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Some statistical properties of transequatorial loops

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Abstract

Yohkoh soft X-ray telescope brought plenty of high quality images, it provides a good chance to research coronal loops, especially for transequatorial loops (TLs). In this paper, we focus on the statistical results of TLs including static properties and dynamic properties.

There are two types of classification about TLs: according to configuration and according to magnetic polarities of footpoints, respectively. The footpoints of TLs never root in sunspot, in a general way, they exist in moderately strong field. The mean separation value of TLs is close to 30° and the separation value varies with solar cycle. The helicity patterns of active regions connected by TLs are discussed, the mean twist value of TLs is close to zero. The formation of TLs is generally thought to be caused by magnetic reconnection, the relationship of TLs eruption with flare and CME is introduced.

Keywords: Sun; Coronal loop

1. Introduction

Skylab observations first viewed transequatorial loops (TLs) which connect regions in the opposite solar hemispheres (Chase et al., 1976; Švestka et al., 1977). After that no other missions observing soft X-ray images worked, until *Yohkoh* mission (Tsuneta et al., 1991) was launched in 1991. *Yohkoh* provided a full decade of soft X-ray images from solar disk, revealing for the first time the geometry and topology of large-scale magnetic field reconfigurations and magnetic reconnection processes. The TLs have drawn attention renewedly since the *Yohkoh* was launched.

Transequatorial loops are relevant to solar dynamo model. An essential ingredient of the solar dynamo process is the Babcock–Leighton mechanism for the generation of the poloidal field, which requires that field lines reconnect across the solar equator. TLs are formed by magnetic reconnection which connect the opposite sides of equator reflecting the large-scale structure of the poloidal field (Jiang et al., 2006).

In this paper, we provide a brief overview of the observational characteristics of transequatorial loops and give some discussion about it.

2. Properties of transequatorial loops

Some statistical properties of the transequatorial loops found recently are demonstrated in this section.

2.1. Classification

Transequatorial loops are classified through two methods: one is according to configuration, the other is according to magnetic polarities of footpoints.

Pevtsov (2000) found 87 transequatorial loops using *Yohkoh* data from 1991 to 1998 and classified them according to configuration. These TLs are classified in two distinctive categories: one is 'connection', the other is 'reconnection'. The connection loops may be appear ('S type') or unsheared ('U type') and the reconnection loops form a system of the letters 'X' or 'Y' by analogy with classical X- and Y-types of magnetic reconnection. According to this classification, 61 loops (70%) belong to the connection type and 26 (30%)

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are of the reconnection type. The statistical results for this classification are listed in Table 1.

Chen et al. (2006a) identified 356 transequatorial loops using the whole data set of *Yohkoh* from 1991 to 2001. They classified TLs according to the magnetic polarities of the footpoints of TLs. Based on this criterion, TLs fall into two categories: PTLs in which the magnetic polarities of the footpoints are the same as the preceding polarities and FTLs in which the footpoint polarities are the same as the following polarities of active regions, respectively. It is found that about 66% of the TLs are PTLs, this result is shown in Table 2. The preference of PTLs indicates that TLs is more easily to connect the preceding polarities than the following polarities.

2.2. Footpoints

Transequatorial loops may develop between existing active regions or between mature regions and new magnetic flux shortly after flux emergence (Pevtsov, 2000). There is a dark gap between the apparent end of TLs and the interconnected active regions in soft X-ray images (Fárník et al., 2001). Several different reasons can explain the appearance of X-ray gaps near TL footpoints: low temperature, decreased density due to increased magnetic field near the footpoints, and possibly real existence of a gap between the TL footpoints and active region loops. However, it is not very clear about the generation of this gap.

The footpoints location of transequatorial loops are discussed in detail by Fárník et al. (2001). Most TLs root in moderately strong fields at the periphery of active regions. There are also situations that footpoints of TL appear in extremely weak magnetic fields less then 30 G detached from the active region field structures and cases when TLs are clearly rooted in quite strong fields (several hundred gauss). Some TLs their footpoints are near sunspot penumbrae, some root very close to sunspots, but it is never seen that any TL roots in a sunspot.

