Spectropolarimetery of umbral fine structures from Hinode: evidence for magnetoconvection

Lokesh Bharti,1*† Chandan Joshi,1 S. N. A. Jaaffrey1 and Rajmal Jain2

1Department of Physics, University College of Science, Mohanlal Sukhadia University, Udaipur 313 001, India
2Physical Research Laboratory, Department of Space, Government of India, Navrangpura, Ahmedabad 380 009, India

Accepted 2008 November 5. Received 2008 October 28; in original form 2008 February 12

ABSTRACT
We present spectropolarimetric analysis of umbral dots and a light bridge fragment that show dark lanes in G-band images. Umbral dots show upflow as well as associated positive Stokes V area asymmetry in their central parts. Larger umbral dots show downflow patches in their surrounding parts that are associated with negative Stokes V area asymmetry. Umbral dots show weaker magnetic field in central part and higher magnetic field in peripheral area. Umbral fine structures are much better visible in total circularly polarized light than in continuum intensity. Umbral dots show a temperature deficit above dark lanes. The magnetic field inclination shows a cusp structure above umbral dots and a light bridge fragment. We compare our observational findings with 3D magnetohydrodynamic simulations.

Key words: Sun: granulation – Sun: magnetic fields – Sun: photosphere – sunspots.

1 INTRODUCTION
Two models of the umbral dots (UDs) are under discussion these days. The first is the cluster model (Parker 1976; Choudhuri 1986) that suggests that UDs are the top of the intrusion of the field free material between the flux tubes beneath the sunspot. The second model is known as the monolithic model (Weiss 2002, and reference therein) and suggests that UDs show up because of magnetoconvection in monolithic flux tube. Recent simulations by Schüssler & Vögler (2006) with grey radiative transfer show UDs appearing due to magnetoconvection in strong background magnetic field. The knowledge of the nature of UDs is essential to understand the energy transport from below the sunspot (see reviews from Solanki 2003; Thomas & Weiss 2004, and reference therein on the subject).

Bharti, Joshi & Jaaffrey (2007a) analysed Dopplergrams obtained from filtergraph data, and found a correlation between intensity and velocity in UDs, which suggests a magnetoconveective origin. Using high-quality G-band images from Hinode, Bharti, Jain & Jaaffrey (2007b) reported on dark lanes in UDs. These separate observational findings are compatible with some aspects of simulations by Schüssler & Vögler (2006). Socas-Navarro et al. (2004) analysed peripheral UDs in detail from spectropolarimetric data and found higher temperature (∼1 kK), weaker field (∼500 G), small upflow (∼100 m s⁻¹) and more inclined field (∼10°) in UDs.

In this article, we present spectropolarimetric analysis of dark laned umbral fine structure from Hinode spectropolarimetric data.

The high polarimetric sensitivity and spatial resolution achieved by Hinode spectropolarimeter now it became possible to compare observational results directly with predictions of numerical simulations (Rezaei et al. 2007; Sainz Dalda & Bellot Rubio 2008).

2 OBSERVATIONS AND INVERSION TECHNIQUE
We used spectropolarimetric data obtained by the spectropolarimeter onboard the Hinode (Kosugi et al. 2007) on 2006 December 12. The four Stokes profiles of the two iron line pairs at 630.15 nm (the Lände factor g = 1.67) and 630.25 nm (g = 2.5) were recorded for the active region 10 930 close to the disc centre (µ = 0.99). We used fast map. The integration time for fast map was 3.2 s. The field of view comprises an area of 295 × 162 arcsec². The spatial sampling for the fast map was 0.316 arcsec along the slit and 0.295 arcsec in the scanning direction. The spatial resolution of the resulting spectropolarimetric map is approximately 0.6 arcsec for the fast map with the spectral sampling at 2.15 pm. The calibration of the spectropolarimetric data is described by Ichimoto et al. (2007). We used the solar-soft pipeline to calibrate the spectropolarimetric data.

