PROPERTIES OF UMBRAL DOTS FROM STRAY LIGHT CORRECTED HINODE FILTERGRAMS

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ABSTRACT

High-resolution blue continuum filtergrams from Hinode are employed to study the umbral fine structure of a regular unipolar sunspot. The removal of scattered light from the images increases the rms contrast by a factor of 1.45 on average. Improvement in image contrast renders identification of short filamentary structures resembling penumbrae that are well separated from the umbra–penumbra boundary and comprise bright filaments/grains flanking dark filaments. Such fine structures were recently detected from ground-based telescopes and have now been observed with Hinode. A multi-level tracking algorithm was used to identify umbral dots (UDs) in both the uncorrected and corrected images and to track them in time. The distribution of the values describing the photometric and geometric properties of UD s is more easily affected by the presence of stray light while it is less severe in the case of kinematic properties. Statistically, UD s exhibit a peak intensity, effective diameter, lifetime, horizontal speed, and a trajectory length of 0.29I1, 272 km, 8.4 minutes, 0.45 km s−1, and 221 km, respectively. The 2 hr 20 minute time sequence depicts several locations where UD s tend to appear and disappear repeatedly with various time intervals. The correction for scattered light in the Hinode filtergrams facilitates photometry of umbral fine structure, which can be related to results obtained from larger telescopes and numerical simulations.

Key words: Sun: photosphere – sunspots – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

The dark umbral background is populated by small, bright features called umbral dots (UDs). The size of UD s ranges from 0′′8 to about 0′′2 based on previous studies by Sobotka et al. (1997a) and Tritschler & Schmidt (2002), while a recent work by Riethmüller et al. (2008b) shows that the size distribution of UD diameters is a maximum around 0′′3 or 225 km, suggesting that most of the UD s are spatially resolved. Sobotka et al. (1997a) also observed that the larger, long-lived UD s are seen in regions of enhanced umbral background intensity. The darkest parts of the umbral core, referred to as dark nuclei, are often devoid of UD s. Based on their relative location, UD s can be classified as “central” and “peripheral.” While the former are seen in the inner regions of the umbra, the latter dominate the umbra–penumbra boundary. Peripheral UD s are usually brighter than the central ones. The intensity of UD s ranges from about 0.2 to 0.7 times the normal photospheric intensity at visible wavelengths. The typical speeds of UD s are ≈400 m s−1 (Sobotka et al. 1997b; Kitai et al. 2007; Riethmüller et al. 2008b; Sobotka & Puschmann 2009). Most mobile UD s emerge near the umbra–penumbra boundary and move toward the center of the umbra (Riethmüller et al. 2008b) with speeds of 700 m s−1. UD s do not have a typical lifetime, with values ranging from 10 minutes to 2.5 minutes (Sobotka et al. 1997a; Riethmüller et al. 2008b; Hamidivafa 2011; Watanabe et al. 2009). The spread in the values arises from the manner in which UD s can be grouped based on their size, lifetime, and spatial location.

Parker (1979) proposed that UD s are manifestations of hot non-magnetized plasma pushing its way in the gappy umbral field. While the detection of such weak fields in the umbra remains elusive, observations indicate a reduction of 300–500 G in UD s (Schmidt & Balthasar 1994; Sotas-Navarro et al. 2004) with the contrasted ones residing in locations where the magnetic field is ≈2000 G and is inclined more than 30′ (Watanabe et al. 2009). Central and peripheral UD s exhibit an enhancement in temperature of 550 K and 570 K, respectively (Riethmüller et al. 2008a). The measurements of Doppler velocities in UD s show that peripheral UD s have an upflow of ≈0.4–0.8 km s−1 (Rimmele 2004; Riethmüller et al. 2008a; Sobotka & Jurčák 2009). Central UD s on the other hand exhibit very weak downflows (Sobotka & Puschmann 2009) while Hartkorn & Rimmele (2003) detected downflows of up to 0.3 km s−1. Ortiz et al. (2010) reported downflows at the edge of UD s measuring 400–1000 m s−1 at a spatial resolution of 0.14′′. Three-dimensional MHD simulations of Schüssler & Vögler (2006), which model UD s as narrow upflowing plumes in regions of intense magnetic fields, predicted a central dark lane in UD s, which was subsequently verified from high-resolution ground-based observations (Rimmele 2008; Sobotka & Puschmann 2009; Ortiz et al. 2010) as well as from space (Bharti et al. 2007). Recent observations from the 1.6 m New Solar Telescope (NST) indicate that UD s are not perfectly circular but possess a mean eccentricity of 0.74 in the photosphere (Kilcik et al. 2012).

