Coronal X-ray Jets

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Abstract. The soft X-ray telescope (SXT) aboard *Yohkoh* has discovered *coronal X-ray jets* associated with small flares (microflares - subflares) in X-ray bright points (XBPs), emerging flux regions (EFRs), or active regions (ARs). These newly discovered jets may provide clues to solving the coronal heating mechanism and acceleration of high speed solar wind. The recent development of observations and theoretical modeling of X-ray jets are reviewed with emphasis upon the role of magnetic reconnection in generating these jets.

Introduction

It has been revealed that our universe is full of jets (i.e., well collimated, high speed plasma flows), ranging from extragalactic jets ejected from active galactic nuclei to much smaller stellar jets ejected from young stellar objects (e.g., *Burgarella et al.* [1993]). As the observations with high spatial resolution have been developed further and further at various wavelengths, more and more jets have been discovered (e.g., *Mirabel and Rodriguez* [1994]). This is a trend of modern astronomy and astrophysics in the latter half of this century.

The same trend is applied also to solar physics. From more than 30 years ago, solar observers have noted that there are many Hα jets in the solar atmosphere, such as spicules [*Beckers* 1972] and surges [*Roy* 1973]. As the wavelength range as well as the spatial/temporal resolution of observations have been increased, new types of jets have been found, e.g., macrospicules [*Bohlin et al.* 1975], EUV jets [*Brueckner and Bartoe* 1983], and so on.

The soft X-ray telescope (SXT) [*Tsuneta et al.* 1991] aboard *Yohkoh* was not an exception of this trend, and in fact, it found a new type of jet, *coronal X-ray jets* (see Fig. 1 for a typical example; *Shibata et al.* [1992b, 1994b], *Strong et al.* [1992]). The X-ray jets are associated with small flares (microflares - subflares) and thus could be closely related to coronal heating as well as acceleration of high speed solar wind. Some of small scale structures observed in the solar wind may be related to these jets [*Feldman et al.* 1993, *Hammond et al.* 1995]. In this article, I will review recent development of observation and theory of these coronal X-ray jets with emphasis upon the role of magnetic reconnection.

Observation

Yohkoh/SXT Observations

X-ray jets have been observed with the soft X-ray telescope (SXT) aboard *Yohkoh*. SXT observes soft X-rays in the wavelength range of 3 – 40 Å emitted from thermal plasmas with temperature of $2 \times 10^6 - 2 \times 10^7$ K. The field of view is either full sun (full frame image = FFI) or partially restricted area covering one active region (partial frame image = PFI). The spatial resolution of FFI is either 5″ or 10″, and that of PFI is 2.5″. Time resolution depends on the observing modes, and ranges from 2 sec to a few hours. The *Yohkoh* satellite was launched on Aug. 30, 1991, and since then more than 2 million soft X-ray images of the Sun have been taken almost continuously. It should be noted that SXT has no doppler shift measurement. Hence the velocity of X-ray jets discussed in this article (as well as in other papers on X-ray jets) is based on only apparent motion.

Statistical Properties of X-ray Jets

(1) Length, Velocity, and Lifetime: *Shimojo et al.* [1995a] have made a comprehensive statistical study of 100 X-ray jets observed during 1 Nov 1991 – 30 Apr 1992, and found the following. The length of the jets ranges from 1×10^4 km to 4×10^5 km, and the average length $\approx 1.5 \times 10^5$ km (Fig. 2). Their widths are $5000 - 10^5$ km, and the average width $\approx 1.7 \times 10^4$ km. The apparent velocity is $\approx 10 - 400$ km/s in most cases, though a few exceeded 1000 km/s, and the average velocity ≈ 200 km/s. The number of jets decreases as the length, the width, or the velocity increases. This trend is more clearly seen in the distribution of the lifetime of the jet; the number of jets decreases as the lifetime increases from 100 sec to 10 hours, and shows a power-law distribution.

