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Trans-Equatorial Loop System Arising from Coronal Hole Boundaries through Interactions between Active Regions and Coronal Holes

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Abstract It is not clear how trans-equatorial loop systems (TLSs) are formed, although they have been observed often with *Yohkoh*/SXT. We focus here on a TLS that appeared on 27 May 1998. Yokoyama and Masuda (*Solar Phys.* **254**, 285, 2009) proposed a new scenario for the formation mechanism of the TLS. In this scenario, they pointed out the importance of magnetic interaction between an active region and a coronal hole to make "strong-seed magnetic fields" before a transient (bright and short-lived) trans-equatorial loop was created. The main aims of this study are to verify the scenario and to make the TLS formation mechanism clear, based on observational data. *Yohkoh*/SXT images, SOHO/MDI magnetograph data, and Kitt Peak coronal-hole maps were mainly used for our analyses. We investigated the TLS in detail from the time that there were no signatures of the TLS to its clear appearance. The following results are obtained: *i*) an active region emerged in the vicinity of a coronal-hole boundary, *ii*) the coronal-hole boundary retreated during the period when the active region was developing, *iii*) temporal variations of soft X-ray intensities were roughly synchronized between the coronal-hole boundary and a trans-equatorial region, and *iv*) new closed loops were observed in soft X-rays clearly at the coronal-hole boundary. Since *i*), *ii*), *iii*), and *iv*) are just what we expect in the scenario of YM2009, the scenario found support. We conclude that the TLS was originating with large-scale magnetic fields of the coronal-hole boundary through magnetic reconnection between the active region and a coronal hole.

1. Introduction

The *Soft X-ray Telescope* (SXT; Tsuneta *et al.*, 1991) onboard the *Yohkoh* satellite (Ogawara *et al.*, 1991) often observed large-scale bright loops whose footpoints were rooted in active regions in the northern and the southern hemispheres, respectively. This type of soft X-ray bright loop has been called a trans-equatorial loop system (TLS; *e.g.*, Švestka *et al.*, 1977; Pevtsov, 2000). TLSs usually have a large-scale structure with a poloidal magnetic

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component. Harra, Matthews, and van Driel-Gesztelyi (2003) reported the appearance of a cusp shape in the corona above a TLS. The appearance of a cusp shape of a TLS was also found in Pevtsov (2004). These papers show evidence of flaring behavior in the fully-developed TLS at the equatorial region. The flaring behavior in a TLS could be the cause of an interplanetary disturbance, and it would affect the terrestrial space environment because the disturbance related with a TLS could involve the equatorial region. The trans-equatorial loops might be a source of southward components of the interplanetary magnetic field when a trans-equatorial loop expands to a distance of 1 AU and beyond (*e.g.,* Saito *et al.*, 2007). Actually, it has often been observed that trans-equatorial loops erupted into the interplanetary space. Khan and Hudson (2000) studied TLSs, and they reported that the disappearance of trans-equatorial loops was related to coronal mass ejections (CMEs). Some authors have pointed out that TLSs were related to large magnetic eruptions such as CMEs. Gopalswamy *et al.* (2006) described the importance of trans-equatorial loops for pre-erupting structures and explained that an eruption involving a trans-equatorial region had a larger volume than one involving only a single active region. van Driel-Gesztelyi *et al.* (2008) discussed how large CMEs were produced and cited TLSs as one of the causes. Zhou, Wang, and Zhang (2006) studied the relationship between Earth-directed CMEs and their source regions in the interval from 1997 to 2003. They reported that TLSs represent 40% of the source regions of the Earth-directed CMEs. Therefore, TLSs are important for space weather. There are studies of the development of TLSs that already have active regions or trans-equatorial loops. On this point, Wang *et al.* (2007) described the trans-equatorial activities in the early November 2004 specifically. They demonstrated examples of TLSs and concluded that the trans-equatorial activities are common phenomena, which are manifested as formation, growth, and eruption of the trans-equatorial loops. They even showed the temperature distribution in TLSs and the light curves of TLSs. However, there are few studies that really focus on the whole period, which includes the situation of no active regions, from the birth to the consummation of a TLS. This is one of the reasons why we studied the formation process of a TLS from the birth of its footpoint active regions in this paper. Tsuneta (1996a) investigated a TLS connecting two active regions that were located relatively close to the Equator and suggested that magnetic reconnection between the two active regions in the corona resulted in the TLS. Even in this event, the trans-equatorial loops already existed in previous solar rotations according to Pevtsov (2000). In spite of many observations of TLSs, the formation mechanisms of TLSs have not become well understood in detail. It is difficult to explain the TLS formation mechanism by the same process as an emerging flux of active regions due to magnetic loop sizes and magnetic loop directions of TLSs. Although it would be ideal to follow the full formation process of a TLS, *i.e.*, from active-region emergence to the clear appearance of the TLS, it is difficult to follow one event continuously for a long time due to solar rotation. A formation mechanism of a transient TLS was investigated in Yokoyama and Masuda (2009, hereafter YM2009). They made it clear that an eruption of a loop structure was essential for the formation of the transient TLS. They assumed seed magnetic fields that existed before the appearance of the transient TLS. The transient TLS was regarded as one portion of the full process of the TLS. However, it has not become clear where the pre-existing seed magnetic fields came from and how the fields became strong enough to be the source of an energetic eruptive event and a TLS seen in soft X-rays. In order to really approach the formation mechanism of the TLS, it is necessary to investigate a few days prior to the appearance of the active regions which will be connected by the TLS in the future.

YM2009 proposed that magnetic interactions between an active region and a coronal hole would yield strong magnetic fields for the TLS. Let us summarize the scenario of YM2009 here. It will be helpful for understanding what this paper is aiming for. Figure 6 in Yokoyama and Masuda (2009, henceforth YM2009) shows schematic drawings of the scenario. Initially, there are weak-semi-open magnetic fields at coronal holes close to active regions. Such large-scale magnetic fields are seeds of a future TLS (seed magnetic fields). The potential magnetic field calculated from the photospheric magnetic-field data before the two active regions had appeared represents large-scale-closed magnetic-field lines connecting both polar regions, of course below the open magnetic-field lines. Large-scale-closed magnetic-field lines might exist. However, it is not important whether the seed magnetic-field lines are closed or not at a high altitude (around the source surface). The magnetic reconnection which we considered in Figure 6 in YM2009 takes place at a lower altitude. Of course, it is not easy to make a current sheet at such a lower altitude. However, now we have emergence of the two active regions in both hemispheres. That magnetic pressure (and flare activities) could effectively work. Anyway, the most important thing is how to make strong-seed magnetic fields which can produce intense soft X-ray emissions (large amounts of high-temperature plasma) in a short period. Magnetic reconnection takes place between the seed magnetic fields and emerging magnetic flux of the active regions. As a result of repeating this process, the seed magnetic fields become stronger. It is not so essential that this process occurs simultaneously in each hemisphere. It is acceptable even if there is a time lag of the occurrence of the process between the northern and the southern hemispheres. Then, these strong magnetic fields expand and erupt due to destabilization associated with some energetic phenomena at the active regions of the footpoints. Here, one might ask why the stable large-scale loop structure could be transformed to the eruption. A theoretical model suggests that emerging magnetic flux could cause an eruption of large-scale magnetic structure such as a CME (Chen and Shibata, 2000). They showed that magnetic-flux emergence triggered the loss of equilibrium of a flux rope and leads to the eruption of a CME. Observationally, Khan and Hudson (2000) investigated the event of the disappearance of trans-equatorial loops and indicated that shock waves associated with flaring activity at the footpoint active region might destabilize the large-scale structures that produced CMEs. In the TLS event analyzed in YM2009, such a flaring activity from an active region in the northern hemisphere was also observed. A large-scale loop structure could erupt both theoretically and observationally. To return to the scenario of YM2009, magnetic reconnection takes place between anti-parallel magnetic-field lines that are made by the expansion and the eruption of the seed magnetic fields. Finally, energy generated by the magnetic reconnection is injected into the chromosphere and it induces chromospheric evaporation. Then, a TLS appears in soft X-rays through the processes. The final stage of the processes is similar to the mechanism of long-duration events of solar flares (Shibata *et al.*, 1995; Tsuneta, 1996b). In the initial stage of the TLS, an important process of the scenario is the magnetic interactions between the active regions and the coronal holes. They play key roles for the TLS to make the strong-seed magnetic fields. What phenomena are expected to be observed when the magnetic interactions take place between the active regions and the coronal holes in the process of the TLS formation? The expected phenomena are summarized in Figure 1. Initially, *i*) a magnetic active region emerges in the vicinity of a coronal hole. As a result of it, *ii*) the coronal-hole boundary shrinks by magnetic reconnection between the active region and the coronal hole, and *iii*) the magnetic reconnection causes soft X-ray flux enhancement at both the coronal-hole boundary and its opposite side (low-latitude region). Finally, *iv*) new closed loops are created in soft X-rays at the coronal-hole boundary.

