Umbral Fine Structures in Sunspots
Observed with Hinode Solar Optical Telescope

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Abstract

A high resolution imaging observation of a sunspot umbra was made with the Hinode Solar Optical Telescope. Filtergrams at wavelengths of the blue and green continua were taken during three consecutive days. The umbra consisted of a dark core region, several diffuse components, and numerous umbral dots. We derived basic properties of umbral dots (UDs), especially their temperatures, lifetimes, proper motions, spatial distribution, and morphological evolution. The brightness of UDs is confirmed to depend on the brightness of their surrounding background. Several UDs show fission and fusion. Thanks to the stable condition of the space observation, we could for the first time follow the temporal behavior of these events. The derived properties of the internal structure of the umbra are discussed from the viewpoint of magnetoconvection in a strong magnetic field.

Key words: Sun: magnetoconvection — Sun: sunspot — Sun: umbral dots

1. Introduction

The umbral fine structure in sunspots has been studied by many authors. Recent reviews are given in Thomas and Weiss (2004) and in references cited therein. The study of umbral fine features is very essential for our understanding of the magnetoconvection in a strong magnetic field atmosphere of celestial bodies. Because the spatial size of the umbral fine structures, such as umbral dots (UDs), is very fine, it was very hard to obtain their basic characteristics. It was especially very difficult to follow the temporal evolution of the fine features from ground-based telescopes, due to the influences of variable atmospheric seeing conditions.

Solar Optical Telescope (SOT) on board Hinode, successfully launched on 2006 September 23, was designed to observe the solar fine structure with a 50 cm mirror from space (Ichimoto et al. 2007; Kosugi et al. 2007; Shimizu et al. 2007; Suematsu et al. 2007; Tsuneta et al. 2007). The resolving power in the flight condition was confirmed to have nearly the theoretical one of 0.″2. With Hinode/SOT, we observed the temporal evolution of the umbral fine structures during the period of 2007 March 2–4. The spatial distribution of the umbral structure as well as its temporal evolution, lifetimes, proper motions, and temperatures were studied during a three-day period. Besides the basic characteristics stated above, we could follow the temporal evolution of fission and fusion events of the umbral dots. In the following section we describe the details of our observation, and the analysis procedures in section 2; we give our results in section 3, and finally discuss and summarize our results in section 4.

2. Observation and Reduction

We observed a roundish sunspot in an active region, NOAA 10944, from 2007 March 2 through March 4. The region was fairly inactive during the three-day period, and disintegrated on March 5. The region observed in Hα with the Domeless Solar Telescope (DST) at Hida Observatory is shown in figure 1. The main sunspot remained as the α type for three days. Among the data taken with the Hinode/SOT, we report on the results obtained from a time-series imaging observation by the Broadband Filter Imager (BFI), shown in table 1. The green continuum images were taken through a filter (λ = 5550 Å, Δλ ≃ 5 Å), while the blue continuum images were taken through a different filter (λ = 4504 Å, Δλ ≃ 5 Å). Both continuum images were taken in a cadence of 1 frame/30 s. The pixel
The field of view (FOV) of the continuum images was 55.8″ × 55.8″. To follow the temporal evolution correctly without the projection effect, we transformed all of the images as if they are seen from the top. The daily evolution of the umbral region in the green continuum is shown in figure 2.

We applied a median filter (window: 1″ × 1″) to all of the images to identify slowly varying features, such as the dark core area and diffuse components. The effect of median filter processing for structure identification is shown in figure 3. All of the images were co-aligned among them by finding image displacements, which gave the maximum correlation between consecutive frames.

The proper motions of UDs were derived by tracking the identified features along the time series of the images. Identification of the features was done visually on a PC screen. The lifetimes of UDs were determined by measuring the time spans, during which the UDs showed a 1.2-times larger brightness than their surrounding background. The temperatures of the umbral features were estimated from their color values, i.e., the intensity ratio $I_{\text{blue}}/I_{\text{green}}$. The relation between the intensity ratio and the temperature was calculated assuming blackbody radiation. The temperature distribution over the region is shown in figure 4.
temperatures of normal granules surrounding the spot are \( \approx 6000 \) K, while those of intergranular lanes are \( \approx 5000 \) K. These temperature values are consistent with those thus-far known.

3. Internal Structure of Umbral Region

As shown in figure 2, the brightness distribution of the umbral area is not uniform. The umbra observed by us consists of a dark core region, diffuse components, and bright umbral dots, as was observed in previous ground-based work under superb atmospheric conditions (Thomas & Weiss 2004). In our observation, the dark core almost kept its location and size, while the spot gradually evolved and deformed during a three-day period. In the dark core, UDs were very scarcely detected. Diffuse components were observed to stay at nearly the same location, and to develop into light bridges. UDs were numerously detected to appear and disappear, except in the dark core region. The characteristics of individual components are considered separately in the following subsections.