(2) Physical Conditions: According to preliminary analysis of small X-ray jets (length $< 7 \times 10^4$ km) observed with PFI mode *Shimojo et al.* [1995b], the temperature of the jet is nearly comparable to that of the footpoint flare, $\sim 4 - 6 \times 10^6$ K, and the electron density is of order of a few $\times 10^9$ cm^{-3}.

Shimojo et al. [1995b] then estimated that the total thermal energy content of the footpoint flare is $10^{27}-10^{28}$ erg, the total thermal energy of the jet is $10^{26}-10^{27}$ erg, and the kinetic energy of the jet is $10^{25}-10^{26}$ erg, for these smaller jets.

(3) Footpoint of Jet: Many small or thin jets are ejected from X-ray bright points (XBPs) in coronal holes or quiet regions. Similar jets occur also from XBP-like structures in active regions (ARs). The XBPs are usually not resolved well in SXT images. The jets ejected from XBP-like structures in ARs tend to appear at the western edge of the preceding spot in the AR. Such XBP-like structures often correspond to satellite spots (or emerging flux) in ARs. In some cases, the footpoint of the jet is resolved well, and found to be "anemone" active region (***anemone type***: 19 percent, see section 2.4 and Figs. 1 and 3) or single loop (***upside-down Y type***: 13 percent). The jets with unresolved bright point (***XBP type***) are many (60 percent).

(4) Shape of Jet: *Shimojo et al.* [1995a] found that the jets showing ***constant width*** (43 percent) or ***converging shape*** (33 percent) are much more common than the jet with ***diverging shape*** (14 percent). There are also some jets with a peculiar shape, such as undulating or untwisting shape, though the number of these jets is small (10 percent). It is interesting to note that ***converging shape*** of X-ray jets is very similar to the shape of EFR surges [*Kurokawa and Kawai* 1994] and macrospicules [*Karovska and Habbal* 1994].

Two Types of Interaction of Emerging Flux with Pre-existing Magnetic Fields

Many jets are ejected from emerging flux regions, especially when emerging flux interact with pre-existing coronal magnetic fields. *Shibata et al.* [1994a] have studied the interaction between emerging flux region (EFR) and overlying coronal magnetic fields, and found that there are fundamentally two types of interaction (reconnection) (Fig. 3);

(1) *Anemone-jet type*: This type occurs when emerging flux appears in a coronal hole (also see Fig. 1 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 are ejected from the AR in the vertical direction, which suggests reconnection between emerging flux and the (nearly vertical) open coronal fields of the surrounding unipolar region.

(2) *Two-sided-loop 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

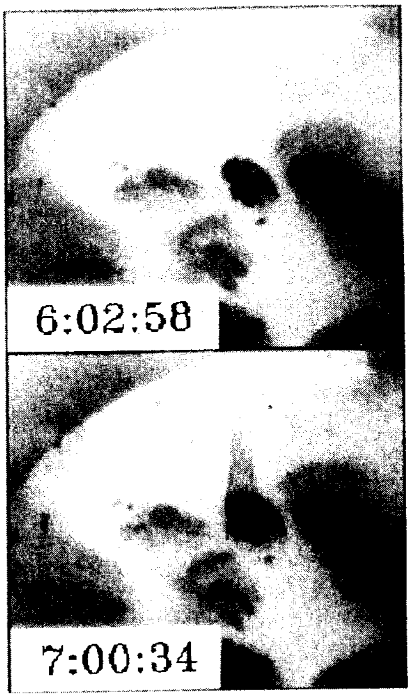

Figure 1 A gigantic X-ray jet occurred in NOAA 7001 on 1992 Jan. 11 observed with *Yohkoh*/SXT (from *Shibata et al.* [1994a]). This is one of the largest jets observed so far. The size of each frame is 1200″ x 1040″ ($\simeq 8.6 \times 10^5$ km x 7.5×10^5 km). The shape of the active region at the footpoint of the jet looks like a sea anemone, and hence this AR is called *anemone-AR*. The maximum length of the jet is probably greater than 3×10^5 km, and the apparent velocity is within the range of 90 – 240 km/s.