We emphasize that the main aims of this study are to verify the scenario of YM2009 and to make clear the formation mechanism of the TLS based on observational data. We focus on the event analyzed in YM2009 to investigate magnetic interactions between the active regions and the coronal hole, and we make clear the roles and contributions of the

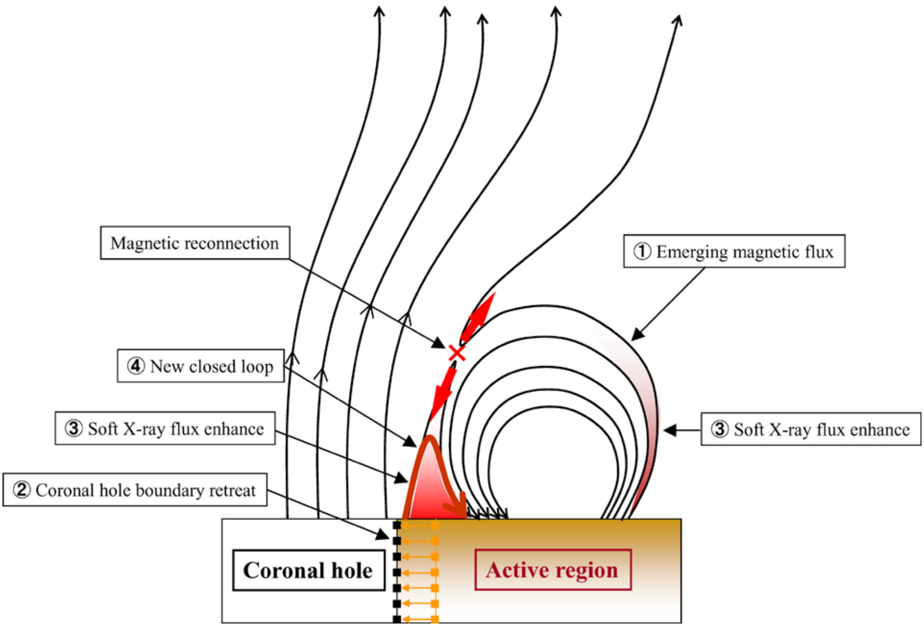

Figure 1 Schematic of magnetic interactions between an active region and a coronal hole at the coronal-hole boundary. (1) Magnetic flux of the active region emerges in the vicinity of the coronal-hole boundary. (2) Magnetic reconnection takes place and results in retreat of the coronal-hole boundary. (3) Soft X-ray enhancement at both the coronal-hole boundary and its opposite side. (4) A new closed loop is created at the coronal-hole boundary.

magnetic interactions for the TLS formation. We report observations and analyses of the magnetic interactions during the TLS formation in Section 2, and in Section 3 we discuss the formation mechanism of the TLS. We put forward a scenario for the initial process of the TLS formation.

2. Observations and Analyses

2.1. Data Overview

A TLS observed at the end of May 1998 was one of the clearest TLSs in the *Yohkoh*/SXT observations (September 1991 – December 2001). It was clearly seen at the west limb of the Sun as shown in Figure 2(F). Since this TLS was an isolated event, it provides us with valuable information to understand the TLS dynamics as a simple case. If other energetic regions existed near the TLS or interacted with the TLS, the event would be unremarkable. Fortunately, there were no other energetic regions in the vicinity of the TLS except for the active regions of the footpoints of the TLS itself. This situation favored the appearance of the TLS. Additionally, the loop of the TLS on 27 May 1998 was large. The loop length was about 0.5 – 0.6 million kilometers. This structural feature facilitates the identification of the dynamics of the TLS. 1998 was in the rising phase of Solar Cycle 23. Active regions tend to appear at a higher latitude than in the maximum phase of the solar cycle, which is generally known as Spörer's law. Therefore, when an active region in one hemisphere is connected to

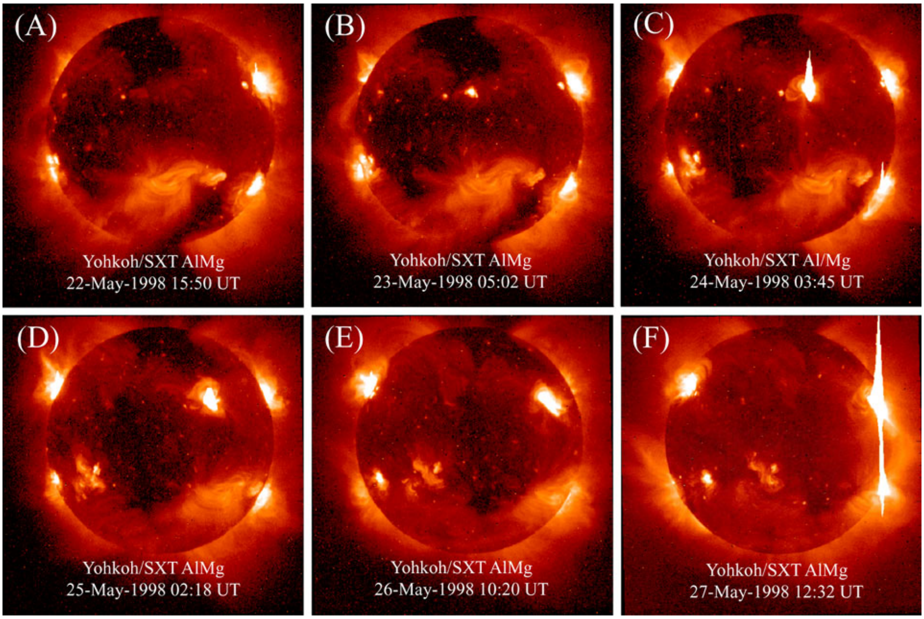

Figure 2 *Yohkoh*/SXT daily images taken with the Al/Mg/Mn filter. The images are arranged in chronological order. A coronal hole occupies the north polar region and extends to mid-latitudes. In panel (A), there are neither trans-equatorial loops nor bright regions at the north footpoint-to-be of the TLS. The bright region in the southern hemisphere is an active-region remnant. An active region appears in the vicinity of the north polar coronal-hole boundary after panel (B). An active region of the south footpoint-to-be of the TLS is seen in the southern hemisphere after panel (E). A clear TLS is seen at the west limb of the Sun in panel (F).

another active region in the opposite hemisphere by a magnetic loop, the loop size would tend to be large in the rising phase. The solar-cycle dependence of the loop size of TLSs was statistically investigated by Chen, Bao, and Zhang (2006). They measured the distances between the two footpoints of TLSs observed with *Yohkoh*/SXT in Solar Cycles 22 and 23, and they reported that the average separation of the footpoints of TLSs was statistically larger in the rising phase than that in the maximum phase.

