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X-RAY AND RADIO OBSERVATIONS IN THE INITIAL DEVELOPMENT OF AN X-CLASS SOLAR FLARE

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ABSTRACT

The EIT/SOHO and SXT/YOHKOH plasma ejecta accompanied by an unusual drifting radio continuum and early hard X-ray emission observed prior to the impulsive phase of the September 24, 2001, X-class flare are analyzed. The paper presents some of the first reported observations from the new Hard X-Ray Spectrometer instrument (HXRS), as well as imaging data from *Yohkoh* plus radio spectral observations in the decimetric band. The early hard X-ray observations revealed a soft spectrum that we interpret as non-thermal, located within loop structures observed in soft X-rays along the magnetic neutral line. The hard X-ray emission continued for more than one hour. In the initial phase of the flare, the hard X-ray emission arose in structures closely identifiable with the early soft X-ray loops, which appeared to evolve smoothly into the post-flare loop system of the flare maximum. At this time the decimeter spectra showed loosely-correlated spiky emission at frequencies consistent with the densities inferred from soft X-rays, but with rapid drifts implying motions along magnetic field lines.

Key words: X-ray, radio spectra, solar flares, initial phase.

1. X-RAY SPECTRA

The flare of 24 September 2001 (see Table 1) had an extraordinarily long development as seen in hard X-rays. In this paper we make use of data from the HXRS during the impulsive phase, and HXRS plus the imaging instruments on *Yohkoh* during the initial development. HXRS is a scintillation-counter spectrometer with 8 energy bands, covering the range 13-500 keV. Its unique feature is a gain-changing capability to allow it to respond to very large flares; this was not needed for the September 24, 2001 event discussed here. Its basic time resolution is 0.2 sec, its effective area 4.5 cm^2 for each of two detectors, and its entrance window 1.02 mm Al. It also has an onboard radioisotope calibration source (Am^{241}).The instrument was built in the Czech Republic and launched as a secondary payload on the Multispectral Thermal Imager. (see Fárník et al (2001)). We show in Figure 1 the HXRS photon fluxes for this event. These show an extraordinarily long-duration hard X-ray event beginning at about 10:10 UT; the *Yohkoh* observations extend the onset time back close to the beginning of the GOES event, but only in the L (13-23 keV) band of the Hard X-ray Telescope (HXT); flare mode and the full HXT four-channel spectra began only at about 09:45 UT. We note that the availability of the HXRS data greatly helps in this case to fill the gaps in the hard X-ray time series for such a long-duration event, when observed by satellites (such as *Yohkoh* and MTI) in low Earth orbits. The initial phase of the flare chiefly interests us here, since almost no hard X-ray observations of early flare development have been reported. Note that long-duration hard X-ray emission is expected for long-duration flares according to the Neupert Effect (Dennis and Zarro (1993)) and is also observed in flares with gradual onsets (Hudson and McKenzie (2000)).

`Table 1. Flare parameters`

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GOES class X2.6
H-alpha class 2B
GOES times 0930-1040-1139 UT
Location S16E23
NOAA region 9632
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The rapid variations seen in hard X-rays, and discussed below in the context of the decimeter variability, suggest the presence of particle acceleration. In principle thermal relaxation in a dense medium could also explain the rapid variability. The detection of these variations in the three lowest energy bands of the HXT instrument, with its relatively large effective area, gives us an opportunity to determine the spectrum during the earliest phase of the flare (09:45 - 10:18 UT). Table 2 shows the spectral estimates

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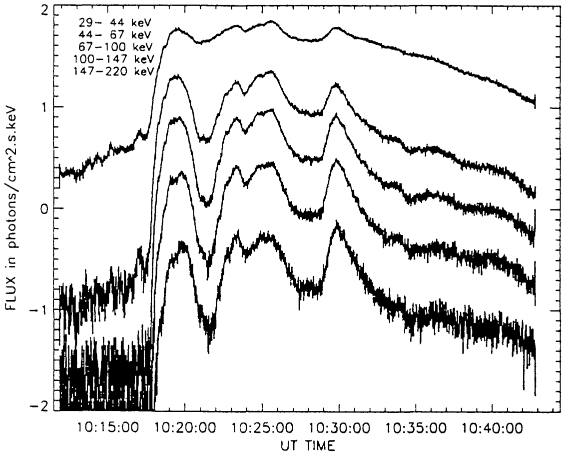

Figure 1. Hard X-ray observations of the flare of 24 September 2001, showing data from the Hard X-Ray Spectrometer (HXRS) on board the MTI satellite.

for the event at 10:04 UT. Here "slope" refers to the power-law coefficient γ in $F_{h\nu} = A(h\nu)^{-\gamma}$ photons (cm^2 sec keV)$^{-1}$, as fit to the counting rates of adjacent channels (Sato et al., (1998)).

