REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-01-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
06-01-2009	REPRINT	

4. TITLE AND SUBTITLE
Viewing radiation signatures of solar energetic particles in interplanetary space

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62601F

6. AUTHORS
S. W. Kahler
B. R. Ragot*

5d. PROJECT NUMBER
1010

5e. TASK NUMBER
RD

5f. WORK UNIT NUMBER
A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory /RVBXS
29 Randolph Road
Hanscom AFB, MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RV-HA-TR-2009-1106

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBXS

11. SPONSOR/MONITOR'S REPORT

20091207059

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Reprinted from *Advances in Space Research*, Vol. **43**, 2009 pp. 1484-1490
NRC Senior research associate

14. ABSTRACT
A current serious limitation on the studies of solar energetic particle (SEP) events is that their properties in the inner heliosphere are studied only through in situ spacecraft observations. Our understanding of spatial distributions and temporal variations of SEP events has come through statistical studies of many such events over several solar cycles. In contrast, flare SEPs in the solar corona can be imaged through their radiative and collisional interactions with solar fields and particles. We suggest that the heliospheric SEPs may also interact with heliospheric particles and fields to produce signatures which can be remotely observed and imaged. A challenge with any such candidate signature is to separate it from that of flare SEPs. The optimum case for imaging high-energy ($E > 100$ MeV) heliospheric protons may be the emission of π^0-decay γ-rays following proton collisions with solar wind (SW) ions. In the case of $E > 1$ MeV electrons, gyrosynchotron radio emission may be the most readily detectible signal. In both cases we may already have observed one or two such events. Another radiative signature from nonthermal particles may be resonant transition radiation, which has likely already been observed from solar flare electrons. We discuss energetic neutrons as another possible remote signature, but we rule out γ-ray line and 0.511 MeV positron annihilation emission as observable signatures of heliospheric energetic ions. We are already acquiring global signatures of large inner-heliospheric SW density features and of heliosheath interactions between the SW and interstellar neutral ions. By finding an appropriate observable signature of remote heliospheric SEPs, we could supplement the in situ observations with global maps of energetic SEP events to provide a comprehensive view of SEP events.

15. SUBJECT TERMS
Solar energetic particles   Interplanetary magnetic fields   Coronal mass ejections

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCL	UNCL	UNCL	UNL		Steven W. Kahler
					19B. TELEPHONE NUMBER *(Include area code)*

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 43 (2009) 1484–1490

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Viewing radiation signatures of solar energetic particles in interplanetary space

S.W. Kahler *, B.R. Ragot [1]

Air Force Research Laboratory, RVBXS, 29 Randolph Road, Hanscom AFB, MA 01731, USA

Received 18 August 2008; received in revised form 14 November 2008; accepted 6 January 2009

Abstract

A current serious limitation on the studies of solar energetic particle (SEP) events is that their properties in the inner heliosphere are studied only through in situ spacecraft observations. Our understanding of spatial distributions and temporal variations of SEP events has come through statistical studies of many such events over several solar cycles. In contrast, flare SEPs in the solar corona can be imaged through their radiative and collisional interactions with solar fields and particles. We suggest that the heliospheric SEPs may also interact with heliospheric particles and fields to produce signatures which can be remotely observed and imaged. A challenge with any such candidate signature is to separate it from that of flare SEPs. The optimum case for imaging high-energy ($E > 100$ MeV) heliospheric protons may be the emission of π^0-decay γ-rays following proton collisions with solar wind (SW) ions. In the case of $E > 1$ MeV electrons, gyrosynchrotron radio emission may be the most readily detectible remote signal. In both cases we may already have observed one or two such events. Another radiative signature from nonthermal particles may be resonant transition radiation, which has likely already been observed from solar flare electrons. We discuss energetic neutrons as another possible remote signature, but we rule out γ-ray line and 0.511 MeV positron annihilation emission as observable signatures of heliospheric energetic ions. We are already acquiring global signatures of large inner-heliospheric SW density features and of heliosheath interactions between the SW and interstellar neutral ions. By finding an appropriate observable signature of remote heliospheric SEPs, we could supplement the in situ observations with global maps of energetic SEP events to provide a comprehensive view of SEP events.
Published by Elsevier Ltd. on behalf of COSPAR.

Keywords: Solar energetic particles; Interplanetary magnetic fields; Coronal mass ejections

1. Introduction

Forecasting the occurrence of SEP events has become increasingly important as we consider their impact on the human exploration of space (Turner, 2006). At the current time we must rely on solar flare and coronal mass ejection (CME) signatures to predict the temporal, spatial, and energetic variations of heliospheric SEP events, but the presumed SEP production in CME-driven shocks can be only loosely connected to those solar signatures (Kahler, 2001). Furthermore, we rely on statistical studies of in situ observations to determine the characteristics of the heliospheric SEP events. Although the 1 AU in situ observations give us detailed information on heliospheric SEP spectra and composition, the lack of a complementary global context for SEP production and the loss of SEP source information imposed by particle scattering on magnetic fluctuations during SEP transport in the inner heliosphere are clearly severe impediments for our characterization and understanding of those SEP events. The low ambient densities and weak magnetic fields of the heliosphere restrict any radiative SEP signatures to low levels not yet observed. In contrast to these limitations, the SEPs accelerated in solar coronal flare structures are remotely observed and diagnosed with microwave, optical, X-ray, and γ-ray emission and neutron detections. The RHESSI spacecraft is a solar observatory that provides

* Corresponding author.
E-mail address: stephen.kahler@hanscom.af.mil (S.W. Kahler).
[1] NRC Senior Research Associate.