Figure 2 displays daily snapshots taken with *Yohkoh*/SXT from 22 May 1998 to 27 May 1998. Active regions and a large-scale loop which contained the TLS are shown. Not only trans-equatorial loops but also active regions were barely seen at the footpoints-to-be of the TLS in *Yohkoh*/SXT images before 22 May 1998. On 22 May 1998, however, only a foggy region was seen at the south footpoint-to-be of the TLS (Figure 2(A)). It was an active-region remnant. A distinct active region was seen at the same position in *Yohkoh*/SXT images during previous solar rotations. First, an active region, which became the north footpoint of the TLS later, began to appear in the northern hemisphere. Then, another active region, which became the south footpoint of the TLS, appeared in the southern hemisphere. Finally, a soft X-ray trans-equatorial loop appeared clearly between the two active regions on 27 May 1998. These observations make it possible to analyze the TLS development from the very initial phase before any signature of the TLS to its clear appearance. YM2009 focused on this TLS for analyses to derive information about a formation mechanism of a transient TLS. This paper focuses on the same event in order to find the origins of the TLS itself.

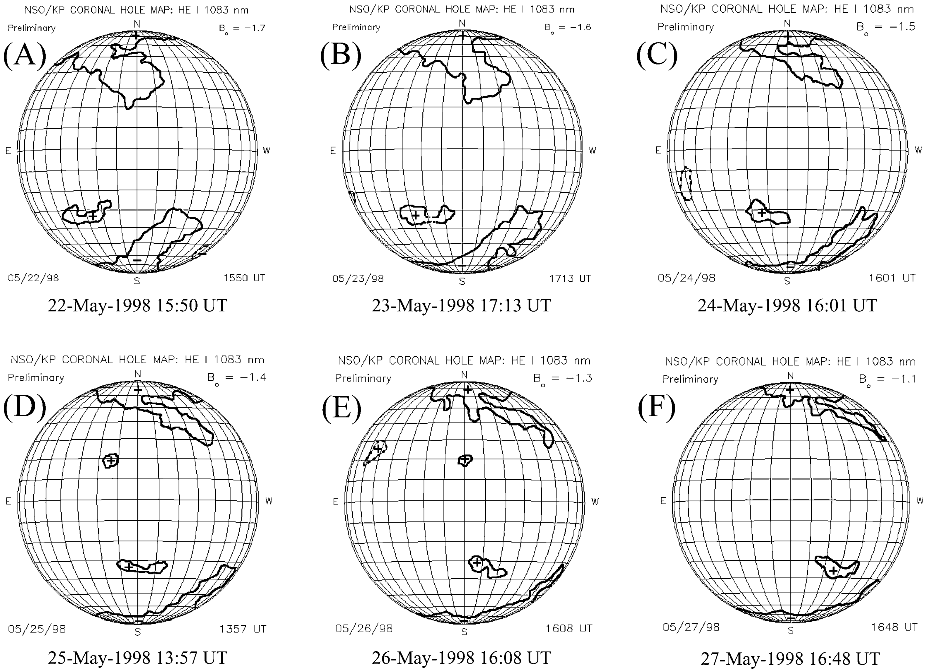

Figure 3 Kitt Peak coronal-hole maps. The maps are arranged in chronological order. The north and the south polar regions are occupied by coronal holes. The magnetic polarity of a coronal hole is denoted by $+$ and $-$ for positive and negative, respectively. Polar coronal holes in both hemispheres extend to mid-latitudes. The north and the south polar coronal holes have positive and negative magnetic polarities, respectively.

2.2. Emerging Active Region

Figure 2(A) is a *Yohkoh*/SXT image taken on 22 May 1998. It is hard to recognize any soft X-ray bright regions in the northern hemisphere at the footpoint-to-be of the TLS in Figure 2(A). The north polar region was occupied by a dark region in soft X-rays, a coronal hole. Coronal holes are generally recognized as dark regions in *Yohkoh*/SXT images due to low-density coronal plasmas. It is generally believed that coronal holes are dominated by open magnetic-field lines which are extending out into the interplanetary space (*e.g.*, Wang, Hawley, and Sheeley, 1996). The coronal holes were also identified in the coronal-hole maps at the same place in the polar region. (See Figure 3; National Solar Observatory/Kitt Peak.) Detailed information on the Kitt Peak coronal-hole map is explained in Harvey and Recely (2002). The daily data of the Kitt Peak coronal-hole map are available from ftp://nsokp.nso.edu/kpvt/coronal_holes/daily/. The south polar region was also occupied by a coronal hole. These polar coronal holes extended to middle latitudes in both hemispheres. On 23 May 1998, as shown in Figure 2(B), a soft X-ray bright point began to appear in the vicinity of the low-latitude boundary of the north polar coronal hole. Then, the bright point developed as a soft X-ray active region. The development of the active region was recognized as an increase in size of the bright region in soft X-rays. Finally, the TLS was seen at the west limb of the Sun on 27 May 1998, as shown in Figure 2(F).

What was seen in the magnetic-field data at the corresponding region where the active region was observed in soft X-rays? Photospheric magnetic-field data have been obtained with the *Solar Oscillations Investigation/Michelson Doppler Imager* (MDI; Scherrer *et al.*, 1995)

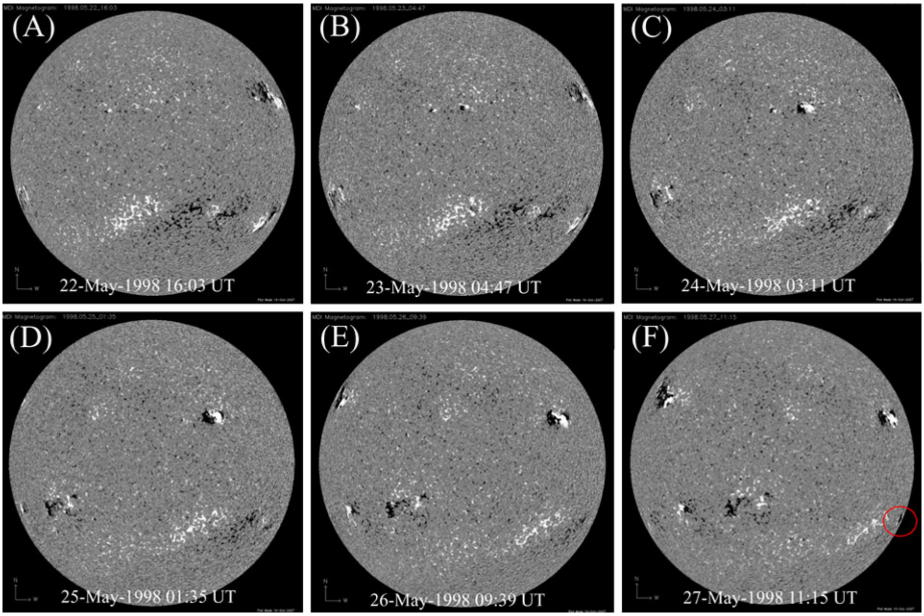

Figure 4 SOHO/MDI magnetograms. The data are arranged in chronological order. White and black areas denote positive and negative magnetic polarities, respectively. In panel (A), there are no magnetic active regions at the north footpoint-to-be of the TLS. A magnetic region is seen at the north footpoint-to-be of the TLS after panel (B). It develops day by day. In panel (F), footpoints of the TLS are at the west limb of the Sun. A bipolar magnetic region is faintly visible in the red circle at the south footpoint of the TLS. These data are available from http://soi.stanford.edu/production/mag_gifs.html.