2.3. Separation values of TLs and relation with solar cycle

Based on the data of Skylab, Chase et al. (1976) obtained that the average length of the loops is about 20° with the longest loop of 37°. They supposed that this was the real maximum of interconnecting loops on the Sun, but Chase et al. (1976) used Skylab data only having the relatively short 9-month period, this induce that the result may be not very accurate. Recently, Fárník et al. (1999) found two long transequatorial loops (with lengths of 47 and 61 heliographic degrees) from *Yohkoh* SXT data. They provided evidence that the upper limit in length of 37° was only determined during the period of Skylab observations. Pevtsov (2000) studied 87 TLs and showed the average footpoint separation of them to be approximately 30° with a maximum of 75°. Chen et al. (2006a) also calculated the separation and found that the mean value of footpoint separation is about 27°, which is close to Pevtsov's (2000) result.

The separation values of footpoints of TLs varing with solar cycle are exhibited in Fig. 1. The period of 1991–1995 is the declining phase of solar cycle 22 and the period of 1997–2001 is the increasing branch of solar cycle 23. From Fig. 1 we can see that the mean value of separation decreases gradually year by year from 1991 to 1995 and it also decreases from 1997 to 2001. In 1996, a change of magnetic polarity took place, and the mean value of separation for this year is close to the average value of the whole TLs. Spörer's law shows the solar latitude at which new sunspots appear gradually decreases, from high latitudes at the beginning of a solar cycle to low latitudes at the end of the cycle. The footpoint separation of TLs also decreases year by year following solar cycle and the mean value is lower in the declining phase (1991–1995) than in the ascending part (1997–2001) (Fig. 1), this trend is consistent with Spörer's law. If we assume that a TL reflects the poloidal component of the Sun's magnetic fields, this finding is in favor of Stenflo (1988)'s result: the radial component of the Sun's large-scale magnetic field has a branch which drifts equatorwards that starts at a latitude of 30°.

Similar to other solar activities, transequatorial loops also show the 11-year solar cycle (Pevtsov, 2000, 2004). This result was confirmed by Chen et al. (2006a). Fig. 2

Table 1
Classification according to configuration (Pevtsov, 2000)

Connection (61 total)		Reconnection (26 total)	
U	S	X	Y
25	36	16	10

Table 2
Classification according to the magnetic polarities of the footpoints (Chen et al., 2006a)

Category	Number	Fraction (%)
PTL	229	66
FTL	127	34

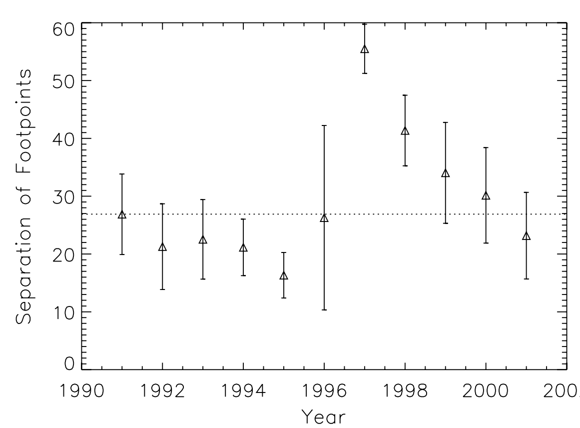

Fig. 1. The separation in different years. The triangle shows the average value in each year. The error bar is for 1σ interval. The dotted line shows the overall average value (Chen et al., 2006a).