0273-1177/$36.00 Published by Elsevier Ltd. on behalf of COSPAR.
doi:10.1016/j.asr.2009.01.013

dedicated solar flare observations in the X-ray and γ-ray range up to 20 MeV with good spatial, temporal and spectral resolution (Lin et al., 2002).

Here we consider some possible remote signatures of heliospheric SEPs that might serve as future observable diagnostics. Our recent calculations of γ-ray line and continuum emissions from SEP interactions with solar wind (SW) ions (Kahler and Ragot, 2008) are briefly reviewed. We also examine several other SEP interactions that might serve to produce observable heliospheric SEP signatures. It is important that we consider all possible forms of remote SEP information – radiative, magnetic, electric, particle, or other. We point out that at the relatively low energies of SW particles, remote observations, perhaps not thought possible several decades ago, are now becoming a reality and will complement various in situ observations in the heliosphere and at the termination shock and heliosheath.

2. Candidate SEP signatures

2.1. γ-Ray continuum emission

We have recently considered (Kahler and Ragot, 2008) the possibility of remote detection of γ-rays produced in the near-Sun heliosphere by the interaction of very intense SEPs with SW particles, as shown in Fig. 1. This work was motivated by three factors. First, in the galaxy γ-ray line (Tatischeff and Kiener, 2004) and high-energy ($E >$ 70 MeV) continuum emission (Strong and Mattox, 1996) resulting from cosmic ray collisions with interstellar gas and dust has been observed. Second, SEP spectra and temporal variations for relatively large gradual events have been well characterized during the past solar cycle (Mewaldt et al., 2005), providing a SEP data base for selecting events to model in the near-Sun heliosphere. Finally, the GLAST spacecraft (Bhattacharjee, 2008), launched on 2008 June 11, will provide a new capability for sensitive measurements of γ-rays from heliospheric SEPs.

Two γ-ray regimes were explored (Kahler and Ragot, 2008). First, we considered γ-ray line emission resulting from excitation by 3–30 MeV nuc^{-1} ions on SW gas and dust in the ~5–15 $R_\odot$ region using the estimated peak 3–30 MeV proton spectrum of the large gradual SEP event of 2003 October 28 and the excitation cross sections of Kozlovsky et al. (2002). The calculated intensities for the strongest lines (1.37, 4.44, and 6.13 MeV of ^{24}Mg, ^{12}C, and ^{16}O, respectively) were slightly lower than the combined observed diffuse extragalactic component background (Strong et al., 1996) and the weaker calculated background from the inverse Compton scattering of cosmic ray electrons on the solar photon halo (Moskalenko et al., 2006). Intensities consistent with the inverse Compton scattered component have recently been detected in the two higher energy ranges of 100–300 MeV and >300 MeV by Orlando and Strong (2008). However, over the short (~1–10 h) timescale of the peak of a gradual SEP event less than a single count would be recorded in the GLAST Burst Monitor, rendering this approach hopeless.

The prospects for an event detection were more favorable, however, for π^0-decay γ-rays resulting from collisions of high energy ($E \gtrsim$ 300 MeV) SEP protons on SW ions. We used an E^{-2} differential energy spectrum to represent the 2005 January 20 SEP event peak (Fig. 2) and calculated not only that the π^0-decay γ-ray intensity was three orders of magnitude above background but that over the event peak hour the Large Area Telescope (LAT) on GLAST would have detected $\gtrsim 10^4$ counts (using the correct 0.6 cm^{-2} s^{-1} sr^{-1} value for the γ-ray intensity of I_{π^0}, which we erroneously took as 0.3 cm^{-2} s^{-1} sr^{-1}). The SEP differential fluence spectrum for the January 20 event has also

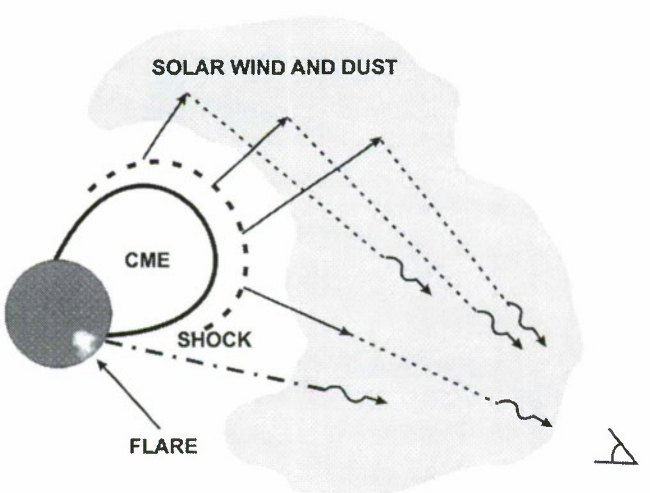

Fig. 1. γ-Ray imaging of both flare (dashed-dot line and wiggly arrow) and interplanetary (thin dashed lines and wiggly arrows) SEP populations. The CME drives a shock (thick dashed line) from which SEPs propagate outward (straight arrows) to interact with solar wind and dust ions (gray area) and produce γ-rays. From Kahler and Ragot (2008).

