules show a much less regular structure than that suggested by previous photographs. The granules are rarely circular. Their shape is often polygonal, elongated, or complex: many of them, but not all, are of uniform brightness with sharply defined edges.

4.3. **Large-scale variations of structure.**—The two photographs of Plate 2 are of regions where the granular structure is particularly irregular. Further comments are given in the legend.

4.4. **Associations of granules.**—It turns out that some granules are not completely separated but touch, or merge into each other, forming amorphous groups of greater size. In associations they can delineate complex shapes. Plate 3 (first row) gives three examples; left, the grouping of the granules traces a ring; middle, a crescent; right, a complex filament.

4.5. **Intergranular regions.**—The darker material between the granules is not of constant brightness. In some places granules seem to be missing, their place being taken by small areas whose material is generally darker than the neighbouring intergranular space. These are the "poles". Plate 3 (second row) shows three examples of such formations.

4.6. **Striations.**—Curious alignments of the structure are sometimes revealed; the granules are drawn out in lines, isolated or in parallel arrangements over a distance of as much as 45''. These linear arrangements may be evident either in the granules themselves or in the dark intergranular material. Plate 3 (bottom) shows an example, and they may also be seen in parts of Plate 1 (top photograph). Similar structures which have been seen previously on other photographs have been interpreted as effects of atmospheric turbulence. Our photographs seem to confirm that these striae, although rather rare, are probably real.

4.7. **Isophotometric contours.**—We have drawn curves of equal intensity for different values of brightness, using the isophotometer of the Sacramento Peak Observatory, New Mexico, placed at our disposal by the Director, Dr J. Evans.

Three areas have been selected each of size 15'' x 20'' and are shown on Plate 4. In each of these areas five tracings have been made corresponding to five equal steps of brightness. The left column is a region of normal granulation. The region in the centre column contains a dark "pore" on the left and a particularly bright granule at the bottom. The right-hand column is selected from one of the regions referred to above which is darker and contains only granules smaller than the mean diameter.

Examination of the isophotes confirms the complexity and irregularity of the granules. As an example the photograph at the top left shows a particularly large granule right of centre. The isophotes in the bottom two photographs show its complex outline and its internal structure of three nuclei.

5. **Measurement of autocorrelation functions of brightness.**—We wish to obtain finally the power spectrum of the granulation. To derive this we have first measured the one-dimensional brightness distribution by scanning across
the negative with a very small spot of light. The scans were each made along
a length of 24 mm with a square spot of 0.02 mm side (\( \equiv 0.14 \)), using a recording
microphotometer. The resulting traces were measured at intervals of 0.021 mm
\( (\equiv 0.142) \). This value is within the interval required by the sampling theorem
(20), which for a cut-off of \( 0.37 \) demands an interval not greater than \( 0.18 \)
for the complete description of the microphotometer curve. With the Cambridge
electronic computer (EDSAC II) the 1100 readings from each scan were
converted into intensities using the calibration curve of the emulsion, and the
autocorrelation function found for a shift of up to 100 measures, or 14". If
the \( N \) successive brightness values are \( I_1, I_2 \ldots I_n \), the autocorrelation function
\( \phi(j) \) for a shift \( j \) is defined as

\[
\phi(j) = \frac{\sum_{k=N-j}^{N} (I_k - M)(I_{k+j} - M)}{\sum_{k=1}^{N-j} (I_k - M)^2}
\]

where \( M \) is the mean brightness defined as

\[
M = \frac{\sum_{k=1}^{N} I_k}{N}.
\]

In all, six scans were made across different parts of the best negative (frame 221).
The autocorrelation functions for each scan have been computed, and two of
them are shown in Fig. 3 (a) and (b), plotted as a function of angular distance
on the Sun. These curves show an initially steep descent followed by small
fluctuations about the values \( \phi = 0.2 \) to 0.3. Part of the long period fluctuation
is probably instrumental in origin, but the fluctuations do not repeat from one
scan to another and so are chiefly of a random nature. We emphasize that we
have not used a moving average to eliminate the effects of slow changes of
brightness across the photograph, real or spurious; had we done so the
autocorrelation functions would have diminished to zero.

The "half-width" of the initial descent is a measure of the resolution of
the photograph. The half-widths of the curves shown in Fig. 3 are \( 0.50 \)
and \( 0.72 \). The half-width of the autocorrelation curves for the other four
scans are \( 0.75, 0.79, 0.79 \) and \( 0.97 \). These results show that the average
quality varies considerably over the area of the photograph. The best definition
is along the line of scan of Fig. 3 (a) (half-width \( 0.50 \) ) but this autocorrelation
function curve is a measure only of the average definition along this line. As
the measurements were made with a small spot no appreciable contribution
to these curves from photographic grain may be expected. Were there a
contribution from grain a peak at the origin of the autocorrelation curve would
be expected. Such a peak cannot be discerned on these curves.