The extent to which UD s can be resolved depends on the spatial resolution, which is presently 0′′14 (Sobotka & Puschmann 2009; Ortiz et al. 2010) for a 1 m ground-based telescope at 450 nm. This has been made possible with the aid of adaptive optics and post-processing techniques to minimize the contribution from “seeing.” On the other hand, Hinode (Kosugi et al. 2007) with a 50 cm aperture in space has a resolution of 0′′23 at the same wavelength and can operate for long periods in

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the absence of Earth’s atmospheric turbulence. Furthermore, since UDs are present in the darkest regions of sunspots, contamination by stray light can strongly influence photometric investigation of these structures. The motivation of this paper is to study the influence of stray light on the properties of UDs using \textit{Hinode} data and how its removal compares with existing high-resolution ground-based observations as well as numerical simulations. This exercise has been done taking into account the trade off between marginally coarser spatial resolution and simulations. The rest of the paper is organized as follows. The observations are described in Section 2 and the results are presented in Section 3. In Section 4, we summarize our findings and discuss their implications.

2. OBSERVATIONS AND DATA PROCESSING

We utilize high-resolution blue continuum filtergrams of the sunspot in NOAA AR 10944 acquired by the Broadband Filter Imager of the Solar Optical Telescope (SOT; Tsuneta et al. 2008), on board \textit{Hinode} from 00:14 to 02:34 UT on 2007 March 1. The sunspot was located very close to disk center (N0.7W4) at a heliocentric angle of $\Theta = 4^\circ$. The 1024 $\times$ 512 filtergrams had a pixel sampling of 0"054 and were taken at a cadence of 6 s with an exposure time of 102 ms. Initial processing of Level-0 data to Level-1 included dark correction, flat fielding, and removal of bad pixels, and was carried out using the “fg_prep” routine in SolarSoft. The images were subsequently co-aligned using a two-dimensional (2D) cross-correlation routine.

In order to reduce the noise in the dark regions of the umbra, four successive filtergrams were added to yield a sequence of 326 images with a cadence of $\sim 26$ s. The averaging was carried out to keep the temporal resolution identical to the analysis of Watanabe et al. (2009) who had previously studied the same active region with the above data set. Applying the running average to the filtergrams leads to a reduction of power especially in the high spatial frequency domain as shown in the top panel of Figure 1, which depicts the azimuthally averaged power spectrum. The bottom panel of Figure 1 illustrates the difference in power between the single and mean image as a function of the spatial scale. Since the power is proportional to the square of the intensity, the relative intensity difference between the images varies from 2% to 5% for spatial scales of 0''2 and 0''5, respectively. This implies that averaging successive filtergrams should not significantly affect the detection of small-scale structures within the umbra. We estimate the intensity fluctuations in the umbra to be 1.5% of the quiet-Sun (QS) intensity. This value corresponds to three times the standard deviation of a small region in the umbral dark core. Averaging the filtergrams reduces the noise by $\approx 6\%$.

\textit{Instrumental stray light}. The blue continuum filtergrams were corrected for instrumental stray light using the point-spread function (PSF) described by Mathew et al. (2009). This PSF was derived from transit observations of Mercury on 2006 November 8. Mathew et al. (2009) showed that the removal of stray light renders an improvement in the contrast of bright points in the QS by a factor of 2.4–2.75 at 430 nm. As the transit observations were taken close to disk center, the same PSF was utilized for removing stray light in the blue continuum filtergrams. The PSF is a weighted linear combination of four Gaussians (see Table 1 of Mathew et al. 2009). The deconvolution is carried out using an IDL maximum likelihood routine$^\text{6}$ (Richardson 1972; Lucy 1974). The method uses the instrument PSF to iteratively update the current estimate of the image by the product of the previous deconvolution and the correlation between re-convolution of the subsequent image and the PSF. The algorithm can be expressed as follows:

\[
I = O \ast P.
\]  

The Image ($I$) is a result of the convolution between the Object ($O$) and the PSF ($P$). Given $I$ and $P$, the most likely $O$ can be iteratively determined as

\[
O^{t+1} = O^t \ast \left( \frac{I}{C} \ast \text{conj} P \right),
\]  

where $C = O^t \ast P$ under the assumption of Poisson statistics. Here, $t$ refers to the iteration cycle.

The corrected and uncorrected sequences were subsequently normalized to the QS intensity. Figure 2 shows a typical scatter plot of intensities in a corrected filtergram and the corresponding uncorrected image. Following stray light correction, the minimum umbral intensity corresponding to the dark umbral core, reduces from 0.1$I_{\text{QS}}$ to 0.05$I_{\text{QS}}$, which is above the estimated noise level in the filtergrams. In addition, the fraction of pixels in the umbra having an intensity less than 0.3$I_{\text{QS}}$ in both Figure 1. Top: azimuthally averaged power spectra of single (solid line) and average of four blue continuum filtergrams (cross symbol). Bottom: difference in power spectra of a single and average filtergram as a function of spatial scale (gray plus symbols). The black cross symbols represent average values of the difference in bins of 0''05 with the vertical bars denoting the rms value.

