RAPPORTEUR PAPER

Sun and Corona
+
Transient Phenomena in the Heliosphere

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30th ICRC
July 3 - 11, 2007, Merida, Mexico
Sessions SH 1.2 - SH 1.7 + SH 2.1 - 2.4
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<td><strong>19</strong></td>
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INTRODUCTION
SUN AND CORONA + TRANSIENT EFFECTS IN THE HELIOSPHERE

SUN AND CORONA
Flares: γ, n, e, ions
CMEs
IP Shocks
Particle Transport
CIRs
Forbush Decrease
ENERGETIC PHOTONS AND ELECTRONS

Study of several large flares
• Zero Time - 8.8 GHz Radio Emission
• Hard X-ray emission in Phase B and C
• 245 MHz shows peak in Phase A
• Effective p acceleration in Phase C
  (similar in other events, e.g. Sept 7, 2005)

ACS / SPI / Integral
Hard X-rays

SH 1.2
• Hard x-ray (> 150 keV) from ACS/SPI
  Integral
• Coronas-F: γ-rays (0.1-20 MeV)

Struminski & Zimovets, SH 1.2 - 188
Modelling time profiles of 2.223 MeV $\gamma$-emission

Variables:
Density profile in photosphere $\alpha T$ (Stochastic acceleration)
Best Fit: Model 5, i. e. enhanced density

SH 1.2 - 951 (Trottskaja & Miroshnichenko)
PHOTONS FROM INVERSE COMPTON EMISSION AT THE SUN

\[ \gamma \text{-ray spectrum for different solar modulation conditions} \]

\[ \text{Angular distance from the Sun} \]

Modelling IC Flux with modulated GCR spectrum and the photon field of the Sun

SH 1.2 - 600 (Orlando et al.)

IC Flux from EGRET

With high sensitivity GLAST Measurements:
Infer electron spectrum in the inner heliosphere
**SOLAR NEUTRONS -1**

- **High Energy Solar Neutrons** provide information on the acceleration process at the Sun
- Time and duration of \( n \) production is directly related to the acceleration time of ions
- Energy of \( n \) is related to acceleration process
- Observation with NM, SNT and instruments on S/C
- SNTs provide energy and directional information
- Neutron propagation is not influenced by the magnetic field

**SOLR NEUTRON TELESCOPE STATIONS (SNT)**

SH 1.2 - 191 (Matsubara et al)
Neutron observations with NM and SNT and S/C observations:

• Systematic search for solar neutrons in X-class flares during 2005 - 2006  
  SH 1.3-191; Matsubara et al.,

Result: Only September 7, 2005 event showed neutron signal

September 7, 2005 event investigated by several authors:

Neutron Time Profile and Spectra, September 7, 2005  
  SH 1.3-0374; Watanabe et al.

Neutron Spectrum derived from SNT(using SNT E-ch)  
  SH 1.3-0912; Sako et al.,

Neutron spectrum from SNT (using timing+response)  
  SH 1.3-1225; Gonzalez et al.

October 28, 2003: Neutron Time Profile  
  SH 1.3-0371; Watanabe et al.

April 15, 2001: Neutrons and Protons in the event  
  SH 1.3-099; Muraki et al.
Fit of long lasting time profile using Hua’s Loop Model, assuming injection time profile from 4.4 MeV γ-line

- $\lambda = 5000$ (scattering parameter)
- $\delta = 0.20$ (convergence parameter)
- $s = -3.6$ (p spectral index)
- $L = 38,600$ km (from RHESSI and GOES/SXI)
NEUTRON ENERGY SPECTRA

Independent approach to infer Energy Spectrum of Neutrons:

Monte Carlo Simulation, using:
- Decay during propagation to Earth
- Attenuation in atmosphere
- Energy response of several channels of the SNT

Neutron Injection Spectrum $\sim E^{-3.0}$

SH 1.3 - 912 (Sako et al.)

