Formation Process of a Light Bridge Revealed with the Hinode Solar Optical Telescope

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Abstract

The Solar Optical Telescope (SOT) aboard HINODE successfully and continuously observed a formation process of a light bridge in a matured sunspot of the NOAA active region 10923 for several days with high spatial resolution. During its formation, many umbral dots were observed emerging from the leading edges of penumbral filaments, and intruding into the umbra rapidly. The precursor of the light bridge formation was also identified as the relatively slow inward motion of the umbral dots which emerged not near the penumbra, but inside the umbra. The spectro-polarimeter on SOT provided physical conditions in the photosphere around the umbral dots and the light bridges. We found the light bridges and the umbral dots had significantly weaker magnetic fields associated with upflows relative to the core of the umbra, which implies that there was hot gas with weak field strength penetrating from subphotosphere to near the visible surface inside those structures. There needs to be a mechanism to drive the inward motion of the hot gas along the light bridges. We suggest that the emergence and the inward motion are triggered by a buoyant penumbral flux tube as well as the subphotospheric flow crossing the sunspot.

Key words: Sun: magnetic fields — Sun: photosphere — Sun: sunspots

1. Introduction

A sunspot provides us with a unique site to understand interaction between very strong magnetic fields and convective flows driven by subsurface heat transfer. Convective flows are especially important in breakup and disappearance of a sunspot during its lifetime. But the process is still poorly understood. One of the well-known signatures of sunspot breakup is formation of a light bridge (LB) which is a lane of relatively bright material dividing an umbra into two parts (Bray & Loughhead 1964). The formation is a result of reestablishment of the granular surface as a precursor of the decay of a spot (Vázquez 1973). LBs have been classified based on morphological arrangement and brightness. A strong LB, which separates umbral cores, is further distinguished as either penumbral or photospheric according to fine structures observed within it (Sobotka et al. 1993; Sobotka et al. 1994). A faint (or umbral) LB, which is a faint narrow lane within the umbra, most likely consists of a chain of umbral dots (Muller 1979). The classification is somewhat phenomenological, but implies that there should be some sort of relationship among LBs, umbral dots, and penumbrae.

It is obvious that gas in a LB must have a temperature higher than a surrounding umbra because of its brightness. It is important to know magnetic and velocity structures of a LB to understand how the hot gas is continuously provided to the LB, otherwise the gas inside the LB is cooled down and the LB disappear. Spectrometric observations of photospheric Zeeman-sensitive lines indicate that LBs typically have a weakened magnetic field strength relative to the nearby umbra with field lines inclined from the local vertical (Lites et al. 1991; Ruedi et al. 1995; Leka 1997). Furthermore, it is found that field strengths and inclinations increase and decrease with height, respectively, by a detailed analysis of Stokes spectra (Jurčák et al. 2006), which suggest a canopy-like magnetic structure above the LB. There are no systematic findings considering vertical velocities in LBs (Leka 1997), but a positive correlation between the brightness and upflow velocities is reported by Rimmele (1997), which is interpreted as evidence of the hot gas originating from subphotospheric convection. These observational results can be explained theoretically in terms of a cluster model, where an umbra consists of tight bundle of isolated flux tubes separated by field-free columns of hot gas (Parker 1979; Spruit & Schmarr 2006). But it is still unknown what triggers development
of a LB, and what is a role of penumbral and umbral dots in the development.

LBs are also important from the viewpoint of chromospheric and coronal activities. Observations in Hα show surges are ejected from a LB in some situations (Roy 1973; Asai et al. 2001; Bharti et al. 2007). Berger & Berdyugina (2003) found constant brightness enhancement over a LB in 1600 Å ultraviolet images from the Transition Region and Coronal Explorer (TRACE), and suggested a steady chromospheric heat source over a LB. Katsukawa (2007) found that formation of a LB is spatially and temporarily coincident with heating of coronal loops seen in TRACE 171Å images. These observations suggest that LBs serve a role not only to dissolve a sunspot, but to release or dissipate magnetic energies stored in a sunspot.