\textsuperscript{6} Called Max_Likelihood.pro, from the AstroLib package.
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Figure 2. Change in umbral intensity after removal of stray light. Displayed is a scatter plot of uncorrected \(I_{\text{uncorr}}\) and corrected \(I_{\text{corr}}\) blue continuum intensity in the umbra. Note that the axes are scaled differently. The solid and dashed lines refer to the intensity histograms of the CR and UN filtergrams, respectively, with a bin size of 0.01\(I_{\text{QS}}\). A magnified version of the trailing halves of the histograms is shown in the inset.

sets of images is \(\approx 93\%\). The removal of stray light decreases the mean umbral intensity from 0.202\(I_{\text{QS}}\) to 0.167\(I_{\text{QS}}\) while the rms contrast increases from 0.059 to 0.086, which is a factor of 1.45. The middle and bottom panels of Figure 3 show the uncorrected and corrected images, respectively. The umbral region is extracted from the sunspot shown as the contoured region (top panel of Figure 3). The stray light corrected image exhibits various fine scale features which are described in the following section. Hereafter “uncorrected” and “corrected” will be referred to as UN and CR, respectively.7

3. RESULTS

3.1. Umbral Fine Structure

1. Short filaments. Figure 3 depicts three examples of short filaments (shown in dashed circles) near the periphery of the umbra that closely resemble penumbral filaments. These short structures have varying lengths with a dark lane and two adjacent brightenings, and a bead-like brightening at the tip of the filament facing the umbra. The width of the filaments shown in the figure range from 165 to 200 km, where the latter can be considered an upper limit for these structures. These dark filaments are similar to the ones reported by Rimmele (2008) and Sobotka & Puschmann (2009) and in numerical simulations (Rempel et al.2009b). However, to the best of our knowledge this is the first time that such filaments have been seen in Hinode observations. Their morphology is different from the traditional dark lane associated with UDs as observed by Rimmele (2008), Sobotka & Puschmann (2009), and Ortiz et al. (2010). The filament indicated by the largest circle in the bottom panel of Figure 3 partially obscures a neighboring filament to its right.

Figure 4 depicts the temporal evolution of a set of dark filaments and bright UDs. One can identify at least two main filaments labeled F1 and F2. The time separation between individual frames is 100 s. The lifetime of F1 and F2 is estimated to be 18 and 10 minutes, respectively.

These values can be regarded as lower limits since both of them were present from the start of the sequence. The black plus symbol marks the position of a bright grain/UD that is seen during the chosen sequence. The UD starts at the end of F2 and ends adjacent to F1 on its left. The total displacement of the UD from frames 1 to 11 (cross symbol) is \(\approx 0\;\text{arcsec}\) for the 18 minute sequence. In general, these localized brightenings/UDs move from the tip/end of one filament onto the flank of another. This motion is continued until they can no longer be distinguished from the background. The dark filaments usually maintain their

\[\text{Figure 3. Improvement in image contrast after removal of stray light. Top: sunspot in NOAA AR 10944. The white contour refers to the umbral area chosen for analysis. The dotted white box represents a selected field of view shown in Figure 4. Middle: magnified view of umbra before stray light correction. Bottom: stray light corrected image. The images in the middle and bottom panels have been scaled identically. The white dashed circles enclose short filaments that are described in Section 3.1.}\]
form during the motion of the UDs after which they can either diffuse or break up into even smaller dark segments.

2. Light bridges. In addition to UDs, sunspot umbrae often exhibit light bridges (LBs). These can be broadly classified into two categories, namely—strong and faint (Sobotka et al. 1993, 1994). While the former split the umbra into individual cores and represent an abrupt change in the umbral morphology, the latter are usually less than 1″ in width and are composed of a chain of UDs. The top panel of Figure 3 shows the umbra to be devoid of any large-scale structuring, but Figure 5 indicates a faint LB near the right-hand side of the umbra, that is nearly horizontally orientated above an umbral dark core. The image is an average of 120 filtergrams covering a 50 minute duration. The LB consists of several bright grains resembling UDs whose width is ≈0′.23 and is close to the resolution limit of Hinode. The average grain spacing on the LB is estimated to be 0′.25 while the length of the LB is nearly 3″.8.

Figure 6. Depiction of MLT algorithm for three intensity levels. The original image comprises of an arbitrary distribution of intensities. The maximum and minimum intensity range is split into three intermediate levels and the objects are sequentially tagged from the highest to the lowest level. The object boundary is determined using the background image from which the features can be isolated as shown in the bottom right panel.

3.2. Properties of UDs

This section describes the physical properties of UDs, which were determined from the time sequence of the UN as well as CR blue continuum image sequences. Identifying and tracking of UDs involve the following steps.

1. Defining the umbra–penumbra boundary. The sequence of CR images is added to obtain a mean image. After smoothing the mean image using a 11 × 11 pixel boxcar, the umbra–penumbra boundary is defined by a single continuous contour corresponding to an intensity of 0.3IQS. This contour is used to construct a binary mask that allowed us to extract the umbral region from individual images.

