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UMBRAL DOTS OBSERVED IN PHOTOMETRIC IMAGES TAKEN WITH 1.6 m SOLAR TELESCOPE

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SUMMARY: Umbral dots (UDs) were observed using the 1.6 meter solar telescope. Achieved conventional diffraction limit in the TiO 705.68 nm spectral line used was $0''.1$. The 418 UDs were analysed. Median diameter was $0''.5$ and median intensity difference between darkest part of the UD's background and brightest part of the UDs was 37%. Despite the achieved resolution, no UDs substructures were visible. The analysed UDs appeared to be circular.

Key words. sunspots – methods: observational

1. INTRODUCTION

Umbral dots (UDs) are small-scale structures distributed across the umbra. Modelling showed that appearance of the UDs is a natural consequence of the magnetoconvection under the conditions set by a strong magnetic field (Schüssler and Vögler 2006). This was confirmed by Rempel et al. (2009), Cheung et al. (2010) and Bharti et al. (2010), however all authors used MURaM code (Vögler et al. 2005), same as Schüssler and Vögler (2006). Heinemann et al. (2007) state that UDs are caused by overturning convection using PENCIL code (Heinemann et al. 2006). Heinemann et al. (2007) also saw indications of the umbral dots substructure, similar to those showed in Schüssler and Vögler (2006).

Schüssler and Vögler (2006) and consequently Bharti et al. (2010) observed in their simulations that resulting bright features have a horizontally elongated form with a central dark lane. A similar dark lane was also observed by Heinemann et al. (2007) in their simulations. Schüssler and Vögler (2006) found that simulated UDs correspond well to the observed UDs in the central parts of the umbrae when brightness, lifetime and size are considered. Bharti et al. (2010) could not reproduce small, short-lived UDs. The UDs from their simulation existed for 25 to 28 minutes, covered averaged areas of 0.08 to 0.14 Mm^2, with brightness of 1.6 to 1.7 factor larger than the surrounding dark background with the corresponding values for the continuum brightness at 630 nm of 2.6 to 2.9.

Rimmele (2008), Riethmüller et al. (2008), and Ortiz et al. (2010) stated that they had seen a signature of UDs dynamics as described by the Schüssler and Vögler (2006) model. Riethmüller et al. (2008) claimed that although the vertical cuts of their data sets and inversion data agree with the model, they could not detect the strong down-flows associated with the central dark lane. They reasoned that such observational result is caused by the limited spatial resolution of their data of $\sim 0''.32$. Ortiz et al. (2010), with the resolution of $0''.14$ saw the substructure of the UD in the form of dark lanes, although not all UDs possessed the dark lane. The estimated size of the substructures matches the achieved resolution. At similar resolution, Rimmele (2008) saw some of the UDs with the dark substructure of the estimated size $\sim 0''.12$. Also, Rimmele (2008) observed that if the UD was located near the edge of the umbra the dark feature would extend out from the bright dot, with the appearance of a comet-like tail.

Rimmele (2008) noted that UDs have lifetime close to 30 minutes, as predicted by the Schüssler and Vögler (2006) model. Bharti et al. (2010) similarly predicted that the average UDs lifetime is between 25 and 28 minutes. On the other hand, Hamedivafa (2008) stated that the average lifetime of the UDs is between 7 and 10 min, while Watanabe et al. (2009) measured the average lifetime as 7.3 minutes.

This paper presents a preliminary analysis of the UDs observed with the 1.6 meter telescope. Results presented here give an additional insight in behaviour of the UDs, and can serve as an evaluation data for the observing of umbra with various spectral lines and bands.

2. DATA AND ANALYSIS

The data set used was obtained on September 22, 2010 using the photometry with the broad band filter centred at TiO 705.68 nm spectral line at New Solar Telescope (NST) at Big Bear Solar Observatory (Cao et al. 2010). The TiO broadband filter was chosen due to technical reasons. Its use in optical path was suitable for ongoing engineering work. The work on the instrumental installation takes priority over obtaining scientific data during the commission phase. The line parameters of the molecular lines are suitable for umbral observation (Sinha and Tripathi 1991a,b). The TiO line is molecular spectral line and hence should be suitable. The broad passband of the filter used allowed us to observe the photosphere at the level close to $\tau_{500} = 1$.