The Solar Optical Telescope (SOT, Tsuneta et al. 2007, Suematsu et al. 2007, Tarbell et al. 2007, Ichimoto 2007) on the new Japanese spacecraft HINODE (Kosugi 2007) enables us to observe dynamics and evolution in the photosphere not only with high spatial resolution (0.2 arcsec) under seeing-free condition, but with uninterrupted coverage longer than a day owing to the sun-synchronous polar orbit. In this paper, we present a successful observation of a formation process of a LB with SOT, which took place in a big matured sunspot in NOAA active region 10923 from 13 Nov 2006 through 17. This observation is the first time ever for us to see evolution of a LB longer than several days with high spatial resolution better than 1 arcsec.

2. Filtergram Observation

We obtained an image sequence of the sunspot continuously through three channels G-band 4305 Å Ca II H 3968 Å and blue continuum (BC) 4504 Å of the broadband filter imager (BFI) on SOT from Nov. 10, 2006 until the spot went beyond the west limb. The area of 220° × 110°, which was full field-of-view of BFI, was covered by 2x2 summing (0.108 arcsec per pixel) in this observation. The time cadence of this BFI observation was not so high, but to release or dissipate magnetic energies surrounding the umbra, and we can see their inward migration and intrusion into the umbra everywhere around the umbra. Many umbral dots (UDs) are also observed moving inward near the boundary of the umbra. Most of them emerge from leading edges of the penumbral filaments migrating inward, and become invisible after they travel about 2000 km from the leading edges of the penumbral filaments. There exist numerous UDs deep inside the umbra, but those are generally less distinct than the UDs near the boundary, and their proper motions are less significant. These properties of UDs are consistent with previous works (Kitai 1986; Grossmann-Doerth et al. 1986), in which UDs are divided into two classes: peripheral (or penumbral origin) UDs, and central (or umbral origin) ones.

The LBs we are now interested in develop from 14-Nov-2006. Even before its development, intrusion of penumbral filaments into the umbra is outstanding on the southwest side of the umbra where the LBs form after that. The similar intrusion of penumbral filaments is seen all around the umbra, but the intrusion is extreme in this region because the distance of the intrusion is as long as about 4000 km there in some cases. Such deep intrusion is preferentially observed around this region during the observing period. An example of the intrusion is indicated by the arrow in Fig. 1. Another signature of the formation of the LBs is numerous central UDs seen in the southwest side of the umbra. Not only brightness of each UD but their number density seems larger than the rest of the umbra. This is clearly visible in the image at 14-Nov-2006 00:00 of Fig. 1.

Internal structures of the umbra drastically changes at around 11:00 on 14-Nov-2006. UDs born from the penumbral filaments become able to migrate deeper than before with much higher velocities on the southwest side of the umbra. Many bright UDs are observed to emerge one after another, and rush into the umbra from southwest to northeast. The UDs are called “rapid UDs” hereafter to distinguish them from the peripheral or central UDs. The continual emergence and the inward motion of the rapid UDs along a trail lead to a chain-like structure of the UDs, which can be classified as an umbral LB (Muller 1979). There are two LBs in which the rapid inward migration of
UDs are observed at 12:00 14 Nov. The northern one (indicated by LB1 in Fig. 1) is more active than the southern one (indicated by LB2). The migration of the rapid UDs lasts for longer than a day along LB1. The bright lane becomes gradually longer, and finally connects with the opposite side of the umbral boundary. The inrush motion of the rapid UDs is investigated in detail in the next subsection. The inward migration of the rapid UDs is also seen along LB2. But the LB does not develop so much, and disappear on 16 Nov. It needs more investigation to know what makes the difference between LB1 and LB2, but this is possibly because the emergence of the rapid UDs is less frequent in LB2.

The LB developed along the northern path (LB1) gets brighter after the LB connects with the opposite side of the umbral boundary. Especially the western part of the LB become bright on 16 Nov. The central part of the LB is like a stagnation point of hot gas, and becomes thick and bright. After that, bright UDs newly emerge on the southeast side of the central bright region. This emergence of UDs from the LB look like leakage of hot gas from the LB. The motion of the UDs born near the LB are slower than that of the peripheral UDs, which is already reported by Kitai (1986). The development of the LB stops on 17 Nov. The northeastern and southwestern sides of the LB are disconnected from the boundary of the umbra, but the central part of the LB stays until 17 Nov. After that, the central part of the LB also disappears.

