Correlation analysis of solar wind parameters and secondary cosmic rays flux

Nikola Veselinović, Mihailo Savić, Aleksandar Dragić, Dimitrije Maletić, Dejan Joković, Radomir Banjanac, Vladimir Udovičić and David Knežević

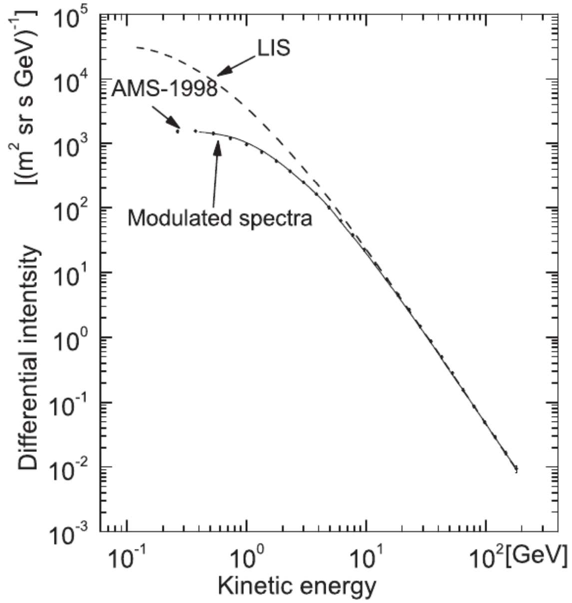
Progress report

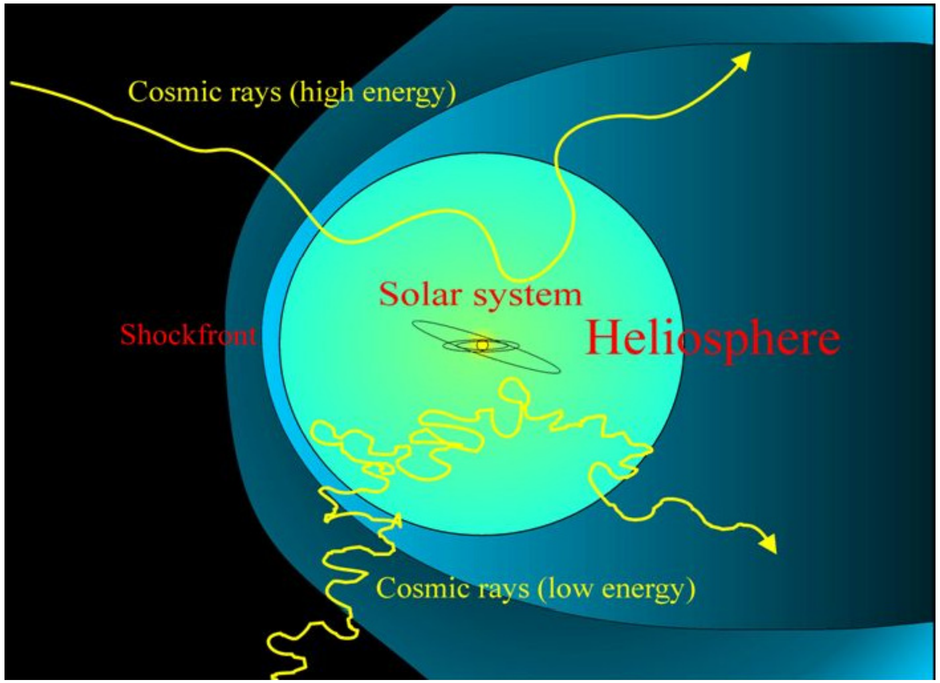
30th Symposium and Summer School on Physics of Ionized Gases,
Tuesday, August 25, 2020, Šabac

Cosmic rays modulation

- **C**osmic **R**ays (CR)
  - high-energy particles arriving from outer space (mainly protons)
- CR interact with helioshere - **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**

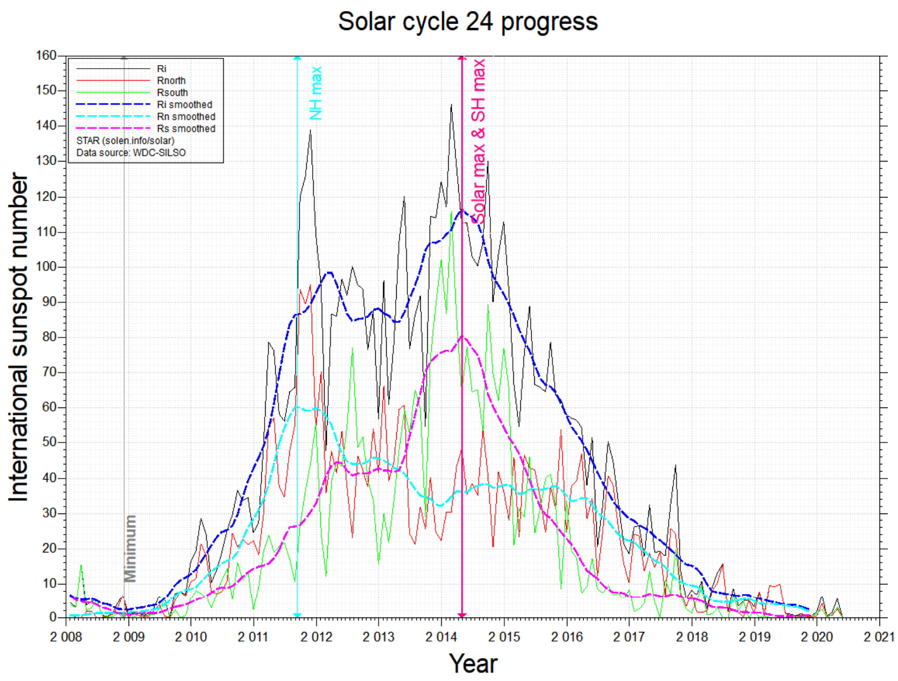
$$R \equiv pc / Ze.$$

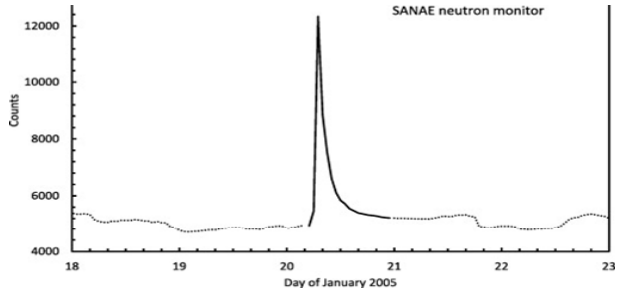


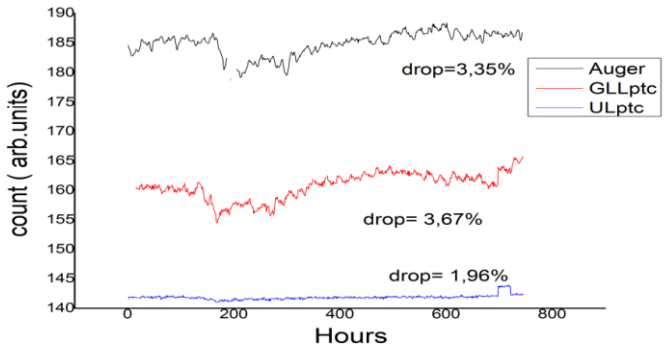


Solar Activity

type	Amplitude of CR flux change	origin
Periodic variations		
11-years and 22-years	Up to 30%	Solar cycles (change of sunspot number)
27-days	< 2%	due to Sun's rotation
daily	0,5 %	flux anisotropy due to Earth's movement through heliosphere
Sporadic variation		
GLE	Up to 300%	additional flux of charged particles (solar energetic particles SEP) from CME
Forbush decrease	~10%	decrease due to reflection of low energy CR from the shockwave in heliosphere







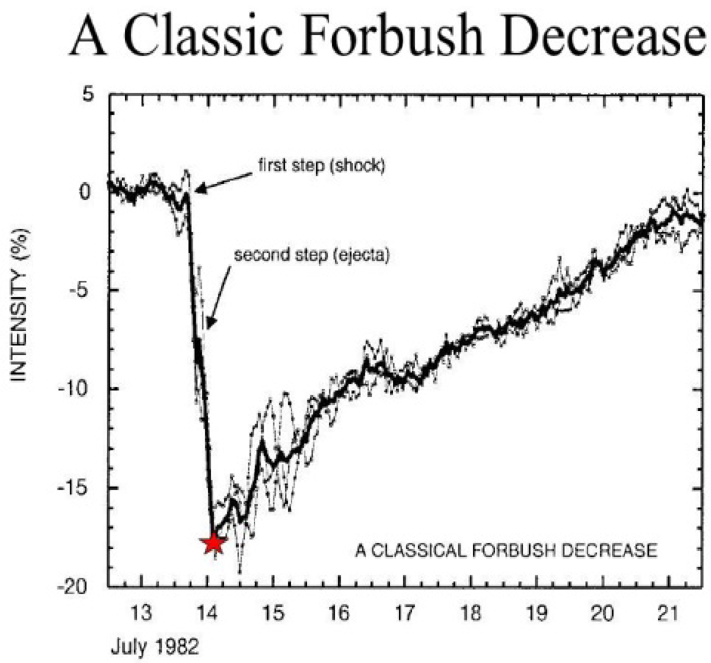
Solar Activity

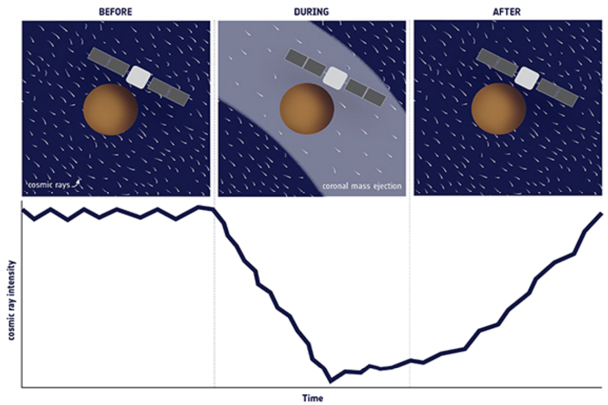
Forbush decrease

- Forboush decreases (FD)
  - A FD is a transient decrease followed by a gradual recovery in the observed galactic cosmic ray intensity.

