Serbian space weather research activities

Nikola Veselinović
(on behalf of the Serbian Space Weather Community)

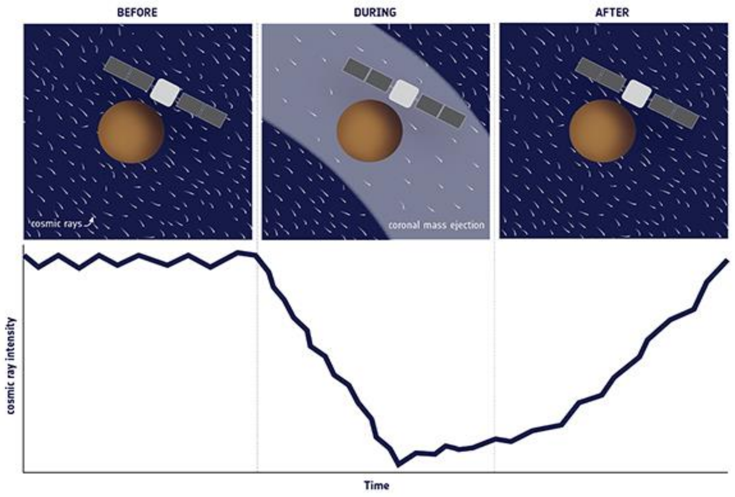
UN Workshop on the International Space Weather Initiative:
The Way Forward
Vienna, 28 June 2023.

Space weather related research

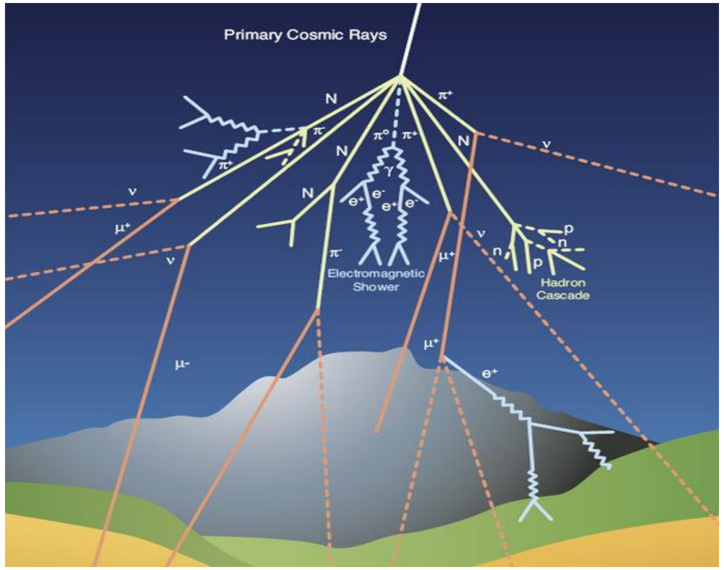
- Faculty of Mathematics, University of Belgrade
  - Department of astronomy
    - Solar Physics magnetic field inference
- Institute of Physics, Belgrade
  - Laboratory for astrophysics and physics of ionosphere –VLF station
    - *lower* level *ionosphere monitoring using VLF radio signals and modeling* Solar forcing of the Earth's ionosphere system
    - Part of ISWI **"AWESOME"** Space Weather Monitor Program
  - Low-background laboratory for nuclear physics – Muon station
    - Correlation analysis of solar energetic particles and secondary cosmic ray flux
    - Production of the cosmogenic radionuclides in soil

