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# THE SUN AS A PARTICLE ACCELERATOR: HARD X-RAY AND $\gamma$-RAY DIAGNOSTICS OF ENERGETIC PARTICLES

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**Abstract.** Explosive phenomena of magnetic energy conversion in the solar corona lead to the production of energetic particles at all energies. While some fast particles (electrons and ions) produce high energy radiation when interacting with the solar atmosphere (X-rays,$\gamma$-rays), others escape in the corona and interplanetary medium, produce radio emission and may eventually reach the Earth's orbit. I shall illustrate here with some high-energy observations the properties that can be derived on energetic particles. I will concentrate on some of the observations obtained in the last years at high spectral resolution with RHESSI and INTEGRAL/SPI and on the spatially resolved observations provided by RHESSI. I shall present some open questions still being discussed and give a brief overview of future observations in the field of high energy solar physics.

Keywords: Sun, flares, particle acceleration, X-rays, gamma-rays

## 1 Introduction

The Sun is a powerful particle accelerator. This has been known for years, since the first detection of solar energetic protons by ground-based neutron monitors, the first detection of solar flares in radio and X-rays, the first observations of gamma-ray line flares from energetic protons in 1972 and first detection of >100 MeV solar neutrons aboard SMM/GRS in 1982 (see e.g. Vilmer, MacKinnon and Hurford 2010 for a review).

Solar flares and coronal mass ejections (CMEs) are the most powerful events in the solar system. In several tens of minutes, they can convert up to $10^{32}$ ergs of magnetic energy into accelerated particles, heated plasma and ejected solar material. An estimate of this energy budget has been performed for some events (see e.g. Emslie et al (2004)). It is found that the energy contained in energetic electrons and ions interacting at the Sun is a large amount of the magnetic energy which can be released in active region during a solar flare. Understanding particle acceleration in flares therefore provides powerful constraints on coronal energy conversion processes.

## 2 Hard X-ray and gamma-ray diagnostics of flare energetic particles

The most quantitative diagnostics of energetic particles interacting at the Sun are provided by hard X-ray/$\gamma$-ray observations which give information on electron and ion energy spectra, numbers and energy contents. Fig. 1 (Left) shows a theoretical HXR/GR spectrum of a solar flare from 1 keV to 100 MeV. Flare accelerated electrons (energies above > 10 keV) produce bremsstrahlung continuum emission by their braking in the Coulomb field of ambient ions, and above 500-700 keV of ambient electrons. This continuum is dominant below 1 MeV and again in the 10-50 MeV range. Energetic ions with energies in the > 1 MeV/nuc to 100 MeV/nuc range produce through interaction in the solar atmosphere a complete $\gamma$-ray line (GRL) spectrum which consists of several nuclear de-excitation lines, neutron capture and positron annihilation lines (see e.g. Ramaty, 1986; Share and Murphy, 2006 and Vilmer, MacKinnon, Hurford, 2010 for reviews). When ions over a few hundred MeV/nuc are produced in the flare, nuclear interactions with the ambient medium produce secondary pions whose decay products lead to a broad-band continuum at photon energies above 10 MeV (with a broad peak around 70 Mev from neutral pion radiation) and also secondary neutrons which, if energetic enough, may escape from the Sun

