IMAGING DIAGNOSTICS OF SOLAR NON-THERMAL PARTICLES

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Abstract. Non-thermal hard X-ray, gamma-ray and radio emission are the most direct signatures of the presence of energetic particles in the solar atmosphere. This paper lays emphasis on hard X-ray and radio imaging data, obtained during and outside flares, which reveal the sites where particles interact with the ambient medium. These observations, which provide more or less direct information on the topology and dynamics of the magnetic structures in which particles are accelerated and propagate, are discussed in the framework of the "statistical flare" scenario.

Key words: Sun: Hard X-ray and radio emission – Sun: particle acceleration – Sun: fragmentation

1. Introduction

Energy release in the solar Corona leads to particle acceleration during and outside flares on time-scales ranging from a few seconds or less to hours and days. Possible acceleration and energy release processes have been recently reviewed in Melrose (1990) and Vlahos (1993). Most of the models developed so far involved the formation of large scale neutral sheets and/or spatially extended coronal shock waves. It is only since the last decade that new ideas have started to develop and led to the "statistical flare" concept (see Vlahos 1993, 1994). In this context, the primary energy release or acceleration process is fragmented: particles are accelerated on short time-scales ($\sim$ 10-100 ms) (Güdel and Benz 1990) in a multitude of small scale volumes ($\sim 10^{19}$ -10^{21} cm^3 ; e.g. Haerendel 1987) randomly distributed over larger scale volumes ($\sim 10^{28}$ cm^3).

Though there is a number of theoretical arguments why the primary acceleration process should be fragmented (Vlahos 1993, 1994), this idea is not yet clearly substantiated by observations with no spatial resolution. Indeed the detection of fast time fluctuations in hard X-ray (HXR) bursts (see Vilmer et al. 1994 and references therein) and of fine temporal and spectral structures in the mm-dm radio emission sometimes correlated with HXR's around 30 keV (Benz 1985; Correia and Kaufmann 1987; Aschwanden et al. 1990; Aschwanden and Güdel 1992) does not necessarly reflect the fragmentation of the primary acceleration process. Alternatively: (i) fast temporal variations may, at least partly, reflect some modulation of the emission process and/or of the particle pitch angle distribution; (ii) fine spectral structures may be a natural consequence of the propagation of elementary beams in a

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fibrous Corona (Aschwanden 1993; MacKinnon and Pick 1991; Klein 1994; Vlahos and Raoult 1994).

The present paper lays emphasis on specific imaging observations, relevant to accelerated particles, which have been obtained with high spatial and/or temporal and/or spectral resolution over a large field of view. Although the resolution of current imaging observations do not allow to access spatial and temporal scales expected in fragmentation scenarios, they provide unique information on the morphology and dynamics of the macroscopic magnetic structure involved in particle production and transport, during and outside flares. Section 2 briefly indicates the location and the emission process of the HXR and radio emitting sources. Section 3 discusses transient signatures of non-thermal particles outside and prior to flares. Observations relevant to the trigger and to acceleration during flares are described respectively in sections 4 and 5. Section 6 deals with long term acceleration outside flares and conclusions are drawn in section 7.

2. HXR and radio diagnostics of non-thermal particles

Electromagnetic signatures reveal the sites where accelerated particles interact with the ambient medium. For the great majority of flares, it is inferred, from radiospectrographic observations of fast drifting bursts, that acceleration occurs in the low Corona in regions where the ambient electron density ranges from some 10^9 to some 10^{10} cm^{-3} (see Klein 1994 and references therein). It is also widely recognized that: (i) electron and ion acceleration is simultaneous within $\sim$1 s (Forrest and Chupp 1983); (ii) radio emission from millimeter (mm) to dekameter (dam) wavelengths is due to electrons drawn from the same accelerator (e.g. Trottet 1986; Pick et al. 1990; Chupp et al. 1993). Multi-wavelength imaging observations appear thus as a powerful way to study the topology and the dynamics of the small and large scale magnetic structures in which particles are accelerated and/or propagate.

HXR and mm to cm radio emission are due to respectively bremsstrahlung and gyrosynchrotron radiation. Imaging observations localize the energetic particles in the low solar atmosphere in closed magnetic structures with typical heights and sizes ranging from some 10^3 to some 10^4 km (e.g. Duijveman and Hoyng 1983; Matsushita et al 1992; Alissandrakis et al. 1988; Dulk et al. 1986). These structures will be referred to as small scale ones in the following.