3.1. Dark Core

The daily evolution of the umbral core is shown in figure 5. The temperature of the dark core was around 3850 K on March 4. As the continuum brightness gradually increased, the core temperature is expected to have increased with time. This tendency seems to be natural, because the spot was in a decaying phase. We could identify virtually no UDs in the dark core. The absence, or very low brightness, of UDs in dark cores is confirmed in our observation from space, without the ambiguity of the seeing conditions in ground-based observations. This is, probably, due to the positive correlation between the UD’s brightness as well as the background brightness, as stated in a later section.
3.2. Diffuse Component

In figure 5, we can see the daily evolution of the diffuse components. Their locations were rather stable during the three days. They increased in brightness with time. The temperature ranged from 4250 K to 4500 K on March 4, which was 500 K hotter than the dark core. They finally took the form of light bridges. In our case, the light bridges are of the umbral type, neither of penumbral type nor of photospheric type, so the fine structures in the diffuse components have forms similar to UDs (Muller 1979).

3.3. Umbral Dots

As reported in many papers (Kitai 1986; Sobotka et al. 1997a; Thomas & Weiss 2004), UDs are classified into two classes: (1) central or umbral origin, and (2) peripheral or penumbral origin. UDs of the former type appear and disappear in the central parts of the umbra. Their proper motions are known to be small. On the other hand, UDs of the latter type originate in the penumbral area. The tips of inner penumbral filaments start to be separated and move into the umbral area with a larger velocity than the former type (Kitai 1986).

In our present study, we identified about 100 umbral dots during a three-day period. We classified them, as in previous work, into three classes according to their ways of birth, i.e., umbral origin (UUDs), penumbral origin (PUDs), and light-bridge origin (LUDs).

3.3.1. Size

UDs generally have dot-like shapes. We measured their linear sizes, and found that the sizes of the majority of UDs are from 0.0032 (220 km) to 0.005 (350 km). However, several percent of UDs have linear sizes of 0.0024, i.e., the theoretical resolution limit of the telescope. We should have in mind that much smaller UDs can exist in umbrae.

3.3.2. Lifetime

The lifetimes of UUDs range from 4 through 20 min, and their average is 14.6 min. Those of PUDs range from 5 through 35 min, and their average is 13.9 min, while LUDs ranges from 4 through 40 min, and their average is 16.0 min. Thus, the lifetimes of UDs do not depend on the types of UDs.

3.3.3. Proper motion

The proper motions of both UUDs and LUDs showed a similar behavior. Their speeds are virtually null, 0.5 km s\(^{-1}\) at maximum. Their directions of motions were random. On the other hand, PUDs showed higher speeds of about 0.9 km s\(^{-1}\) at their birth, and gradually slowed down to 0.5 km s\(^{-1}\).

3.3.4. Temperature

The temperatures of UUDs range from 4200 K to 5500 K, and their average is 4600 K. Those of LUDs range from 4800 K to 5600 K, and their average is 5100 K. PUDs are generally hotter at their birth, and then cool down. Their temperatures range from 4700 K to 5900 K, and their average is 5460 K.

3.3.5. Light curve

The temporal variation of the brightness is found to depend on the type of UDs. UUDs and LUDs increase in brightness linearly, and then darken linearly with time. The light curve of a long-lived UUD/LUD is shown in figure 6a. On the other hand, PUDs darken continuously (figure 6b).
3.4. Brightness/Temperature of UDs and Surroundings

The brightness of UDs is found to depend on those of the surrounding brightness. UDs seen in brighter background appear to be brighter/hotter than those in dark regions. The correlation between the peak brightness of the UDs and their background brightness is shown in figure 7. From our temperature analysis, UDs are found to be around 300 K hotter than their surroundings, irrespective of the type of UDs. The relation was first reported by Sobotka et al. (1992a), and has been studied by Sobotka et al. (1992b, 1993) and recently by Sobotka and Hanslmeier (2005). Our observation from space with $0^\prime.24$ resolution fully confirms their results, from an analysis of the blue/green continuum brightness.

3.5. Fission and Fusion of Dots

Some of UUDs and LUDs show fission and fusion, while the majority of UDs keep their identities during their lives. One case of fission was observed in the sample of 30 UUDs, while one fission and two fusion events were detected in the sample of 31 LUDs. Sobotka et al. (1997a) noticed these events in tracking the evolution of UDs. The temporal behavior of fission and fusion is shown in figure 8. Fissions occurred at the end of the UDs’s life. They disintegrated into smaller parts and faded away. On the other hand, two UDs merged into one and formed a bright UD when the fusion of UDs occurred. As for the PUDs, we have not detected these phenomena. The detailed evolution of the events was first observed in our work.