- FDs generally consist of two phases:
  - main phase, i.e., the sharp decrease in cosmic ray flux,
  - recovery phase, i.e., gradual recovery to pre-FD

- FD are generally thought to arise due to the shielding of CR by a propagating diffusive barrier.
  - The main processes at work are the diffusion of CR across the large-scale magnetic fields carried by the ICME and their advection by the solar wind





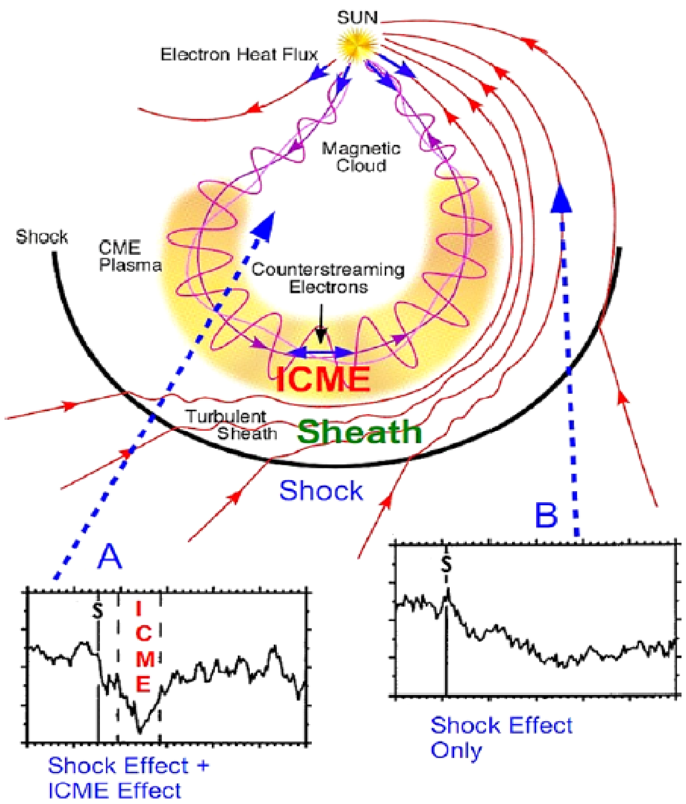
Solar Activity

Forbush decrease

- Modulation can be described using Parker equation
  - the four physical mechanisms governing the GCR modulation are diffusion, drifts, convection, and energy loss
  - Fokker-Planck transport equation of particle random walk in the frame of reference of small-scale magnetic irregularities

- Disturbances in solar wind parameters cause short-term depressions in the CR flux
  - Eg. Proton speed, density and temperature, accompanied by highly fluctuating compressions of interplanetary magnetic field.

- FD profile is generally well (anti)correlated with the interplanetary magnetic field and the solar wind speed profiles.

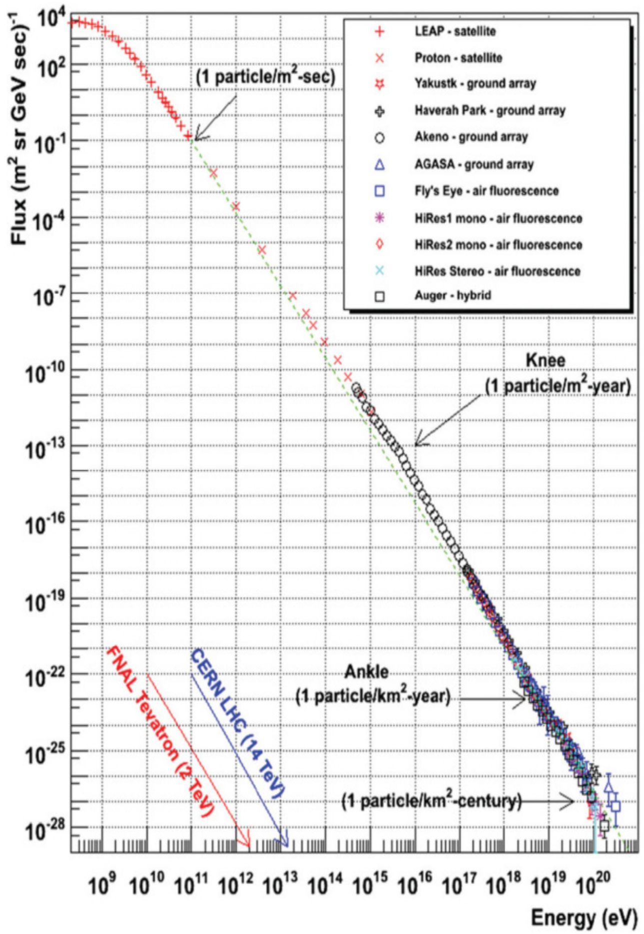


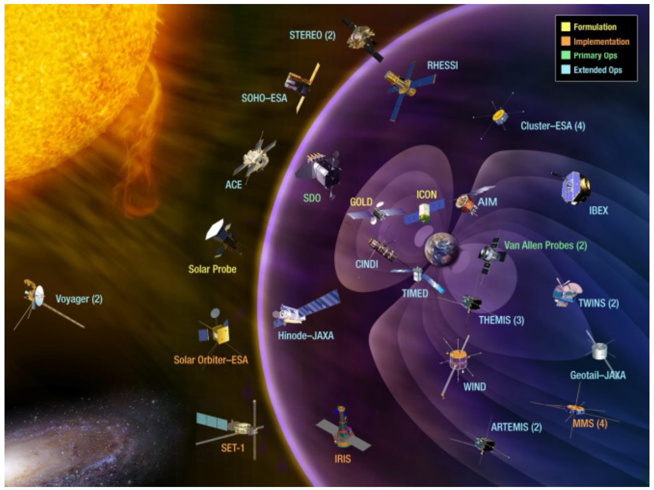
Cane, Space Sci. Rev. 2000

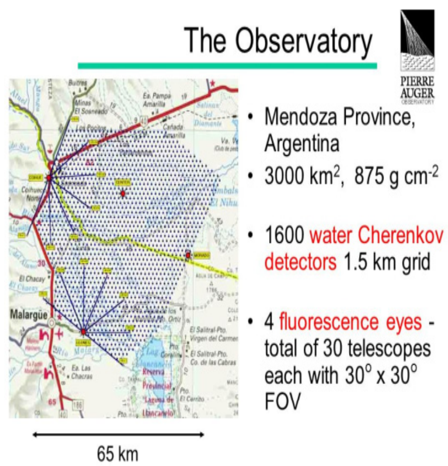
Detection of CR

Can be:

- Outside the heliosphere (Voyager)
- Above the atmosphere (various satellites)
- High in the atmosphere (high altitude balloons)
- On ground
  - when they arrive at Earth, they collide with the nuclei of atoms in the upper atmosphere, creating more particles SECONDARY CR
- Underground (secondary muons, neutrinos…)

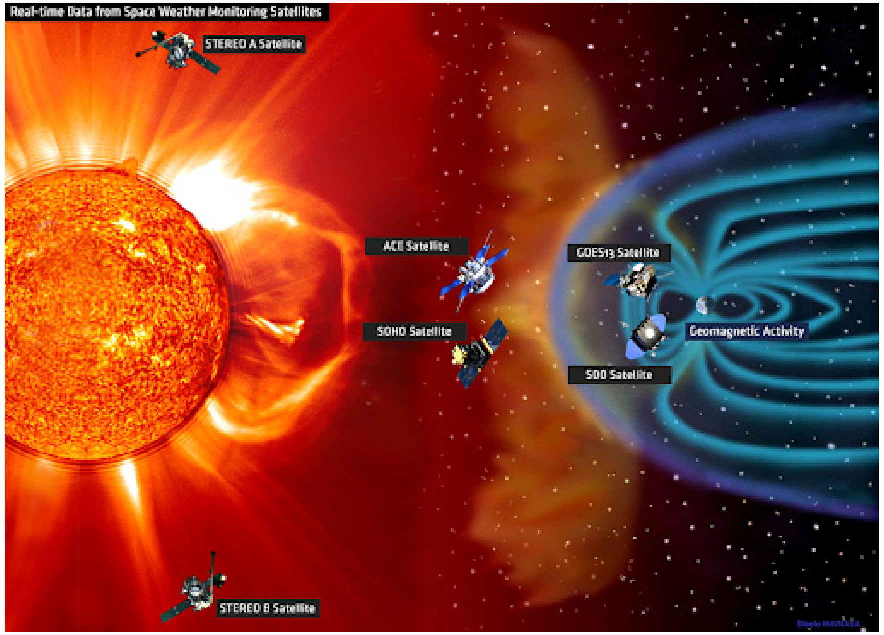


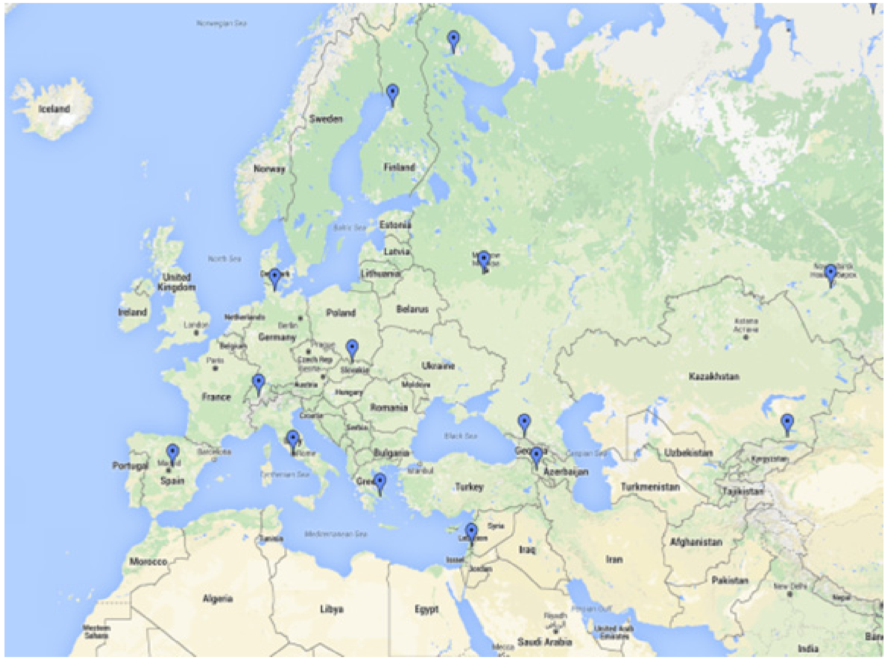




Satellites and Ground systems

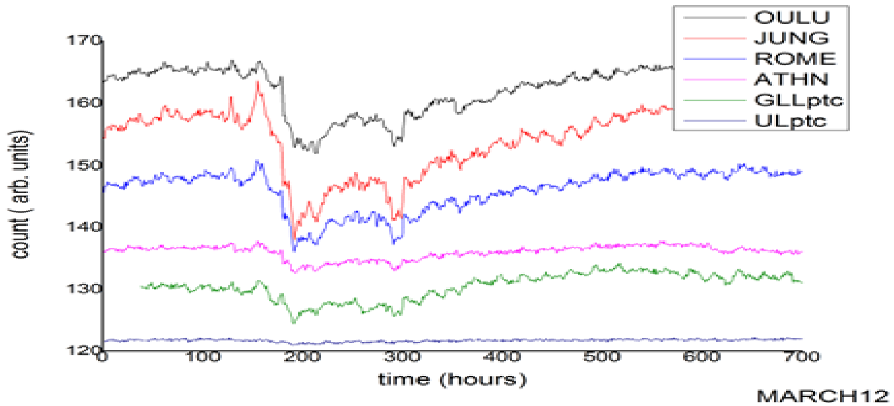
- Space missions
  - Variability of SEPs is continuously monitored by space missions over the last several decades. Most space missions are able to measure mainly the low-energy range of particles, up to several hundred MeV
- Modulation effects have been studied extensively by the neutron monitors
  - Sensitive up to several tens of GeV, depending on their geomagnetic location and atmospheric depth.
- Muon detectors at ground level and underground level
  - Sensitive to primary particles of higher energies than NMs. Underground muon detectors correspond to even higher energy primaries.
- Muon observations complement NM observations
  - in studies of long-term CR variations, CR anisotropy and gradients or rigidity spectrum of Forbush decreases