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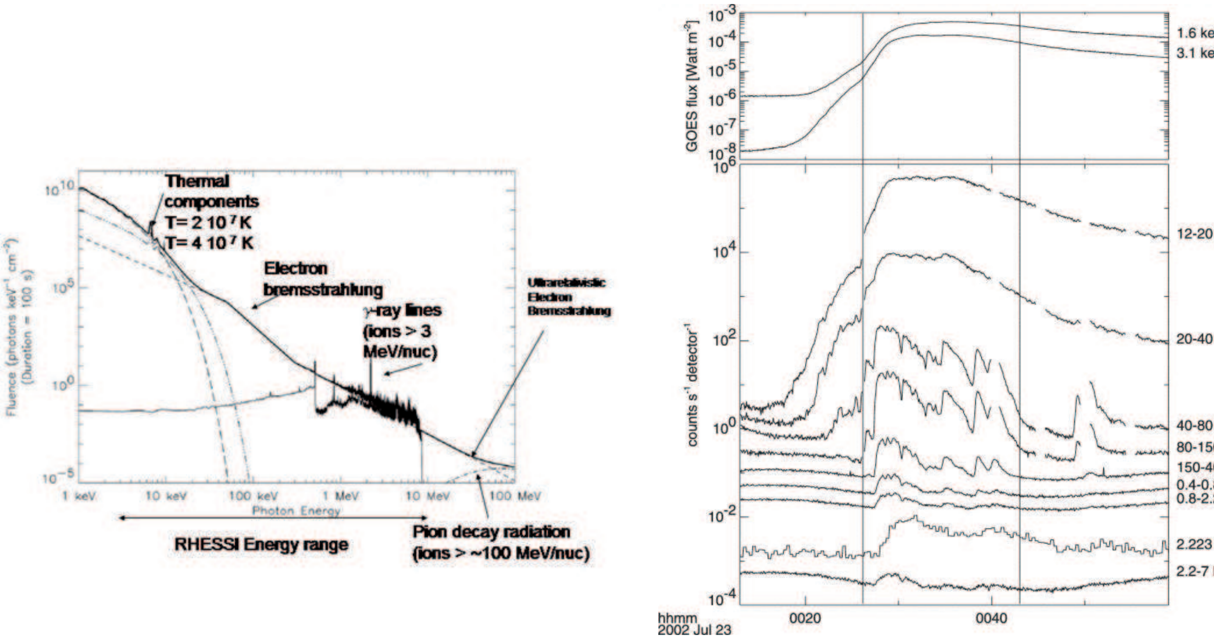


**Fig. 1.** Left: Theoretical HXR/GR spectrum. Right: RHESSI HXR and $\gamma$-ray count rates for the 2002 July 23 flare, scaled to fit: 20-40 keV 0.3; 40-80 keV 0.07; 80-150 keV 0.02; 150-400 keV; 400-800 keV 0.001; 800-2218 keV 0.0005; 2218-2228 keV 0.01; and 2228-7000 keV 2 10-5. The slow variation through the interval is due to the background from cosmic-ray interactions with the atmosphere and spacecraft (from Lin et al., 2003).

and be directly detected in interplanetary space or at ground level (resp > 10 MeV or 200 MeV neutrons) (see e.g. Chupp and Ryan, 2009 for a review).

The temporal and spectral characteristics of HXR/GR and GRL radiations provide strong constraints on acceleration timescales (< 100 ms for electrons, <2s for ions), electron and ion energy spectra, numbers as well as energetic ion abundances. Fig. 1 (Right) shows an example of the temporal evolution of HXR and GR line emissions observed by RHESSI for the 23 July 2002 flare. The 2.223 MeV line from neutron capture radiation is as expected delayed by $\simeq$ 100 s with respect to the prompt $\gamma$-ray lines in the 2.2-7 MeV range. This is due to the time needed for the thermalization of the fast neutrons produced in the nuclear reactions before they can be captured by ambient hydrogen to produce deuterium in an excited nuclear state leading to the emission of a 2.223 MeV photon.

High energy observations of solar flares have been observed for three solar cycles. Before the launch of the solar dedicated RHESSI mission (Lin et al., 2002), emission above 100 keV was one of the last domain where no spatially resolved observations were obtained. Before the launch of RHESSI and of INTEGRAL in 2002 (Vedrenne et al., 2003) quantitative constraints from HXR/GRL spectroscopy had been deduced from observations with limited spectral resolution. Since then several flares have been observed in the hard X-ray domain at high spectral resolution with RHESSI and several $\gamma$-ray flares have been observed with both RHESSI and INTEGRAL for which a detailed $\gamma$-ray line shape analysis could be achieved.