onboard the ESA-NASA *Solar and Heliospheric Observatory* (SOHO; Domingo, Fleck, and Poland, 1995). In Figure 4(A), no magnetic active regions were seen in the SOHO/MDI magnetogram at the position of the north footpoint-to-be of the TLS on 22 May 1998. Thereafter, strong magnetic fields appeared at the same position after 23 May 1998, and it developed as a magnetic active region. Comparing with the Kitt Peak coronal-hole maps in Figure 3, the magnetic active region was located in the vicinity of the north polar coronal-hole boundary. This means that the magnetic flux emerged close to the coronal hole. We investigated the development of the emerging magnetic flux by using SOHO/MDI magnetograms from 22 to 25 May 1998. We did not treat the period after 26 May 1998 because the magnetic active region approached the west limb of the Sun due to solar rotation. It is difficult to estimate the amounts of magnetic flux at the limb of the Sun because the SOHO/MDI magnetograph records only line-of-sight magnetic-flux density. We investigated the positive and negative magnetic flux in the box as shown in Figure 5(A). The box size is 200×200 arcseconds and it includes the whole of the magnetic active region. We calculated the mean magnetic-flux density in the box. The mean magnetic-flux densities of positive and negative polarities were defined by the total positive and negative signals in the box divided by the total number of pixels of the box, respectively. The box was migrated westward with the solar rotation. The mean magnetic-flux density of both polarities was very weak on 22 May 1998. This means that the magnetic activities were very low at the north footpoint-to-be of the TLS. Then, the magnetic-flux density increases gradually from 23 May 1998. This magnetic signature is consistent with the development of the soft X-ray active region as shown in Figure 2. We defined the region where the absolute value of the magnetic-flux density is greater than

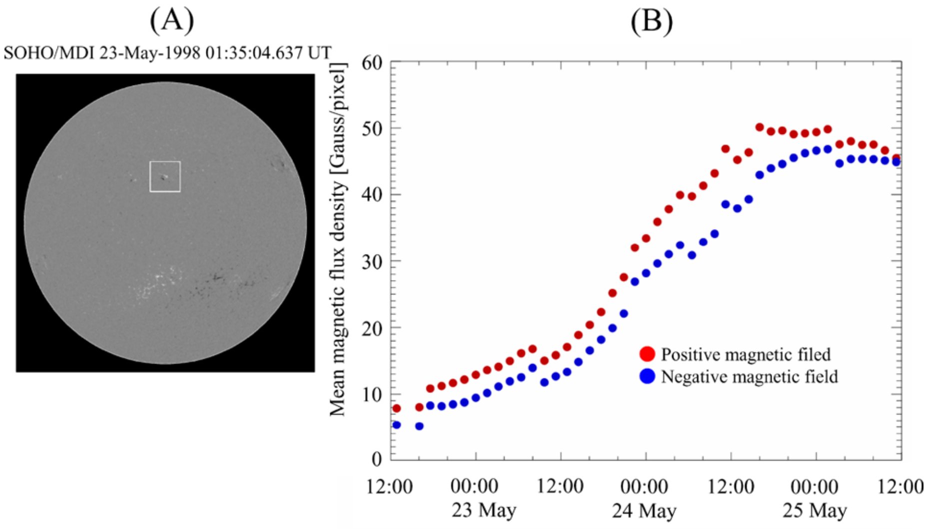

Figure 5 (A) SOHO/MDI magnetogram taken 23 May 1998 01:35:04.637 UT. The white box denotes the region for analyzing temporal variations of magnetic-flux density. The box size is 200 × 200 arcseconds. (B) The temporal variations of the magnetic-flux density in the area shown in panel (A). The red and blue circles denote positive and negative magnetic polarities, respectively.

50 Gauss as the magnetic active region. Negative magnetic flux of the magnetic active region on 24 May 1998, evaluated by counting the pixels which satisfied the definition, was about 7.6×10^{21} Mx.

2.3. Coronal-Hole Boundary Retreat

We examined the relationship between the north polar coronal hole and the development of the active region in the northern hemisphere. In order to reveal the relationship, we investigated temporal variations of soft X-ray intensities along the white line as shown in Figure 6(A). The white line was located to cover both the active region and a part of the north polar coronal hole. The position of the white line was migrated westward in accordance with solar rotation from 22 to 25 May 1998. For this analysis, we used *Yohkoh*/SXT full-Sun image data taken with the Al/Mg/Mn filter. Figure 6(B) shows a result of the analysis. The horizontal bright zone at the center in Figure 6(B) originates with an active-region core. The bright core was tiny at the beginning of the period of the analysis. Then, the width of the bright zone expanded both northward and southward. The dark region of the northern side on the white line in Figure 6(A), where the soft X-ray intensities are low, indicates the north polar coronal hole. In Figure 6(B), the boundary between the bright core and the dark region shifts northward gradually. The coronal hole seems to shrink. This is called "coronal-hole boundary retreat" (Baker, van Driel-Gesztelyi, and Attrill, 2007). One might wonder if this retreat of the coronal-hole boundary only appeared to occur due to a projection effect, *i.e.*, the coronal-hole boundary was just hidden by line-of-sight tall loops of the active region. Let us examine the Kitt Peak coronal-hole maps from 22 to 25 May 1998 (Figure 3). The behavior of the low-latitude boundary of the north polar coronal hole in the Kitt Peak daily coronal-hole maps represents the position of the low-latitude boundary of the north polar coronal hole shifting northward day by day. Also, there are other probabilities for position changes of the coronal-hole boundary due to the migration, diffusion, or pile-up to