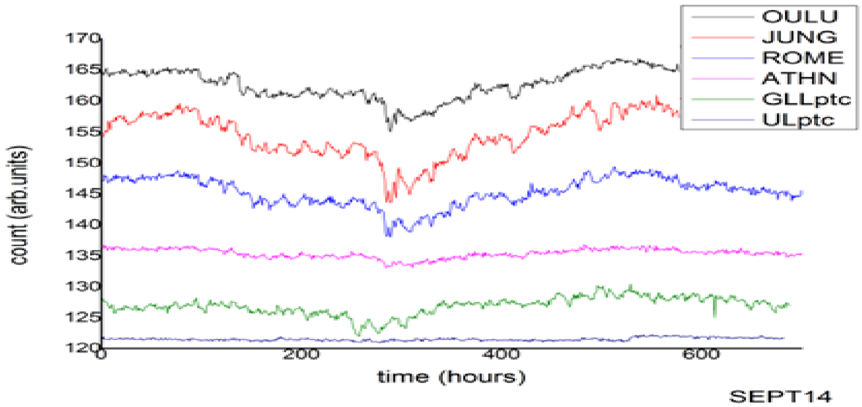


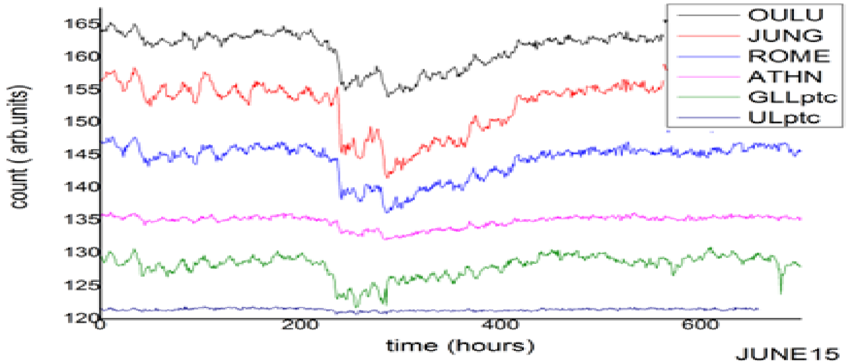


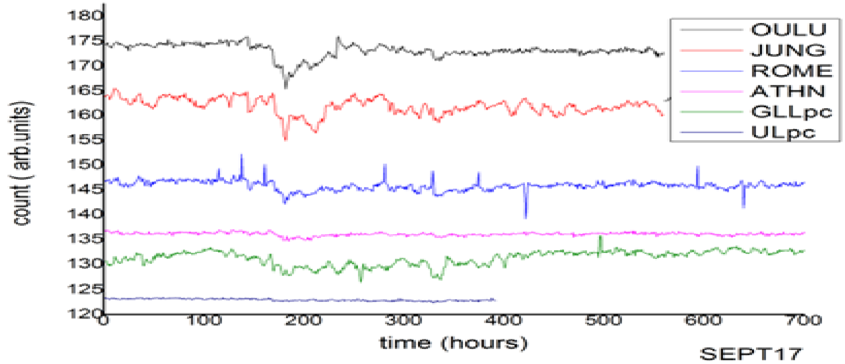
Solar activity

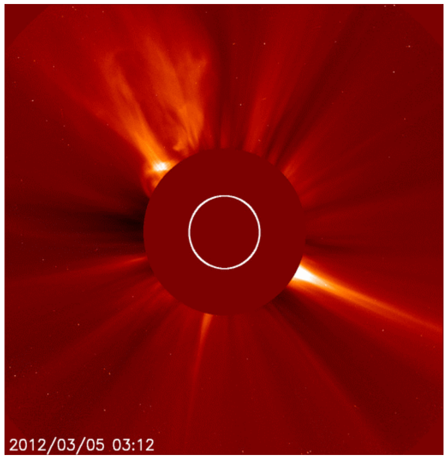
ground measurements Forbush decrease

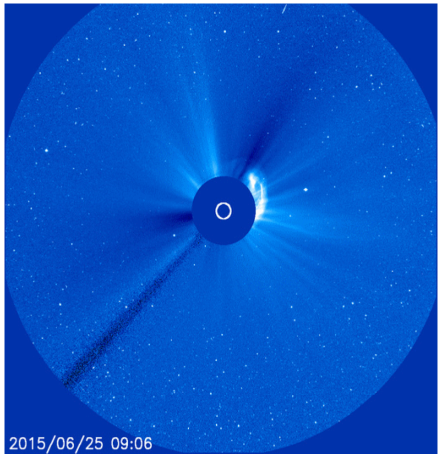


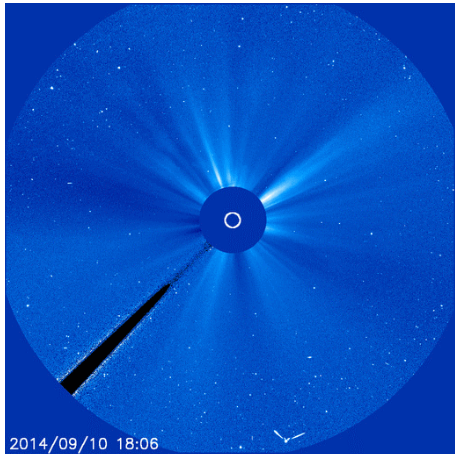


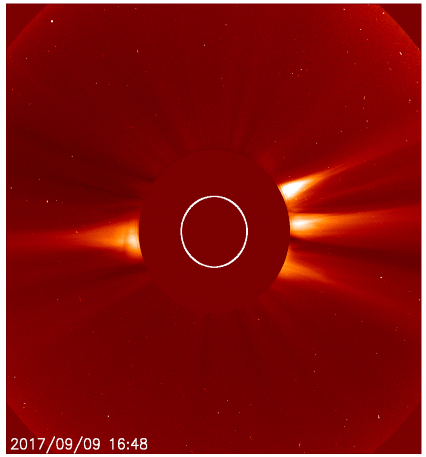








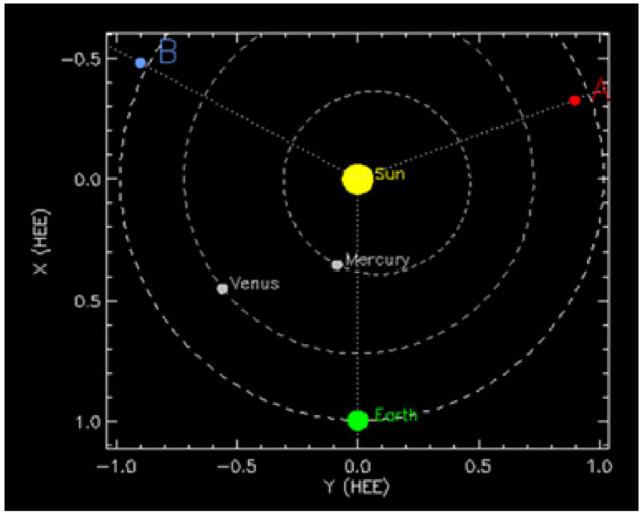


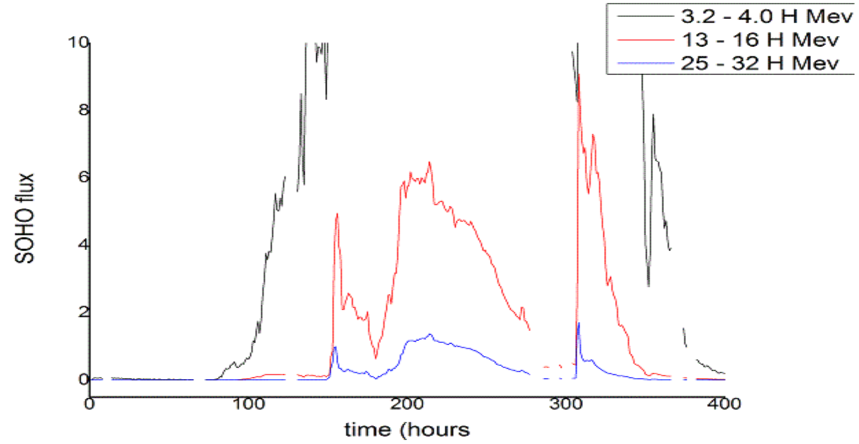


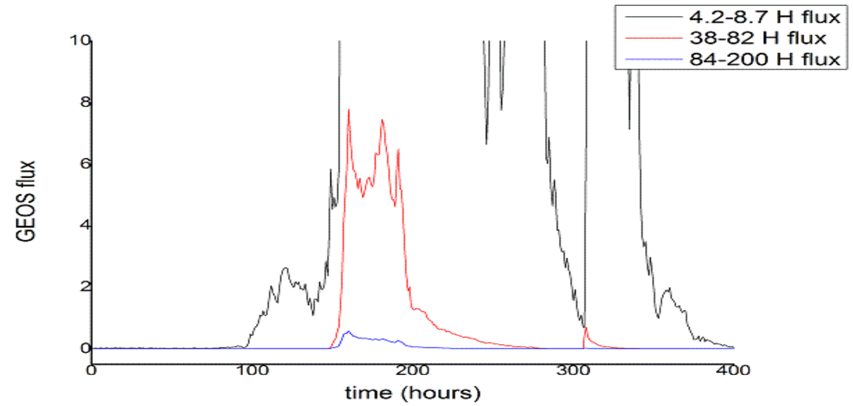
Solar activity

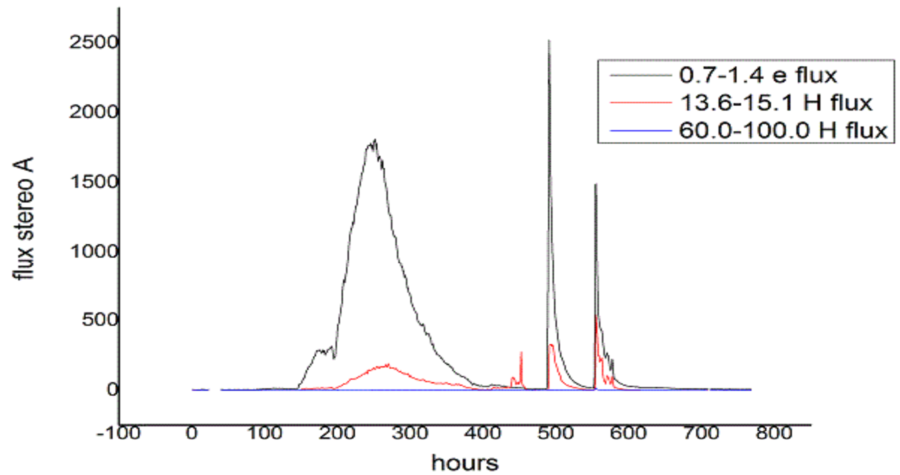
Spaceborne measurements

- **SOHO** (Solar-Heliospheric Observatory),
- **GEOS** (Geostationary Operational Environmental Satellites),
- **STEREO** (Solar Terrestrial Relations Observatory)
  - Two nearly identical spacecraft were launched in 2006 into orbits around the Sun
  - Communication with STEREO B stopped 2014.