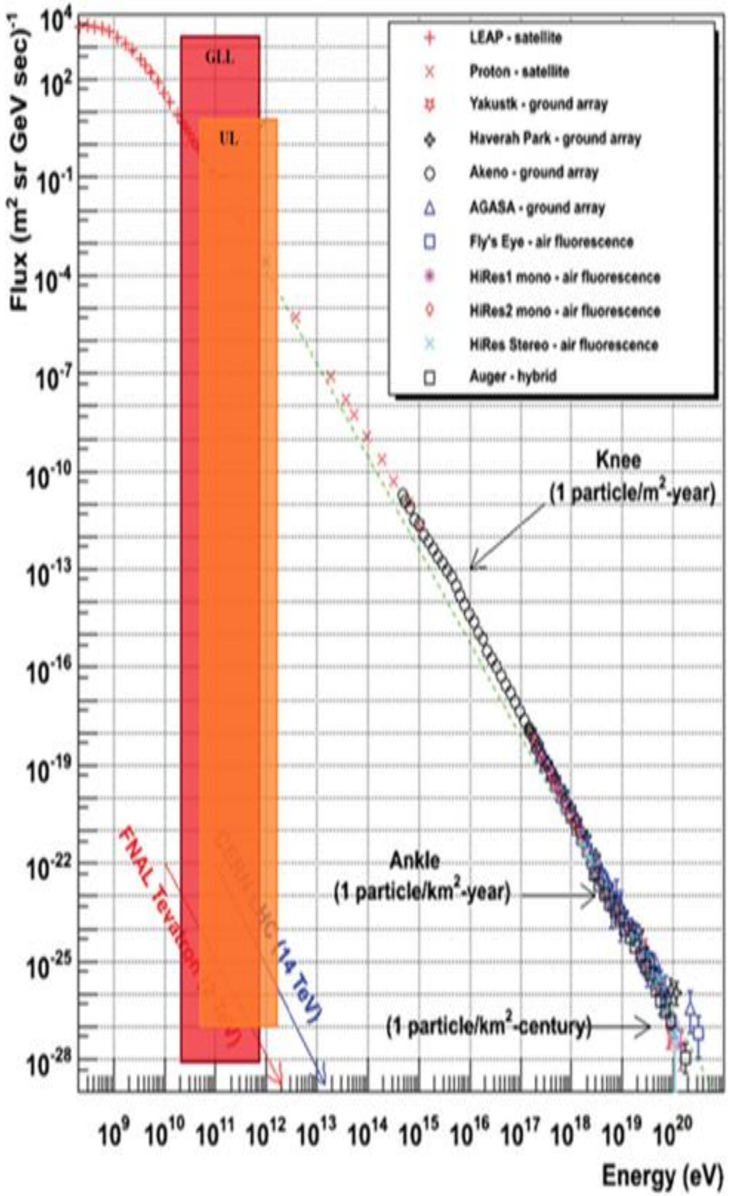
Galactic cosmic rays

Galactic cosmic rays entering heliosphere are modulated (low energy CRs) by interplanetary magnetic field which is carried away from the Sun by the solar wind. Cosmic rays are additionally modulated by coronal mass ejections and shock waves, which can produce **Forbush decrease**, a transient decrease in the observed galactic cosmic ray intensity.



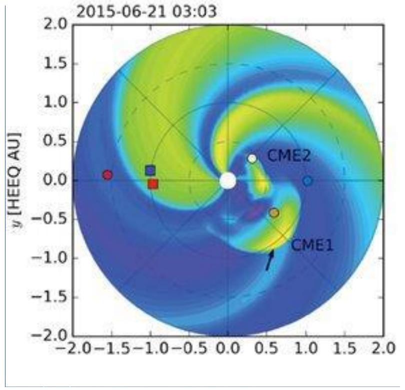
Primary cosmic rays interacts with atmosphere and produce a shower of secondary cosmic rays. Measured flux at ground (and underground) level is related with flux of galactic cosmic rays of different energies.



