A Microwave Study of Coronal and Chromospheric Ejecta

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Abstract

We have studied the radio properties of 18 X-ray coronal jets (observed by the Yohkoh SXT) using Nobeyama 17 GHz data. We also searched for chromospheric ejecta (Hα surges) during the time intervals that the X-ray images were available. Microwave emission was associated with the majority of the X-ray jets. The radio emission came from the base or the lower part of the jets. We detected radio emission from almost all jets which showed flare-like activity at their footpoints. The 17 GHz time profiles were gradual and unpolarized, implying that the emission was thermal. When possible, we computed the physical properties of the X-ray-emitting ejected plasma. In one two-sided-loop type jet and one anemone-type jet, the observed microwave fluxes from the lower part of the jets were well above the fluxes predicted from the computed electron temperatures and emission measures of the soft X-ray-emitting material on the basis of thermal free-free emission. We interpreted the large discrepancies in terms of the presence of lower temperature material which cannot be detected by the SXT but produces strong microwave free-free emission. This is the first time that such material is observed in two-sided-loop type jets. Thus our observations confirm the theoretical prediction by Yokoyama and Shibata (1996). We detected no cool material at the base of the jets. We also observed an Hα surge which was not associated with an X-ray jet and showed no signatures on the SXT images but was detected with the Nobeyama Radioheliograph. The emission of the microwave surge-associated source was free-free from the chromospheric plasma. Constraints for the surge density were derived.

Key words: Sun: activity — Sun: corona — Sun: chromosphere — Sun: radio radiation — Sun: X-rays,gamma rays

1. Introduction

The soft X-ray telescope (SXT) on board the Yohkoh satellite (Tsuneta et al. 1991) allowed the detection of X-ray jets which are transitory enhancements with well-collimated motion (Shibata et al. 1992). They involve the ejection of 10^{12} - 10^{14} g of coronal material with apparent velocities between 10 and 400 km/s (Shibata, Yokoyama and Shimojo, 1994). Shibata, Nozawa and Matsumoto (1992) proposed that the jet plasma is accelerated and heated by magnetic reconnection between emerging flux and the pre-existing magnetic field. Two types of such interaction have been observed (Shibata, Yokoyama and Shimojo, 1994; Shibata, 1998). Most frequent is the anemone type which exhibits vertical or oblique jets that usually occur when emerging flux appears in coronal holes. The other is the two-sided-loop type which occurs when emerging flux appears in a quiet region where the magnetic field is almost horizontal. In the latter case hot plasma is ejected along coronal loops away from both sides of the emerging flux.

Collimated flows of plasma (surges) have been observed in Hα filtergrams for many years. They are straight or slightly curved ejections of material stretching out from active regions. Hα surges last about 30 min and are recurrent with a period of one hour or more (Schmieder et al. 1995).

Kundu, Shibasaki and Nitta (1997) reported the first detection of microwave emission from X-ray jets using the Nobeyama Radioheliograph at 17 GHz. The 17 GHz emission was unpolarized and came mainly from the base and/or the lower part of the jets. Occasionally, the detection of microwave emission (Verma, 1986) associated with Hα surges has been reported.

In this paper, we study a large sample of X-ray jets and we compute the properties of the ejected plasma when possible. We also search for chromospheric ejecta (surges) that might have occurred during the time intervals that the X-ray images were available. We then compare the SXT and/or Hα information with images of the jets obtained with the Nobeyama Radioheliograph at 17 GHz. The SXT is most sensitive to hot plasma above 2×10^6 K, whereas the microwave observations can be sensitive to cooler material as well. Thus, in principle, the radio images of the jets could provide information on the physical conditions of the jets that is not available from the SXT images.

