A CLOSE LOOK AT SUNSPOTS

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ABSTRACT

Sunspots at their photospheric level show many interesting targets for the Visible-Light Imager and Magnetograph onboard the Solar Orbiter: Umbral dots and diffuse background, penumbral filaments, penumbral grains, and interactions of fine structures at umbral and penumbral borders. All these features require an extremely high spatial resolution both in imaging and in spectroscopy.

Key words: Sun; sunspots; observation.

1. INTRODUCTION

Plasma motions in strong magnetic fields with wide range of inclinations can be studied in sunspots. Although several large solar telescopes (e.g. NSST and GREGOR) equipped with adaptive optics will be in operation when the Solar Orbiter will fly, the absence of disturbing terrestrial atmosphere and the possibility of uninterrupted long-period observations are clear advantages of the close-up remote sensing from space. Visible-light imaging and 2D spectroscopy with resolution of 80 km on the solar surface can answer many questions about fine structures in sunspots, giving better constraints to physical models of the umbra and of the penumbra.

The lower limit of the size of directly observable structures is given by the photon mean free path l, inversely proportional to the opacity coefficient. In Figure 1 we show a plot of l ($\lambda = 5000$ Å) versus geometrical height z in the solar photosphere, calculated for four model atmospheres: HSRA (Gingerich et al. 1971), plage (Solanki & Steenbock 1988), a small (Collados et al. 1994) and a large sunspot (Maltby et al. 1986, model M). The zero of the geometrical height corresponds to the unity optical depth ($\tau_{5000} = 1$) in each model and represnts roughly the local bottom of the photosphere. We can see that the photon mean free paths in the photosphere are quite similar for all four models. Adopting $\tau_{5000} = 2/3$ ($z \simeq 22$ km) as an effective formation height of the λ 5000 Å continuum, the photon mean free path is of about 90 km in quiet regions (HSRA) and about 70 km in plages and sunspots.

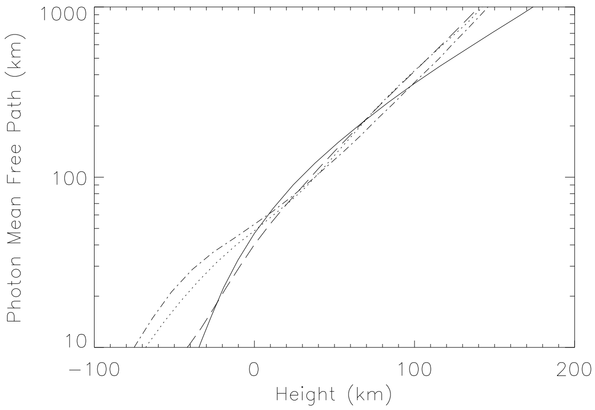

Figure 1. Photon mean free path at λ 5000 Å versus geometrical height for different model atmospheres: HSRA (solid line), plage (dots), small spot (dash-dot), and large spot (dashes).

2. UMBRAL DOTS

Umbral dots (UDs) are tiny bright features of different intensities, embedded in a dark diffuse background of the umbra (Figure 2). The umbral diffuse background itself is a challenge for future observations, due to its inhomogeneities in brightness, magnetic field, and possibly also in line-of-sight velocities. A large amount of parasitic light scattered from the surrounding penumbra and photosphere make the present ground-based observations of the diffuse background quite difficult.

The theoretical explanation of UDs is based on two different approaches, either assuming that the umbra is a dynamic bundle of thin magnetic flux tubes separated by field-free plasma which penetrates into layers near to the visible surface (Parker 1979), or that the umbra is formed by a single inhomogeneous thick flux tube where the magnetoconvection takes place. Recent numerical simulations (e.g. Rucklidge

