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HIGH-ENERGY PARTICLES AT AND FROM THE SUN

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Abstract. Non thermal particles up to relativistic energies contain a large fraction of the energy released during solar activity, especially flares and coronal mass ejections. The Sun gives us a unique opportunity to observe radiative signatures of these particles at time scales relevant to their acceleration, to measure in space those particles which escape from the Sun, and to image the environment where the particles are accelerated. Shock waves of coronal mass ejections and magnetic reconnection during flares are the most plausible origins of energetic particle populations. The paper outlines recent work with emphasis on the French Solar-Terrerstrial Physics community.

1 Introduction

The typical thermal energy of a particle in the solar corona is around 100 eV. Yet, during transient events electrons up to 100 MeV and protons up to several GeV have been observed through their gamma-ray emission or by particle detectors. The emission of high-energy charged particles accompanies flares or similar phenomena of explosive energy release, where magnetic reconnection plays a crucial role. When coronal mass ejections, i.e. large-scale destabilised magnetic field configurations, propagate through the corona at super-alfvenic speeds, they drive shock waves which are another well-known particle accelerator.

The following brief review of recent results especially of the french research community cooperating within the *Programme National Soleil-Terre* (PNST) starts with observations of energetic electrons in a simple flare. A cartoon scenario is presented that we then use to explain deviations during the large events and to discuss some open questions, especially with regards to time-extended particle acceleration in the corona and the origin of energetic particles in space. New observational tools and projects are then briefly addressed. The french scientific community is very active in this field, with original radio instruments like the Nançay Radioheliograph and Spectrograph, and the WAVES spectrograph aboard the *Wind* spacecraft, optical and EUV telescopes (THEMIS, SoHO/LASCO, SoHO/EIT), as well as MHD theory and modelling of coronal magnetic field dynamics.

2 High-energy particles at and from the Sun : a multi-instrument view of a simple event

A multi-instrument view of electron acceleration in a relatively simple solar flare is shown in Fig. 1.a (Vilmer et al., 2002). The top panel displays the time histories of X-rays at different photon energies. Soft X-rays (e.g., $h\nu$=6-12 keV) show thermal emission from plasma heated during the flare. Hard X-rays (HXR; e.g. 50-100 keV) are mostly emitted by non thermal electrons of about 100 keV, i.e. a thousand times the thermal energy in the quiet corona. The emission is short, impulsive, and detailed timing analyses reveal acceleration times of a few seconds or shorter (see Vilmer & MacKinnon, 2003, and references therein). The second panel from top gives the dynamic X-ray spectrum as a colour-scale plot. Radio emission at dm and m-wavelengths (frequencies $\leq$500 MHz) is shown in the three bottom panels of Fig. 1.a. This stems mainly from electron beams which generate radio waves through a beam-plasma instability, at the local plasma frequency or its harmonic. The emission starts near 400 MHz, pointing to an acceleration region with a thermal electron density $\sim 5\times10^8$ cm^{-3}. The second panel from bottom gives the time evolution at a few individual frequencies. The bottom panel displays the emission from the electron beams at lower frequencies, i.e. greater height in the corona (> 1 R$_\odot$