In the dm-dam radio domain the emission is due to collective processes. Though these processes are not yet fully understood, radio bursts constitute a unique way to trace the large scale magnetic structures in which energetic electrons propagate. As, at a particular observing frequency, the emission is produced close to the fundamental or first harmonic of the local plasma frequency, multi-frequency imaging observations allow us to visualize these structures at different altitudes. Typical source altitudes are in the range of some 10^4 to some 10^5 km (e.g. Trottet 1986).

3. Transient signatures of non-thermal particles outside and prior to flares

Small scale activity such as X-ray, EUV and UV flaring bright points, coronal jets,... is frequently observed in the quiet Sun (e.g. Dere 1991). Soft X-ray imaging by YOHKOH shows that the Corona is in a constant state of brightening, fading and reconfiguration on all spatial and temporal scales (Acton et al. 1992). In contrast signatures of non-flare associated short lasting (a few seconds to a few minutes) accelerations have not been systematically detected with this small scale activity. Whenever clearly identified these signatures were associated with active regions. The most unambiguous observations comprise: (i) low energy impulsive electron events (e.g. Lin 1993); (ii) HXR micro-flares (Lin et al. 1984), but these have not been detected during the solar minimum (Lin et al. 1991) and (iii) m-dam type III electron beams (Axisa et al. 1973; White et al. 1986). Imaging observations have shown that the production of these beams is associated with cool material motion above a magnetic neutral line (Axisa et al. 1973; Mein and Avignon 1985; Chiuderi-Drago et al. 1986). It should be premature to conclude that short lasting particle acceleration is rare outside active regions because: (i) no systematic search has been performed; (ii) the present sensitivity of HXR detectors and radiospectrographs may be unsufficient; (iii) systematic radio imaging observations, which are the most unambiguous and sensitive ones, are only available at a few discrete frequencies in the meter domain.

Signatures of non-thermal particles have been detected a few tens of seconds to a few minutes prior to the flash phase (defined as the rapid increase of the HXR emission) in 15-20% of the HXR flares. They consist in a weak HXR emission, in decimetric pulsations and in metric type III's (Benz et al. 1983). Type III production implies that particle acceleration is not a continuous process but results from a succession of short ($\leq$1 s) accelerations. Furthermore imaging observations show that within one group of type III's, sources are found at different locations (e.g. Benz et al 1983; Raoult et al. 1985; Chupp et al. 1993). This indicates that individual electron beams propagate along different flux tubes implying that beam injection in the Corona takes place in complex magnetic field topologies. These characteristics of the pre-flash radio emission suggest that the primary acceleration presents some degree of fragmentation.

4. Trigger of the bulk production of flare-associated particles

The flash phase of a flare starts with the steep increase of the HXR emission at all energies (Klein et al. 1987). For impulsive events the typical rise time of the HXR burst ranges from a few seconds to a few tens of seconds. The growth of a flare from its pre-flash to its flash phase corresponds thus to a fast and large increase of the number of energetic particles at all energies that is to a greatly enhanced efficiency of the accelerator. It has been frequently observed that the flash phase onset is nearly coincident in time with the appearance of new ~30 keV X-ray and cm-m radio sources at different locations from those observed during the pre-flash phase (Machado et al. 1988; Raoult et al. 1985; Willson et al. 1990; Chupp et al. 1993). Recent (13.9 - 22.7) keV imaging X-ray observations of one flare (Sakao et al. 1992) show that: (i) the HXR emission pattern evolves drastically during the pre-flash phase; (ii) the HXR pre-flash sources are located $\sim 2 \times 10^4$ km away from those detected during the flash phase. These observations show that the flash phase onset is accompanied by a sudden increase of the spatial complexity of the emission pattern produced by non-thermal electrons This indicates that fast activation of new magnetic structures in the flaring region is a necessary condition to trigger efficient acceleration. Moreover, as shown by the occurrence of type III groups during the rise of HXR bursts, the efficiency of the accelerator does not increase gradually with time but rather sporadically (Kane and Raoult 1981; Benz et al. 1983; Raoult et al. 1985; Chupp et al. 1993).

5. Imaging signatures of energetic particles during flares

Early imaging observations by SMM and HINOTORI provided first evidence for non-thermal emission at the footpoints of flaring loops (Duijveman et al. 1982). However they did not, in general, allow to separate thermal and non-thermal sources unambiguously (see Vlahos et al. 1986) mainly because these data were restricted to below 20-30 keV energies where a large fraction of the emission may be due to thermal bremsstrahlung of the hot ambient plasma. New HXR imaging capabilities by the HXT instrument on YOHKOH, which provide observations above 50 keV with a time resolution down to 0.5 s (Kosugi et al. 1991), will, in principle, help to clarify the situation. As an example Sakao et al. (1992) observed that the spatial distribution of the HXR emitting sources evolves on a time-scale of a few seconds during an impulsive HXR burst, suggesting that successive HXR peaks correspond to energy release in different loops.