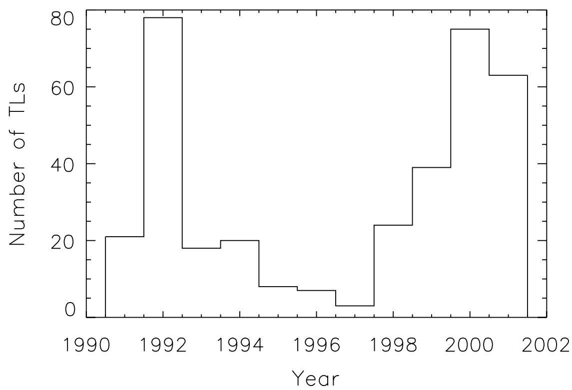

Fig. 2. The number of TLs in different years. Years 1991–1996 belong to solar cycle 22 and years 1996–2001 belong to solar cycle 23 (Chen et al., 2006a).

demonstrates the number of TLs in different years. In the declining phase of the solar cycle, the number of TLs decreases; in the rising phase, it increases. The number of TLs is large in high solar activity (1992, 2000), and is small in low activity (1996, 1997).

2.4. Helicity patterns

In this section, we consider the correlation of current helicity of the active region pairs connected by TLs, then we introduce the twist values of TLs themselves.

Canfield et al. (1996) found that the handedness of active regions is important in formation of TLs. They searched the 1991–1995 *Yohkoh* SXT database and analyzed 27 pairs of regions which were close in longitude, but on opposite sites of the equator. For the 27 pairs of active regions, 17 pairs of regions form the transequatorial loops, among the 17 pairs, 15 pairs of regions have the same chirality. Fárník et al. (1999) studied two cases and found that the active region pairs connected by TLs have the same chirality. Pevtsov (2000) calculated 22 pairs of active regions connected by TLs. In 15 cases (68%) both regions have the same chirality, and in seven cases (32%) the regions have the opposite chirality.

Chen et al. (2006b) obtained different results from them. Using the force-free factor α_{best}, they calculated the helicity patterns of 43 pairs of active regions which are connected by the transequatorial loops (TLs) and found that the helicity patterns of the active regions pairs have no obvious regularity: about 50% of the active region pairs show the same chirality and about 50% of them show the opposite helicity patterns. The result is viewed in Fig. 3. Several reasons can cause the difference: different instruments were used, the rule is not very strong, all of them used small data sets.

Rust and Kumar (1996) identified 23 cross-equator 'S' shape coronal structures using *Yohkoh*/SXT data set. Among these structures, 12 cases belong to the type of forward 'S' shape, 11 cases belong to the type of inverse 'S' shape. Some transequatorial loops also exhibit 'S' shape

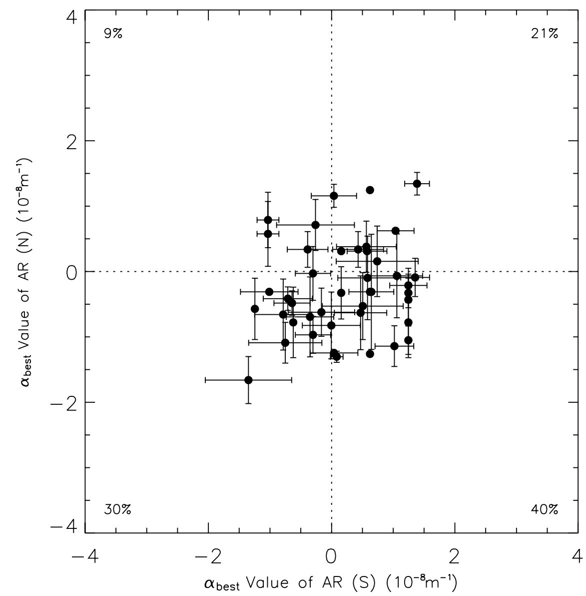

Fig. 3. Correlation of α_{best} of the active region pairs connected by transequatorial loops. *X*-axis shows the α_{best} value of the active regions in the southern hemisphere, *Y*-axis demonstrates the α_{best} value of the active regions in the northern hemisphere. Error bars correspond to 1σ of the mean helicity values from multiple magnetograms of the same active region. Points without error bars correspond to active regions represented by a single magnetogram (Chen et al., 2006b).

