

The Variable Structure of the X-ray Corona as Viewed by Yohkoh

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Recent findings on the variable structure of the corona by the soft X-ray telescope on board *Yohkoh* are reviewed, with emphasis upon the structure and evolution of active regions, and the long term evolution of the global structure of the corona.

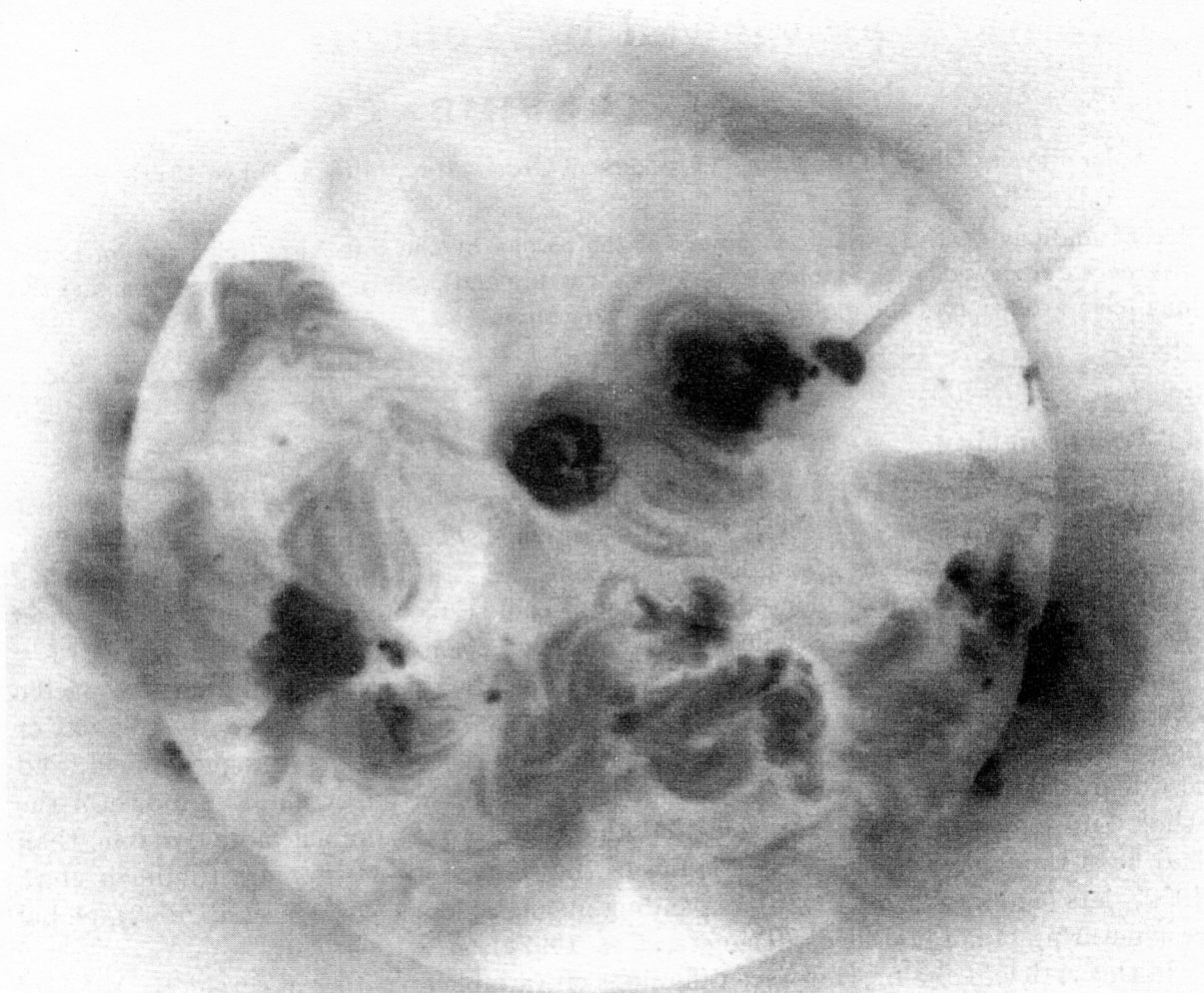
1. Introduction

The Solar-A spacecraft (Ogawara *et al.* 1991) was successfully launched on August 30, 1991 (Ogawara *et al.* 1992), and was named *Yohkoh* which means "sunbeam" in Japanese. *Yohkoh* carries a soft X-ray telescope (SXT) (Tsuneta *et al.* 1991) that has been producing an unprecedented sequence of whole-Sun images at 3 - 60 Å (Acton *et al.* 1992). The routine data typically consist of some tens of whole-Sun images (FFI = full frame images; see Figure 1) per day, with much higher time resolution for specific observations of restricted areas (PFI = partial frame images), such as active regions or flares. The X-ray emission reveals the connectivity of the coronal magnetic field, and also shows where strong coronal heating is occurring. In particular, the movie of the whole-Sun SXT images has revealed that the solar corona is much more dynamic than had been thought, *i.e.*, the corona is full of transient loop brightenings (Shimizu *et al.* 1992), jets (Shibata *et al.* 1992b), expanding magnetic loops (Uchida *et al.* 1992), global restructuring of coronal fields (Tsuneta *et al.* 1992a), *etc.*