Recent and unique mm radio observations with imaging capabilities, obtained at 48 GHz with the Itapetinga radiotelescope, clearly demonstrate the preceding suggestion. Herrmann et al. (1993) have shown that the complex time evolution of the mm emission pattern observed during one burst may be attributed to at least two inhomogeneous and spatially separated sources with changing relative brightness. Fig. 1 (Correia et al. 1994) shows

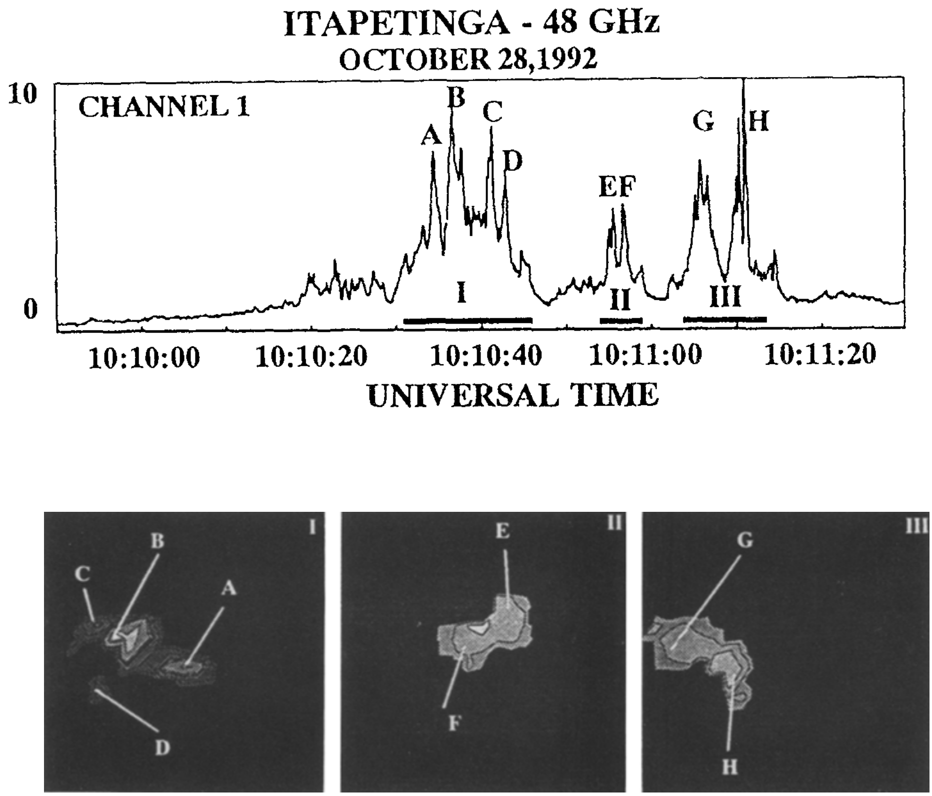

Fig. 1. Upper part: Time profile of the October 28,1992 burst at 48 GHz; lower part: emission center distributions for the time intervals I to III. The size of the dynamic burst map is 20"x20" and the outermost iso-intensity contour corresponds to the 50% level of the distribution maximum (courtesy of Correia et al. 1994).

a spectacular example of the complex and fast evolution of the mm emission pattern during a short (~60 s) burst. The event comprises essentially three main bursts (of 10-20 s typical duration) marked I, II and III (Fig. 1, upper part). Each of these bursts contains several peaks, marked by capital letters. Fig. 1 (lower part) displays the spatial distribution, over a 20"x20" field, of the 48 GHz emission during bursts I, II, III. It is evident that not only do bursts I, II, III arise from different locations, but successive peaks within bursts I, II and III are also observed at different places. Such a complexity is also revealed by high time resolution (<1 s) and large field of view imaging data in the cm radio domain. For example:

– Position changes greater than a few 10^3 km have been detected at 17 GHz, on time-scales of a few seconds, by Kai and Nakajima (1986).

