SOLAR CYCLE IN THE PHOTOSPHERE AND CORONA

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ABSTRACT

EIT/SOHO data in four EUV lines and MDI/SOHO (1996-2002), and soft X-ray YOHKOH data (1991-2001) are analyzed in the form of coronal synoptic maps for the investigation of solar cycle variations of the corona and magnetic field. The evolution of coronal structures is closely related to sunspot activity, photospheric magnetic field, and topology of the large-scale magnetic field. The coronal structures visible in extreme ultraviolet and soft X-rays as extended bright loops, reflect the non-axisymmetrical magnetic structure of the Sun, changing with the solar cycle. The long-living coronal structures are related to complexes of solar activity and display the quasiperiodic behavior (impulses of coronal activity) with periods of 1.0-1.5 year in the axisymmetrical distribution of EUV and X-ray fluxes during the current cycle.

Key words: Sun; Solar cycle; EUV and X-ray corona; Magnetic flux.

INTRODUCTION

Coronal structures reveal a very important information for understanding the evolution of the large-scale solar magnetic field during the solar cycle. There is a long history of coronal investigation (Secchi, 1877; d’Azambuja, 1945; Waldmeier, 1957; Leroy and Trellis, 1974; Rūsin, et al. 1990; Wilson, 1988). These studies found equatorward and poleward migrating structures in coronal emissions, which sometimes are called “coronal activity waves”. In our recent paper we have identified the coronal activity waves in the extreme ultraviolet data from SOHO/EIT (Benevolenskaya et al., 2001). It is found, that the bright coronal structures, which migrate to the poles during the rising phase of the solar cycle, are formed by density enhancements in the poleward footpoints of magnetic field lines. These magnetic lines connecting the magnetic fields of the following parts of active regions with the polar field are represented by giant polar coronal loops. In other words, these giant magnetic loops connect the toroidal field of the new solar cycle with the polar poloidal field formed during the previous cycle, providing an important link between these two types of evolving magnetic topology.

Here, we present our results of investigation of large-scale coronal activity in EUV and X-ray in the comparison with the evolution of sunspot activity and photospheric magnetic field during the solar cycle. We have used synoptic observations of the solar corona during 1991-2001 in soft X-rays from the SXT instrument on Yohkoh (Tsuneta et al., 1991) and during 1996-2002 in EUV from SOHO/EIT (Delaboudiniere, et al, 1995). The first period covers the declining phase of solar cycle 22 and the rising phase of the current cycle, 23.

SYNOPTIC STRUCTURE OF THE CORONA

The synoptic maps of EUV images in three lines Fe and He II (171 Å, 195 Å, 284 Å and 304 Å) are represented by values of the line intensity centered on the central meridian. We have constructed the EUV synoptic map for Carrington rotation from CR1911 to CR1989, June 28, 1996 – May 23, 2002. The synoptic maps in soft X-ray are constructed by the same procedure (Benevolenskaya et al., 2002). The image sets (from which the SXT synoptic maps were derived) consist of full-disk solar images taken in two different filters of the Yohkoh Soft X-ray Telescope: a thin Al filter with an approximate pass band of \( \approx 6 \rightarrow 13 \) Å (Al), and a composite Al/Mg/Mn filter with a slightly shorter bandpass of \( \approx 5 \rightarrow 12 \) Å (AlMg), from 11 November 1991 to 19 September 2001. The resolution of these maps is 1° in both longitude from 0° to 360° and latitude from -83° to 83°. The example of coronal synoptic maps in EUV and soft X-ray for Carrington rotation 1949 are shown in Figure 1.

To obtain the latitudinal distribution we averaged the synoptic maps over longitude, and plotted as a function of latitude and time. The latitudinal distribution of the EUV and soft X-ray intensity are shown in Fig. 2a-c. For comparison, in Fig. 2d-g we plotted the azimuthally averaged distributions of the line-of-sight magnetic flux, \( B_{||} \) (SOHO/MDI),
Synoptic maps for Carrington Rotation 1949

Figure 1. Synoptic coronal maps for 1–28 May 1999. Panels from upper to bottom: EUV flux in Fe IX, X (171 Å), Fe XII (195 Å), Fe XV (284 Å) lines and in He II (304 Å). $B_\parallel$-component of the magnetic field (NSO/KPPO), the grayscale range is [-50 G 50 G]. X-ray flux in the A Mg filter and X-ray flux in the Al filter (natural logarithmical scale).

and the corresponding unsigned (absolute) magnetic flux, $|B_\parallel|$, obtained from the Kitt Peak Observatory synoptic magnetic maps. The zonal magnetic neutral lines separating magnetic polarities at high latitudes are seen as the contrast lines between white and black colors in Fig. 2d.