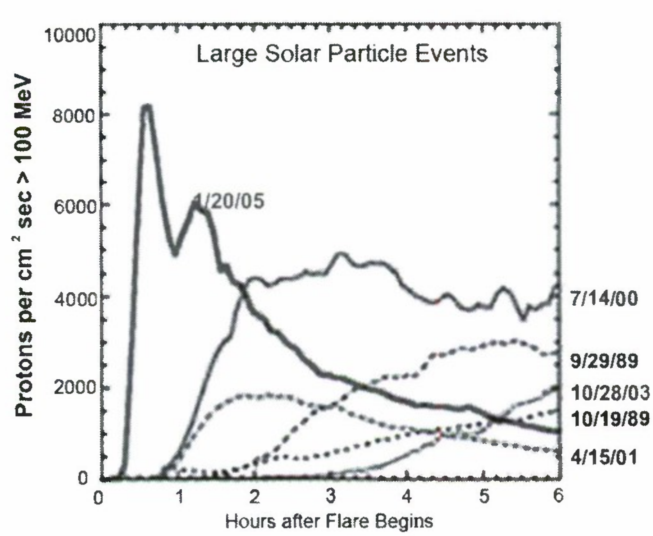

Fig. 2. Time profiles of the $E >$ 100 MeV intensities of the largest SEP events of the last 30 years. The 2005 January 20 event used in our γ-ray calculation had the fastest rise of any of the events. From Mewaldt et al. (2005).

been calculated from neutron monitor data and is steeper and less intense than the intensity spectrum we used. When the calculated neutron-monitor integral fluence above 300 MeV matches that of our normalized intensity spectrum, the γ-ray flux and total LAT counts are reduced by a factor of 3 (R. Murphy and A. Tylka, private communication), but still produce a very detectible LAT signal. Details of the line and π^0-decay emission calculations are given in Kahler and Ragot (2008).

A major problem in detecting any near-Sun heliospheric SEP event signature is to distinguish that signal from a similar signature of solar flare SEPs. The low signal intensities and the very high ($\leqslant 1^0 \approx 4\ R_\odot$) detector angular resolution required to make that distinction combine to make a formidable observing challenge. We (Kahler and Ragot, 2008) suggested that the flare and heliospheric SEP signals could be distinguished from each other either temporally, when a later heliospheric signal follows or dominates an earlier flare signal, or spatially, when the flare region lies over the solar limb and only the heliospheric component is observed. Ryan (2000) considered in detail how protons accelerated in antisunward propagating shocks might precipitate back to the lower corona or chromosphere as an explanation for observed long-duration solar γ-ray flares. His concept is similar to our suggestion of a temporal separation between flare and heliospheric SEP sources, except that he would have the later collisions and γ-ray production from the heliospheric SEPs occurring in much lower and denser coronal regions rather than in the SW.

2.2. Positron-decay 0.511 MeV line emission

We expect that a corresponding heliospheric SEP signature resulting from collisions of SEP ions with SW ions should match each observed signature of flare SEP ions with solar ambient atmospheric ions. Collisions of high energy ($E \gtrsim 300$ MeV) SEP protons on SW ions will produce not only the π^0-decay γ-rays considered in our earlier work (Kahler and Ragot, 2008) but also π^+ and π^- mesons, which decay into μ^+ and μ^- mesons and then into positrons and electrons. Positrons are also produced as products of collisions of lower energy ($E \gtrsim 10$ MeV) SEPs with ambient ions to produce radioactive β^+-emitting nuclei (Ramaty et al., 1975). Production of those nuclei can be greatly enhanced if the SEP composition has a high ^{3}He abundance in the 1–10 MeV nuc^{-1} energy range (Kozlovsky et al., 2004). The positrons decay into a pair of 0.511 MeV γ-rays when they annihilate directly with ambient electrons or after forming positronium. From positronium only 25% decay into the 0.511 MeV γ-rays, while the remaining 75% undergo a three-γ-ray decay.

Could the 0.511 MeV line also be observed from the heliospheric SEP-generated positrons as it is in some solar flares? The π^+-decay positrons are formed with energies of $\sim$30 MeV and for annihilation they require thermalization times of $\sim 10^{13}/n_1$ s, where n_1 is the ambient density in cm^{-3} (Ramaty and Murphy, 1987). In heliospheric regions of density $n < 10^8$ cm^{-3} those relativistic positrons will leave the inner heliosphere with essentially no 0.511 MeV line emission. The β^+-emission positrons have lower characteristic energies of $\sim$1 MeV and shorter thermalization times of $\sim 4 \times 10^{12}/n_1$ s, but they too should rapidly propagate away from the inner heliosphere before decay into the 0.511 MeV line is possible. Thus, the long positron thermalization times preclude the possibility of observing heliospheric 0.511 MeV line emission. Direct detection of the positrons themselves at 1 AU is not precluded here, but as charged particles scattered by magnetic field fluctations, they lose the spatial information of their sources that we are seeking.

2.3. Neutrons and neutron-capture 2.23 MeV γ-ray emission

Since energetic neutrons travel directly from their source regions to an observer, directional information on neutrons produced by heliospheric SEP collisions with SW ions could produce information on the SEP temporal–spatial distribution. Neutrons are produced primarily by p–α interactions above $\sim$30 MeV nuc^{-1}, where the production cross sections are only slightly energy dependent (Ramaty et al., 1975). In the case of heliospheric SEPs the thin-target model of interactions is appropriate for neutron production calculations, rather than the more efficient thick-target model usually assumed (i.e., Murphy et al., 1987) for flare SEPs, which are stopped in the dense flare target region. The β^- decay of the neutrons en route to the observer will modify the observed neutron energy spectrum, but this could provide model-dependent information on the SEP-source distance from the observer that would not be available from the heliospheric π^0-decay γ-rays. Neutron emission in the 36–100 MeV range associated with a solar flare located 6^0–9^0 behind the solar east limb was observed on 1991 June 1 (Murphy et al., 1999). Comparison of that event with a second neutron and γ-ray flare event on 1991 June 4 indicated that a thin-target neutron source was possible only if the SEP spectrum was extremely hard. Although the June 1 flare was an extremely energetic event (Kane et al., 1995), it suggests that energetic neutron emission could, with a sufficiently sensitive detector, serve as a remote signature of heliospheric SEP events.

