PARTICLE ACCELERATION BY THE SUN

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Abstract. Observations of hard X-ray/ γ -ray continuum and γ -ray line emission show that electrons are accelerated to >~ 100s of MeV and ions up to GeV energies, respectively, in large solar flares. The flare-accelerated electrons above ~20 keV and ions above a few MeV often contain >~10-50% or more of the total energy released, indicating that the particle acceleration is intimately related to the energy release mechanism. RHESSI observations show strong evidence that both the ion and electron acceleration are associated with the process of magnetic reconnection. Direct *in situ* observations of solar energetic particles (SEPs) near 1 AU indicate that shock waves driven by fast (>~1000 km/s) coronal mass ejections (CMEs) accelerate ions and electrons to similarly high energies, at altitudes of ~2-40 solar radii. Both CMEs and large flares involve the transient release of up to ~10^{32}-10^{33} ergs. Frequent acceleration of electrons to ~10 keV is observed in smaller flares and even in microflares. Radio type III bursts indicate that electron acceleration can occur high in the corona, often without flare signatures at lower altitude. At 1 AU, hundreds of small impulsive SEP events are detected per year near solar maximum. These are dominated by <~1 to ~100 keV electrons and often accompanied by tens of keV to MeV/nuc ions, strongly enriched in 3He and heavies,. Here I review the recent RHESSI and related *in situ* observations as they bear on the fundamental acceleration processes that are occurring.

INTRODUCTION

The Sun is the most energetic particle accelerator in the solar system. In large solar flares, the detection of nuclear γ -ray lines and pion decay emissions produced by nuclear collisions of energetic ions with the solar atmosphere, show that ions are accelerated to ~10-100 MeV and GeV energies, respectively (see Mandzhavidze and Ramaty, 1993 for review). Similarly, the detection of hard X-ray (HXR)/γ -ray continuum emissions produced by bremsstrahlung collisions in the solar atmosphere, show that electrons are accelerated to >~100s of MeV. Ions and electrons up to about the same energies are also seen in large gradual solar energetic particle (SEP) events observed near 1 AU, but they, however, appear to be accelerated by shock waves driven by fast coronal mass ejections (Kahler, 199). Thus, the Sun appears to have *two* separate ways to accelerate particles up into the galactic cosmic ray energy range. Large flares and fast CMEs are the most powerful explosions in the solar system, both releasing up to ~10^{32}-10^{33}ergs. Furthermore, in large solar flares the accelerated > ~tens of keV electrons and >~ few MeV ions often contain up to ~10-50% or more of the total energy released (Lin and Hudson, 1976; Lin et al., 2003), indicating that the particle acceleration must be intimately related to the energy release process. In gradual SEP events, of order ~10 % of the total energy of the fast CMEs goes into accelerated particles (mostly into ions) (Mewaldt et al., 2005); this is about the efficiency required if acceleration by supernovae shock waves is to be the source of galactic cosmic rays.

Flares of all sizes, ranging down to microflares (~10^{-6} the energy release of the largest flares) that occur every few minutes near solar maximum, show non-thermal

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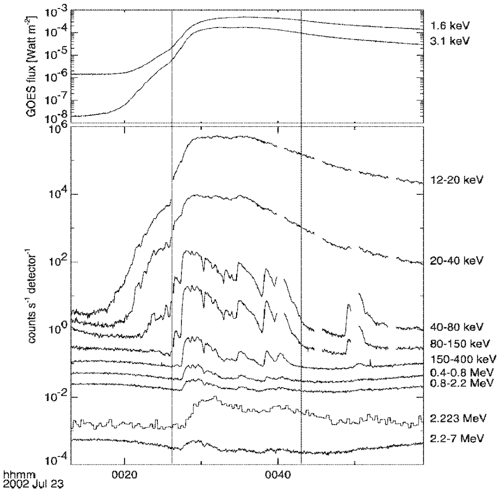
HXR emission implying electron acceleration, but only to ~10 keV energies (Lin et al., 2001; Christe et al., 2008; Hannah et al., 2008). Solar type III radio bursts are generated by electrons accelerated in the corona that escape to the IPM. Impulsive electron events are frequently detected near 1 AU (see Lin 1985 for review), typically at ~1-100 keV energies. Low energy, ~0.01-1 MeV/nucleon ions are typically detected in these events, but with remarkable enrichments in the rare isotope ^{3}He (sometimes more ^{3}He than ^{4}He), as well as enhanced Fe and ultra-heavy nuclei. Hundreds of these *impulsive SEP events* are detected per year near solar maximum. The relationship between the energetic particles at the Sun and the energetic particles observed near 1 AU is not understood. Here we compare RHESSI (Ramaty High Energy Solar Spectroscopic Imager) observations that provide information on the energetic particle populations in solar flares, with the energetic particle measurements from the Wind, ACE, and other spacecraft near 1 AU.