The target of the observation was the active region NOAA AR 11108. The data sequence consists of 141 bursts with 100 images in each burst. The exposure time for an individual frame was 1 ms. The cadence of the data between bursts is 15 s. The time series covers the time interval of ~ 35 minutes. The data were acquired in the morning with fairly constant average seeing levels. Low order adaptive optic was used. The images have a sampling of $0''.034$ per pixel, which resulted in data oversampling.

In a work such as this, where one tries to observe structures at the edge of the diffraction limit of the telescope, the decision on which criterion will be used to describe the telescope resolution has to be made. The conventional diffraction resolution (λ/D) gives resolution of $0''.09$ for this spectral line, while at the same time the Rayleigh criterion gives a value of $0''.11$, and Sparrow's criterium gives $0''.086$. The data were obtained using the instrumentation located in a Coudé room utilising the newly installed low order adaptive optic (AO) system. With the dataset obtained utilising an AO system, together with the post image processing it is possible to resolve clearly Sparrow's limit for the given spectral line. Cases of such a good resolving are already known from a previous works, for example the work of Berger et al. (2004), where the authors managed to reach the resolution of $0''.1$ in G-band using 1 meter telescope. However, during observational run for this dataset, the seeing was average, causing the high levels of noise in the umbrae. In order to increase the reliability of the dataset all structures below $0''.09$ are filtered out, in order to remove the potential noise artefacts. This procedure in effect changed the resolution of our dataset. The Sparrow criterion is set on $0''.09$, conventional criterion at $\sim 0''.1$, while Rayleigh criterion gives: $\sim 0''.12$.

The data were speckle reconstructed based on the speckle masking method of von der Lühe (1993) using the code described in Wöger et al. (2008). The images were filtered in space removing all features smaller than $0''.09$. Since Rimmele (2008) estimate size of the umbral substructures was $\sim 1''.2$, filtering out the structures smaller than $0''.09$ should not remove the umbral substructures. However, the filtering reduced the contrast of the images by 10%.

The cadence of our reconstructed data provided us with a Nyquist frequency of 67 mHz. After the speckle reduction, images were co-aligned using a Fourier co-aligning routine, which uses cross-correlation techniques and mean squared deviation to provide the sub-pixel co-alignment accuracy. However, the sub-pixel image shifting was not implemented in order to avoid interpolation errors. Instead, the procedure was iterated 6 times to achieve the best possible co-alignment.

Identification of the UDs in the field of view was performed with the modified method applied by Sánchez Almeida et al. (2004). Instead of playing series back and forth to detect the UDs we used the NAVE method (Chae and Sakurai 2008) to track the plasma flow of individual UDs. Also, the analysis of UDs displacement and UDs tracking was performed using the NAVE with following restrictions: only UDs that appeared for more than 0.75 minutes and were at least $0''.09$ in diameter entered this analysis. The constraining criteria and methodology of small structures selection was described in detail in Andić et al. (2011). To measure dimensions of the UDs accurately the measuring was done when they were the brightest. For each UDs the time of their maximum intensity was chosen. The intensity profile from that instance was used and the diameter was measured utilising a method of full-width at half maximum (FWHM). In the case when the UD was not of spherical shape, the FWHM was measured from the light profile along the longest part of UD.

To ensure that only UDs are analysed the penumbral structures were masked out by using a binary mask that was based on the intensity cutoff by factor 0.7 of the maximum intensity. Beside this, structures located close to the edge of umbra, with distances $< 0''.7$ were ignored.

