THE FINE STRUCTURE OF PHOTOSPHERIC SUNSPOTS AND FACULAE

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Abstract: A 30-cm refractor has made it possible to get a 3-hour time sequence of very fine white light photographs of a sunspot, wiht a resolution always approaching 0″3. This photometric reduction of these pictures has displayed the following sketch of the penumbral fine structure: bright grains, nearly as bright as the normal photosphere, generally lined up in the form of filaments, are seen against a dark background, the intensity of which is only 60% of that of the photosphere. These grains have a motion opposite to the Evershed effect, towards the spot centre, with a velocity which is maximum (0.5 km/sec) at the boundary umbra-penumbra. A new 50-cm reflector has been recently put into operation at the Pic du Midi Observatory. This instrument has already given a lot of fine pictures which clearly show the fine structure of penumbras and umbras, in different wavelengths and for different positions of a regular spot on the disk. The fine structure of photosphere faculas near the limb has also been revealed on some high quality pictures. Slides will be presented to illustrate these results.

Introduction

High resolution pictures of the photosphere are quite frequently obtained at the Pic du Midi Observatory. At present this resolution is that of the new 50-cm refractor. Among other studies, the white light fine structure of sunspots is being studied. The first series of sunspot pictures, taken at 5-min intervals over a 3-hour period, had already been obtained on July 5, 1970 with the 30-cm refractor, still used as this time, allowing a morphological and microphotometrical study of the penumbra (Muller, 1973a, b).

More recently, in July 1973, a large, regular and fairly stable sunspot has been photographed at five different positions on the solar disk, with a resolution always approaching the theoretical limit set by the new 50-cm objective. Moreover, the pictures near the limb show the photospheric faculae network. In this paper we present the new results, recently obtained, concerning the fine structure of sunspot penumbras and the latest observations.

Properties of the Fine Structure of a Sunspot Penumbra

Morphological and Kinematic Properties

The penumbra appears to consist of bright grains, generally lined up in the form of filaments, showing up against a dark background. Moreover, one notices that there are some "dark areas"; these have some importance for penumbral photometry, as we shall see later (Fig. 1).

220 grains were individually followed during the 3 hours of the film sequence in order to study their properties (Muller, 1973a).

The bright grains form all over the penumbra. They move towards the umbra. Their horizontal velocity is zero at the penumbra-photosphere boundary (as for the photospheric granules) and maximum at the umbral boundary (0.5 km/sec) (Fig. 2). Therefore, the grains never originate in the photosphere, nor do they enter it.

They disappear in the penumbra proper or, if they form near enough to the umbra and live long enough, they can enter the umbra and their appearance becomes similar to that of umbral dots.

The life time of the grains is a function of their place of origin within the penumbra: it is maximum and of the order of 3 hours or more for those forming in the middle part of the penumbra, and of 50 and 40 min, respectively, for the grains formed in the inner and outer part of the penumbra (Fig. 2).

The Evershed effect in this same spot was measured thanks to the spectra obtained at Oslo on July 8, 1970 (i.e. 3 days later) and kindly lent by P. Maltby; these spectra do not reveal the two Evershed components; therefore, it is an Evershed effect visually averaged which is showed in Figure

Fig. 1. Sunspot, Rome number 5847, photographed on July 5, 1970 with the 38-cm refractor of the Pic du Midi Observatory. A — penumbral dark areas.

3. The radial velocities are quite normal, i.e. directed outward, so that it is opposite to the displacement of the bright grains; furthermore, while the Evershed effect is maximum at the penumbra-photosphere boundary, on the contrary, the velocity of the bright grains displacement is maximum at the umbral boundary. If one tries to restore this averaged Evershed effect, taking into account the penumbral grain motion (which is probably a displacement of material, considering the similarity of the properties of the photospheric granules and the adjoining penumbral grains), it is necessary to consider a motion of the dark material, directed out of the penumbra with a speed of about 3 km/sec at the penumbra-photosphere boundary.