HARD X-RAY/γ-RAY OBSERVATIONS OF SOLAR FLARES

Accelerated electrons. The RHESSI) mission (Lin et al., 2002), launched on February 5, 2002, provides high resolution imaging (as fine as 2.3 arcsec) and spectroscopy (to ~1 keV FWHM) from soft X-rays (3 keV) to γ -rays (17 MeV). The first γ -ray line flare observed by RHESSI was the intense GOES class X4.8 flare of 23 July 2002 (Lin et al., 2003). The flare HXR and γ -ray observations (Figure 1) divide naturally into a rise phase (~00:18 to ~00:27 UT) dominated by a coronal HXR source that appears to be non-thermal, an impulsive phase (~00:27 to ~00:43 UT) with continuum and γ -ray line emission extending up to >~7 MeV, and a decay phase (>~00:43 UT) dominated by a superhot (~40 MK) thermal source. The spatial distribution of HXR sources (Krucker et al., 2003) is shown superimposed on TRACE 195A images, together with the simultaneous spatially integrated X-ray spectra, in a movie at: http://hesperia.gsfc.nasa.gov/hessi/presentations/video/

A remarkable coronal HXR source with a steep double power-law spectrum above 10 keV (exponents $\gamma_L \sim 5$ and $\gamma_H \sim 6.5$, with break at 20–35 keV) dominates the flare X-ray emission during the rise, with little or no footpoint emission. The energy in accelerated electrons during this time, however, is significant, comparable to that released in the impulsive phase. During this flare's impulsive phase, RHESSI shows three HXR footpoint sources together with a coronal superhot (T ~ 40 MK) thermal source that dominates below ~30 keV (see movie). The temporal variations of the hard X-ray fluxes of the different foot points are closely correlated, and the footpoints and coronal source show correlated and systematic motions. This strongly suggests magnetic reconnection in the corona, possibly at or near the thermal coronal source. Magnetic field lines reconnecting in the corona will form new closed loops. Electrons accelerated in the process will travel down the legs of the newly-formed loop, producing bremsstrahlung HXR emissions at the two footpoints that are closely correlated in time. As the next pair of field lines reconnect in the corona they form a new loop with a pair of new HXR footpoints, leading to an apparent motion of the footpoints. The HXR footpoint separation speed, V_f , thus provides a measure of the reconnection rate, since the magnetic field strength in the corona, B_c, multiplied by inflow speed, V_c, in the corona must equal V_f in the chromosphere times the footpoint magnetic field B_f, i.e., $B_c V_c = B_f V_f$. Figure 2 plots the motion of the two main footpoints for the 23 July 2002 flare, where typically $B_f V_f$ = (~50 km/s) x (~1000 G) gives ~5 kV/m for the V x B convection electric field. Then with the RHESSI measurement of the HXR footpoint width, w_f, (~ km), the rate that magnetic flux is being reconnected can be determined,: $d\Phi/dt = B_f V_f w_f$ = ~2 x 10^{18} Maxwells/s. Other large γ -ray line flares observed by RHESSI give comparable numbers. Figure 2 (bottom) shows the footpoint HXR fluxes are roughly proportional to the footpoint separation speed, as expected if the rate of electron acceleration is proportional to the reconnection rate.



