CORONAL TRANSIENTS IN RADIO AND X-RAYS

MUKUL R. KUNDU
Department of Astronomy, University of Maryland, College Park, MD USA

September 23, 1996

Abstract. We present a summary of several studies of transient coronal phenomena based upon high spatial resolution radio imaging data along with Yohkoh SXT and HXT observations. In addition to normal flares the studies also involve such exotic events as active region transient brightenings (ARTB) and coronal jets and bright points. We provide evidence of nonthermal processes in flaring X-ray bright points from spatially resolved meter-wave data, existence and propagation of type III burst emitting electrons in coronal jets, radio signatures of ARTB's, and beaming of electrons producing microwave and hard X-rays. The implications of these observations are discussed.

1. Introduction

A close connection between the energetic electrons emitting microwaves and hard x-rays has been known to exist for a long time. This connection is manifested in two forms: the similarity of the intensity profiles in the two spectral domains (e.g. Kundu 1961), and a single flaring loop as the source for both hard x-ray and radio emission, regardless of whether the microwave source is located at the loop top (e.g. Marsh & Hurford, 1981) or at the foot points (e.g. Shevgaonkar & Kundu, 1984). The hard x-ray source is generally at the foot points. Hoyng et al. (1983) described an event observed with SMM, in which they concluded that the microwaves (2 cm wavelength) came from the loop top and the hard x-rays ($\leq 32keV$) from the foot points. However, their conclusion cannot be generalized. Prior to the launch of Yohkoh, there were few published studies of microwave and hard x-ray sources using simultaneously obtained imaging data; the availability of HXT images has increased the number of studies in this area, but we still have no clear picture of the location of the hard x-ray source relative to the microwave source in a flaring loop.

The hard X-ray properties of flares have been discussed recently by Sakao (1994) using Yohkoh/HXT data: (1) during the impulsive phase, a source in hard X-rays ($> 33keV$) is observed on each side of a magnetic neutral line, suggesting that they are the foot points of a single flaring loop; (2) hard X-ray emission from the two sources varies simultaneously to within 0.1 seconds at the 1 sigma level, strongly supporting the idea that hard X-rays ($> 30keV$) are emitted from near the footpoints of a flaring loop by energetic electrons streaming downward from near the top of the loop; (3) the footpoint sources often show asymmetry in hard X-ray emission, the

Astrophysics and Space Science **243**: 15-22, 1996.

brighter source being located in a weaker magnetic field region than the weaker (or less bright) source. This suggests that the brighter footpoint has higher electron precipitation due to weaker magnetic field convergence which permits more electrons to reach the chromosphere than at the stronger-field footpoint. It is important to know the relationship of radio properties to these HXR properties. However, microwave imaging data simultaneous with HXT data with comparable spatial ($\sim 5"arc$) and temporal (0.5 sec) resolution have been available only recently.

In this paper, we study two radio events observed simultaneously with the Yohkoh/HXT experiment and at 17 GHz with the Nobeyama Radioheliograph (NRH). We also discuss the radio emission associated with some other coronal transients, namely active region transient brightenings and coronal X-ray jets and flaring bright points.

2. Microwave and Hard X-ray Observations of Footpoint Emission from Solar Flares

A popular model for impulsive solar flares is the thick target-loop model, in which nonthermal electrons accelerated in a coronal loop precipitate into the chromosphere at the loop footpoints. We present data for two events in which radio and hard X-ray images suggest such a sequence of events (Kundu et al. 1995a). The events were observed on May 28 and 30, 1993 by the hard X-ray imaging telescope (HXT) on the Yohkoh spacecraft, and by the Nobeyama 17 GHz radioheliograph. One event (May 30, 1993) was also observed with the SXT experiment (data were not available for the other event). Both events at 17 GHz were spiky in their impulsive phase which was of short duration ($\sim 1min$); they were strongly polarized, degree of polarization being 30% or higher. In one case (May 28, 1993) bipolar structure with two footpoint sources of opposite polarity was observed at 17 GHz. These oppositely polarized sources observed in the May 28, 1993 event coincide in position with the double "footpoint" sources observed with the HXT experiment in the high energy bands up to M2 (Fig. 1). For the May 30, 1993 event the 17 GHz flaring source is elongated at one end, where the weaker HXT source is; it is unipolar (degree of polarization, 45%). These results for May 30 are consistent with an asymmetric magnetic structure in the flaring loop; the stronger HXT source is located above the weaker magnetic field (with no 17 GHz source at this location because of weaker magnetic field); the weaker magnetic field also leads to excess precipitation of energetic electrons resulting in a stronger HXR source. This is the first reported identification of a bipolar microwave flaring source with the two polarities co-spatial with the two "footpoints" of the HXR source.