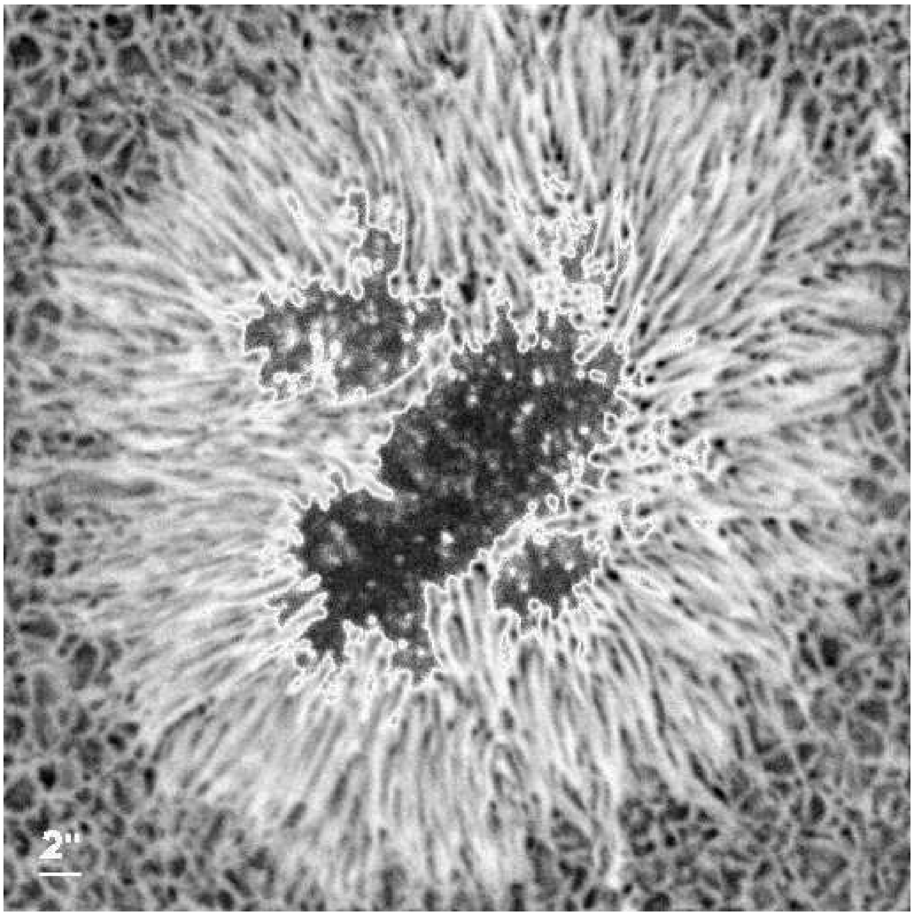

Figure 2. Umbral dots in sunspot NOAA 8580. The frame was taken on 13 June 1999 at the SVST, La Palma. The penumbra and photosphere are shown in negative grey scale to increase the contrast in the umbra.

et al. 2000) revealed several regimes of non-linear compressible magnetoconvection where UDs can be formed.

Since UDs are observed at the resolution limit of contemporary telescopes, their observed brightnesses and sizes differ from the real ones. At present, the real intensities and sizes can be determined only by indirect means—spectroscopically or by two-colour photometry. The first results (Beckers & Schröter 1968) indicated that the real intensity of all UDs is comparable to that of the quiet photosphere and that their sizes are very small—around $0\farcs2$. More recent observations have shown that the real intensities and sizes are in a broader range. Sobotka et al. (1993) found from spectroscopic observations that the real intensity $I_{\rm ud}$ of UDs is proportional to the intensity of the local dark diffuse background $I_{\rm db}$: $I_{\rm ud} = 3 \cdot I_{\rm db}$. Nevertheless, the question of the real brightness of UDs and its relation to the intensity of their dark surroundings is still open.

Observed sizes of UDs range from the resolution limit of $0\farcs25$ to nearly $0\farcs9$. The sizes larger than $0\farcs6$ correspond rather to clusters of UDs than to individual ones. Sobotka et al. (1997) published a histogram of effective diameters of UDs (Figure 3), where the number of UDs increased strongly with decreasing size and there was no "typical" diameter of UDs. It means that we observe structures that are unresolved by our present instruments. Observations with spatial resolution of $0\farcs1$, free of scattered light, should tell us much more about the real brightnesses and sizes of UDs.

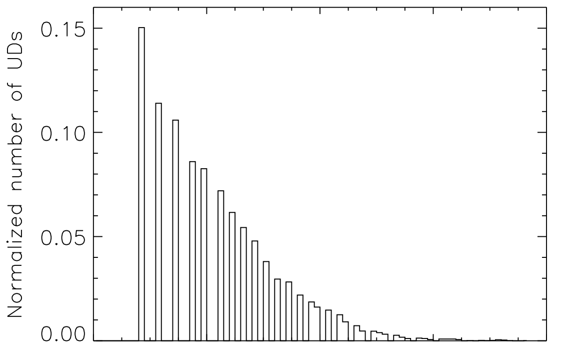

Figure 3. Normalized number of UDs vs. observed diameters (Sobotka, Brandt, & Simon 1997).