– One dimensional images of 10 moderate bursts performed by Kattenberg and Allaart (1983) at 6 cm with a 0.1 s time resolution show the existence of two sources, spatially separated by 10" to 100", having different characteristics: (i) a narrow (<10") and bright ($T_b > 10^8$ K) spiky source which exhibits flux and position variations on time-scales sometimes unresolved with the 0.1 s sampling time; (ii) a broader (>15") and fainter ($T_b < 5 \times 10^7$ K) source which shows a more gradual evolution in time.

– Imaging observations with both high spectral and spatial resolution have been recently reported for a weak burst by Lim et al. (1994) at 21 frequencies in the range 1-18 GHz. The spatial distribution of the microwave burst comprises three sources, but the number and location of sources is found to be dependent upon the observing frequency. However the 12 s time resolution is insufficient to decide if this complexity reflects either that different sources with different spectra radiate during the whole event or that the different sources switch on at different times.

By using combined HXR/gamma-ray spectral measurements and m radio imaging observations, the morphology and dynamics of the large-scale magnetic structure guiding the accelerated particles have been studied, in detail, for a few energetic flares giving rise to gamma-ray line and > 10 MeV photon emission. Some of the results are illustrated, for one flare, in Fig. 2 (Chupp et al. 1993). The figure shows the time histories in several X-ray and gamma-ray energy bands (left panel) and the projected locations onto the solar disk of the 164 MHz and 327 MHz radio emitting sources (right panel) for three intervals of time: (a) before the onset of the (114-199) keV emission; (b) from the onset of the (114-199) keV emission till that of the (10-25) MeV one; (c) from the onset of the (10-25) MeV emission till the end of the (114-199) keV one. As it is generally observed (see section 4), efficient particle production, giving rise to ~100 keV HXR emission, was initiated when a new radio source S2 appeared in the Corona. The new result shown in Fig.2 is that an additional radio source S3 switched on at the onset of the (10-25) MeV emission. It is of particular interest that a new Hα bright feature appeared outside the main flare ribbons in association with S3. The onset of the >10 MeV emission was associated with: a sudden increase of the electron and proton interaction rates, a hardening of the electron spectrum, and an increase of the proton to electron ratio that is with a step-like increase efficiency of the accelerator. These results and similar ones, obtained for two other large flares (Trottet et al. 1993; Trottet et al. 1994), provide evidence that changes in the spectra of both accelerated electrons and ions are closely connected with changes of the spatial distribution of the particle interaction sites inside the active region large-scale magnetic structure. As these changes occur on time-scales much shorter than particle drift times across the magnetic field, they also reflect that, as the flare evolves, different small-scale magnetic structures are activated. This is supported by the