2. The identification of UDs was carried out using a 2D multi-level tracking (MLT; Bovelet & Wiehr 2001) algorithm that has been described by Riestmühler et al. (2008b) for detecting UDs. The algorithm identifies objects at different intensity levels starting from the highest level and tagging them uniquely while progressing to lower intensities, until the minimum level is reached. The number of objects (NOs) detected depends on the number of levels (NLs) defined. The latter was chosen by implementing the algorithm for different levels and counting the total NOs detected. For both the UN and CR images, the NOs increase exponentially with the NLs. A nonlinear least-squares fit provided an optimal value of 33 and 25 intensity levels for the UN and CR images, respectively. The above values correspond to the knee of the best fit.

3. Defining the background image. The thin plate spline technique (Barrodale et al. 1993) was employed to construct the background umbral image, i.e., the intensity distribution in the absence of UDs. Each UD is defined by the intensity contour corresponding to \((I_{\text{max}} + I_{\text{bg}})/2\), where \(I_{\text{max}}\) and \(I_{\text{bg}}\) refer to the maximum/peak and background intensity, respectively. Figure 6 depicts the functionality of the algorithm based on three levels for an arbitrary distribution of features. For each UD, the following quantities are determined: \(I_{\text{max}}, I_{\text{bg}}, I_{\text{mean}}, \text{ and } D_{\text{eff}}\). The effective diameter \(D_{\text{eff}}\) expressed in km is calculated as \(\sqrt{4A/\pi}\), where \(A\) is the total number of pixels. In addition, the spatial location
of the maximum intensity ($X_p$, $Y_p$) is also noted. This information is required to track the UDs in the image sequence. Before saving the above information for each UD, the routine also checks whether the UDs are separated from the umbral–penumbral boundary. Only those features that are at least 2 pixels inward from the edge of the umbral mask are saved and considered for analysis. The fraction of objects that did not get filtered using the above criteria is less than 5%.

4. **Tracking the UDs in time.** Each UD is identified in the successive frame if $X^i_p$, $Y^i_p$, and $X^{i+1}_p$, $Y^{i+1}_p$ are at the most 1 pixel apart (where $i$ refers to the frame index). The condition of 1 pixel separation is to ensure that the horizontal speed of the UD does not exceed 1.5 km s$^{-1}$, which is obtained from the spatial sampling of $0.05$ and a cadence of 26 s. If a UD cannot be identified in the current frame, the tracking is extended to two successive frames. If this also fails, the tracking is terminated.

5. Once tracking is completed, the following additional properties are determined from the UD trajectories: lifetime ($T$), horizontal speed ($V$), birth–death distance ($L_{bd}$), and trajectory length ($L_{t}$). The effective diameter as well as the mean, maximum, and ratio of maximum-to-background intensities are averaged over the trajectory of the UD. The horizontal velocity is calculated as the ratio of the trajectory length and the lifetime.

6. Categorizing UDs into peripheral and central is carried out using a second boundary that lies $≈0.8$ inward from the original umbral mask. UDs that originate in between these two contours are labeled as peripheral and the rest as central.

Figure 7 shows the histogram of the various physical properties of all UDs (central and peripheral) whose lifetime exceeds 50 s (two frames). These UDs constitute $≈95\%$ of the total NOs detected and tracked in both time sequences. The histograms have been normalized to unity for comparison. The bin size of the quantities corresponding to the UN and CR data is identical. We now turn to the quantitative differences between the physical properties of UDs derived from the UN and CR sets and whose mean values are summarized in Table 1.

1. **Intensity.** Removal of stray light produces an extended tail in the histogram while the peak and minimum shift to moderately lower values similar to what was seen in Figure 2. This is more evident in the histogram of peak intensity ($I_{max}$). The average value of $I_{mean}$ and $I_{max}$ are 0.24 and 0.26$I_{QG}$, respectively, for the UN set while the same for the CR sequence are 0.24 and 0.29$I_{QG}$, respectively. The histogram of $I_{mean}$ peaks at 0.21 and 0.13$I_{QG}$ for the UN and CR data, respectively, while for $I_{max}$ the distribution peaks at 0.16 and 0.19$I_{QG}$, respectively, which is in agreement with Hamedivafa (2011). The maximum intensity of peripheral UDs is on an average 36% greater than that of the central ones after stray light correction.

The distribution of $I_{max}/I_{bg}$ peaks at 1.18 and 1.58 for the UN and CR sequences, respectively. In case of the latter the histogram exhibits a conspicuous tail with $I_{max}$ being $≈4$ times greater than $I_{bg}$ for nearly 3% of the UD population. As a result, the estimated mean value of the ratio becomes 2.5 in comparison to 1.48 in the UN sequence. Such a trend is similar to the area histogram of continuum intensity at 630 nm obtained for numerically simulated UDs (Bharti et al. 2010).

