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Relationship of solar flare accelerated particles to solar energetic particles (SEPs) observed in the interplanetary medium

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Abstract

Observations of hard X-ray (HXR)/γ-ray continuum and γ-ray lines produced by energetic electrons and ions, respectively, colliding with the solar atmosphere, have shown that large solar flares can accelerate ions up to many GeV and electrons up to hundreds of MeV. Solar energetic particles (SEPs) are observed by spacecraft near 1 AU and by ground-based instrumentation to extend up to similar energies as in large SEP events, but it appears that a different acceleration process, one associated with fast coronal mass ejections is responsible. Much weaker SEP events are observed that are generally rich in electrons, ^{3}He, and heavy elements. The energetic particles in these events appear to be similar to those accelerated in flares. The Ramaty high energy solar spectroscopic imager (RHESSI) mission provides high-resolution spectroscopy and imaging of flare HXRs and γ-rays. Such observations can provide information on the location, energy spectra, and composition of the flare accelerated energetic particles at the Sun. Here, preliminary comparisons of the RHESSI observations with observations of both energetic electron and ion near 1 AU are reviewed, and the implications for the particle acceleration and escape processes are discussed.

Keywords: RHESSI; SEPs; γ-rays; Flares; CMEs; Electrons

1. Introduction

The Sun is the most energetic particle accelerator in the solar system. In large solar flares, nuclear γ-ray lines and pion decay emission have been detected that are produced by energetic ions with ~10–100 MeV and GeV energies, respectively, in nuclear collisions with the solar atmosphere (Lin et al., 2003). HXR/γ-ray continuum emissions, produced by bremsstrahlung collisions of energetic electrons with the atmosphere, have been observed up to >~100 MeV. Ions and electrons up to about the same energies have been directly detected by in situ space observations (ground-based observations for the most energetic ions) in the interplanetary medium (IPM) near 1 AU in SEP events. Somewhat surprisingly, the energetic ions and electrons that produce the HXR and γ-ray emissions in solar flares appear to be accelerated by a different process than the SEPs observed near 1 AU – those appear associated with fast coronal mass ejections (CMEs) and the shocks they drive, or possibly by high coronal acceleration processes. These extremely energetic particle acceleration phenomena are associated with enormous transient releases of energy, >~10^{32} ergs, by the Sun. For large solar flares the energy in accelerated particles can be a significant fraction of the total energy released (Lin and Hudson, 1976). For the fast CMEs, however, most of the energy released is contained in the ~10^{15}–10^{16} grams of coronal material ejected at high (>~1000 km/s) speed.

The Sun exhibits a wide range of acceleration phenomena. Flares of all sizes, ranging down to microflares (~10^{-6} the energy release of the largest flares) or

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smaller, appear to accelerate electrons (Lin et al., 2001). For flares, the frequency of occurrence increases rapidly as the size decreases, suggesting the possibility that the total averaged energy release might be significant for the heating of the corona.

Solar type III radio bursts are generated by electrons accelerated in the corona that escape to the IPM. A large fraction, perhaps most, of type III bursts are unaccompanied by flares. In the IPM near 1 AU, impulsive electron events are often detected at ~1–100 keV energies, sometimes down to energies of ~0.1 keV. 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 (Lin et al., 1996). These impulsive events are closely associated with type III bursts that extend into the IPM. The more energetic (>~30 keV) electrons in these events, however, often show delayed onsets that suggest injections ~10 min after the type III burst at the Sun.

Low energy ions, up to ~MeV/nucleon energies, are observed to accompany impulsive electron events (Reames et al., 1985). These are typically ^{3}He-rich (enhancements of $\sim 10^2 - 10^4$ over solar abundance) and rich in heavy elements such as Fe. Although the solar wind is rarely enriched in ^{3}He, there is often a enhanced background of suprathermal ^{3}He. This is likely due to numerous injections that are not large enough to detect as impulsive events.