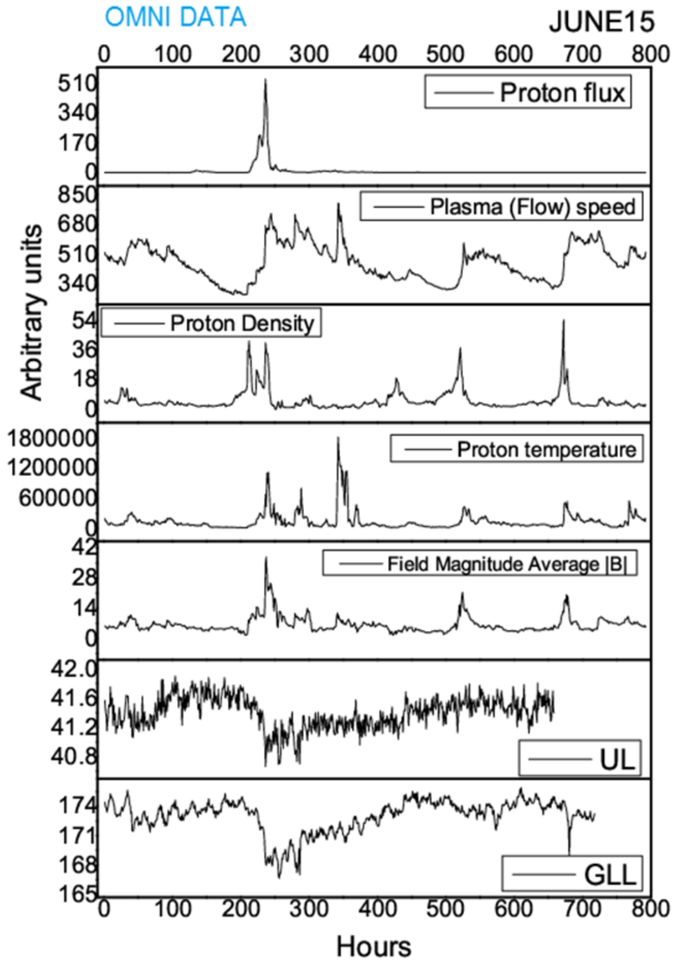


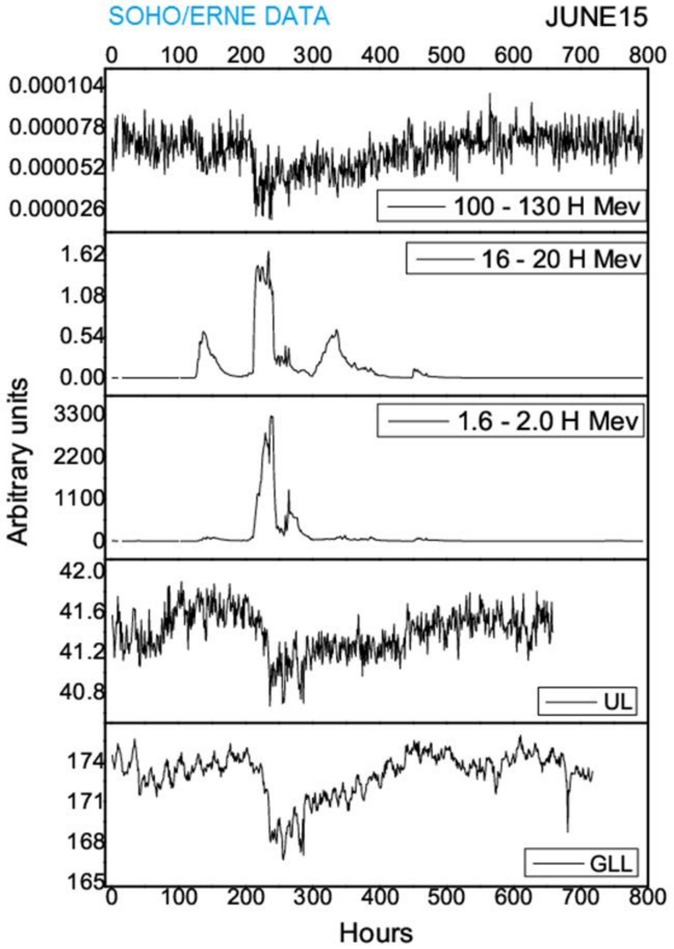
Connection between Solar Energetic Particles (SEP) fluence spectra and CR

Measurements of magnetic field and plasma parameters in near-Earth space (L1) detect regularly coronal mass ejections, so it is important to understand the **correlation** between near-Earth particles fluxes associated with these CMEs and Forbush decreases.



Global view of CME modeled with EUHFORIA for 21 June 2015 (Pomoell & Poedts, 2018)





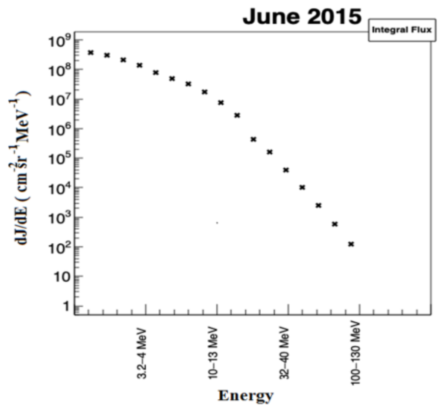
Connection between Solar Energetic Particles (SEP) fluence spectra and CR

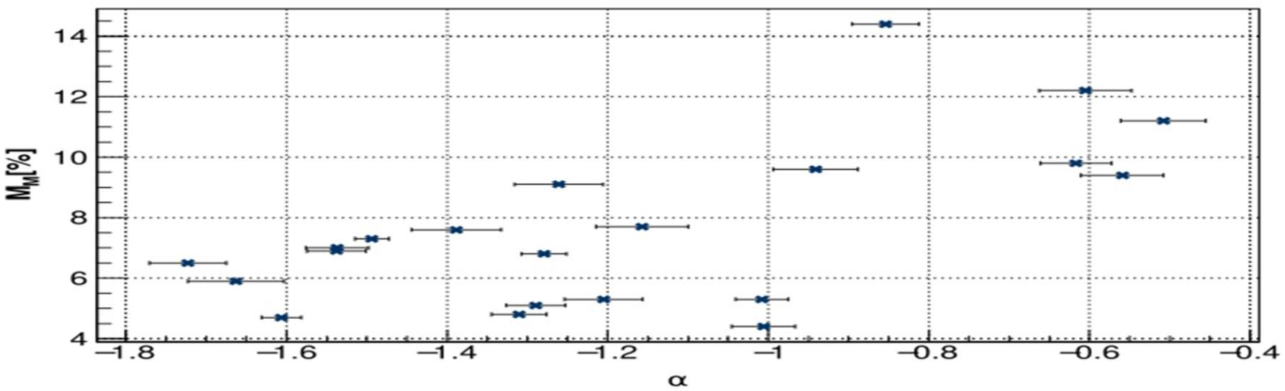
We fitted SEP fluence spectra (protons!), measured by SOHO/ERNE, with double power law. We observed largest correlation between power exponents and CME velocities (*r=0.77*)