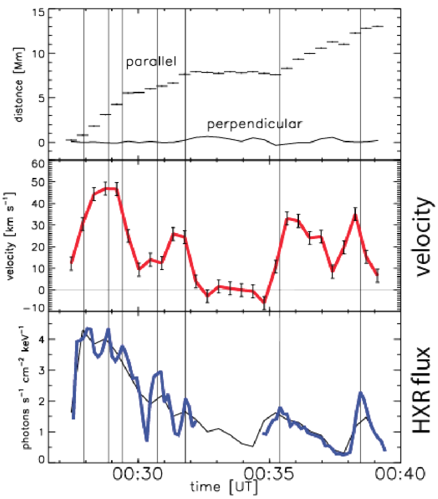


FIGURE 1. RHESSI HXR and γ -ray count rates (in units of counts s−1 per detector) for the 2002 July 23 flare, scaled to fit: 20–40 keV × 0.3; 40–80 keV × 0.07; 80–150 keV × 0.02; 150–400 keV; 400–800 keV × 0.001; 800–2218 keV × 0.0005; 2218–2228 keV × 0.01; and 2228–7000 × 2 × 10−5. The thick shutter is inserted at ~0026, 0041, 0044, and 0050 UT and removed at ~0040, 0043, 0049 UT. The vertical lines separate the impulsive phase from the rise and decay. The slow variation of the γ -ray rates through the interval is due to the background from cosmic-ray interactions with the atmosphere and spacecraft. (Lin et al., 2003)

FIGURE 2. The motion of the two main footpoints for the 23 July 2002 flare observed by RHESSI. Top panel: the position of the moving footpoint versus time. Center panel: The speed computed from the top panel versus time. Bottom panel: the hard X-ray flux versus time. A rough correlation is evident between the speed and hard X-ray flux. (Krucker et al., 2003)

Accelerated ions. For the 23 July ’02 solar flare, RHESSI obtained the first high resolution spectroscopy of prompt de-excitation γ -ray lines, showing that the Fe, Mg, Si, Ne, C, and O had mass-dependent red shifts of 0.1–0.8%, implying downward motion of accelerated protons and alphas along magnetic field lines that are not radial, but tilted toward the Earth by ~40º (Smith et al., 2003). RHESSI also imaged a solar flare in a γ -ray line - the strong and extremely narrow (intrinsic width <~0.1 keV) 2.223 MeV neutron capture line – for the first time (Hurford et al., 2003), thus unambiguously locating the accelerated ions in the flare. Since then, RHESSI has imaged a number several more flares in this line, including the Halloween 2003 series of giant flares - October 28, 29 and November 2 (Hurford et al., 2006). Comparison of imaged and spatially-integrated fluences show that most, if not all, of the γ -ray line emission in every flare imaged was confined to compact sources with size scales of tens of arcsec or smaller, that are located in the flare active region. Thus, the γ -ray producing ions appear to be accelerated by the flare process and not by a widespread shock driven by a fast coronal mass ejection. Furthermore, the 28 October event yielded the first image to show double-footpoint γ -ray line sources straddling the flaring loop arcade, closely similar to what is seen in the HXR image (Figure 3), and strongly supporting a similar flare origin, e.g., magnetic reconnection, for the ion acceleration as for the electrons. With RHESSI's 35 arcsec resolution at this energy and limited statistics, it is not surprising that this is seen for only the most intense γ -ray line flare with very wide flare loop arcade.

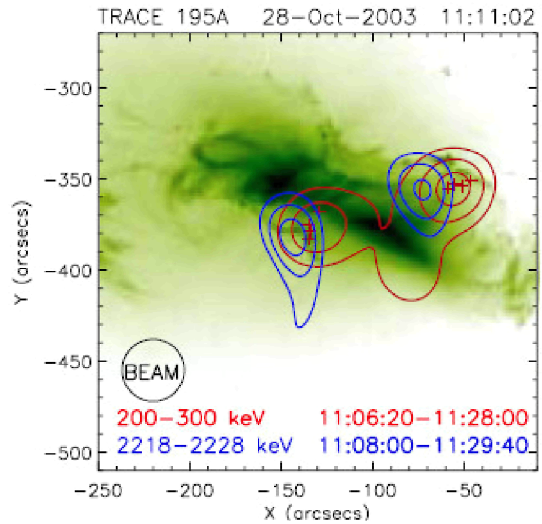


FIGURE 3. RHESSI γ -ray line image of the 28 October 2003 solar flare (Hurford et al., 2006). The blue contours show the flare-averaged (RHESSI was in shadow for the first few minutes of the flare) 2.223 MeV neutron-capture γ -ray line (produced by 10–100 MeV ions) image, together with the 200–300 keV hard X-ray continuum (produced by energetic electrons) image made through the same grids and using the same analysis procedure. The angular resolution is indicated by beam circle (upper right). The accelerated electrons and ions appear to be separated by ~10,000 km.