2. Observations and Data Reduction

The methodology of our study was to choose time intervals during which the Yohkoh SXT observed X-ray jets. We used 18 different jet events which occurred from July 1992 to December 1994. The X-ray observations were made with the thin aluminium (Al 1265 Å) and the "sandwich" (Al/Mg/Mn) filter and they were taken either in the partial-frame mode or in the full-frame mode. The full frame images were used only in cases when jets were not recorded in the partial frame images. We have calculated the electron temperatures and emission measures of the jets. Since the jets undergo rapid changes, the evaluation of the plasma parameters derived by the filter ratio method for the full-frame images (FFIs) must be done very carefully (Shimojo et al. 1998). In our analysis, we did not consider the FFIs that were observed more than 2 min apart from one another. For the rest of the FFIs, we computed the plasma parameters for the time of each Al (sandwich)-filter image using both the previous and following Al/Mg/Mn (Al) images. In all cases, the uncertainties were larger than the uncertainties introduced by photon statistics. Only the cases in which the two pairs of the computed plasma parameters at a given time, agreed within a factor of 2 were used in our study. We also searched for Hα surges that might have occurred during the periods when X-ray images were available. Our Hα dataset revealed only one surge which occurred on October 2, 1993.

The Nobeyama Radio Heliograph (NoRH) observations at 17 GHz were made with a spatial resolution of $10''$ and a temporal resolution of 0.5-1 min. We produced full disk maps at 17 GHz, corresponding to the times of the soft X-ray jets of our collection.

3. Results

3.1. *General properties of jet-associated radio emission*

Our sample contained one two-sided loop type jet which was observed on July 22, 1992. All the others were either vertical or oblique jets. Most of the jets (13 of the 18) were associated with small flare-like events at their footpoints (see also Shimojo et al. 1996). None of these events triggered the flare mode of the SXT. Microwave emission was observed in the majority of the X-ray jets (more than 75%, see also Kundu, 1998; Kundu, Shibasaki and Nitta, 1997, who refer to the same sample). The radio emission was associated either with the base of the jets or with the base and the lower part of the jets. We should point out that microwave emission was detected at the base of all jets, but one, which exhibited X-ray intensity enhancement at their footpoints. Three of the four jets that were not associated with radio emission, did not show any flare-like activity at their footpoints. All the jets with no detectable microwave emission were small events with apparent projected lengths between 1.75×10^4 and 4.8×10^4 km. We note that the average length of 100 jets studied by Shimojo et al. (1996) was 1.5×10^5 km while the length of the larger jets of his sample was 4×10^5 km. However, even in these cases, the jet plasma might have emitted 17 GHz emission which was below the detection threshold of the NoRH. The same argument is also true of the absence of radio emission from the upper part of all X-ray jets of our sample.

The 17 GHz jet emission was unpolarized and in most cases gradual. These features suggest that the 17 GHz emission was thermal. In a typical impulsive flare we would expect the nonthermal emission at 17 GHz to be stronger than any thermal free-free component. Of course, we cannot exclude the possibility that nonthermal emission was present but relatively weak, due either to a low turnover frequency in the radio spectrum or to a particularly steep radio spectrum at high frequencies.

The computed electron temperatures and emission measures of the jets were used for the prediction of radio flux from the observed soft X-ray-emitting material on the basis of thermal free-free emission. For the events which