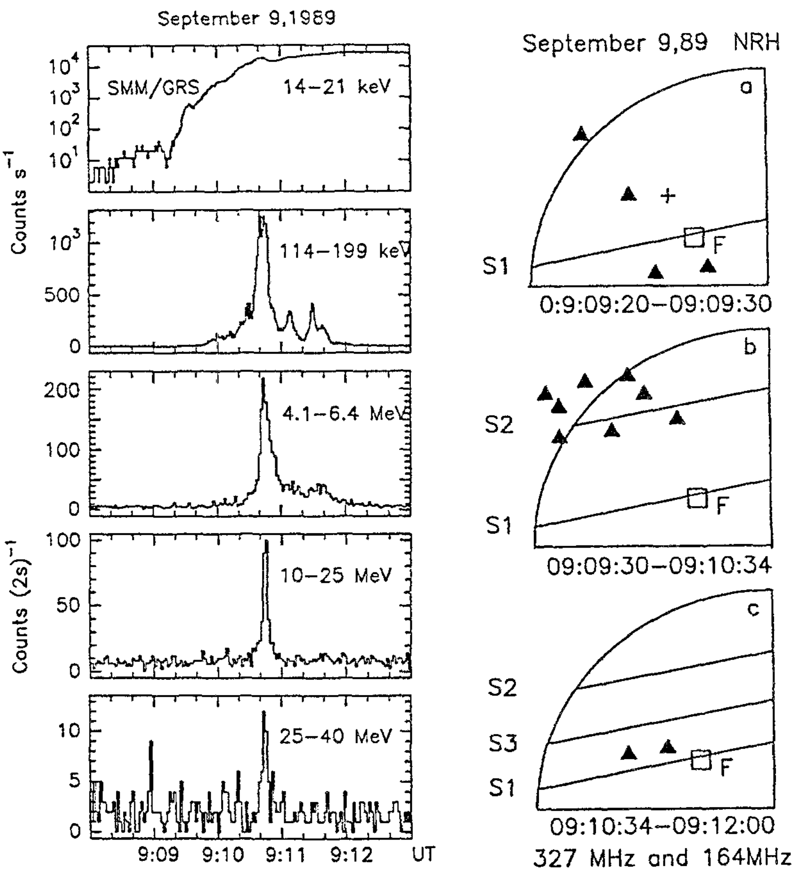

Fig. 2. Left panel: Time histories of the X-ray and gamma-ray emission in different energy bands detected during the September 9, 1989 flare. Right panel: location of the m radio emitting sources obtained with the Nançay Radioheliograph: solid triangles indicate the locations of 164 MHz type III's, open triangles correspond to source S2 at 164 MHz, and the + shows the location of the 164 MHz pre-flash emission. The solid lines shows the one-dimensional location of the 327 MHz emitting sources labeled S1 (pre-flash), S2 and S3. The optical flaring region is marked by a F (adapted from Chupp et al. 1993).

fact that : (i) a small change (~7x10^3 km) of the location of the microwave energy release region may be associated to a large change (~3.5x10^5 km) in the related metric type III burst location (Lantos et al. 1984); (ii) HXR and mm-cm radio imaging observations provide direct evidence for rapid changes of the small-scale structure activated during a flare.

The observations discussed so far are relevant to short duration (a few mn) flares generally referred to as impulsive flares. Nevertheless impulsive and gradual HXR flares do not form two separate classes of events (Crosby et al. 1993). A comprehensive discussion of long duration (gradual) flare acceleration has been given in Klein (1994). He concluded that short and long duration flares do not necessarily correspond to different acceleration scenarios. Indeed spatial-temporal complexity is also detected during long duration flares (Trottet et al. 1993). The slower time evolution observed during long events may simply reflect that particle acceleration and transport take place in a more dilute ambient medium.

In summary imaging observations show that distinct small and large-scale magnetic structures are successively and/or simultaneously activated on time-scales ranging from a few seconds to a few tens of seconds. Globally the spatial complexity increases as the flare evolves. Moreover the activation of new magnetic structures is correlated with changes in the characteristics (numbers, spectra, proton to electron ratios) of the accelerated particles. Therefore the morphology and dynamics of the flaring region magnetic field appears to play a leading role in determining the efficiency of particle acceleration.

6. Signatures of long lasting acceleration outside flares

Metric radio noise storms are the most frequent manifestations of long lasting (tens of mn to days) acceleration of a few tens of keV electrons outside flares. Multi-frequency radio imaging observations, combined with white light coronographic images and soft X-ray data, have shown that noise storms, like flares, are related to re-structuring of the plasma magnetic field configuration of the associated active region and of the overlying Corona (Svestka et al. 1982; Kerdraon et al. 1983; Stewart et al. 1986; Raulin et al. 1991; Raulin and Klein 1993). Noise storms present further phenomenological similarities with flare-associated radio emission such as: (i) the occurence of bright, narrow band (a few MHz) and short-lived (<1 s) type I bursts; (ii) their association with the production of electron beams (dam type III storms). This suggests that noise storms, like flares, are a part of the coronal response to the evolving topology of the active region magnetic field, but the rate of energy released is smaller.

7. Conclusion

Imaging HXR and radio signatures of non-thermal particles, reviewed in this paper, indicate that:

– Particle acceleration during and outside flares presents some phenomenological similarities and is systematically associated with restructuring of the plasma-magnetic field configuration of an active region and of the overlying Corona. However, if not associated with an active region, large scale (e.g. coronal mass ejections) and small scale (e.g. XR flaring bright points, coronal jets,...) coronal activity is not necessarily accompanied by detectable signatures of non-thermal particles.

- Earlier findings by de Jager and de Jonge (1978) that short duration flares consist in a succession of short-lived (a few to a few tens of seconds) bursts are confirmed. But in addition it is found that: (i) successive short-lived bursts are emitted at different sites thus in spatially distinct small scale (a few 10^3 km) structures; (ii) the activation of different structures produces particle populations with different characteristics; (iii) the distribution and time evolution of flaring small scale structures govern the access of particles to more extended ones; (iv) HXR and radio sources associated to long duration flares are also complex but their variations are observed on longer time-scales (minutes).

The observations are globally consistent with the idea that bulk particle acceleration is built up from energy release at a variety of sites. Moreover, the better the spectral, temporal and spatial resolution, the more complex is the observed spatial-temporal structure of the non-thermal HXR and radio emitting pattern. On the other hand such a complexity has not yet been properly considered in attempts to model particle acceleration. The "statistical flare" concept thus constitutes a new and promising approach to put all manifestations of accelerated particles in a common framework.

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