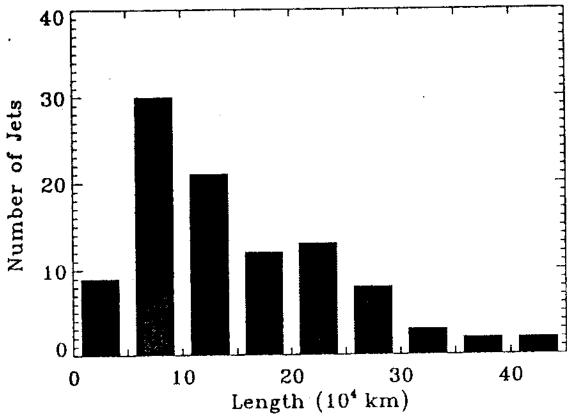

Figure 2 Histograms of length of X-ray jets (from *Shimojo et al.* [1995a]).

jets occurring in closed loop systems. (Much smaller active region transient loop brightenings found by *Shimizu et al.* [1992] may also be a result of the jets occurring in closed loop systems.)

These two types of interaction of EFRs with coronal field are basic types of interaction of emerging flux and the pre-existing field in the solar atmosphere. The *anemone-jet* could be a prototype of jets with *converging shape* ejected from unresolved XBPs.

Evidence of Magnetic Reconnection

The reconnection model (*anemone-jet* model in Fig. 4) can account for various observational characteristics of X-ray jets, which are thought to be observational evidence of magnetic reconnection:

(a) *Converging Shape of Jets*: This shape suggests that the cross-section of flux tube decreases with height, i.e., the field strength increases with height. Such situations arise if there is a neutral point near the footpoint of the jet as in the *anemone-jet* model in Fig. 3. This situation is expected also when the satellite spots appear in an opposite polarity region, and in fact such magnetic field properties have been confirmed by comparing NSO/Kitt Peak magnetogram with SXT images of many jets [*Shimojo et al.* 1995c].

(b) *A Gap Between Footpoint of Jet and Brightest Part of Footpoint Flare*: Though the footpoints of jets roughly correspond to small flares, close examination of the footpoints has revealed that often small flares (or loop brightenings) occur separately (by more than a few thousand km) from the exact footpoints of jets (Fig. 1). This characteristic is also seen in tiny XBP jets. Such a gap is expected for magnetic reconnection mechanism, because the heated reconnected field lines are quickly ejected in opposite directions to form one bright loop and a separate jet in the other direction (Fig. 3).

(c) *Change of Topology of Footpoint Active Region*: When the ARs at the footpoints of jets can be resolved well, their morphology changes substantially during the jets. For example, a loop system appeared during the 12 Nov. 1991 jet [*Shibata et al.* 1992b], while a loop system disappeared during the 11 Jan. 1992 jet (Fig. 1). In some cases, the jet moved perpendicularly to the jet axis at a few 10 km/s during the ejection of the jet, which has been referred as ***whip-like motion*** of jet [*Shibata et al.* 1992b, 1994b, *Canfield et al.* 1995]. This might be an evidence of dynamical rearrangement of magnetic field configuration as a result of reconnection.