The energetic neutrons produced by p–α collisions between energetic heliospheric SEPs and the SW ions will produce 2.23 MeV γ-ray line emission from capture by SW protons. However, two neutron timescales limit this capture process: the 15-min lifetime against β^- decay and the required thermalization by elastic scattering before SW proton capture. In solar flares the 2.23 MeV emission is generated in the $n > 10^{16}$ cm^{-3} density region of the photosphere after a thermalization time of $\sim$100 s for $\sim$1–100 MeV neutrons (Wang and Ramaty, 1974; Ramaty et al., 1975). However, the SW densities, lower by orders of magnitude, preclude any neutron thermalization, and detectible 2.23 MeV line emission from heliospheric SEPs is therefore not expected. We note, however, that

2.23 MeV emission was observed on 1989 September 29 in association with a GLE, a fast CME, and a solar flare located 5^0–15^0 behind the solar west limb. Vestrand and Forrest (1993) and Cliver et al. (1993) suggested that a fraction of the $E > 30$ MeV protons at the coronal shock may have precipitated back to the solar atmosphere and then produced the observed emission via neutron generation. Our consideration here of neutron production by heliospheric SEPs suggests the alternative possibility of direct atmospheric precipitation of the energetic neutrons from the SEP–SW interactions, which, although unlikely, avoids the problem of achieving charged particle precipitation through converging coronal magnetic fields.

2.4. Electron synchrotron emission

Bursts of gyrosynchrotron radiation from $E \gtrsim 100$ keV electrons in solar flare loops are commonly observed in the microwave range (Bastian et al., 1998). Can synchrotron emission also be observed from transient energetic electron populations that escape the Sun? Bastian et al. (2001) described a fast CME on 1998 April 20 in which the expanding CME loops were imaged directly in radio wavelengths with the Nancay radioheliograph out to ~3.5 $R_\odot$. Their interpretation was that the emission was synchrotron emission from nonthermal electrons with energies from ~0.5 to 5 MeV in fields of ~0.1 to several G. The long-duration phase of an X-class flare event on 2003 November 3 was also interpreted in terms of electron gyrosynchrotron emission from a large coronal structure with $B \sim 2$ G (Dauphin et al., 2005). Matching modulations were observed in hard X-rays by RHESSI and in the decimetric/metric continuum at the Nancay Radioheliograph during a fast CME. Another event, in which radio loops were observed in a CME out to >2.1 $R_\odot$ on 2001 April 15 (Maia et al., 2007), provides a third example. The inferred electron high-energy cutoff ranged from 1 to 10 MeV and the estimated field B was ~1 G. These events were imaged at the four Nancay observing frequencies from 432 to 164 MHz, and their cospatial emission at different frequencies indicated synchrotron, not plasma emission, as the source. The 1998 and 2001 events originated from the southwest solar limb and were accompanied at 1 AU by large $E \gtrsim 100$ keV electron and $E > 10$ MeV proton events, suggesting that the escaping nonthermal electrons may have been imaged near the Sun.

Can we see synchrotron emission from electrons propagating even farther from the Sun? An interplanetary type-II-like burst was observed with the Wind/WAVES instrument on 2003 June 17–18, which Bastian (2007) interpreted as synchrotron emission. The burst followed a strong type III burst and preceded a type II burst and was observed when the CME height was $\gtrsim 10$ $R_\odot$ (Fig. 3). He argued that the frequency band width, drift rates and the single smoothly varying emission lane of the burst were inconsistent with plasma emission from a propagating shock. Acceptance of a new class of low-frequency (<5 MHz) synchrotron emission must await the discovery of further such examples, but, if found, these bursts could be the basis for tracking distributions of $E \gtrsim 100$ keV electrons in space. Deriving detailed spatial information about electron and shock sources would require direction finding and triangulation analyses from space observations such as the STEREO/SWAVES instruments (Bougeret et al., 2008). A more ambitious proposal is the Solar Imaging Radio Array, a mission to perform aperture synthesis imaging of low frequency (<15 MHz) bursts (MacDowall et al., 2005). A large number of baselines would be provided by a 12–16 microsatellite constellation in Earth orbit about 0.5×10^6 km from the Earth. High-resolution images of the entire sky over a range of frequencies should go far to determine emission mechanisms of solar bursts and the roles of SEPs in producing those bursts (see Fig. 4).