Power exponents seem to be better predictor variables of FD magnitude than CME velocities, especially in the case of events where FD magnitude corrected for magnetospheric effect is larger than 6%. (based on IZMIRAN database).

$$\frac{dJ}{dE} = \begin{cases} E^{-\alpha} \exp\left(-\frac{E}{E_b}\right) & E \leq (\beta - \alpha)E_b, \\ E^{-\beta}\left[(\beta-\alpha)E_b\right]^{\beta-\alpha} \exp(\alpha - \beta) & E > (\beta - \alpha)E_b, \end{cases}$$

Zhao et al.,2016





Dependence of FD magnitude of various FDs on power exponent of fitted function

	$M_M \geq 6\%$					$M_M < 6\%$				
	α	β	V_{meanC}	V_{mean}	V_{max}	α	β	V_{meanC}	V_{mean}	V_{max}
M	0.82	0.76	0.84	0.85	0.78	-0.55	-0.25	-0.08	-0.10	0.62
M_M	0.77	0.76	0.52	0.49	0.55	-0.38	0.01	0.23	0.19	0.17

Veselinović N. et al. Eur. Phys. J. D 75, 173 (**2021**); https://doi.org/10.1140/epjd/s10053-021-00172-x
Savić M. et al. Adv. Space Res. 71,4,(**2023**); https://doi.org/10.1016/j.asr.2022.09.057
as presented at ESWW 2022, Zagreb, Croatia

Impacts of Extreme Space Weather Events on September 6th, 2017 on Ionosphere and Primary Cosmic Rays

The strongest X-class solar flare event in 24th solar cycle, X9.3, occurred on September 6th, 2017 accompanied by earthward-directed CMEs.

Significant changes of ionospheric parameters (sharpness and effective reflection height) and few orders of magnitude increase of electron density are observed as well as extensive modulation of CR detected with ground muon detectors and in-situ satellite measurements due to heliospheric inhomogeneities.

Multivariate analysis is on the way (PCA, machine learning,…)