Because of the weakness of this early phase, the determination of the background counting rates is somewhat uncertain, and this probably dominates the systematic error of the estimates. We note that the M2 band excess is only about 25% of the background rate at peak time. However we believe that the spectral estimates point clearly to a non-thermal bremsstrahlung model; the channel ratios (shown for adjacent pairs of channels in Table 2) are formally inconsistent with thermal models in any plausible temperature range, say below 6×10^7 K.

Table 2. Hard X-ray spectrum at 10:04 UT

HXT Channel	HXT Counts	Slope
13-23 keV	1.26	
23-33 keV	1.02	3.3
33-53 keV	0.25	5.5

2. X-RAY IMAGING, SOHO/EIT AND MDI OBSERVATIONS

Yohkoh missed the impulsive phase almost exactly, but obtained images after the return to daylight at about 10:58 UT. Figure 2 shows the location of a remarkable early plasma ejection, which appeared to move outward from the site of the early X-ray flare brightening. As often is the case (e.g. Hudson et al. (2000)), the flare ejecta take the form of loops moving outward in a direction apparently different from that of the arcade forming later. This flare does not provide a clean view of the arcade, but it can be seen in the right panel of Figure 2 to encompass not only the site of the ejection, but also the pre-flare active-region structure (left panel of Figure 2). Overlays of hard and soft X-ray images show that the hard X-ray brightening at 10:04 UT occurred in or close to the soft X-ray loops forming at that time, see Figure 3. The hard X-ray contours cannot be interpreted in detail because of the low flux at this time. The SOHO EIT data prior to the flare impulsive phase also show the plasma ejection in the bubble-form, see Figure 4, which display the difference image in the 195 Å band between 10:00 and 10:14 UT.

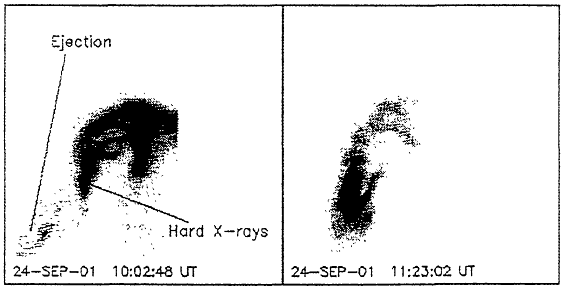

Figure 2. Early and late soft X-ray images at 5 arcsec pixel size, somewhat saturated. The image on the left captures a loop-type ejection moving to the SE away from the site of the hard X-ray source. On the right one sees the bright arcade, which includes the region of the pre-flare loops.

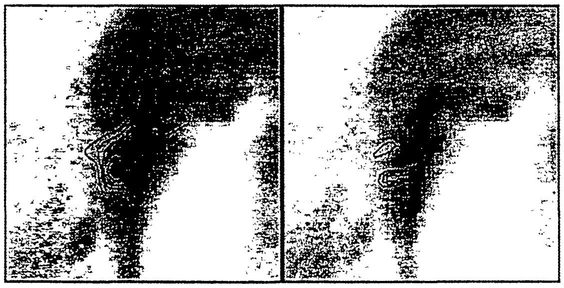

Figure 3. Soft and hard X-ray images at around 10:04 UT. Left, SXT image in the AlMg filter at 10:03:52 UT with 13-23 keV hard X-ray contours superposed; right, same image with 23-33 keV contours. The images are 2′29″ (114 Mm) across and have N up, W to the right. The minimum hard X-ray contour is 50% of peak brightness in each case.

