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Fine structure in a dark umbra

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Abstract. An excellent-quality time series of images of a large dark umbra of the leading sunspot of NOAA 10634 was acquired on 18 June 2004 with the 1-m Swedish Solar Telescope at La Palma, simultaneously in blue, red, and *G*-band channels. The temporal and spatial resolutions are 20 s and $0\farcs14$. A 2-hour long series of the red continuum images is analysed, showing the faintest umbral fine structures. In addition to umbral dots, often clustered to more stable "granules" or aligned to short chains, we observe large, low-intensity elongated structures with dark central channels, resembling extremely faint light bridges. At the periphery of the umbra, bright umbral dots move inwards, showing a similarity to penumbral grains. Kinematic properties of umbral fine structures are studied.

1 Introduction

Sunspot umbrae, when observed under high spatial resolution and sufficient signal-to-noise ratio, show inhomogeneities in brightness. Chevalier (1916) detected a small-scale granular-like pattern in the umbra in his collection of sunspot photographs obtained under a resolution of $0\farcs7$–$1''$. The existence of "umbral granulation" was reported later by several observers (Thiessen 1950; Bray & Loughhead 1964; Bumba et al. 1975). Bumba & Suda (1980) claimed that the spatial distribution of "granules" inside the umbra is identical with that in the photosphere. The term "umbral dots" (UDs) was introduced by Danielson (1964). In the set of photographs from the balloon-borne experiment Stratoscope he detected very small, bright point-like features. The spatial distribution of UDs was different from the photospheric granulation pattern. It is accepted now that the "umbral granules" correspond to unresolved groups and clusters of UDs observed with moderate spatial resolution. Referring to observations with the 91-cm telescope at Kitt Peak, Livingston (1991) claimed that the umbra has a radial filamentary structure with dark "voids" (dark nuclei) free of UDs between bright filaments. So, UDs might be only seeing-induced artifacts. However, the existence of UDs was confirmed by many posterior observations and UDs have been considered as typical representatives of the bright umbral component, embedded in the dark, "diffuse" umbral background with smoothly varying intensity (Sobotka 1999).

2 Observations and data processing

The large leading sunspot of NOAA 10634 was observed on 18 June 2004 from 07:43 to 15:30 UT with the 1-m Swedish Solar Telescope (SST, Scharmer et al. 2003) equipped with adaptive optics. The spot, located near disk centre (N13, E6), was in the phase of growth. The images were acquired in a frame-selection mode (selection interval 20 s), simultaneously in three wavelength bands: blue (4507.5±4.6) Å, red (6020.0±13.0) Å, and *G* band (4308.6± 5.8) Å. Exposure times were 11–14 ms and the pixel size corresponded to $0\farcs0405$.

After dark- and flatfield corrections, the stray light was eliminated following Martínez Pillet (1992). Parameters of the scattering were determined for each wavelength from the shapes of photometric profiles across the solar limb. The level of stray light, originating mostly in the instrument, was 8.5 % in blue, 6.5 % in red, and 8.7 % in *G* band. The deconvolution of the instrumental profile of the diffraction-limited 1-m telescope and the noise filtering was carried out simultaneously, applying Wiener filters with noise suppression starting at $0\farcs11$ (blue), $0\farcs14$ (red), and $0\farcs13$ (*G* band). Regarding the correction of wavefront aberrations done by the adaptive optics, these values characterise the spatial resolution in the best frames. No other restoring techniques were applied.

The image rotation was compensated and the frames were aligned and de-stretched. Finally, a subsonic filter with a cutoff at 4 km s^{-1} was applied to the series of images. For further analyses we selected the best part of the time series taken in the red channel from 12:15 to 14:12 UT, containing 350 frames. The field of view was reduced to $20\farcs25\times20\farcs25$ (500×500 pixels), covering most of the umbra. For the purpose of visualisation and feature tracking, it is good to eliminate large-scale intensity variations. We calculated a smooth, time-dependent intensity “background” using 2D spline fits to local intensity minima in the umbra for each frame, averaging them over a period of 140 s (7 frames). This interpolated “background” intensity was subtracted from the images. The motions of umbral features were studied using the methods of local correlation tracking (LCT, November & Simon 1988) and feature tracking (Sobotka et al. 1997).

3 Results

The observed umbra was very dark. After the stray-light correction, the minimum intensity in the umbra was 0.05 (blue) and 0.09 (red) in units of the average intensity of the undisturbed photosphere ($I_{\rm ph}$). In Fig. 1 (left) we present one of the images with subtracted large-scale intensity variations, showing the complex internal structure of the umbra. An MPEG movie, covering 90 minutes of the time series, can be found at `http://www.asu.cas.cz/~sdsa/gallery-astropictures.html`.

Bright isolated UDs are not very frequent in this dark umbra. Many of them are located at the periphery and move inwards. These UDs are often followed by faint bright tails, resembling tails of penumbral grains, or by dark “wakes” (resembling dark cores of penumbral filaments). Some of the bright UDs are static or slowly moving. They can be found both in the peripheral and central parts of the umbra and are often clustered.

At the bottom left and upper right regions in the umbra, clusters of faint UDs create granule-like features, separated by dark lanes. These non-moving features with diameters of about $0\farcs6$–$0\farcs7$ rapidly change their shape but live substantially longer (about 40 minutes) than individual UDs. They are sometimes surpassed by bright inward-moving UDs.