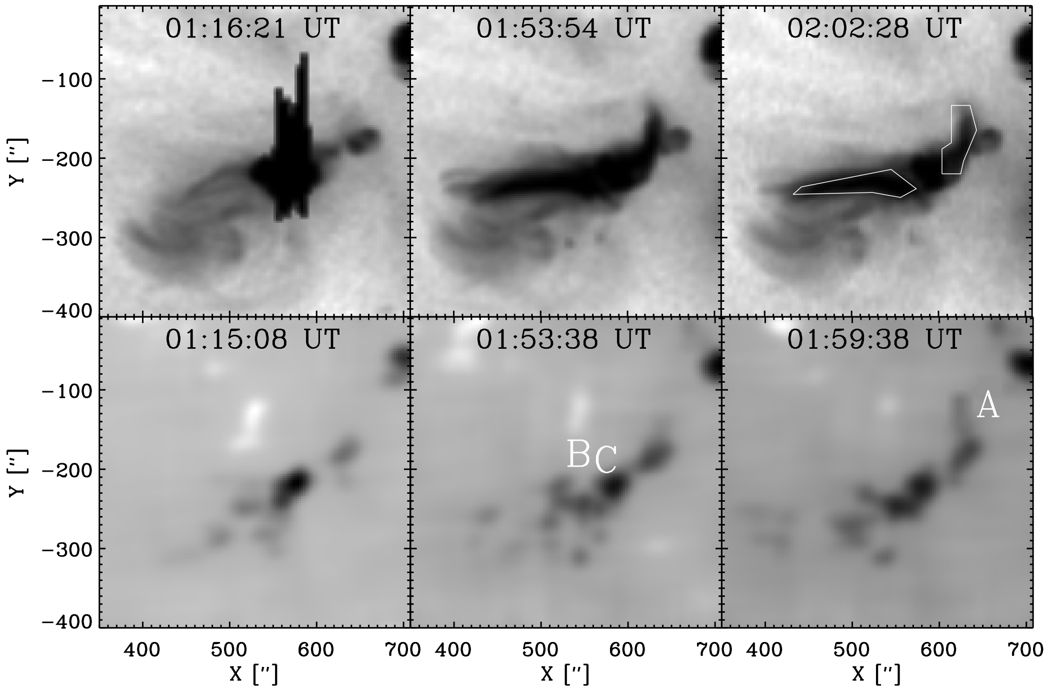

Fig. 1.. The July 22, 1992 two-sided-loop type jet. Top row: SXT images of the jet extracted from full-frame images of the Sun (negative display). Bottom row: the corresponding NoRH 17 GHz emission (negative display). All SXT images presented in this paper have been obtain with the thin Aluminium filter. In this and subsequent solar images the axes labels indicate seconds of arc from the center of the disk. The boxes indicate the regions we used for the computation of the X-ray flux from sources A and B. Solar north is up and solar east to the left.

showed X-ray base enhancement and radio emission from the base of the jet only, the predicted radio flux can be compared directly to the observed radio flux from the jet base. We computed reliable plasma parameters for two such events. The predicted fluxes were in agreement with the observed fluxes. In two other cases, the predicted radio fluxes associated with the lower parts of the jets were well below the observed radio fluxes (see below).

3.2. The July 22, 1992 jet

The jet occurred about 270″ northeast from the small sunspot of active region NOAA 7235, in a region where relatively weak loop emission was observed by SXT. The first SXT image was obtained at 01:16 UT (upper left frame of Figure 1) and clearly shows enhanced X-ray emission associated with the dominant radio component. The next SXT frame was obtained at 01:53 UT and shows the two-sided-loop type jet: it seems that the region flared up due to the emergence of new flux and subsequently hot plasma was ejected along coronal loops away from both sides of the emerging flux. The NoRH images show the microwave counterparts to the ejected hot X-ray-emitting material (the sources A and B in Figure 1). The flux of these sources was rising while that of component C (which was associated with the emerging flux) decayed.

Only the electron temperatures and emission measures computed for the 01:53 UT frame satisfied the criteria that we defined in section 2. The computed temperatures and emission measures for the two sides of the jets were $4.6 \pm 1.3 \times 10^6$ K and $7.0 \pm 1.6 \times 10^{45}$ cm^{-3}, respectively. The predicted 17 GHz emission for the emerging flux area is in agreement with the observed microwave flux. However, the predicted radio fluxes for both sides of the jet are 18-40 times lower than the corresponding observed fluxes: the predicted 17 GHz fluxes were 0.007 ± 0.002 SFU while the observed fluxes of each side of the jet were about 0.18 SFU. For comparison, we note that at the time of the first SXT image (01:16 UT), the corresponding observed fluxes were 0.03 SFU. These large discrepancies may be due to a lower temperature plasma which cannot be detected by the SXT but is sensitive to microwave free-free emission. Unfortunately, no Hα data were available, so we cannot determine whether the additional cooler material was chromospheric or came from the chromosphere-corona transition region. The apparent velocity of the radio source A (western jet) was about 55 km/s. This velocity is close to the lower end of the observed velocities of Hα surges (40-100 km/s, see Zirin, 1988).