https://doi.org/10.1017/S0252921100029900 Published online by Cambridge University Press

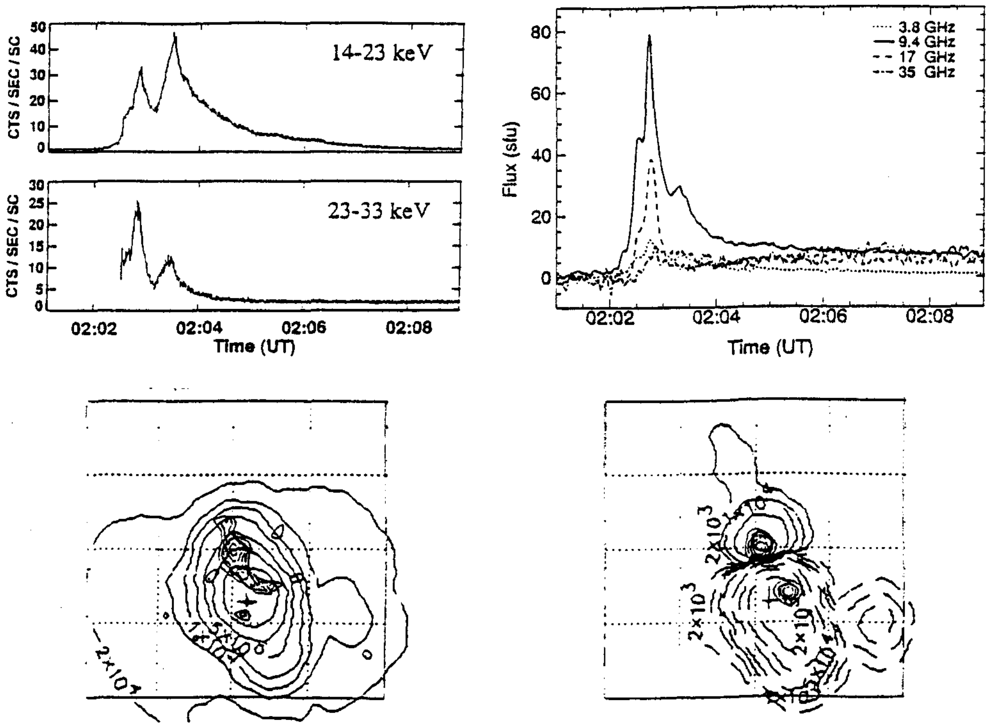

Fig. 1. Figure 1: (Top) The time profiles of the 1993 May 28 flare as seen in hard X-rays (HXT L and MI channel data, left panel) and radio (Toyokawa patrol data, right panel). (Bottom) NRH 17 GHz images of the 1993 May 28 two-footpoint flare, overlaid on HXT hard X-ray images. The left panel shows the 17 GHz total intensity image (heavy contours) overlaid on the L channel (14 - 23 keV) HXT image at 02:03:28; the right panel shows the circular polarization map at 17GHz (solid broken heavy contours overlaid on the HXT M2 channel (33 - 53 keV) image at 02:02:43. Note that the two oppositely polarized 17 GHz sources coincide with the two "footpoints" in the M2 hard X-ray image. FOV, 5′ x 5′.

The SXT observations of May 30 indicate that at least two flaring loops participated in the SXR emission. Two foot point sources clearly brightened up in the course of the flare. This suggests that soft x-ray emission at these points could be an extension of the hard x-ray emission occurring at the same locations.

3. Active Region Transient Brightenings (ARTB's)

The observation of transient microwave (2 cm) brightenings using the Very Large Array and their relationship with brightenings in Soft X-rays observed simultaneously by the Yohkoh satellite was first reported by Gopalswamy et al. (1994). They found that the peak flux of the microwave brightenings was smaller than the previously reported fluxes by two orders of magnitude. The microwave sources were highly polarized (up to 100%) and were situated on the periphery of a sunspot umbra. Among the many transients observed in X-rays and microwaves, two were observed simultaneously. The microwave sources were found to be closer to the umbra than the X-ray sources in projection; they appeared to be located at the footpoints of the loop-like X-ray transients. The conclusion was that the increase in emission measure accompanied by a small scale heating could account for the X-ray brightening. The microwave emission could be interpreted as due to thermal gyroresonance or nonthermal gyrosynchrotron process during the X-ray brightening. The magnetic field in the microwave source region was found to be 1200-1800 G.