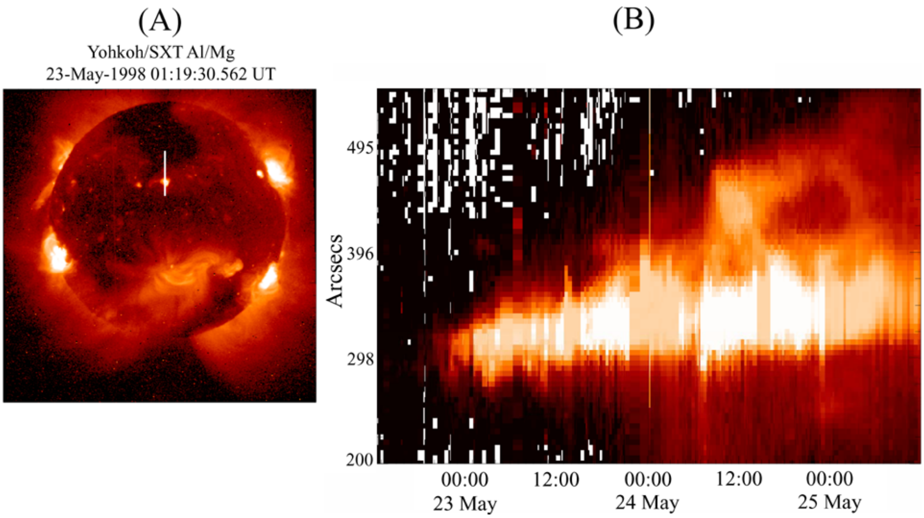

Figure 6 (A) *Yohkoh*/SXT image taken with the Al/Mg/Mn filter at 23 May 1998 01:19:30.562 UT. The white line denotes the position for analyzing temporal variations of soft X-ray intensities. The length of the white line is 354 arcseconds. (B) The temporal variations of the soft X-ray intensities of *Yohkoh*/SXT images taken with the Al/Mg/Mn filter along the white line in panel (A). The vertical axis indicates the latitude direction in pixel scale. The range of the vertical axis corresponds to the length of the white line in panel (A).

the North of the magnetic flux. We checked a de-rotated MDI magnetogram time sequence around the coronal-hole boundary region. The result shows that there are no systematic variations around the region while the magnetic active region emerged. Therefore, we think that the coronal-hole boundary retreat is not due to migration of the magnetic flux. The retreat of the coronal-hole boundary is not due to the projection effect, but is real.

It is thought that two different magnetic configurations coexist at the footpoint of the TLS. One is the closed magnetic fields of the active region, and the other is open magnetic fields of the coronal hole. When the active region developed in the vicinity of the coronal hole, it is expected that the coronal hole should be stressed by magnetic pressure of the active-region development and that magnetic reconnection should take place at the coronal-hole boundary (Baker, van Driel-Gesztelyi, and Attrill, 2007). According to the Kitt Peak coronal-hole maps, the north polar coronal hole had a positive magnetic polarity. The closer part of the magnetic active region to the north polar coronal hole had a negative magnetic polarity. When open magnetic-field lines of the coronal hole reconnect with the closed magnetic-field lines of the active region, a part of the open magnetic-field lines results in closed magnetic-field lines. From Figure 5(B), it is clear that magnetic flux was supplied continuously from the magnetic active region. The retreat of the coronal-hole boundary would continue while the active region develops and magnetic reconnection goes on at the coronal-hole boundary. Such magnetic interactions between the active region and the coronal hole would contribute to make strong-seed magnetic fields of the TLS on the basis of the scenario of YM2009.

In Figure 3, it is clearly shown that the size of the north polar coronal hole around the active region of the north footpoint-to-be of the TLS became smaller than that at the beginning. It is possible to estimate roughly the magnetic flux in the reduced area of the coronal hole by using coronal-hole maps and SOHO/MDI magnetograms. We compared coronal-hole maps from 22 and 24 May. This is because increases of the emerging magnetic flux are noticeable from 22 to 24 May, as shown in Figure 5(B), and the magnetic interactions between the active region and the coronal hole are expected to take place in this period. The positive-open magnetic flux in the reduced area of the coronal hole was about 0.9×10^{21} Mx.

2.4. Simultaneous Variations of Soft X-ray Intensity

In the previous subsections, we described the development of the active region and the retreat of the coronal-hole boundary as observed with *Yohkoh*/SXT. However, one might ask how these phenomena were concerned with the TLS formation. We are interested in the relationship between the TLS formation and the magnetic interactions between the active region and the coronal hole. Two boxed regions shown in Figure 7(A) were prepared in order to analyze temporal variations of the soft X-ray intensities. One is a boundary region of the north polar coronal hole, and the other is a trans-equatorial region. "Polar region" in Figure 7(A) denotes the boundary region of the north polar coronal hole. A reason for preparing the boundary region for the analysis is that some soft X-ray features are expected to be observed due to energy injections caused by magnetic interactions at the coronal-hole boundary. "Equatorial region" in Figure 7(A) denotes the trans-equatorial region. The trans-equatorial loop activities would increase if the magnetic interactions at the coronal-hole boundary would affect the trans-equatorial region (Figure 1). A period from 26 May 1998 00:00 UT to 28 May 1998 12:00 UT was selected for the analysis. Since the TLS appeared clearly during this period, it is adequate to derive information about the relationship of the activities between the coronal-hole boundary and the trans-equatorial loop. We used *Yohkoh*/SXT full-Sun images that were taken with the Al/Mg/Mn filter. The size of the two boxes is 103×103 arcseconds. The positions of the two boxes were adjusted in accordance with solar rotation to follow the targets for the analysis. Excessive brightening sometimes occurred in the active region caused by energetic phenomena such as flares and caused saturated pixels in *Yohkoh*/SXT images. Since such saturated pixels are not useful for the analysis, the boxes were prepared carefully so as not to include the saturated pixels. Figure 7(B) shows the result of the analysis. At the beginning of 26 May 1998, the soft X-ray intensities were lower at the both regions. Then, the soft X-ray intensities increased gradually in the both regions from later on 26 May 1998 and were higher in both regions after the middle of 27 May 1998. The temporal variations of the soft X-ray intensities between the two regions were roughly synchronized. There is a good correlation for the soft X-ray intensities between the two regions. It could be said that the magnetic interactions between the active region and the coronal hole were related to the trans-equatorial activities.

2.5. Appearance of New Closed Loops

What kind of topological changes should be observed when magnetic interactions take place between the active region and the north polar coronal hole? Baker, van Driel-Gesztelyi, and Attrill (2007) reported observational evidence of magnetic interactions. They described that an emerging active region near a coronal hole created new-closed magnetic loops at the coronal-hole boundary. When an active region emerges near a coronal hole, closed magnetic fields of the active region press against the open magnetic fields of the coronal hole. Consequently, magnetic reconnection takes place at the boundary between the active region and the coronal hole. This type of magnetic reconnection is called "interchange reconnection" by Crooker, Gosling, and Kahler (2002). In this study, the magnetic-field topology of the active region and the north polar coronal hole is basically the same as the interchange reconnection model of Crooker, Gosling, and Kahler (2002). Therefore, it is expected that magnetic reconnection should probably take place between the active region and the north polar coronal