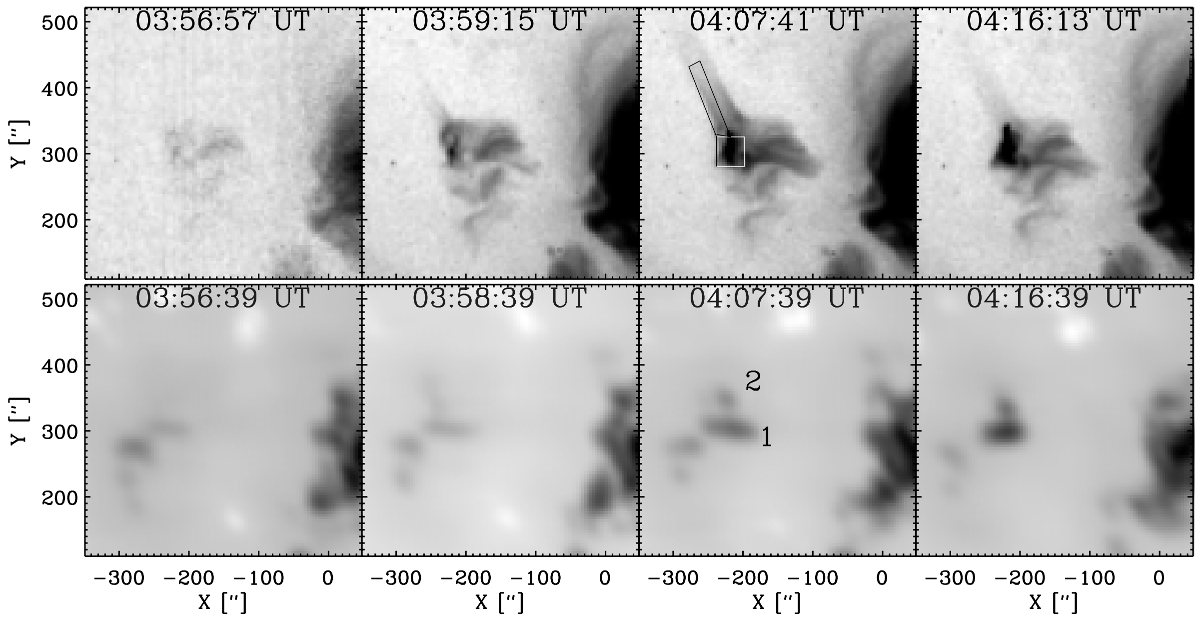

Fig. 2.. Same as in Fig. 1 for the February 9, 1993 anemone-type jet. The boxes indicate the regions we used for the computation of the X-ray flux from the base of the jet and the eastern part of the jet.

3.3. The February 9, 1993 jet

This anemone-type jet occurred about 220″ east of active region NOAA 7417. No partial-frame SXT images were available. The exposure time of the first SXT frame was only 78 ms but it shows some weak loop-like X-ray emission (near the center of the upper left frame of Figure 2). The associated microwave emission is very low. At 03:59 UT, the X-ray emission from that region increased considerably and there is evidence of plasma ejection from its northeast edge but the radio emission is still insignificant. At 04:07 UT, the X-ray emission from the footpoint of the jet as well as the emission of the collimated jet itself increased further. At the same time the microwave emission consists of two components: one is associated with the footpoint of the jet (source 1 in Figure 2) and the other with the lower east part of the jet (source 2 in Figure 2). There is no radio emission associated with the west part of the jet. The last available SXT image shows that the collimated plasma emission has decayed but the footpoint emission is still strong. The 17 GHz jet-associated emission reached maximum values at the final stages of the X-ray jet.

We computed the electron temperatures and emission measures for the 04:07 UT SXT image. The computed temperature and emission measure for the lower part of the eastern side of the jet were $6.0 \pm 1.1 \times 10^6$ K and $1.3 \pm 0.4 \times 10^{46}$ cm^{-3}, respectively. The predicted and observed fluxes for the footpoint of the jet are consistent, given the large uncertainties involved. However, the predicted radio flux for the east part of the jet at 4:07 UT is 10-22 times lower than the observed flux: the predicted 17 GHz flux was 0.013 ± 0.005 SFU while the observed flux was about 0.19 SFU. For comparison, we note that at the time of the first SXT image (03:57 UT), the corresponding observed flux was 0.01 SFU. Again, we may interpret this disagreement in terms of the presence of a cooler temperature material which cannot be seen by the SXT. The predicted fluxes for the west part of the jet at 04:07 UT are below the NoRH detection limit. It seems that the additional cooler material was present only at the eastern part of the jet at least since 04:07 UT. If we attribute the entire microwave flux to cooler material not detectable by the SXT then the flux of the cool jet reaches a maximum value about 10 min after the X-ray maximum. Schmieder, Golub and Antiochos (1994) reported a case where the chromospheric Hα plasma was delayed by 3-4 min with respect to an X-ray brightening.