2. **Size.** Stray light removal reduces the mean effective UD diameter from 295 km to 272 km. The histogram for the latter is narrower and shows a strong peak at 257 km while the former is more broader with a maximum around 288 km. For the CR sequence, central and peripheral UDs have a mean effective diameter of 298 km and 239 km, respectively, which is consistent with the findings of Riethmüller et al. (2008b). The sizes of peripheral UDs are smaller than those of central UDs, which is similar to that found by Riethmüller et al. (2008b). Bharti et al. (2010) state that the average diameter of simulated UDs is $≈320$ km with the histogram suggesting that UDs do not have a typical size. In comparison, the histograms of the effective diameter shown in Figure 7 and that obtained by Riethmüller et al. (2008b) tend to be nearly symmetrical.

3. **Horizontal speed.** Central as well as peripheral UDs tend to be mobile with speeds of $≈510$ and 460 m s$^{-1}$, respectively, for the UN set. In the CR sequence, the speeds of central and peripheral UDs tend to be nearly the same, 460 and 440 m s$^{-1}$, respectively, which is in good agreement with Kilcik et al. (2012). Riethmüller et al. (2008b) find peripheral UDs to be faster than central ones by 40 m s$^{-1}$, respectively, while Watanabe et al. (2009) report a difference of 170 m s$^{-1}$. Although the above values show peripheral UDs to be slower than central UDs, the maximum speed of the former is nearly 200 m s$^{-1}$ greater than the latter. In addition, the difference in the value is small compared with the spread in the distribution. The reduced speed of peripheral UDs in our case could be attributed to the umbral region defined by the mask described earlier. Nearly 15% of the population tend to be stationary in both sequences. Figure 7 shows that the overall trend of the histograms for the UN and CR sets

| Parameter   | All UDs | Central UDs | Peripheral UDs |
|-------------|---------|-------------|----------------|
|             | No Stray Corr. | With Stray Corr. | No Stray Corr. | With Stray Corr. | No Stray Corr. | With Stray Corr. |
| $I_{mean}$ ($I_{QG}$) | 0.24 ± 0.07 | 0.24 ± 0.13 | 0.21 ± 0.05 | 0.21 ± 0.09 | 0.27 ± 0.08 | 0.28 ± 0.16 |
| $I_{max}$ ($I_{QG}$) | 0.26 ± 0.09 | 0.29 ± 0.17 | 0.23 ± 0.06 | 0.25 ± 0.12 | 0.30 ± 0.10 | 0.34 ± 0.21 |
| $I_{max}/I_{bg}$ | 1.48 ± 0.34 | 2.50 ± 1.26 | 1.43 ± 0.28 | 2.33 ± 0.91 | 1.54 ± 0.39 | 2.72 ± 1.57 |
| $D_{bd}$ (km) | 295 ± 101 | 272 ± 68.0 | 337 ± 81.0 | 298 ± 54.0 | 241 ± 98.0 | 239 ± 69.0 |
| $V$ (km s$^{-1}$) | 0.49 ± 0.35 | 0.45 ± 0.32 | 0.51 ± 0.36 | 0.46 ± 0.32 | 0.46 ± 0.33 | 0.44 ± 0.32 |
| $T$ (minutes) | 8.80 ± 11.9 | 8.40 ± 10.5 | 7.10 ± 8.70 | 8.90 ± 11.7 | 10.9 ± 14.7 | 7.80 ± 8.70 |
| $L_{bd}$ (km) | 94. ± 120 | 112 ± 144 | 90. ± 109 | 109 ± 143 | 100 ± 133 | 115 ± 145 |
| $L_{t}$ (km) | 240 ± 314 | 221 ± 283 | 215 ± 271 | 233 ± 309 | 271 ± 360 | 206 ± 245 |

**Note.** The numbers in the parentheses denote the number of UDs in that group.
Figure 7. Histogram of various UD properties for both time sequences. Mean intensity—$I_{\text{mean}}$, maximum intensity—$I_{\text{max}}$, maximum-to-background intensity ratio—$I_{\text{max}}/I_{\text{bg}}$, effective diameter—$D_{\text{eff}}$, horizontal speed—$V$, lifetime—$T$, birth–death distance—$L_{\text{bd}}$, and trajectory length—$L_{\text{tj}}$. Bin sizes are 0.05$I_{\text{QS}}$, 0.15, 40 km, 100 m s$^{-1}$, 2 minutes, 50 km, and 75 km, respectively. The gray shaded and unshaded histograms correspond to the UN and CR time sequences, respectively. The $y$-axis represents the fraction of UDs in each bin.

are quite similar with some minor differences in the leading half of the distribution.

