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RESULTS FROM THE YOHKOH SATELLITE

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ABSTRACT

The Japanese sun observing satellite, Yohkoh, has been operational for five years and her scientific instruments are still in good condition. They have revealed ample of evidences that solar flares were triggered by magnetic reconnection, which was, for the first time, clearly indicated to take place in the solar corona. Cusp structures in soft X-rays and a new type of hard X-ray sources at the top of flaring loops have strongly supported the scenario originally proposed by C-S-H-KP. Nonthermal energy input in hard X-rays and thermal energy estimated from soft X-rays are fundamentally consistent with the interpretation of thick-target and chromospheric-evaporation models (Neupert effect). X-ray jets, another discovery of Yohkoh, were also associated with magnetic reconnection, as a result of the interaction of emerging fluxes with pre-existing coronal loops. Temperature structures of active regions, quiet sun, and coronal holes had very dynamic differential-emission-measure (DEM) distributions and high-temperature tails of DEM were considered to come from the contribution of flare-like activity.

Key Words : X-ray solar physics, Solar flares, Solar corona, *Yohkoh*

I. INTRODUCTION

The *Yohkoh* mission was launched on August 30, 1991 and is going to celebrate its fifth anniversary in orbit with no serious degredations of performance in the scientific instruments at the moment of this IAU Regional meeting. During the period of five years, *Yohkoh* observed more than a thousand flares, which provides the best opportunity so far to understand the fundamental characteristics of solar flares, and active and dynamic corona in all the declining phase of solar activity.

Yohkoh has four scientific instruments, two X-ray imagers (Hard X-ray Telescope; HXT and Soft X-ray Telescope; SXT) and two spectrometers (Wide Band Spectrometer; WBS and Bragg Crystal Spectrometer; BCS). The capability of the *Yohkoh* scientific instruments is summarized in *Solar Physics*, vol. **136** (Svestka and Uchida, 1991). *Yohkoh* is also accommodated with an extensive international collaboration by having the participation of US and UK scientists.

II. SOLAR FLARES

(a) Magnetic Reconnection

i) Soft X-ray morphological structures

A good example showing dynamic morphological changes of the magnetic field is the flare occurred on December 2, 1991. The preflare observation suggests that the current sheet is created by the magnetic field configuration change a couple of hours prior to the main phase of the flare (Tsuneta 1992). A X- or Y-shaped configuration appears above the flare loop top. Further above the X(Y)-shape, a bright blob is ejected with a velocity of about 50 kms^{-1}. The dimension of the entire configuration gradually increases during the course of flare progress in eruptive flares.

SXT can obtain the temperatures and emission measure (EM) maps of the flares by looking at the intensity ratio in pictures taken with different filter combinations. The temperature distribution of the 1992 February 21 flare show clearly that magnetic reconnection takes place in this long-duration event. At the onset of the flare, high temperature patches are scattered around above the top of the flaring loop. The highest temperature seen in the SXT wavelength reaches 13×10^6 K. As the flare progresses, the chromospheric material fills into the loop and a high density region is produced at the apex. A distinct characteristic in the decay phase is that the highest temperature regions appear along the outer skin of the post flare loop. The size of the post flare loop increases with time. The evaporated material continues to condense at the loop top, however the temperature of the most dense part is only 7×10^6 K, when the temperature of the outer skin of the loop is still 11×10^6 K.

Combining the morphological change and the temprature distribution of the flaring loop, it is evident that the magnetic field topology changes in flares. The reconnection of magnetic field lines takes place during the flare. All these characteristics can only be explained by the CSHKP model (Carmichael 1964, Sturrock 1968, Hirayama 1974, Kopp and Pneuman 1976).

ii) Hard X-ray loop-top sources

Imaging of solar flares in hard X-ray is quite important for understanding the location of energy release and the mechanism of particle accelerations taking place in solar flares. Again in several of limb-impulsive flares, Masuda et al. (1994) found that an additional hard X-ray source exists, as well as double foot-point sources. Loop-top sources in impulsive phases are well correlated with foot-point sources within the instrument's time cadence, which suggests that the loop-top source could be an interaction region of the reconnection jet and the soft X-ray loop.