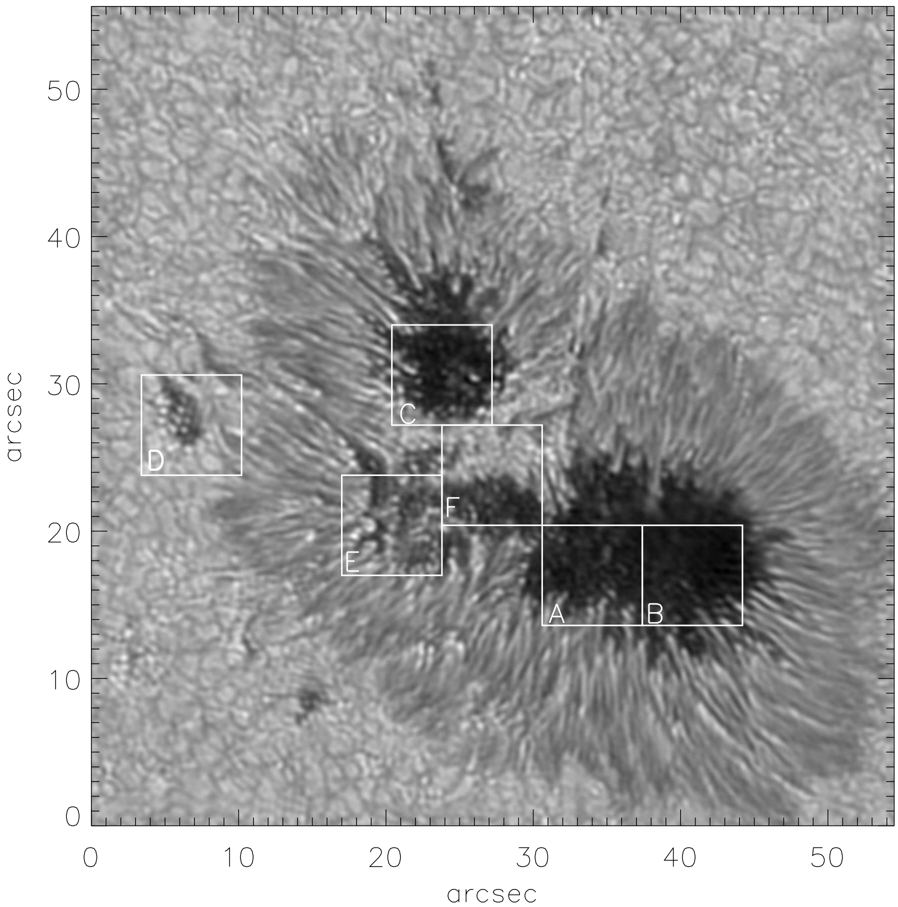

Fig. 1. *The observed NOAA AR 11108 with TiO 705.68 nm spectral line. Six white squares represent areas zoomed in Fig. 3.*

3. RESULTS

The angular resolution of NST in TiO spectral line revealed plethora of the details in the umbra (Fig. 1).

In this work, a statistical analysis of 489 UDs is performed (Fig. 2). Out of them, 318 were tracked in the bigger umbra, 143 in smaller and 28 in pores surrounding the spot. In all 3 regions the UDs had similar values for diameter and brightness, and persisted for a similar period of time. The median observable time for UDs from pores and smaller umbra was the same, 35 minutes, while the median observable time in larger umbra was shorter, 33.25 minutes. Diameter of the UDs varied from the median size in two umbras of $0\farcs5$ to the median size of $0\farcs4$ for the UDs in pores.

Brightness was calculated as a percentage of difference in the intensity between the brightest pixel in UD and the darkest pixel in the background surrounding the UD. The brightest UDs were observed in pores with the 43.9% difference in the intensity between the darkest part of the background and the brightest part of UD. The bigger umbra had the median value for the intensity difference (i.e. brightness) of 36.6% while in the smaller umbra the median brightness was 30.6%.

Since the UDs substructure was observed with instrumentation of the resolution coarser than NST's one (Rimmele 2008, Riethmüller et al. 2008, Ortiz et al. 2010), there was an expectation to see clearly the UDs substructures in this dataset. However, not a single UD in this dataset had a dark lane as described in the model of Schüssler and Vögler (2006).