The central part of the umbra is dominated by two faint filamentary structures with dark central channels, resembling extremely weak light bridges. They are composed of small aligned point-like features that show an organised motion. The average intensity of the

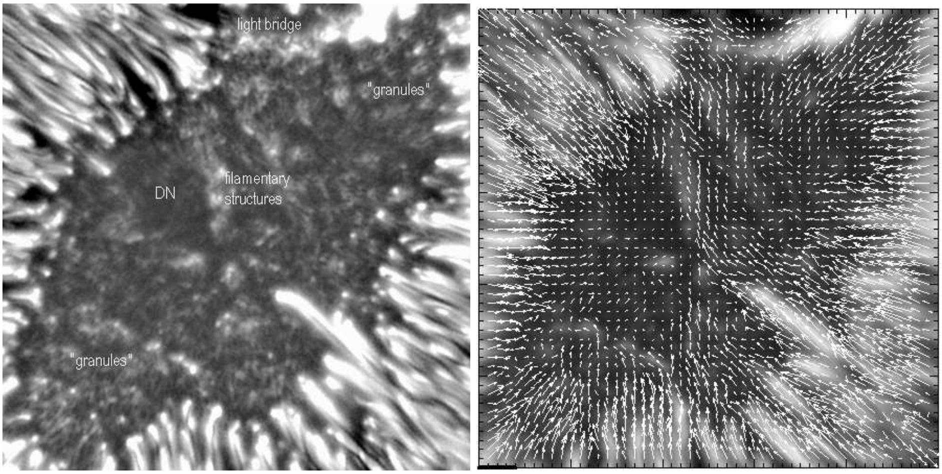

Figure 1. *Left:* Image of the umbra, showing various morphological structures. DN denotes a dark nucleus. Large-scale intensity variations are subtracted. The field of view is approximately $20'' \times 20''$. *Right:* Map of horizontal velocities calculated by LCT. The length of the black horizontal bar at the bottom left corner represents 1 km s^{-1}.

filamentary structures is by 0.1 I_{ph} higher than the intensity of the interpolated "background".

In addition to bright UDs and the granule-like and filamentary structures mentioned above, the whole umbra is covered by a relatively stable small-scale grainy and/or filamentary (alignments of unresolved UDs?) pattern with rms fluctuations of only 0.01–0.02 I_{ph}. The bright inward-moving UDs travel in this background pattern. Even the dark nucleus, the less intense part of the umbra, where the strongest magnetic field is expected, shows a very faint grainy and filamentary structure. Identical patterns were detected also in the blue bandpass, proving that we observe real structures. So, the umbral background does not have the diffuse character as it was expected in the past.

The LCT map of horizontal velocities, calculated with the tracking window of $0.''3$ and averaged over a period of 117 minutes, is shown in Fig. 1 (right). We can see that the motion field of penumbral grains merges into the motion field of inward-moving peripheral UDs. The typical LCT speed of these UDs is 500 m s^{-1}. The global motion of bright features along each of the two faint filamentary structures has opposite direction, with a typical LCT speed of 300 m s^{-1}. This gives an impression of a large-scale organised flow in the central part of the umbra, possibly connected with the horizontal motions in the extended bright penumbral filament seen at the bottom right part of the field of view.

Positions, horizontal velocities, lifetimes, and sizes of features brighter by 0.06 I_{ph} than the interpolated "background", larger than $0.''14$, and living longer than 2 minutes, were measured using the feature tracking method. The mean horizontal velocities of UDs and bright features in the faint filamentary structures are equal to 370 m s^{-1}. The median speed of UDs (330 m s^{-1}) is slightly higher than that in the faint filamentary structures (300 m s^{-1}) due to the presence of fast-moving peripheral UDs. The average lifetimes of UDs and of the bright features in the faint filamentary structures are similar, 9 and 10 minutes, respectively, and their mean diameters are equal to $0\farcs18$ (130 km). To compare the positions of features with different horizontal velocities, let us term “slow” features all features with average speeds below 300 m s^{-1} and “fast” features those with speeds above 500 m s^{-1}. The “slow” features can be found everywhere in the umbra, while the “fast” ones are mostly located at the peripheral parts of the umbra and inside the faint filamentary structures.

4 Conclusions

An-excellent quality 2-hour time series of images of a large and dark sunspot umbra acquired with the 1-m SST in the red continuum around 6020 Å was studied. Thanks to the spatial resolution of $0\farcs14$ and the signal-to noise ratio around 200, we detected the faintest point-like, granule-like, and filamentary features in the umbra.

Bright peripheral UDs show morphological (bright tails, dark “wakes”) and kinematic (inward-directed speeds of 500 m s^{-1}) similarity to penumbral grains. Static or slowly moving UDs are often clustered in relatively stable granule-like structures separated by dark lanes. Large, low-intensity filamentary structures with dark central channels are probably extremely faint light bridges. They consist of small features, similar in size to UDs, that move in an organised way along the axis of the structure. The whole umbra shows a slowly evolving grainy and/or filamentary low-contrast “background” pattern, which is surpassed by the inward-moving peripheral UDs.

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