(b) Double Foot-Points and Chromospheric Evaporation

The hard X-ray images of the 1991 November 15 flare show a clear double foot poit structure during its impulsive phases (Sakao 1993). Though the soft X-ray intensity of the flare is quite strong, an X2.2 flare, sharp spikes of hard X-ray bursts are concentrated in a minute. Corresponding to those spikes, hard X-ray emissions in both of the low band (22.7 - 32.7 keV) and the M1 band (32.7 -52.7 keV) are from the foot points, where accelerated high energy electrons precipitate into cool dense chromosphere. Spatial and temporal coincidence with white light images of the flare suggests this scenario.

Temporal variation of the both foot points is coincident within 0.2 sec. By taking the flare loop size of 1.5 $\times$ 10 ^{9} cm, the time lag less than 0.2 sec suggests either that the particle velocity is about 1/3 of the light velocity or that the energy release location is within 100 km from the loop top, if particles travel with a speed of 1,000 kms^{-1}.

Comparing the brightness of each source in hard X-ray, and the magnetic field strength of the foot point, Sakao (1993) proposed an "anti- cornucopia" model of hard X-ray flares. Based on his statistical study, he concluded that the hard X-ray brighter foot point is in the weeker magnetic field, i.e., the X-ray brightness is anti-correlated with the magnetic field strength. This study tells that the flare loops are sometimes asymmetric, and that fast electrons precipitates more to the foot point of the weaker magnetic field, because the stronger mirror effect hinders electron precipitation.

Fully blueshifted soft X-ray lines are observed in the earliest phase of flares. At the onset of hard X-ray bursts in the 1991 December 16 flare, a completely blueshifted CaXIX resonance line is observed during the hard X- ray bursts. Line profiles during the implusive phase are highly asymmetric and considered to be the superposition of the profiles from plasmas with various line-of-sight velocities. The time sequence of spectra reveals that the nonthermal line broadening and the blueshifted component of the emission lines are different phenomena. The position of the line center comes back to the rest wavelength, which can be derived from the observation at the decay phase of the flare. This is the first time that the fully displaced emission line is observed in the high resolution X-ray spectra and supports a scenario of chromospheric evaporation. Following the impacts on the chromosphere of the electrons that produce the hard X-rays, heated plasma flows up into the corona. This flare is one of the most extreme cases that have strong blueshifts, but most of flares anyhow show similar lineshifts, depending on the location of flares on the solar disk.

(c) X-ray jets; Unified Concept with Magnetic Reconnection

Collimated X-ray ejection in the solar corona is also one of the new discoveries of *Yohkoh*. Statistical characteristics of X-ray jets observed by *Yohkoh* are summarized by Shimojo et al. (1996) and extensive numerical simulations have been carried out with the emerging flux magnetic reconnection model (Yokoyama and Shibata 1994, 1995, Yokoyama 1996).

X-ray jets are observed in full-frame images of SXT on more than ~20 occasions per month (during November 1991 - April 1992). Almost all X-ray jets except a few limb-events are associated with flares. X-jets occur nearly simulatenously (within a few minutes) with flares. The length of X- ray jets ranges from 10 ^{4} km to several of 10 ^{5} km, and the (apparent) translational velocity is 10 - 400 kms^{-1}. Temperatures of X- ray jets are typically several 10^6 K.

Observations of magnetic field often shows mixed polarities near the footpoints of X-ray jets (Shimojo et al. 1996), which could be formed by the emergence of small scale magetic flux tubes. If X-ray jets tend to occur in mixed polarity regions, magnetic reconnection is expected to occur between emerging flux and pre-existing magnetic fields, leading to production of jets, as well as flares, changing magnetic configuration.

Two types of X-ray jets are expected accoring to the configuration of the coronal field. If the coronal field is nearly horizontal, the two-sided- loop (-type jet) is expected. When the coronal field is oblieq, the coronal jet is observed. The anemone-type (-jet) is a vertical jet, which takes place when an emerging flux appears in a quiet region where the coronal field is approximately horizontal. Numerical simulations with the resistive MHD equations (Yokoyama and Shibata 1996) successfully reproduce many of observed characteristics of X-ray jets. Further the simulations reveal new features, such as fast-mode MHD shock and associated cool jets which are expected to be confirmed in future observations.

III. ACTIVE REGIONS

If the magnetic reconnection could be the cause of triggering the flare activity in the corona, it can also trigger other activity taking place in various places of the corona, where the density of coronal magnetic loops is high. In solar active regions, *Yohkoh* observed numerous but tiny loop brightenings (Shimizu et al. 1992). They occupy the regions in the low-end of flares in various diagrams showing their characteristics. They can be called microflares or nanoflares. The released energy of these events is considerably less than 10^{29} ergs, which is a low-end of the subflare energy range. The occurence rate is a few events per hour, depending on the characteristics of mother active regions. Maximum temperatures attained in these events do not seem to differ much from normal flares (Watanabe et al. 1995).