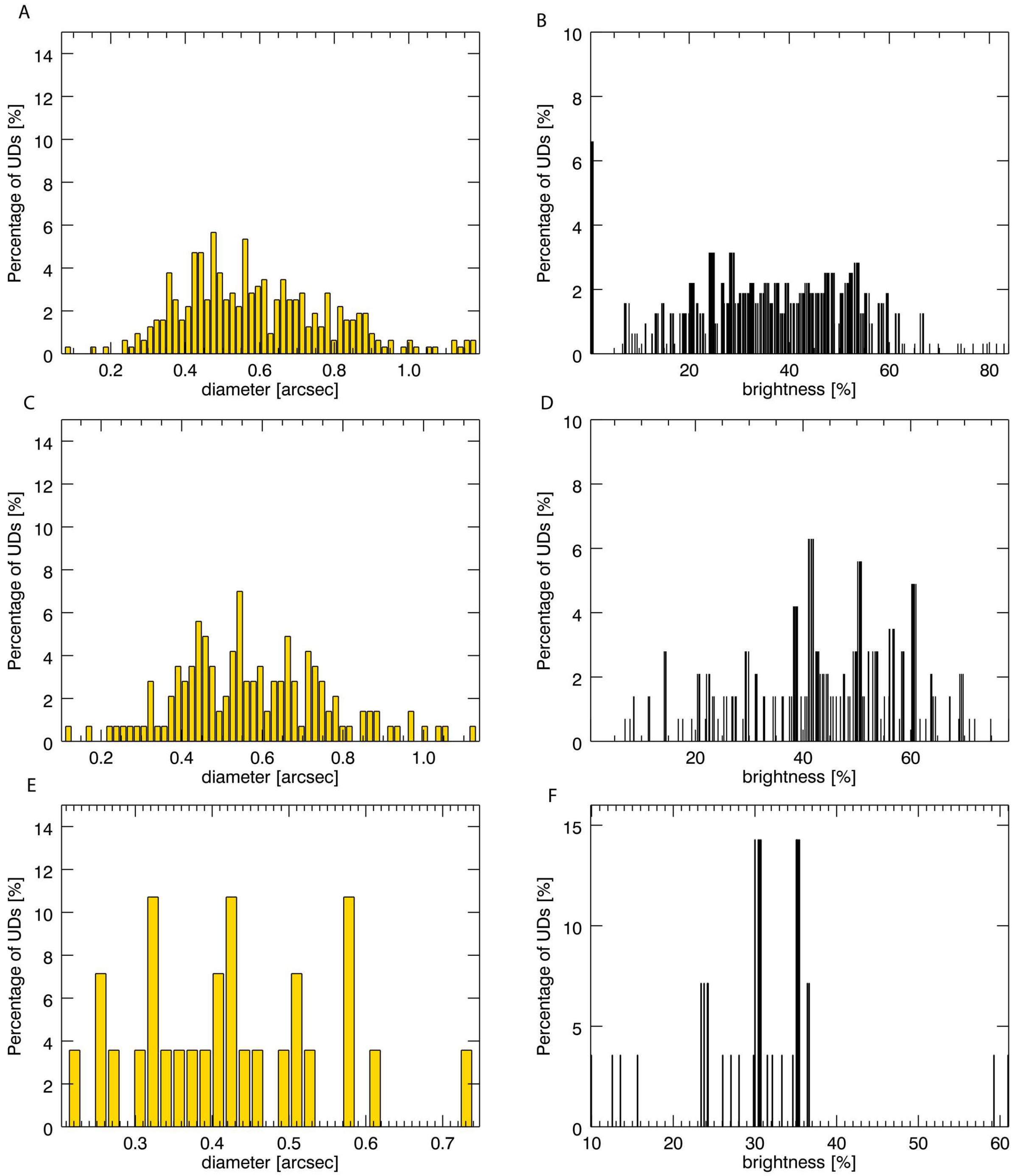

Fig. 2. *Results of the statistical analysis of UDs. Panels A and B represent results for UDs from larger umbra, panels C and D for smaller umbra, while panels E and F represent the results for the UDs observed in pores. Panels A, C and E represent the distribution of diameters of the analysed UDs, while panels B, D and F give the distribution of the difference in intensity between the darkest pixel surrounding the UD and the brightest pixel in UD.*