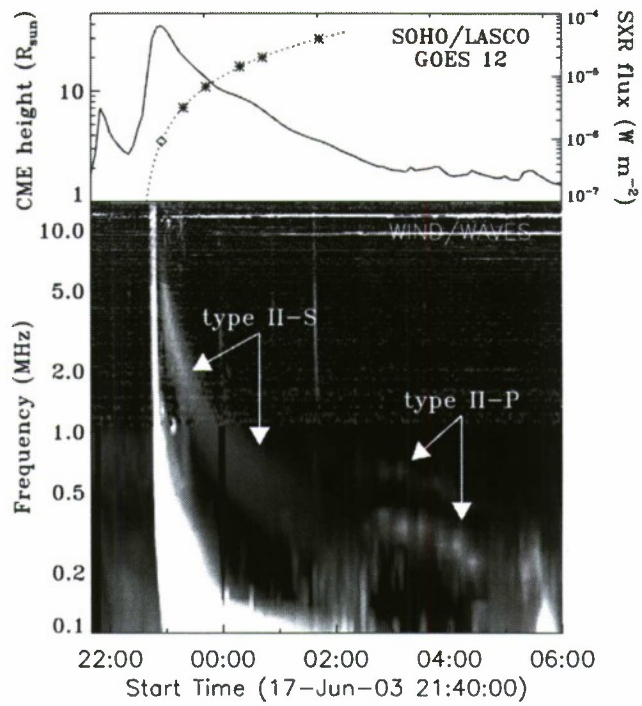

Fig. 3. Bottom panel: example of IP type II-s and type II-p radio bursts on 2003 June 17 observed with the Wind/WAVES RAD1 and RAD2 receivers. The type II-s burst follows the type III fast-drift bursts (not marked) and has a single smooth, diffuse, broad-band profile compared with the subsequent type II-p burst. Top panel: The GOES-10 class M6.8 soft X-ray flare profile and the height of the leading edge of the CME observed on the southeast quadrant of the sun with the SOHO/LASCO. From Bastian (2007).

2.5. Resonant transition radiation

Resonant transition radiation (RTR) is an incoherent continuum emission mechanism in astrophysical plasmas. Transition radiation arises when nonthermal charged particles pass through small-scale inhomogeneities, but it was considered to be weak until Platonov and Fleishman (2002) showed that its intensity was greatly enhanced by plasma resonance (hence RTR) at frequencies just above

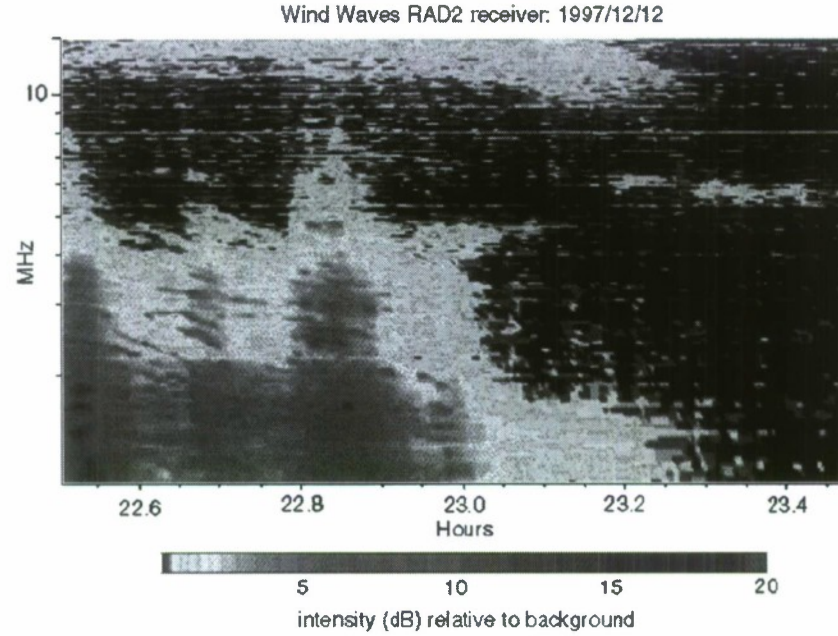

Fig. 4. Multiple fibers and striae observed in the 1–10 MHz region by the Wind/WAVES instrument on 1997 December 12. In this unusual case the zebra pattern is observed both in the continuum and in fast-drift type III bursts. This is Fig. 1 of Chernov et al. (2007) with kind permission of Springer Science and Business Media.

the local plasma frequency ω_p (Nita et al., 2005). The emission intensity scales as $\langle(\Delta n)^2\rangle/n^2$ (where $\langle(\Delta n)^2\rangle$ is the mean square of the inhomogeneities, so the emission is enhanced in more turbulent regions (Fleishman et al., 2005). Evidence for RTR has been found in solar flare bursts characterized by cospatial and simultaneous emission in the decimetric range from RTR and in the centimetric range from gyrosynchrotron emission (Fleishman et al., 2005; Nita et al., 2005). The interpretation is that the lower energy ($\leqslant$100 keV) electrons produce the RTR, and the higher energy ($\gtrsim$ 300 keV) electrons the gyrosynchrotron emission. RTR is suppressed at $\omega < \omega_p^2/\omega_B$, where ω_B is the electron gyrofrequency, so dense, high-β plasmas are favorable for enhanced RTR. The calculated turbulence levels in several flare studies (Nita et al., 2005; Fleishman et al., 2005; Yasnov et al., 2008) are $\langle(\Delta n)^2\rangle/n^2 \sim 10^{-7}$–$10^{-5}$.