4. Lifetimes. UDs do not exhibit a typical lifetime as is evident from Figure 7 (second column third row). The distribution is exponential with the peak coinciding with the smallest lifetime bin. With a cutoff of 75 s, our analysis puts the mean value of central and peripheral UDs at 8.9 and 7.8 minutes, respectively, for the CR image sequence. This is consistent with lifetimes obtained by Hamedivafa (2008) and Riethmüller et al. (2008b). According to Hamedivafa (2011), who obtained a similar exponential distribution, central and peripheral UDs have a typical half-life of 5 and 3 minutes, respectively, while Watanabe et al. (2009) report moderately smaller lifetimes of 6.5 and 7.8 minutes, respectively. These values however are much smaller than the ones obtained by Bharti et al. (2010), who report mean values of $\approx$25 minutes for simulated UDs. UDs that are present at the beginning or at the end of the time series
constitute only 5% of the total number and do not influence the lifetime histogram.

5. Trajectory. The bottom panels of Figure 7 correspond to the birth–death distance and trajectory length of UDs, respectively. The overall distribution of the above quantities appear quite similar in both image sequences. Nearly 55% of the UD population have trajectory lengths of less than 150 km and mean horizontal speeds of 375 m s\(^{-1}\). By comparison, the rest of the group are relatively mobile with speeds of 550 m s\(^{-1}\). The relation between \(L_I\) and \(L_{bd}\) shown in Figure 8 illustrates that for a given trajectory length there exists a range of birth–death distances. However, the maximum value of \(L_{bd}\) varies linearly for any \(L_I\) or even when the latter is averaged within a certain length range. The linear relation is shown for the square symbols, which correspond to the maximum birth–death distance for a given trajectory length within bins of 100 km.

The trajectories of UDs from their point of origin to death are shown in Figure 9. These paths have been overlaid on the time-averaged image from the stray light CR sequence. The figure only shows the trajectories of those UDs whose lifetime exceeds 10 minutes. These features constitute 23% of the UD population. Peripheral UDs have a tendency to move inward into the umbra with a nearly linear trajectory. At least two strong dark cores can be identified in the umbra, which have been labeled DC1 and DC2 in the figure. One finds that UDs tend to gather or terminate near the edges of these dark cores, which is qualitatively in agreement with Watanabe et al. (2009). Furthermore, there does not appear to be a strict segregation of the nature of trajectories on the basis of the location/origin of UDs. For instance, UDs with nearly linear radial tracks are not necessarily confined to the periphery of the umbra while those with squiggly trajectories having birth–death distances less than 200 km are mostly located in the inner regions of the umbra. The latter are observed particularly in the bright parts of the umbra including the region between DC1 and DC2 as well as the LB on the northern boundary of DC1.

Table 2 lists the linear correlation coefficients (CCs) between various properties for both UN and CR sequences (values within parentheses for the latter). The CCs are calculated between \(V\), \(T\), \(L_{bd}\), as well as \(L_I\) with \(I_{\text{max}}\) and \(D_{\text{eff}}\). CCs greater than 0.3 are shown in boldface. The peak intensity of UDs is poorly correlated with its horizontal speed. If one considers the correlation between the peak intensity at the point of origin of \(L_{bd}\) for a given trajectory \(I_{\text{max}}\) and \(T\), the correlation is shown to be moderate. CCs greater than 0.5 are shown in boldface. The peak intensity of UDs is not strongly correlated with its horizontal speed. If one considers the correlation between the peak intensity at the point of emergence with the average velocity (total distance/total time), there is no substantial change from the values cited in the table. Brighter, central UDs have larger birth–death distances as well as trajectory lengths as indicated by the moderate CC that is seen in both the UN and CR sets. However, the CC worsens in the case of peripheral UDs which tends to bring down the same for the entire sample of UDs.

Table 2

| Correlation Between | All UDs | Central | Peripheral |
|---------------------|---------|---------|------------|
| \(I_{\text{max}}\) and \(V\) | \(-0.06(-0.004)\) | \(-0.04(0.01)\) | \(-0.01(0.01)\) |
| \(I_{\text{max}}\) and \(L_{bd}\) | \(0.24(0.31)\) | \(0.35(0.45)\) | \(0.20(0.25)\) |
| \(I_{\text{max}}\) and \(L_I\) | \(0.25(0.27)\) | \(0.30(0.39)\) | \(0.22(0.25)\) |
| \(I_{\text{max}}\) and \(T\) | \(0.33(0.28)\) | \(0.34(0.38)\) | \(0.30(0.29)\) |
| \(D_{\text{eff}}\) and \(V\) | \(0.21(0.20)\) | \(0.09(0.13)\) | \(0.27(0.26)\) |
| \(D_{\text{eff}}\) and \(T\) | \(0.08(-0.04)\) | \(0.27(-0.13)\) | \(-0.18(-0.06)\) |
| \(D_{\text{eff}}\) and \(L_{bd}\) | \(0.21(0.02)\) | \(0.16(-0.16)\) | \(0.31(0.16)\) |
| \(D_{\text{eff}}\) and \(L_I\) | \(0.04(0.03)\) | \(0.28(-0.10)\) | \(-0.05(0.08)\) |
| \(V\) and \(L_{bd}\) | \(0.25(0.23)\) | \(0.23(0.17)\) | \(0.27(0.33)\) |
| \(T\) and \(L_{bd}\) | \(0.36(0.89)\) | \(0.90(0.91)\) | \(0.84(0.86)\) |
| \(T\) and \(V\) | \(-0.03(-0.02)\) | \(-0.01(-0.05)\) | \(-0.03(0.02)\) |