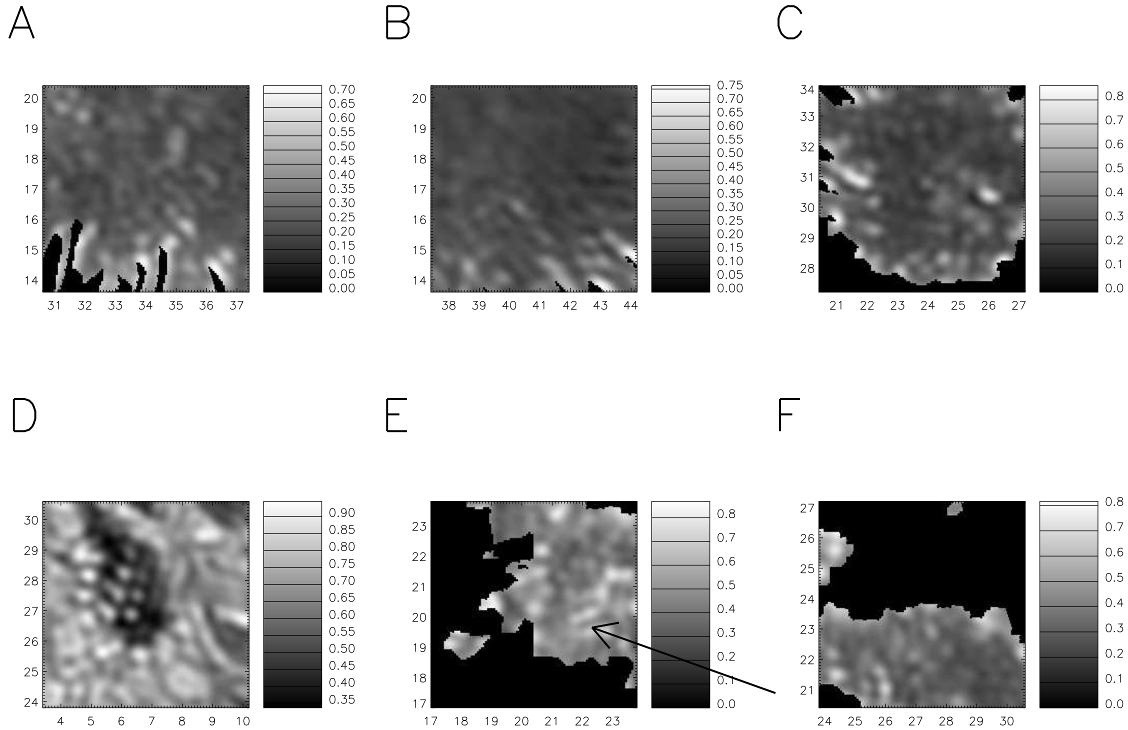

Fig. 3. *The zoomed in areas from Fig. 1. Each panel corresponds to the square marked with the same letter. In the panels A, B, C, E and F we masked out the penumbral structures using the intensity of the image as the criterion. All pixels with the values larger than 0.7 of the maximum intensity value of the whole field of view are masked out. Panel D was not masked out because the pore does not contain the penumbra. Black arrow points at the structure presented in detail in Fig. 5. The colour bars represent the intensity of the panels all of them normalised to the maximum intensity of the whole image from Fig. 1.*

In six zoomed in areas (Fig. 3) UD's appeared to have mostly circular shape. This is hard to notice in the low contrast area of A i B areas, unless one inspects light profiles. The background intensities around UDs vary, posing an additional problem in resolving a dilemma whether the observed structure is a single UD with the dark lane or there are several UDs close together. Different levels of umbral background intensity make hard to accurately measure FWHM of the structure and to distinguish one structure from another. The NST resolution cannot answer the following question: "Are we seeing one UD surrounded with ones of smaller intensity or we see one bigger structure that has different intensity levels across its surface?" (Fig. 4A). Of course, there are UDs that are clearly defined as separate objects, circular, and without any visible substructure (Fig. 4B). In the parts of the umbra that are brighter, the NST can even detect very faint UDs with the qualities of a single structure (Fig. 4C).

In the high contrast areas, (Fig. 3 D, E and F) circular shapes seem to be more apparent. However, Fig. 3 E and F show some elongated structures. The two structures at Fig. 3E located at coordinates $\sim$ (22″.5, 19″.5) are the most similar to the assumed shape of the model (Schüssler and Vögler 2006). The shape smaller in size and similar in shape and the intensity distribution was discussed in Rimmelle (2008, Fig. 4). However, the twin structure from our dataset is most likely a collection of several UDs located close to each other and poorly resolved with the NST resolution in TiO spectral line. This line of thoughts occurs when one inspects intensity profiles of those structures. Fig. 5 presents the same elongated structure visible in Fig. 3E. Intensity profile from Fig. 5 shows that the part of the structure has two intensity peaks located very close to each other. Such a profile might indicate two possibilities: first, a single structure with the dip in the intensity in the middle; second, two close individual structures that cannot be resolved with the achieved angular resolution.