To derive accurate photospheric height stratification of the temperature (T), magnetic field strength (B), line-of-sight (LOS) velocity (V₉₀), and inclination (γ), we employ the srat code (Ruiz Cobo & del Toro Iniesta 1992). This code presumes hydrostatic equilibrium and local thermodynamic equilibrium. By solving numerically the radiative transfer equation for polarized light, the inversion code srat computes the synthetic Stokes profiles. The optimal parameters for the model were determined iteratively. The difference between the observed and synthetic Stokes profiles was minimized using a non-linear, least-square Marquardt’s algorithm. The values of the
physical parameters are computed at only a few grid points called nodes instead of computing at all optical depths of the model. For rest of depths, they are approximately computed by the cubic-spline interpolation between the equidistantly distributed grid points. We perform the SIR inversion with only one magnetic component, for which we allow five nodes in $T(\tau)$, three for $B(\tau)$, $V_{\text{los}}(\tau)$ and $\gamma(\tau)$.

$G$-band time series obtained in the broad-band filter were used to follow the evolution of the sunspot fine structure as seen in the spectropolarimetric maps (see Bharti et al. 2007b). Wiener filtering was applied to the $G$-band images for the point spread function correction of telescope. Understanding of the evolution of the umbra fine structure is necessary as they may have common physical origin (Bharti et al. 2007c; Katsukawa et al. 2007; Rimmele 2008). Here, we would like to mention that it is our aim to investigate dark lane in UDs as reported by Bharti et al. (2007b) and the spectropolarimetric fast scan at 0.6 arcsec spatial resolution cover similar features.

The calibrated Stokes profiles were used to create maps of total circular polarization and Stokes $V$ area asymmetry (Bellot Rubio et al. 2007).

3 RESULTS

We have chosen $G$-band images, whose timing was close to the spectropolarimetric scans. Fig. 1 shows one of the $G$-band images taken close to the fast spectropolarimetric scan time at 04:15:32 UT that covers emerging sunspot in the spectropolarimetric map. The $G$-band time series shows that the UD ‘a’ has been formed from a peripheral UD that fragmented in two UDs. The UD ‘b’ emerges from a bright bands (Bharti et al. 2007b). The bright band fragments and a UD forms, it grows gradually and shows a threefold dark lane. At 04:15:32 UT, it shows a central bright structure surrounded by a dark ring and five fragments separated by dark lanes. The time series show that this UD fragments and again converts into a bright band. A larger UD ‘c’ forms from a bright band that shows complex shapes during its evolution. In Fig. 1, it shows clearly threefold dark lanes. The light bridge that develops from the dark cored penumbral filament shows central dark lanes and its fragments show dark lanes. At the head of the light bridge, a triangular-shaped bright structure ‘d’ is seen that forms from the light bridge fragments in upper part and conglomeration of a UD that appears from the diffuse background. This UD is marked by ‘e’. Individual UDs are seen. However, their boundary is not clearly visible. Close to the vertex of the triangular structure ‘d’, a light bridge fragment is seen that shows dark lane. Dark lanes in UDs and light bridge fragments are visible but only UD ‘c’ shows more clearly dark lane in the $G$-band image. Fig. 2 shows enlarged view of a part of Fig. 1 that shows dark lanes in umbral fine structures very clearly.

Fig. 3 illustrates map of the emerging sunspot taken from the spectropolarimetric fast scan. Panel (a) of Fig. 3 shows the continuum intensity map; the fine structure is very similar to that of the $G$-band image. Comparison with the $G$-band image in Fig. 1
Fig. 4 shows the height stratification of plasma parameters according the mixing inversion. This figure shows temperature \(T(\tau)\), magnetic field strength \([B(\tau)]\), LOS velocity \([V_{\text{los}}(\tau)]\) and inclination \([\gamma(\tau)]\) as a function of altitude and horizontal distance across the lines in panel (a) of Fig. 3 for umbral fine structures for optical depths \(0 > \log(\tau) > -2.5\). We find these parameters reliable for \(\log(\tau) < -2.0\); i.e. errors are higher in the upper atmosphere. From the top downwards, the plot shows UDs ‘a’, ‘b’, ‘c’ and the light bridge fragment.