The relationship between the energetic particles at the Sun and the energetic particles observed near 1 AU is not understood. Here we compare the energetic particle measurements from the Wind and ACE spacecraft near 1 AU with RHESSI observations that provide detailed information on the energetic particle populations at the Sun. In particular, the October 28 and November 2, 2003 large flares were the first for which RHESSI had γ-ray line observations and SEP ions were observed by Wind and ACE near 1 AU. In addition, we summarize the comparisons between RHESSI hard X-rays observations and energetic electron observations from Wind.

2. Energetic ions at the Sun and SEPs at 1 AU

RHESSI has detected γ-ray line emission from six solar flares to date, with SEP events detected near 1 AU for three of them: October 28, 29, and November 2, 2003. A major SEP event occurred following the 2002 April 21 flare that was well observed by RHESSI (Gallagher et al., 2002), but no γ-ray line emission was detected, indicating that no significant acceleration of energetic (>~10 MeV) ions occurred in the flare. The flare and CME initiation were closely related in time, with the impulsive hard X-ray emission starting the whole process.

The first γ-ray line flare detected by RHESSI (Lin et al., 2003), a GOES class X4.8 on 23 July 2002, was accompanied by a very fast (2180 km/s) and wide CME. Since it was located at S13 E72 near the east limb of the Sun, it was not surprising that no SEPs were detected by the ACE or Wind spacecraft near the Earth. No SEPs were detected by the Mars Global Surveyor (MGS) spacecraft located on the opposite side of the solar system very close to the nominal Parker spiral field from the flare region, however, even though two previous SEP events (July 16 and 19) were detected from the same active region. This suggests that even a very fast and wide CME may not always accelerate SEPs.

SEP events were detected from the 28 October, 29 October, and 2 November 2003 γ-ray line flares observed by RHESSI. For 28 October (Fig. 1) and 2 November, a preliminary estimate of the number

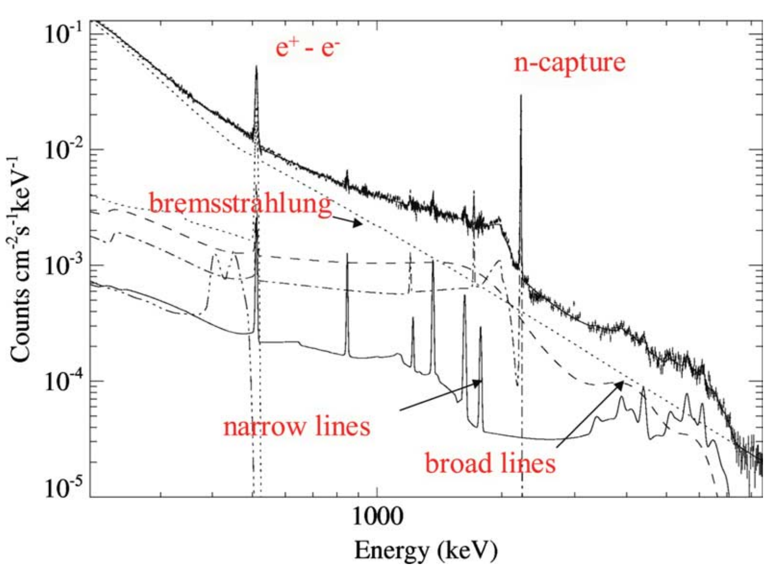

Fig. 1. γ-Ray count rate spectrum observed by RHESSI in the 28 October X17 solar flare (Smith et al., 2004).