A major, as yet unexplained surprise of the RHESSI γ -ray line imaging was the finding that the γ -ray line footpoint sources in both the 23 July '02 and Oct '03 flares were displaced from the corresponding 0.2–0.3 MeV electron-bremsstrahlung emission footpoints by 14 and 17 ± 5 arcsec in the 28 Oct '03 flare , and by ~ 25 ± 5 arcsec in

23 July '02 flare. This implies spatial differences in acceleration and/or propagation between accelerated ions and electrons in these solar flares.

Magnetic reconnection & particle acceleration. RHESSI observations are generally consistent with magnetic reconnection playing a central role in solar flares. In many flares, such as 23 July '02, the coronal thermal source observed by RHESSI above the lower temperature loops seen by TRACE move upward with time, suggesting the energy release site moves to high altitudes with time, in agreement with classical flare models (Sturrock, 1966; Shibata, 1995). In some flares a second much weaker coronal source is detected above the normal thermal source (Sui and Holman, 2003). The centroids of the two sources, obtained at energies from ~8 to >20 keV, show a systematic behavior with the most energetic centroids located closest to the region in between the two sources with less and less energetic centroids the further away from that point. This is consistent with a temperature gradient away from that point, suggesting a large scale current sheet with energy release from magnetic reconnection in the region in between, again consistent with classical flare models.

For the 23 July '02 flare, assuming that Coulomb collisions dominate the energetic electron and ion energy losses (thick-target), we estimate a minimum of $\sim 2 \times 10^{31}$ ergs is released in accelerated > 18 keV electrons during the rise phase, with $\sim 10^{31}$ ergs in ions above 2.5 MeV and about the same in electrons above 30 keV released in the impulsive phase. There could be much more energy in accelerated particles if their spectra extends to lower energies. At the time of the soft X-ray plasma emission peak, the energy in the thermal plasma is about one order of magnitude less, thus confirming that a large fraction of the energy released in the flare goes into particle acceleration, especially electrons.

Thus a fundamental questions generally not addressed in flare particle acceleration models is: how can such a large fraction of the energy released in flares end up in accelerated electrons? The process of magnetic reconnection changes the magnetic topology allowing the energy in the magnetic field to be converted into fast flows. Thus, most of the energy is initially in the flowing ions. It is important to note here that *in situ* measurements in the Earth's distant (~60 Earth radii) magnetotail have showed strong evidence for electron acceleration to ~300 keV peaking in the ion diffusion region of a magnetic reconnection event (Oieroset et al 2003). Recently, Drake et al (2006) proposed that magnetic reconnection should generate multiple elongated magnetic islands. The magnetic tension in these islands will tend to decrease the elongation, and fast electrons in these islands will be Fermi-accelerated by reflecting off of the ends of the islands as they collapse. The pressure of the accelerated electrons eventually becomes large enough to stop the collapse. They argue that in this process a large fraction of the magnetic energy released by reconnection will go into electron acceleration. They are able to reproduce the electron spectrum detected in the distant magnetotail event, with the measured plasma parameters. Furthermore, recent measurements from the 4-spacecraft Cluster mission showed enhancements of energetic tens of keV electrons in magnetic islands in the magnetotail (Chen et al 2008). Although such direct comparison is not possible as yet for solar flares, their predicted electron spectra for solar flare conditions resemble those inferred from RHESSI solar flare HXR observations. As mentioned above, in large solar flares the accelerated ions above a few MeV contain a comparable amount of energy to the electrons, but how they might be accelerated in a process associated with magnetic reconnection is not clear.