The first column of Fig. 4 illustrates the temperature stratification of the observed UDs and the light bridge fragment. At \(\tau = 1\), UDs ‘a’, ‘b’, ‘c’ and the light bridge fragment are 780, 810, 1220 and 870 K, respectively, hotter than the coolest part of the sunspot. This is in agreement with Sobotka & Hanslmeier (2005) who reported that from two colour photometry, on average, UDs are about 1000 K hotter from the coolest area in the umbra. In all cases, these structures are cooler in the higher layers. In case of UD ‘c’, a temperature drop can be seen around \(\log(\tau) = -1.5\), which is co-located with dark lane. This dark lane has higher contrast in the line core of the 630.25 nm line as shown by the dotted line overplot in Fig. 4. However, as shown by the solid line overplot in Fig. 4, this dark lane is not visible in the continuum of the 630.25 nm line. This indicates that dark lanes have lower temperature compared to the surrounding at the same optical depth. This is in agreement with Schüssler & Vögler (2006) and Spruit & Scharmer (2006). They suggest that the surfaces of constant optical depths are elevated in these structures, so that they correspond to lower temperature. This dark lane can be produced by the effect of the density and the gas pressure. The 

\[ \text{sec} \] code takes those into account only approximately under the approximation of hydrostatic equilibrium. Ruiz Cobo & Bellot Rubio (2008) modelled dark lanes in penumbral filaments and suggested that dark lanes are produced by locally enhanced density and pressure that shift the \(\tau = 1\) level to higher layers. All three thermodynamic parameters (temperature, density and gas pressure) are likely to play a role, as suggested by Borrero (2007). The dark lane is identified clearly in the temperature map at higher layers (not shown here), which is consistent with an elevated \(\tau = 1\) level lies above UD in the higher layers. We find a temperature variation in the UD ‘c’, which suggests that multifield dark lanes are the manifestation of a temperature deficit. To our knowledge, this is the first observational evidence of temperature deficit in dark lanes of UDs.

The second column of Fig. 4 shows the magnetic field strength stratification of these structures. The field strength in UDs decreases rapidly with depth. On the other hand, background field strength increases slightly. We find that there is a strong difference between the values in the central part and the peripheral part of UDs. The magnetic field is less in the central part and higher in the peripheral parts. At \(\tau = 1\) level, with respect to the dark nuclei, this difference is found to be 441, 440, 900 and 325 G for UD ‘a’, ‘b’, ‘c’ and the light bridge fragment, respectively. This is in agreement with findings of Schüssler & Vögler (2006). We find higher magnetic field in the peripheral part of these structures. Joshi, Bharti & Jaaffrey (2007) reported similar trend in and around UDs in their analytical study on the Joule heating in UDs that suggests the higher magnetic field in the peripheral part of UDs.

The LOS velocity stratification for these umbral fine structures is shown in the third column of Fig. 4. UD ‘a’, ‘b’ and ‘c’ show upflow of 300, 280 and 450 m s\(^{-1}\), respectively, with associated downflow at edges. The light bridge fragment shows upflow in the middle and downflow at the right edge.

The fourth column of Fig. 4 depicts the inclination stratification for these UDs and the light bridge fragment. We can see more inclined field above these structures. At \(\tau = 1\), the field is inclined around \(10^\circ\) for UDs ‘a’ and ‘b’ and the light bridge fragment. However, the field is strongly inclined for UD ‘c’, up to \(20^\circ\) at \(\tau = 1\). Such inclined fields form a cusp above these structures. Cusp above UDs predicted by Schüssler & Vögler (2006) in the simulations. Borrero, Lites & Solanki (2008) reported magnetic field wrapping around penumbral filaments. This is consistent with the field geometry we observed for UDs.

Shown in Fig. 5 is the LOS velocity map of the region of interest shown by outer rectangle in Fig. 1 for the fast scan at \(\log(\tau) = -1.5\). The UD ‘c’ shows upward velocity up to 450 m s\(^{-1}\). On the other hand, other UDs show upflow of the order of 300 m s\(^{-1}\) which is in agreement with finding of Vecino-Navarro et al. (2004) and Bharti et al. (2007a). However, we observed downflow patches around larger UD ‘c’. This is in agreement with Bharti et al. (2007a) who reported downflow around UDs. However, we have not observed downflow around smaller UDs. That may be due to the lower spatial resolution in analysed data for present study. Upward velocity in the central parts and downflow around the peripheral parts of UDs suggest their magnetoconvection origin as reported by Schüssler & Vögler (2006). Since this sunspot was located close to the disc centre hence the LOS component of the velocity is assumed to be vertical.