Can RTR also be observed outside the flaring active regions? Chernov et al. (2007) have discussed fine structure observed in the 14–5 MHz observing range of the Wind/WAVES radio receiver. In 14 selected events the fine structure was in the form of fibers, similar to the zebra patterns observed in the metric range. In most of the events shock fronts were observed in white light coronagraph images to cross narrow streamers in the wakes of CMEs. Their suggestion was that fast electrons at the shock front traversed the density inhomogeneities of the streamers to produce RTR. They point out that while $\Delta n/n$ may be only a few percent in the corona, it can exceed unity in the CME streamers. The interplanetary scintillation (IPS) observations of a CME at about 10 $R_\odot$ (Lynch et al., 2002) indicated that $\Delta n/n$ was somewhat lower than in the preceding slow solar wind, but still on the order of unity. An ~10 min enhancement in the IPS signal implied a small structure 30 times denser than the background. These observations support the point of Chernov et al. (2007) that the large density fluctuations of the near-Sun region may provide a favorable situation for observing RTR.

2.6. EUV spectroscopy

While the above techniques detect direct products of heliospheric SEPs, EUV spectroscopy can provide diagnostics of shock regions in which SEPs may be produced. Remote observations of various ionic line profiles from shock regions can yield their suprathermal velocity distributions as well as abundance and ionic charge-state information as functions of space and time (Pagano et al., 2008). Suprathermal protons might be detected from Lyα emission following charge exchange with SW hydrogen atoms (Kahler et al., 1999). Line broadening attributed to shock heating has already been detected at the fronts of a number of CMEs (Ciaravella et al., 2006) with SOHO/UVCS observations, but a detector with much higher sensitivity and wider spectral range would be needed to get line profiles of many ions with various charge-to-mass ratios.

3. Imaging solar wind structures

In the preceding sections we have suggested potential techniques for imaging various kinds of radiations produced by the energetic electrons or ions escaping the corona to become heliospheric SEP events. One or more of these techniques could prove to be a valuable complement to in situ SEP observations for defining the heliospheric spatial and temporal variations of SEP events. In general, the proposed observations would require high detector sensitivities and angular resolutions to separate the transient SEP radiant signals from high backgrounds.

Here we point out that imaging structures in the very tenuous solar wind (SW) has also been a challenge for heliospheric studies. Charge exchange between SW α particles and interstellar H atoms in the heliosphere produces emission in the 30.4-nm line. Because the charge-exchange process is velocity dependent, 30.4-nm spectral observations could determine spatial variations of SW speeds and densities, but the expected weak radiance (Gruntman et al., 2006) would limit realistic observations to several all-sky images per year. A recent proposal by Morgan et al. (2008) is to measure the 103.196 and 103.76 nm line profiles of the collisional component of O VI in the SW along lines of sight directed away from the Sun. On an inner-heliospheric spacecraft the O^{+5} bulk flows and effective ionic temperatures deduced from those EUV lines could complement the in situ SW particle measurements to determine extended SW structures. Thomson-scattering of solar white-light photons was also at one time considered a difficult challenge. However, because of a very steady zodiacal white-light background the Solar Mass Ejection Imager has imaged CMEs (Webb et al., 2006) two orders of magnitude fainter than that background (Jackson et al., 2004). Recently, images of SW density streams have been obtained by heliospheric imagers on the STEREO spacecraft (Sheeley et al., 2008; Rouillard et al., 2008).

The energetic neutral atoms (ENAs) produced by interactions of SW ions with interstellar neutrals are another important kind of remote SW observations. Model simulations have shown that 25–100 keV ENA fluxes produced from charge exchange of ions accelerated at corotating interaction regions could explain ENA fluxes observed on the SOHO spacecraft (Kóta et al., 2001). The recent Voyager 2 in situ plasma and nonthermal ion measurements (Decker et al., 2008) and STEREO directional measurements of ~4–20 keV ENAs from the heliosheath (Wang et al., 2008) have shown the importance of nonthermal pick-up ions to the dynamical processes of the termination shock. The Interstellar Boundary Explorer (IBEX) mission (McComas et al., 2006), successfully launched on 2008 October 19, will map the full sky in ENAs in the energy range from ~10 eV to 6 keV. McComas et al. (2004) have stressed the important complementarity of the IBEX global maps to the Voyager 1 and 2 in situ measurements at the termination shock and heliosheath to provide a full picture of the SW interaction with the interstellar medium.

The large-scale structure of the inner heliospheric magnetic field is also beginning to be explored. Magnetic field characteristics of large flux-rope CMEs have been determined from Faraday rotation measurements of single-frequency signals from spacecraft (Jensen and Russell, 2008). A much more detailed determination of both transient and slowly evolving SW magnetic fields is anticipated from Faraday-rotation observations with the Mileura Widefield Array (Salah et al., 2005) operating at 80–300 MHz.

The mapping of heliosheath ENAs and SW magnetic fields and the imaging of white-light SW streams and ICMEs are cases in which remote signatures of dynamic SW processes have been identified and used as the basis of global measurements to complement the in situ measurements. As with the SW and heliosheath, the first studies of SEPs have been limited to in situ observations. The successes in probing large-scale SW and heliosheath features with remote observations should encourage us to seek similar remote signatures of SEPs to complement the extensive current in situ SEP measurements.

4. Summary

Our goal here has been to encourage the development of concepts for the remote observation of heliospheric SEPs. We have shown that remote observations are becoming a reality for SW and heliosheath structures. These remote observations add the necessary context to interpret properly and understand the physics deduced from the in situ observations. We have suggested a number of candidate remote signatures produced by various kinds of heliospheric SEPs interacting with SW fields or particles, which we summarize as:

1. Pion-decay γ-rays as signatures of $E \gtrsim 300$ MeV nuc^{-1} ions,
2. Energetic neutrons as signatures of $E \gtrsim 30$ MeV nuc^{-1} ions,
3. Electron synchrotron emission as a signature of $E \gtrsim 0.3$ MeV electrons, and
4. Resonant transition radiation (RTR) as a signature of $E \lesssim 100$ keV electrons and of energetic ions.