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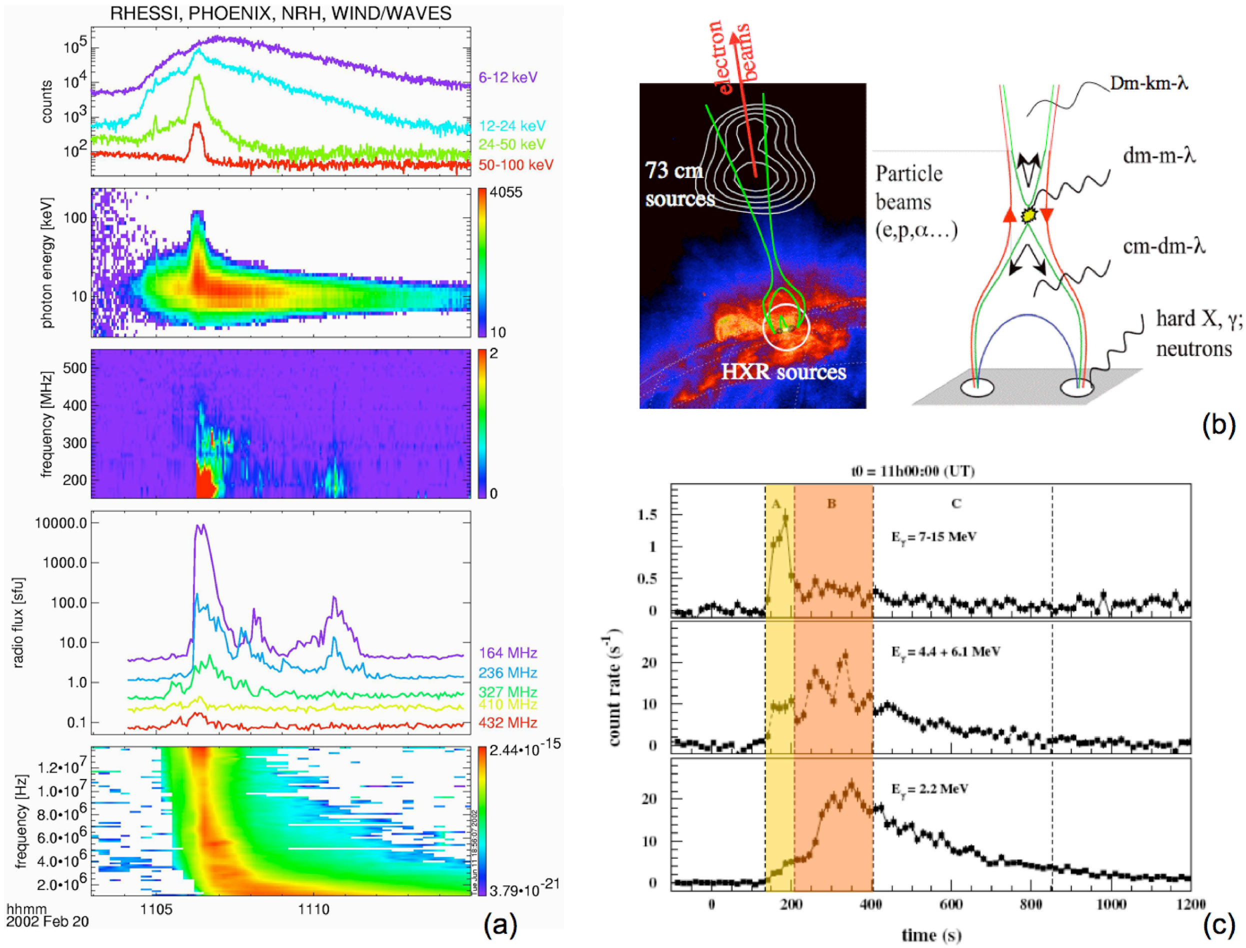


Fig. 1. (a) Multi-frequency observations of the radiative signatures of energetic electrons from the chromosphere to the high corona. From top to bottom : (1) time profiles at selected X-rays energies, (2) dynamic hard X-ray spectrum (RHESSI), (3) dynamic dm-m-wave radio spectrum (Zurich), (4) selected dm-m-wave time histories (Nançay), (5) dynamic deca-hectometre wave spectrum (*Wind*/WAVES) (Vilmer et al., 2002). (b) Left : Overlay of the hard X-ray sources (RHESSI; black contours within the white circle) and radio sources (white contours; Nançay Radioheliograph) on an EUV image (SoHO/EIT; colour scale from blue over red to yellow) of the flaring active region (Vilmer et al., 2002). The green lines are a schematic drawing of a plausible magnetic configuration. Right : cartoon scenario for flare-related particle acceleration as derived from these observations. (c) Gamma-ray time profiles of a large solar flare obseved by INTEGRAL (Kiener et al., 2006).

above the photosphere). It is readily seen that the emission occurs the later, the lower the frequency. This reveals the upward motion of the electron beams through the corona and towards interplanetary space. At still lower frequencies the beams can be tracked until they reach the spacecraft.

