Solar Cosmic Rays in Merida
(30th ICRC): New Results and Ideas

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Gran Evento en Merida…
Abstract

• Based on generous materials of the 30th International Cosmic Ray Conference (Merida, Yucatan, Mexico, 3-11 July 2007), we critically review the most keen, disputable questions of solar energetic particle (SEP) production at/near the Sun. The main of them are following:

• Two classes of SEP events: Impulsive vs. Gradual, or SEP event continuum?
• Multiple acceleration processes at/near the Sun
• High-energy cutoff of solar cosmic ray (SCR) spectrum
• Two mechanisms for particle acceleration at the Sun (on the data of the GLE of 20 January 2005)
• Two-source acceleration scenario for GLEs: Solar and interplanetary aspects
• New concept of Ground Level Enhancement
• Long-Standing Problems and Arising matters
Reality: Our Dynamical and “Mysterious” Sun
CME and ICME
Zurbuchen & Richardson, 2006
Images vs. Reality
Two classes of SEP events

1. Observational Properties and Underlying Physical Mechanisms: Flare or CME?
2. Interpretation: Impulsive vs. Gradual or SEP Event Continuum?
## Two Classes of SEP Events (Reames, 1996)

<table>
<thead>
<tr>
<th>Parameters of particles, observation method</th>
<th>Impulsive events</th>
<th>Gradual events</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particles:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^3\text{He}/^4\text{He}$</td>
<td>~ 1</td>
<td>~ 0.0005</td>
</tr>
<tr>
<td>H/He</td>
<td>~ 1</td>
<td>~ 0.1</td>
</tr>
<tr>
<td>Fe/O</td>
<td>~ 10</td>
<td>~ 100</td>
</tr>
<tr>
<td>$Q(\text{Fe})$</td>
<td>~ 20</td>
<td>~ 14</td>
</tr>
<tr>
<td><strong>Duration:</strong></td>
<td>Hours</td>
<td>Days</td>
</tr>
<tr>
<td><strong>Longitude cone</strong></td>
<td>&lt;30 degrees</td>
<td>~ 180 degrees</td>
</tr>
<tr>
<td><strong>Radio type</strong></td>
<td>III, V (II)</td>
<td>II, IV</td>
</tr>
<tr>
<td><strong>X-rays</strong></td>
<td>Impulsive</td>
<td>Gradual</td>
</tr>
<tr>
<td><strong>Coronograph</strong></td>
<td>-</td>
<td>CMEs (96%)</td>
</tr>
<tr>
<td><strong>Solar Wind</strong></td>
<td>-</td>
<td>IP Shock</td>
</tr>
<tr>
<td><strong>Events/year</strong></td>
<td>~ 1000</td>
<td>~ 10</td>
</tr>
</tbody>
</table>
Two Classes of SEP Events (Reames et al., 1996). Dependence of Particular Event, Particle Energy, and Observer’s Locations (Cane et al., 2007)
Energy Dependence of the Mean Ionic Charge State of Fe ions (Tylka et al., 2001).
2. Multiple Acceleration Processes at/near the Sun

- Particle Intensity-Time Profiles
- Manifestations in X-Rays and Gamma-Radiation
- Escaping and Precipitating SEPs
GLE of 29 September 1989: Two-Peak Structure
P1: A Common Occurrence
(After Shea and Smart, 1996)
Multiple Acceleration Processes at/near the Sun
(Struminsky & Zimovets, 2007)
Source Spectrum by Different Data:
Integral energy spectra of accelerated solar protons in the sources by estimates for the four SEP events (Miroshnichenko, 2003).

A number of escaping particles is methodically higher than a number of precipitating (interacting) ones.
3. High-Energy Cutoff of Solar Cosmic Rays

- Observational and Theoretical Aspects
- Ground-Based Observations for Protons
- Spectral Breaks in SEPs for Heavier Ions
Solar Cosmic Rays: Upper Limit Spectrum: Miroshnichenko, 2003; also Muraki et al., 2007

The integral energy spectra for the largest proton events observed near the Earth in 1942-2000. The spectrum for galactic cosmic rays is also shown (dotted line).
The 20 January 2005 GLE: Rigidity Spectrum

Durham/Mt. Washington

Milagro/Climax

Milagro/Milagro

Higher, unanalyzed Milagro channels

Spectral index softens from 6.5 to ~8 at ~4GV

Paper 1152, Morgan et al.
Mewaldt et al., 2007: Spectral Breaks on 29 October 2003 (Shock Acceleration, Ellison-Ramaty, 1985)
GLE of 29 September 1989:
Proton energy spectrum by IMP 8, GOES 7, NM (Lovell et al. 1998, shaded) and calculated spectra (Berezhko and Taneev, 2003).

