Correlation of solar wind parameters with cosmic rays observed with ground station

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Overview

- Cosmic rays
  - Transport through heliosphere
    - Solar activity and space weather
    - Parker equation
  - Transport through geomagnetic field
- Interaction with atmosphere
  - Detection of cosmic rays
    - Satellite
    - Airborne, ground detectors
    - Underground detectors
- Low level laboratory
- Measurement of solar activity
  - Comparison between ground detectors
  - Comparison with satellite
- Plans for future
- Conclusion
Cosmic rays

- Major phenomenon in our galaxy
  - Energy density ~ star light, thermal, B field
  - Regulate the equilibrium between the different phases of the interstellar medium
  - Control ionisation, heating
  - Regulate star formation
  - Control astrochemistry
  - Generate turbulent magnetic field
  - Produce Li, Be and B

Major unknown
- Sources are not well known (Galactic and Extragal.)
- Acceleration processes are uncertain
Cosmic rays

- Primary cosmic rays spectrum
  - Power law
    \[ j(E) = \frac{dN}{dE} \propto E^{-\gamma} \]
  - \( \gamma \sim 2.7 \)
- Cosmic rays composition
  - Depends on CR energy
  - \(~80\% \text{ protons}, ~12\% \text{ helium nuclei rest} \) are electrons and nuclei of heavier elements
Transport through heliosphere

- **Solar wind**
  - stream of charged particles released from the upper atmosphere of the Sun
- **CR interact with heliosphere** - modulation of CR
- **Magnetic field and solar wind depend on activity of the Sun** *(space weather)*
- **CR modulation will increase when solar activity is higher and decrease when activity is lower.**
- **Solar modulation depends on energy of the CR**
- **Magnetic rigidity**
  
  \[ R \equiv \frac{pc}{Ze}. \]
Transport through heliosphere equation

- Propagation in the heliosphere was described by Parker (1965) equation

\[
\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i} \left[ \kappa_{ij}(s) \frac{\partial f}{\partial x_j} \right] - \mathbf{U} \cdot \nabla f - \mathbf{V}_d \cdot \nabla f + \frac{1}{3} \nabla \cdot \mathbf{U} \left[ \frac{\partial f}{\partial \ln p} \right] + Q
\]

- \( f(R,R,t) \) number of charged particles per unit volume of phase space
- Magnetic rigidity \( R \)
- Gyroradius \( r_g = \frac{R}{cB} \).
Transport through heliosphere

Equation

\[
\frac{\partial f}{\partial t} + \nabla \cdot (Vf - K \cdot \nabla f) - \frac{1}{3} (\nabla \cdot V) \frac{\partial f}{\partial \ln p} = q
\]

- Scattering of cosmic rays by turbulence is described by the cosmic-ray diffusion tensor
- the diagonal elements describe diffusion of particles parallel \((K_\parallel)\) and perpendicular \((K_\perp)\) to the mean magnetic field,
- off-diagonal, antisymmetric terms \((K_A)\) describe effects of gradient and curvature drift

\[
K = \begin{pmatrix}
K_\perp & K_A & 0 \\
-K_A & K_\perp & 0 \\
0 & 0 & K_\parallel
\end{pmatrix}
\]
## Solar activity

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<tr>
<th>type</th>
<th>Amplitude</th>
<th>origin</th>
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<tbody>
<tr>
<td><strong>Periodic variations</strong></td>
<td></td>
<td></td>
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<tr>
<td>11-years and 22-years</td>
<td>Up to 30%</td>
<td>Solar cycles (change of sunspot number)</td>
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<tr>
<td>27-days</td>
<td>&lt; 2%</td>
<td>due to Sun’s rotation</td>
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<tr>
<td>daily</td>
<td>0.5%</td>
<td>flux anisotropy due to Earth’s movement through heliosphere</td>
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<tr>
<td><strong>Sporadic variation</strong></td>
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<tr>
<td>GLE</td>
<td>Up to 300%</td>
<td>additional flux of charged particles from CME</td>
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<tr>
<td>Forbush decrease</td>
<td>~10%</td>
<td>decrease due to reflection of low energy CR from the shockwave in heliosphere</td>
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</table>
Solar activity
Sporadic events

• Violent processes at the Sun produces disturbance of the heliosphere.

• This disturbance interact with geomagnetic field.

• This interaction have disruptive potential on our civilization.
SPACE WEATHER
Related to Social Infrastructure
Transport through geomagnetic field

- Geomagnetic field also affect CR
- Dipole approximation
- $R_s$ (geomagnetic cutoff rigidity)
  - Smallest rigidity for charged particle to reach surface

$$R_c = \frac{M \cos^4 \lambda}{4 \tau^2}$$
Interaction with atmosphere

Secondary CR

- Primary CR interact with nuclei from atmosphere
- **Secondary CR shower**
  - Particles that are created from interaction

- Electromagnetic cascade
  - \( \pi^0 \to 2\gamma \)
  - \( \gamma \to e^- + e^+ \) pair production
  - \( e \to e + \gamma \) *bremsstrahlung*

- Hadronic and mesonic cascade
  - \( p + p \to p + \Delta^+ \to p + n + \pi^+ \)
  - \( \pi^+ \to \mu^+ + \nu_\mu \)
  - \( \pi^- \to \mu^- + \nu_\mu \)

- Shower spread with every new generation of particles
- Must be corrected with atmospheric parameters in mind
Detection of CR can be:

- Outside the heliosphere (Voyager)
- Above the atmosphere (various satellites)
- High in the atmosphere (high altitude balloons)
- On ground (secondary CR)
- Underground (secondary muons, neutrinos...)