Notes. The values shown in the table correspond to the uncorrected sequence while those in parentheses represent correlations from the stray light corrected set. CCs greater than 0.3 are shown in boldface.
suggest that there are regions along trajectories that are traced by subsequent UDs. This would of UDs is poorly correlated with its horizontal speed. The lifetime trend is expected since the trajectory length is dependent on the other hand, are strongly correlated with trajectory lengths. This peripheral UDs exhibit a better, although moderate, correlation distance for peripheral UDs. In comparison to central UDs, Figure 10.

Top: histograms of time delays associated with each event class: BB (gray), BDB (solid black), DD (black dotted). Bottom: spatial distribution of the occurrences of all three event classes (see the text), which are indicated by the plus, triangle, and cross symbols, respectively. The color coding indicates the normalized time delay associated with that spatial location for each event class. BB: Birth–Birth, BDB: Birth–Death–Birth, and DD: Death–Death. (A color version of this figure is available in the online journal.)

distance for peripheral UDs. In comparison to central UDs, peripheral UDs exhibit a better, although moderate, correlation between mobility and trajectory lengths. The lifetimes, on the other hand, are strongly correlated with trajectory lengths. This trend is expected since the trajectory length is dependent on the number of frames for which the feature is tracked. The lifetime of UDs is poorly correlated with its horizontal speed.

3.3. Spatial and Temporal Coincidence

The time sequence movie reveals that UDs tend to move along trajectories that are traced by subsequent UDs. This would suggest that there are regions/pockets in the umbra that favor the emergence and disappearance of UDs. There could also exist a time delay or a set of delays between the appearance of one UD and the emergence/disappearance of another at the same spatial location. This aspect is dealt with in the following manner. From the information table of each UD, one can extract the time interval between the (1) birth of two UDs, (2) birth of one UD with the death of another and vice versa, and (3) death of two UDs, where all three classes of events refer to the same spatial location. These events can be referred to as birth–birth (BB), birth–death–birth (BDB), and death–death (DD), respectively. We confine our analysis and discussion to central UDs, since the origin of peripheral UDs is predominantly in the penumbra (Sobotka & Jurčák 2009; Watanabe et al. 2009).

The top panel of Figure 10 shows the distribution of the number of events in the three classes for all UDs whose lifetime exceeds 150 s. The histograms indicate that there is no unique time lag between successive events in either class, although BDB and DD have a tendency to have shorter time delays than the BB class. Mean time delays of 45.5, 52.0, and 49.8 minutes were estimated for the three classes, respectively. If the minimum lifetime of the UDs is varied in the range 50 s to 10 minutes, the mean value of the distribution in all three event classes are limited within ±5 minutes of the above values. Taking the average time delay for this range of lifetimes, one obtains 46, 53, and 47 minutes for the each event class, respectively. By comparison, the number of events in BB are fewer than the other two for any given minimum lifetime. However, for short-lived UDs ($T < 150$ s), the number of BB and DD events are comparable with mean time delays of 45, 46, and 52 minutes in the three classes, respectively.

The bottom panel of Figure 10 shows the spatial distribution of the occurrences of all three event classes, which are indicated by the plus, triangle, and cross symbols, respectively. The color corresponds to the normalized time delay associated with that spatial location for each event class. The figure indicates that the pockets of sustained emergence as well as disappearance are scattered everywhere in the umbra with no specific pattern in the distribution. The figure also shows that a particular spatial location is not limited to the event class as at least 12 and 20 instances were estimated to be common to BB and BDB and BDB and DD, respectively. While a similar characteristic of spatial coincidence of inter event classes is seen for UDs with lifetimes of less than 2 minutes, the number of coincidences is higher, namely, 19 cases each for the above two inter event classes. This would suggest that short-lived UDs tend to reappear or emerge from the point of disappearance of former UDs.

4. SUMMARY AND DISCUSSION

We employ a 2 hr 20 minute time sequence of high-resolution blue continuum filtergrams of the sunspot in NOAA AR 10944 from Hinode SOT to determine the properties of UDs and analyze the umbral fine structure after careful removal of instrumental stray light. The motivation of our study stems from the fact that stray light reduces image contrast, which could influence the photometric and geometric properties of umbral features. After deconvolving the filtergrams with an instrumental PSF, whose wings describe the scattered light in the telescope, we find that the rms contrast of the images increases by a factor of 1.45. In addition, the mean umbral intensity decreases by ≈17%.