Diffusive Shock Acceleration;
$\beta$ - Alfvén wave spectral index.
$E_{\text{max}} = 300$ MeV?
4. Two Mechanisms for Particle Acceleration at the Sun

- Two last GLEs of the 23rd of Solar Activity
- GLE69: 20 January 2005
- GLE70: 13 December 2006
Solar Activity Cycle 23

ISES Solar Cycle Sunspot Number Progression
Date Through 31 Jul 07

Updated 2007 Aug 1
NOAA/SEC Boulder, CO USA
The 20 January 2005 GLE69: Largest One after the GLE05 of 23 February 1956
The 20 January 2005 GLE: Two Acceleration Mechanisms?

Sanae neutron monitor
20 January 2005

P1 06:54
P2 07:06
P3 07:24

Start: 06:50

% Increase

Time (hr)

Paper 862, Moraal et al.
The 20 January 2005 GLE: Two Acceleration Mechanisms?

Paper 862, Moraal et al.
The 20 January 2005 GLE: Two Acceleration Mechanisms?

PULSE 1 - 06:35

DIFFUSION AND SCATTERING

FOCUSSED INJECTION

GAMMA, X-RAYS & NEUTRONS

2.5 - 3.0 \( R_S \)

PULSE 2 - 06:41

CME

SUPERCRITICAL SHOCK

ISOTROPIC INJECTION

Paper 897, McCracken & Moraal
The 20 January 2005 GLE: Rigidity Spectrum

Durham/Mt. Washington

Milagro/Climax

Milagro/Milagro

Higher, unanalyzed Milagro channels

Spectral index softens from 6.5 to ~8 at ~4GV

Paper 1152, Morgan et al.
THE GENERIC SOLAR ENERGETIC PARTICLE EVENT  
(GLE and Lower Energies)

THE IMPULSIVE PHASE
- A highly anisotropic pulse of cosmic rays at Earth
- Coincident release of high energy gamma and neutron pulses
- Hard cosmic ray spectrum
- Acceleration low in corona
- Scatter free propagation due to focusing close to the Sun.
- High He/He ratio; high ionization state.
- From western third of solar disk

THE GRADUAL PHASE
- Mildly anisotropic pulse of cosmic radiation at Earth
- Soft cosmic ray spectrum
- Acceleration high in the corona, >2.5-3.0 Rs
- Diffusive propagation to Earth
- From central regions of solar disk

Similar conclusion by Vashenyuk et al., Paper 897, McCracken & Moraal
Paper 643
The 13 December 2006 GLE70

Map of neutron monitors' asymptotic cones. Cross is IMF direction from ACE data.
13 December 2006 GLE70: Energy Spectrum

![Graph showing the energy spectrum of protons with different time stamps and labels: 03:05 UT, 03:40 UT, 04:00 UT, GOES11, and Ballon, 08:20 UT.](image)
5. Two-source acceleration scenario for GLEs

- Two-source model for GLEs
- Magnetic Reconnection in Acceleration Scenarios
- Extended Coronal Structures
- Prompt and Delayed Components
- Statistics of Two-Component GLEs
Production of SEPs in the Solar Atmosphere: Separation of Two Classes of SEP Events – Impulsive and Gradual Ones (Yoshimori et al., 2000)
Two-Source Model (Perez-Peraza et al., 1992)
a. Proposed model for the IMF structure during the GLE of 28 October, 2003;
b. Spatial structure of the IMF near the Earth, reconstructed with use of IMF and solar wind data (Miroshnichenko et al., JGR, 2005)
Direct Field Acceleration in a Magnetic Neutral Current Sheet (Perez-Peraza et al., 2007)

(a): Neutron Monitor Data
(b): NCS Acc. Ec=1300MeV
(c): NCS Acc. Ec=2000MeV
Direct Field Acceleration in a Magnetic Neutral Current Sheet (Perez-Peraza et al., 2007)

(a): Neutron Monitor data
(b): NCS Acc. Ec=850 MeV
(c): NCS Acc. Ec=50 MeV
Stochastic Process in a Fast Magnetosonic Wave Environment (Perez-Peraza et al., 2007)

(a): Stoch. Acc. Mono Inj. $\alpha=0.05\ s^{-1}$, $\tau=1\ s$, $E_0=1\ MeV$

(b): Stoch. Acc. Mono Inj. and Adia. Dec. $\alpha=0.05\ s^{-1}$, $\tau=1\ s$, $\rho=0.035\ s^{-1}$, $E_0=1\ MeV$

(c): Stoch. Acc. with NCS injection $\alpha=0.07\ s^{-1}$, $\tau=1\ s$, $E_c=4.5\ MeV$

September 29, 1989

GOES-7

Neutron Monitor Data
Stochastic Process in a Fast Magnetosonic Wave Environment (Perez-Peraza et al., 2007)

PROTONS/(MeV.cm^-2.str.)