If UDs are manifestations of some convective processes, we can expect upflows and a decrease of mag-

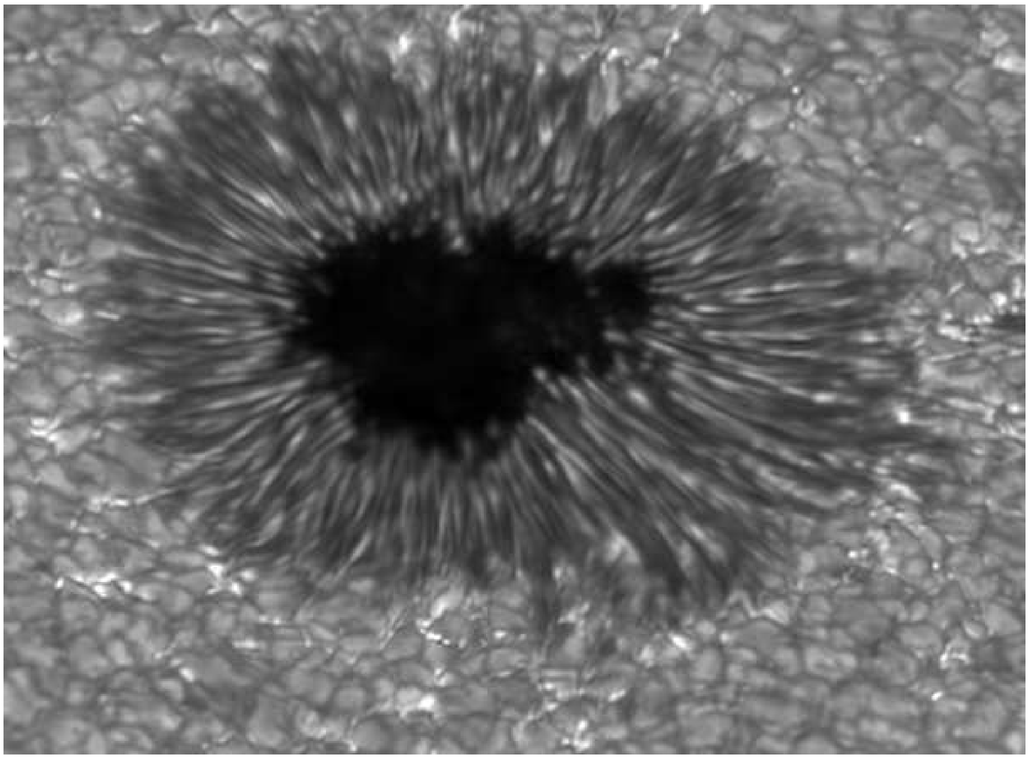

Figure 4. Fine structures in the penumbra are well seen in this speckle reconstructed image of sunspot NOAA 8704, taken in G-band on 20 September 1999 at the DOT, La Palma (courtesy P. Sütterlin).

netic field strength in them. Only recently, indications of such small-scale fluctuations were found. Rimmele (1997) reports a weak correlation between the upflows of 50 m/s and small-scale umbral brightenings. The magnetic field, measured from splitting of spectral lines, does not show fluctuations on the spatial scale of UDs but it is reduced by 1%–20% on spatial scales larger than $1''$(e.g. Schmidt & Balthasar 1994, Tritschler & Schmidt 1997). The absence of strong changes of the magnetic and velocity fields in UDs can be explained by different formation heights of the continuum and spectral lines. For this reason it is important to use photospheric lines with lowest effective formation heights.

Lifetimes of UDs range from 1 minute to more than 2 hours. The number of UDs rapidly decreases with increasing lifetime, so that 66% of UDs live shorter than 10 minutes and only 7% longer than 40 minutes (Sobotka et al. 1997).

3. PENUMBRAL FILAMENTS AND GRAINS

The most typical feature of penumbral fine structures is the elongated shape, a consequence of the strongly inclined magnetic field. An important question is, how the strength and inclination of magnetic field differ between bright and dark penumbral filaments. This problem is difficult to solve for two reasons: (1) Magnetic-sensitive lines are formed at different heights than the continuum and (2) a very high spatial resolution in the spectrum is required. Only in the past decade some positive results were obtained. Wiehr (2000), using the deep-formed line FeI 6842.7 Å, found that the dark, long penumbral lanes host a 10% stronger and $\leq 30^\circ$ flatter magnetic field as compared to the field in bright penumbral filaments. This result, as well as the finding that the Evershed flow is confined to the dark penumbral filaments (e.g. Shine et al. 1994), still needs to be confirmed by high-resolution 2-D spectroscopy and could be an interesting problem for the Visible-Light Imager and Magnetograph.

Bright penumbral filaments consist of penumbral grains (PGs, Muller 1973), elongated comet-like bright features. A theoretical explanation for PGs has been suggested by Schlichenmaier et al. (1998). According to their model, a PG is the intersection of an inclined thin magnetic flux tube with the visible surface. Hot sub-photospheric plasma flows upward along this tube. As the tube rises, its inclination decreases, so that the intersection exhibits a horizontal motion toward the umbra. Bright filaments are interpreted as dimmer and thinner tails of PGs. Their width is very small, only 50 km.