Autocorrelation functions have been published by other investigators.
Wlérick (21) has studied a photograph taken by W. A. Miller at the R.C.A.
Laboratories with an 11.3 cm objective. The half-width of Wlérick's curve
is \( 1.23 \). One photograph taken at Mount Wilson, "of exceptionally fine
definition", has been analysed by Frenkel and Schwarzschild (22). This
photograph was taken with the 60 ft solar tower diaphragmed to 10 cm aperture,
the effective wave-length being 5800 A. The half-width of their curve is \( 0.91 \),
Fig. 3.—Autocorrelation functions computed from two scans across the best negative.
but as the calculated cut-off of the telescope is 1\textquoteleft.11, it seems likely that much of the first part of their autocorrelation curve is instrumental in origin. Uberoi (23, 24) has also analysed a high quality Mount Wilson photograph. This photograph, taken with the same 10 cm aperture and also at a wave-length of 5800 A, yields an autocorrelation curve of half-width 0\textquoteleft.76. For the same reason, much of this curve is instrumental in origin, as the author shows.

The significance of the autocorrelation curve found in this investigation will be discussed in a later paper.

6. Measurement of contrast

6.1. Introduction.—In the measurement of contrast a large instrumental correction is inevitable. Even if the optical system is free from aberration the correction is a considerable one, while aberrations too small to be noticed in ordinary visual tests will increase the correction greatly. In the absence of information about the optical quality of a telescope and the photographic emulsion the magnitude of the correction is very uncertain. The method usually used to obtain the correction is that of Wanders (25) which involves scanning radially across the limb. This must be done on separate photographs taken with longer exposures and almost inevitably gives erroneous results. In addition, the curve given in Fig. 2 for an ideal telescope shows that a great loss of contrast may be expected at frequencies near the cut-off. Probably all the observations made so far have been undercorrected.

6.2. Previous observations.—Two quantities characterize the brightness properties of the granular structure. One is the root mean square brightness variation, and the other is the mean contrast between granular and inter-granular regions. In Table I we list previous determinations of these quantities. In the last two columns the upper figure for each determination is the uncorrected direct measurement, and the lower figure, in brackets, is the value as corrected for instrumental effects by the individual investigators.

We may reconsider these data in the light of the known contrast transmission functions for an ideal telescope, assuming a correction appropriate to the mean granule size. This would appear to be a minimum correction if only because no allowance has been made for the smaller transmission function corresponding to the first harmonic, which may be supposed to exist if there is light–dark asymmetry in granulation. The correction to the observed contrast must be at least that indicated for an ideal telescope and in practice will be larger by an unknown amount which depends upon the properties of the instrument and the seeing.

As an example, we take the observations of Keenan. In obtaining his correction he assumed a mean granule size of 1\textquoteleft.1. But the transfer function for an aberration-free objective of this size is only 0.37. This means that the correction must be at least a factor of 1.27, giving a contrast of at least 28 per cent. The correction may be expected to be considerably bigger than this because of instrumental imperfections and seeing, and especially as Keenan mentions that there are no granules on his photograph smaller than 1\textquoteleft in diameter.

The observations of ten Bruggencate and Müller—a continuation of earlier work (29, 30) with the Potsdam tower telescope—gave a value that is superficially in good agreement with that of Keenan. We have, however, already
Above: A part of the solar surface near the centre of the disk. Dimensions of field 90° × 75°.

Below: Enlargement of field in which the granulation is particularly uniform. Dimensions of field 48° × 40°.

D. E. Blackwell, D. W. Dewhirst and A. Dollfus, Solar granulation observed from a manned balloon
Enlargements of regions in which the granulation is noticeably irregular.

**Top:** In the centre is a region where the granules are particularly bright. To the right a dark region where the granules are of unusually low contrast.

**Bottom:** At the top right a region where the granules are small; on the left, dark spots and "pores".

*Each field has dimensions 50" × 40".*

D. E. Blackwell, D. W. Dewhirst and A. Dollfus, Solar granulation observed from a manned balloon.

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System
Top row: Examples of granules of complex shapes.
Second row: Examples of small dark areas and "pores".
Third row: Left, a region of high contrast.
Centre, a region of normal contrast.
Right, a region of low contrast.
Bottom: Example of structures aligned in parallel streaks.
(All the same scale; dimension of the squares: $12'' \times 12''$.)

D. E. Blackwell, D. W. Dewhirst and A. Dollfus, Solar granulation observed from a manned balloon.
Contours of lines of equal brightness for three regions. The isophotes correspond to equal increments of brightness.

