DETECTION OF NONTHERMAL RADIO EMISSION FROM CORONAL X-RAY JETS


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ABSTRACT

We report the detection of a type III burst in association with a dynamic X-ray coronal jet observed by Yohkoh/SXT. The type III burst observed with the Nançay (France) multifrequency radioheliograph is spatially and temporally coincident with the X-ray jet. The radio locations at different frequencies (236.6 and 164 MHz) are aligned along the length of the jet. The observation of the type III burst in association with the X-ray jet implies the acceleration of electrons to several tens of keV, along with the heating responsible for the production of soft X-rays. This association implies the existence of open field lines in dense coronal structures identified on the Sun’s disk. This is the first observation of dense coronal structures on the disk, along which type III emitting nonthermal electrons propagate. We find that this structure begins to form before the type III emission. At the time of the type III burst we estimate a density of $6 \times 10^9$ cm$^{-3}$ for a temperature of $\sim 5$–6 MK at an altitude of 20,000 km.

Subject headings: Sun: activity — Sun: corona — Sun: flares — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

The soft X-ray telescope (SXT) on Yohkoh (Tsuneta et al. 1991) allows us to view the solar corona in its natural X-ray emission, and with vastly improved time resolution when compared with previous soft X-ray observations. Accordingly, these data have the potential to provide a qualitative new view of meter-wave radio phenomena and the structures they propagate in.

Yohkoh has revealed an X-ray corona much more dynamic than had been suspected. In particular, SXT has discovered X-ray jets, or transitory X-ray enhancements with well-collimated motion. These X-ray jets are among the most interesting new discoveries from Yohkoh (Shibata et al. 1992; Strong et al. 1992). In many cases, the jets are associated with small flares at or near their apparent footpoints. The motion appears to be a real flow of plasma, although no Doppler shift has yet been detected by the Yohkoh/bent crystal spectrometer instrument which could be linked to a jet. This is consistent with the sensitivity of the instrumentation.

The typical size of a jet, as observed by SXT, is $5 \times 10^3$–$4 \times 10^3$ km, the translational velocity is 30–300 km s$^{-1}$, and the corresponding kinetic energy is about $10^{25}$–$10^{28}$ ergs. These parameters are determined mainly by the observing circumstances and should not be taken as average values. Many of the X-ray jets are associated with flares in X-ray bright points (XBPs), emerging flux regions (EFRs), or active regions (ARs). In some cases, a void appears at the footpoint of the jet after the ejection.

Kundu et al. (1994, 1995) provided the first conclusive evidence of nonthermal processes occurring in flaring XBPs identified in the Yohkoh soft X-ray data, using the occurrence of type III bursts from the Nançay (France) metric radioheliograph data. It has been speculated that these XBP flares are triggered by a rearrangement of the coronal field structure as magnetic flux emerges from the photosphere and reconnects to the preexisting fields. If in the process open field lines are generated above the flaring region, then we expect to see type III—like emission at metric wavelengths associated with most XBP flares, as electrons accelerated at low altitudes gain access to open field lines and propagate well out into the corona. As they propagate, they will pass through progressively higher levels of the corona and generate type III bursts at lower and lower frequencies.

We have extended this study of nonthermal radio emission using the Nançay radioheliograph data at metric wavelengths to the observations of coronal jets. We have found evidence of nonthermal radio emission in the form of type III bursts associated with several coronal jets reported by M. Shimojo & K. Shibata (private communication). Pick et al. (1994) and Aurass, Klein, & Martens (1995) reported the Yohkoh/SXT observations of large, faint coronal structures excited at the times of fast-drift radio bursts. In both cases the radio bursts were type U bursts, implying closed field lines.

We note further that with regard to the EFR/AR associated coronal jets, we should be able to distinguish between the radio signatures of "anemone-type" jets and "two-sided" jets (Shibata, Yokoyama, & Shimojo 1994). In the former, we expect normal type III bursts extending over a broad frequency range, whereas in the latter case, where propagation is on low-lying closed field lines, we expect to see type III bursts of very restricted bandwidth, because the type III—producing electron streams will be propagating more or less parallel to equidensity levels of the Sun’s atmosphere, and therefore plasma radiation within a limited frequency range will be emitted.

In this paper we present a unique example of association, both spatial and temporal, of a nonthermal type III burst emission with a coronal X-ray jet.

2. OBSERVATIONS

The coronal jet event reported here was observed by Yohkoh/SXT on 1992 August 16. The intensity increase be-
tween 12:30 and 12:45 UT in soft X-rays was associated with a type III burst observed with the Nançay radioheliograph. The jet was observed fully in both X-rays and metric radio wavelengths. Because the jet happens to occur in the SXT observing region, the soft X-ray data have relatively frequent sampling. X-ray images in two filters, Al A1265 (thin aluminum) and Al 11.6 μm (thick aluminum) were obtained every 32 s.