In this article, I shall review recent findings on variable structure of corona by *Yohkoh*/SXT, mainly on the following subjects: (1) structure and evolution of active regions (from emerging flux regions to global restructuring events) and (2) long term evolution of global structure of the corona (mainly based on X-ray synoptic charts). A preliminary report on the white light observations by the aspect sensor of *Yohkoh*/SXT is given by Hudson (1994). The reader should refer to the *Yohkoh* special issue of *Publ. Astr. Soc. Japan* (1992, vol. 44, No. 5), Acton *et al.* (1992), and Tsuneta & Lemen (1993) for reviews of initial discoveries by *Yohkoh*/SXT, and to Hudson (1993), Uchida (1993), and Tsuneta (1993) for reviews of flare observations by *Yohkoh*/SXT. See also Antonucci (1994) for a review of earlier soft X-ray observation.

2. Structure and evolution of active regions

Structure and Evolution of EFRs: Emerging flux regions are observed as very bright compact regions in SXT images, and hence are easily recognized in FFIs. They rapidly grow in size and in brightness (Figure 2), with rapid fluctuations in shape and brightness (Kawai *et al.* 1992), often accompanied by small flares and jets (Shibata *et al.* 1992b). In general, the SXT bright features coincide well in space with H α arch filament systems (Kawai *et al.* 1992). Ishido *et al.* (1992) studied the size evolution of several EFRs and found that the apparent velocity of the increase in size of EFRs is large ($\sim 3 - 5$ km/s) in the very early phase (less than 5 hours after birth), but is small ($\sim 1 - 2$ km/s) in the later phase. This evolution is similar to that of the separation velocity of the two footpoints of the emerging flux (Harvey & Martin 1973; Chou 1993), although the expansion speed of



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FIGURE 1. A full Sun soft X-ray image (negative) taken by *Yohkoh*/SXT on Nov. 12, 1991. The image was taken at an effective energy of ~ 1 keV with $5''$ pixels and 2.67 sec exposure time (a compressed image is shown here). Note that an X-ray jet is ejected from a small active region (NOAA 6918) in the northwest (upper right) quadrant of the solar disk (Shibata *et al.* 1992b).

coronal X-ray loops is larger than the separation velocity (< 1.2 km/s). Large expansion speeds of the coronal parts of emerging flux loops has also been found theoretically by Shibata *et al.* (1989) using 2D MHD numerical simulations, and the model has been extended to 3D by Matsumoto *et al.* (1993).

A preliminary study of the thermal evolution of an EFR (NOAA7150) by Su *et al.* (1993) using the filter ratio method (Hara *et al.* 1992) has shown that the average temperature of the EFR increases with age from 2×10^6 K to 3.5×10^6 K in 3 days. Considering the very rapid increase in size of EFRs, this seems to be consistent with the well-known scaling law of Rosner *et al.* (1978), but may not be necessarily in agreement with the analysis of Skylab data by Little and Krieger cited by Webb (1981).

Interaction of EFRs with Pre-existing Magnetic Fields: Shibata *et al.* (1993a) have