Left column: Normal region.
Centre column: Region containing a small dark area (on the left) and a particularly bright granule (at the bottom).
Right column: A region with unusually small granules.
Dimensions of each field: 20° × 15°.

D. E. Blackwell, D. W. Dewhirst and A. Dollfus, Solar granulation observed from a manned balloon.
pointed out that Keenan's value is undercorrected, and in addition the correction for the large wave-length difference is quite unknown.

The Mount Wilson photograph used by Frenkiel and Schwarzschild can tell us little about the contrast of the small scale granulation because the cut-off of the telescope is at 1".1 and even at 1".5 the contrast transmission function of an ideal telescope at 5800 A is only 0.15.

The r.m.s. value of 3.2 per cent obtained by Richardson and Schwarzschild was measured on a spectrogram and no instrumental correction can be estimated because of the possibility, for example, of astigmatism in the grating. The r.m.s. value of 5.4 per cent derived by these authors is for an average element size near 2", and as the contrast transmission function for structure of this size is 0.36 for an aberration-free system, this means that the r.m.s. brightness fluctuation is probably at least 15 per cent.

The contrast given by Leighton is substantially a peak to peak brightness measurement over a scan of length 120".

Thiessen's observations were made visually with the 60 cm refractor of the Hamburg Observatory and his value of contrast agrees well with that found by Waldmeier, who does not, however, give details of the method of observation.

The work of Plaskett (37) gave a total amplitude variation of 8 per cent on his best plates; however, this work refers to brightness variations in a large scale structure with elements about 5" in diameter.

6.3. Present results.—On our photographs, taken with a 29 cm objective at a wave-length of 5300 A, the r.m.s. fluctuation of brightness measured on a microphotometer tracing is 4.6 per cent. Taking an effective transmission function of 0.25 appropriate to a mean granule size of 1".4 (see Section 4.2) we obtain a corrected r.m.s. fluctuation of 18 per cent, without any additional correction for seeing.

The same microphotometer scans show that areas with an observed contrast of up to 7 per cent occur frequently, while a contrast of 9 per cent is not
uncommon (excluding those areas where there are known sunspots or pores). The isophotometer tracings show that the mean contrast between granular and intergranular regions is 11 per cent. This value is slightly higher than that indicated by the microphotometer scans probably because it refers to small regions selected for their good definition, while the microphotometer scans were made at random along the larger dimensions of the photograph. For further discussion we take the observed mean contrast between granule and intergranular space to be 10 per cent. This gives the ratio of mean contrast to r.m.s. brightness fluctuation of 2.2, which seems reasonable. Applying the same correction for a contrast transmission function of 0.25 we get a corrected value of 40 per cent. However, this correcting factor is a lower limit not only because the seeing will reduce the effective contrast transmission function (although because of the nature of our observational material we suppose that any further correction will be small), but also because the effective width of the intergranular regions is probably much less than 1.4.

Our final result of a contrast of 40 per cent is not inconsistent with most of the values previously obtained by other investigators, provided that the observed values quoted in Table I are corrected anew by the larger factors indicated by the discussion in Section 6.2. However, the corrections that we have made to our own observed contrast are minimal. Simply interpreted this contrast implies a difference of temperature between mean granule and mean intergranular space of 520°K.

Acknowledgments

We particularly wish to acknowledge our debt to Professor R. O. Redman, who initiated this investigation and encouraged us throughout. The work was financed chiefly by a Royal Society Government Grant with help from French special funds, the balloon being placed at the disposal of Meudon Observatory by the French Air Ministry. We are especially grateful to M. Charles Dollfus of Paris who gave invaluable help and advice about the aeronautical problems. Dr P. B. Fellgett and Dr E. H. Linfoot gave advice at all times; the former also computed the autocorrelation functions on EDSAC II in the Cambridge University Mathematical Laboratory. We are indebted to Dr W. H. Steavenson who provided part of the optical apparatus, and also to T. I. Aluminium Ltd. who gave the aluminium tubing used in constructing the telescope tube.

The Observatories,
Madingley Road,
Cambridge:
1959 February 24.

References

(2) Hansky, A., Mitt. Pulkovo, x, 81, 1905.
(3) Macris, C., Ann d'Astrophys., x6, 19, 1953.
(6) Bray, R. J. and Loughhead, R. E., The Observatory, 77, 201, 1957.
Solar granulation observed from a manned balloon: I

(13) Duffieux, P. M., L'Intégrale de Fourier et ses applications à l'optique, Rennes 1946.
(20) See, for example, Goldman, S., Information Theory, London, 1953, p. 67.