Photometric Properties

The purpose is the determination of the mean actual brightness of the penumbral grains and that of the interfilamentary spaces, the measured brightness being corrected by the spread function.

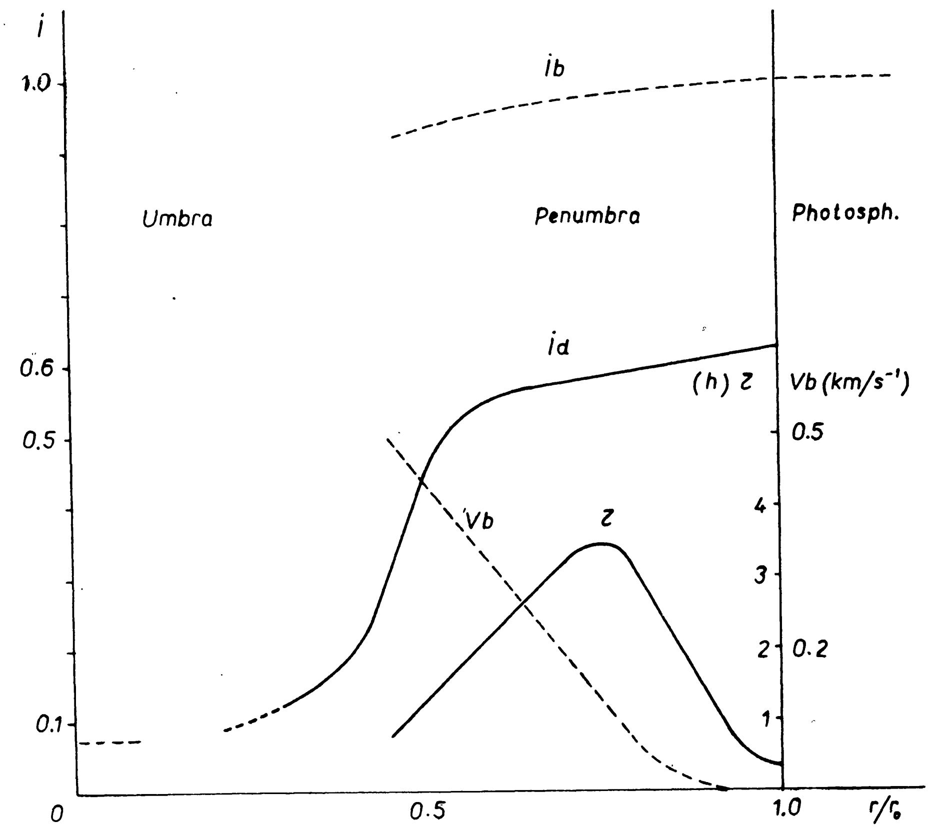


Fig. 2. Penumbral properties. Photometrical profile: *Ib* — intensity of bright grains, *Id* — intensity of dark background, τ and *Vb* — distributions of life-time and speed of the bright grains.