On the other hand, the energetic ions in large gradual SEP events appear to be accelerated by an entirely different process not related to magnetic reconnection – namely acceleration by the collisionless shock driven by a fast, >~1000km/s coronal mass ejection at altitudes of several to 40 solar radii. RHESSI has detected γ -ray line emission from more than 25 solar flares through 2005, with SEP events detected near 1 AU for many of them, including the 20 Jan 2005 event that is the most intense at energies above a few hundred MeV since the February 1958 event. It is also the event where the SEPs arrive quickest, within minutes, after the flare X-ray peak. The very limited CME observations (the SOHO coronagraph was quickly saturated by the penetrating SEPs!) indicate that the CME velocity in this event ranged from ~2500 to ~3500 km/sec, implying that the CME was only < 2-3 Rs above the solar surface when the first GeV protons were released. It is uncertain whether a shock could form and accelerate particles to GeV energies in the short time and distance available. Very preliminary analysis suggests that in the flare-accelerated proton spectrum (derived from RHESSI γ -ray observations) is extremely hard; similarly, the SEP proton spectrum at 1 AU) is also extremely hard.

MICROFLARES, TYPE III RADIO BURSTS, AND IMPULSIVE SEP EVENTS AT 1 AU

The Sun also accelerates particles extremely frequently, in much weaker bursts. The large solar flares discussed above occur on average about once a month during solar maximum, but smaller flares occur much more frequently, ranging down to microflares (~10^{-6} the energy release of the largest flares) that occur every few minutes near solar maximum. Previous measurements show that microflares also produce non-thermal HXR emission (Lin et al., 1984, 2001), implying electron acceleration, but generally to lower <20 keV energies than large flares. RHESSI provides uniquely high sensitivity in the ~3-15 keV range, and near solar maximum X-ray emission in this energy range was continuously present (Fig. 4, top), possibly made up of many small microflares (Krucker et al 2002), The microflares that are clearly visible typically show non-thermal HXR emission in the form of a steep power law extending up to ~10 keV, observed above the ~10^7 K thermal emission (Fig. 4, bottom). Recently, Christe et al (2008) and Hannah et al (2008) have systematically searched five years of RHESSI observations and found over 25,000 HXR microflares; essentially all of these occur in active regions and show evidence for non-thermal HXR emission, suggesting that they are similar to large flares.

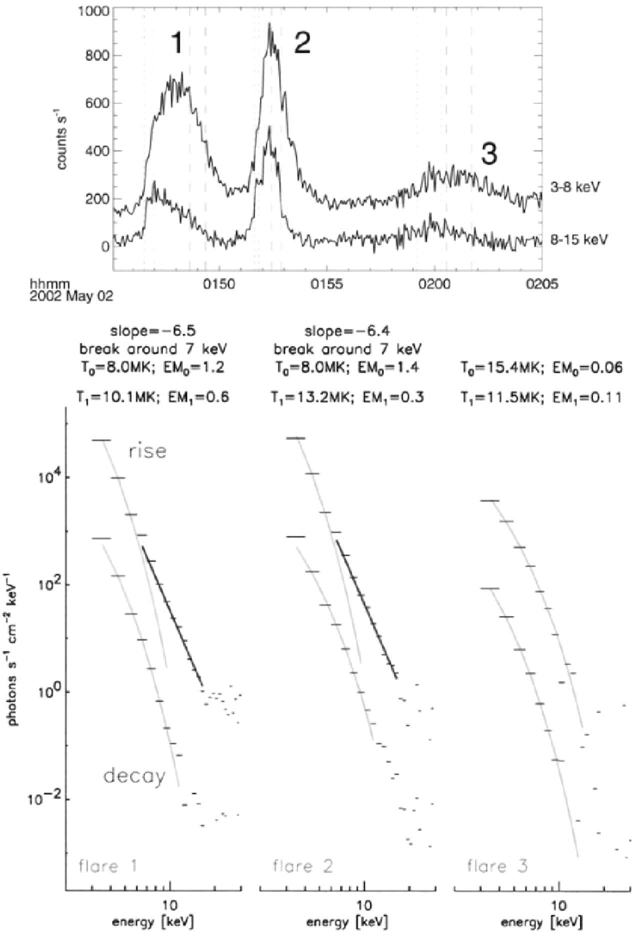


FIGURE 4. Top: X-ray count rates from a sun-lit portion of a single orbit of RHESSI, showing at least three microflares. Bottom: Energy spectra for the three microflares, showing the ~10^7 K thermal emission at the time of peak soft X-ray emission, and the non-thermal power-law tail on the rise. No non-thermal emission was detected for the third event that was on the West limb of the Sun (Krucker et al., 2002).