Relation to Microflares

Shibata et al. [1995] studied the relation between microflares and jets in some emerging flux regions. Figure 4 shows time variation of the total soft X-ray intensity of the active region 7176 from its birth on 19 May 1992

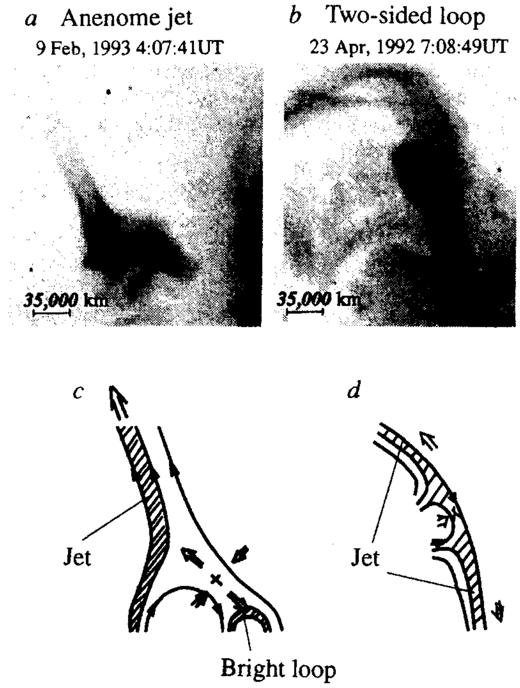

Figure 3 SXT images of two types of interaction of emerging flux with overlying coronal magnetic fields. (a) *Anemone-Jet* type observed on 9 Feb. 1993. (b) *Two-sided-loop* type observed on 23 Apr. 1992. Schematic illustration of (c) *Anemone-Jet* type and (d) *Two-sided-loop* type. (from *Yokoyama and Shibata* [1995a,b]).

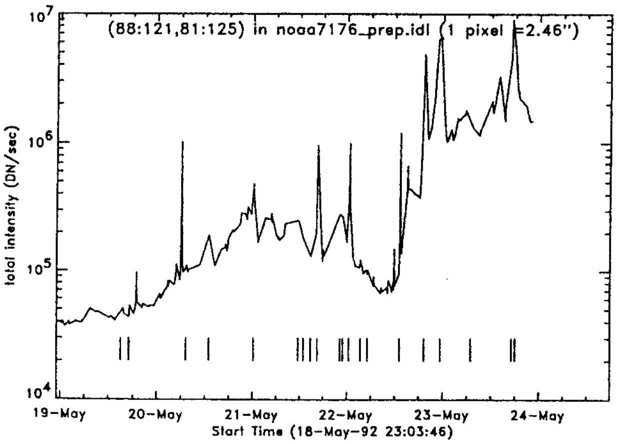

Figure 4 Time variation of the total soft X-ray intensity of the active region 7176 from its birth on 19 May 1992 to 24 May 1992 [*Shibata et al.* [1995]]. This region appeared in coronal hole and and showed characteristics of *anemone-jet* type. The short vertical lines in the figure show the time when the jets are ejected.

to 24 May 1992. This region appeared in coronal hole and showed characteristics of ***anemone-jet*** type. The short vertical lines in the figure show the time when the jets are ejected. It is remarkable that more than 20 jets were produced in 5 days after the birth of the region. It is interesting to note that the emerging flux region began to decay just after ejecting several jets on 21 May, suggesting that the jets might play a role in active region decay. All jets during these 5 days were associated with microflares (see sharp spikes in the intensity curve of Fig. 4). On the other hand, the fraction of microflares associated with jets is about 60 percent. Since the probability of detection of jets is not 100 percent because of limited time cadence of observations, this would suggest that more microflares may be associated with jets.

Relation to Hα Surges, Type III Bursts, and CMEs

If we study Hα surges associated with subflares and corresponding SXT images, we usually find X-ray bright points (or loops) at the footpoints of surges [e.g., ***Schmieder et al.*** 1995, ***Okubo et al.*** 1995]. ***Shibata et al.*** [1992b], ***Canfield et al.*** [1995], ***Okubo et al.*** [1995] found some examples showing both X-ray jets and Hα surges in the same direction. In particular, ***Canfield et al.*** [1995] found some new observational signatures of magnetic reconnection in surges, that is, ***converging footpoint*** and ***moving blue shift.***

Kundu et al. [1995] found that a Type III burst was associated with an X-ray jet on Aug. 16 1992, and that the density derived from X-ray jet is consistent with that derived from the Type III burst. The discovery of association with Type III bursts implies the existence of high energy electrons in these small flares and jets, and supports the view that the generation mechanism of X-ray jets and microflares may be physically similar to that for larger flares.