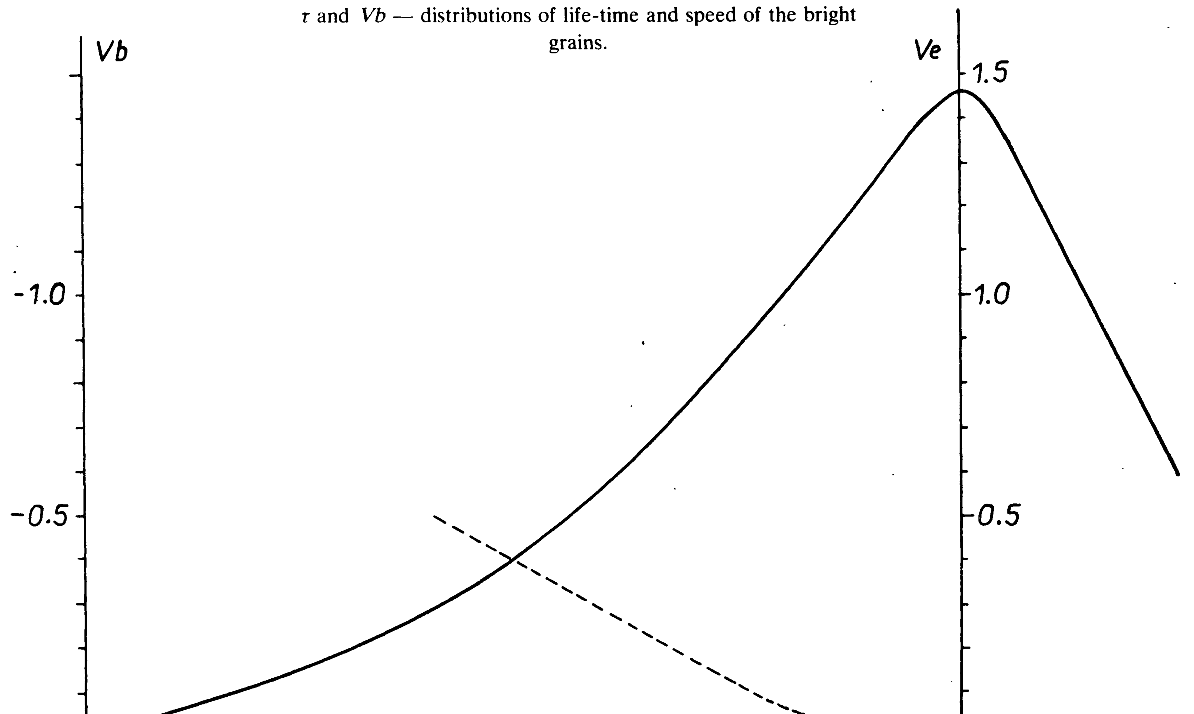


Fig. 3. Comparison between the Evershed effect *Ve* (———) and the displacement of bright grains *Vb* (– – – –) observed through the sunspot penumbra of Figure 1.

1. Method of Correction

We want to know the statistical distributions and mean values of the brightness in the penumbra; for this purpose as in a first step, one corrects the transverse profile going through the maximum of the brightness of several individual grains, by using the iterative method, described by Wittmann (1971), and adapted for our particular case (Muller, 1973b). But the iterations only yield an approximate profile, because the most interesting parts of the curve, having a strong curvature (maxima and adjacent minima), are overcorrected. We adjust then the profile until its convolution product with the spread function fits the observed one.

Of course, this correction function is not exactly known, but it is possible to find a minimum and a maximum correction function which sets the limiting values. These functions have been taken in the following form:

$$\varphi_{(r)} = N[(1-A)\,\mathrm{e}^{-(r/a)^2} + A\,\mathrm{e}^{-(r/b)^2}]\,.$$

For the minimum correction function, φ_m, one chooses the parameters A, a and b, so that the profile of $\varphi_{(r)}$ is the nearest possible to the Airy function.

The maximum correction function, φ maximum, is determined by physical conditions: we assume that the intensity within the sunspot umbra cannot decrease when receding from its centre.

We then apply $\varphi_{(r)}$ to the interfilamentary space which is directly extended by the umbra and we cause the parameters to vary until the profile along the interfilamentary space becomes horizontal. Nevertheless, the parameter a is keeping the value it had in φ minimum, because the resolution is close to the theoretical one of the instrument. For every grain considered, the mean transversal profile between the minimum and maximum corrected profiles obtained will be considered, at present, as the actual one.

In order to give some statistical values, as a second step, we notice that the corrected intensities are proportional to the observed ones. This permits one to determine the corrected brightness of the maxima and minima of a great number of grains profiles, only by the measure of their corresponding observed brightness without making the long computations. We can then give some mean values.

