PHYSICAL PARAMETERS OF SOLAR X-RAY JETS
- Observation and Simulation -

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ABSTRACT

The solar X-ray jet is one of the most interesting findings of the soft X-ray telescope (SXT) aboard Yohkoh. In this paper, we examine physical parameters of the solar X-ray jets using Yohkoh/SXT observations and numerical simulations. We searched for the high resolution image data (PFIs) of jets which can be used to derive physical parameters of jets, and found 14 events for that special purpose. These jets are relatively small events because of small field of view of the PFIs (length of the jet < 5 × 10^5 km and lifetime < 10 min). For these 14 jets, we estimated the following physical parameters. The temperature of jets is 3 – 7 MK. The density of jets lies in the range of (0.7 – 4.0) × 10^6 cm^-3. The thermal energy content of jets is 10^{28} – 10^{27} ergs. The X-ray intensity distribution along an X-ray jet often shows an exponential decrease with distance from the footpoint. This distribution persists from the early phase to the decay phase. We also performed 1D-hydrodynamic simulations of chromospheric evaporation based on the reconnection model of jets to examine the possibility that jets are evaporation flow induced by reconnection. Our simulations reproduce well various observed properties of jets such as exponential intensity distribution, its evolution, temperature, and density.

1. INTRODUCTION

The soft X-ray telescope (SXT: Tsuneta et al. 1991) aboard Yohkoh (Ogawara et al. 1991) has a better temporal coverage and resolution than previous solar X-ray instruments, and has revealed many previously unknown dynamic phenomena in the corona (e.g., Acton et al. 1992; Uchida 1993; Tsuneta and Lemen 1993; Hudson 1994; Shibata 1994; Shimizu et al. 1992). Among various newly discovered dynamic phenomena, one of the most interesting findings is the common occurrence of X-ray jets (Shibata et al. 1992, 1994; Strong et al. 1992; Shibata, Yokoyama and Shimojo, 1996a,b; Shimojo et al. 1996).

According to the statistical study of 100 X-ray jets by Shimojo et al. (1996), these X-ray jets are transitory X-ray enhancements with apparent collimated motions and have the following observed characteristics (Figure 1): 1) Most are associated with small flares (microflares – subflares) at their footpoints; 2) Their length lies in the range of a few × 10^4 – 4 × 10^5 km; 3) Their width is 5 × 10^3 – 10^5 km; 4) The apparent velocity is 10 – 1000 km s^-1 with an average of about 200 km s^-1; 5) The lifetime of the jet ranges from a few minutes to 10 hours and the distribution of the observed lifetime is a power law with an index of ≃ 1.2; 6) 76% of the jets show constant or converging shapes: the width of the jet is constant or decreases with distance from the footpoint. The converging type tends to be generated with an energetic footpoint event and the constant type by a wide energy range of the footpoint event. 7) The X-ray intensity along an X-ray jet often shows an exponential decrease with distance from the footpoint (Figure 2). 8) This exponential intensity distribution holds from the early phase to the decay phase (Figure 2).

Aurass, Klein and Martens (1994), Kundu et al. (1995) and Raulin et al. (1996) reported that the metric Type III bursts occur in association with X-ray jets. They suggest that electron beams propagate along the X-ray jet, and the flare associated with the X-ray jet produces non-thermal electrons. Recently, Shimojo, Shibata and Harvey (1998) found that that 8% of the studied jets occurred at a single pole, 12% at a bipole, 24% in a mixed polarity and 48% in a satellite polarity. They also found that X-ray jets favored regions of evolving magnetic flux (increasing or decreasing).

Shibata et al. (1992) and Yokoyama and Shibata (1995, 1996) proposed that the X-ray jets are produced by the magnetic reconnection. Their scenario is as follows: A magnetic bipole emerges in a locally unipolar magnetic field region. In this case, a neutral point appears just above a magnetic bipole, and magnetic reconnection would occur there. A reconnection-heated hot plasma will be quickly transferred to both open fields and closed (reconnected) fields. Note that this open field may not be a real open field but can be part of a large scale loop near its footpoint. Hot plasma flows along open field lines and forms a hot (X-ray) jet, whereas hot plasma transferred to the lower branch forms a hot loop (i.e., loop brightening or a flare loop). The two-dimensional MHD numerical simulations of this scenario were performed by Yokoyama and Shibata (1995, 1996) and they succeeded in reproducing various observed characteristics of the X-ray jet and the Hα surge. However, their simulations did not reproduce some of the properties of the jets, such as

the exponential X-ray distribution along a jet. Why were these properties not reproduced? One reason may be that their simulations did not include heat conduction.