![Graph showing flux vs energy with various markers and labels for different experiments and phenomena.](image)
Primary Space Weather Satellites for SEC

- **ACE**
  - Solar wind composition, speed, and direction
  - Magnetic field strength and direction

- **SOHO**
  - Solar EUV Images
  - Solar Corona (CMEs)
  - NASA SOHO

- **STEREO**
  - CME Direction and Shape
  - Solar wind composition, speed, and direction
  - Magnetic field strength and direction

- **GOES**
  - Energetic Particles
  - Magnetic Field
  - Solar X-ray Flux
  - Solar X-Ray Images

- **POES**
  - High Energy Particles
  - Total Energy Deposition
  - Solar UV Flux

- **NOAA STEREO**
  - (Ahead)

Events are observed on and near the sun
- No measurements until the Particles or CMEs are 99% of the way to Earth
- This provides only 30 minutes lead time for CMEs and no lead time for other events

NASA.GOV
Ground systems

- Various methods are used to detect CR.
- Some indirect methods includes measurement of concentration of cosmogenic radioisotopes $^{10}\text{Be}$ and $^{14}\text{C}$ in a sample.
- Neutron monitors are standard detectors for ground measurements.
Low level laboratory for nuclear physics
Institute of physics, Belgrade, Serbia

- 78 m a.s.l.,
  Geographic coordinates
  44° 51’ N, 20° 23’ E
- Minimal vertical rigidity 5.3 GV.

- Consist of two parts:
  - Ground level (GLL)
  - Underground (UL) level, dug in 12m of loess.

- Scientific research activities in the LBLNP are in the fields of nuclear and high energy physics. They are related in particular to cosmic-ray physics, nuclear spectroscopy, radon and environmental radiation measurements

- [http://cosmic.ipb.ac.rs/](http://cosmic.ipb.ac.rs/)
Low level laboratory for nuclear physics

Cosmic rays physics

- Two scintilating detectors 100cm x 100cm x 5cm, with addition of two smaller 50cm x 23cm x 5cm.
- Aquisition of date use fADC (C.A.E.N. N1728B)
- Digital spectroscopy
- Time resolution of the events is 10 ns, stored in a list
Low level laboratory for nuclear physics

Simulation packages

- Response of the detectors are calculated from simulation
- Range of energy for the primary CR found
• Comparison with nearby NM
  – The amplitude of a Forbush decrease is one of its main characteristics.

• Dependence of FD amplitude on median rigidity (or energy) is expected to follow the power law:
  \[ \frac{\Delta N}{N} \sim R_m^{-\gamma} \]

  • \( \gamma \) should be \(~0.4\)–1.3)
  • should be \(~0.4\)–1.3)
Solar activity
ground measurements Forbush decrease

MARCH12

JUNE15

SEPT14

SEPT17
• Found dependence of FD amplitude on median rigidity illustrates applicability of our setup for studies of consequences of CR solar modulation process in the energy region exceeding sensitivity of neutron monitors.

• Amplitude of Forbush decrease is inverse proportional to component of the diffusion tensor parallel to magnetic field which depends on CR rigidity.

• Higher power indices can be due to more complex variation of GCR. This more complex variation is a result of series of CMEs during this event that leads to large compound ICME structure with multiple shocks and transient flow.

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<td>0.79±0.16</td>
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<tr>
<td>June 2015.</td>
<td>0.57±0.05</td>
<td>0.58±0.02</td>
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<td>Sept. 2017.</td>
<td>1.27±0.16</td>
<td>0.86±0.07</td>
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Comparison with satellite data

- **STEREO (Solar Terrestrial Relations Observatory)**
  - Two nearly identical spacecraft were launched in 2006 into orbits around the Sun
  - Communication with STEREO B stopped 2014.

FD March 2012
Comparison with satellite data

- Linear correlation with solar wind parameters (STEREO) during extreme solar event hourly MARCH12

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<th>LMKS</th>
<th>KIEL</th>
<th>THUL</th>
<th>ULpc</th>
<th>ULptcR</th>
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</tbody>
</table>
Comparison of ground and satellite data

\[ r = r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \]

Correlation matrix of linear correlation coefficient (in %) for Belgrade cosmic ray station with its temperature and pressure corrected underground and ground level detectors (UL_tpc, GL_tpc), only pressure corrected (UL_pc, GLL_pc), raw data (UL_raw, GLL_raw) and Rome, Oulu, Jungfraujoch (JUNG) and Athens NMUs for March 2012.
Plans for future

• Enlarging the network of stations and collaboration with Georgia state university
  – Goal is to build a portable and low-cost cosmic ray muon telescope which could be easily duplicated and installed anywhere around the globe for studying the correlations between the cosmic ray muon flux variations and the dynamical patterns of the space and earth weather

• New method for temperature correction of cosmic rays’ muon flux
  – Goal is to use this method to get clear data for studying space weather but also to use CR as thermometer for high altitude layers

\[ \left( \frac{\delta I}{I} \right)_T = \int_0^{h_0} \alpha(h) \cdot \delta T(h) \cdot dh \]
Conclusion

• Muon detectors at Low level laboratory are used to find rigidity dependence of Forbush decrease. These data for transient solar modulation of GCR are obtained over much higher range of rigidities than region sensitive to NM thus allowing more extensive studies of cosmic-ray solar modulation processes.

• Comparison of ground data with satellite data outside geomagnetic field shows different correlation depending on energy recorded particles thus allowing better understanding of correlation between Forbush decreases and CME that can lead to hazardous event on Earth.

• Dependence of FD amplitude on median rigidity can lead to better models of propagation of CR through heliosphere thus giving condition of the heliosphere.
Thank you for your attention!

http://cosmic.ipb.ac.rs/