## 3 Energy release and electron/ion interaction sites

HXR (> 20 keV) images usually show double compact sources ((F) in Figure 2 Left). They are interpreted as the footpoints of magnetic loops in which electrons propagate from the acceleration site before impinging on the chromosphere and produce thick-target X-ray emission. Such double compact sources are observed in most events. However, in a small number of events, compact (LT) above the loop-top sources are observed. They are found to be located at higher altitudes at higher X-ray energies and can be interpreted as the result of the energization of the plasma by shocks originating from the reconnection site in the low corona. In addition to these loop-top sources, coronal (C) sources are also observed with RHESSI at energies up to 20 keV (see Fig. 2 Left from Sui et al., 2003). While the temperature of the loop-top sources increases towards higher altitudes, the temperature of the coronal sources increases towards lower altitudes. These observations could indicate the formation of a current sheet between the loop top and coronal sources in which the magnetic energy conversion takes place. Few events of this kind (< 5) have been observed so far (see e.g. the review by Fletcher et al., 2010), and this is one of the goal of the future hard X-ray imagers to search for such configurations in many more events.

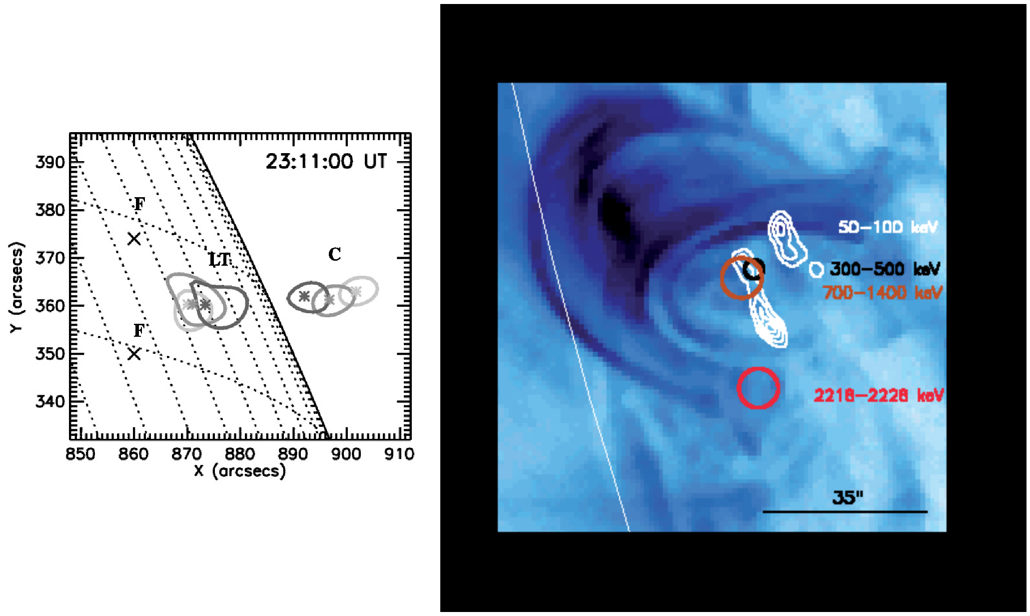


**Fig. 2.** Left: RHESSI images observed in different energy bands. Loop top sources in the following energy bands: 6-8 keV, 10-12 keV and 16-20 keV (from light to dark contours) are shown. The contours of the coronal sources above the limb are respectively for the 10-12, 12-14 and 14-16 keV energy bands (from light to dark). The crosses mark the two footpoints of the X-ray loop (from Sui and Holman, 2003). Right: Respective location of $\gamma$-ray source at 2.2 MeV and of hard X-ray sources observed with RHESSI. The circles represent 1 $\sigma$ errors for the 300-500 keV , 700-1400 keV and 2218-2228 keV maps made with identical parameters. The white contours show the high resolution 50-100 keV map with 3" resolution. The background is a TRACE image showing the post-flare loops (adapted from Hurford et al.,2003).