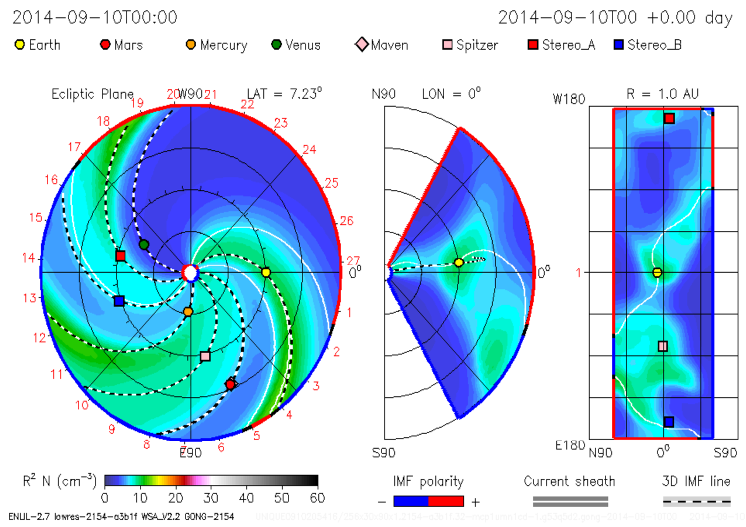


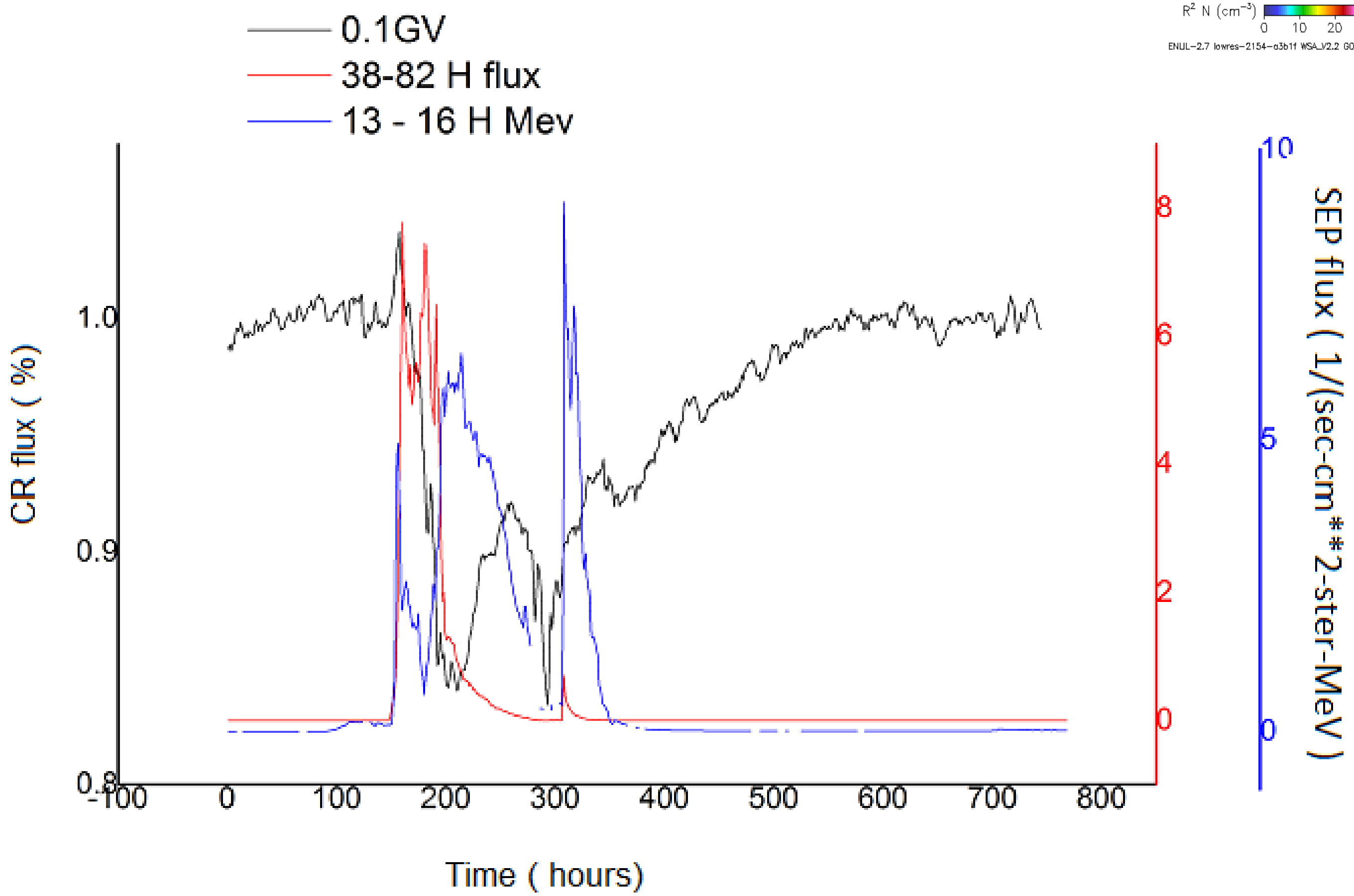


Solar activity

Spaceborne measurements

- **SOHO** (Solar-Heliospheric Observatory)

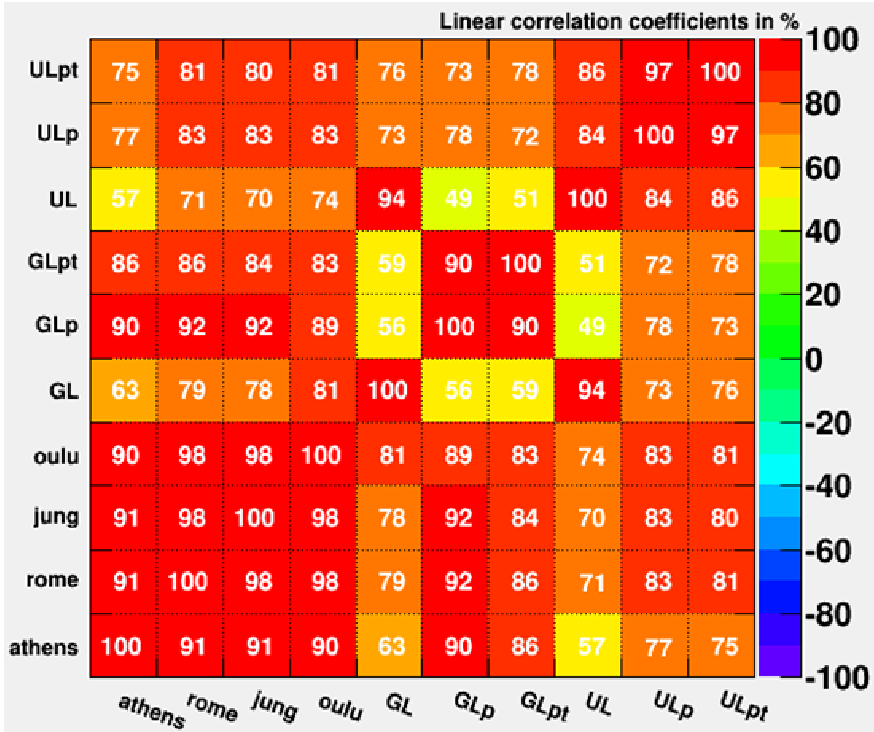




Correlation between different sets of data

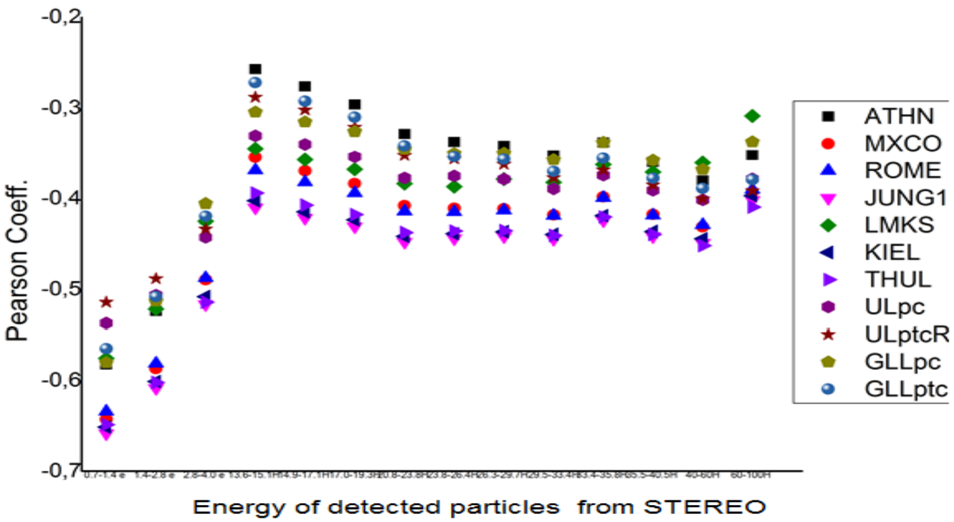
- **Data sets are 1h timeseries**
- **Pearson Correlation**
  - linear relationship between two sets of data.
  - R=1 correlation
  - R=-1 anticorrelation
  - R=0 no correlation

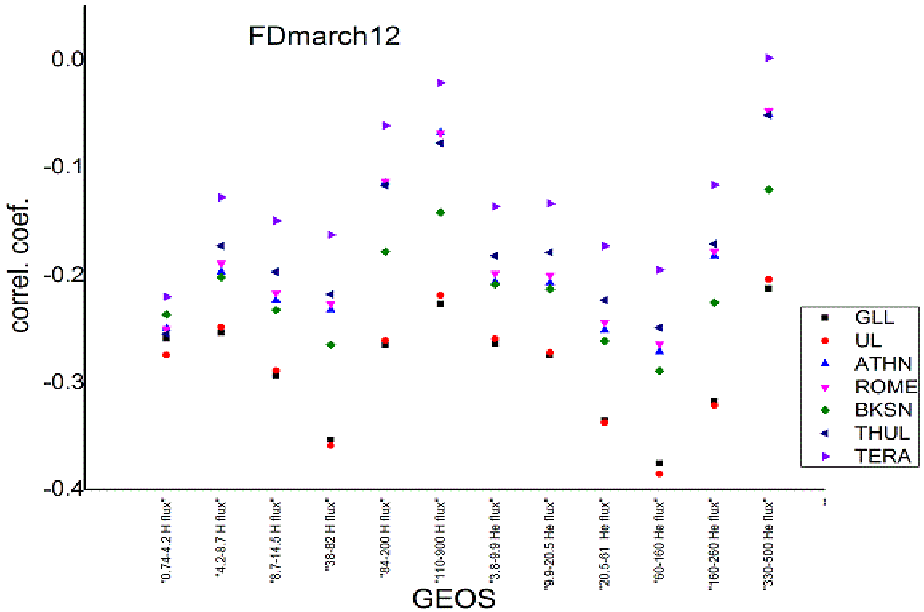
$$r = r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