Electrons accelerated at the Sun will also produce radio emission through wave-particle interactions and through synchrotron emission. When impulsively accelerated electrons escape from the Sun, the faster electrons run ahead of the slower ones, generating bump-on-tail velocity distribution that is unstable to the growth of Langmuir waves. These waves then interact with the ambient plasma to produce radio emission at the plasma frequency or its harmonic. As the electrons travel to lower and lower density the radio emission goes to lower frequencies, leading to the characteristic fast drift solar type III radio burst. When the type III burst drifts down to near the local plasma frequency at 1 AU, the escaping electrons and Langmuir waves can be directly detected *in situ* (Lin et al 1984). A large fraction of type III bursts are unaccompanied by flares or microflares, and on occasion, type III storms, where bursts occur every few seconds for a period of days, are detected at low, <~MHz, frequencies. It should be noted that many HXR flares and microflares do not have associated type III radio bursts—presumably the electrons are trapped and unable to escape. On the other hand, many type III bursts are not accompanied by hard X-rays—either the electrons are accelerated high in the corona where the ambient density and/or number of accelerated electrons are too low for detectable hard X-ray emission.

The type III bursts that extend into the interplanetary medium are often associated with an impulsive SEP event detected in the IPM near 1 AU. Many impulsive electron events often extend down to below ~1 keV (Lin et al., 1996) and many are detected even in the energy range ~0.1 to ~1 keV (Gosling et al., 2003). Such low energy electrons must originate high in the corona since energy losses to Coulomb collisions limit the amount of coronal material they can traverse.

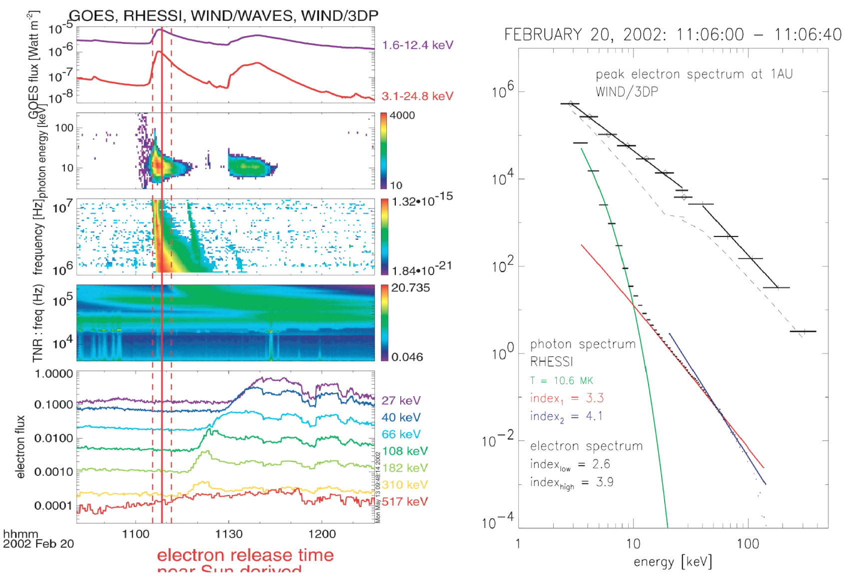


FIGURE 5. Example of a flare hard X-ray burst observed by RHESSI with corresponding solar type III radio burst and energetic electrons (and Langmuir waves) observed in situ by theWIND spacecraft (Krucker and Lin, 2002). Top panel: GOES soft X-rays; second panel: Spectrogram of RHESSI X-rays from 3 to 250 keV; third and fourth panels: radio emission observed by the WIND WAVES instrument; fifth panel: Electrons from ~20 to ~400 keV observed by WIND 3-DP instrument. b. Top trace: energy spectrum of the electrons observed by WIND 3-D P instrument; bottom trace: X-ray spectrum observed by RHESSI, fitted to a thermal spectral shape at low energies, and to a double power-law at high energies (Krucker and Lin, 2002).