Figure 1 (Plate L22) shows a sequence of SXT images in the thin Al filter aligned with a continuum image and a magnetogram from Kitt Peak. We see a jet in Figures 1e–1g. The jet seems to be ejected from an XBP which was resolved by the SXT (with pixel resolution of 2'5) into several component sources which had different variabilities with time. It should be noted that this XBP brightened well before the jet, decaying quite rapidly following it. The jet reached its maximum intensity (which was rather broad) around 12:37:28–12:38:32 UT. The velocity of the jet was about 300 km s⁻¹ at 12:37:28 UT and 100 km s⁻¹ at 12:38:32 UT, as determined by visual estimates of the apparent motion.

The jet occurred on the eastern edge of the active region AR 7260, which consisted of a large leader spot and an emerging flux region (EFR) embedded in the following polarity part (see Figs. 1k–1l). About 50° northwest from the XBP, another small, bright loop was seen in association with a newly emerged bipole which became the central part of the later development of the EFR. At least two flares were attributable to this bipole (12:21 and 13:51 UT). Our XBP flared up again at 14:41 UT, again ejecting a jet. Radio counterparts to the flares at 13:51 and 14:41 UT were also observed at the Nançay radioheliograph in the form of a strong metric continuum emission. Although the XBP appears to have some structure in X-rays, Figures 1k–1l reveal no noticeable photospheric features corresponding to the XBP. Indeed, no major emerging flux is identified at the position of the XBP on the basis of medium-resolution (2'–5') data (Leka et al. 1994). However, we cannot rule out the possibility of minor flux emergence which may have been observed with higher spatial resolution. The heliographic coordinates of the XBP were 0.46 R₀ east and 0.16 R₀ north, corresponding to a radial projection factor of ~0.3.

The type III burst referred to earlier occurred at 12:37:50 UT between the two SXT times defining the broad maximum of jet intensity (Fig. 2). We consider this temporal association between the SXT jet and type III to be excellent, as illustrated in Figure 2. The locations of type III sources at 236.6 and 164 MHz are indicated in Figure 3 (Plate L23) with crosses. Note that the 164 MHz position is located on the extension of the jet (that is, the jet is not quite visible at that location). We shall discuss this point later. The type III burst had brightness temperatures of $T_b \sim 3.5 \times 10^8$ K depending upon the frequency, and it was unpolarized.

The X-ray time profiles of the jet and the XBP are shown in Figure 2. Five areas were selected as shown in Figure 3. Note that "A" corresponds to the entire XBP, "B" refers to the base of the jet, and "E" refers to the farthest area from the XBP. The X-ray intensity appears to decrease along the jet in a manner consistent with the exponential falloff found by Shibata et al. (1992) and is generally delayed in a manner consistent with the visual appearance of outward flow along the jet.

Using the SXT filter ratio, we have obtained temperature and emission measure at three locations, i.e., the flaring XBP, the base, and the top of the jet, at their individual intensity peaks (Table 1). Here the top of the jet refers to an area of about 30 pixels whose centroid is on the outer edge of box E. This is slightly closer to the jet than the position of the 236.6 MHz radio burst, but considering that the radio beam is rather broad (~1'), we can regard the two places as largely overlapping. Because the images to be paired were taken at slightly different times (~32 s), we have interpolated one image to be aligned in time with the other. In order to improve the signal-to-noise ratio, we averaged signals from several pixels. Further, we subtracted the dark background in floating points (instead of integers) for higher accuracy, which is important for analyzing a diffuse region such as the jet. We found that the temperature is quite similar at the three locations (first column of Table 1). The error bars quoted for the temperatures reflect only statistical errors. The second column shows average emission measure per SXT pixel (2'46). To convert emission measure to density, we assumed the filling factor to be unity and a range of thickness at each location, comparable with its apparent size. The assumed thickness is 5–10 SXT pixels (8.6 × 10⁻¹–1.7 × 10⁴ km) for the XBP and 2–5 SXT pixels (3.4–8.6 × 10³ km) for the jet. The range of densities in the

![Figure 2](https://example.com/figure2.jpg)

**Figure 2**—Soft X-ray time profiles at various parts along the jet and at the compact region at the base of the jet (A, B, C, D, and E have the same meaning as in Fig. 3). The bottom part of the figure shows the type III time profiles observed at different frequencies. The vertical line through the burst profile indicates the type III burst considered in this paper.

<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature from SXR (10⁶ K)</th>
<th>Emission Measure from SXR (10¹⁶ cm⁻³)</th>
<th>Electron Density from SXR (10⁶ cm⁻³)</th>
<th>Electron Density from Radio (10⁶ cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bright Point</td>
<td>5.8 ± 0.2</td>
<td>7.7</td>
<td>39-55</td>
<td>...</td>
</tr>
<tr>
<td>Base of Jet</td>
<td>5.6 ± 0.9</td>
<td>1.8</td>
<td>26-42</td>
<td>...</td>
</tr>
<tr>
<td>Top of Jet</td>
<td>5.8 ± 1.5</td>
<td>1.0</td>
<td>6-10</td>
<td>6.9</td>
</tr>
</tbody>
</table>

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Fig. 1.—(a)–(j) Sequence of SXT images showing the development of the soft X-ray jet as well as the main active region AR 7260. The compact region from which the jet originated is shown by an arrow. (k)–(l) Kitt Peak National Observatory white-light image and magnetogram. Each panel is 5.4 × 5.4. North is up, and west is to the right.