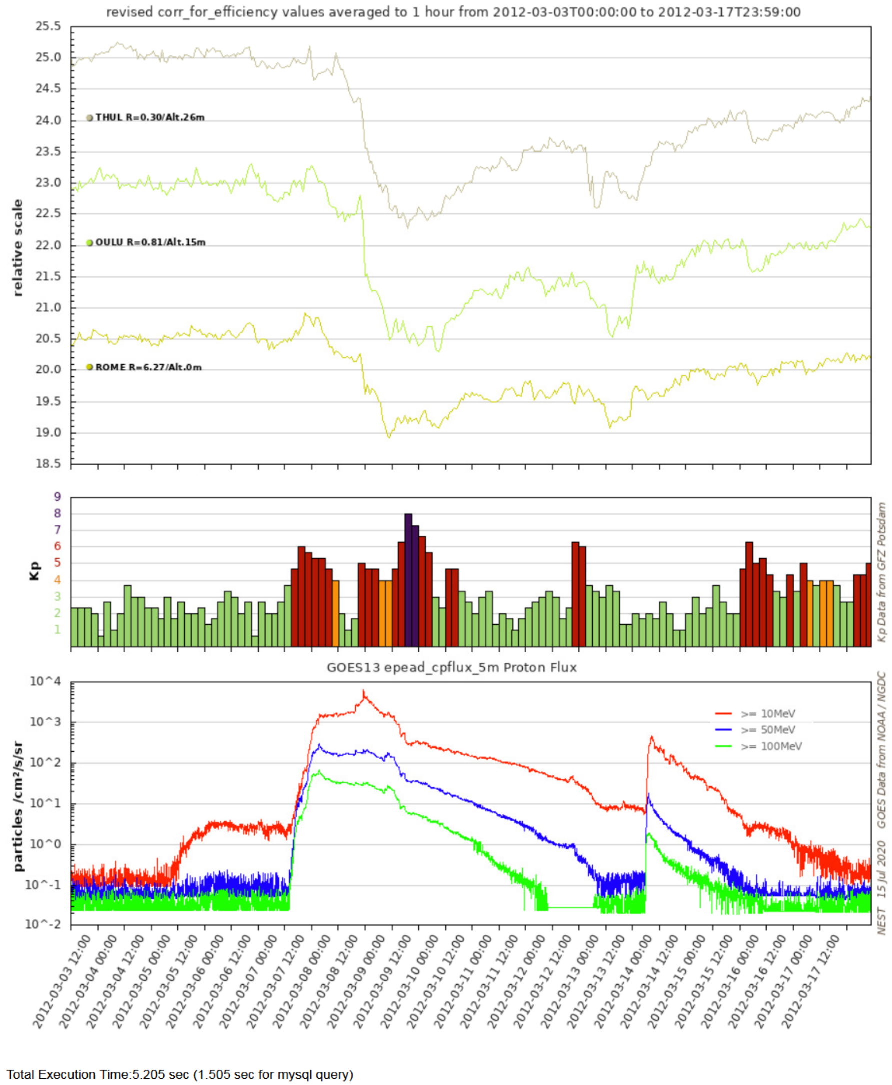


Correlation matrix of linear correlation coefficient (in %) for Belgrade cosmic ray station with its temperature and pressure corrected underground and ground level detectors (UL_tpc, GL_tpc), only pressure corrected (UL_pc, GLL_pc),raw data (UL_raw, GLL_raw) and Rome, Oulu, Jungfraujoch (JUNG) and Athens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

Correlation between different sets of data

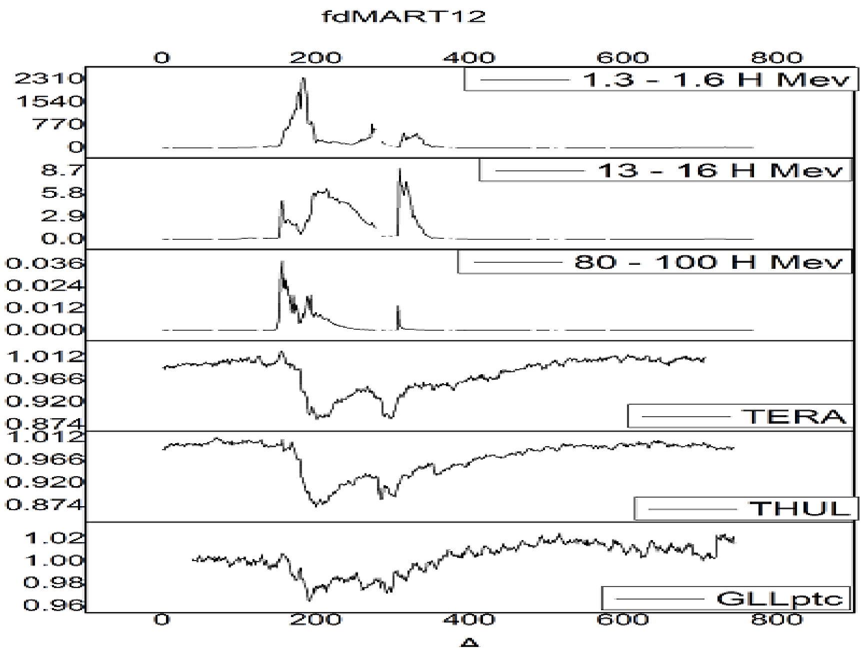


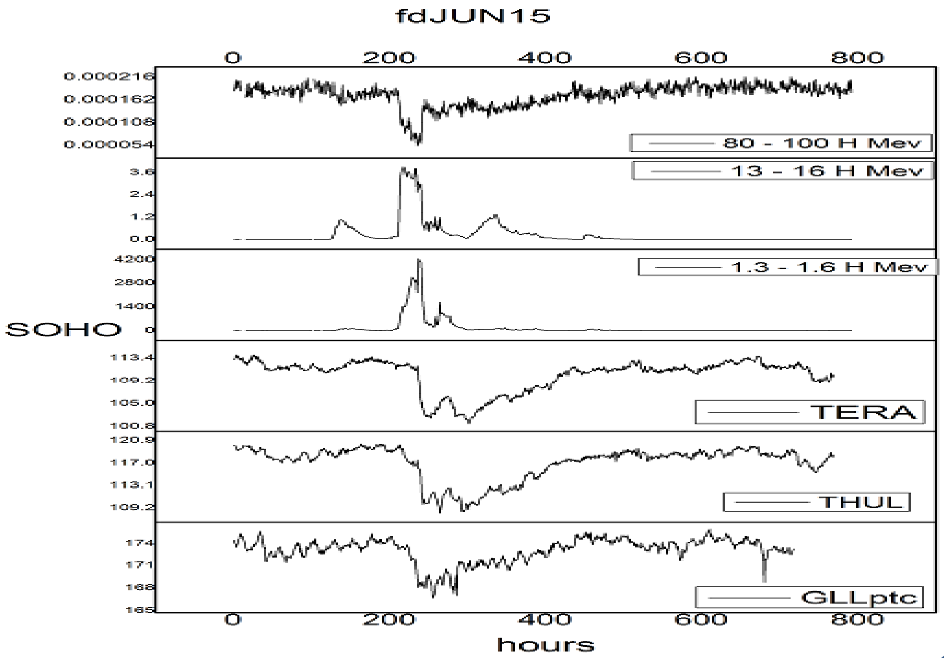


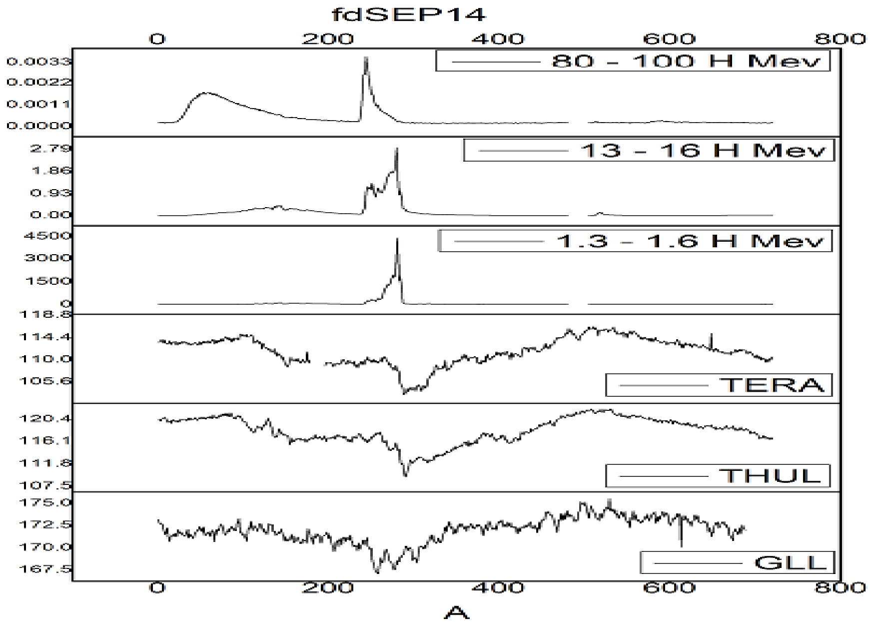


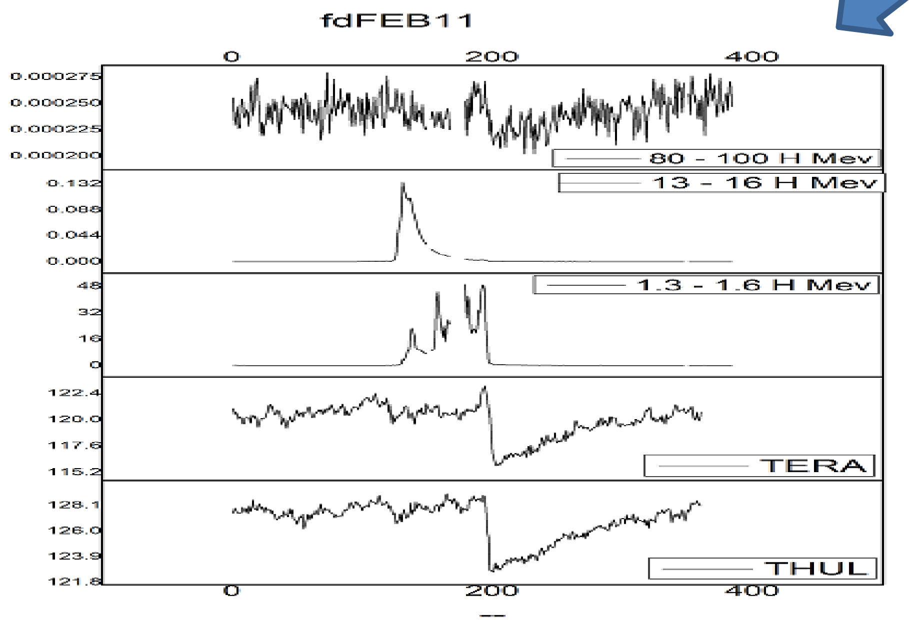
Correlation with satellite data

Preliminary!