Results — Photometric Properties of the Penumbra

The intensities of the penumbral dark background have been found for the external penumbra 0.60 and for the internal penumbra 0.52. The unity being the intensity of the photosphere.

The intensities in the centre of the dark penumbral areas (Fig. 1), previously reported, with dimensions greater than 1″5, almost unmodified by the correction, confirm these results. The mean function, used for the correction, thus appears to be very close to the true spread function.

The grains with maximum brightnesses in the range of 0.95—1.00 are most frequent in the umbra.

The mean intensity of the bright grains is found for the external penumbra 0.95 and for the internal penumbra 0.90

The grain width is defined as the width at the mean intensity between the maximum and adjacent minima of a profile, and we find: observed width 0″43 and corrected width 0″36, i.e. 260 km.

Moreover, the bright grains cover 43% of the surface of the penumbra.

Conclusion

All these results allow one to present the following picture of the penumbra: it appears to consist of bright grains, lined up in the form of filaments, whose brightness at 5280 Å in close to the photospheric one, and which show up against a dark background of brightness 0.6. The bright grains form all over the penumbra and they move towards the umbra with a speed of up to 0.5 km/sec near the umbra-penumbra boundary; there they disappear, if they have been formed near enough to the umbra and if their life-time, which can reach several hours for those which form around the middle penumbra, is sufficiently long. Figure 2 summarizes all this.

Observations with the New 50-cm Objective

The quality of the observations can still probably be improved by the use of the new 50-cm objective recently put into operation: the optics are better and the proportion of scattered light is greatly reduced.

In the course of the first campaign whit this instrument, a large, regular and fairly stable spot was photographed and a resolution close to the theoretical one of the instrument was reached; good images have been obtained for 5 positions on the solar disk in 3 wavelengths (λ 5280, 5750 and 6300 Å) which will allow us to study particularly the centre-to-limb variation of the interfilamentary contrast in the penumbra. We have already been able to go into the following details.

Width of the Penumbral Filaments

In the case of the spot photographed at the centre of the solar disk (Fig. 4) the observed width of the finest penumbral filaments is 0″39 on the average at 5750 Å. For the 1970 spot, with quite comparable dimensions, it was found equal to 0″42 at 5280 Å. Besides, for the smallest sunspot, these filaments have a mean width of 0″35 at 5750 Å (Fig. 6). So it seems that the resolution has really been improved. And, taking into account the reduction which has been described for the 1970 picture (yielding an actual filament width of 0″35 for an observed width