White et al. (1995) made a search for radio emission from active-region soft X-ray transient brightenings identified in Yohkoh SXT observations of active region AR 7260. In four events 17 GHz radio emission was clearly detected by the Nobeyama Radioheliograph. The time profiles of the 17 GHz data were very similar to those of the soft X-ray fluxes, and the 17 GHz flux was very close to that expected from plasma with the temperature and emission measure derived for the soft X-ray-emitting material from filter ratios. No impulsive nonthermal radio emission was detected from any of the four events, although each was at least GOES class B1 in soft X-ray size. Weak hard X-rays may have been detected by GRO/BATSE from the strongest of the events, but not from the two others. These negative results leave open the possibility that there is a difference between active region transient brightenings and solar flares, in that the former do not convert a significant amount of the released energy into accelerated electrons.

In contrast to Gopalswamy et al.'s results which show that radio brightenings occurred in the penumbra of a large sunspot, and were very highly circularly polarized (up to 100%), White et al.'s observations generally involved brightenings in loops away from sunspots and were unpolarized (Fig. 2). The majority of the VLA radio brightenings were not associated with soft X-ray increases measured by GOES. Radio emission at 17 GHz has a peak flux which matches that expected from thermal bremsstrahlung in a plasma with the derived (from SXT filter ratios) temperature (typically $6 - 7 \times 10^6 K$) and emission measure of the soft X-ray-emitting material.

4. Nonthermal Radio Emission from Coronal X-ray Bright Points and Jets

X-ray bright points (XBPs) have been known since the Skylab days. Yohkoh/SXT (Tsuneta et al. 1991; Strong et al. 1992), provided more spectacular examples of XBPs and flaring XBPs. In particular SXT revealed that flaring XBPs

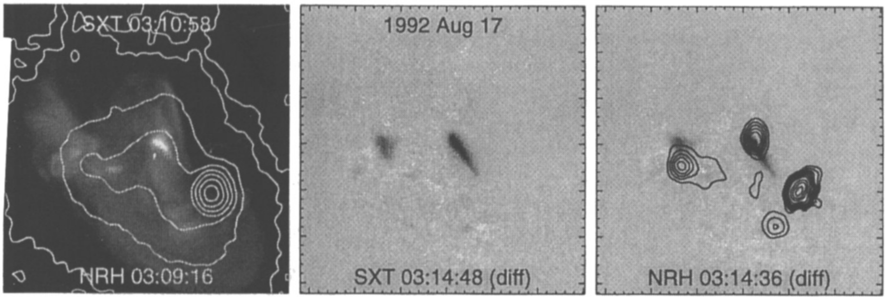

Fig. 2. Figure 2: Overlays of NRH 17 GHz radio images and Yohkoh SXT soft X-ray images (thin Al filter) for one ARTB discussed by White et al. (1995). The first panel shows pre-brightening images in soft X-rays (grey-scale, square-root intensity display) and 17 GHz (contours) overlaid. The middle panel shows the difference of the SXT image corresponding to the time given by the label, and the SXT image in the first panel. The rightmost panel shows the same SXT difference image overlaid with contours of the Nobeyama 17 GHz difference image. The 17 GHz brightness-temperature contours in the left-hand panel are at 9, 10, 15, 20, 30, 50, 90, 160, 280x $10^3 K$, and in the right-hand panels the contours are at 4, 6, 8, 10, 12, 15, 18, 21, 25, 30, 40, 50, 70, and 90 x $10^3 K$. The axes are labelled in arcseconds north-south and east-west from apparent disk center at the time of the images.

sometimes have jets associated with them. The SXT has revealed many other jet-like features, i.e., a transitory X-ray enhancement with an apparent collimated motion. Their motion appears to be a real flow of plasma. The coronal X-ray jets are among the most interesting discoveries (Shibata et al. 1992) made of the dynamical behavior of the corona. In many cases, jets are associated with small flares at their footpoints.

The typical size of a jet is 5 x $10^3 - 4$ x $10^5 km$, the translational velocity is $30 - 300 kms^{-1}$, and the corresponding kinetic energy is about $10^{25} - 10^{28}$ erg. Many of the X-ray jets are associated with flares in X-ray bright points (XBPs), emerging flux regions (EFRs), or active regions (ARs).