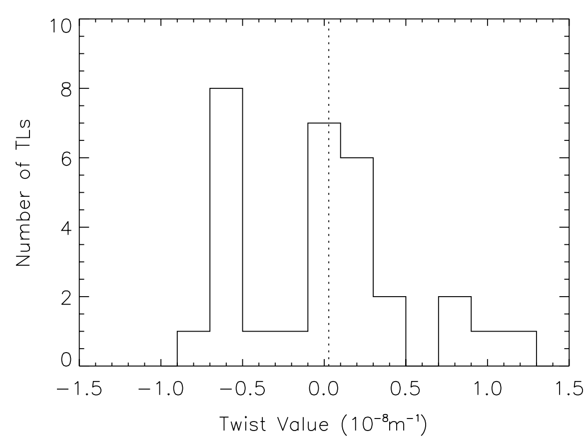

Fig. 4. Distribution of the twist values of transequatorial loops. Dotted line shows the average value (Chen et al., 2006b).

or inverse 'S' shape (Pevtsov, 2000), but their twist signs can't be assured only from its structure, thus force-free field extrapolation is needed. Fárník et al. (1999) obtained the twist values of two TLs through extrapolation. Recently, Chen et al. (2006b) calculated 30 TLs also through force-free field extrapolation, the results are exhibited in Fig. 4. 15 TLs have the positive twist signs, 11 TLs that the twist signs are negative and 4 TLs the extrapolation values are zero. The mean value of these TLs is close to zero.

2.5. Formation and disappearance of TLs

The formation of transequatorial loops is thought to be reconnection of field lines. Švestka et al. (1977) researched a newly born TL and concluded that the TL was most probably born through reconnection of magnetic field lines extending from the two active regions towards the equator. Tsuneta (1996) studied an X-shaped transequatorial loop and provided a strong evidence that magnetic reconnection is responsible for the TL formation: (1) Transequatorial loops were newly created without observation previously. (2) An clearly X-point are seen in the soft X-ray images. (3) The plasma temperature of the downstream side of reconnection is 4–7 MK, whereas that of the upstream side is 2 MK. Fárník et al. (1999) observed two TLs having the same reconnection type as the case studied by Švestka et al. (1977). Further confirmed by Harra et al. (2003) who gave several observational evidence to support the origination of TL by magnetic reconnection.

Khan and Hudson (2000) investigated three cases and found that a sequence of homologous disappearance of TLs were associated with a major flare and CME. They suggested that flare-generated shock waves may cause the eruption of transequatorial loops and the disappearance of TL in association with the onset of a CME. Glover et al. (2003) looked for a sample of 18 TLs to investigate the association of TLs with CME activity and conclude that the scenario observed by Khan and Hudson (2000) is unusual. They found there isn't a relationship between the changes of TLs and the generation of CME, but they obtained that the length and the asymmetry in longitude of TL have contribution to the production of CMEs.

3. Conclusion and discussion

Observational properties of transequatorial loops are reviewed in this paper. TLs are classified by two methods: one is according to configuration, the other is according to magnetic polarities of footpoints. Based on the first method, there are 'connection' type and 'reconnection' type: about 70% of TLs belong to 'connection' type and about 30% of TLs belong to 'reconnection' type. Based on the second method, TLs are also divided in two categories: the magnetic polarities of footpoints are the same as the preceding polarities (PTL) and the magnetic polarities of footpoints are the same as the following polarities (FTL). For all the selected TLs, PTL has a preference: about 66% of TLs are PTLs. Most TLs root in moderately strong fields at the periphery of active regions, the separation values of TLs change following solar cycle. There isn't a common idea about the helicity relationship of active region pairs connected by TLs which need research further. Magnetic reconnection induces the formation of TLs, there is no clear relation between the disappearance of TLs and production of CME.

About transequatorial loops, there are several aspects that have to be clarified. The origination of TL is generally thought to be caused by magnetic reconnection, but what causes the magnetic reconnection and how the magnetic reconnection generates the TL, what about the relationship between the evolution, eruption of transequatorial loops and flare, CME, this whole process is not clear. Moon et al. (1996) found there is a correlation between the TLs and the sympathetic flares, but we don't know whether the TLs induce the generation of sympathetic flares or the sympathetic flares make the TLs formation. The density and temperature of the TL and their variation during the period of TL evolution haven't been investigated. All these questions are advocated to study further.

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