September 7, 2005 Event (Mexico SNT)
ENERGETIC CHARGED PARTICLES
Spectra, Composition, and Charge States

**IMPULSIVE EVENTS**
Acceleration related to Flare Process
“Flare Particles”

**GRADUAL EVENTS**
Acceleration related to Coronal / Interplanetary Shock
“Shock accelerated Particles”

<table>
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<tr>
<th>particles</th>
<th>3He-rich</th>
<th>gradual</th>
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<tr>
<td>3He/4He</td>
<td>~ 1</td>
<td>~ 0.0005</td>
</tr>
<tr>
<td>[Fe/O]/[Fe/O]</td>
<td>~ 10</td>
<td>~ 1</td>
</tr>
<tr>
<td>H/He</td>
<td>~ 10</td>
<td>~ 100</td>
</tr>
<tr>
<td>QFe</td>
<td>~ 20</td>
<td>~ 14</td>
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<tr>
<td>Duration</td>
<td>hours</td>
<td>Days</td>
</tr>
<tr>
<td>Long. Distrib</td>
<td>&lt; 30°</td>
<td>~ 180°</td>
</tr>
<tr>
<td>Metric Radio</td>
<td>III, V</td>
<td>II,III,IV,V</td>
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<td>Solar Wind</td>
<td>-</td>
<td>Ipl, shock</td>
</tr>
<tr>
<td>Event Rate</td>
<td>~ 1000/a</td>
<td>~ 10/a</td>
</tr>
</tbody>
</table>

Lin, 1970; Pallavicini et al., 1977, Reames 1999
ENERGETIC CHARGED PARTICLES
Spectra, Composition, and Charge States

IMPULSIVE EVENTS
Acceleration related to Flare Process
“Flare Particles”

GRADUAL EVENTS
Acceleration related to Coronal / Interplanetary Shock
“Shock accelerated Particles”

| particles          | \(^{3}\text{He}/\text{He}\) | \([^\text{Fe}/\text{O}] / [\text{Fe}/\text{O}]_{\text{cor}}\)| | [Mass 100-200] | \(\text{H}/\text{He}\) | \(Q_{\text{Fe}}\) | \(3\text{He-rich}\) | \(\text{gradual}\) |
|--------------------|-----------------|--------------------------|-----------------|-----------------|----------------|----------------|----------------|
| electron rich      | ~ 1             | ~ 10                     | > 100           | ~ 10            | ~ 10-20 \(Q(\text{E})\) | ~ 100          | ~ 0.001 – 0.1 |
| proton rich        | ~ 0.001 – 0.1   | ~ 1                      | ~ 100           | ~ 10            | ~ 10-20 \(Q(\text{E})\) | ~ 10 at < 500 keV | ~ 20 at > 10 MeV/n |

<table>
<thead>
<tr>
<th>Duration</th>
<th>Long. Distrib</th>
<th>Metric Radio</th>
<th>Solar Wind</th>
<th>CME</th>
<th>Event Rate</th>
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<tr>
<td>hours</td>
<td>&lt; 30°</td>
<td>III, V</td>
<td>-</td>
<td>Y (narrow)</td>
<td>~ 1000/a</td>
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<tr>
<td>Days</td>
<td>~ 180°</td>
<td>II,III,IV,V</td>
<td>Ipl. shock</td>
<td>Y</td>
<td>~ 10/a</td>
</tr>
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</table>
ENERGETIC CHARGED PARTICLES

$^3$He-rich, Heavy Ion-rich Events

Strong energy dependence of $Q_{\text{Fe}}(E)$ for ALL $^3$He-rich, Fe-rich events observed so far. Möbius et al, ICRC 2003; Klecker et al., 2006 Kovaltsov et al., 2000; Kocharov et al., 200x

Numerical Model combining Stochastic Acceleration, Coulomb Loss, Ionization + Recombination with Interplanetary Propagation