Table 1
γ-Ray line – SEP comparison

	October 28, 2003	November 2, 2003
Energetic particles at the Sun		
2.2 MeV line fluence (photons/cm^2)	>1380 ± 11	518 ± 8
4.4 MeV	>91 ± 11	35 ± 7
2.2/4.4 ratio	15.2	14.8
Power law index	3.8	3.8
Np (>30 MeV)	$>7.2 \times 10^{33}$	2.7×10^{33}
Solar energetic particles at 1 AU (fluence integrated over the event)		
Power law index above 30 MeV	3.4	3.5
Np (>30 MeV)	1.8×10^{34}	9.1×10^{32}

(>30 MeV) and exponent of a power-law fit to the spectra of energetic protons (Table 1) were obtained from the observed narrow line fluences of the 2.223 MeV neutron-capture line and the 4.443 MeV carbon line (Ramaty and Murphy, 1987). (During the 29 October flare, RHESSI passed close to the South Atlantic Anomaly so the background is high and the line fluences uncertain.) These can be compared to the number and power-law exponent for the energetic protons observed near 1 AU (using ACE, GOES 10, and SAMPEX spacecraft to provide full energy coverage), integrating over the entire event to obtain the fluences. The observed proton spectra are double power-law with a downward break at ∼20–30 MeV; the exponent above the break is given in Table 1. The integrated fluence will probably overestimate the number of particles accelerated/injected near the Sun, since scattering in the interplanetary medium will allow some particles to cross 1 AU distance more than once (Li et al., 2003).

The spectral exponents for the γ-ray producing protons (3.8) and the protons at 1 AU (3.4–3.5) are essentially the same, within measurement uncertainties, while the total numbers are within a factor of 2–3. Furthermore, very preliminary estimates of the Ne line fluences, which are sensitive to protons down to ∼2.5 MeV, indicate that they are unusually low, suggesting that the γ-ray producing proton spectrum flattens at low energies, similar to what is observed for the protons detected at 1 AU. Given that our current understanding is that the γ-ray producing protons are accelerated by a different process (flares) from the SEP protons (fast CMEs), this is very surprising. The detailed analysis of the full γ-ray spectrum, lines and continuum, will provide information on the composition of the energetic heavy ions (since they produce broad lines), which can then be compared to the observed composition of the SEPs.

3. Energetic electrons at the Sun and at 1 AU

Electrons accelerated at the Sun and interacting with the solar atmosphere will produce hard X-rays through bremsstrahlung collisions, and radio emission through wave particle interactions and through synchrotron emission. As the faster electrons run ahead of the slower ones when the impulsively accelerated electrons escape from the Sun, bump-on-tail distributions will be generated that are 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.

If the HXR-producing and escaping electrons come from a single acceleration, a hard X-ray burst should be detected with a near simultaneous type III burst starting at high frequencies. 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. Fig. 2(a) shows an example of this, while Fig 2(b) 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.

Fig. 3 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. 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 rough 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 at the Sun indeed are somehow related to the electrons in these impulsive events observed in the IPM. 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.

As mentioned above, for many of the impulsive electron events observed at energies of tens of keV,

