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 in XBPs, EFRs, or ARs. The common observed characteristics of these jets are discussed mainly from morphological points of view. It is suggested that magnetic reconnection between emerging magnetic flux and the overlying coronal/chromospheric magnetic field is a key physical process for producing these jets.

1. Introduction

Yohkoh/SXT has revealed that *X-ray corona is much more dynamic than had been expected.* Among various newly discovered dynamic phenomena, one of the most surprising findings is the discovery of *coronal X-ray jets* (Shibata *et al.* 1992b). Here X-ray jets are defined as transitory X-ray enhancements with an apparent collimated motion. In many cases, jets are associated with small flares at their footpoints, and seem to be physically similar to *transient loop brightenings* (Shimizu *et al.* 1992).

In this short report, we will summarize observed characteristics of X-ray jets, and briefly discuss the magnetic reconnection model for these jets.

2. Observed Characteristics of X-ray Jets

We found the following characteristics of jets (Shibata *et al.* 1992b, Shibata *et al.* 1994, Shimojo 1994):

(1) *Frequency:* The number of X-ray jets observed in FFI images is more than 10–20 jets per month (during Nov. 91 – Mar. 92). The total number of jets has already exceeded 100 until August of 1992.

(2) *Association with Flares:* Almost all X-ray jets except for limb events are associated with small flares (or loop brightenings) in XBPs, EFRs, and ARs. These flares correspond to

microflares – subflares or C-class flares. Jets occur nearly simultaneously with flares within a few minutes.

(3) *Physical Conditions of Jets* (preliminary):
- length $\approx 1 \times 10^4$ km – 4×10^5 km
- (apparent) translational velocity $\approx 10 - 400$ km/s in most cases, though a few exceeded 1000 km/s (Shimojo 1994). An upper limit of observed velocities could be due to "velocity filter" effect of low time resolution coming from current cadence of FFI observations.
- temperature $\approx 2 \times 10^6 - 10^7$ K
- electron density $\approx 3 \times 10^8 - 3 \times 10^9$ cm^{-3}
- mass $\approx 10^{12} - 10^{14}$ g.
- kinetic energy $\approx 10^{26} - 10^{28}$ erg.

(4) *Jets ejected from XBPs:* Many small or thin jets are ejected from XBPs in coronal holes or quiet regions. Similar jets occur also from XBP-like structures in active regions. The XBPs are usually not resolved well (see Fig. 1), but sometimes can be identified with opposite polarity regions embedded in locally uniform polarity region.

(5) *Site for Jets in ARs:* 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, and some of these jets are identified with Hα surges (Shibata *et al.* 1992b).

(6) *Two Types of Jets ejected from EFRs and ARs:* The jets ejected from EFRs/ARs in coronal holes show often *anemone-jet* type (Fig. 1; Shibata *et al.* 1994); i.e., the ARs at the footpoints of these jets look like "sea anemone" and show a radial array of loops connecting the opposite polarity of the AR magnetic field with the unipolar region surrounding it. On the other hand, the jets (or loops) associated with EFRs/ARs in quiet regions show *two-sided-loop (jet)* type (Fig. 1); the transient loop brightenings (or jets) suddenly appear at both sides of EFRs/ARs along the nearly horizontal field in quiet region. These two types of interaction of EFRs/ARs with overlying coronal field are basic types of general interaction of emerging flux and pre-existing field in the solar atmosphere. The *anemone-jet* could be a prototype of jets ejected from unresolved XBPs.

(7) *Shape of Jets:* Some jets have nearly *constant width* along the jets, though there are also many *diverging* or *converging (upside-down Y or helmet-streamer type)* jets (Shimojo 1994). The latter is similar to the shape of EFR surges (Kurokawa and Kawai 1993). There are also *undulating or meandering jets*, suggestive of *helical jets*, though the number of such jets are small.

(8) *Edge-Brightened Intensity Distribution:* Some of well resolved jets show edge-brightened intensity distribution, as shown in three anemone-jets in Fig. 1, suggesting hollow cylindrical shell structure.

(9) *Reccurrency:* The jets tend to recur at the same place.

(10) *Seperation between Footpoints of Jets and Flares :* 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 seperately (by a few thousand km) from the exact footpoints of jets (see Fig. 1). This characteristic is also seen in tiny XBP jets (Fig. 1).

(11) *Change in Morphology at Footpoint ARs:* When the ARs at the footpoints of jets can be resolved well, their morphology changed much during the jets. For example, a loop system appeared during the 12-Nov-91 jet, while a loop system disappeared during the 11-Jan-92 jet (see Fig. 1).

(12) *Whip-like Motion:* Some jets show whip-like motion; the jets (apparently) move perpendicularly to the direction of elongation of jets at a few 10 km/s.

(13) *Colliding Jets:* Sometimes jets are ejected from one footpoint of the loop and collide another footpoint of the loop, producing secondary XBP flare or bright point a few 10 sec – a few min later (Strong *et al.* 1992).