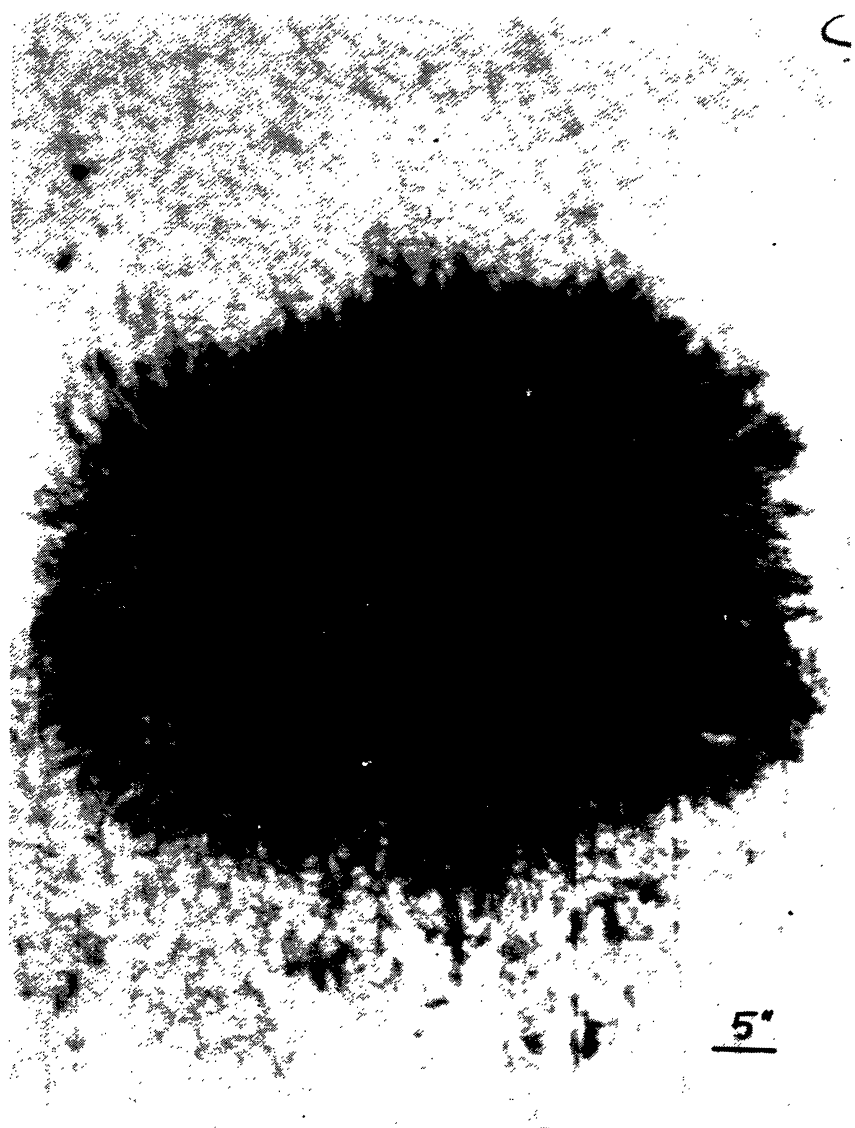
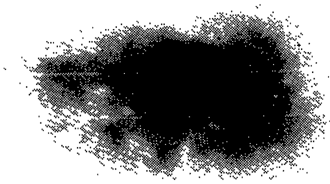


Fig. 4. Sunspot followed in the course of the July 1973 campaign of observations. The spot near the centre of the solar disk, July 3.



a b

Fig. 5a, b. Umbral dots of the July 3 sunspot.