KINETIC ENERGY (MeV)

(a): Stoch. Acc. with NCS Injection
\( \alpha = 0.17 \text{ s}^{-1}, \tau = 1 \text{ s}, E_c = 4.5 \text{MeV} \)

(b): Stoch. Acc. Mono Injection
\( \alpha = 0.07 \text{ s}^{-1}, \tau = 1 \text{ s}, E_0 = 1 \text{MeV} \)

\( \alpha = 0.07 \text{ s}^{-1}, \tau = 1 \text{ s}, E = 1 \text{MeV}, \rho = 0.02 \text{ s}^{-1} \)

Neutron Monitor Data

October 28, 2003
Large GLEs of 1956-2006 with Two Components
(Vashenyuk et al., 2007)

<table>
<thead>
<tr>
<th>GLE No.</th>
<th>Date of GLE</th>
<th>Type II Onset</th>
<th>Flare Importance</th>
<th>Helio-coordinates</th>
<th>PC spectrum (exponential)</th>
<th>DC spectrum (power-law)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$J_0$ $E_0$</td>
<td>$J_1$ $\gamma$</td>
</tr>
<tr>
<td>1/05</td>
<td>230256</td>
<td>0331*</td>
<td>3B</td>
<td>N25W85</td>
<td>$1.4 \times 10^6$ $1.30$</td>
<td>$4.2 \times 10^6$ $5.2$</td>
</tr>
<tr>
<td>2/31</td>
<td>070578</td>
<td>0327</td>
<td>1B/X2</td>
<td>N23W82</td>
<td>$5.6 \times 10^4$ $0.71$</td>
<td>$1.2 \times 10^4$ $4.1$</td>
</tr>
<tr>
<td>3/38</td>
<td>071282</td>
<td>2344</td>
<td>1B/X2.8</td>
<td>S19W86</td>
<td>$5.7 \times 10^3$ $0.65$</td>
<td>$7.2 \times 10^3$ $4.5$</td>
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<tr>
<td>4/39</td>
<td>160284</td>
<td>0858</td>
<td>-/-</td>
<td>S??W132</td>
<td>-</td>
<td>$5.2 \times 10^4$ $5.9$</td>
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<tr>
<td>5/42</td>
<td>290989</td>
<td>1133</td>
<td>??/X9.8</td>
<td>S24W105</td>
<td>$1.9 \times 10^4$ $1.54$</td>
<td>$3.5 \times 10^4$ $4.1$</td>
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<tr>
<td>6/44</td>
<td>221089</td>
<td>1805</td>
<td>2B/X2.9</td>
<td>S27W31</td>
<td>$7.5 \times 10^4$ $0.87$</td>
<td>$1.5 \times 10^4$ $6.1$</td>
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<tr>
<td>7/47</td>
<td>210590</td>
<td>2219</td>
<td>2B/X5.5</td>
<td>N35W36</td>
<td>$6.3 \times 10^3$ $0.83$</td>
<td>$2.7 \times 10^3$ $4.1$</td>
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<tr>
<td>8/55</td>
<td>061197</td>
<td>1155</td>
<td>2B/X9.4</td>
<td>S18W63</td>
<td>$7.3 \times 10^3$ $1.20$</td>
<td>$5.0 \times 10^3$ $4.3$</td>
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<tr>
<td>9/59</td>
<td>140700</td>
<td>1020</td>
<td>3B/X5.7</td>
<td>N22W07</td>
<td>$3.3 \times 10^5$ $0.35$</td>
<td>$2.0 \times 10^4$ $6.4$</td>
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<tr>
<td>10/60</td>
<td>150401</td>
<td>1319</td>
<td>2B/X14.4</td>
<td>S20W85</td>
<td>$1.3 \times 10^5$ $0.53$</td>
<td>$3.5 \times 10^4$ $5.3$</td>
</tr>
<tr>
<td>11/65</td>
<td>281003</td>
<td>1102</td>
<td>4B/X17.2</td>
<td>S16E08</td>
<td>$1.4 \times 10^4$ $0.59$</td>
<td>$1.5 \times 10^4$ $4.4$</td>
</tr>
<tr>
<td>12/67</td>
<td>021103</td>
<td>1703</td>
<td>2B/X8.3</td>
<td>S14W56</td>
<td>$5.6 \times 10^4$ $0.33$</td>
<td>$2.7 \times 10^3$ $6.6$</td>
</tr>
<tr>
<td>13/69</td>
<td>200105</td>
<td>0644</td>
<td>2B/X7.1</td>
<td>N14W61</td>
<td>$2.5 \times 10^6$ $0.49$</td>
<td>$7.2 \times 10^4$ $5.6$</td>
</tr>
<tr>
<td>14/70</td>
<td>131206</td>
<td>0226</td>
<td>2B/X3.4</td>
<td>S06W24</td>
<td>$1.1 \times 10^6$ $0.33$</td>
<td>$4.4 \times 10^4$ $5.5$</td>
</tr>
</tbody>
</table>
6. New Concept of GLE: Solar and Interplanetary Aspects