Kundu et al. (1994) provided the first conclusive evidence of nonthermal processes occurring in flaring XBP's identified in the Yohkoh Soft X-ray data and the occurrence of type III bursts from Nancay (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 pre-existing 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 low down 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.

https://doi.org/10.1017/S0252921100029900 Published online by Cambridge University Press

Kundu et al. (1995b) extended this study of nonthermal radio emission using the Nancay Radioheliograph data at metric wavelengths to the observations of coronal jets. They found evidence of nonthermal radio emission in the form of type III's associated with several coronal jets reported by Shibata et al. They reported a type III burst associated with a unique XBP-ejected coronal jet. The coronal jet event was observed by Yohkoh/SXT on August 16, 1992 between the times 12:30 and 12:45 UT. This intensity increase in soft X-rays was associated with a type III burst observed with the Nancay radioheliograph (Fig. 3). Two other jet-radio events were observed by Raulin et al. (1995) on December 6, 1991 and April 21, 1992. The intensity increases during these jet events were associated with type III bursts observed with the Nancay radioheliograph.

Figure 3 shows the excellent spatial association of the type III bursts with the jets. The locations of type III sources at 236 and 164 MHz are indicated in the figure. Note that the 164 MHz position is located on the extension of the jet (that is, the jet is not quite visible at that point). The type III bursts had brightness temperatures of $Tb \sim 10^7 - 5$ x $10^8 K$ depending upon the frequency, and they were polarized in the range 0 - 10 percent.

Most jets are associated with small flares with apparent average velocity of $\sim 190 km/s$. A significant fraction of the jets occur in the same region and time as $H\alpha$ surges. Generally the temperature of the jets lies in the range $4 - 6$ x $10^6 K$. Since the background temperature is $3 \sim 5MK$, this implies a temperature increase in the jet of ~ 1.25 above the background. However, the density in the jet increases to > 3 times above the background. For the Aug. 16, 1992 jet, the computed parameters are $Te \sim 6MK$; Ne (top of jet) $\sim 7\ 10^8 cm^{-3}$, base of jet $\sim 3\ 10^9 cm^{-3}$, BP $5\ 10^9 cm^{-3}$; EM (top of jet) ~ 1 x $10^{44} cm^{-3}$, base $\sim 2.0\ 10^{44} cm^{-3}$, BP $\sim 8\ 10^{44} cm^{-3}$. The electron density derived from the type III burst (on plasma radiation interpretation) is ~ 7 x $10^8 cm^{-3}$, in good agreement with SXR derived value.

It has been known from observations of limb flares at meter wavelengths that type III emitting electrons propagate along radio structures corresponding to coronal streamers of higher than ambient electron 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 drift from high to low frequencies with speeds of $\sim 1/3c$. The association of type III bursts with coronal jets on the disk show that it is a general situation for type III electrons to propagate in dense coronal structures. The existence of type III's would suggest the acceleration of electrons to speeds of $\sim c/3$ along with the plasma flows. Thus along with the heating responsible for the soft X-ray jet, electrons of several tens of Kev energy are generated which emit plasma radiation in the form of type III's.

The identification of the type III emission with the jet suggests several additional ideas. First, the location of the low frequency type III bursts

https://doi.org/10.1017/S0252921100029900 Published online by Cambridge University Press