3.4. The October 2, 1993 Hα surge

An Hα surge occurred on October 2, 1993 southwest of the sunspot of active region NOAA 7590 (see Figure 3). The SXT images (partial frame mode) showed no X-ray trace of the surge activity. The NoRH images show a strong component ($T_b \sim 10^5$ K) associated with a sunspot and a diffuse component associated with the plage and/or loop emission. We searched for microwave signatures of the surge after we subtracted out the stable active region emission using the running difference image technique. At the onset of the Hα surge, the NoRH difference image shows a

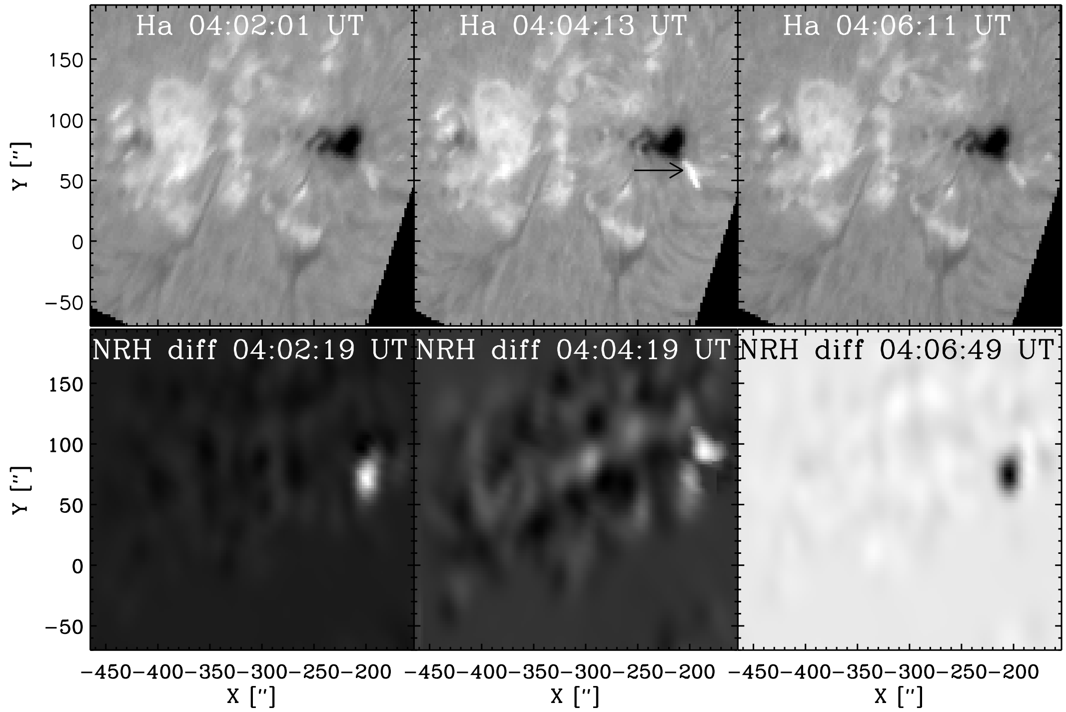

Fig. 3.. The October 2 1993 Hα surge. Top row: Hα images from Hiraiso Solar Observatory. At 04:04:13 UT the surge (indicated by the arrow) reached its maximum intensity. Bottom row: 17 GHz running difference images. Each difference image was produced by subtracting the previous NoRH image from the image recorded at a given time.

strong source associated with the base of the surge. At about 04:04 UT, during the peak of the surge activity, the strongest source of the difference image map was associated with an expanding loop, northwest of the sunspot. At 04:06 UT, the difference image reflects the decay of the original source associated with the base of the surge but the intensity of the loop-associated source has not changed significantly.