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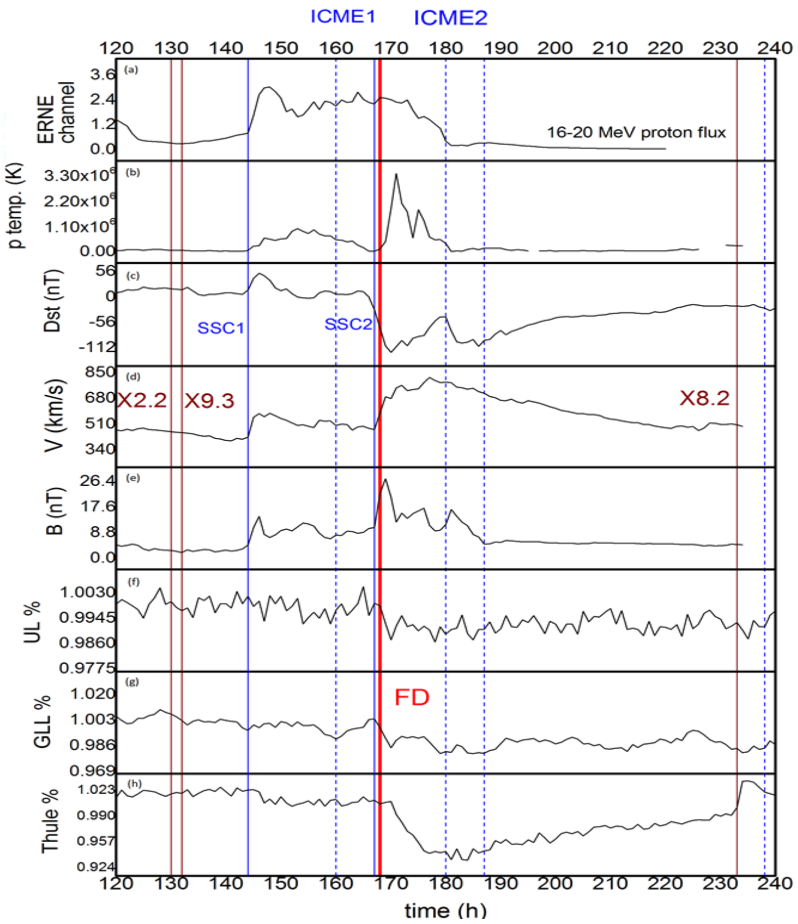
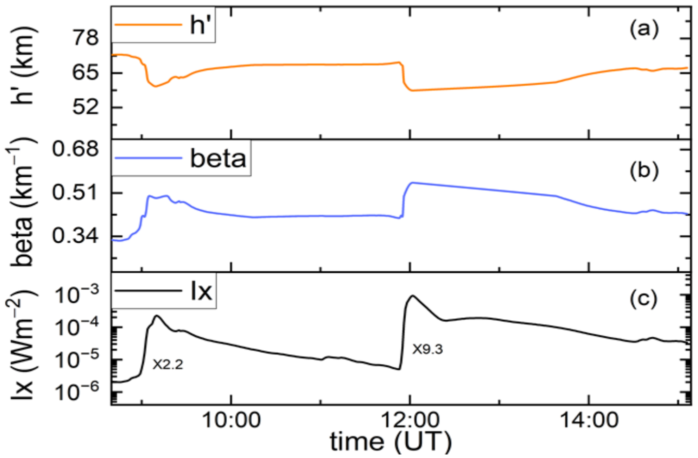
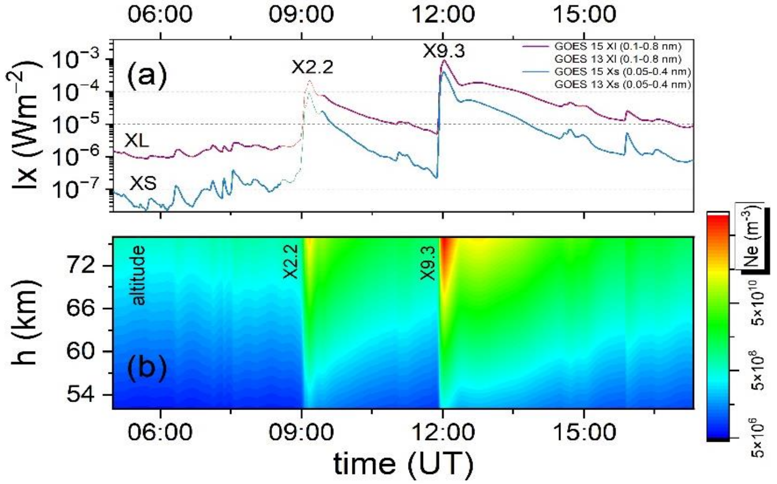


M_M=8.3%

reasonably good agreement with the value quoted in IZMIRAN database (7.7%)





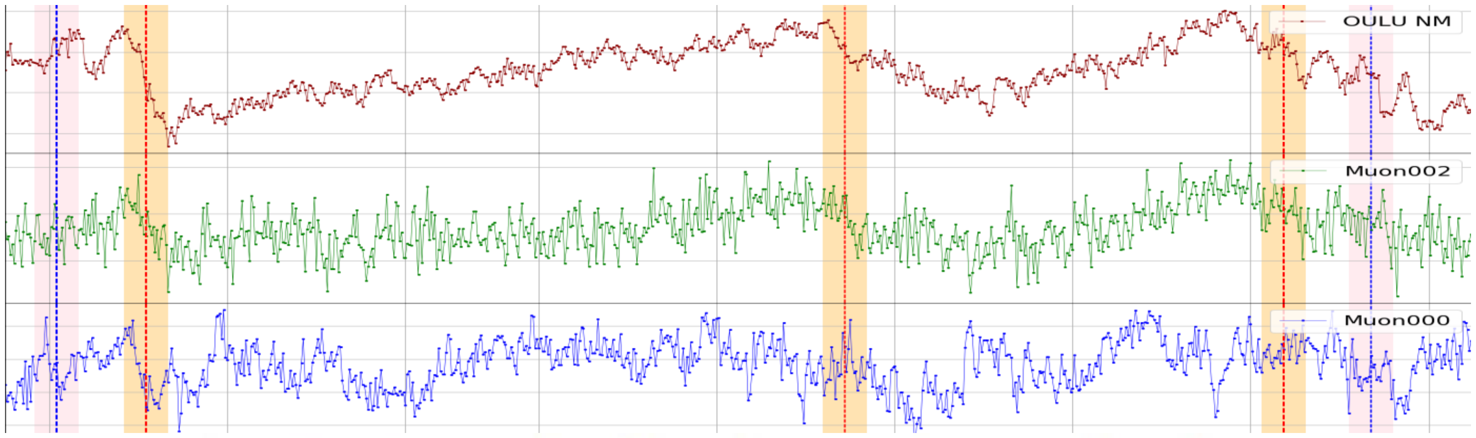
Kolarski A. et al. Remote Sens. 15(5), 1403 (**2023**); https://doi.org/10.3390/rs15051403