Because UDs can be smaller than $0^\prime.24$ (Sobotka et al. 1997a; Sobotka & Hanslmeier 2005), fusion and fission events may be due to a temporal brightness variation inside an unresolved cluster of much smaller UDs. Fusion/fission may correspond to be brightening/decaying phase of such a cluster of UDs.

4. Summarizing Discussion

Weiss et al. (2002), from their simulation of three-dimensional non-linear magnetoconvection in a strongly stratified compressible layer, gave two important suggestions on the internal structure of sunspots. The first one was that UDs are a manifestation of small-scale convective cells, whose sizes are strongly reduced compared to normal granules by a strong magnetic field. The second one was that diffuse background components, which are larger in size than UDs, and correspond to clumps of vigorously convecting plumes, from which the magnetic flux is expelled. According to their suggestion, the umbral area is separated into (a) regions of strong fields and small-scale convection and (b) regions of weak fields and large-scale vigorous convection. Spectroscopic observations on the magnetohydrodynamic (MHD) nature of UDs have been made by several researchers. Wiehr and Degenhardt (1993) and Socas-Navarro et al. (2004) obtained results that the magnetic field strength is weaker and that small or virtually null upflows exist in UDs, while Lites et al. (1991) detected no indication of a reduced field strength in UDs. It seems that no comprehensive observational view of MHD behavior of UDs has been obtained at present. Especially the differences of the MHD behavior among the types of UUD/LUD/PUD are unknown.

As suggested in previous studies, and confirmed in our present observation, PUDs have different characteristics from
Fig. 8. Temporal evolution of fission and fusion of UDs shown in pseudo-colors. The left column shows the fusion of two UDs, while the right column shows the fusion of another UD. From all of the images, the background intensities were subtracted to enhance the dot structures.

UUd/LUDs from the viewpoint of their birth places and proper motions. Because UUDs/LUDs are immobile and hotter than their surroundings, they probably correspond to small-scale magnetoconvection in a strong magnetic field, as was suggested by Weiss et al. (2002). On the other hand, PUDs show systematic proper motions from penumbrae to umbrae, and seem to be a natural extension of so-called penumbral grains. We think that the interchange instability model at penumbrae by Schlichenmaier et al. (1998) well explains PUDs. However, one important point remains unexplained. UUDs/LUDs and PUDs have a common size of around 200–300 km. Why do UUDs/LUDs of magnetic convective origin in umbrae and PUDs of penumbral origin have nearly the same geometrical sizes? What are the physical factors that determine the UD size of 200–300 km? Is there a common mechanism that controls the sizes of the fine structures in both umbrae and penumbrae?

Diffuse components are observed to be hotter than the dark core of umbrae. Thus, they probably correspond to plumes of vigorous convection with a weak magnetic flux, as suggested by Weiss et al. (2002). Since LUDs observed in these diffuse components are observed to have a much higher temperature than UUDs, we suspect that convection is stronger in these diffuse components. However, according to Weiss et al. (2002), small-scale convective plumes, i.e., UDs, are not expected to appear in large-scale vigorous plumes of convection, i.e., diffuse components. This expectation is contrary to our observed result. In our three-day observation, it was observed that the diffuse components and the dark core maintained their identities. Garcia de la Rosa (1987), from an analysis of the temporal evolution of many sunspots, suggested that sunspots consist of a cluster of several large fragments, and that they maintain life-long identities from the birth to the decay of sunspots. In the fragments, UUDs will be formed, as suggested by Weiss et al. (2002). At the interfaces of fragments, convection from deeper layers is expected to intrude the interfaces, resulting in rather bright diffuse components.

In both the vigorous convective plume model by Weiss et al. (2002) and the fragment model by Garcia de la Rosa (1987), the occurrence of LUDs in diffuse components remains unexplained. It may be related to the question why UDs have common geometrical sizes irrespective of their types. A similar mechanism, such as the interchange instabilities proposed by Schlichenmaier et al. (1998), may work to form UDs in addition to magnetoconvection.

The discussion and suggestions stated above, including a conjecture of the absence of UDs in the dark core (Lites et al., 1991), are to be studied by further observations and analyses. In our next paper, we will report on our analysis of spectropolarimeter data obtained for the same sunspot by Hinode/SOT. The temporal evolution of the vector magnetic field and the Doppler velocities in and around the UDs will give us more conclusive views of magnetoconvection in sunspots.

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