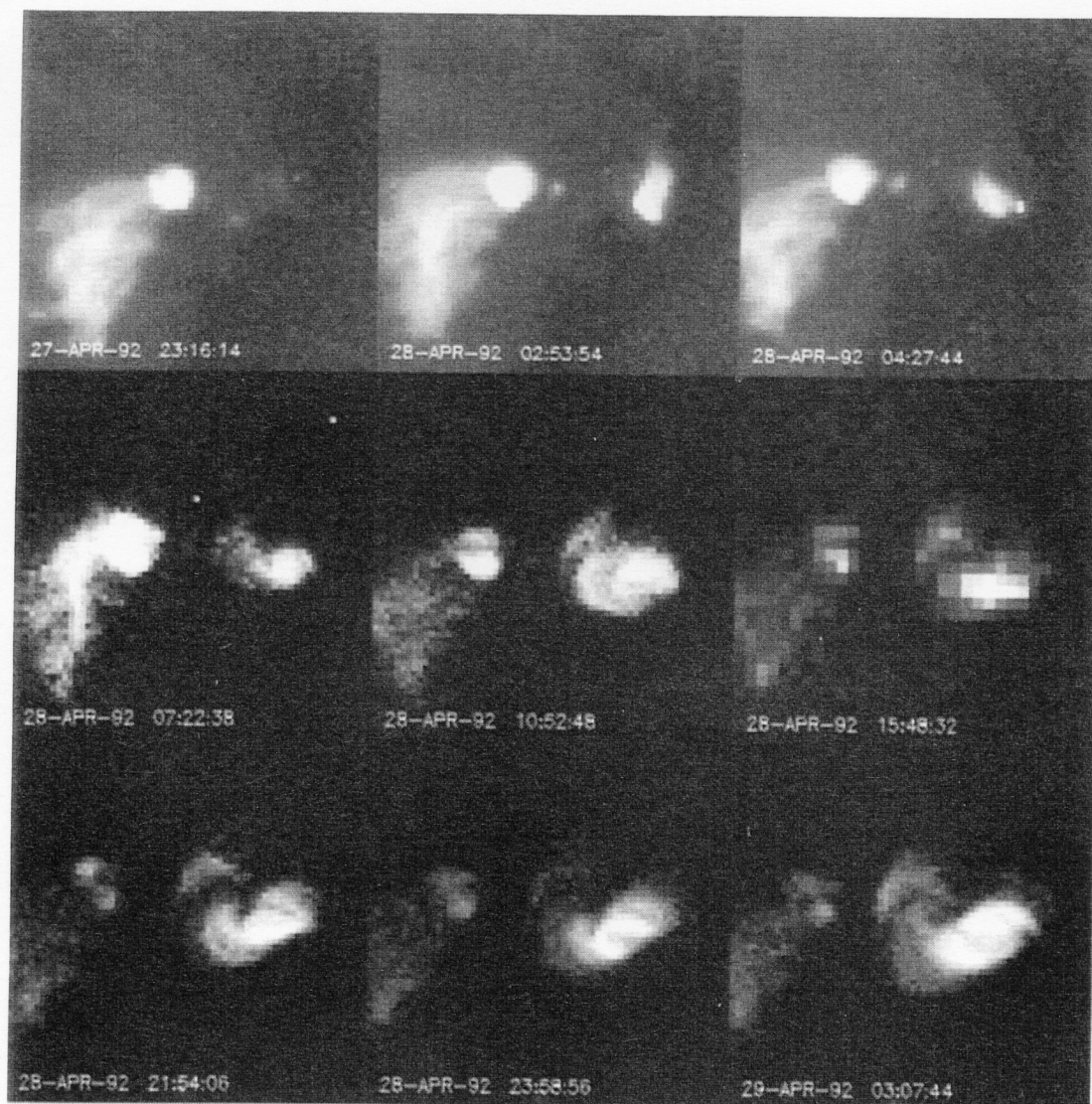


FIGURE 2. The rapid growth of emerging flux region, NOAA7150 (courtesy of G. Kawai). The size of each frame is $640'' \times 640''$.

studied the interaction between EFRs and overlying coronal magnetic fields, and found that there are fundamentally two types of interaction (reconnection) (see Figure 3):

(1) *Anemone-jet type*: This type occurs when emerging flux appears in a coronal hole (Figure 4 for a typical example). The EFR (or AR) looks like a “sea anemone”, and an α -type sunspot is sometimes seen at the center of the “anemone”. In many regions, jets (Shibata *et al.* 1992b) are often ejected from the AR in the vertical direction, which suggests reconnection between emerging flux and the (nearly vertical) coronal fields of the surrounding unipolar region.

(2) *Double-loops (Two-sided-loops) type*: This type is seen when emerging flux appears in a quiet region. Large-scale loop brightenings occur on both sides of the emerging flux, suggesting reconnection between the emerging flux and an overlying (nearly horizontal) coronal magnetic field. The loop brightenings seem to correspond to the jets occurring in closed loop systems. A reconnection model of two-sided loops has been developed by Yokoyama & Shibata (1993) by using 2D resistive MHD numerical simulations (Shibata *et al.* 1992a), extending their previous emerging flux model (Shibata *et al.* 1989).