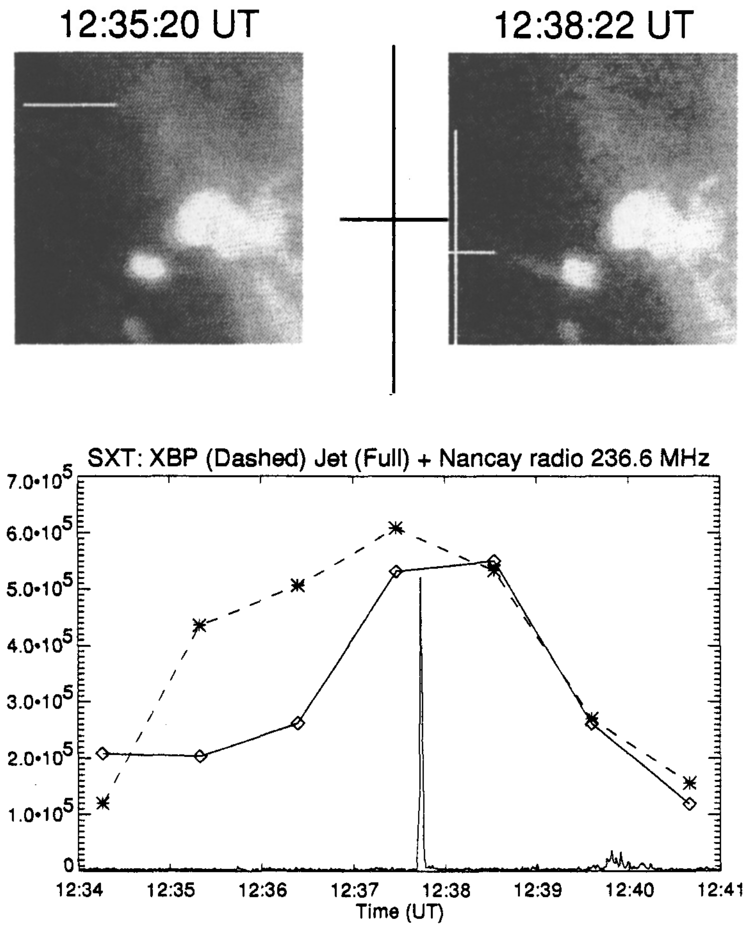

Fig. 3. Figure 3: Soft X-ray images of the jet of August 16, 1992. The two upper panels show the pre-jet ejection image (left) and the maximum of enhancement of jet emission (right). The bottom panel shows the time profiles of the XBP (crosses), the X-ray jet (diamond) and of the type III bursts at 236.6 MHz. The horizontal bar on upper left image represents 1 arcmin.

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. This also 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. Secondly, the continutiy of jet structure opens the possibility that the electron acceleration may take place considerably lower than the altitude corresponding to the starting frequency of the type III emission. Thirdly, 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. Indeed, at the location of the type III at 236 MHz there is good agreement between the electron density derived from the type III burst observation (on the plasma radiation interpretation) and that derived from the SXT observations (7 x $10^8 cm^{-3}$).

Acknowledgements

This research at the University of Maryland was supported by NSF grant ATM 93-16972 and NASA grant NAGW-1541.

References

Gopalswamy, N., Payne, T. E. W., Schmahl, E. J., Kundu, M. R., Lemen, J. R., Strong, K. T., Canfield, R. C. and de La Beaujardiere, J.: 1994, *Ap. J.* **437**, 522

Hoyng, P., Marsh, K. A., Zirin, H. and Dennis, B. R.: 1983, *Ap. J.* **268**, 865

Kundu, M. R., Nitta, N, White, S., Shibasaki, K., Enome, S., Sakao, T., Kosugi, T. and Sakurai, T.: 1995a, *Ap. J.* , in press

Kundu, M. R., Raulin, J. P., Nitta, N., Hudson, H. S., Shimojo, M., Shibata, K., and A. Raoult: 1995b, *Ap. J. Lett.* , in press

Kundu, M. R., Strong, K. T., Pick, M., Harvey, J. N., Kane, S. R., White, S. M., Hudson, H. S.: 1994, *Ap. J. Lett.* **427**, L59

Kundu, M. R.: 1961, *J. Geophys. Res.* **60**, 4308

Marsh, K. A. and Hurford, G. J.: 1980, *Ap. J. Lett.* **240**, L111

Sakao, T.: 1994, 'A New Look At the Sun' in S. Enome and T. Hirayam, ed(s)., *Proc. Kofu Symposium*, India, p. 169

Shevgaonkar, R. K. and Kundu, M. R.: 1985, *Ap. J.* **292**, 733

Shibata, K., Ishido, Y., Acton, L. W., Strong, K. T., Hirayama, T., Uchica, Y., Mc Allister, A. H., Matsumoto, R., Tsuneta, S., Shimizu, T., Hara, H., Sakurai, T., Ichimoto, K., Nishino, Y., Ogawara, Y.: 1992, *Publ. Astron. Soc. Japan* **44**, L173

Strong, K. T., Harvey, K. Hirayama, T., Nitta, N. Shimizu, T., Tsuneta, S.: 1992, *Publ. Astro. Soc. Japan* **44**, L161

Tsuneta, S. et al.: 1991, *Solar Phys.* **136**, 37

White, S., Kundu, M. R., Shimizu, T., Shibasaki, K. and Enome, S.: 1995, *Ap. J.* , in press