2. OBSERVATIONS OF X-RAY JETS

Since the apparent velocity of X-ray jets lies in the range of 10 - 1000 km s$^{-1}$, with an average velocity of about 200 km s$^{-1}$ (Shibata et al. 1992 and Shimojo et al. 1996), it is difficult to measure temperature of jets using low time resolution data such as Full Frame Images (FFIs) of Yohkoh/SXT whose typical cadence is every 2 min. Therefore we searched for X-ray jets in Partial Frame Images (PFIs) that are taken in higher time resolution. We found 47 jets in PFIs during the period between 1992 April and 1995 March. Among them, we selected 14 events for the temperature analysis that had enough signals at the X-ray jets. These 14 events are relatively small; their length and width are about 100,000 km and 10,000 km, respectively. This is because the field of view of PFIs is about 5 × 5 arcmin and the center of field of view is usually placed on the center of an active region.

In order to derive temperature of jets using filter-ratio method (Hara et al. 1992), we have to use two X-ray images in different filters taken at the same time. However SXT cannot take two images at the same time. For this reason, if we derive the temperature of rapidly-variable phenomena, we have to give due considerations to the uncertainty resulting from the time difference between the two images. Figure 3 is an example of the temperature analysis of a jet. If we calculate temperature at 22:45 UT when an image was taken with AI1 filter (three dotted-dashed line on figure 3a), we obtain two values (figure 3b), depending on whether the paired AI12 image is before (plus mark) or after (square marks). This difference between the two values should be taken as uncertainty from the time difference between the two images. We note that this uncertainty exceeds the uncertainty from photon statistics. Since the uncertainty from the time difference is minimum at the peak time of X-ray intensity of jets, the physical parameters of jet which are presented in this paper are spatially averaged value at that time.

We summarize the observational results of physical parameters of jets.

- Temperature of jets $\sim$ 3–7 MK (Ave. 6 MK)
- Density of jets $\sim$ 0.7–4.0 $\times$ 10$^9$ cm$^{-3}$ (Ave. 2.0 $\times$ 10$^9$ cm$^{-3}$)
- Thermal energy of jets $\sim$ 10$^{25}$ – 10$^{27}$ ergs

$^1$Solar X-ray jets usually occur in the edge of active regions. (Shimojo, et al. 1996)
• Temperature of flares $^2$ ~ Temperature of jets
• Thermal Energy of a jet ~

10% of Thermal energy of a flare $^2$

(Figure 4)

From observational results of Yohkoh/SXT, we found that
the apparent velocity of X-ray jets is about 200 km/s
which is near sound speed rather than Alfvén speed
in the corona. Since X-ray jets are always associated
with small flares at their footpoints, there is a possibilit-
ity that some X-ray jets are hot plasma flows of chro-
mospheric evaporation induced by small flares. On the
other hand, Yokoyama and Shibata (1995, 1996) per-
formed two-dimensional MHD numerical simulations
of X-ray jets on the basis on a magnetic reconnection model
(Figure 6). Their simulation, however, did not reproduce
following properties of jets : 1. The exponential X-ray
intensity distribution along a jet. 2. The density of the
simulated jets is somewhat lower than the observed. This
difference between simulations and observations may be
because their simulation did not include heat conduction.
For these reasons, we extended their model. We consider
the left-side reconnected flux tube in figure 6, and per-
formed one-dimensional hydrodynamic numerical simula-
tions of X-ray jets along the reconnected tube. Note that
the reconnected tube is part of a large scale loop (Figure
6).

Figure 3. An example of a temperature analysis of an X-
ray jet. (a) Time variation of total X-ray intensity of
the jet. Solid line and plus mark indicate total intensity
which is observed with Al1 filter. Dashed line and aster-
isk indicate total intensity which is observed with Al12
filter of Yohkoh/SXT. (b) Time variation of temperature
of jets. Cross marks indicate temperature which is calcu-
lated using an Al12 filter images which are taken before
Al1 images. Asterisks indicate temperature which is calcu-
lated using an Al12 images taken after Al1 images.
The vertical bars show photon-statistic error.