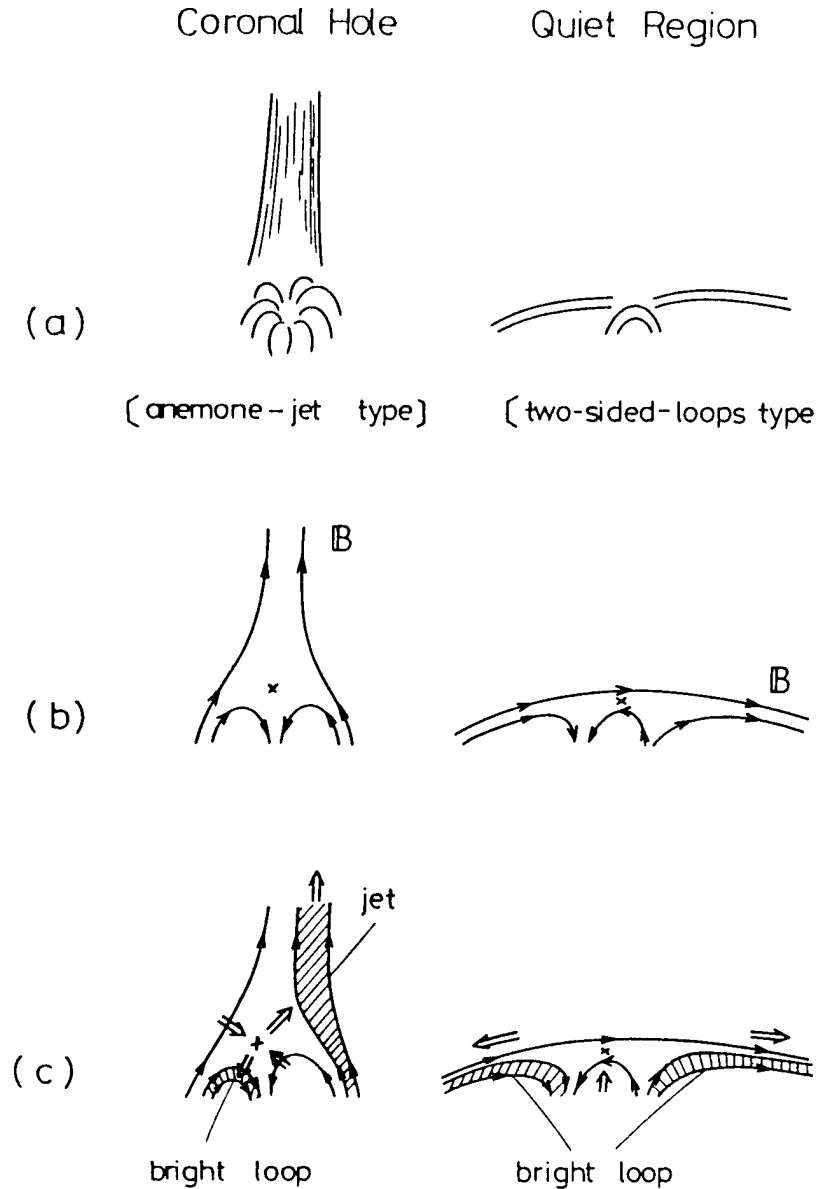


FIGURE 3. Schematic illustration of two types of interaction between emerging flux and overlying coronal fields (Shibata *et al.* 1993a).

Jets: The *Yohkoh*/SXT has revealed that there are many jet-like features in the solar corona, *i.e.*, transitory X-ray enhancements with an apparent collimated motion (Shibata *et al.* 1992b; Strong *et al.* 1992). According to preliminary studies, the length of jets found in FFI ranges from 10^4 km to more than 4×10^5 km, the apparent projection velocity is within a few 10 and 1000 km/s, though most of jets have velocities less than a few 100 km/s, and the total kinetic energy of these jets is estimated to be $10^{25} - 10^{28}$ erg. Almost all jets except for limb events are associated with flares in X-ray bright points (see Strong *et al.* 1992; Nitta *et al.* 1992; Harvey *et al.* 1993, for study of XBP's found by *Yohkoh*) emerging flux regions, and active regions. They sometimes occur several times from the same X-ray feature. It is likely that some flare-like loop brightenings (e.g., Shimizu *et al.* 1992) correspond to jets occurring in closed loop systems. As discussed above, various types of magnetic reconnection especially interactions between emerging