Shown in Fig. 6 (right-hand side) is enlarged Stokes V area asymmetry map of selected UDs in Fig. 3(a). Contours of continuum intensity image (left-hand side) are plotted over area asymmetry map (right-hand side). On comparing with rectangular region in velocity map in Fig. 5, one can see that upflow region of UD ‘c’ shows positive area asymmetry whereas downflow patches around this UD show negative area asymmetry. Similar trend can be observed for UDs in a triangular region ‘d’ and the light bridge fragment. UD ‘b’ shows very interesting pattern of area asymmetry, as shown in Fig. 2. It shows bright ring with dark lanes around a bright UD. We can see this ring as positive area asymmetry signature with lesser positive area asymmetry in the centre, producing a donut-shaped structure. Auer & Heasley (1978) suggested that to produce an area asymmetry \(\delta A\), a gradient in the velocity is required. On the other hand, a combination of gradients in the field strength or orientation and velocity can produce an asymmetry in much more efficient manner. We observed positive area asymmetry in the upflow region and negative area asymmetry at the downflow region of UDs, however, only brighter UDs show up positive area asymmetry above background noise.
Figure 4. From left- to right-hand side: temperature, magnetic field strength, LOS velocity and inclination. From top to bottom: UDs a, b, c and light bridge. For UD 'c' continuum (solid line) and core intensity (dotted line) overplotted. Positive velocity corresponds to upflow and negative velocity to downflow.
The spatial resolution of our observations is insufficient to confirm such flow pattern. We observed downflow patches around a larger UD, and a comparison with the dark lanes in the G-band image suggests that downflows are not associated with dark lane end points. This larger UD may have different origin, as a result of flux separation (Weiss, Proctor & Brownjohn 2002). Thus, granular-like convection similar to quiet regions appears in a large field-free patches. Hence, we could observe downflows surrounded around overturning convective cells. However, the stratification of plasma parameters that we found for UD ‘c’, which displays several dark lanes, is compatible with the results of Schüssler & Vögler (2006).

Riehmüller, Solanki & Lagg (2008) presented an analysis similar to ours of a large number of central and peripheral UDs. They used Hinode normal spectropolarimetric scan at a resolution of (0.3 arcsec) and obtained results similar to that of ours. At the log(τ) = 0 level, they found that peripheral UDs on average exhibit a temperature enhancement of 570 K, a weaker magnetic field of 510 G and an upflow of 800 m s$^{-1}$. On the other hand, their central UDs on average display a 550 K higher temperature, a weaker field of 480 G and no significant upflow signature. However, we find central UD ‘b’ and ‘c’ are hotter by 810 and 1221 K, respectively, show upflow of a few times 100 m s$^{-1}$ and have a more inclined field (10° and 20°, respectively). The downflows around the UDs reported by Riehmüller, Solanki & Lagg (2008) are in good agreement with our present study and confirm the findings of Bharti et al. (2007a).

The asymmetry in the area that we studied suggests that there are gradients in the magnetic field, the upflow and downflow velocities, and in the inclination of the magnetic field. Sánchez Almeida & Lites (1992) suggested the so-called $\Delta \gamma$ mechanism, that is the simultaneous variation of the velocity and magnetic field inclination to explain area asymmetry. Solanki & Montavon (1993) showed sign dependence of an area asymmetry on combinations of gradients of these quantities. Equations (2) and (3) of Solanki & Montavon (1993) show the sign of the observed area asymmetry $\delta A$ in and around UDs. These equations are given by

$$\text{sign}(\delta A) = -\text{sign}\left(\frac{\partial \text{V}_{\text{los}}}{\partial r} \frac{\partial |B|}{\partial r}\right),$$  

$$\text{sign}(\delta A) = -\text{sign}\left(\frac{\partial \text{V}_{\text{los}}}{\partial r} \frac{\partial (\cos \gamma)}{\partial r}\right).$$

where $V_{\text{los}} > 0$ for a velocity directed away from the observer.