The picture on the left of Fig. 1.b (Vilmer et al., 2002) is an EUV image taken during the flare by SoHO/EIT (colour-coded, blue meaning dark, yellow bright), with overlaid contours of the HXR emission (RHESSI, black) and the radio emission at 73 cm wavelength (410 MHz, Nançay Radioheliograph, white). The HXR emission comes from compact sources in the chromosphere, while the radio emission is due to upward moving electron beams much higher in the corona. A simple magnetic configuration is sketched by green lines, with open magnetic flux including a current sheet on top of a magnetic loop, in which particles are accelerated in the course of magnetic reconnection. Following HXR timing analyses by Aschwanden and coworkers (cf. Aschwanden, 2002), the height of the acceleration region is typically 1.7 times the radius of the underlying loop. In the cartoon scenario in the right-hand panel of Fig. 1.b the yellow symbol indicates the presumed reconnection region.

Possible acceleration processes include acceleration by a DC electric field in the reconnection region, stochastic acceleration by different types of plasma waves, or acceleration by the shock that develops at the interface of the reconnection outflow and the ambient plasma (Miller et al., 1997; Aschwanden, 2002; Mann et al., 2006). Downward propagating electron beams generate bremsstrahlung HXR as they penetrate into the dense low layers of the solar atmosphere. The electrons propagating upwards from the acceleration site do not emit detectable HXR because the ambient plasma is too dilute to generate significant bremsstrahlung. But they emit coherent radio emission at dm and longer wavelengths.

The overall scenario is well confirmed by observations :

- Historically well-known signatures of solar flares, i.e. emissions in the Hα line (Trottet et al., 2000) and the white-light continuum (Fletcher et al., 2007), have been shown to have time profiles that resemble those of HXR emission, i.e. a typical signature of electron acceleration. This resemblance suggests that the energetic electrons carry energy to the chromosphere where the optical emissions are excited. An improved quantitative knowledge of the temperature to which the chromosphere is heated is needed to make further progress.
- THEMIS observations showed that the optical emissions in lines of neutral hydrogen may be linearly polarised during solar flares. The polarisation is generated by the impact of energetic particles or their return currents on the hydrogen atoms (Hénoux & Karlický, 2003; Xu et al., 2005).

The scenario is nevertheless intentionally oversimplified. E.g., current sheets have typical sizes of a few ion gyro radii, i.e. a few hundreds of metres in the solar corona. These dimensions are out of reach of remote sensing observations. We also know from existing models that a huge amount of energy converted during a flare appears as kinetic energy of non thermal electrons and ions (see Emslie et al., 2005, and references therein). It is hard to imagine that the acceleration occurs in a tiny volume within a large-scale and overall stable coronal structure. Particles are more likely accelerated in multiple coronal current sheets which fill macroscopic volumes that we can observe through their brightenings during flares (see Dauphin et al., 2007, and references therein).

3 Gamma-ray observations of high-energy electrons and ions

Based on overall simultaneous timing, the expectation from whole-Sun spectroscopic observations, which were the only gamma-ray diagnostics before RHESSI, was that the sources of emission from electrons and ions would not be distinguishable. The major surprise from RHESSI was that the gamma-ray emissions from energetic protons and from relativistic electrons did not come from the same place (Lin et al., 2003). A simple model of acceleration by direct electric fields, which would eject protons and electrons into different directions, is not applicable, because sufficiently large DC fields cannot be sustained over the required volumes in the corona. Adiabatic particle drifts are too slow. The observation therefore remains to be understood and possibly gives clues to the acceleration processes at work.

But upon close inspection gamma-ray radiation from electrons and protons has different time profiles, too. A remarkable example are the INTEGRAL observations of a large gamma-ray flare in Fig. 1.c (Kiener et al., 2006). The time profile of gamma-ray bremsstrahlung from relativistic electrons rises first, then falls sharply (yellow shading in Fig. 1.c), while the time profile of the nuclear line emission in the (4.4-6.1) MeV range, due to accelerated protons, continues to rise (orange shading). Clearly, the time evolutions are different and point to different acceleration time histories, in line with the different locations of gamma-ray sources from electrons and ions mentioned before. The 2.2 MeV line (bottom panel) is produced by the capture of neutrons on neutral hydrogen. The delay with respect to other features reflects the thermalisation of neutrons before capture, and is unrelated to acceleration. By studying the time evolutions of the line emission from different O ions, Kiener et al. (2006) were furthermore able to show that the target densities of proton bombardment also change during the flare, suggesting that different acceleration regions act during this event. Clearly, particle acceleration in major flares does not occur in a simple scenario, but involves a variety of regions in the corona and extended (tens of minutes or even more) episodes of acceleration.