Space weather related activity – THE WAY FORWARD: Portable muon detector

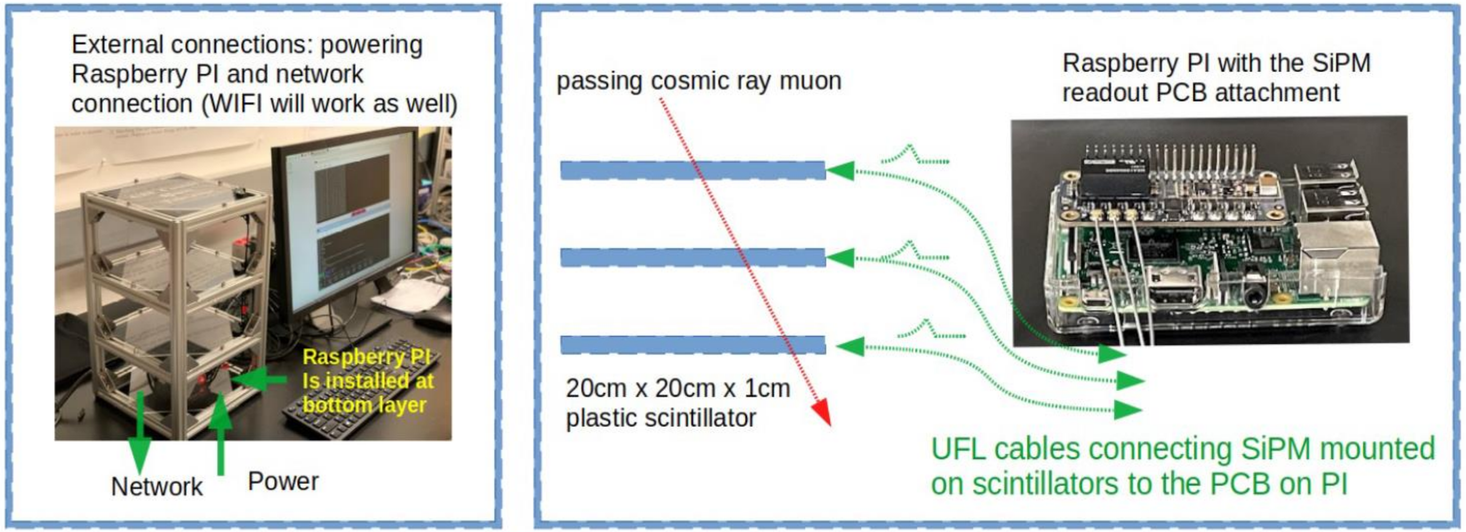
Development of cosmic rays´ muon detector as a part of collaboration led by Georgia state university, Atlanta, USA. The goal is building a worldwide network of cosmic ray detectors for monitoring space & terrestrial weather in real-time at global scale.

Low-cost detector (~600 USD).

Portable, modular, standardized and extendable. A minimum site requirement is a small desk, power and network connection.