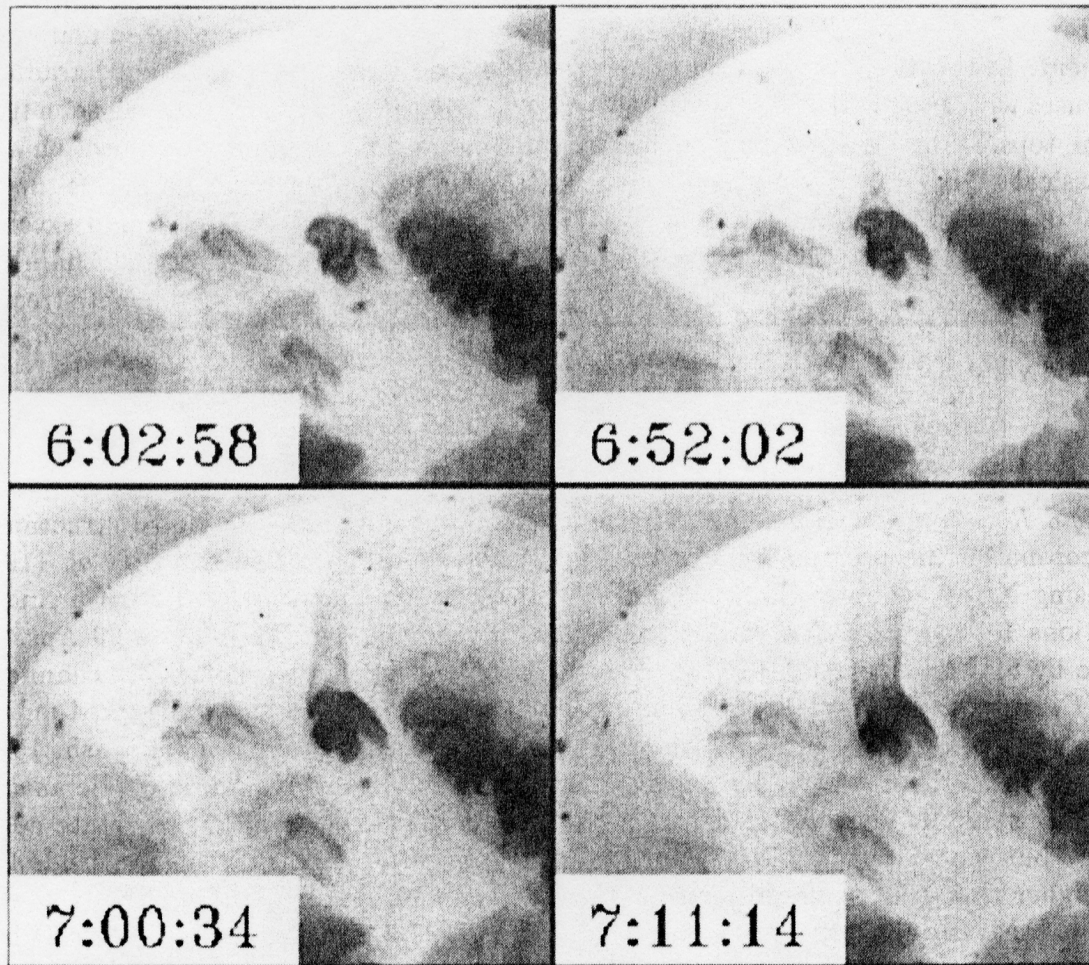


FIGURE 4. A typical example of an “anemone-jet” that occurred in NOAA 7001 on 1992 Jan. 11 (Shibata *et al.* 1993b). The shape of the active region at the footpoint of the jet looks like sea anemone, and hence this AR is called *anemone-AR*. The surrounding region is a coronal hole. The maximum length is probably greater than 3×10^5 km, and the apparent velocity is within the range of 90 – 240 km/s.

flux (or expanding magnetic flux) and pre-existing fields have been suggested to play a central role in generating these X-ray jets (Shibata *et al.* 1992b).

AR Expansion and CMEs: The SXT movie revealed that almost all active regions show continual or intermittent expansion with a velocity from a few to a few 10 km/s (Uchida *et al.* 1992). (It is interesting to note here that the opposite case also occurs; *shrinking loops* were clearly observed in an active region NOAA7420 during the week of Feb. 7 – 14, 1993.) The slower events (at a few km/s) seem to be a result of growth of ARs due to successive emergence of magnetic flux as discussed above, whereas the faster expansion (at a few 10 km/s) may be physically more similar to a CME (Watanabe *et al.* 1992; Klimchuk *et al.* 1993). A typical example of the faster events occurred at the east limb of the Sun on Dec. 9, 1991, as reported by Uchida *et al.* (1992).