2.2. Inrush motion of the umbral dots

Space-time plots shown in Fig. 2 illustrates time evolution of brightness along LB1. The penumbral side of the LB has inward motion of penumbral filaments and peripheral UDs for all over the period although it is not easy to distinguish the UDs with the penumbral filaments in this space-time plots. The velocities of the inward motion of the peripheral UDs are about 0.7 km/s, and there appear to be no large difference in the speeds among the UDs. The inward velocities of the peripheral UDs are almost constant during their travel, but they may suffer weak deceleration just before they become invisible, which is marginally seen in Fig. 2 (b). The intrusion of the peripheral UDs stops at a certain place indicated by a dashed line in Fig. 2 (a) for most of the UDs. Some of the peripheral UDs have larger intrusion about 2000 km deeper than the others. The forefront of the peripheral UDs appears to move inward gradually with respect to the center of the umbra before the LB formation.

The high speed migration of the rapid UDs starts at around 11:00 14 Nov. The rapid UDs emerge near the leading edge of the penumbral filaments quasi-periodically, and rush into the umbra with almost a constant velocity until they reach the middle of the umbra. The time interval of the emergence is about a quarter of an hour. The inward velocities of the rapid UDs are 1 to 2 km/s, which is significantly faster than that of the peripheral UDs. The rapid UDs suffer deceleration near the middle of the umbra, which is clearly seen in Fig. 2 (b), but the inward motion lasts with the speed slower than 0.5 km/s. Lifetimes of the rapid UDs are mostly several tens of minutes, but some of them have a lifetime longer than one hour. The continual inward motion of the rapid UDs pushes the forefront of the LB gradually as shown by the dash-dotted line in Fig. 2 (a), and finally the LB reaches the opposite side of the umbra boundary. The migration speed of the forefront is about 0.03 km/s.

Fig. 3 shows emerging process of rapid UDs at the boundary between the umbra and the penumbra. The
UDs seem a part of a leading edge (or a penumbral grain) of a bright penumbral filament before its emergence. The inward migration of the leading edge is clearly visible in the BC movie. When the leading edge reaches a certain place, elongation and disintegration happens at the leading edge of the penumbral filament at around 11:15. The disintegrated part becomes a UD, and continues to move inward with the high velocity. The UD breaks up into two UDs at 11:35, and both the UDs continue to migrate deep into the umbra along a channel. The penumbral filament stops its inward migration after the emergence of the UD.

The inward motion of the central UDs are also observed in the deep umbra even before the inrush motion of the rapid UDs starts at around 11:00 14 Nov. An example of the inward motion of the central UDs is indicated by the white dashed line in Fig. 2 (b). They are dark and less distinct compared with the rapid UDs, but they are long-lived (longer than 2 hours). The inward motion of the central UDs begins to be observed at around 18:00 13 Nov, which is about 17 hours before the inrush motion starts. At that moment, the inward velocity of the central UDs is slower than 0.1 km/s. But the velocity gets larger toward the formation of the LB, and it is about 0.5 km/s just before the inrush motion starts. It appears that this inward motion of the central UDs is a precursor of the LB formation which is newly identified by HINODE SOT thanks to its long-term continuous observation with the high spatial resolution.

After the LB develops to some extent, the forefront of the peripheral UDs changes its evolution at around 0:00
15 Nov. The leading edges of the penumbral filaments and the peripheral UDs become able to intrude deeper than before. The structures indicated by the asterisks in Fig. 2 (a) has brightness similar to the penumbrae, and their inward velocities are also similar to those of the penumbrae and the peripheral UDs. A measurement of vector magnetic fields in this region, which is described in the next section, shows there is a more inclined field than the umbra there. It appears that the evolution of the LB due to the intrush motion of the rapid UDs is followed by further intrusion of the penumbral filaments into the umbra, leading to formation of the penumbral LB (Muller 1979).