3. SIMULATIONS OF X-RAY JETS

"Chromospheric evaporation" is a phenomenon com-
monly observed in solar flares. Many authors studied this
phenomenon, arguing that the blue shift of X-ray spectral
lines in flares signifies evaporation. As computer tech-
ology has progressed, we now can study the evaporation-
flow in a computer. Recently, Hori et al. (1997) de-
veloped a "pseudo-two-dimensional" model of solar flare
loops based on one-dimensional simulation, and reported
the effect of multi-loop system of the flare loop.

$^2$The flares occurred at the footpoints of jets

We calculated the dynamics in loops using one-
dimensional hydrodynamic code which included radiative
cooling and heat conduction (Hori et al. 1997). We con-
sider a system of loops which have semicircular shape
with a constant cross section (Figure 5). The radius of
this loop system is about $16 \times 10^4$ km, and the width
of each loop is about $1 \times 10^4$ km. As initial conditions,
the temperature of the corona is 2 MK, the density of
the corona is about $2 \times 10^6$ cm$^{-3}$, the temperature of
the chromosphere is $1 \times 10^6$ K, and the density at the
bottom of the chromosphere is about $10^{15}$ cm$^{-3}$. The
energy input is assumed to be near the footpoint of loop
system. We consider two cases for this system. In case 1,
this system consists of a single loop and the time depen-
dence of energy input is shown in the upper-right panel
in figure 5. In case 2, this system consists of 20 thin loops
(pseudo-two-dimensional model, Hori et al., 1997). We
input energy as shown in the lower-right panel in figure
5. We assume that the heating mechanism is magnetic
reconnection in case 2, because the magnetic recon-
nection heats the different flux loops successively. The total
input energy is $4 \times 10^{28}$ ergs in case 1 and case 2.
Figure 5. Initial conditions and the method of energy input.

Since our primary concern is to compare simulations with observations, we “observed” the simulation results under the response of the real two filters (the Al1 and the Al12 filters) of Yohkoh/SXT. We also discuss the "observed" temperature and density of the simulated jet, which are derived from the "observed" images with above two filters using the filter ratio method (Hara, et al. 1992). Figure 7 shows the X-ray intensity distribution along the simulated jets. Upper panel shows the case 1 and lower panel shows the case 2. We find that the evaporation front move from the footpoint (left) to the loop top (right) in both cases. The velocity of the evaporation front is 100 ~ 200 km/s. The maximum temperature in the jet region (between the footpoint and the evaporation front) is 3.3 MK in case 1 and 4.6 MK in case 2. Figure 6 shows that the X-ray intensity along the jet decreases exponentially with distance from the footpoint, and that this exponential intensity distribution holds from the early phase to the decay phase. However, we can also find that in case 1 the X-ray intensity near the footpoint decreases with distance from evaporation front in the late phase (520 sec). This is because in case 1 the temperature near the footpoint in the late phase rapidly decrease due to the heat conduction. In contrast, in case 2, even if one loop cools down, there are still hot loops which are being heated, so that the average intensity near the footpoint maintains high brightness. Another difference between case 1 and case 2 is the temperature distribution along the jet (Figure 8). The temperature distribution in case 1 shows that the temperature decrease with distance from the footpoint. On the other hand, we found hot region in front of the evaporation front in case 2. The reason for this is that our "observed " loop in case 2 consists of many different loops. Namely, there are hot loops which are being heated by the heat conduction front that the originates from large energy input, and these hot loops are “observed ” in front of evaporation front in our multi-loop system.

4. DISCUSSION

We summarize the observed properties of jets which our simulations have to reproduce.

- Temperature of jets ~ 3–7 MK
Density of jets $\sim 0.7-4.0 \times 10^9$ cm$^{-3}$

The X-ray intensity along an X-ray jet often shows an exponential decrease with distance from the footpoint and this exponential intensity distribution holds from the early phase to the decay phase.

Our simulations reproduced these properties. This suggests that the X-ray jets are the evaporation flows. In particular, the configuration of case 2 is more suitable than case 1 since the X-ray intensity near the footpoint decreases in the late phase in case 1. Therefore, X-ray jets are the evaporation flow which may be produced by magnetic reconnection, since magnetic reconnection is the process in which successive energy release occurs on different magnetic field line as in case 2. In this study, we found that the temperature distribution is clearly different between case 1 and case 2. If X-ray jets are observed by SXT in high time resolution ($\sim 1$ image per 10 sec) and we get the temperature map of X-ray jets, we would find which configuration is better, case 1 or case 2, on the basis on the difference in “predicted” temperature distribution for case 1 and 2.

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