One of the most intriguing result from RHESSI imaging comes from the observations of the first GRL event imaged. The 2.2 MeV neutron capture line location was indeed displaced by 20" from the centroid of the HXR sources in the 50-100 keV range imaged in the same conditions (Fig.2 Right) (Hurford et al., 2003). Although the 2.2 MeV line images the neutron interaction site rather than the energetic ion interaction site itself, it was nevertheless shown in Hurford et al. (2003) that the 2.2 MeV line emission locates the energetic ion interaction region within 1", thus still implying a previously unexpected significant displacement between the ion and electron interaction sites. Imaging in the GRL domain with RHESSI has been achieved now for 5 events (see Vilmer, MacKinnon & Hurford, 2010, for a review). For four of the five events, a single unresolved source was observed in the GRL domain but given the constraints of the imaging technique, there is no evidence that the true GRL line sources are predominantly single sources, a result that would be in contrast to typical hard X-ray double sources. Statistically significant displacements between HXR anf GRL sources were observed in three of the five events. Given the limited number of observations, it is difficult to make definite conclusions on the relative locations of electron and ion interaction sites. Improving the imaging in the GRL domain is clearly one of the goals of future instruments.

The different electron and ion interaction sites observed in a few events can be interpreted as revealing either different electron and ion acceleration sites or showing different transport for electrons and ions accelerated in the same site. The explanations of these displacements (clearly NOT instrumental) are however still largely unknown.

## 4 Constraints on energetic electrons and ions deduced from high resolution X-ray/$\gamma$-ray spectrum

HXR/GR observations obtained with high spectral resolution enable detailed analysis of the bremsstrahlung continuum and resolution of individual $\gamma$-ray lines. In the HXR domain bremsstrahlung photon spectra at high resolution can be directly inverted to get the effective mean electron flux spectrum in the source (see e.g. Piana et al. 2003) (Fig. 3 Left). This quantity is the electron spectrum that would be required to observe the photon spectrum in a homogeneous source and is the only quantity which can be derived from the photon spectrum without making any assumption on the transport of electrons between acceleration and emitting sites. Fig. 3 (Left) shows the comparison of the values of the electron flux spectrum deduced by forward fitting of a model electron spectrum to the photon spectrum and of the regularized inverted spectrum. The electron flux spectrum is an essential quantity to really constrain acceleration models. Such spectra have been obtained however so far for very few (< 10) events (see e.g. Kontar et al., 2010 for a review).