Correlation with satellite data

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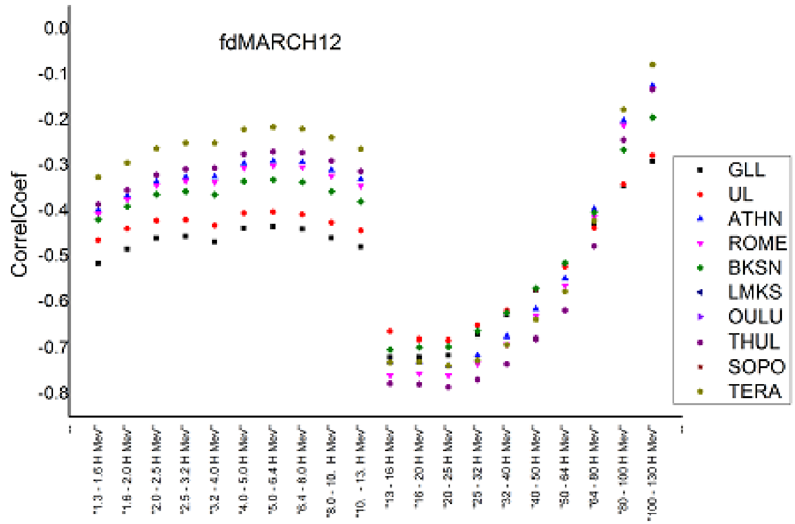
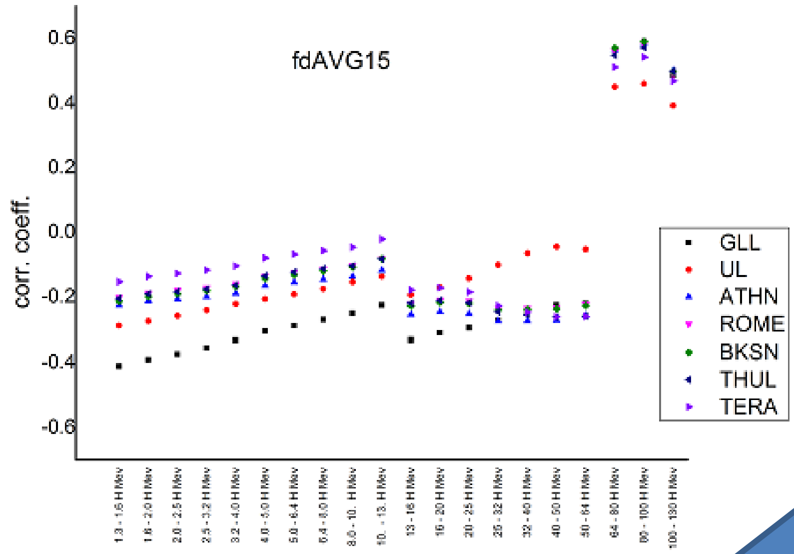
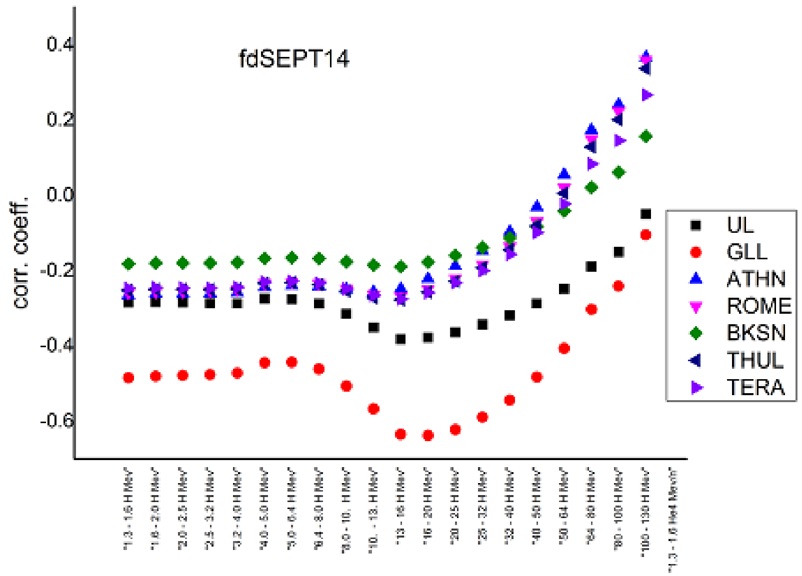
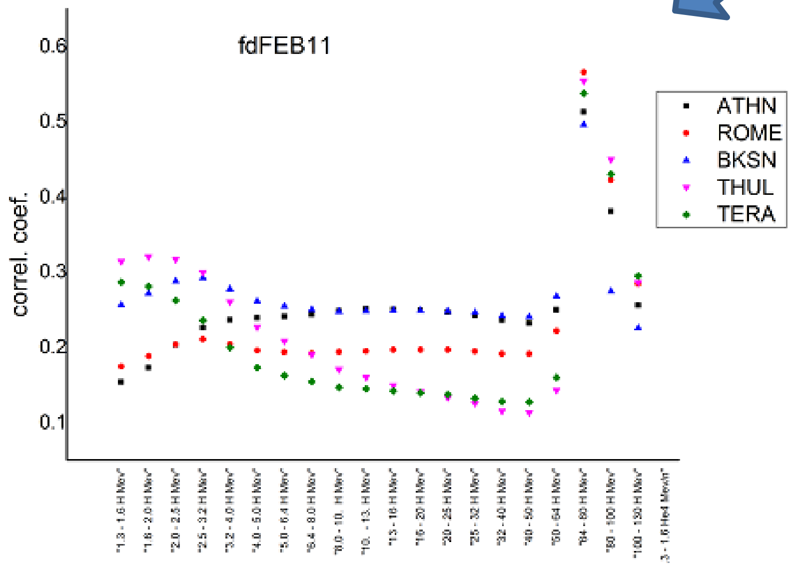




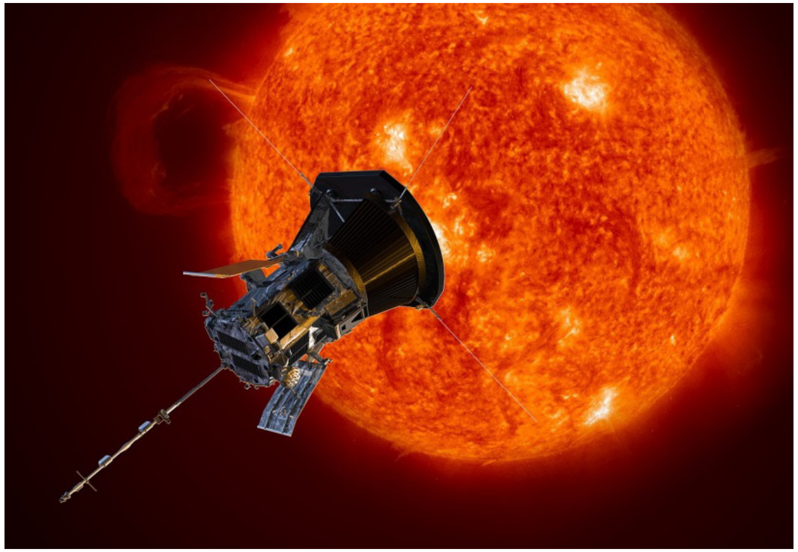


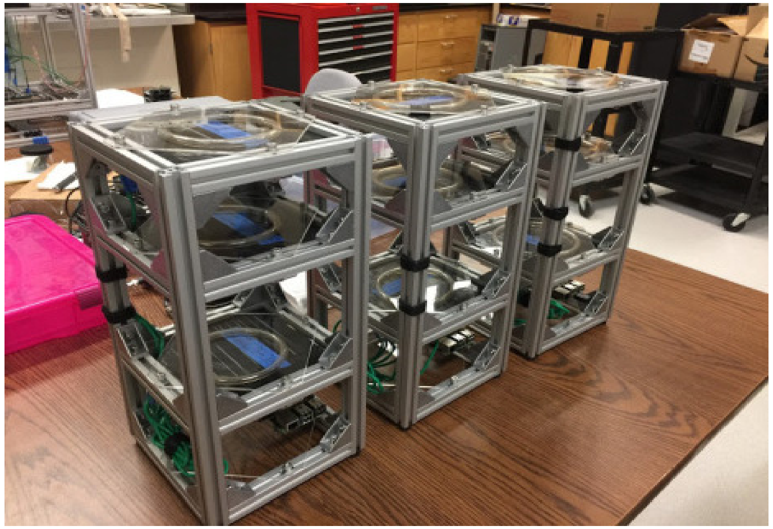


Date	18.2.2011	8.3.2012	12.9.2014	22.6.2015
Vcms (km/s)	584	1198	906	1040

New satelites and ground stations

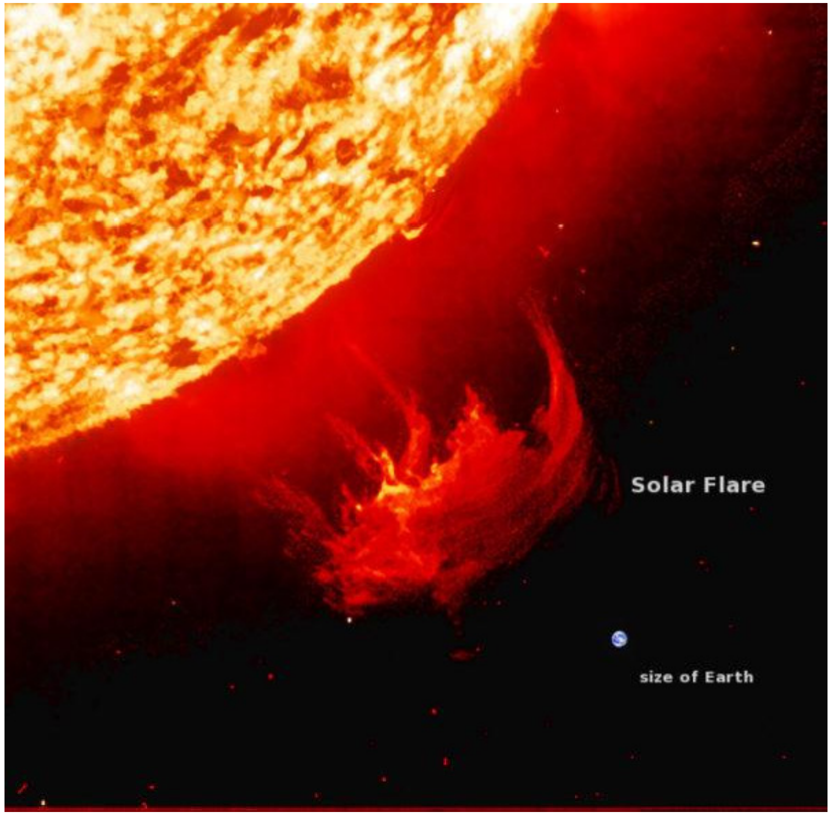
- In recent years more satellites dedicated to space weather
  - Solar Orbiter, Parker Solar Probe , PROBA-3, Space Weather Follow-On L1, ….
- More ground stations dedicated to research interaction of CR with environment
  - CR and space weather
  - Using CR as a probe for condition in upper atmosphere
  - CR are background noise for sensitive underground research (dark matter, …)
- 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





Conclusion

- CR interact with heliosphere and can be used as a probe for space environment and for prediction of space weather
- Correlation of CR with SEP fluxes is important to understand this interaction but correlation is complex.
- Comparison of ground data with satellite data outside geomagnetic field shows different correlation depending on recorded particles` energy thus allowing better understanding of correlation between Forbush decreases and CME that can lead to hazardous event on Earth.