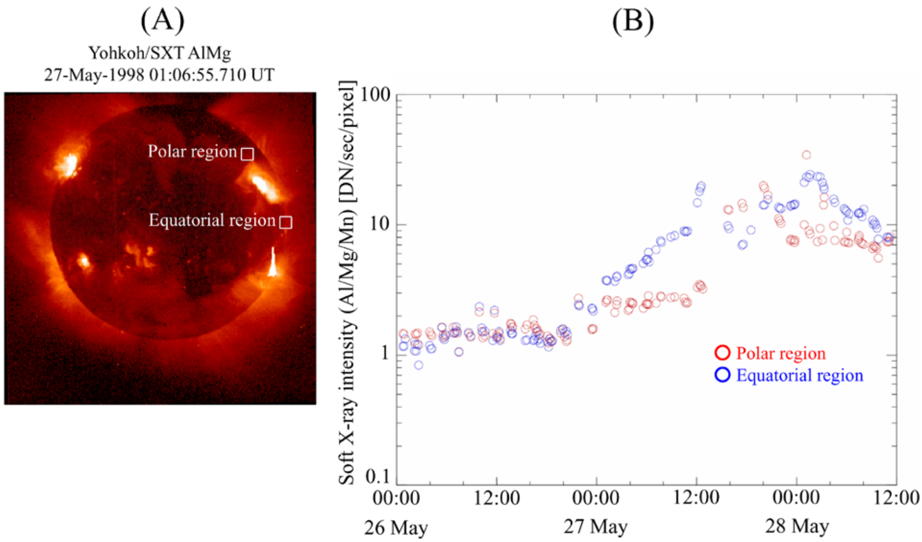

Figure 7 (A) *Yohkoh*/SXT image taken with the Al/Mg/Mn filter on 27 May 1998 01:06:55.710 UT. The regions shown by white boxes are used for analyzing temporal variations of the soft X-ray intensities. The "Polar region" represents the boxed region around the north polar coronal-hole boundary. The "Equatorial region" represents the boxed region in the trans-equatorial loop. The size of the two boxes is 103 × 103 arcseconds. (B) The temporal variations of the soft X-ray intensities of *Yohkoh*/SXT images taken with the Al/Mg/Mn filter in the two boxes in panel (A). Counts are normalized to an exposure time of one second. Mean soft X-ray intensity indicates soft X-ray counts per pixel in the box. The red and blue circles denote the temporal variations of the soft X-ray intensities at the "Polar region" and the "Equatorial region", respectively.

hole through the same process as Baker, van Driel-Gesztelyi, and Attrill (2007) reported. Also, as a result, closed loops of the same type are expected to be found in *Yohkoh*/SXT images.

We checked the area around the north polar coronal-hole boundary in *Yohkoh*/SXT images taken on 27 May 1998, when the TLS appeared clearly. Figure 8(A) is a snapshot of the north polar coronal-hole boundary of *Yohkoh*/SXT images. This image was taken at 27 May 1998 12:41 UT. The sharpness of this image is enhanced. Although just a little brightening was seen at the north polar coronal-hole boundary in soft X-rays, it is difficult to identify clear soft X-ray bright loop structures between the active region and the coronal-hole boundary. Figure 8(B) is a *Yohkoh*/SXT image taken at 27 May 1998 20:30 UT. It was taken a few hours later than Figure 8(A). Figure 8(C) is a *Yohkoh*/SXT image taken at 27 May 1998 23:33 UT. The sharpness of these images is enhanced in the same manner. In Figure 8(B) and (C), loop structures like a bridge can be identified from the north edge of the active region to the north polar coronal-hole boundary. Comparing Figure 8(A) with (B), the boundary of a dark region changed into a bright region. We could advance the interpretation that a part of the coronal hole in Figure 8(A) was no longer a coronal hole in Figure 8(B). Figure 8(D) is a differential image between Figure 8(A) and (B). Positive/negative signals shown as bright/dark regions in Figure 8(D) indicate increases/decreases in soft X-ray intensity. In Figure 8(D), it could be confirmed that there are loop structures that are connecting the active region and the north polar coronal-hole boundary. Because the active region was located close to the west limb of the Sun, it was easy to recognize topological changes of the coronal-hole boundary. Thanks to this positional advantage, the shape of the loop structures could be clearly recognized. In Section 2.3, the magnetic interactions between the active re-

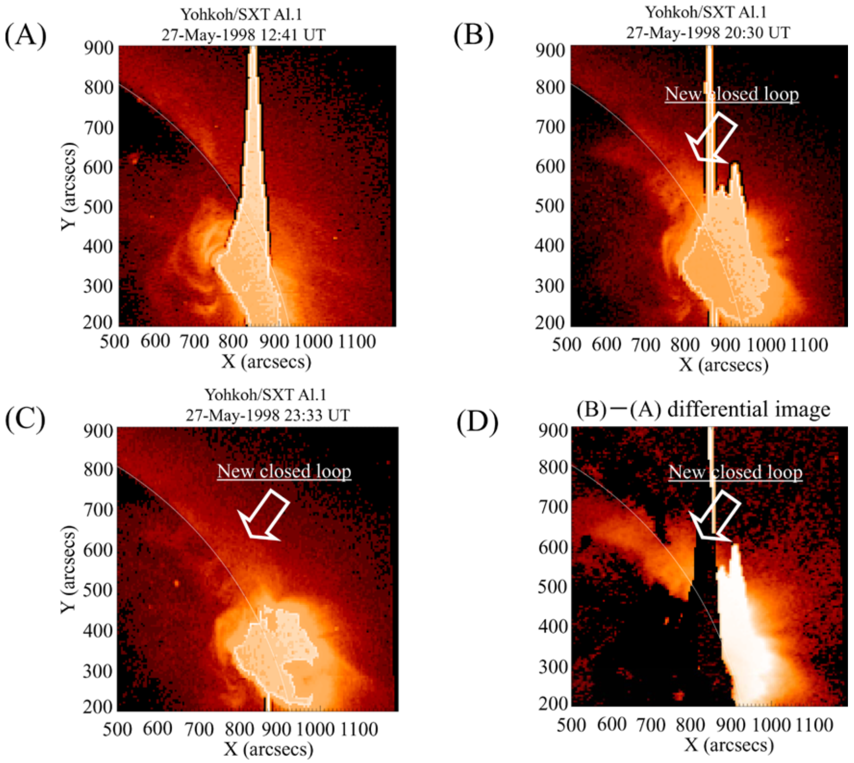

Figure 8 *Yohkoh*/SXT image taken with the thin aluminum filter on 27 May 1998. (A) This image was taken at 12:41 UT. There are no bright loops at the coronal-hole boundary. The image is influenced by saturated pixels due to excessive brightening at the active region. (B) Bright loops are seen at the coronal-hole boundary. (C) The bright loops are basically the same as that in panel (C). (D) Differential image subtracting (A) from (B). New closed loops are shown by the arrow. The sharpness of the images in panels of (A), (B), and (C) are enhanced by a Laplacian kernel.

gion and the coronal hole were observed as the northward shift of the coronal-hole boundary. However, it was difficult to recognize the topological changes at the coronal-hole boundary since the active region was located closer to the solar disk center at the time.

It is reasonable to suppose that an energetic process took place between the active region and the north polar coronal hole. The topological changes of the soft X-ray loop structures shown in Figure 8 are similar to the new magnetic-field lines drawn in Figure 1 of Baker, van Driel-Gesztelyi, and Attrill (2007), which were explained as products of the interchange reconnection between an active region and a north polar coronal hole.