With scattered light accounted for, one is able to identify short filamentary structures resembling penumbral but well separated from the umbra–penumbra boundary. The features consist of a dark filament with bright filaments/grains adjacent to it. The width of the dark filament is at the resolution limit of Hinode, suggesting that these structures are largely unresolved. Their lifetimes are of the order of 10–20 minutes during which bright grains can transit from one filament to another remaining close to the dark filament. The existence of similar features...
Table 3
Comparison of a Few Physical Properties Obtained Previously from Hinode, Ground-based Observations and Numerical Simulations

| Reference Source | UD Identification Algorithm | \(D_{\text{eff}}\) (km) | \(I_{\text{max}}/I_{\text{bg}}\) | \(V\) (km s\(^{-1}\)) | \(T\) (minutes) |
|------------------|-----------------------------|------------------------|-----------------------------|------------------------|----------------|
| No stray light correction | Hinode | MLT | 295 ± 101 | 1.48 ± 0.34 | 0.49 ± 0.35 | 8.8 ± 11.9 |
| Watanabe et al. (2009) | Hinode | Intensity thresholding | 184 | 1.73 | 0.44 | 7.35 |
| With stray light correction | Hinode | MLT | 272 ± 68 | 2.50 ± 1.26 | 0.45 ± 0.32 | 8.4 ± 10.5 |
| Hamedivafa (2008) | 0.5 m SVST | Low-noise curvature detection | 230 | <1.0 | 0.42 ± 0.20 | 10.5 ± 10.5 |
| Riethmüller et al. (2009b) | 1.0 m SST | MLT | 272 ± 53 | 1.17 ± 0.1 | 0.42 ± 0.20 | 10.5 ± 10.5 |
| Sobotka & Puschmann (2009) | 1.0 m SST | Low-noise curvature detection | 125 | 2.4 | 0.34 | 9.1 |
| Kilcik et al. (2012) | 1.6 m NST | Area & intensity thresholding | 254 | ... | 0.45 | 8.19 |
| Rempel et al. (2009a) | Simulations | Area & intensity thresholding | 295 | ... | 0.35 | 12.9 |
| Bharti et al. (2010) | Simulations | MLT | 420 | 2.88 | ... | 25.1 |

has already been reported by Rimmele (2008) and Sobotka & Puschmann (2009) based on ground-based observations from larger telescopes as well as from numerical simulations (Rempel et al. 2009b). We, however, do not find sub-structures in UDIs, namely, the dark lanes, which represent hot convective plumes, since they are still below the detection capability of Hinode. The observations of Bharti et al. (2007) are reminiscent of fragments where these events occur in the umbra and in general do not highlight a specific pattern. In addition, there are several pixels where events from either class can overlap. This would suggest that UDIs tend to reappear or emerge from the location of disappearance of former UDIs.

Table 3 gives mean values of a few properties obtained previously from Hinode, ground-based observations, and numerical simulations. The values obtained from the UN sequence are in good agreement with those reported by Watanabe et al. (2009) for the same data set described in this paper, although they employed a different identification routine. On the other hand, the corresponding values obtained from the stray light CR images are consistent with Hamedivafa (2008), Riethmüller et al. (2008b), and Kilcik et al. (2012). The ratio of maximum-to-background intensity \(I_{\text{max}}/I_{\text{bg}}\) is particularly in good agreement with those obtained by Sobotka & Puschmann (2009) and Bharti et al. (2010). There appears to be some differences between the results derived from numerical simulations by Rempel et al. (2009a) and Bharti et al. (2010), which show UDIs to be larger, slower, and longer-lived than those retrieved from observations. The deviations between the two sets of simulations could be attributed to the boundary conditions and the treatment of numerical diffusivities (Kilcik et al. 2012). In the case of observations, there is general consensus that UDIs are typically 250 km in diameter and have lifetimes of 10 minutes and horizontal speeds of 450 m s\(^{-1}\). Another point of disagreement between simulations and observations is the ubiquitous presence of UDIs in the former that do not give any indication of structuring in the umbra, i.e., faint LBs and umbral dark cores.

With the exception of intensity versus diameter, none of the UD properties are well correlated with each other (Kilcik et al. 2012). In simulations, the CC is nearly 0.6 but can vary between 0.02 and 0.3 depending on the sample of UDIs taken from relatively bright locations in the umbra (Kilcik et al. 2012). The monotonicity seen in simulations exists with a significant scatter between the intensity and diameter of UDIs. The differences between observations and simulations need to be addressed with complementary polarimetric observations at high spatial resolution (<0.15), which could provide additional constraints for MHD models. This is necessary for determining the physical mechanisms driving UDIs and their kinematics, for which instruments such as the CRISP (Scharmer et al. 2008) and the Gregor Fabry-Pérot Interferometer (Denker et al. 2010) will be crucial.

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