Some of gigantic jets (with length more than 2×10^5 km) show an intermediate feature between well-collimated jets and loop-like ejection similar to coronal mass ejection.

Theory

Acceleration Mechanism

How are jets accelerated in the magnetic reconnection process described above ? ***Shibata et al.*** [1992b] discussed three possibilities;

(1) The ***evaporation flow (jet)*** [***Hirayama*** 1974] as a result of a flare that is produced by the reconnection. In this case the jet is accelerated by the gas pressure gradient force which is enhanced by the flare [***Sterling et al.*** 1993]. The velocity of the main part of the flow is of order of sound speed, $C_s \simeq 500(T/10^7\mathrm{K})^{1/2}$ km/s.

(2) The ***magnetic-twist jet*** [***Shibata and Uchida*** 1986], which is accelerated by the $\mathbf{J} \times \mathbf{B}$ force in relaxing magnetic twist as a result of reconnection between a twisted loop and an untwisted loop.

(3) The ***reconnection jet*** [e.g., ***Heyvaerts et al.*** 1977] which is accelerated (like a slingshot) by the $\mathbf{J} \times \mathbf{B}$ force in the reconnection process.

The velocity of both magnetic twist jet and reconnection jet is of order of Alfven speed, $V_A \simeq 1000(B/10\mathrm{G})(n/10^9\mathrm{cm}^{-3})^{-1/2}$ km/s. Since the observed velocities of many jets are within the range of possible speeds by the above mechanism, at present it is not possible to identify which jets belong to which type. We need more detailed theoretical modeling as well as finer observations such as doppler shift measurement, which would be possible by SOHO.

Emerging Flux Reconnection Model

Heyvaerts et al. [1977] developed the emerging flux reconnection model for flares and proposed that surges correspond to reconnection jets. ***Shibata et al.*** [1989] succeeded to make a physically realistic emerging flux model, by studying nonlinear evolution of magnetic buoyancy (Parker) instability. ***Shibata et al.*** [1992a] then applied this model to the reconnection between emerging flux and overlying coronal field in a realistic situation, and found that the reconnection began with formation and ejection of magnetic islands (plasmoids). ***Yokoyama and Shibata*** [1995a,b] extended ***Shibata et al.*** simulation to a greater extent, and succeeded to model coronal X-ray jets as well as Hα surges (see also ***Yokoyama*** 1995). Their main results are summarized in the following.

(1) When the reconnection occurs between emerging flux and horizontal coronal field, two hot jets (or two hot loops) and one cool jet (or cool dense plasmoid) are produced (Fig. 5a). The two hot jets (loops) might correspond to ***two-sided-loop*** discussed in section 2.

(2) When the coronal field is not horizontal but vertical or oblique, there occur a hot jet, a cool jet (originally from cool, dense plasmoid) to one side of the hot jet, and a small hot loop which is located separately from the footpoint of the jet (Fig. 5b). Both the hot and cool jet move perpendicularly to the coronal magnetic field. This may correspond to ***whip-like motion*** observed in X-ray jets. The resulting magnetic field configuration is ***upside-down Y*** shape, which is very similar to the shape of ***anemone-jet*** and ***converging jet.*** The observed separation between footpoints of jets and flares (brightest part) can also be explained by this model. The observation of some X-ray jets associated with Hα surges is also

nicely explained by theoretically predicted coexistence of a hot jet and a cool jet.