2.6. Brief Summary of Observations and Analyses

A TLS was observed with *Yohkoh*/SXT at the west limb of the Sun, identified initially on 27 May 1998. In order to investigate the origin of the TLS, we start on 22 May 1998 when an active region of the north footpoint-to-be of the TLS began to appear. Before that, there were neither active regions at the footpoints of the TLS nor was there soft X-ray connectivity between the northern and the southern hemispheres in *Yohkoh*/SXT images. Firstly, a soft X-ray point source was observed with *Yohkoh*/SXT in the northern hemisphere around

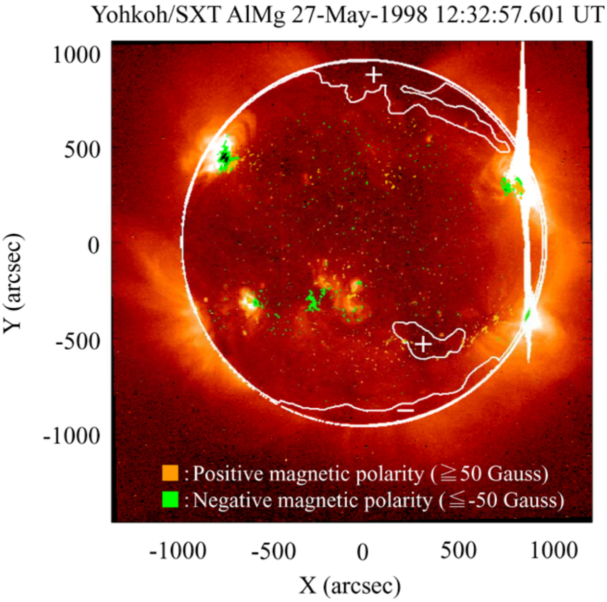

Figure 9 Superposed map of *Yohkoh*/SXT image, SOHO/MDI magnetogram, and Kitt Peak coronal-hole map on 27 May 1998. The *Yohkoh*/SXT image was taken with the Al/Mg/Mn filter at 12:32 UT. The SOHO/MDI magnetogram was taken at 12:51 UT. The Kitt Peak coronal-hole map was made at 16:48 UT. The SOHO/MDI magnetogram and the Kitt Peak coronal-hole map were de-rotated in order to overlay the *Yohkoh*/SXT image. White curves at the west limb on the superposed map are caused by de-rotated limb edges of the Kitt Peak coronal-hole map. Orange: positive magnetic polarity (≥ 50 Gauss). Green: negative magnetic polarity (≤ -50 Gauss), respectively.

22 May 1998. The soft X-ray point source developed as a soft X-ray active region, and was also observed with the SOHO/MDI magnetograph at the same position as emerging magnetic flux. The Kitt Peak coronal-hole maps showed that the north polar region was located in a polar coronal hole and that the north polar coronal hole extended to the middle latitude. Comparing the Kitt Peak coronal-hole maps with the *Yohkoh*/SXT images or the SOHO/MDI magnetograms, the active region was located in the vicinity of the north polar coronal-hole boundary. During the period from 22 to 25 May 1998, the *Yohkoh*/SXT images showed that the coronal-hole boundary retreated simultaneously with development of the active region, as also supported by the Kitt Peak coronal-hole maps. The Kitt Peak coronal-hole maps showed that the north polar coronal-hole boundary shifted northward during the same period. Temporal variations of soft X-ray intensities were analyzed at the boundary region of the north polar coronal hole and a trans-equatorial region. The soft X-ray intensities showed a gradual increase at both regions, and the temporal variations of the soft X-ray intensities were roughly synchronized between the two regions. Finally, carefully examining the north polar coronal-hole boundary in *Yohkoh*/SXT images, there were clear new soft X-ray loops which connected the active region and the north polar coronal-hole boundary. A part of the north polar coronal hole changed into a bright region in soft X-rays at the same time. That part of the north coronal hole was no longer a coronal hole. The new soft X-ray loops suggest that magnetic interactions between the active region and the north polar coronal hole took place at the boundary. A clear spatial relationship among the trans-equatorial loop, the magnetic active region, and the coronal hole is displayed in Figure 9. The polar coronal holes extend close to the magnetic active regions, and legs of the trans-equatorial loop are rooted in the magnetic active regions.

3. Discussion and Conclusion

YM2009 proposed a new scenario for a TLS formation mechanism. An important portion of their scenario entails magnetic interactions between an active region and a coronal hole. Accordingly, some characteristic magnetic features are expected to be observed around the coronal-hole boundary if the magnetic reconnection takes place between the active region and the coronal hole. Also, energetic features are expected to be observed in the trans-equatorial region if such magnetic interactions contribute to the TLS formation. In the case of the TLS on 22 – 27 May 1998, the active region developed in the vicinity of the north polar coronal-hole boundary. It is considered that closed magnetic fields of the active region pressed open magnetic fields of the north polar coronal hole at the boundary. This magnetic pressure toward the north polar coronal hole would trigger magnetic reconnection if magnetic polarity were oppositely oriented for the active region and the coronal hole. In fact, the SOHO/MDI magnetograms and the Kitt Peak coronal-hole maps showed that the north polar coronal hole with positive polarity was in close proximity to the negative magnetic polarity of a following part of the magnetic active region. This magnetic situation is likely to give rise to magnetic reconnection. This situation is very similar to X-ray jet phenomena (Shimojo and Shibata, 2000; Shimojo *et al.*, 2001). The physics of X-ray jet phenomena might be useful for understanding the process of the TLS formation. Fárník and Švestka (2002) reported X-ray jets in trans-equatorial loops. This fact should assist in adapting an idea of the X-ray jet phenomena to the TLS formation mechanism as an analogy. Yokoyama and Shibata (1995) presented results of magnetohydrodynamic simulations of a reconnection process which took place between emerging magnetic flux and outer coronal magnetic fields. When magnetic reconnection takes place between open and closed magnetic-field lines, part of the open magnetic-field lines transform into closed magnetic-field lines. This is consistent with the observations that the coronal hole with open magnetic-field lines retreated at the boundary as shown in Figure 6(B). Another part of the open magnetic-field lines created by the open-closed magnetic reconnection would move away from a reconnection point. In Yokoyama and Shibata (1995), the magnetic reconnection produces upward jets and hot loops at the side of the emerging magnetic flux. Hot and dense plasmas rise at the boundary region between the emerging magnetic flux and the outer coronal magnetic fields. This is also consistent with the soft X-ray intensity enhancement which was seen at the coronal-hole boundary in the *Yohkoh*/SXT images (Figure 7). Recently, Shimojo *et al.* (2007) reported fine structures of X-ray jets observed with the *X-Ray Telescope* (XRT: Golub *et al.*, 2007; Kano *et al.*, 2008) onboard the *Hinode* satellite (Kosugi *et al.*, 2007). *Hinode*/XRT makes it possible to observe the corona with higher spatial and temporal resolution than ever before. X-ray bright loops were clearly recognized beside X-ray jets by Shimojo *et al.* (2007). Energy created by the magnetic reconnection was injected into footpoints along the magnetic-field lines. Some portion of the energy was converted into thermal energy. As a result, soft X-ray brightening was observed on both sides of the emerging magnetic flux. This corresponds to the soft X-ray enhancement that was seen simultaneously at both the trans-equatorial region and the boundary region of the north polar coronal hole. This might be the reason why good correlation appears in the soft X-ray intensities of the two regions, as shown in Figure 7. The energetic process at the boundary region of the north polar coronal hole might basically be the same as the mechanism of the X-ray jets with respect to magnetic reconnection between emerging magnetic flux and outer coronal magnetic fields.