4 Energetic particles in interplanetary space and their solar origin

From the cartoon scenario we expect a simple relationship between energetic particles that emit HXR and gamma-rays in the solar atmosphere - they come from energetic particles streaming downward from a coronal acceleration site - and particles detected in space - they come from the same acceleration site, but stream upward. There are simple events where this scenario might fit, although even in those cases we presently do not understand the quantitative relationship e.g. between the electron spectra inferred from HXR emission in the low solar atmosphere and those measured at spacecraft near 1 AU (Dröge, 1996; Krucker et al., 2007).

The improved sensitivity of particle instruments, and correlative studies with solar activity, have recently brought new insight into the relationship of energetic particles in space and solar activity.The most frequently observed particle events, which are estimated to occur at a rate of about 1000/year (Reames, 1999), are produced during flares, but also with much weaker activity. Wang et al. (2006) and Pick et al. (2006) identified quite unconspicuous jets seen at EUV wavelengths as the coronal origin of moderately energetic ions (energies of the order of a few MeV/nucleon) in space. Particles up to 10 MeV were seen without any accompanying HXR signature of electron acceleration in the corona (Klein & Posner, 2005). Hence minor activity in the corona can produce pronounced enhancements of energetic particle fluxes in space. The origin of the particles is probably magnetic reconnection, which Wang et al. (2006) localise at the interface between bipolar magnetic field emerging in an active region and overlying open magnetic flux from a pre-existing coronal hole. So the geometry of this configuration is different from our cartoon scenario, but the particle acceleration is again related to magnetic reconnection in an active region. Resonant acceleration with different types of plasma waves is a prominent candidate, since it explains naturally why certain ion species, such as ^{3}He, are orders of magnitude more abundant in the accelerated particle populations than in the quiet corona. In periods of strong solar activity, recurrent jets and the ensuing injections of accelerated particles contribute to maintain a superthermal ion component in interplanetary space over several days (Wang et al., 2006).

5 Coronal mass ejections, flares, and the origin of large solar energetic particle events in space

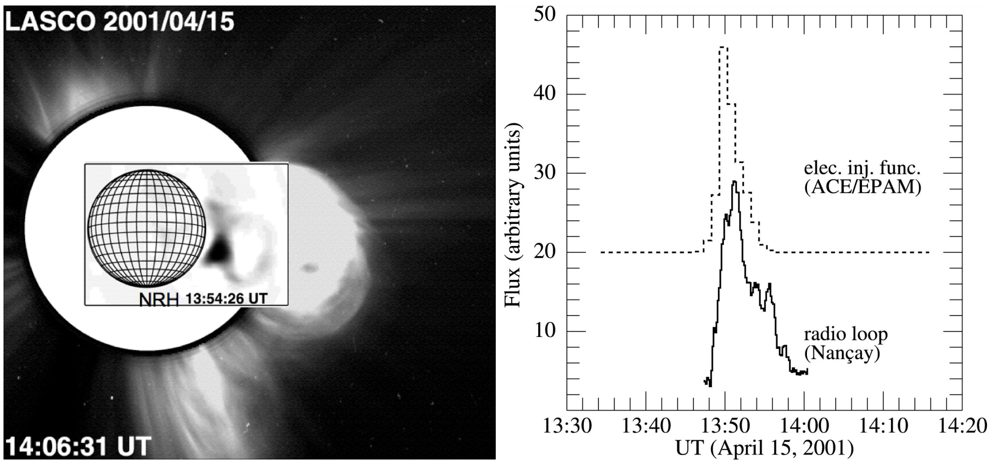
As long as flares were the only known manifestation of explosive energy conversion in the corona, it appeared natural to relate any discrete solar particle event in space to them. But large-scale shocks higher up in the corona were proposed as an alternative mechanism since the 1960s (cf. Carmichael, 1962). This idea gained widespread support when fast coronal mass ejections (CME) observed with space borne coronagraphs were shown to not be a mere consequence of a flare, but an independent manifestation of magnetically driven disturbances of the corona. Many researchers concluded in the 1990s that the energetic particles detected in situ during large events are accelerated at the bow shock of the CME (see review in Reames, 1999). But on closer inspection statistical relationships between CME speed and energetic particle intensities in space are loose and inconclusive.