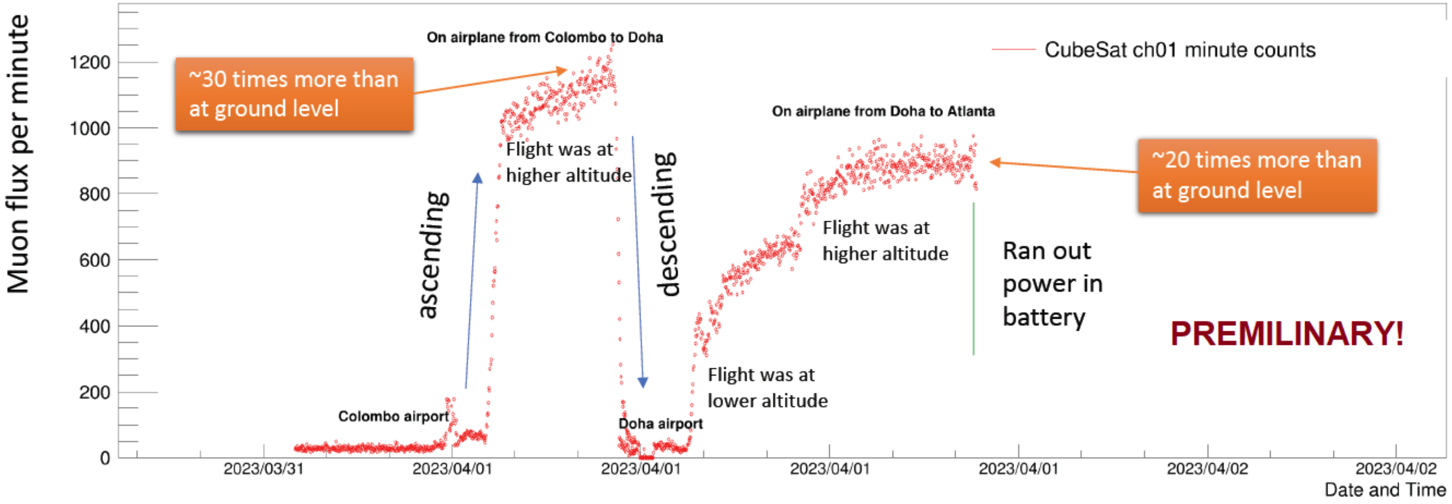


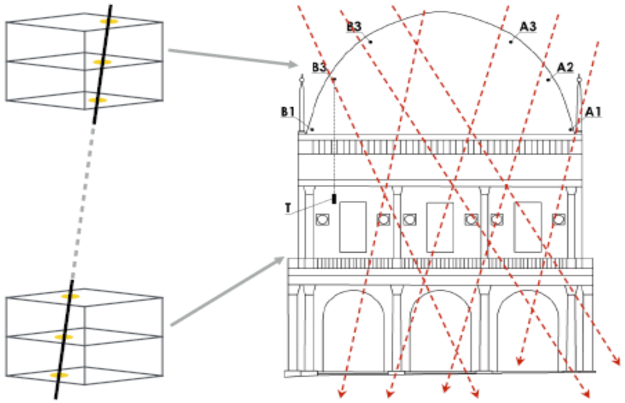
Low-Cost Cosmic Ray Muon Detector Setup and Readout



Space weather related activity – THE WAY FORWARD: Portable muon detector

- The **success** of the project requires **collaboration** and partnership, to jointly develop worldwide network of stations and create **global or local outreach or research projects** which include citizen scientists. A growing list or participant and we are looking for many more institutions to join the effort.





CR tracking to monitor stability of historical buildings Bonomi et al. 2019. Brescia

Cosmic Ray Distributed Observatory over one smaller region or/and worldwide

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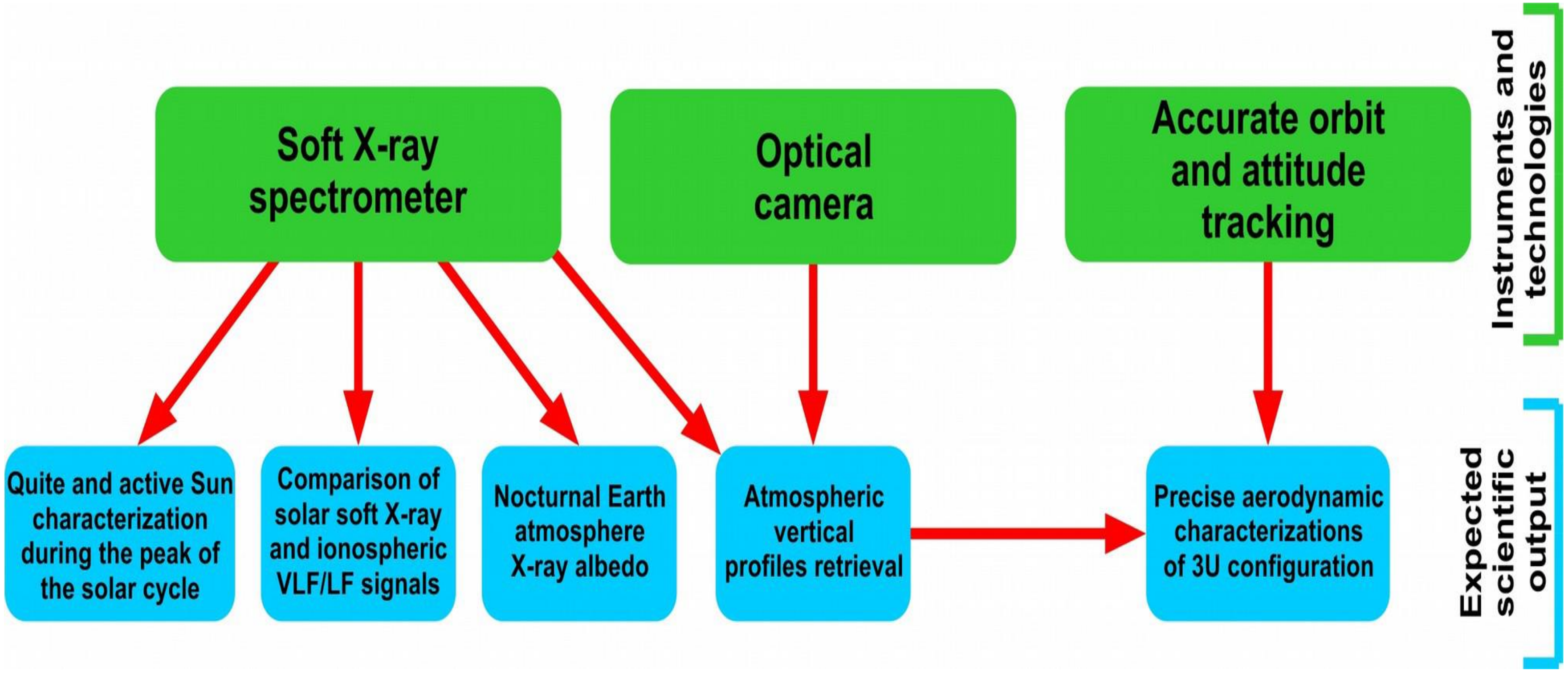
Space weather related activity – THE WAY FORWARD: CubeSat