The coronal EUV map (Fig. 2a,b,c) shows in each hemisphere two sets of bright migrating structures: low-latitude structures that migrate toward the equator following the evolution of $|B_\parallel|$ (low-latitude coronal activity waves or “butterfly” diagram) and high-latitude structures, or high-latitude waves, that migrate toward the poles parallel to the magnetic neutral line. High-latitude coronal structures are located $15 - 20^\circ$ higher in latitude than the neutral line. In the SXT coronal maps (Fig. 2e and 2f), the low-latitude migrating structures are similar to those in the EUV map. However, the high-latitude structures look differently without pronounced brightening in the polar regions and more uniform latitudinally, connecting the low-latitude bands with the polar regions. The high-latitude structures appear mostly during the rising phase of the solar cycle.

Figure 2. The axisymmetrical distributions of coronal and magnetic structures as a function of latitude (from $-83^\circ$ to $83^\circ$) and time from 11 November 1991 to 16 July 2002 (Carrington rotations from 1849 to 1991) for: a) EUV flux in Fe IX, X lines (available only since CR1911, 28 June 1996); b) X-ray flux in the Al Mg filter; c) X-ray flux in the Al filter; d) $B_\parallel$-component of the magnetic field (SOHO/MDI), the grayscale range is [-1 G 1 G]; e) unsigned magnetic flux $|B_\parallel|$ (NSO/KPPO), in the [0 1 G] range.

In the individual EUV synoptic maps the high-latitude structures are easily identified as longitudinally extended bright structures at $50 - 83^\circ$ latitude, marked as A-D in Fig. 3a. In the corresponding SXT maps, they represent diffuse structures extended in latitude from $\sim 30^\circ$ to the polar boundaries of our maps at $83^\circ$ (e.g. feature D in Fig. 3b).

The comparison between the high-latitude coronal structures and the photospheric magnetic field (Fig. 3c) shows that these structures represent giant loops connecting the polar poloidal magnetic field formed during the preceding cycle and the toroidal field of the new cycle. In EUV we mostly see the poleward footpoints of these structures, while in the SXT data we see the whole giant loop structures on the disk. On the solar limb these structures are seen in EUV as footpoints of the giant loops and sometimes as whole giant loops connecting the following parts of the active regions with the polar regions (Fig. 4a). These polar giant loops are clearly seen in SXT data on the solar disk (e.g. feature D in Fig. 4b). A schematic picture showing the magnetic connections

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Figure 3. Synoptic maps for CR1999 (1-28 November 1997): a) natural logarithm of the EUV intensity in Fe IX,X lines, log S; b) natural logarithm of intensity of the X-ray flux in the AlMg filter, log F; c) B\perp-component of the magnetic field, [20G 20G]. Vertical lines indicate the position of the solar limb of the EIT image of 1997 November 19, shown in Fig. 4a-b; and A, B, C, D marks indicate coronal structures corresponding to the giant polar loops in Fig. 4a. Arrows in the magnetic map show the regions of the positive polarity, α, (the following part of an active region) and the negative polarity, β, (the polar field), which are connected by loop D.

Figure 4. a) EUV/EIT image in Fe XV line. The arrows identify footpoints of the giant loops (A-D) that are parts of the longitudinally extended high-latitude structures indicated in Fig. 3a; b) X-ray image in the AlMg filter showing the giant loop D on the disk.

Figure 5. Topology of the magnetic field and polar giant loops structure.

between the leading and following polarities of active regions and polar field are represented in Figure 5.

The axisymmetrical distributions of the coronal intensity shown in Fig. 2 also reveal that the high-latitude coronal structures (visible as bright connections between the low-latitude coronal structures and solar regions) tend to appear quasi-periodically with \( \approx 1-1.5 \) year period, correlating with 'impulses' of magnetic flux. Moreover, Wolfson et al. (2000) have found that at 45° and higher, the coronal emissions correlate with the lower-latitude (30°) magnetic flux. Our results agree with this conclusion and provide an explanation. We can conclude that the correlation between the high-latitude coronal emission and the low-latitude magnetic flux is related to the giant coronal loops connecting the low-latitude active regions with the polar regions.

Figure 6 shows the variations of averaged intensities of the soft X-ray and EUV in high- and low-

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magnetic field changes the polarity.

Therefore, the results of the investigation of the EUV and soft X-ray corona during the solar cycle have provided an important information about the process of the polar magnetic field reversals. We can conclude, that it is necessary to include coronal processes of dissipation of erupted magnetic fluxes in the models of the solar cycle together with the processes in the photosphere and convection zone.

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