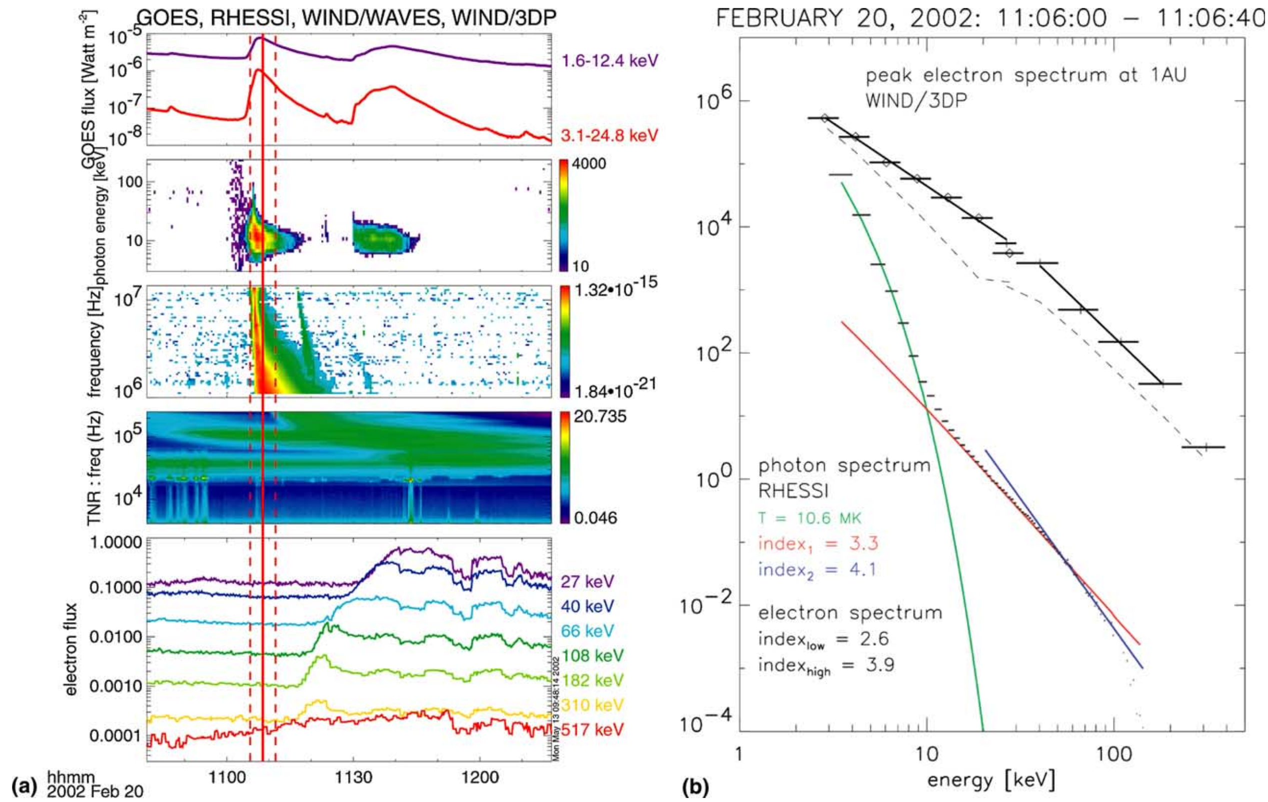

Fig. 2. (a) Example of a flare hard X-ray burst observed by RHESSI with corresponding solar type III radio burst and energetic electrons (and Langmuir waves) observed in situ by the WIND spacecraft (Krucker and Lin, 2002). Top panel: GOES soft X-rays; second panel: Spectrogram of RHESSI X-rays from 3 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).

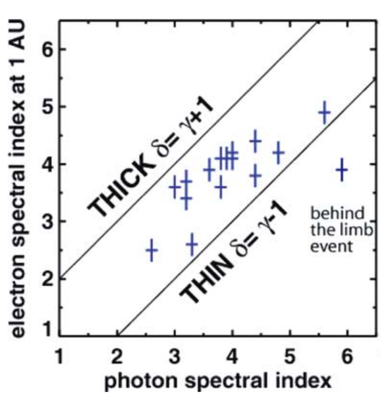

Fig. 3. Comparison of power-law exponent for the hard X-ray spectrum at the peak of the burst measured by RHESSI with the power-law exponent for the electron spectrum measured at the time of maximum at each energy. δ and γ are the power-law exponents for the electron and hard X-ray spectra, respectively (Krucker et al., 2004).

the inferred injection of electrons back at the Sun appears to be delayed by ~10 min from the start of the type III radio burst, suggesting acceleration by a coronal or CME shock wave (Krucker et al., 1999, 2002). Many impulsive electron events often extend down to below ~1 keV (Lin et al., 1996) and many are detected even in the energy range ~0.1–1 keV (Gosling et al., 2003).

Recently, WIND 3DP observations (which covers from a few eV up to >~300 keV electrons) of three scatter-free impulsive electron events with delayed onset at >~30 keV (Haggerty and Roelof, 2002) were carefully analyzed to accurately determine the injection near the Sun (Wang et al., 2004). The event shown in Fig. 4 extends down to < ~0.4 keV, and it shows a rapid, nearly symmetric rise and decay. This indicates essentially scatter-free propagation from the Sun to 1 AU, since scattering would result in a slowly decaying tail in the time profile (Lin, 1974).