The extreme narrowness of penumbral filaments was also stressed by Sánchez Almeida & Bonet (1998) who found that the spatial spectrum of penumbral intensity fluctuations was flat up to the highest observable frequency. This implies that the true structure of penumbral filaments has not been resolved yet.

Proper motions of PGs can be studied using time se-

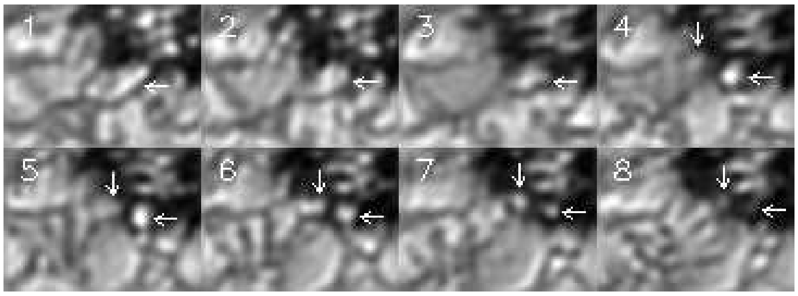

Figure 5. Two examples (←, ↓) of penetration of bright features into a pore's umbra. Time differences between successive frames are 2 minutes (Sobotka et al. 1999).

ries of high-resolution images. In the inner penumbra, up to 0.6–0.7 of the distance from the umbra to the photosphere, PGs move mostly toward the umbra with typical speed of 0.4 km/s (Sobotka et al. 1999a). Schlichenmaier's model is consistent with this type of motion. However, in the outer penumbra, most of PGs move outwards, toward the photosphere, with typical speed 0.5 km/s. This type of motion has no theoretical explanation yet.

4. UMBRAL AND PENUMBRAL BORDERS

The borders between umbra and penumbra (U/P), umbra and photospheric granulation (U/G), and penumbra and photospheric granulation (P/G) are characterized by abrupt changes in strength and inclination of magnetic field. Under such circumstances, interaction of moving plasma with magnetic field give rise to many interesting small-scale effects, important for our knowledge about the sunspots' stability and evolution but insufficiently studied till now.

4.1. Umbra – penumbra

This border represents a transition between a nearly vertical magnetic field to a strongly inclined one. The U/P border is not homogeneous in space and it is often observed that some PGs penetrate deep into the umbra (examples can be seen in Figures 2 and 4). Many of the invard-moving PGs cross the U/P border, lose their elongated shape and continue to move as UDs. For this reason, some of UDs observed at the periphery of the umbra have a penumbral origin. It would be desirable to study temporal changes of horizontal speed, brightness, and magnetic field of these features during their passage across the U/P border.

4.2. Umbra – photospheric granulation

Solar pores (sunspots lacking penumbrae) constitute an almost ideal laboratory in which to study the interaction of a vertical magnetic field with surrounding convective motions. Mesogranular flows in the vicinity of pores push small granules and granular fragments toward the U/G border and some of them penetrate into the umbra, where they move inward as bright short-lived features very similar to UDs (Sobotka et al. 1999b). Two examples are shown in Figure 5. The penetration is often accompanied by the presence of elongated bright features located near the pore's edge (see frame 8 in Figure 5), which may indicate a local tilt of the magnetic field. The capture of bright fetaures by pores might be a microscale manifestation of the "turbulent erosion", which results in the decay of pores.

4.3. Penumbra – photospheric granulation

The effects on the P/G border and in the sunspot moat have been studied extensively. It was found that granules, facular points, and moving magnetic features in the vicinity of sunspots move away from the penumbra (e.g. Muller & Mena 1987) with speeds ≤ 1 km/s. This type of motion probably removes small-scale fragments of magnetic flux from the spot, so that its detailed study is crucial for our understanding of the mechanisms of sunspot decay. Also here many questions remain open: Are facular points moving faster than granules in the moat? How do the facular points originate and how do they evolve? What happens with the outward-moving PGs when they reach the P/G border? How the penumbral bright and dark features interact with the surrounding granulation? A really close look at sunspots yielding very high spatial resolution imaging and 2-D spectroscopy should open a new insight in these problems.

ACKNOWLEDGMENTS

I am grateful to the organizers of the Solar Encounter meeting for their hospitality and financial support. This work was accomplished under Grant A3003903 by the Grant Agency of the Academy of Sciences of the Czech Republic (ASCR) and under the Key Project K2043105 of the ASCR.

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