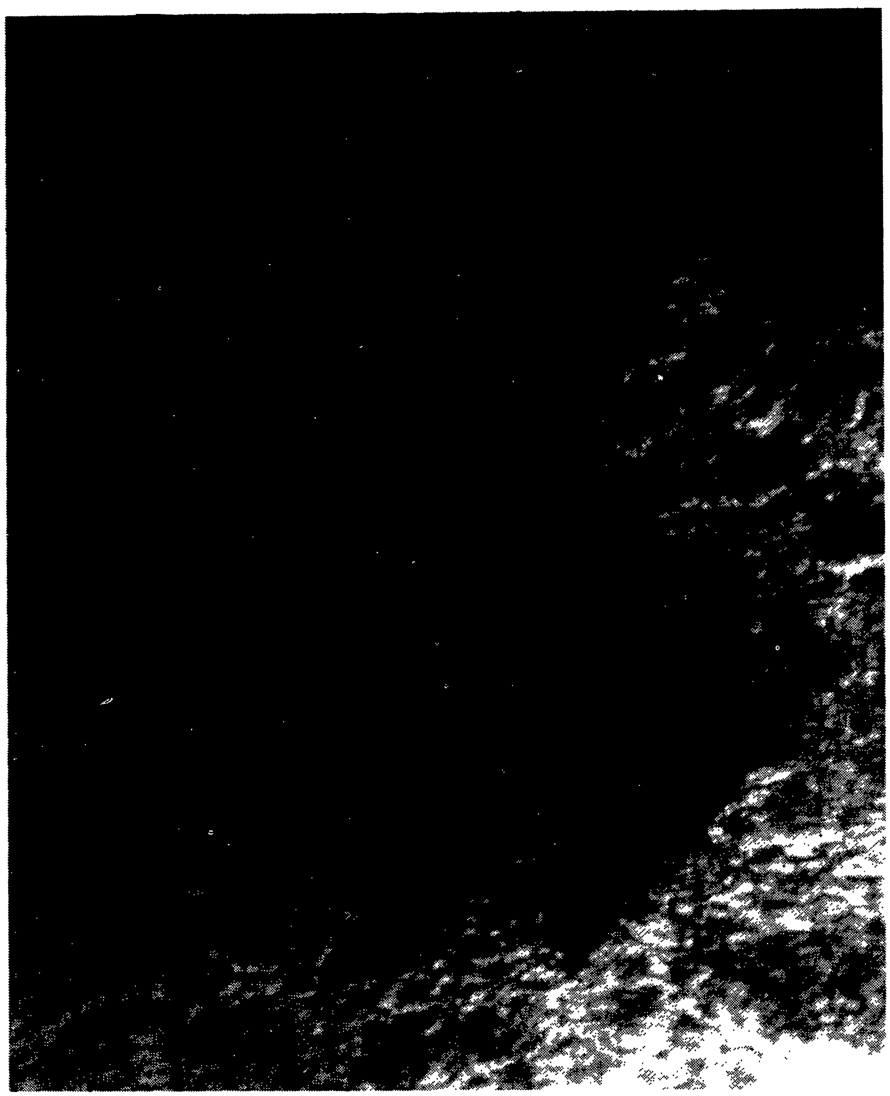


Fig. 6. The spot of July 10 (2′ from the limb). Notice the granular network of the photosphere some of whose cells are normally bright (photospherical granules) and some other brighter than the latter (facular granules).

of 0″42), we can place the actual width of the penumbral filaments between 0″3 and 0″4.

Properties of Umbral Dots

As it is well known, the spot umbras are filled with umbral dots (Fig. 5). Their brightness grows weaker as they approach the umbra centre. Some dots appear much brighter than others. On the average, the observed diameter of the dots is 0″4.

Properties of Photospherical and Facular Granules

In the high resolution pictures of the solar limb, the photospherical and facular granules appear very clearly up to a few seconds of arc from the limb (Fig. 7). We notice that the photospherical granules appear with smaller dimensions there than at the centre of the disk:

	Position centre	Mean diameter
Photospherical granules	1′50″ from limb	1″4
	1′	0″9
Facular granules	1′	0″9
	0″30	0″8

For all that, we must remember that accurate measurements are quite delicate. However, at the centre of the solar disk, our observations agree well

Fig. 7. The spot of July 11 (3″ from the limb) and the granular network of the photosphere.

with those obtained previously by other authors (quoted by Bray and Loughhead, 1967). On the other hand the number of photospherical granules per unit surface area seems to be the same at the centre of the disk and near the limb.

As to the facular granules, the mean diameter is 0″9 at 1′ from the limb, i.e. they have the same dimensions as the neighbouring photospherical granules. Furthermore, like in the latter case, their diameter decreases near the limb, reaching 0″8 at 30″. Thus, they appear to have much smaller dimensions than the 1—2″ which has so far been assumed. The equality of the dimensions of the facular and photospherical granules prompts us to ask whether facular granules could in fact be photospherical granules, brighter than the average. As a matter of fact, facular granules look like bright granules as we can easily see at distances from the limb where the photospherical granules are still sharply defined and where facular granules already appear (Figs 6 and 7): there, the granular network of the photosphere appears to be clear and quite ordinary, but some cells are brighter than the average.

Fig. 8. The granular network of the photosphere: photospherical and facular granules.

Thus, the facular granules look like photospherical granules whose brightness has been enhanced in the upper photospheric layers (no facular granules are seen above the limb). Furthermore, for both photospherical and facular granules, the horizontal apparent cross-section seems to decrease with height.

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