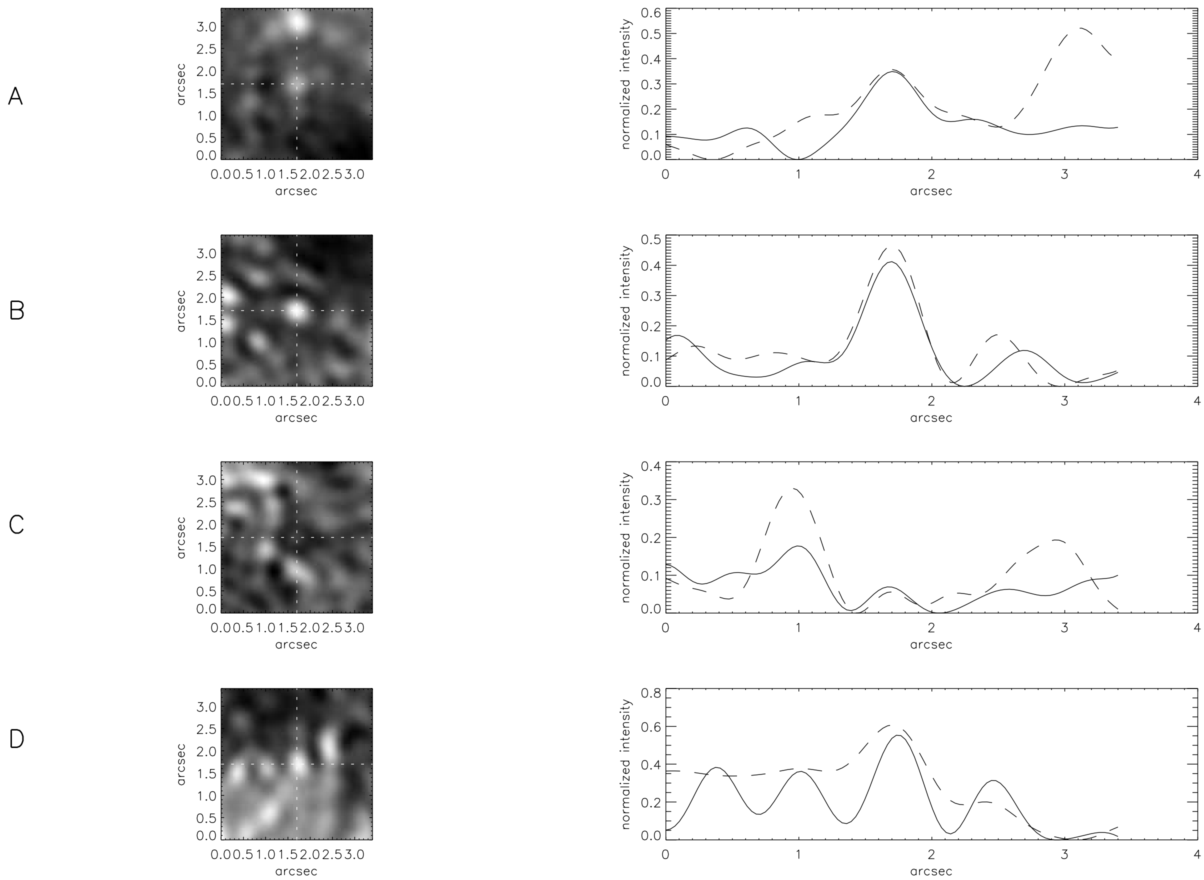

Fig. 4. *Zoomed UDs with the corresponding intensity profiles. Panel A represents a UD located in Fig. 3A. The panel consist of the intensity map of a UD, with the UD in the middle of the frame, and a graph of two intensity profiles from the frame. Profiles are obtained from locations marked with doted lines in a frame. Solid line represents profile the across X axis, while dashed line represent the profile across Y axis. Profiles are made pronounced by subtracting the minimum from the profile and then normalising the profile to the maximum intensity value from the frame itself. Panel B represents UD located in Fig. 3B. Panels C and D represent UDs located in Fig. 3A.*

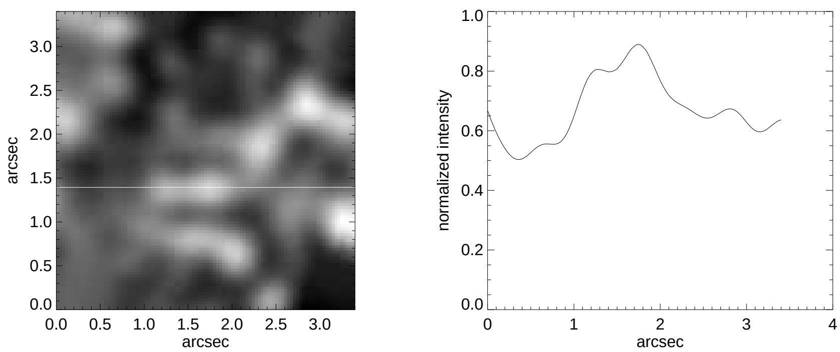

Fig. 5. *The structure with visible dark lane from Fig. 3E. Left panel presents the image of the structure. The image was rotated so that part of the structure is horizontal, the white horizontal line represents the location of the intensity profile in the image. Right panel represents the intensity profile across the horizontal part of the structure.*