3. RADIO OBSERVATIONS

The event was well-observed by the Ondřejov, Potsdam and WAVES/WIND spectrometers in a broad range of radio frequencies. Radio observations show interesting pre-flare processes starting at 9:22 UT, i.e. 55 minutes before the flare impulsive phase (10:17 UT). In radio data, fast-drift bursts were observed at 9:22:10-9:23:00 UT in the 0.8-1.3 GHz frequency range, and they were followed by an unusual

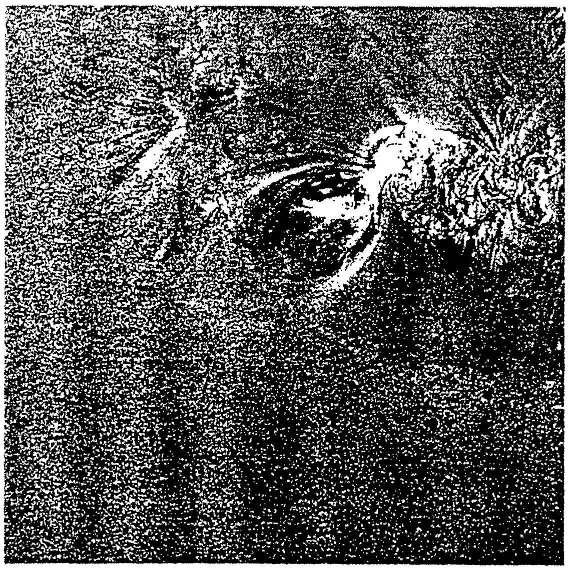

Figure 4. Difference image derived from the SOHO-EIT observations in 195 Å line at 10:00 and 10:14 UT. The expanding 'bubble' corresponds to the radio source observed by Nancay heliograph.

drifting radio continuum at 9:24-10:17 UT in the 400-40 MHz frequency range, see Figure 5. This drifting continuum is accompanied by several metric as well as interplanetary type III bursts observed by the WAVES/WIND spectrograph (see Figure 7). The frequency drift of the drifting continuum is -0.07 MHz s^{-1}. At the same times the Nancay radioheliograph shows the 327 and 164 MHz radio sources at positions southeast of the flare (in direction of the ejected SXT/YOHKOH loop), and where the EIT/SOHO bubble-form structure can be seen (Figure 4). Later on, just before the flare impulsive phase (10:00-10:17 UT) a new group of weak fast reverse drifting bursts appeared in the 0.8-2.0 GHz range (Figure 6) which were associated with the early hard X-ray emission. These radio bursts are limited only to the high frequency radio range and they have a positive frequency drifts of about 130 MHz $^{-1}$, which indicate that these bursts are generated in the closed magnetic field structures. As shown in Figure 6, the decimeter band reveals a swarm of fast-drift bursts prior to the main impulsive phase at about 10:18 UT. It is natural to ask if the time variability resembles that observed in soft and hard X-rays and described above. Unfortunately, as shown also in Figure 6, there is no detailed one-to-one correlation, although there are strong coincidences (e.g. for the 11:04 UT event shown in Figure 6 and discussed above. The data are too marginal for us to distinguish between flare-like brightenings, with a well-understood relationship between non-thermal and thermal effects, and some other process (as suggested for example by Warren and Warshall (2001) that may be happening in the early development of flare ribbons.

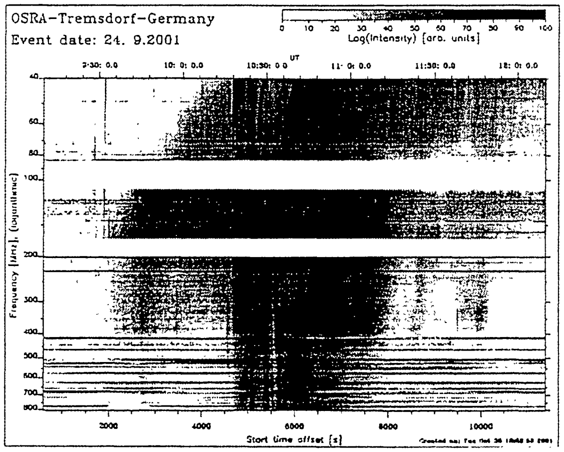

Figure 5. Dynamic spectrum from the Potsdam-Tremsdorf radiospectrometer, 40-800 MHz (courtesy Dr. A. Klassen).