Global Restructuring of Coronal Magnetic Fields Associated with Filament Eruption: It has been found that large arcade structures suddenly (in a time scale of 30 min to 1 day) appear in SXT images after filament eruption (or filament disappearance) (Watanabe *et al.* 1992; McAllister *et al.* 1992; Tsuneta *et al.* 1992a; Hanaoka *et al.* 1993). The size of

arcade structure ranges from 10^5 km to $\sim 10^6$ km, making them almost global in scope in extreme cases. Such a global restructuring event occurred on Nov. 12, 1991, near the polar region (Tsuneta *et al.* 1992a) in association with a disappearance of the polar crown filament. In this event, the height of the arcade (a few hundred thousand km) gradually increases with time with a velocity of a few km/s. A cusp-like structure is seen sometimes at the tops of the loops forming such an arcade, suggesting magnetic reconnection as in a classical CSHKP (= Carmichael-Sturrock-Hirayama-Kopp-Pneuman) model (Sturrock 1992) of CME-related flares (Shibata 1991). Note that *Yohkoh*/SXT has found excellent examples of this class of flares, which show beautiful cusp shapes, e.g., an LDE flare that occurred on Feb. 21, 1992 at the west limb (Tsuneta *et al.* 1992b). A helmet streamer observed near the pole, such as the event on Jan. 24, 1992, (Hiei *et al.* 1993), may be the side view of this kind of global restructuring event.

3. Long term evolution of global structure of corona

Rigid Rotation of Coronal Holes: The long-term evolution of the global structure of the corona has been extensively studied by Takahashi (1993) and Kozuka *et al.* (1993) by using X-ray synoptic charts. Figure 5 shows X-ray synoptic charts for Carrington rotations 1851 (from 5 Jan. 92 to 1 Feb. 92) to 1854 (from 27 Mar. 92 to 23 Apr. 92) made by Slater & Lemen (1993). It is seen that the dark coronal hole (CH) channel at 45° (Carrington longitude) keeps approximately the same shape for more than 4 months (from Feb. 92 to May 92), *i.e.*, shows rigid rotation (Takahashi 1993, Hayashi 1992). This confirms the discovery by Skylab (Timothy *et al.* 1975). From systematic analysis of X-ray synoptic charts, Takahashi (1993) found that low-latitude CHs rotate nearly rigidly but high latitude CHs do not, although the rotation rates of high latitude CHs are higher than that of photospheric plasma.

Active Nests and Active Longitudes: Takahashi (1993) and Kozuka *et al.* (1993) have noted the X-ray counterparts of active longitudes and nests (Zwaan 1987) seen in other ways. It is seen from Figure 5 that there are fundamentally two active longitudes, around 0° and 180° in the *Yohkoh* time interval. The δ -type sunspots producing many flares often appear in active longitudes. It is interesting to note here that these active longitudes correspond to giant bipolar magnetic regions (GBMR) situated on the global neutral line (Saito *et al.* 1993). On the basis of the ‘triple dipole model’ (Saito *et al.* 1989) of global solar magnetic field distribution, Saito predicted the existence of very large coronal loop structures above GBMRs in active longitudes. Such very large coronal loop structures have actually been observed on the limb in FFI images when the GBMR crosses the limb (Saito *et al.* 1993).

Anemone-ARs: The *Yohkoh*/SXT has revealed that many of ARs appearing in coronal holes show structure similar to “sea-anemone” as described above. Such ARs are called *anemone-ARs* (see Figure 4). The *anemone-ARs* tend to appear in coronal holes (far from the active longitudes) in the northern hemisphere during January 1992 – March 1993 (Shibata *et al.* 1993c). This tendency is opposite to the number of sunspots, which are more in the southern hemisphere during the same period. This as well as the apparently less-sheared field structure of the *anemone-ARs* suggest that the *anemone-ARs* are a signature of less-active ARs (*i.e.*, α -type spots) in spite of much magnetic flux, and that the origin of activity (or anti-activity) may be deeply rooted in the convection zone since the origin of the *anemone-ARs* seems to be closely related to the origin of coronal holes.

Topology of Global Coronal Magnetic Fields: The SXT movie has clearly shown that the topological pattern of global coronal magnetic fields changes with time as ARs emerge (as discussed above), evolve, and decay. It is not a rare phenomenon that the magnetic