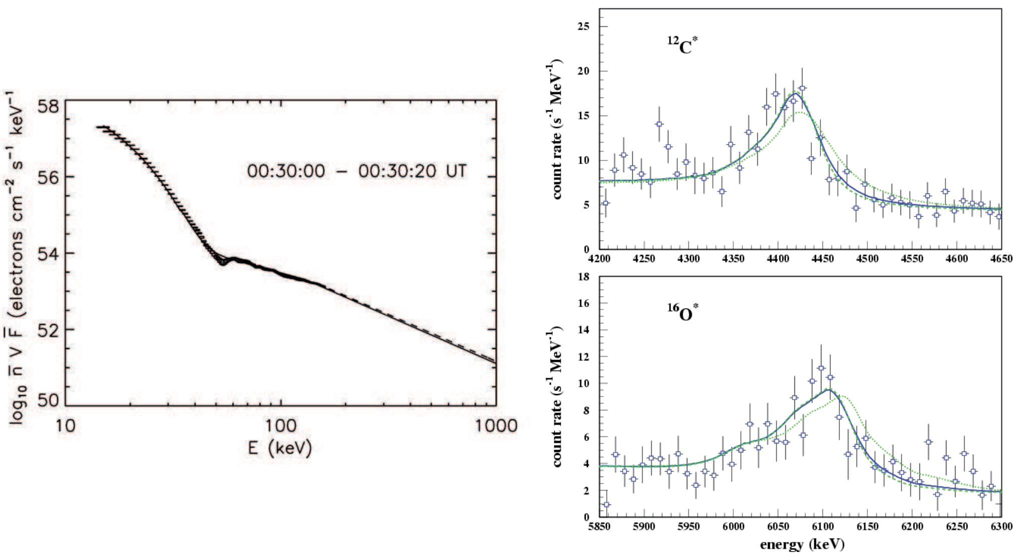


**Fig. 3.** Left: Regularized mean electron flux spectrum obtained from inversion of the photon spectrum (data points) observed by RHESSI (Piana et al., 2003). The solid line shows the forward fitted electron spectrum necessary to reproduce the same X-ray spectrum (Holman et al, 2003). Right: Observed and calculated line shapes of the 4.44 and 6.13 MeV ambient $^{12}$C and $^{16}$O deexcitation lines observed by INTEGRAL/SPI for the 28 October 2003. The dashed line represents the calculated line shape for a downward isotropic distribution. The full line and dotted line represent the calculated line shapes for other models (see Kiener et al., 2006 for details) (from Kiener et al., 2006).

Spectral resolution in the $\gamma$-ray line domain allows to better constrain the line fluences and to analyse line shapes. This provides information on proton and $\alpha$-particle energy and angular distributions. Figure 3 right shows an example of the $\gamma$-ray line shapes measured for a solar flare at high spectral resolution with INTEGRAL/SPI. The comparison of the results of detailed calculations of line shapes to the observations provide strong constraints on the ratio of accelerated helium with respect to accelerated protons ($\alpha$/p) in the flare (Kiener et al., 2006). The line shapes depend however on many parameters: angular distribution of interacting ions, spectral index of the energetic ions and $\alpha$/p so that only the combination of line shapes and line fluences can provide information on regions of allowed parameters: in the case shown in the figure, this leads to the determination of the ion spectral index between -3 and -4, a relatively low value of $\alpha/p$ around 0.1 and a relatively wide angular distribution of emitting ions (Kiener et al., 2006). The number of solar flares for which $\gamma$-ray line spectra at high resolution have been obtained is still very small ( around 5 combining RHESSI and INTEGRAL/SPI observations) (see Vilmer et al., 2010 for a review) but this is a very promising field to improve the constraint on ion acceleration in solar flares.

## 5 Conclusions

Two particular advances characterise the HXR/$\gamma$-ray observations in the last solar cycle:

-spectral resolution adequate to allow direct inversion of the HXR continuum photon spectrum to derive the energetic electron spectrum produced in flares.

-spectral resolution to reveal $\gamma$-ray line shapes to better constrain line fluences and the derived parameters on accelerated ions.

-imaging with a higher dynamic range in the HXR domain allowing to image some coronal HXR sources.

-first $\gamma$-ray images, showing for a few events an unexpected behaviour of the electron and ion interaction sites.

Only a few of the observed HXR events are however adequate to be analysed at high spectral resolution or are strong enough to provide images with a high dynamic range in the HXR domain. In the near future, STIX (Spectrometer/Telescope for Imaging X-rays) instrument aboard Solar Orbiter should provide HXR observations at high spectral and spatial resolution with a sensitivity of 15 times the one of RHESSI. In the $\gamma$-ray domain where the number of events analysed with high resolution spectroscopy or that can be imaged is still very limited, we look forward to further observations with RHESSI and INTEGRAL in the coming maximum. In the higher energy range not discussed here we expect new results from flares observed with the non-solar dedicated mission FERMI. New instrumentation such as GRIPS should provide observations in the $\gamma$-ray domain with improved angular resolution and sensitivity. Finally, several new missions aimed at understanding particle acceleration at the Sun are being studied for the $> 2020$ timeframe either on the ESA or NASA side. A package of HXR/$\gamma$-ray instrumentation is proposed for these missions (e.g. on the ESA side, the SPARK (Solar Particle Acceleration, Radiation and Kinetics) mission proposed by UCL/MSSL as a M3 mission).

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