For many of the impulsive electron events observed at energies of tens of keV, the inferred injection of electrons back at the Sun appears to be delayed by ~10 minutes from the start of the type III radio burst, suggesting acceleration by a coronal or CME shock wave (Krucker et al., 1999; Haggerty & Roelof, 2002). For several extremely scatter-free electron events, Wang et al (2007) was able to infer the injection profiles at the Sun, and found that the~0.4 to ~8 keV electrons show onsets starting prior to or at the type III burst injection, early enough that they could be the source of the radio emission, while the injection for >15 keV electrons is delayed by ~8 minutes relative to the type III burst injection. At 1 AU the Langmuir waves responsible for type III radio emission are detected primarily when ~2-12 keV electrons arrive at the spacecraft (Lin, 1985). Sometimes the HXR-producing and escaping electrons appear to come from a single acceleration, resulting in a HXR burst occuring nearly simultaneous with a type III burst starting at high frequencies (Fig. 5a). Fig. 5b shows the flare X-ray spectrum (both thermal and HXR) observed by RHESSI, and the electron spectrum measured by the WIND 3D Plasma & Energetic Particle (3-DP) experiment (Lin et al., 1995). Both spectra fit a double power-law with a downward break at a few tens of keV.

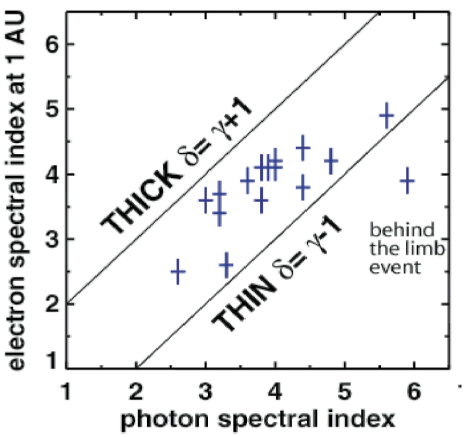


FIGURE 6. Comparison of power-law exponent for the hard X-ray spectrum at the peak of the burst measured by RHESSI with the power-law exponent for the electron spectrum measured at the time of maximum at each energy. δ and γ are the power-law exponents for the electron and hard X-ray spectra, respectively (Krucker et al., 2007).

Figure 6 shows a comparison of power-law exponents above the break for the electron spectra observed by WIND at 1 AU, with exponents for the HXR photon spectra observed by RHESSI, for ~15 events that have the timing consistent with a single acceleration (Krucker et al., 2007). The points should fall on the "Thick" target line if the escaping electrons directly sample the accelerated population (without any energy changes), and the accelerated electrons produce the HXRs as they lose all their energy to Coulomb collisions, i.e., if the acceleration occurs high in the corona and some of the electrons escape to the IPM while the rest are trapped in the solar atmosphere. The "thin" target line would be for the case where the electrons produce the HXRs as they escape, but the collisions are too few to modify the spectrum. The data points appear to show a good linear correlation with larger electron exponents for larger HXR exponents (with the exception of the behind the limb event), suggesting that the electrons producing the HXRs indeed are related to the electrons in these impulsive events observed near 1 AU. The RHESSI images typically show the HXRs come from footpoints where the ambient density is high—presumably the electrons are losing their energy to collisions, i.e., thick target. The points, however, do not lie on the "Thick" line or the "Thin" line, indicating that the relationship is more complex than these simple models. The number of escaping electrons, however, is typically only ~0.1-1% of the number required to produce the HXR emission.

In the future, space missions going close to the Sun – Solar Orbiter ().22 AU), Solar Probe Plus (9.5 solar radii), and Solar Sentinels (4 spacecraft going to ~0.25 AU) – will provide definitive observations to resolve the relationship between particle acceleration at the Sun and in the IPM.

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