Solar and Heliospheric Physics

Rapporteur Talk

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Key questions

1. Where and how is particle acceleration taking place?
2. How is propagation processing particle fluxes, spectra, etc?
3. How have conditions in the heliosphere evolved over time?
1. Where and how is particle acceleration taking place?
Solar Energetic Particles

- Accelerated during Coronal Mass Ejections (CMEs) and flares

PAMELA, 2012/05/17

Bruno et al SH7a
SEP proton spectra

2012 05/17, 01:50UT - 05/22, 03:00UT

\[ \gamma_a = 0.87 \pm 0.15, \quad \gamma_b = 2.45 \pm 0.09 \]

\[ E_0 = 3.0 \pm 1.2, \quad E_r = 494.2 \pm 81.7 \]

Event-integrated intensity [MeV$^2$sr$^{-1}$cm$^{-2}$]

Event-integrated fluence [sr$^{-1}$cm$^{-2}$]

\[ R_b = 0.73 (9.9 \times 10^{-5}) \]

Bruno et al SH7a
SEP electron spectra

- 717 solar electron events
  (45-450 keV STEREO/SEPT)

Dresing, Kuhl, SH3g
Multi-spacecraft SEP observations

The Influence of CME Characteristics on the Spread of SEPs

In our study, we have only used the LASCO catalog. It should be noted, however, that the mass and kinetic energy values given in the catalog are generally considered preliminary and may be subject to change in the future. Additionally, for most of the events in the Cohen et al. study (and all of the three-spacecraft events), the LASCO catalog identifies the CME as a 'halo' CME and thus reports its width as 360°. Thus, we have not used this parameter in our study. Finally, in some events LASCO observations are subject to projection effects due to the travel direction of the CME; these have not been corrected for.

3. Three-Spacecraft Events

Plots of the calculated widths for the identified three-spacecraft events of Cohen et al. are plotted versus the CME parameters in Figure 1. There is substantial scatter in the results, but there is a suggestion of an increase in width with increasing speed for at least 10 MeV/n. Any correlation is less apparent for 0.3 and 1 MeV/n. The same could be said for the kinetic energy correlations, while the mass plots show no clear correlation at any energy. In contrast to the other parameters, the plots versus CME acceleration appear to exhibit positive correlations at all energies. However, this is largely driven by two events which have the largest and smallest accelerations: 27 January 2012 and 25 February 2014, respectively (the latter actually having significant deceleration). The remaining events do not appear to be well organized by the CME's acceleration.

Although the plots in Figure 1 have been grouped by energy, there is no evidence of a species dependence in any of the correlations (or lack thereof). This is consistent with the results of Cohen et al. who did not find a species dependence to the calculated widths.

Cohen et al. SH3f

- STEREO H, He, O, Fe (0.3-10 Mev/nuc)
- Width of SEP event in interplanetary space does not correlate with Coronal Mass Ejection (CME) properties
September 2017 events at Earth and STEREO A

**Introduction:**
Shown below are figures that provide an overview of solar proton intensities, X-ray flares, and interplanetary shocks during September, 2017.

Figure 1 (left): The time history of near-Earth solar energetic particle (SEP) activity as seen by GOES-13. Also indicated are M and X-class flares, (top labels) and L1 interplanetary shocks (S). Some of this front-side activity is also observed at STEREO-A. The September 18 CME was aimed 15° to the west of STEREO-A.

Figure 1 (right): As an illustration of the extreme "spike-like" nature of the September 2017 SEP event at STEREO-A, we show time histories of protons in three energy intervals from the Low-Energy Telescope (LET)[1]. Note that the three narrow proton spikes stand out above the exponential decay of the September 10 event by factors ranging from \(\sim 25\) to \(\sim 400\) (measuring from the dotted line to the top of the spike). This shows that the September 18 CME shock was a very efficient accelerator in spite of its \(1380\) km/s launch speed.

Figure 2: All heavy elements accelerated at this shock showed "spikes" extending \(~250\) times above the extrapolated decay profile of the pre-shock ion intensity. The heavy-ion profiles are all from the LET Telescope on STEREO-A.

Mewaldt et al SH3d

- September 2017 events at Earth and STEREO A
Effective dose at altitude of 35 kft during GLE #5 integrated over the first 3 hr of the event.

- Radiation dose associated with GLEs

Effective dose at 35 kft over first 3 hr of GLE 5, from neutron monitor data.