One of important findings by *Yokoyama and Shibata* [1995a,b] is that the hot jet ejected from the current sheet region is not the reconnection jet itself, but the secondary jet accelerated by the enhanced gas pressure behind the fast shock. This is because the reconnection jets cannot directly escape from the current sheet region, and collide with the ambient magnetic field (or loop), then creating the fast shocks at both ends of the current sheet. Hence, according to this model, the X-ray jet is not the reconnection jet itself, but the newly discovered secondary jet ejected from the region heated by the fast shock.

Discussion

The reconnection between emerging flux and coronal field produce plasmoids (magnetic islands). In real three dimensional space, such plasmoids (magnetic islands) would be seen as a helical filament (or loop). Hence we can expect that the small scale loop-like (either cool or hot) ejection may be associated with microflares and/or X-ray jets. In this sense, the physics of microflares and X-ray jets may be similar to those of larger flares [*Shibata* 1995]. As discussed in section 2, the number of X-ray jets increases with decreasing length (or lifetime, etc.), similar to statistical properties of flares and microflares. (It is interesting to note that this tendency is also seen in explosive events observed with EUV (CIV) [Cook and Brueckner 1991], though the relation between X-ray jets and EUV explosive events has not yet been clarified.) This suggests that X-ray jets may be a part of microflares or all microflares may be accompanied by X-ray jets. The latter seems to be supported by the observations shown in Fig. 5. If so, the total energy of microflares would be larger than that estimated before and may be sufficient to heat the corona, since previous estimates of microflare energy neglected kinetic energy of jets [*Yokoyama and Shibata* 1995a]. The acceleration of high speed solar wind might also be explained by the process related to microflares and X-ray jets. Both observational and theoretical studies of energetics of X-ray jets will be highly desired in the context of coronal heating and solar wind acceleration.

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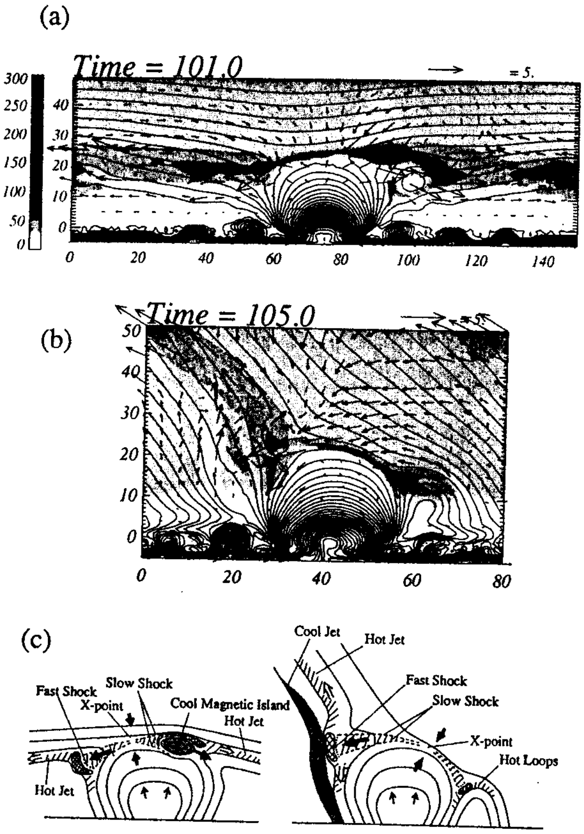

Figure 5 MHD numerical simulation of magnetic reconnection model for X-ray jets (from *Yokoyama and Shibata* [1995a,b]). (a) ***Two-sided-loop type***, in which the initial coronal field is horizontal. (b) ***Anemone-jet type***, in which the initial coronal field is oblique. Both figures show temperature distribution (grey scale; darker region is hotter), magnetic field lines (lines), and velocity vectors. The unit of length is ~ 200 km. The velocity of the hot jet is about 0.3 – 1.0 in unit of coronal Alfven speed $V_{A,cor}$ (~ 1000 km/s). (c) Schematic illustration of physical processes found from numerical simulations.

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