Kartavykh et al., SH 1.4 - 649 Ionic Charge States: Pérez-Peraza et al., SH 1.4β774

Result:
Acceleration Must be in the low corona Altitude $< 0.2 \, R_S$
GRADUAL EVENTS

Energy Dependent Ionic Charge States

Large Variability of $Q(E)$ for Heavy Ions, in particular for Fe

From SEP Event Averages:
At low energies of up to ~ 250 keV/amu:
$Q_{Fe} \sim 10$, similar to Solar Wind

At Interplanetary Shocks:

$Q_{Fe}(E) \sim 10.5$ independent of energy in the energy range 0.18-0.43 MeV/n

Mazur et al., 1999; Möbius et al., 1999

SH 1.4 - 667 (Klecker et al.)
NEW OBSERVATIONS : LARGE (GRADUAL)EVENTS

\(^3\text{He} \) at IP Shocks

\(^3\text{He} / \, ^4\text{He} \) ratio at \(~1\ \text{MeV/nuc}\) ions at interplanetary shocks.
He does not show Solar Wind Composition:
Scenario:
\(^3\text{He} \) from suprathermal ions from previous \(^3\text{He}\)-rich events
(Mason et al., 1999)

Desai et al., 2004

\(\theta_{\text{Bn}} > 60^\circ\)

0.2-0.4
0.4-1.0
4.5-7.6
7.6-16.3
(MeV/n)

1999

SH 1.4 - 1121 (Wiedenbeck et al)
GRADUAL EVENTS
Spectra and Composition

Spectral breaks scale with $Q/A$:
Fit with $j \sim j^{-\gamma} \exp(-E/E_0); E_0 \sim (Q/M)^\beta$

SH 1.4-1186 (Mewaldt et al.)
GRADUAL EVENTS
Spectra and Composition

- Relate Energy of spectral break to scattering mean free path (Cohen et al., 2005)

\[ \kappa = \frac{1}{3} \lambda \nu, \quad \kappa \sim (M/Q)^\alpha (E)^{(\alpha+1)/2} \]

\[ E_1/E_2 = \left[ \frac{(Q/M)_1}{(Q/M)_2} \right]^{2\alpha/(\alpha+1)}, \text{i.e.} \]

\[ \alpha = \beta / (2-\beta) \]

\[ \alpha = 2 + q \]

q: power law index of wave turbulence

q > -2 \ldots 0 \quad \text{additional wave power near shock}

Consistent with scenario of acceleration by quasi-parallel shock

SH 1.4 - 1186 (Mewaldt et al.)
GRADUAL EVENTS
Spectra and Composition

ACE

Oxygen
Iron

ULEIS

Intensity (cm$^2$ s^{-1} MeV$^{-1}$)

Day of 2006

E70
W25

Shocks $\theta_{BN}=12 \pm 10^\circ$
$\theta_{BN}=36 \pm 19^\circ$

Fe/O~1

SH 1.4 - 1186 (Cohen et al.)
GRADUAL EVENTS

Spectra and Composition

Dec 6, 2006

**E70**  Shock $\theta_{BN} = 12 \pm 10^\circ$

Type 1 Event: consistent with acceleration at quasi-parallel shock

SH 1.4 - 1186 (Cohen et al.)

Dec 13, 2006

**W25**  $\theta_{BN} = 36 \pm 19^\circ$

Type 2 Event: ?
At high energies:

- $Q_{Fe}(E)$ increasing at $E > 10$ Mev/nuc in many events
- Correlation of high Fe charge with high Fe/O abundance

Labrador et al., ICRC 2005
SCENARIO 1 FOR HEAVY ION ENRICHMENT AND HIGH CHARGE STATES AT HIGH ENERGIES

THREE PHASES OF PARTICLE ACCELERATION

FIRST
FLARE IMPULSIVE PHASE

SECOND
FLARE LATE PHASE

THIRD
SHOCK ACCELERATION

TWO CONDITIONS
(1) Open Field Lines; (2) Magnetic Connection

Cane et al., 2006; SH 1.4 - 405 (Cane et al.)
SCENARIO 2 FOR HEAVY ION ENRICHMENT AND HIGH CHARGE STATES AT HIGH ENERGIES