Mishev et al, SH7f
Long duration solar $\gamma$-ray emission

- 2017 September 10 event, FERMI/LAT >100 MeV
Mechanisms for extended $\gamma$-ray emission

- Acceleration at CME driven shock + back-precipitation
- Trapping and acceleration (2$^{nd}$ order Fermi) in large coronal loops

Ryan et al, SH5d
Comparing interacting particle and SEP numbers

\[ \tau = 1.1e-02 \ (p=0.96) \]
\[ R_s = 1.5e-01 \ (p=0.60) \]

The scatter in the \( N_{SEP}/N_{LDGRF} \) ratio can be explained in the context of the CME model for continuous back precipitation of energetic protons in which the magnetic connection is likely sporadic and unpredictable between the shock front, in particular the nose where acceleration is expected to be most efficient, and the Sun. However, in such a scenario one would expect the intensity-time profile in any given LDGRF to be erratic, atypical of the smooth profiles of most well-measured LDGRFs observed by Fermi/LAT. Even more problematic are the events (in the left of Figure 2) where the particle number at the flare exceeds, in some cases considerably, the particle number in space. If the particles above 500 MeV in space were from the same population as those responsible for the \( \gamma \)-ray emission at the Sun, it would imply that in some cases, more than \( \sim 80\% \) of this population must be extracted from the acceleration process to produce the radiation. This loss from the shock acceleration process is in addition to other processes that reduce shock efficiency such as the finite extent of the shock and proximity to the strong magnetic fields close to the Sun. Finally, two Fermi/LAT detections on 2012 October 23 and 2012 November 27, which were not linked to CME eruptions, suggest that a fast CME is not a necessary requirement for LDGRFs.

An alternate to back precipitation is the scenario where particles are continuously accelerated within extended coronal loops and diffuse to the denser photosphere. Large quasi-static loops have been associated with LDGRF emission. The typically smooth exponential decay of LDGRF emission is also consistent with coronal trapping, with spatial and momentum diffusion governing the precipitation of high-energy particles. To accelerate protons, magnetic turbulence...
Anomalous Cosmic Rays

Leske et al, SH4e

Spectral differences between low solar wind speeds and high speeds: GCR intensities are enhanced at low speeds by ~5%, while the lowest energy ACRs are enhanced ~50-60% in 2007-2008, and ~30% in 2017-2019, with a strong energy dependence.
Anisotropy of ACRs

- Anisotropy measurements at Voyager 2
- Diffusive flow is equatorward and towards nose of termination shock, from flank or tail
- Supports flank or tail as main acceleration site

Cummings et al, SH1a
Modelling ACRs

ACRs in Heliosphere

$A<0$  
$\kappa_1/\kappa_1=.02$

$A>0$  
$\kappa_1/\kappa_1=.02$

Kota et al SH1b
2. How is propagation processing particle intensities, spectra, etc?
Heliospheric modulation of GCRs

- 3D steady state modulation model based on Parker equation:

\[
\frac{\partial f}{\partial t} = - \vec{V}_{SW} \cdot \vec{\nabla} f - \vec{V}_{D} \cdot \vec{\nabla} f + \vec{\nabla} \cdot (K \cdot \vec{\nabla} f) + \frac{1}{3} \vec{\nabla} \cdot \vec{V}_{SW} \frac{\partial f}{\partial \ln R} + Q
\]

- Solar wind plasma convection
- Particle drift
- Particle diffusion
- Energy losses
- Sources/sinks

\( K = \) diffusion tensor
\( f = \) omnidirectional distribution function of GCRs

Eg: Corti et al, SH2b, Bischhoff et al SH1c
Heliospheric modulation of GCRs (1)

- Tune modulation model using proton and electron data at Voyager 1 and PAMELA
- Use GALPROP to derive LISs for a variety of species
Heliospheric modulation of GCRs (1)

- Model predicts eg positron and boron spectra

Bischhoff et al, SH1c
Heliospheric modulation of GCRs (2)

- Modulation model tuned to fit AMS ~1.5 GeV proton flux

Fit results

The residuals fluctuate less than 5%, within 1 or 2 sigma from zero.

Corti et al SH2b
Heliospheric modulation of GCRs (2)

- Decrease of p/He ratio reproduced and attributed to A/Z dependence of diffusion

Corti et al, SH2b
Solar relativistic proton propagation

Dalla et al, SH7e
Energy information from neutron monitors

- More energetic primary
- More energetic secondary
- More neutrons in monitor
- Higher multiplicity

- Time delay <4 ms: correlated arrival of neutrons

Banglieng et al, SH2f
3. How have conditions in the heliosphere evolved over time?
Sunspot number reconstruction

- multi-proxi Bayesian approach, using multiple $^{14}$C and $^{10}$Be datasets

Usoskin et al SH4a
SEP spectra over Myrs

- Analysis of $^{26}$Al in lunar samples
- SEP flux on Myr scale comparable with recent decades

Poluianov et al SH4c
The future: New missions and instrumentation
New missions: Parker Solar Probe