We have also considered but found that 4–7 MeV ion deexcitation, the 2.23 MeV neutron-capture, and 0.511 MeV positron annihilation γ-ray lines from heliospheric SEPs would be too weak for observation. There may well be other possibilities that remain to be discovered.

Acknowledgements

The authors thank the two reviewers for their very helpful comments on the manuscript.

References

Bastian, T.S. Synchrotron radio emission from a fast halo coronal mass ejection. Astrophys. J. 665, 805–812, 2007.

Bastian, T.S., Benz, A.O., Gary, D.E. Radio emission from solar flares. Ann. Rev. Astron. Astrophys. 36, 131–188, 1998.

Bastian, T.S., Pick, M., Kerdraon, A., Maia, D., Vourlidas, A. The coronal mass ejection of 1998 April 20: direct imaging at radio wavelengths. Astrophys. J. 558, L65–L69, 2001.

Bhattacharjee, Y. GLAST mission prepares to explore the extremes of cosmic violence. Science 320, 1008–1009, 2008.

Bougeret, J.-L. et al. S/WAVES: the radio and plasma wave investigation on the STEREO mission. Space Sci. Rev. 136, 487–528, 2008.

Chernov, G.P., Kaiser, M.L., Bougeret, J.-L., Fomichev, V.V., Gorgutsa, R.V. Fine structure of solar radio bursts observed at decametric and hectometric waves. Sol. Phys. 241, 145–169, 2007.

Ciaravella, A., Raymond, J.C., Kahler, S.W. Ultraviolet properties of halo coronal mass ejections: doppler shifts, angles, shocks, and bulk morphology. Astrophys. J. 652, 774–792, 2006.

Cliver, E.W., Kahler, S.W., Vestrand, W.T. On the origin of gamma-ray emission from the behind-the-lim flare on 29 September 1989. Proc. 23rd ICRC (Calgary), 91–94, 1993.

Dauphin, C., Vilmer, N., Lüthi, T., Trottet, G., Krucker, S., Magun, A. Modulations of broad-band radio continua and X-ray emissions in the large X-ray flare on 03 November 2003. Adv. Space Res. 35, 1805–1812, 2005.

Decker, R.B. et al. Mediation of the solar wind termination shock by non-thermal ions. Nature 454, 67–70, 2008.

Fleishman, G.D., Nita, G.M., Gary, D.E. Evidence for resonant transition radiation in decimetric continuum solar bursts. Astrophys. J. 620, 506–516, 2005.

Gruntman, M., Izmodenov, V., Pizzo, V. Imaging the global solar wind flow in EUV. J. Geophys. Res. 111, A04216, doi:10.1029/2005JA011530, 2006.

Jackson, B.V., Buffington, A., Hick, P.P., et al. The solar mass ejection imager (SMEI) mission. Solar Phys. 225, 177–207, 2004.

Jensen, E.A., Russell, C.T. Faraday rotation observations of CMEs. Geophys. Res. Lett. 35, L02103, doi:10.1029/2007GL031038, 2008.

Kahler, S.W. The correlation between solar energetic particle peak intensities and speeds of coronal mass ejections: effects of ambient particle intensities and energy spectra. J. Geophys. Res. 106 (A10), 20947–20956, 2001.

Kahler, S.W., Ragot, B.R. Remote sensing of gamma-ray emission from solar energetic proton interactions with the solar wind. Astrophys. J. 675, 846–852, 2008.

Kahler, S.W., Raymond, J.C., Laming, J.M., 1999. Spectroscopic diagnostics for remote detection of particle acceleration regions at coronal shocks, CP471, Solar Wind Nine, S.R. Habbal et al. (Eds.), AIP, 685–688.

Kane, S.R., Hurley, K., McTiernan, J.M., Sommer, M., Boer, M., Niel, M. Energy release and dissipation during giant solar flares. Astrophys. J. 446, L47–L50, 1995.

Kóta, J., Hsieh, K.C., Jokipii, J.R., Czechowski, A., Hilchenbach, M. Viewing corotating interaction regions globally using energetic neutral atoms. J. Geophys. Res. 106, 24907–24914, 2001.

Kozlovsky, B., Murphy, R.J., Ramaty, R. Nuclear deexcitation gamma-ray lines from accelerated particle interactions. Astrophys. J. Suppl. 141, 523–541, 2002.

Kozlovsky, B., Murphy, R.J., Share, G.H. Positron-emitter production in solar flares from ^{3}He reactions. Astrophys. J. 604, 892–899, 2004.

Lin, R.P. et al. The Reuven Ramaty high-energy solar spectroscopic imager (RHESSI). Solar Phys. 210, 3–32, 2002.

Lynch, B.J., Coles, W.A., Sheeley Jr., N.R. A comparison of mean density and microscale density fluctuations in a CME at 10 $R_\odot$. Geophys. Res. Lett. 29 (19), 1913, doi:10.1029/2001GL014152, 2002.

Maia, D.J.F., Gama, R., Mercier, C., Pick, M., Kerdraon, A., Karlicky, M. The radio-coronal mass ejection event on 2001 April 15. Astrophys. J. 660, 874–881, 2007.