From the SXT images, we computed the coronal plasma parameters at the location of the surge. At the time of maximum surge activity, we found $T_e = 2.8 \times 10^6$ K and $EM = 5.0 \times 10^{45}$ cm^{-3}. The predicted 17 GHz emission on the basis of free-free mechanism is only 0.006 SFU whereas the observed microwave flux of the surge source was 0.18 SFU. The large discrepancy cannot be interpreted in terms of gyroresonance emission because the surge-associated microwave component was practically unpolarized. We point out that the 17 GHz gyroresonance emission, if present, is usually highly polarized because the magnetic field is strong enough to bring the third harmonic of the gyrofrequency in the low corona giving high extraordinary-mode emission but practically no ordinary-mode emission because the second harmonic is still below the transition region (our stable sunspot-associated component, for example, showed 85% polarization). The additional flux may come from a low temperature plasma which cannot be detected by the SXT but produces strong microwave free-free emission. If we attribute the entire radio flux of the surge component to chromospheric material, we get an upper limit for the density of the surge. Given that the SXT is not sensitive to plasma with $T_e < 2 \times 10^6$ K then EM$< 1.6 \times 10^{47}$ cm^{-3}. If the width of the surge source is equal to its apparent size (about 25″), we get $N_e < 6.1 \times 10^{10}$ cm^{-3}.

4. Conclusions

Microwave emission was detected from more than 75% of the X-ray jets. The radio emission was associated either with the base or with the base and the lower part of the jets. We detected radio emission from all, but one, jets which showed flare-like activity at their footpoints. The light curves of microwave jet emission were gradual and unpolarized implying that the emission was thermal. The general properties of the microwave emission associated with the X-ray jets are consistent with the results presented by Kundu, Shibasaki and Nitta (1997).

When possible, we computed the electron temperatures and emission measures of the X-ray-emitting jet plasma. Our computations are in general agreement with the results derived from another data set by Shimojo et al. (1998). We used the computed X-ray plasma parameters to derive the predicted 17 GHz fluxes on the basis of thermal free-

free mechanism. In these computations, it is always important to remember that different coronal heights contribute differently to the microwave and X-ray emissions. For the events which showed enhancement of the X-ray jet base emission and radio emission from the base of the jet only, the predicted radio fluxes were in agreement with the observed ones. This result is consistent with the study of active region transient brightenings at 17 GHz by White et al. (1995).

We found two cases when the predicted free-free fluxes were well below the observed radio fluxes. One event (July 22, 1992) was a two-sided-loop type jet and the other (February 9, 1993) was an anemone-type jet. Both events were among the largest of our collection. Since the SXT is sensitive to hot plasmas above 2×10^6 K, we interpreted the large discrepancies in terms of lower temperature plasmas which cannot be detected by SXT but produce microwave free-free emission. In both cases the lower temperature material was associated with the lower part of the jets. We found no evidence for the presence of any cooler plasma at the base of the jets that we studied. Because of the absence of Hα data for these two events, we have no clues whether the origin of the lower temperature material was chromospheric or came from the transition region. The simulations by Yokoyama and Shibata (1996) predict the existence of cool jets which are adjacent to hot coronal jets for the anemone-type jets as well as for the two-sided loop type jets. Our observations provide the first direct confirmation for the existence of such two-sided-loop type jets. We also derived, when possible, observable quantities of the lower temperature plasma detected by NoRH which are in agreement with chromospheric studies of Hα ejecta. Indeed, the apparent velocity of the source associated with the western side of the two-sided-loop jet was 55 km/s. Using NoRH data, Gopalswamy et al. (1996) observed plasma flow of material which was not detected with the SXT, along a large-scale loop structure. The velocity they measured was at least 60 km/s. The February 9, 1993 radio jet reached maximum, 10 min after the X-ray maximum. The number of cases that cooler material was detected (2 out of 18) should be considered as a lower limit. Some of the other jets may emit weak microwave emission which comes from a lower temperature plasma but it is below the detection threshold of NoRH.

Our search for Hα surges during the time intervals when the X-ray images were available, revealed one surge which was not related to any X-ray jet. But the NoRH difference images clearly detected a source associated with the footpoint of the chromospheric surge. The flux of that source was almost 30 larger than the predicted flux from the SXT plasma parameters. The observed properties of this source ruled out both nonthermal processes and the gyroresonanse mechanism from the third harmonic of the gyrofrequency. The former was ruled out because the time profile of the source showed a gradual rise and fall while the latter was discarded because the source was unpolarized. The emission mechanism was free-free radiation from the chromospheric surge material which was not detected by the SXT. If we assume that the SXT cannot see plasma below 2×10^6 K then we get an upper limit for the density of the surge, $N_e < 6.1 \times 10^{10}$ cm^{-3}. The three cases which are presented in detail in this paper show that the microwave observations are a powerful plasma diagnostic that can provide useful information not available from SXT observations.

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