Posner, Christian et al
- Review Talk
New missions: IMAP

Interstellar Mapping and Acceleration Probe: IMAP
Surveys the edge of our solar system and beyond—Understanding particle energization and interactions across the heliosphere

30 October 2017
Outer Heliosphere

V1

Accelerated Particles
V2

Suite of Instruments

- IMAP-Lo
- IMAP-Hi
- IMAP-Ultra
- MAG
- SWE

Energetic Neutral Atoms (Increasing Energy)
Interstellar Neutral Atoms
Interplanetary or Vector Magnetic Fields
Solar Wind Electrons

SWAPI
CoDICE
HIT
IDEX
GLOWS

Solar Wind, Pickup, Suprathermal, and Energetic Ions;
Energetic Electrons

Dust
UV

Christian et al SH6d
New instrumentation

- Light weight (20 kg) low power (20 W) spectrometer with permanent magnet
- 4 Halbach permanent magnet sectors, $f = 10$ cm, $L = 10$ cm each, provide a dipole magnetic field of ~0.2 Tesla, total weight ~11 kg

Detector Concept (I)

★ Our detector is sensitive to both neutrons and gamma-rays.

★ Detection Principle

1. Neutron Detection Part: Multi-layered Plastic Scintillator Bars - Detected by elastic scattering with Hydrogen atoms. A recoiled proton loses its energy ($E_p$) in the bars. Incident neutron energy ($E_n$) = $E_p / \cos^2 \theta$ - The same technique is used in SEDA-AP FIB.


3. Anti-coincidence Detector Part - Covered by plastic scintillators to reject charged particles.

SONTRAC (e.g., Wunderer et al. 2006; Ormes et al. 2007).

2. SOLAR NEUTRON TRACKING CONCEPT

The neutron/gamma-ray spectrometer, SONTRAC, first conceptually introduced by Glenn Frye et al. (1985), provides a means to measure neutrons in the range of 20-150 MeV in a compact envelope with high efficiency, ideal for a small spacecraft and/or deep-space probes. The SONTRAC concept relies on the measurement of the momentum vector of the recoil proton associated with two interactions within a single scattering volume, e.g., the highly segmented fiber bundle. From a measure of the recoil moment in two successive scatters, the energy and direction of the incident neutron can be readily reconstructed (Figure 1). A system that measures the parameters of both recoil proton tracks in 3-d, provides the necessary and sufficient information to determine the incident neutron energy and direction with no azimuthal ambiguity (Ryan et al. 1993, 2012). The angular and energy resolutions depend on the ability to accurately measure the proton tracks. Imaging allows for a more complete separation of the source signal from the background. By allowing the scatter to take place in a single large block, the solid-angle factor between the scatters is much greater than that for widely separated detectors utilizing the time-of-flight technique, increasing the efficiency. As such, it would have wide fields of view, front and back.

SONTRAC was originally developed for the study of high-energy solar flare processes, but it was expanded to atmospheric physics, radiation therapy, and nuclear materials monitoring (Bravar et al. 2005). Because the original SONTRAC was based on scintillating fibers readout by image intensifiers with CCD detectors, the concept exhibited limitations including slow event rate, large data volume and large physical size/mass (Ryan et al. 2003). The upgraded SONTRAC (discussed in this paper) consists of orthogonally stacked, alternating layers of parallel scintillating plastic fibers read out by arrays of silicon photomultipliers (SiPM), see Figure 1. The prototype consists of a 35x35 scintillating fiber bundle with a 1.36 mm fiber pitch (Fig. 3). Each of the fiber bundle sides is paired with a 32x32 array of 1-mm SiPMs by KETEK (inset to Fig. 4).

Figure 1:

(left) SONTRAC instrument consisting of orthogonally stacked plastic scintillators readout by arrays of SiPMs. A measurement of two recoil tracks from fast neutron interactions determines the incident neutron energy and direction. (right) Mechanical housing for SONTRAC showing the tiling of sixteen 8x8 1-mm SiPM arrays on four surfaces.

Ambrosi et al SH6a

de Nolfo et al PS1-267

Matsushita et al SH6f
New instrumentation

- **AESOP -Lite**

Mangeard et al, SH6b; Mechbal et al SH6c
New neutron monitors

- Blanco et al, PS-265
- Strauss et al, SH6h
Conclusion

- New high energy and multi-spacecraft SEP data, and $\gamma$-ray data key to unsolved questions on solar particle acceleration
- Modulation models of increased sophistication – work in progress on links to microphysics and predictive capability
- Significant progress on understanding past behaviour over Myrs
- Parker Solar Probe and IMAP will provide key new data
Looking forward to hearing about the results in Berlin!!!

Thank you!