They sometimes show that multiple loops are involved in the brightenings for spatially resolved events (Shimizu et al. 1992). Shimizu et al. (1995) also try to compare the energy input of these events to the coronal heating and the slope of the occurence rate of events against the total energy is similar to that derived from flares. The maximum temperatures attained during these tiny events are also statistically investigated (Yuda et al. 1996), and concerning the flare temperature, the solar flare is a homogeneous energy release process in five orders of magnitude or more. This means that if both characteristics are further extraporated down to 10^{24} ergs or less, the entire solar coronal heating cannot be maintained by micro- and nano-flares.

IV. GLOBAL STRUCTURES AND SOLAR CYCLE ACTIVITY

(a) HIGH TEMPERATURE COMPONENT OF CORONAL HOLES

Careful analysis is required for determining properties of coronal holes, because they are faint and elimating the effect of instrumental X-ray scattering from intense active regions is very hard to achieve.

Hara et al. (1994) evaluated the amount of scattered X-rays from both ative and quiet regions in coronal holes using post-launch images, and estimated the temperature and emission measure of coronal holes to be 1.8 - 2.4 × 10^{6} K, and $10^{25.5-26.2}$ cm^{-3}. The derived temperatures are almost the same as those of quiet regions and higher than the previous values, though they are consistent. The spatial distribution of the high temperature component in coronal holes is further more difficult to discuss in the present analysis, however, the existence of the high temperature component in the coronal hole give an important clue to understand the mechanism of high-speed solar wind acceleration in coronal holes.

(b) Long-Term Variability of X-Ray Intensity of the Sun

Yohkoh's continuous observation for five years provides a wonderful data set for investigating the solar cycle activity in X-rays. It is found that active regions show a power-law distribution in X-ray intensity histograms, while quiet regions and coronal holes have different shapes. The overall shapes of the X-ray histograms are similar to those of the photospheric magnetic flux, implying that the coronal X-ray brightness distribution reflects the magnetic flux distribution in the photosphere. Even in quiet regions the X-ray intensity decreased in the declining phase of soar activity cycle.

The time and lattitude diagram made during October 1991 - January 1996 clearly shows the intermittent apearance of bright regions with a time scale of about one year. They are also noticeable in the sunspot number and the total magnetic flux. Each bright structure does not consist of a single active region but a cluster of active regions, i.e., the complexes of activity (Hara 1996). The intermittent appearance in the time-lattitude diagram shows that the emergence of magnetic flux is controlled in a global sense. High-latitude activity is also found.

V. REMAINING PROBLEMS

The most important result of the mission *Yohkoh* can be summarized to the facts that the solar corona is very dynamic and that its dynamism comes mostly from the phenomena triggered by the change of coronal magnetic structures, namely the process of magnetic reconnection in the corona.

In solar flares, high quality soft X-ray images show morphological characteristics favorable for the magnetic reconnection, such as cusp-shape structures, erupting plasmoids etc. However, these features we are observing with *Yohkoh* are only the results of the magnetic reconnection and we are not observing the place where the magnetic reconnection takes place. We need to observe, although it will be very hard to see, the incoming flows into the reconnection point, reconnection jets, and slow shocks which are associated with the magnetic reconnection. One possiblity to see these essential processes associated with the magenetic reconnection will be to observe the FeXXVI lines at the very beginning before evaporating chromospheric material dominates in emission (Tanaka 1986). The behavior of nonthermal line boradenings in these phases will be very important. The other possibility is to have hard X-ray (10 - 20 keV) images with a far increased dynamic range than that of HXT onboard *Yohkoh*.

The contribution of microflares to the heating of active regions is found important, especially to the high-temperature tail of the differential emission measure of thermal plasmas in active region (Watanabe et al. 1995). However, the fundamental question still open is whether these microflares seen in SXT on *Yohkoh* is also essential for the entire coronal heating. The problem is therefore the relationship of hot microflares of *Yohkoh* to microflares contributing to the heating of the cooler coronal gas, like UV-microflares (Porter et al. 1993), which may have a different frequency distribution. The next Japanese sun observing programme, SOLAR-B, will definitely contribute to solve these remaining questions.

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