If particle events in space were produced by CME shocks rather than flares, some fast CMEs without flares should be expected to produce such events. Marqué et al. (2006) attempted to identify such CMEs by looking for fast CMEs with no radio signature of electron acceleration in the corona. Only three such events were found with magnetic connection to the Earth during the phase of rising solar activity between June 1996 and June 1998, but no or only weak energetic particle fluxes in space were detected by the ACE and SoHO spacecraft. There is no evidence that a fast CME alone is able to accelerate large solar energetic particle events at energies exceeding, say, 1 MeV/nucleon.

Where are the particles accelerated, if not at the CME shock ? The gamma-ray event in Fig. 1 shows that particle acceleration during flares may be time-extended, with new episodes of particle acceleration starting several minutes after the flare onset. Radio observations during such events sometimes show that after the most prominent X-ray or gamma-ray emission electrons may still be accelerated in the corona during tens of minutes and emit synchrotron radiation at metre-wavelengths (Dauphin et al., 2005). Maia & Pick (2004) and Klein et al. (2005) demonstrated that such late acceleration signatures could explain why particles detected *in situ* are sometimes released well after the start of the associated flare (see also Krucker et al., 1999; Haggerty & Roelof, 2002).

The corona behind a CME will be in a highly perturbed state, and will relax through magnetic reconnection. Using the Nançay Radioheliograph, Maia et al. (2007) discovered synchrotron emitting electrons in the aftermath of a fast CME (Fig. 2.a). With a model of interplanetary particle transport they derived the injection profile of near relativistic electrons at the Sun from ACE measurements near 1 AU (dashed line in Fig. 2.b), and found it to be remarkably similar to the time profile of the synchrotron radiation in the corona (solid line in Fig. 2.b). The similarity suggests strongly that the near relativistic electrons detected near 1 AU and those producing the synchrotron emission in the corona come from the same accelerator, which has to be located behind the CME front. The acceleration is therefore not related to its shock, but rather to the magnetic restructuring of the

(a)



(b)

Fig. 2. (a) Coronal mass ejection as observed with the LASCO coronagraph aboard SoHO, with inserted snapshot of the 410 MHz radio emission (black shading shows bright emission; Nançay Radioheliograph). (b) Comparison of the time profile of the electron injection derived from a transport model and ACE measurements at 1 AU (dashed line) and the time profile of the 432 MHz synchrotron emission from near-relativistic electrons in the corona (solid line) (Maia et al., 2007).

post-CME corona. The detailed numerical modelling of the particle transport corroborates ideas put forward earlier for both electrons and protons (Laitinen et al., 2000; Klein & Trottet, 2001, and references therein).

6 Outlook

We have learned in recent years that non thermal particle populations are a fundamental consequence of explosive energy conversion in the solar corona. We are able to map the overall context of the flaring magnetic field configurations, and to constrain the time scales of acceleration. They are of the order of a second or shorter, and are a challenge to our present understanding. A suite of instruments for dedicated solar observations from ground and space are at the origin of this knowledge. But much remains to be discovered and understood on the actual action of different plausible acceleration processes, on species-dependent acceleration, on the highest energies to which particles are accelerated at the Sun, and on the partition of energy between thermal and non thermal particle populations and bulk plasma motion.

In the coming years the two-satellite STEREO mission[1] will enable us for the first time to see CME and associated activity from two vantage points, i.e. to get information on the longitudinal extent of CME and their associated shock waves. The FASR[2] project of broadband radio imaging from cm-to-m-waves targets the first ever imaging observations of flare-accelerated electrons in and around the acceleration region. A new window on energetic particle signatures and energy transport during flares is in the far infrared. The first sub-mm observations of flares (Trottet et al., 2002; Kaufmann et al., 2004) revealed an as yet not understood spectral rise at wavelengths $\leq$1 mm. The opening of the far infrared window on solar flares is the aim of the DESIR experiment for the SMESE microsatellite project (Vial et al., 2007) presently under study at CNES. Progress in the *in situ* measurements of solar energetic particles will require a much closer vantage point to minimise distorsion of particle time profiles by interplanetary transport. The *Solar Orbiter/Sentinels*[3] concept is tailored for such measurements.

[1] http://http://lesia.obspm.fr/plasma/STEREO.html
[2] http://www.ovsa.njit.edu/fasr/
[3] http://sci.esa.int/science-e/www/area/index.cfm?fareaid=45

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