3. Evolution of physical quantities

The sunspot was observed also by the spectro-polarimeter (SP) on SOT during this period. The SP performed scanning observations of the spot once or twice per day with the normal mapping mode which scans a target with a step size of 0.15 arcsec. An integration time to get spectra is 4.8 sec at each slit position, and a pixel scale is 0.16 arcsec along the slit. The SP observations provide physical quantities in the photosphere using the two Fe I absorption lines at 6301.5 Å and 6302.5 Å sensitive to magnetic fields. The quantities described below are derived by least-squares fitting to Stokes profiles obtained by SP using the Milne-Eddington model atmosphere (Yokoyama et al. 2007). Fig. 4 shows two dimensional maps of continuum intensities, Doppler shifts, magnetic field strength, and magnetic field inclination at the five periods from 13-Nov-2006 through 15-Nov-2006. Their spatial resolution is high and stable enough to spatially resolve LBs and UDs in the maps.

There is a relatively bright region in the southwest part of the umbra on 13 Nov, which consists of many central UDs. It is obvious that field strength is about 1kG weaker there than the darkest core of the umbra, and no significant Doppler shifts. Fig. 5 shows correlation among the quantities in the photosphere. There is a clear negative correlation between the field strength and the continuum intensities inside the umbra on 13 Nov. The darkest region in the umbra has a field strength about 800 gauss greater than the relatively bright region. This correlation was already reported by many authors (see references in Solanki 2003). A similar correlation is found between the Doppler shifts and the continuum intensities. The difference in the Doppler shifts is as much as 0.8 km/s between the darkest core and the bright region. Since we do not have an absolute wavelength standard in this analysis, it is difficult to determine whether the observed Doppler shifts correspond to upflow or downflow with respect to the solar surface. If we assume the darkest core of the umbra is stationary because gas motion is strongly suppressed by the strong magnetic field, the relatively bright region has an upflow, which can be interpreted as manifestation of subphotospheric convection below the central UDs.

In the map at 07:15–08:13 14 Nov, which is just before the inward motion of the rapid UDs appear, some central UDs are visible in the continuum intensity map. As we mentioned in the last section, the slow inward motion of the central UDs are observed at that moment. It is noticed that weak field regions in the umbra already have a structure resembling the LBs while the structure is not so clear in the Doppler shifts and inclination maps. After the rapid UDs appear around 11 UT on 14 Nov, bright structures in the continuum intensities with weaker field strength evolve along the trails. The rapid UDs have magnetic fields a few hundreds gauss weaker than the nearby umbra. Most of the rapid UDs have a weak blue shift of about 0.2 km/s, but some of the UDs are associated with a slightly larger blue shift up to 0.5 km/s. These velocities are consistent with a previous study using a high spatial resolution spectro-polarimeter (Socas-Navarro et al. 2004). The upflow velocity is as fast as 1.0 km/s if we consider the darkest core of the umbra is stationary. The correlation between the continuum intensities and the Doppler shifts is not so clear near the LBs in Fig. 5 contrary to the result obtained by Rimmele (1997). This means not only the upflows but other factors contribute to the brightness of the UDs and the LBs (Beckers 1977; Spruit & Scharmer 2006).

As the LB develops on 15 Nov, further weakening of the field strength occurs in the LB. The correlation among the continuum intensities, the field strength, and the Doppler shifts becomes less clear as shown in the right-most column in Fig. 5 although further investigation is necessary to understand the reason.

As for the magnetic field inclination, inclined magnetic fields (30 degrees from the local vertical) are observed around the leading edge of a penumbral filament located on the southwest boundary of the region-of-interest in Fig. 4 before the LB formation. The bright continuum intensities are always associated with the inclined fields on 13 Nov, which can be recognized in the leftmost column of Fig. 5. As the LBs develop on 14 – 15 Nov, bright pixels with relatively vertical fields as well as inclined fields grow in the region-of-interest. The drastic change of the relation between the field inclination and the continuum intensity is easily found in Fig. 5. The inclination maps in Fig. 4 shows small contrast around the LBs, which means the inclination in the LBs is not so different from the nearby umbra. The extreme intrusion of the penumbral filaments along the LBs can be recognized as less vertical inclination angles in the inclination maps in Fig. 4. The brightness of the LBs is comparable to that of the leading edge of the penumbrae, but there is a significant difference in the inclination. The field inclination in LBs is reported to be more inclined than the nearby umbra in previous studies (e.g. Leka 1997, Jurčák et al. 2006). We cannot find this signature in the LBs we are now interested in. This is possibly because the LBs here shown are narrower than in the previous studies, and the canopy configuration of magnetic fields might be weak in the LBs. Further investigation using many examples of LBs is necessary to know general properties of LBs.
4. Summary and Discussion

SOT aboard HINODE provided a precious data set to understand the formation process of a LB owing to its high spatial resolution and temporal coverage for several days. We found the following results from the data set:

1) The LB was resulted from continual emergence of the UDps from the leading edges of penumbral filaments and rapid inward migration of the UDps. The inward velocity was significantly faster than that of peripheral UDps and central UDps.