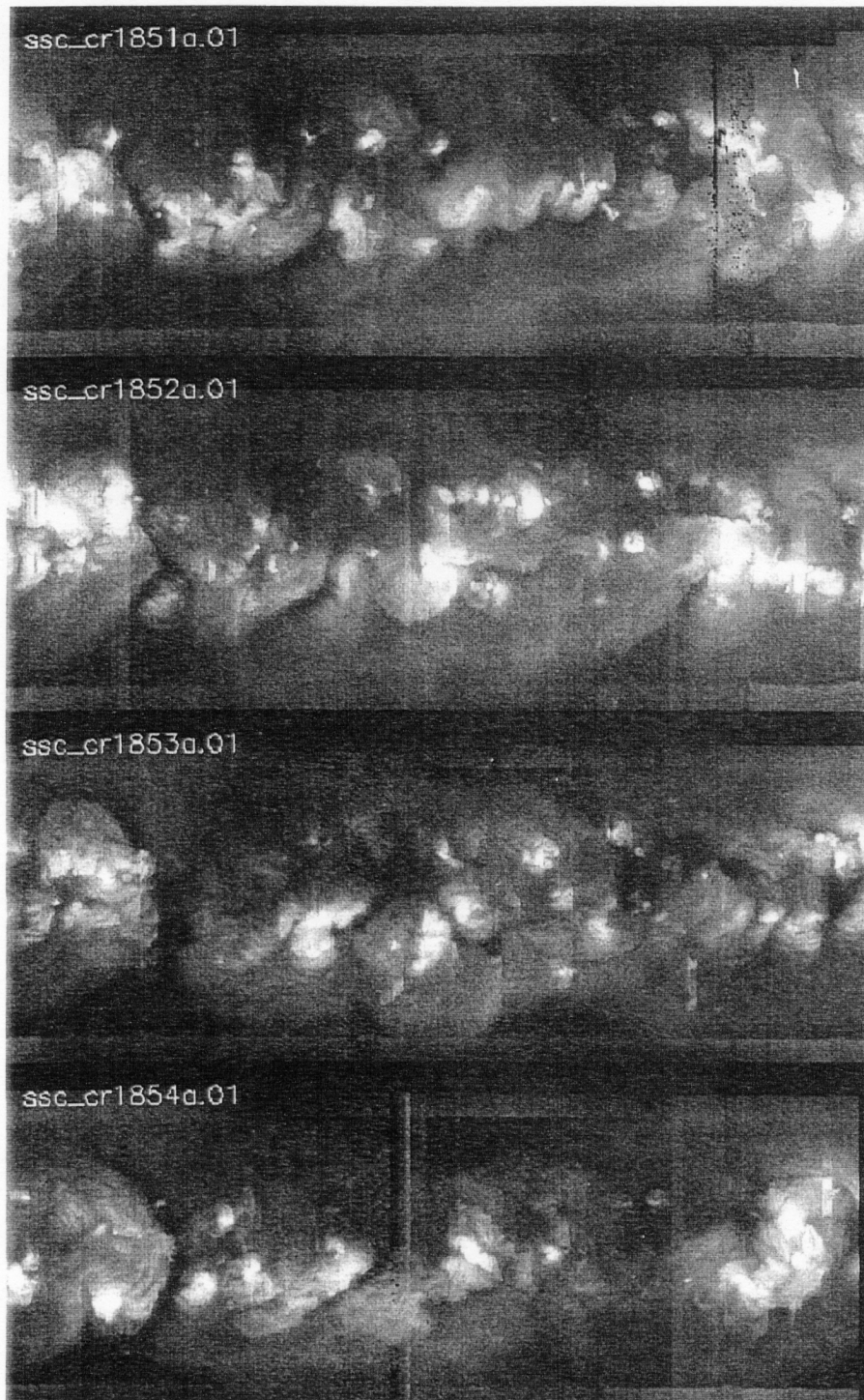


FIGURE 5. X-ray synoptic charts during Carrington rotation 1851–1854 (Jan. – Apr. 1992) made by Slater & Lemen (1993).

field in an AR in the northern hemisphere connects to an AR in the southern hemisphere (*i.e.*, trans-equatorial loops), as observed by Svestka & Howard (1979). The boundary of a coronal hole (CH) depends strongly on the evolution of the neighboring AR. In some cases, a small CH appeared after the filament eruption (Watanabe *et al.* 1992). It is also found that the shape of loops in the ARs in active longitudes are often sheared and twisted; the direction of the shear is opposite in northern and southern hemispheres, and