Model: Mixing of 2 Populations

1. Source with 2 components:
   (1) Coronal Source
   (2) Flare Source
2. Spectra with Q/M and $\theta_{BN}$
dependent roll-over $E_0$ at high energies:
   \[
   F_i = C_i \exp(-E/E_{0i})
   \]
   \[
   E_{0i} = E_0 (Q_i/A_i) * (\sec(\theta_{BN}))^\alpha
   \]
   \[
   \alpha = 2 / (2 \gamma - 1)
   \]
3. Higher injection threshold for large
   $\theta_{BN}$ (simulated by suppression of
coronal component with
increasing $\theta_{BN}$).
4. Averaging spectra over $\theta_{BN}$, i.e.
assuming contributions from
parallel and perpendicular shock

Further Investigation Needed
STEREO / ACE with 3 measurements separated in
longitude may provide the clue
Excellent agreement between instruments on STEREO and near Earth (ACE, SAMPEX, GOES)

Great potential for multi-spacecraft studies from different vantage points:

STEREO - ACE / SOHO

SH 1.4 - 1150 Cohen et al.
SH 1.4 - 1202 Von Rosenvinge et al.
SH 1.4 - 1218 Mewaldt et al.
ACCELERATION AND TRANSPORT OF Solar Energetic Particles

Acceleration and Transport of SEPs

CME propagation + Transport

Shock Accel. Model (quasi-parallel)

Comparison of shock acc, stochastic acc,

Acceleration in stochastic electric fields

Acceleration at perpendicular shock + recirculation

Propagation of e, p in impulsive events

Propagation of e in impulsive events

SEP Event time scales and solar wind streams

Travel delays of impulsive SEPs

Particle Propagation in the 3D Heliosphere

SH 1.7 - 0232, Kota

SH 1.5 - 1273, Li, et al.,

SH 1.5 - 352, Perez-Peraza et al.

SH 1.5 - 0140, Zimovets

SH 2.3 - 1015, Nemeth

SH 1.6 - 653 Dröge et al

SH 1.6 - 1281 Li et al

SH 1.6 - 361, Kahler

SH 1.6 - 366 Ragot & Kahler

SH 1.6 - 455 Malandraki et al.
ACCELERATION AND TRANSPORT OF Solar Energetic Particles

Acceleration at quasi-parallel shock

Fit of Sept 27, 2001 SEP Event

Q/A dependent spectral breaks can be reproduced

Numerical Code for particle acceleration and transport at quasi-parallel shock, including
  • local injection
  • Fermi acceleration at the shock
  • self-consistent excitation of waves at the shock
  • particle scattering and escape

SH 1.5 - 1273 G. Li, et al
Solar release time ($t_{SRT}$) is often computed from the particle arrival time $t_{arr}$ and assuming propagation along the Parker Spiral field line of length $L$

$$t_{arr} = t_{SRT} + \frac{L}{v}$$

- Lengthening of field lines due to turbulence
- Use measured turbulence to simulate lengthening for various length scales $\delta z$

$\delta z = 10^9$

SH 1.6 - 366 (Ragot & Kahler)
ACCELERATION AND TRANSPORT
Propagation in Impulsive Events

Solar Particle Propagation
Combination of:
Azimuthal Transport Close
to the Sun (Coronal Diffusion)
Transport Parallel To \( B \)
Pitch Angle Scattering, Focusing,
Adiabatic Losses
Possible Diffusion Across The
Average Magnetic Field

Transport using focused diffusion model

\[
\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} + \frac{1 - \mu^2}{2L} v \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu} \left( D_{\mu \mu}(\mu) \frac{\partial f}{\partial \mu} \right) = q(z, \mu, t)
\]