2) The precursor of the LB formation was identified as the inward migration of the central UDps. The inward velocity gets faster toward the LB formation.
3) The extreme intrusion of the penumbral filaments into the umbra followed the formation of the LB by the rapid UDs. The intrusion made a penumbral LB which had magnetic fields inclined to the local vertical.

4) The magnetic field properties and their evolution were revealed around the rapid UDs and the LBs with the high and stable spatial resolution of the SP. The LBs had significantly weaker magnetic fields accompanied by upflows relative to the core of the umbra.

Through this observation, we can get some implication on the breakup process of a sunspot. The formation of LBs is a process to breakup a sunspot by injection of the hot and weak field gas into the cold and strong field gas in the umbra. It is important to know what mechanism injects the hot gas into the umbra. The upflows observed in the rapid UDs suggests that the hot gas comes from below the photosphere. At the same time, the rapid UDs are observed to move inward with the larger velocity. The inward motion of leading edges of penumbral filaments can be explained by a buoyant flux tube (Schlichenmaier et al. 1998). On the other hand, the inward motion of the rapid UDs may not be associated with the motion of field lines, but be the motion of the hot gas pushing through surrounding magnetic fields because the magnetic fields inside the umbra got stronger if the field lines were transported into the umbra along the inward motion of the UDs. Each UD has $1.7 \times 10^{18}$ Mx magnetic flux when its field strength and diameter is 2.5 kG and 300 km, respectively. The total number of the rapid UDs moving inward is roughly $\sim 40$ for half a day on 14 Nov, which provides $\sim 7 \times 10^{19}$ Mx magnetic flux into the umbra if magnetic fields are transported by the UDs. Increase of field strength as high as 70 G should be observed inside the umbra when the transported flux was distributed over an area of $10^{18}$ cm$^2$. This is inconsistent with the observation because gradual decrease of the field strength was observed in the umbra during the formation of the LBs. Since most of the rapid UDs emerges from the leading edges of the penumbral filaments, there should be some driving mechanisms to push the hot gas into the umbra near the penumbra.

A possible mechanism is that the emergence of the rapid UDs is related to a buoyant flux tube forming the penumbra where a high speed flow, i.e. Evershed flow, exists along the tube (see references in Solanki 2003). The Evershed flow is an outward directed flow along horizon-
tual magnetic fields in the mid penumbra, and an upflow is also observed at the inner edge of the penumbra, which may be a source of the Evershed flow (Schlichenmaier & Schmidt 2000; Rimmelle & Marigo 2006). If the flux tube is adjacent to a field free region beneath the photosphere as shown in Fig. 6, the buoyant tube by the hot Evershed flow may cause enlargement of the field free region, which helps the hot gas penetrate to the photosphere by the subphotospheric convection. The Evershed flow is not stationary, but has significant temporal fluctuation with a time scale of 10 to 15 minutes (Shine et al. 1994; Rimmelle 1994). The emergence of the rapid UDs has the timescale similar to the temporal fluctuation of the Evershed flow, which suggests that the emergence of UDs might be triggered by high speed blob of the Evershed flow. Since it is difficult to prove this mechanism only from this observation, we need additional investigation to study the spatial and temporal relationship between the Evershed flow and the emergence of UDs.