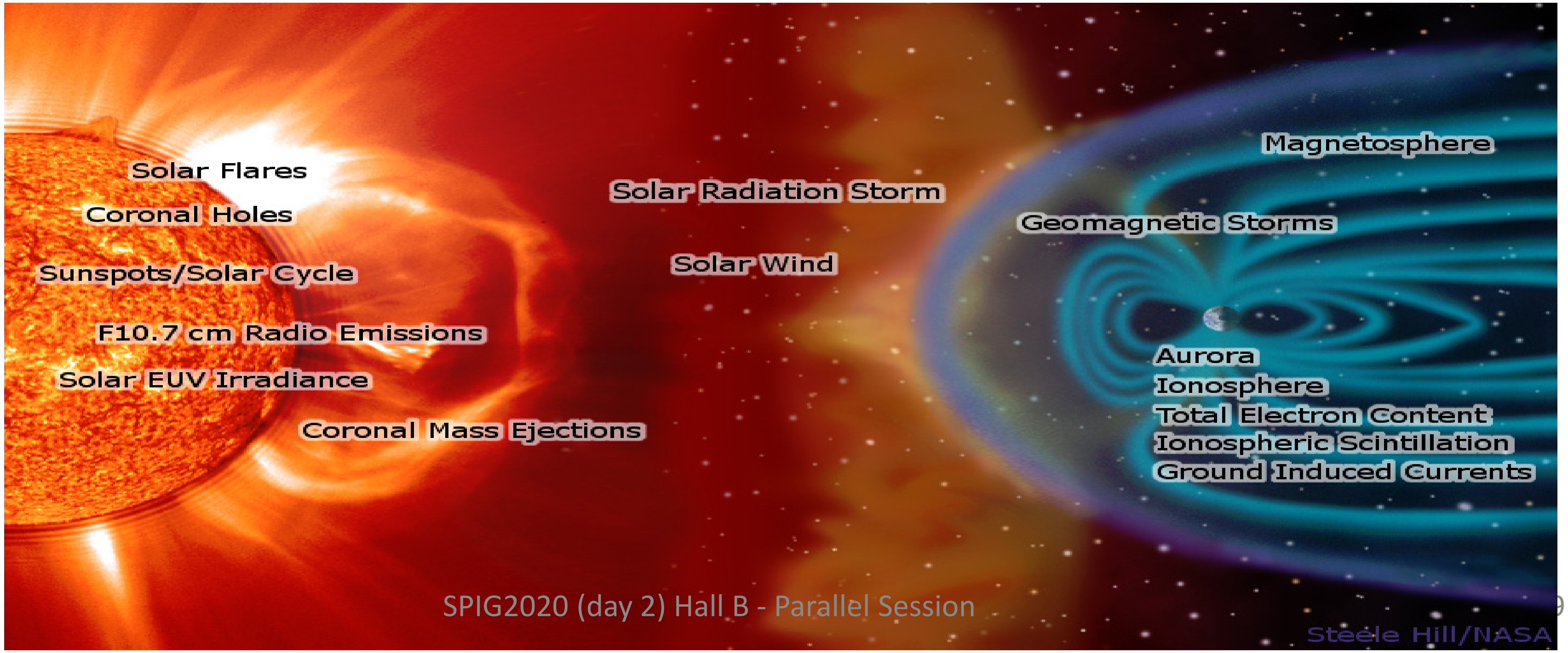

THANK YOU
FOR YOUR ATTENTION!

Backside slides

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.



Solar activity

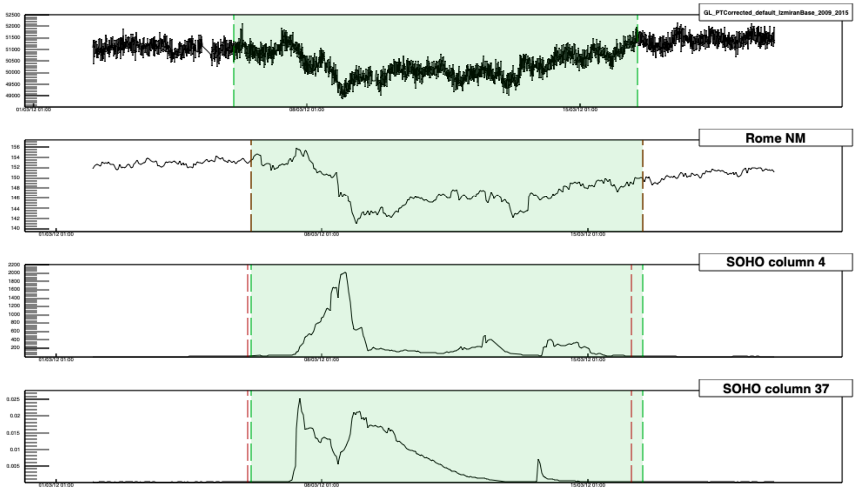
Spaceborne measurements

GEOS H Flux (MeV)	SOHO H Flux (MeV)	STEREO A or B H Flux (MeV)
0.74-4.2	1.3 - 1.6	
	1.6 - 2.0	
	2.0 - 2.5	
	2.5 - 3.2	
	3.2 - 4.0	
4.2-8.7	4.0 - 5.0	
	5.0 - 6.4	
	6.4 - 8.0	
8.7-14.5	8.0 - 10.	
	10. - 13.	
	13 - 16	13.6-15.1
		14.9-17.1
	16 - 20	17.0-19.3
	20 - 25	20.8-23.8
	25 - 32	23.8-26.4
		26.3-29.7
		29.5-33.4
	32 - 40	33.4-35.8
		35.5-40.5
38-82	40 - 50	40.0-60.0
	50 - 64	
	64 - 80	60.0-100.0
84-200	80 - 100	
110-900	100 - 130	

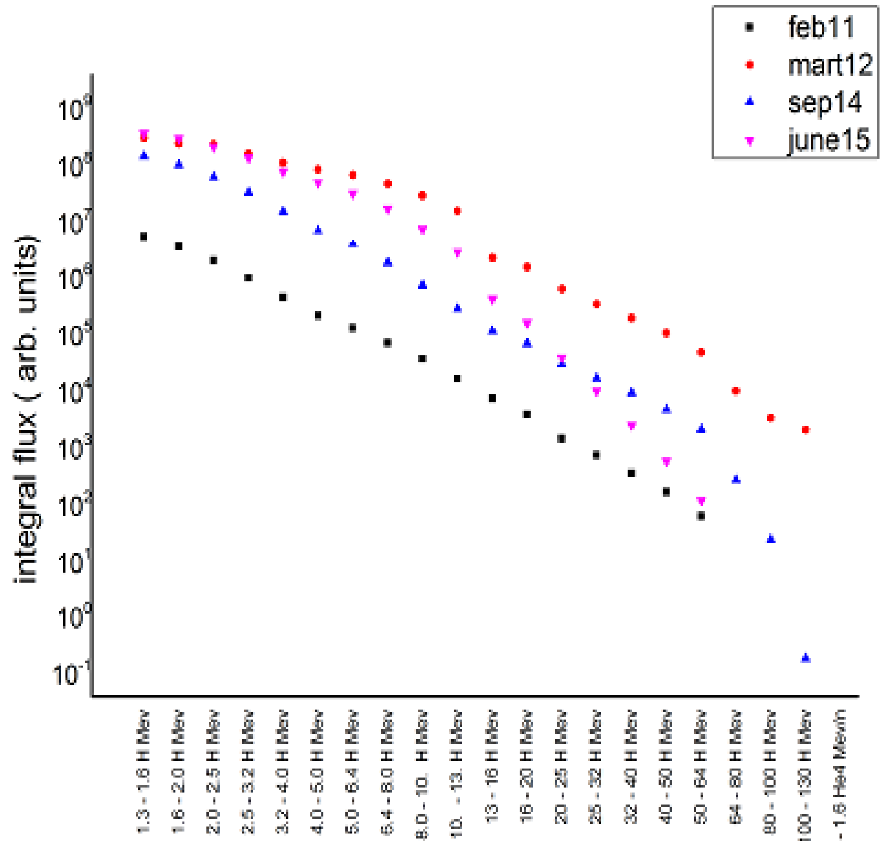
GEOS He4 (MeV/n)	SOHO He4 (Mev/n)	STEREO A or B e Flux (MeV)
		0.7-1.0
	1.3 - 1.6	1.4-2.0
	1.6 - 2.0	
	2.0 - 2.5	2.8-4.0
	2.5 - 3.2	
3.8-9.9	3.2 - 4.0	
	4.0 - 5.0	
	5.0 - 6.4	
	6.4 - 8.0	
	8.0 - 10.	
9.9-20.5	10. - 13.	
	13 - 16	
	16 - 20	
20.5-61	20 - 25	
	25 - 32	
	32 - 40	
	40 - 50	
	50 - 64	
60-160	64 - 80	
	80 - 100	
	100 - 130	
160-260		
330-500		

Onboard instruments detects different energy bands

Integral flux -SOHO



1/(sec-cm**2-ster-MeV/n)



Transport through heliosphere

equation

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

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}^{(S)}\frac{\partial f}{\partial x_j}\right] - \mathbf{U}\cdot\nabla f - \mathbf{V}_{\mathrm{d}}\cdot\nabla f + \frac{1}{3}\nabla\cdot\mathbf{U}\left[\frac{\partial f}{\partial \ell n p}\right] + Q$$

Diffusion
Small scale magnetic field irregoularity

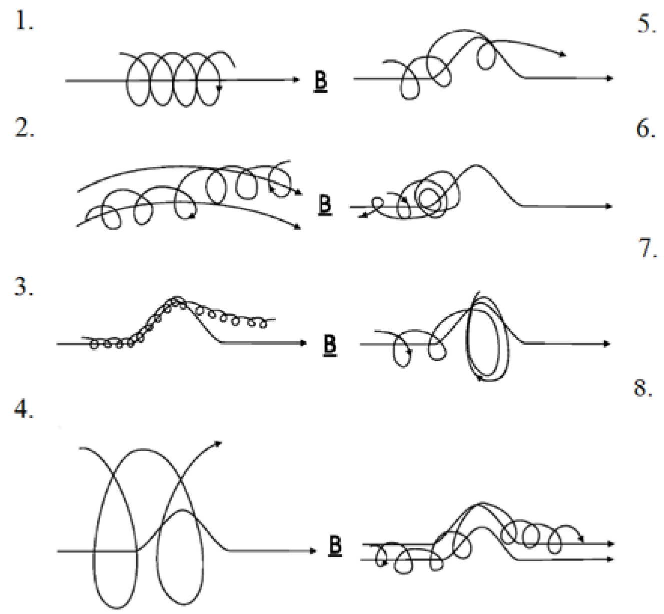
Convection
Presence of the solar wind moving outward from the Sun

Drift
Large scale structure of magnetic field (e.g. gradients, curvature)

Energy change
Due to adiabatic expansion of the solar wind

Source
within helioshere

- f(r,R,t) – number of charged particles per unit volume of phase space
- Magnetic rigidity R
- Gyroradius r_g= R/ cB.