\( \lambda_{II} \) computed with 10-20% slab and 80-90% 2D turbulence, DQLT

SH 1.6 - 653 (Dröge et al.)
CORONAL MASS EJECTIONS - SH 1.7

CME

SOHO / LASCO

ICME

Zurbuchen & Richardson, 2006
## CORONAL MASS EJECTIONS

### SH 1.7

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<td>A Survey of Interplanetary Coronal Mass Ejections During 1996 – 2007</td>
<td>Richardson &amp; Cane</td>
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INFERRING ICME PROPERTIES

Relating expansion speed to radial speed (SOHO / LASCO C2 + C3), assuming constant opening angle of the CME cone

SH 1.7- 1245 (Muñoz et al)

Fit of Magnetic Field Profiles assuming elliptical cross section of flux tube

SH 1.7- 1309 (Vandas et al)
ICME PROPERTIES, 1996-2007

• ICME rate has nearly returned to that during the previous solar minimum;
• ICME rate does not strictly follow the sunspot number;
• Increasing trend in fraction of magnetic clouds?
• Mean ICME speeds are highest during declining phase of this solar cycle.
• ICME rate at Ulysses is comparable to that at Earth (~2/rotation), despite the variations in s/c latitude.

SH 2.1- 0381 (Richardson & Cane)
CMEs AND MODULATION

The correlation between the number of high latitude CMEs and CR is very good.

During A>0 Cycle
Drift from poles to ecliptic
Efficient modulation by High Latitude CMEs

SH 2.1-054 (Lara & Caballero-Lopez)
CMEs AND MODULATION

This cartoon represents the proposed scenario for the CME-CR latitudinal interaction.

High latitude CMEs

Low latitude CMEs

qA > 0 Parallel magnetic field

RC

Heliosphere

The CR flux starts decreasing when the high latitude CME activity increases.

SH 2.1-054
(Lara & Caballero-Lopez)
FORBUSH DECREASE / EFFECTS OF CMEs

Typical Time Profile of Forbush Decrease

Interplanetary Shock arrival: May 15 02:19 (SOHO) Average Speed: 1240 km/s

CME / SOHO May 13, 2005 17:22
M8 Flare 16:57

SH 2.1 - 48 (Jain et al.)
Muon Hodoscope

- Three detectors with thresholds of 2.6, 2.7 and 5.6 GeV
- Using 3 detectors and variation of response with zenith angle allows to reconstruct 2D dynamics of the Forbush decrease
FORBUSH DECREASE EFFECTS

IceTop: Air Shower Array at the South Pole
Ice Cherenkov Counters

Response of IceTop to GCR and SEP

NM McMurdo
IceTop - measurement
High sensitivity (~500 m²) measurements at Antarctica

IceTop - simulation

IMF
SH 2.1 - 729 (Kuwabara et al.)
COROTATING INTERACTION REGIONS - SHOCKS

CIRs observed by STEREO and ACE in early 2007

Unsolved Questions, e.g.
Composition (C/O ~1, different from SEP)
Anisotropies
Large perp. Diffusion?

Questions can be tackled with increasing separation of STEREO A and B

SH 2.2-924 (Müller-Mellin et al.)

SH 2.2 - 1224 (Leske et al.)
THINGS TO HAPPEN BETWEEN NOW AND THE NEXT ICRC

... a Wish List ...

• Looking forward for solar activity to pick up
• Many Flares, CMEs, GLEs …
• Multispacecraft Measurements with STEREO, ACE, RHESSI, TRACE, …
• Modelling Effort on Acceleration in Impulsive Events, including charge stripping, 3He and Heavy Ion enrichment, and interplanetary propagation
• Modelling of CME Propagation, and particle acceleration at the evolving parallel and perpendicular Shock …

SEE YOU AT THE 31th ICRC