It is still not clear what makes the difference in the inward velocity between the rapid UDs and the peripheral UDs. If the Evershed flow is the trigger, the rapid motion should be observed everywhere near the boundary of the umbra. But the rapid motion is observed only along the LBs. The most probable reason is that gradual weakening of the field strength happens by the emergence and slow inward motion of the central UDs before the rapid UDs appear, which was revealed by this observation (see Fig. 4). There might be a field free region beneath the photosphere even before the formation of the LBs, which helps the intrusion of the rapid UDs into the umbra (see Fig. 6). The intrusion makes further weakening of the field strength and helps the catastrophic formation of the LBs. Since the central UDs emerged not near the boundary of the umbra, but inside the umbra, the Evershed flow cannot explain the inward motion of the central UDs. A subsurface flow crossing a sunspot, which is deduced by helioseismic studies (Zhao et al. 2001; Kosovichev 2002), may contribute to move the central UDs and the formation of the LBs.

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References

Asai, A., Ishii, T. T., & Kurokawa, H. 2001, ApJL, 555, L65
Beckers, J. M. 1977, ApJ, 213, 900
Berger, T. E., & Berdyugina, S. V. 2003, ApJL, 589, L117
Bharti, L., Rimmelle, T., Jain, R., Jaaffrey, S. N. A., & Smartt, R. N. 2007, MNRAS, 376, 1291
Bray, R. J., & Loughhead, R. E. 1964, Sunspots, Chapman & Hall, London
Grossmann-Doerth, U., Schmidt, W., & Schroeter, E. H. 1986, A&A, 156, 347
Hirzberger, J., Bonet, J. A., Sobotka, M., Vázquez, M., & Hanslmeier, A. 2002, A&A, 383, 275
Ichimoto, K. et al, 2007, Sol. Phys., submitted
Jurcak, J., Martinez-Pillet, V., & Sobotka, M. 2006, A&A, 453, 1079
Katsukawa, Y. 2007, in ASP Conf. Ser., proceedings of the Sixth Solar-B Science Meeting, ed. K. Shibata, S. Nagata, & T. Sakurai, in press
Kitai, R. 1986, Sol. Phys., 104, 287
Kosovichev, A. G. 2002, AN, 323, 186
Kosugi, T. et al, 2007, Sol. Phys., in press
Lites, B. W., Bida, T. A., Johansson, A., & Scharmer, G. B. 1991, ApJ, 373, 683
Lites, B. W., Scharmer, G. B., Berger, T. E., & Title, A. M. 2004, Sol. Phys., 221, 65
Leka, K. D. 1997, ApJ, 484, 900
Muller, R. 1979, Sol. Phys., 61, 297
Parker, E. N. 1979, ApJ, 230, 905
Rimmelle, T. R. 1994, A&A, 290, 972
Rimmelle, T. R. 1997, ApJ, 490, 458
Rimmelle, T., & Marino, J. 2006, ApJ, 646, 593
Roy, J.-R. 1973, Sol. Phys., 28, 95
Ruedi, I., Solanki, S. K., & Livingston, W. 1995, A&A, 302, 543
Schlichenmaier, R., Jahn, K., & Schmidt, H. U. 1998, A&A, 337, 897
Schlichenmaier, R., & Schmidt, W. 2000, A&A, 358, 1122
Shine, R. A., Title, A. M., Tarbell, T. D., Smith, K., Frank, Z. A., & Scharmer, G. 1994, ApJ, 430, 413
Socas-Navarro, H., Pillet, V. M., Sobotka, M., & Vázquez, M. 2004, ApJ, 614, 448
Sobotka, M., Bonet, J. A., & Vazquez, M. 1993, ApJ, 415, 832
Sobotka, M., Bonet, J. A., & Vazquez, M. 1994, ApJ, 426, 404
Sobotka, M., Brandt, P. N., & Simon, G. W. 1997, A&A, 328, 682
Solanki, S. K. 2003, A&A Rev., 11, 153
Spruit, H. C., & Scharmer, G. B. 2006, A&A, 447, 343
Shimizu, T. et al., 2007, Sol. Phys., submitted
Suematsu, Y. et al., 2007, Sol. Phys., submitted
Tarbell, T. D. et al., 2007, Sol. Phys., in preparation
Tsuneta, S. et al., 2007, Sol. Phys., submitted
Vazquez, M. 1973, Sol. Phys., 33, 897
Yokoyama, T. et al., PASJ, 2007, in preparation
Zhao, J., Kosovichev, A. G., & Duvall, T. L., Jr. 2001, ApJ, 557, 384