A model is applied where the injection time profile is assumed to be triangular, with equal time for rise to the peak and decay back to zero (Fig. 5). The injected electrons were assumed to travel ~1.2 AU, the Parker spiral field line length appropriate for the measured ~400 km/s solar wind. Model time profiles were calculated using the measured spectrum of the event and integrating over the width of each energy channel. The injection time and width were then adjusted to fit the

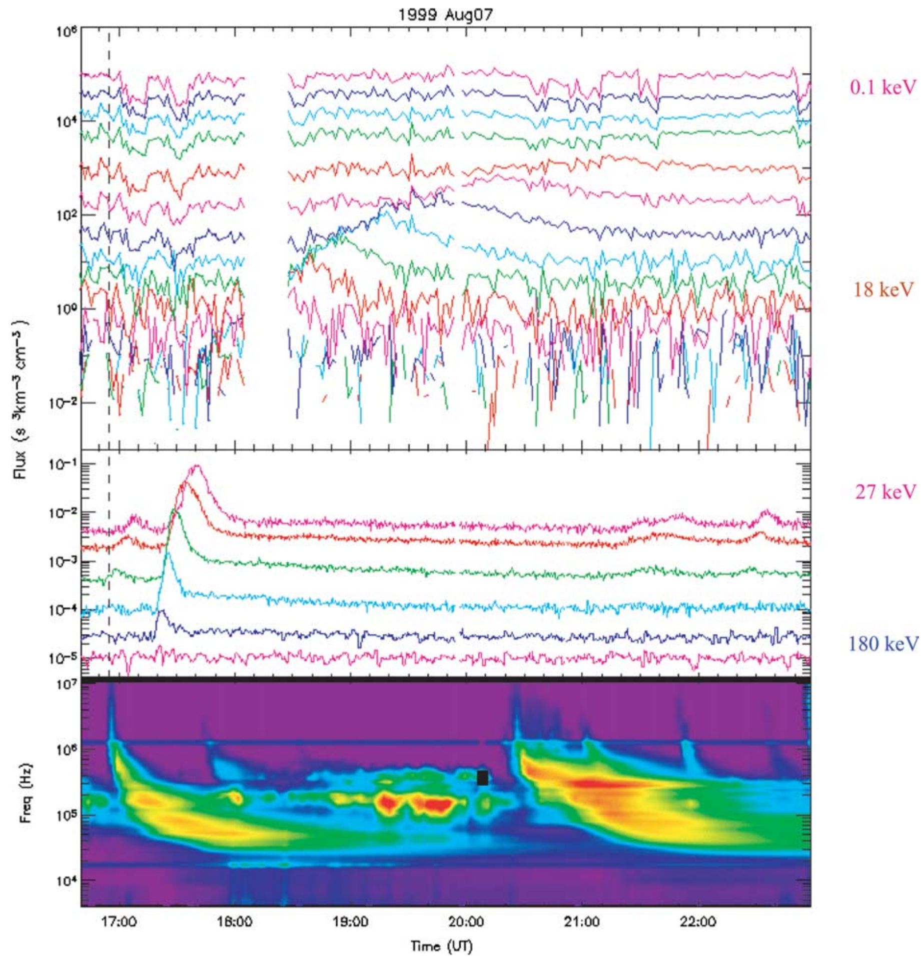

Fig. 4. Scatter-free impulsive electron event observed by the WIND 3-D P instrument at energies from 0.1 to 300 keV (top two panels), and radio dynamic spectrum from the WIND WAVES instrument (Wang et al., 2004).

observed profile in each energy channel. As can be seen (Fig. 5), the injection profiles at energies above ~20 keV are similar, with comparable widths of ~5 min. The best-fit injection times are the same at all energies above ~20 keV, confirming that ~1.2 AU is appropriate for the path length. The onset of the injection for >20 keV electrons is clearly delayed by ~8 min relative to the type III burst injection.