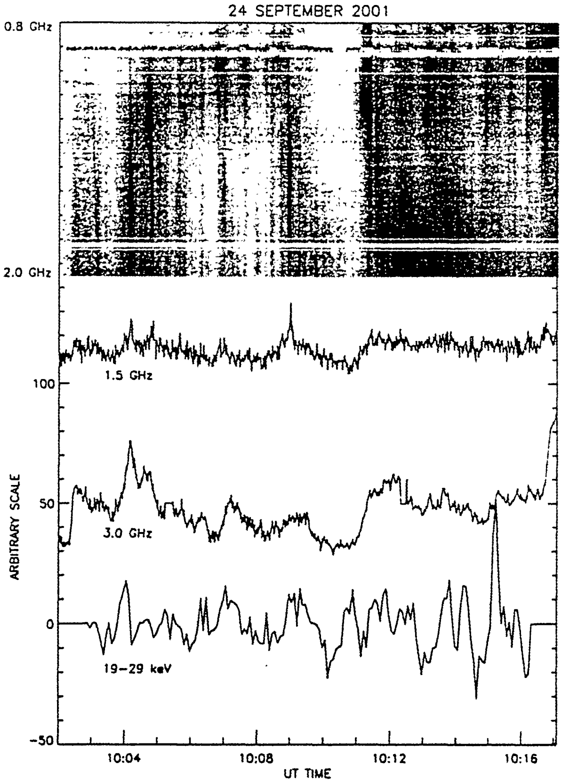

Figure 6. Dynamic spectrum from Ondřejov, 0.8-2.0 GHz, for the early development of the September 24 flare. The fine vertical streaks (fast-drift bursts) correspond to densities 1 - 4 × 10^{10} cm^{-3} on the plasma-frequency fundamental hypothesis (upper part). Light curves for the radio flux at 1.5 GHz and 3.0 GHz and the HXRS hard X-ray flux in the 19-29 keV band (lower part). The X-ray flux was high-pass filtered by subtracting the values smoothed in 200-sec window. There are obvious discrepancies in the comparison, but there are also obvious correlations (for example, the event at 11:04 UT discussed above).

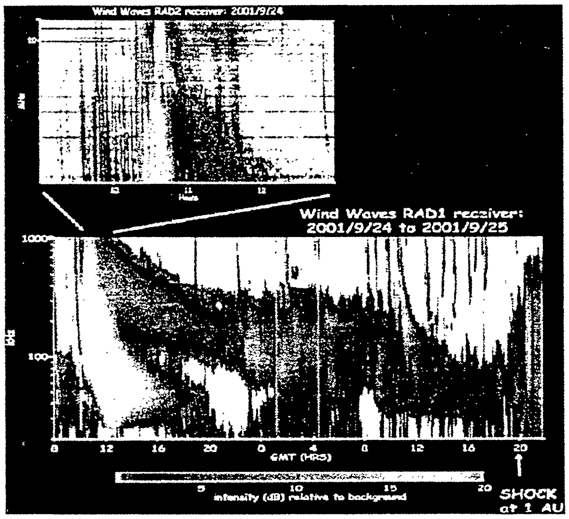

Figure 7. Low-frequency spectrogram from the WAVES experiment on board the WIND spacecraft, consistent with an extension of the decimetric fast-drift structures to the longest wavelengths.

4. DISCUSSION AND CONCLUSIONS

The processes which initiated the flare started about 55 minutes before the flare impulsive phase; plasma ejecta visible in both EIT and SXT images could be followed high into the corona. These processes were accompanied by an unusual drifting radio continuum in the frequency range of 400-40 MHz. The data suggest that small-scale non-thermal processes, including the acceleration of electrons to typical impulsive-phase spectra in the range 10-100 keV, precede the impulsive phase of this flare. These hard X-rays probably came from compact closed field regions at low altitudes. This is not unexpected, since we observed the plasma ejecta prior to the flare impulsive phase. These observations clearly link this kind of phenomenon to the possibility of particle acceleration, as revealed by the hard X-ray brightenings and by the fast-drift radio bursts. The fast-drift bursts appear to extend into the interplanetary medium, implying the participation of open field lines in the non-thermal activity related to early flare development. We note that this requirement stands in conflict with either "tether-cutting" (Moore and Roumeliotis, (1992); Canfield and Reardon, (1998)) or "breakout" (Antiochos, (1998)) reconnection models for flare initiation.

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