- Concept of Multiple Acceleration Processes at/near the Sun
- Extended Coronal Structures
- Two Separate Sources of Acceleration
- CME-Driven Shocks
- Scattering Conditions
- Two Different Paths for PC & DC Particles in the IMF
Two Components: Interplanetary vs. Solar Origin?

- Scattering conditions as a cause of “spike” in the SCR intensity (Fedorov & Shakhov, 1993; Earl, 1995; Fedorov et al., 1995; Ruffolo & Khumlumlert, 1995, and others).
- Two different paths for PC & DC particles in the IMF (Cramp et al., 1997)
- Two individual injections (Torsti et al., 1991, 1992)
- Dual acceleration/release processes (Shea & Smart, 1997; Cramp et al., 1997)
- Two separate sources in extended coronal structures (Miroshnichenko et al., 1995, 1996, 2000)
- GLEs as a separate class of SEP events (Shea & Smart, 1996, 1997; Miroshnichenko et al., 2000, Miroshnichenko, 1997, 2001; Vashenyuk et al., 2005, 2006).
Special Workshop on GLE Concept and NM Status (SEE2007, Greece)?

• Taking into account our modeling results, we do not believe that the hypothesis of “an interplanetary origin” of the features mentioned can resolve alone the problem of relativistic proton events.

• There are some grounds to accept a two-source model of SCR generation itself at/near the Sun, in the frame of the concept of multiple acceleration processes in the solar atmosphere.
7. Long-Standing Problems and Arising Matters

- Observations, Methods, and Theory
- Initial Stage of Acceleration
- Physical Implications of Gamma-Emission and Neutron Data
- Modeling Techniques
- Method of Additional Fluctuations
- Non-Standard Detectors
Spectrum Splitting for Protons and Electrons in the Source (Miroshnichenko, 1995): Expected differentiation of the normalized rigidity spectra of accelerated particles due to different efficiency of acceleration mechanisms and different pattern of energy losses of electrons and protons (dashed and solid lines, respectively).
Energy spectrum of the 4 June 1991 flare
(Share and Murphy, 2000)
Effect of Density Enhancement (EDE) in the Solar Atmosphere on 28 October 2003 (2.223 MeV line)

Models of the Solar Atmosphere Density (left)  
Modelling time profiles of 2.223 MeV g-emission (right)  
Variables: Density profile in photosphere; $aT$ (Stochastic acceleration). Best Fit: Model 5, i.e. enhanced density (Troitskaja & Miroshnichenko, 2007)
CORONAS-F, Event of 20 January 2005, Neutron Capture Line 20.58 MeV (He-3)
Counting rate of the background distributed under Poisson law with \( \lambda = 100 \), weak signal, and their sum (Karpov & Miroshnchenko, 2007)
Muon Bursts at the Baksan Underground Scintillation Telescope (Karpov & Miroshnichenko, 2007)
Muon Diagnostics of the Earth's Atmosphere, Near-Terrestrial Space and Heliosphere: First Results and Prospects

• GLE69 of 20 January 2005: The muon counting rate increases at GRAND Array above 10-sigma level in the 6-minute interval (e.g., D’Andrea & Poirier, 2005)

• GLE70 of 13 December 2006: In 10-minute counting rate summarized over URAGAH super-modules, maximum enhancement value equals to 0.61(+/-0.09)% and is above 6-sigma level (e.g., Timashkov et al., 2007, papers 296, 298, 305)
Saludos de Chichen Itza!
30th ICRC + VIII COLAGE + SEE2007 + … = CONTINUAMOS…

¡MUCHAS GRACIAS!
E. Flueckiger: Take home messages

• New large GLE on December 13, 2006

• Ongoing discussion about two mechanisms for particle acceleration at the Sun (on the basis of the January 20, 2005 GLE)

• Cosmogenic Radionuclides ($^7$Be, $^{10}$Be, $^{14}$C)
  
  New type of Neutron Monitor with time range of up to 100’000 years

• Nitrate technique for GLE archive established

• New probing techniques for space weather applications: muon diagnostics
B. Klecker: 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