A data gap and poor statistics in the ~8–20 keV measurements precluded accurate timing for those energies. The inferred injection profiles for ~0.4–8 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. Previous in situ observations at 1 AU of the Langmuir waves responsible for type III radio emission show that they occur primarily when ~2–12 keV electrons arrive at the spacecraft (Lin, 1985).

The peaks of the injection for ~0.4–8 keV electrons, however, are delayed relative to the injection peaks for >~20 keV electrons, and the durations are much longer, ~30–70 min. In the same study the other two other scatter-free events with delays at energies >~20 keV also show the same injection characteristics.

Thus, the injection at the Sun of electrons at energies below ~10 keV appears to be the source of the solar type III radio burst, while the delayed injection of >~20 keV electrons points to a second injection, possibly related to a coronal or CME shock wave as suggested by Krucker et al. (1999) and Haggerty and Roelof (2002).

It should be noted that many hard X-ray bursts 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. Further more detailed comparisons between RHESSI HXR/γ-ray emission and SEPs observed by ACE and WIND in the IPM will help to resolve the relationship between particles at the Sun and in the IPM.

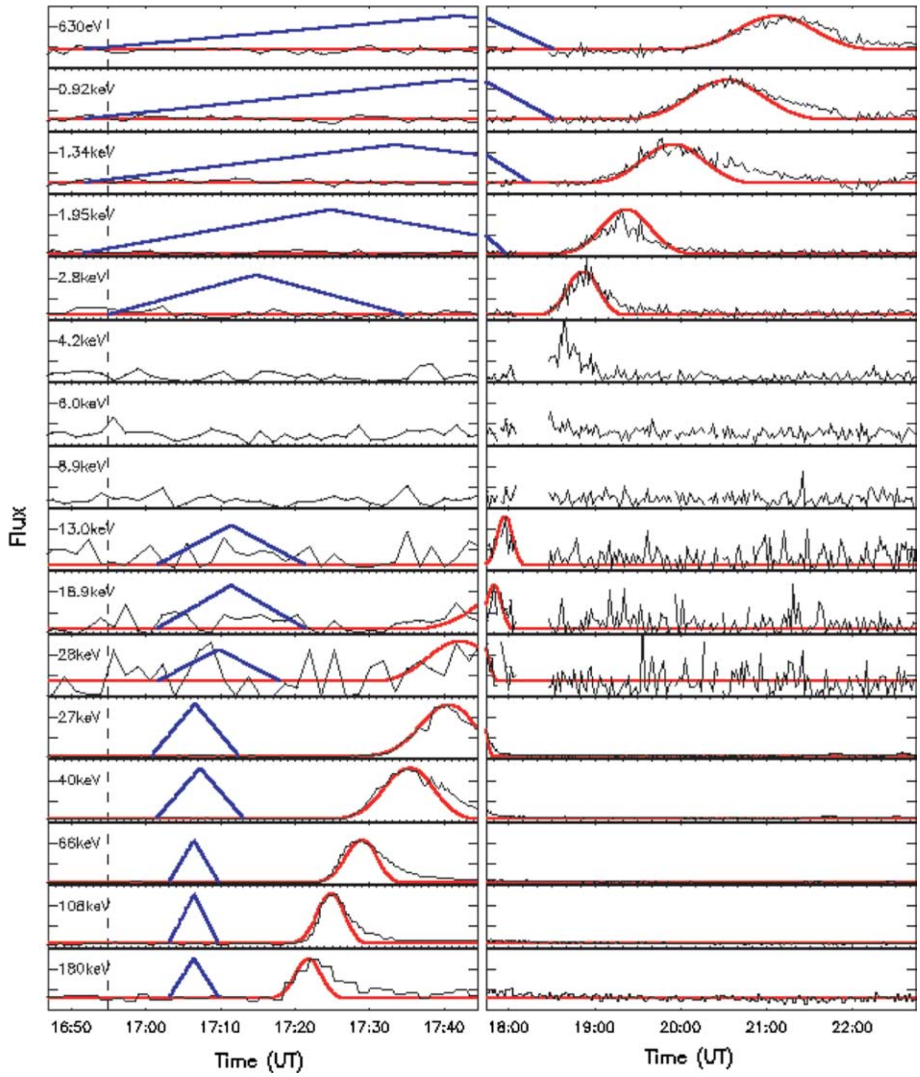

Fig. 5. The inferred injection time profiles at the Sun (left triangles) and fit (smooth curves on right) to the time profiles observed by the WIND 3-D P instrument near 1 AU (Wang et al., 2004).