4. DISCUSSION

The UDs observed in TiO 705.68 nm spectral line had the median diameter of $\sim 0''.5$, larger than the result from the model by Bharti et al. (2010). This result is also larger than results of Watanabe et al. (2009, 2010) who reported the UDs size of $\sim 0.3''$ using Fe I 630 nm and Fe I 709.04 nm spectral lines respectively; and from the results of Sobotka et al. (1999) and Hamedivafa (2009) who reported the size of $0''.3$ using broad band filters centred at spectral lines of 525.7 nm and 542.5 nm. However, the result is in agreement with the result of Rimmele (2008) who reported that the size of UDs varies from $0''.2$ to $0''.5$ in the G-band line. The difference in size might come from the use of the TiO spectral line. This line has lower contrast than the G-band resulting in the shallower light profiles across intensity map. Thus, measuring the size of the structure using FWHM might lead to larger results (Fig. 4), the additional problem was establishing of the background intensity and thus isolating a single structure. Medium intensity difference between the darkest pixel in the background of the UD and the brightest pixel in UD was maximum 44% (in the pores).

Determination of the background intensity is problematic. Intensity levels differ along the umbra. At this point it is not clear whether this is caused by a topology of the umbra itself, or the plethora of smaller structures in the umbra that are not fully resolved. One possible way to look at this problem is to use the 2D spectrometry with the high angular resolution instrument (such as are at the moment: NST at BBSO, USA; GREGOR at Tenerife observatory, EU; space based missions: HINODE and SUNRISE and eventually ATST at the Hawaiian observatory, USA). Such data would provide informations along several heights revealing the shape of the umbral substructures in 3 spatial dimensions.

A significant number of UDs existed longer than our time series, limiting the measured median existence time to 35 minutes, but in the larger umbra, 60% of the UDs had shorter existance time. This result is in agreement with the work of Sobotka et al. (1999), but in disagreement with works of Hamedivafa (2008) and Watanabe et al. (2009).

Although the UDs observed in this dataset were larger than the UDs predicted by the model, no dark lane was observed. There are two possible explanations:

(1.) TiO 705.68 nm spectral line is formed at the optical height where the dark lane do not appear. Schüssler and Vögler (2006) state that the dark lane is starting to appear at the top of a plume that forms an UD. There is a possibility that TiO spectral line covers the optical heights lower than the ones covered by Iron spectral lines used in previous works. However, at this moment, there is no research that would establish the correct difference between the formation heights of the G-band and TiO bands.

(2.) The second possibility is that the resolution achieved in this work in this spectral line is not sufficient to resolve dark lanes. Rimmele (2008) made an estimate of the size using different spectral lines. The TiO spectral line is weaker and thus produces less contrast (Sinha and Tripathi 1991a,b). There is a possibility that in this spectral line, those substructures appear smaller than the reached diffraction limit due to the lower contrast of the line itself, and thus they were removed by the applied filtering.

The solution for this problem will be achieved with observations in G-band line using the NST 1.6 meter telescope. At this moment a conclusion can be made that in TiO spectral line at 705.68 nm, with the diffraction limit of $0''.1$ umbral dots substructures cannot be observed. Moreover, although the TiO spectral line is seen as a good line to study the umbra, the experience with this data set obtained with the average atmospheric seeing condition indicate that the best course of the action would be the use of stronger spectral lines that are capable to produce better contrast in photometry.

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УМБРАЛНЕ СТУРКТУРЕ ПОСМАТРАНЕ СА 1.6 m СОЛАРНИМ ТЕЛЕСКОПОМ

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Претходно саопштење

Умбралне тачке (UDs) су посматране са 1.6 m соларним телескопом. Дифракциона граница у TiO 705.68 nm спектралној линији је $0''.1$. Анализирано је 418 UDs. Средњи пречник је $0''.5$ и средња разлика интензитета између најтамнијег дела UDs околине и најсветлијег дела UDs је 37%. У прикупљеним подацима, UDs нису показале да имају субструктуру. Већина посматраних UDs су биле округле.