Transport through heliosphere

Equation

$$\frac{\partial f}{\partial t} + \nabla \cdot (Vf - K \cdot \nabla f) - \frac{1}{3}(\nabla \cdot V)\frac{\partial f}{\partial lnp} = q$$

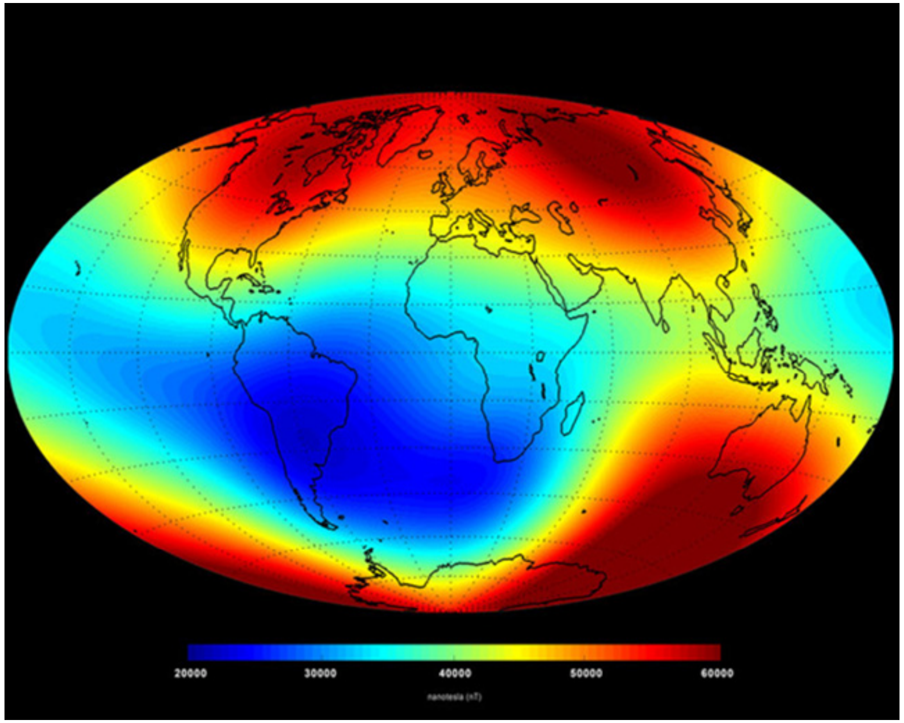
- Scattering of cosmic rays by turbulence is described by the cosmic-ray diffusion tensor
- the diagonal elements describe diffusion of particles parallel ($K_{\parallel}$) and perpendicular ($K_{\perp}$) to the mean magnetic field,
- off-diagonal, antisymmetric terms (K_A) describe effects of gradient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

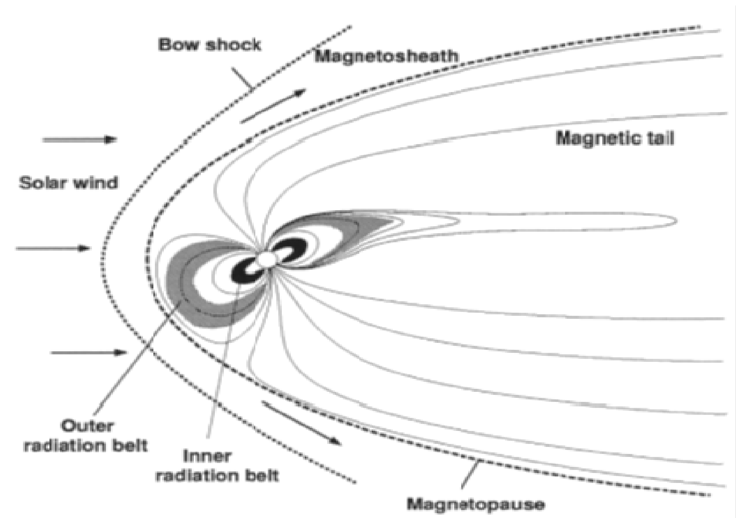
$$\mathbf{K} = \begin{pmatrix} K_{\perp} & K_A & 0 \\ -K_A & K_{\perp} & 0 \\ 0 & 0 & K_{\parallel} \end{pmatrix}$$

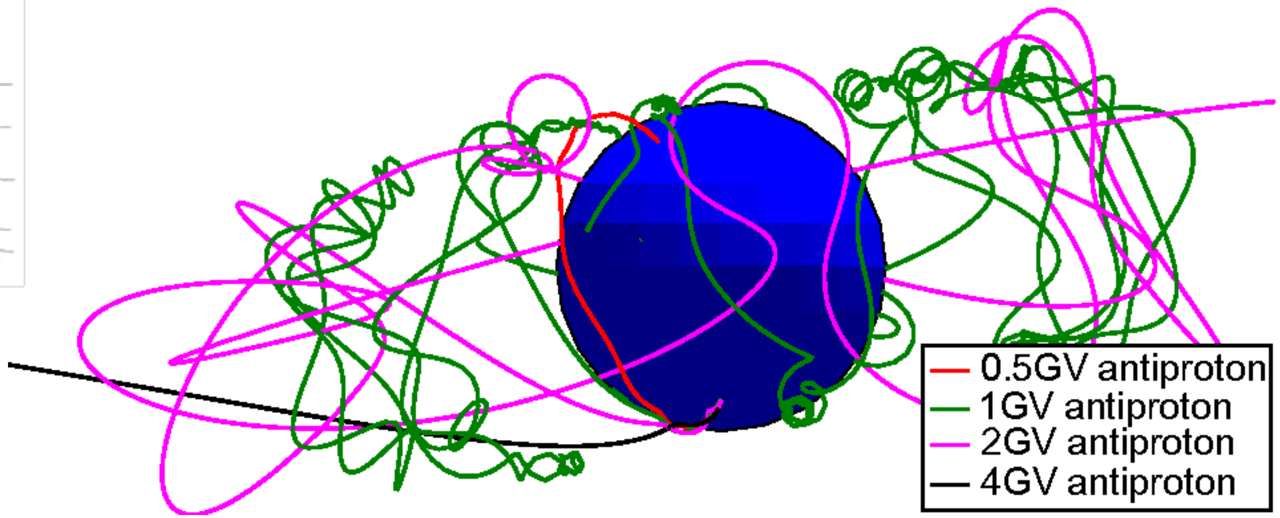
Transport through geomagnetic field

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

$$R_c = \frac{M \cos^4\lambda}{4\, r^2}$$





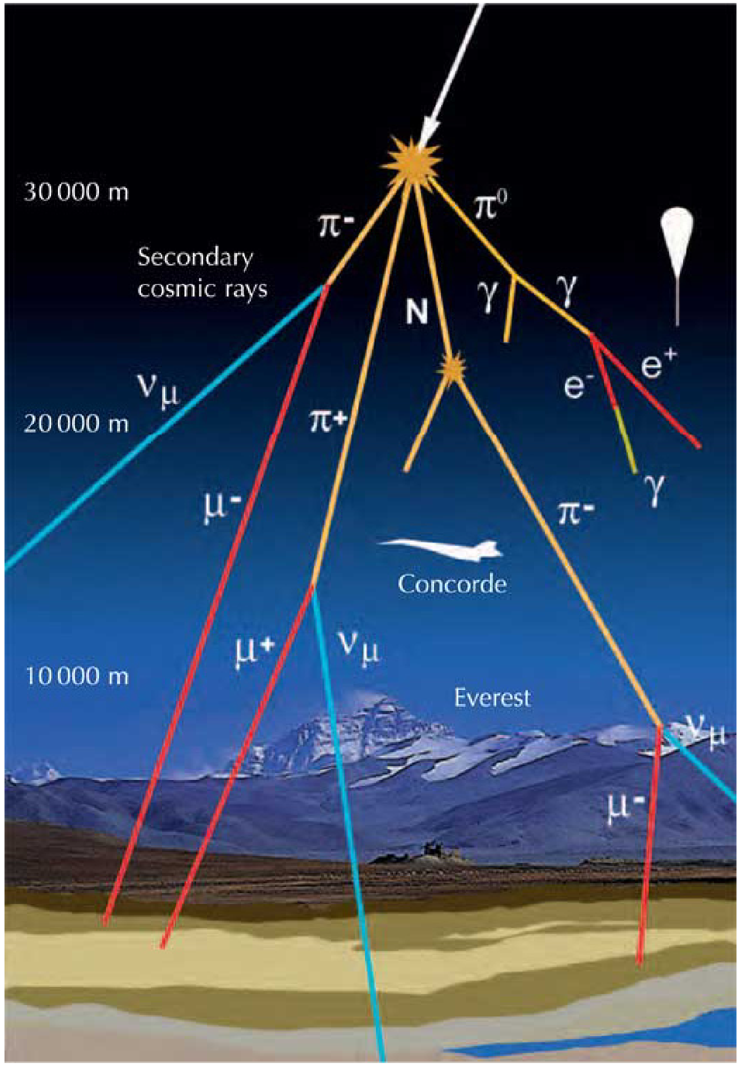


Interaction with atmosphere

Secondary CR

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

- Electromagnetic cascade
  - $\pi^0 \rightarrow 2\gamma$
  - $\gamma^* \rightarrow e^- + e^+$ pair production
  - $e \rightarrow e + \gamma$ *bremsstrahlung*
- Hadronic and mesonic cascade
  - $p + p \rightarrow p + \Delta^+ \rightarrow p + n + \pi^+$
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \nu_\mu$
- Shower spread with every new generation of particles
- Must be corrected with atmospheric parameters in mind



Low level laboratory for nuclear physics

Simulation packages

- Response of the detectors are calculated from simulation
- Range of energy for the primary CR found