It is worthwhile to add some description specifically of the correlation in Figure 7 from late 26 May 1998 to early 27 May 1998. The trend of temporal variations of the soft X-ray intensities shows some discrepancies for the “Polar region” and the “Equatorial region” during this period. The soft X-ray intensities increased gradually at the “Equatorial region”, while there was only a slight increase of the soft X-ray intensities at the “Polar region”. Where did this difference come from? The appearance of a soft X-ray bright region was observed with *Yohkoh*/SXT at the footpoint-to-be of the TLS in the southern hemisphere during

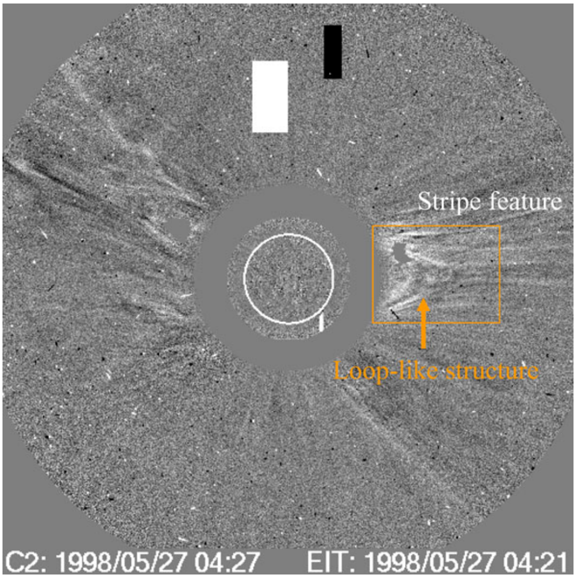

Figure 10 Running-difference image of the corona taken with SOHO/LASCO-C2 at 27 May 1998 04:27 UT. Striped features are extending into the interplanetary space on the west side of the Sun. Loop-like structures, which are indicated by the arrow, are mixed in the striped features as seen in the box at the west side of the Sun.

this period. A small bipolar magnetic active region was recognized in SOHO/MDI magnetograms at the same position where the soft X-ray bright region was seen in *Yohkoh*/SXT images (*e.g.,* Figure 4(F)). This soft X-ray bright region began to appear at the middle of 26 May 1998. *Yohkoh*/SXT images showed that the size of the soft X-ray bright region increased gradually. This could be interpreted as a magnetic active region emerging during this period. The temporal profile of the size of the soft X-ray bright region showed a similar behavior for the soft X-ray intensities at the "Equatorial region". Comparing the position of the magnetic active region with the Kitt Peak coronal-hole maps, they showed that the magnetic flux emerged in the vicinity of the south polar coronal-hole boundary. This magnetic situation was basically the same as the emerging magnetic flux in the vicinity of the north polar coronal-hole boundary, although their magnetic polarities were opposite. Therefore, we could put forward the interpretation that the appearance of the TLS was also strongly related to the active-region emergence at the footpoint-to-be of the TLS in the southern hemisphere. Considering the similarities of the magnetic situations at the northern and the southern hemispheres, it could be thought that the same process of magnetic interactions for the active region and the coronal hole took place with a time lag (about four days) in each hemisphere. These magnetic interactions are very important for the TLS formation, as YM2009 pointed out.

One might think that it is difficult to make the strong-seed magnetic fields of the TLS through the open-closed magnetic reconnection because, if all magnetic-field lines from the polar coronal holes are perfectly open to the interplanetary space, magnetic interactions between the active regions and the coronal holes would only pull out coronal plasmas into the interplanetary space and not form any large-scale loops such as the TLS. Figure 10 shows a running-difference image taken with the *Large Angle and Spectrometric Coronagraph Experiment* (LASCO: Brueckner *et al.*, 1995) onboard the SOHO spacecraft, SOHO/LASCO-C2, at 27 May 1998 04:27 UT. (http://cdaw.gsfc.nasa.gov/CME_list; Yashiro *et al.*, 2004). White areas in Figure 10 indicate an increase in the local brightness or electron density during the interval, while black areas indicate a decrease. A lot of thin striped features are recognized on the west side of the corona. These striped features are extending into the interplanetary space. Also, some loop-like structures are mixed in the striped features at the same region. The striped features and the loop-like structures reflect a configuration of the global coronal magnetic fields. This magnetic configuration might be said to be a helmet streamer where there are two types of large-scale magnetic-field lines. One is really open to interplanetary space, and the other is returning in the corona toward the opposite hemisphere. The active regions at the footpoints of the TLS in each hemisphere developed in such global magnetic fields of the background corona. We conclude from the results of the observations and the analyses that the TLS came from the coronal-holes boundary through magnetic reconnection between the active regions and the polar coronal holes.

The scenario suggested in YM2009 is one of the processes of TLS formation, and likely valid for a type of event like that described in this paper. Since a lot of TLSs have been observed and they show morphological variations, processes different from our scenario might be considered. A key question is how the loops appear in soft X-rays. It is necessary to furnish plasma supply for the TLSs in soft X-rays. It is possible to provide a plasma supply by flares or jet-like activities in only one side of the active region. We should note that the process suggested in YM2009 is not applicable to all trans-equatorial loop systems. For example, a faint loop across the Equator which appeared on 24 May 1998 could be identified in *Yohkoh*/SXT images. We think that this faint loop differed from the trans-equatorial loop on 27 May. On 24 May 1998, the active region in the southern hemisphere has not been appeared yet. This faint loop is connecting the negative polarity region (the following spot region of the active region) in the northern hemisphere and the positive polarity region (a small coronal hole) in the southern hemisphere. The magnetic situation of the TLS which we mainly discussed in our manuscript is opposite to the faint loop. It connected the positive (the proceeding spot) region in the northern hemisphere and the negative (the proceeding spot) region in the southern hemisphere. The formation mechanism of the faint loop on 24 May might be different. It is one of the remaining problems. One possibility is direct interactions between the northern active region and the southern small coronal hole, as proposed by Wang *et al.* (2007).

It has been considered that TLSs may provide clues to the behavior of the solar dynamo (Sakurai and Uchida, 1977). Also, van Driel-Gesztelyi (2006) indicated the same point: that TLSs play an important role in Babcock's dynamo model (Babcock, 1961) in restoration of poloidal magnetic fields. Recently, Jiang, Choudhuri, and Wang (2007) tried to explain the origin of TLSs by a solar-dynamo model. Magnetic fields of active regions originate with toroidal fields, while large-scale magnetic fields of polar coronal holes are poloidal in general. Our study contributes to understanding the global magnetic system for the poloidal and toroidal magnetic fields of the Sun, because an important process for TLS formation as we discussed is magnetic interactions between the active regions (toroidal) and the coronal holes (poloidal). How much of the magnetic flux of the active region is converted to the trans-equatorial loop? The retreated area of the coronal hole in the vicinity of the emerging magnetic flux gives a clue to derive the magnetic flux conversion toward the trans-equatorial loop. In the TLS which we investigated in this study, the negative magnetic flux of the emerging active region was about 7.6×10^{21} Mx, as seen in Section 2.2, and the positive-open magnetic flux of the retreated area of coronal hole was about 0.9×10^{21} Mx, as described in Section 2.3. The fraction of the positive magnetic flux of the area loss of the coronal hole to the negative magnetic flux of the magnetic active region is about 12%. It is considered that about one tenth of the emerging magnetic flux was used for the formation of the trans-equatorial loop. Therefore, the magnetic conversion from the toroidal field to the poloidal field through the TLS is not negligible quantitatively. This is the first quantitative estimation of the TLS contribution for toroidal-poloidal magnetic conversion from observational data. Pevtsov (2000, 2004) statistically investigated trans-equatorial loops by using

Yohkoh/SXT data, which include the declining phase of cycle 22 and the rising phase of cycle 23, and these references reported that approximately 35% of all active regions show a trans-equatorial connection. If all TLSs are created by the process described by YM2009, magnetic-flux conversion from active regions to trans-equatorial loops would be effective quantitatively in the solar dynamo.

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