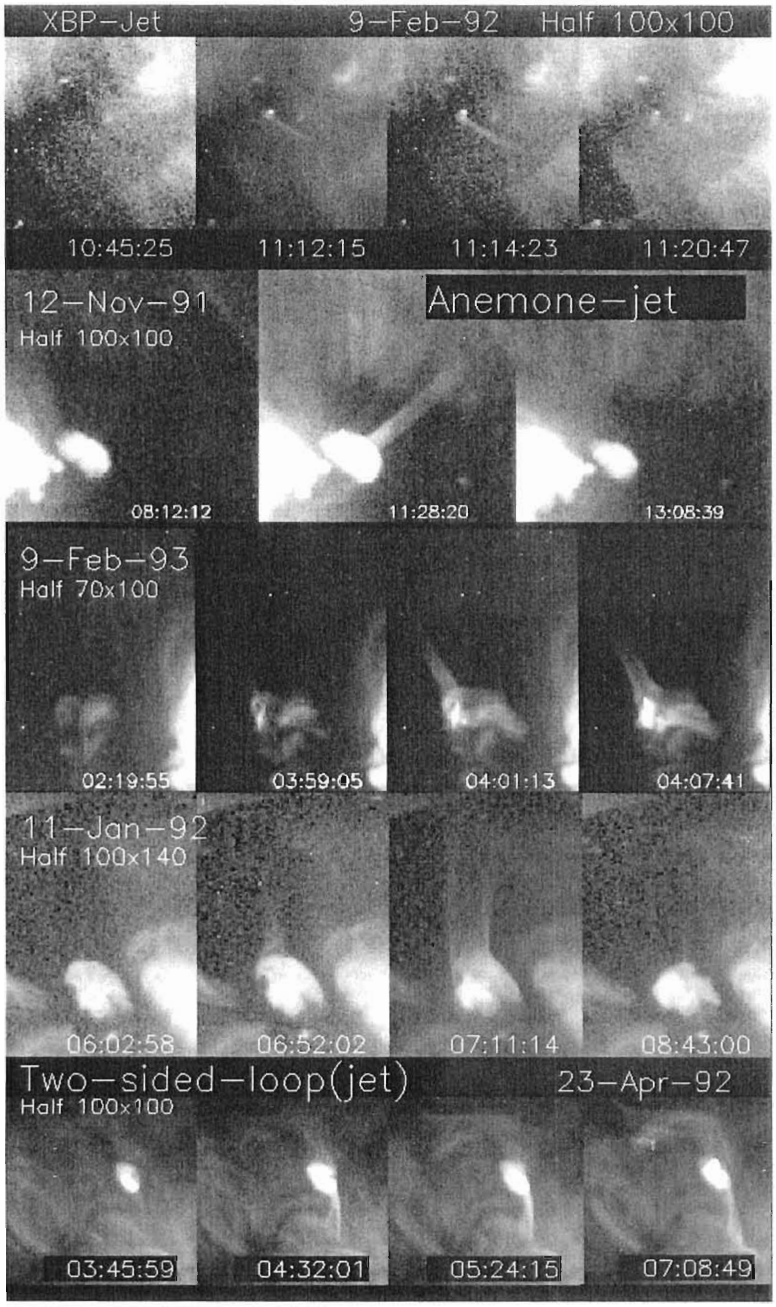

Fig. 1. One XBP-jet (9-Feb-92), three *anemone-jets* (12-Nov-91, 9-Feb-93, 11-Jan-92), and one *two-sided-loop(jet)* (23-Apr-92). All these images are taken with soft X-ray telescope at half resolution mode (1 pixel $\approx$ 5 arcsec); e.g., images with 100×100 pixels (9-Feb-92, 12-Nov-91, 23-Apr-92) show the region with 3.6×10^5 km square. Times are in unit of hh:mm:ss UT. Note that the morphology of the active region at the footpoint of the jets changed during the jets, and also that the brightest parts (flares) in the ARs (and XBP) are slightly separated from the exact footpoints of the jets.

(14) Relation to Hα Surges: There are 10 - 20 pecent correspondence between X-ray jets found in FFI images and Hα surges reported in Solar Geophysical Data during Nov. 91 – Apr. 92 (Shimojo 1994). On the other hand, if we study Hα surges associated with subflares and corresponding SXT images, we usually find X-ray bright points at the footpoints of surges. One such example showing both X-ray jets and Hα surges in the same direction has been discussed by Shibata *et al.* (1992b).

(15) Relation to Coronal Mass Ejection: 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. Examples are jets on 11-Jan-92, 20-Sep-92, 21-Sep-92.

3. Magnetic Reconnection Model for X-ray Jets

Yokoyama and Shibata (1993, 1994) performed two-dimensional MHD numerical simulation of the reconnection between emerging flux and overlying coronal field (see Heyvaerts *et al.* 1977 for a pioneering idea), by extending the preliminary simulation study by Shibata *et al.* (1992a), and found the following characteristics;

– When the reconnection occurs between emerging flux and horizontal coronal field, two coronal jets (or two bright coronal loops) and one cool jet are produced. The two coronal jets (loops) might correspond to *two-sided-loop(jet)* discussed in item (6).

– When the coronal field is not horizontal but vertical or oblique, there occur a coronal jet, a cool jet just side of a coronal jet, and a small bright loop which is located seperately from the footpoint of the jet. The resulting magnetic field configuration is *upside-down Y* shape. These would explain general feature of the *anemone-jet*, and also of some of unresolved XBP-jets in items (6), (7), and (10). Coexistence of both a hot jet and a cool jet would also explain the coexistence of X-ray jets and Hα surges in item (14).

In above case, the jet itself is accelerated (like a slingshot) by the $\mathbf{J} \times \mathbf{B}$ force in the reconnection process. Chromospheric evaporation in association with a sudden energy release in the corona would help in generating dense jet-like flows along reconnected field lines (Shibata *et al.* 1992b). Three dimensional effect such as a sudden release of magnetic twist as a result of reconnection between twisted emerging flux and non-twisted coronal field would also lead to further acceleration of the jet (Shibata and Uchida 1986). These effects should be studied further.

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