Kundu et al. (see 447, L136)
Fig. 3.—SXT image taken at 12:38:22 UT near the time of the jet's maximum intensity. The boxes show the compact region from which the jet originated (A) and different parts of the jet (B–E). The crosses are the positions at 164 and 236.6 MHz of the type III bursts associated with the soft X-ray jet. The smaller the cross, the higher the observed frequency. The size of each cross gives the HPBW of the Nançay radioheliograph at the corresponding frequency.

Kundu et al. (see 447, L136)
second column reflects such geometrical ranges. We believe that the assumption of a unity filling factor is quite justifiable because in the absence of higher resolution data no other assumption about filling factor can be made. This means that the density estimates are lower limits.

3. DISCUSSION

The Yohkoh X-ray jets of the type discussed in this paper consist of highly collimated plasma structures originating in active regions or X-ray bright points. They evolve dynamically on the timescales of the observations (typical sample intervals on the order of minutes), and they are visible in soft X-rays because of density and temperature enhancements relative to the surrounding coronal material. Most jets are associated with small flares. A significant fraction of the jets occur in coincidence with Hα surges (Canfield et al. 1994), which we take as additional evidence that the jet formation requires an actual flow of plasma (as the direct imaging strongly suggests).

Since the late 1950s, it has been known from radio interferometric observations of limb flares at meter wavelengths that type III bursts occur in regions of increased electron density like coronal streamers (Wild, Sheridan, & Neylan 1959). From imaging observations at meter-decimeter wavelengths using the Clark Lake multifrequency radioheliograph, it was in fact shown that type III–emitting electrons propagate along radio structures corresponding to coronal streamers of electron density higher than ambient density by factors of 4–10 (Kundu et al. 1983). It is also known that type III electrons must propagate along open magnetic field lines in order to account for their association with electrons detected in the interplanetary medium (e.g., Lin, 1985). The association of type III–like bursts with coronal jets on the disk shows that it may be a general situation for nonthermal electrons to propagate in dense coronal structures. As mentioned earlier, Pick et al. (1994) and Aurass et al. (1995) have reported the association of U-type bursts with jets. We also have studied three other cases of type III bursts in association with X-ray jets. However, the case presented in this paper is the first example where we have excellent positional and temporal association of a type III burst with an X-ray jet.

In the magnetic reconnection model of X-ray jets (Yokoyama & Shibata 1993, 1994), the jet is accelerated by the $J \times B$ force in the reconnection process. Chromospheric evaporation in association with a sudden energy release in the corona leads to the generation of dense jetlike flows along reconnected field lines (Shibata et al. 1992). The MHD simulation of Yokoyama & Shibata also invoked the existence of open magnetic field lines between structures resulting from the reconnection process. The association of type III bursts with jets established that the acceleration of electrons to speeds of $\sim c/3$ (energies some tens of keV) coincides with these plasma flows. Further, the type III evidence suggests that the jets, which appear to emanate from closed loops, must have open field lines along which the nonthermal electrons propagate. The location of type III bursts at the lower frequency (164 MHz) on the invisible or poorly visible part of the jet suggests that the electron density in that part of the jet is adequate to produce plasma radiation, but not high enough for the jet to be visible in soft X-rays. This is consistent with extrapolation of the decreasing density away from the XBP (Table 1). Closer to the jet, the density derived from 236.6 MHz type III burst observation (on the plasma radiation interpretation) is only slightly smaller than or even comparable with the X-ray derived density at the top of the jet. The slight difference in density may result from two possibilities: either the 236.6 MHz source is higher than the top of the jet, or the jet is thicker than any value within the assumed range.

The flarelike brightnesses associated with jets arising in XBP are typically too weak to be detectable in hard X-rays, so the radio phenomena must serve to identify any nonthermal effects in these events. The type III emission shows clearly that particle acceleration is taking place, as is normal in ordinary flares. The type III emission is extremely short-lived relative to the jet process, as can be seen from Figure 2. Type III bursts often mark the impulsive phase of a flare but do not exactly match the hard X-ray bremsstrahlung of the impulsive-phase particle acceleration. The exact timing of the type III emission presumably reflects not just the electron acceleration itself, but also the occurrence of appropriate conditions in the structure formed by the plasma jet. Observations of further events of this type may enable us to understand these conditions better.

The identification of the type III emission with the jet suggests several additional ideas. First, the location of the low-frequency type III bursts on the extension of the soft X-ray jet argues that the coronal jet can be much longer than inferred from soft X-ray measurements. Second, the continuity of jet structure opens the possibility that the electron acceleration may take place at an altitude considerably lower than that corresponding to the starting frequency of the type III emission. Third, we note that the soft X-ray emission and the radio observing frequency provide two independent means of estimating the electron density at the point of observation.

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REFERENCES


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