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References

Gallagher, P., Dennis, B., Krucker, S., Schwartz, R., Tolbert, K. RHESSI and TRACE observations of the 21 APRIL 2002 X1.5 Flare. Solar Phys. 210, 341–356, 2002.

Gosling, J.T., Skoug, R.M., McComas, D.J. Solar electron bursts at very low energies: evidence for acceleration in the high corona. Geophys. Res. Lett. 30 (13), 1697, 2003.

Haggerty, D.K., Roelof, E.C. Impulsive near-relativistic solar electron events: delayed injection with respect to solar electromagnetic emission. Astrophys. J. 579, 841–853, 2002.

Krucker, S., Larson, D.E., Johnson, B.P., Lin, R.P. On the origin of impulsive electron events observed at 1 AU. Astrophys. J. 519, 864–875, 1999.

Krucker, S., Lin, R.P. Relative timing and spectra of solar flare hard X-ray sources. Solar Phys. 210, 229–243, 2002.

Krucker, S.R., Lin, P., Kontar, E.P. Comparing solar hard X-ray emissions and impulsive electron events seen at 1 AU, 2004 Joint Assembly, 17–21 May, Montreal, Canada, paper SH22A-02, 2004.

Li, G., Zank, G.P., Rice, W.K.M. Energetic particle acceleration and transport at coronal mass ejection-driven shocks. J. Geophys. Res. 108 (A2), 1082, 2003, SSH 10-1 to 10-22.

Lin, R.P. Non-relativistic solar electrons. Solar Phys. 16, 189–256, 1974.

Lin, R.P. Energetic solar electrons in the interplanetary medium. Solar Phys. 100, 537–561, 1985.

Lin, R.P., Hudson, H.S. Non-thermal processes in large solar flares. Solar Phys. 50, 153–178, 1976.

Lin, R.P., Anderson, K.A., Ashford, S., et al. A three-dimensional (3-D) plasma and energetic particle experiment for the WIND spacecraft of the ISTP/GGS mission. Space Sci. Rev. 71, 125–153, 1995.

Lin, R.P., Larson, D., McFadden, J., et al. Observation of an impulsive solar electron event extending down to ~0.5 keV energy. Geophys. Res. Lett. 23, 1211–1214, 1996.

Lin, R.P., Feffer, P.T., Schwartz, R.A. Solar hard X-ray bursts and electron acceleration down to 8 keV. Astrophys. J. Lett. 557, L125, 2001.

Lin, R.P., Krucker, S., Hurford, G.J., et al. RHESSI observations of particle acceleration and energy release in an intense solar gamma-ray line flare. Astrophys. J. Lett. 595, L69–L76, 2003.

Ramaty, R., Murphy, R.J. Nuclear processes and accelerated particles in solar flares. Space Sci. Rev. 45, 213, 1987.

Reames, D.V., von Rosenvinge, T.T., Lin, R.P. Solar ^{3}He-rich events and non-relativistic electron events: a new association. Astrophys. J. 292, 716, 1985.

Smith, D.M., Shih, A.Y., Murphy, R.J., et al. RHESSI spectroscopy of nuclear de-excitation lines in X-class flares, in: American Astronomical Society 204th Meeting, Denver, Colorado, 30 May–3 June, paper 2.01, 2004.

Wang, L., Lin, R.P., Krucker, S., Gosling, J.T. Geophys. Res. Lett., 2004 (in preparation).