The central part of UDs shows $|\partial B|/\partial r < 0$, $\partial \text{V}_{\text{los}}/\partial r > 0$ and $\partial (\cos \gamma)/\partial r > 0$, thus implying positive area asymmetry. In the peripheral part, we find $|\partial B|/\partial r > 0$, $\partial \text{V}_{\text{los}}/\partial r > 0$ and $\partial (\cos \gamma)/\partial r > 0$, which implies negative area asymmetry. Thus, upflow regions show positive area asymmetry and downflow ones show negative area asymmetry. The gradient we found for these quantities and for the area asymmetry in and around UDs is compatible with the model suggested in fig. 2 of Schüssler & Vögler (2006). However, due to the limit set by the spatial resolution of our observations, we cannot observe such asymmetries around smaller UDs (i.e. narrow downflow channels concentrated at the end points of dark lanes). Schüssler & Vögler (2006) also suggested that line forming region above UDs lies in higher height, thus strong field reduction and high upflow velocities may not be observable in spectroscopic observation, this is in agreement with our findings.

Spectropolarimetry of UDs with the Narrowband Filter Imager (NFI) and Dopplergrams of the magnetically insensitive line 5576 Å at a 0.2 arcsec will be very useful for detailed studies of umbral fine structure. On the other hand, observations of umbral fine structure
at different heights in solar atmosphere from ground-based facilities will be our next aim.

ACKNOWLEDGMENTS

Juan Manuel Borrero, Jan Jurčák and Luis Bellot Rubio (who kindly provided sirc code) are gratefully acknowledged for discussion on sirc inversion. We thank Professor Manfred Schüssler and Dr Michal Sobotka for useful discussions. We are indebted to an anonymous referee for useful suggestions to improve the presentation of this work. Dr Nick Hoekzema and Dr Ajay Manglik are gratefully acknowledged for help with language. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in cooperation with ESA and NSC (Norway). This research is supported by Bal Shiksha Sadan Samiti [a non-governmental organization (NGO), Udaipur].

REFERENCES

Auer L. H., Heasley J. N., 1978, A&A, 64, 67
Bellot Rubio L. R. et al., 2007, ApJ, 668, L91
Bharti L., Joshi C., Jaaffrey S. N. A., 2007a, ApJ, 669, L57
Bharti L., Jain R., Jaaffrey S. N. A., 2007b, ApJ, 665, L79
Bharti L., Rimmele T., Jain R., Jaaffrey S. N. A., Smartt R. N., 2007c, MNRAS, 376, 1291
Borrero J. M., 2007, A&A, 471, 967
Borrero J. M., Lites B. W., Solanki S. K., 2008, A&A, 481, L13
Choudhuri A. R., 1986, ApJ, 302, 809
Joshi C., Bharti L., Jaaffrey S. N. A., 2007, Sol. Phys., 245, 239
Socas-Navarro H., Martínez Pillet V., Sobotka M., Vázquez M., 2004, ApJ, 614, 448
Spruit H. C., Scharmer G. B., 2006, A&A, 447, 343
Ichimoto K., Lites B. W., Elmore D. et al., 2007, Sol. Phys., 249, 233
Katsukawa Y., Yokoyama T. et al., 2007, PASJ, 59, S577
Kosugi T. et al., 2007, Sol. Phys., 243, 3
Parker E. N., 1979, ApJ, 234, 333
Rezaei R., Steiner O., Wedemeyer - Böhm S., Schlichenmaier R., Schmidt W., Lites B. W., 2007, A&A, 476, L33
Riethmüller T. L., Solanki S. K., Lagg A., 2008, ApJ, 678, L157
Rimmele T., 2008, ApJ, 672, 684
Ruiz Cobos B., del Toro Iniesta J. C., 1992, ApJ, 398, 375
Ruiz Cobos B., Bellot Rubio L. R., 2008, A&A, 488, 749
Sainz Dalda A., Bellot Rubio L. R., 2008, A&A, 481, L21
Sánchez Almeida, Lites B. W., 1992, ApJ, 398, 359
Schüssler M., Vögler A., 2006, ApJ, 641, L73
Sobotka M., Hanslmeier A., 2005, A&A, 442, 323
Solanki S. K., 2003, Annu. Rev. Astron. Astrophys., 11, 153
Solanki S. K., Montavon C. A. P., 1993, A&A, 275, 283
Spruit H. C., Scharmer G. B., 2006, A&A, 447, 343
Thomas J. H., Weiss N. W., 2004, Annu. Rev. Astron. Astrophys. 2004, 42, 517
Weiss N. O., 2002, Astron. Nachr., 323, 371
Weiss N. O., Proctor M. R. E., Brownjohn D. P., 2002, MNRAS, 337, 293

This paper has been typeset from a \LaTeX file prepared by the author.