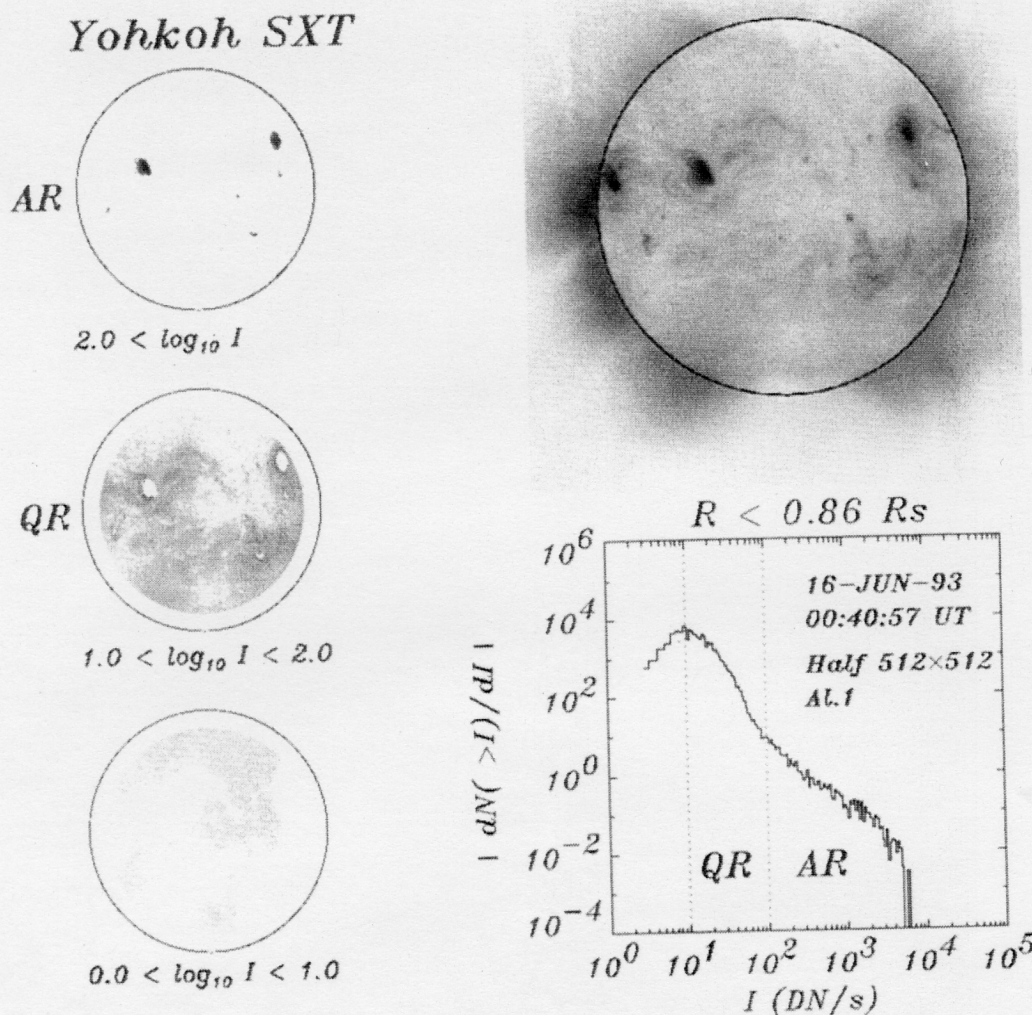


FIGURE 6. The number-distribution of soft X-ray intensity per pixel in an SXT/FFI image taken with thin aluminum filter on 1993 June 16 (shown in right bottom), *i.e.*, the number of pixels with intensity between I and $I + dI$ as a function of I . The FFI image is shown in the right top, and the three images in the left show the spatial distributions of AR-pixels (top), QR-pixels (middle), and darker pixels (including coronal hole). The pixels near the limb and outside the Sun are excluded from statistics. All these figures are from Hara (1993).

is consistent with the direction expected from the Coriolis force acting on a rising (and expanding) magnetic flux tube in the convection zone. This suggests that not only the formation of ARs but also the generation of the twist and shear (*i.e.*, origin of activity) might be deeply rooted in the convection zone.

Long-Term Variation of the Soft X-ray Intensity: According to Hara (1993), the fraction of total soft X-ray intensity (observed by SXT) emitted from ARs is about 90 percent in an active phase (e.g., in Oct. 1991), while it is about 30 percent in a less active phase (e.g., in June, 1992). Hara (1993) further studied the distribution of soft X-ray intensity per pixel in SXT/FFI images (Figure 6), and found that the distribution pattern is different between quiet regions (QR) and active regions (AR). Figure 6 shows that the distribution for AR-pixels is nearly power-law while that for QR-pixels is not. This power-law distribution for AR-pixels reminds us of the power-law distribution of the

solar flare occurrence against total flare energy (e.g., see Hudson 1991) and the idea of episodic heating (Sturrock *et al.* 1984; Parker 1988). Hara (1993)'s result suggests that the different heating mechanisms might work in QR and AR.

4. Summary

The *Yohkoh*/SXT has revealed that *the solar corona is much more dynamic than has been thought, i.e.*, the non-flaring corona is full of loop brightenings, jets, AR expansions from continual growth of EFRs to transient CMEs, global restructuring of coronal magnetic field beyond AR size, and so on. These are controlled by global pattern of magnetic field, such as coronal holes, active longitudes, and active nests. The total X-ray intensity is dominated by ARs (especially in active longitudes) in active phase, but the detailed spectral characteristics of X-ray emission seem to depend on the evolutionary phase of ARs.

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