MacDowall, R.J. et al. Solar imaging radio array (SIRA): a multispacecraft mission. Proc. SPIE 5659, 284–292, 2005.

McComas, D. et al. The interstellar boundary explorer (IBEX), in: Florinski, V., Pogorelov, N.V., Zank, G.P. (Eds.), Physics of the Outer Heliosphere: Third International IGPP Conference, vol. CP719. AIP, New York, pp. 162–181, 2004.

McComas, D. et al. The interstellar boundary explorer (IBEX): update at the end of phase B, in: Heerikhuisen, J. et al. (Eds.), Proceedings of the 5th Annual International Astrophysics Conference, vol. CP858. AIP, New York, pp. 241–250, 2006.

Morgan, H., Fineschi, S., Habbal, S.R., Li, B. In situ spectroscopy of the solar corona. Astron. Astrophys. 482, 981–987, 2008.

Moskalenko, I.V., Porter, T.A., Digel, S.W. Inverse Compton scattering on solar photons, heliospheric modulation and neutrino astrophysics. Astrophys. J. 652, L65–L68 (erratum 664, L143, 2007), 2006.

Mewaldt, R.A., Looper, M.D., Cohen, C.M.S., et al., 2005. Solar-particle energy spectra during the large events of October–November 2003 and January 2005. Proceedings of the 29th International Cosmic Ray Conference, vol. 1. Pune, India, pp. 111–114.

Murphy, R.J., Dermer, C.D., Ramaty, R. High-energy processes in solar flares. Astrophys. J. Suppl. Ser. 63, 721–748, 1987.

Murphy, R.J., Share, G.H., DelSignore, K.W., Hua, X.M. Surprisingly intense neutron emission from a flare behind the limb of the Sun. Astrophys. J. 510, 1011–1017, 1999.

Nita, G.M., Gary, D.E., Fleishman, G.D. Spatial evidence for transition radiation in a solar radio burst. Astrophys. J. 629, L65–L68, 2005.

Orlando, E., Strong, A.W. Gamma-ray emission from the solar halo and disk: a study with EGRET data. Astron. Astrophys. 480, 847–857, 2008.

Pagano, P., Raymond, J.C., Reale, F., Orlando, S. Modeling magneto-hydrodynamics and non-equibrium SoHO/UVCS line emission of CME shocks. Astron. Astrophys. 481, 835–844, 2008.

Platonov, K.Yu., Fleishman, G.D. Transition radiation in media with random inhomogeneities. Physics–Uspekhi 45 (3), 235–291, 2002.

Ramaty, R., Murphy, R.J. Nuclear processes and accelerated particles in solar flares. Space Sci. Rev. 45, 213–268, 1987.

Ramaty, R., Kozlovsky, B., Lingenfelter, R.E. Solar gamma rays. Space Sci. Rev. 18, 341–388, 1975.

Rouillard, A.P., Davies, J.A., Forsyth, R.J., Rees, A., Davis, C.J., Harrison, R.A., Lockwood, M., Bewsher, D., Crothers, S.R., Eyles, C.J., Hapgood, M., Perry, C.H. First imaging of corotating interaction regions using the STEREO spacecraft. Geophys. Res. Lett. 35, L10110, doi:10.1029/2008GL033767, 2008.

Ryan, J.M. Long-duration solar gamma-ray flares. Space Sci. Rev. 93, 581, 2000.

Salah, J.E., Lonsdale, C.J., Oberoi, D., Cappallo, R.J., Kasper, J.C. Space weather capabilities of low frequency radio arrays. Proc. SPIE 5901, 124–134, 2005.

Sheeley Jr., N.R., Herbst, A.D., Palatchi, C.A., et al. Heliospheric images of the solar wind at Earth. Astrophys. J. 675, 853–862, 2008.

Strong, A.W., Mattox, J.R. Gradient model analysis of EGRET diffuse Galactic γ-ray emission. Astron. Astrophys. 308, L21–L24, 1996.

Strong, A.W., Bennett, K., Bloemen, H., et al. Diffuse galactic hard X-ray and low-energy gamma-ray continuum. Astron. Astrophys. Suppl. Ser. 120, 381–387, 1996.

Tatischeff, V., Kiener, J. γ-Ray lines from cosmic-ray interactions with interstellar dust grains. New Astron. Rev. 48, 99–103, 2004.

Turner, R.E., 2006. Space weather challenges intrinsic to the human exploration of space, in: Solar Eruptions and Energetic Particles, Gopalswamy, N. et al. (Eds.), GM 165, AGU, 367–374.

Vestrand, W.T., Forrest, D.J. Evidence for a spatially extended component of gamma rays from solar flares. Astrophys. J. 409, L69–L72, 1993.

Wang, H.T., Ramaty, R. Neutron propagation and 2.2 MeV gamma-ray line production in the solar atmosphere. Solar Phys. 36, 129–137, 1974.

Wang, L., Lin, R.P., Larson, D.E., Luhmann, J.G. Domination of heliosheath pressure by shock-accelerated pickup ions from observations of neutral atoms. Nature 454, 81–83, 2008.

Webb, D.F., Mizuno, D.R., Buffington, A., et al. Solar Mass Ejection Imager (SMEI) observations of coronal mass ejections (CMEs) in the heliosphere. J. Geophys. Res. 111, A12101, doi:10.1029/2006JA011655, 2006.

Yasnov, L.V., Karlicky, M., Modin, E.V. Resonant transition radiation and solar radio bursts. Solar Phys. 247, 351–378, 2008.