Development of first Serbian multi-purpose academic cubeSat, still in the initial phase. Primary scientific goal (using relatively cheap X-ray commercial detector) is to study solar activity from LEO and to correlate acquired data with VLF and CR measurements conducted at the Institute of Physics.
Also, important goal is to include undergraduate and graduate students in all aspects of this project and to rise public awareness.



Space weather related activity – THE WAY FORWARD: CubeSat

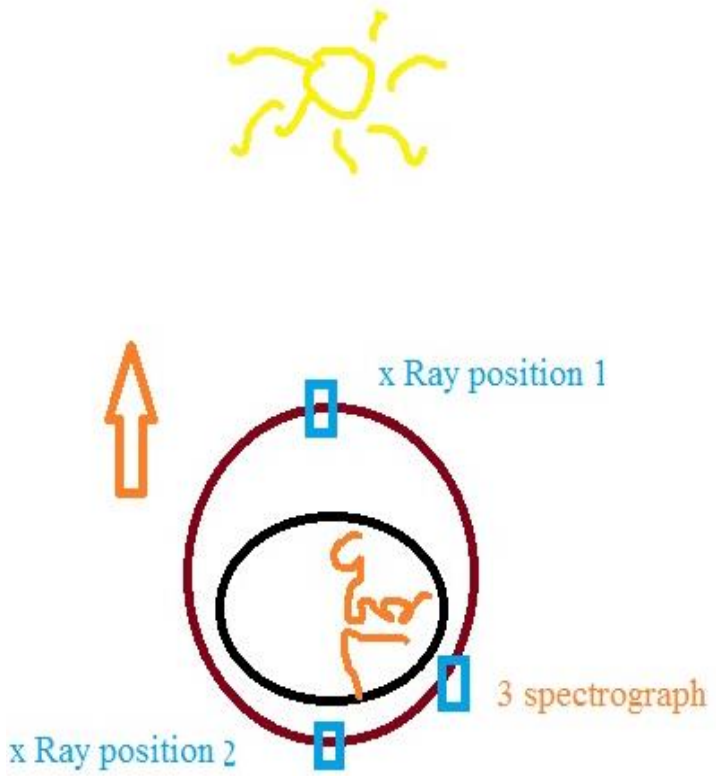
Operation 1: Observation of the Sun in the soft X-ray domain with the available commercial detector X-123

There are affordable detectors at the commercial market with proved performances in the orbital environment. This provides the opportunity to conduct experiments in orbit with scientifically valuable results, with very limited financial resources.

- **X-ray Spectrometer (X123)**
  - Amptek X123 Silicon Drift Diode (SDD)
  - 0.8 – 12 keV bandpass
  - 0.03 keV bins -> 0.15 keV FWHM resolution
  - Δt = 10 seconds cadence
  - FOV = 4°
  - $\Delta V \sim E_{ph}$

Operation 2: Observation of the soft X-ray radiation of the Earth's nocturnal atmosphere

Due to maintaining the spacecraft's continuous direction toward the Sun the cubeSat will be directed towards the Earth during the shaded part of the orbit and can observe its radiation (due to auroras, CR showers,…) with the same instrument. In addition to this, there is very little data on this radiation, and to our knowledge, no cubeSats has ever conducted this type of measurement.



Summary

- Cosmic rays, originated from outside of the Solar system are also sensitive to properties of interplanetary medium and violent energetic events originated from the Sun that can additionally modulate cosmic rays.
- Connection between energetic particles flux measured in-situ at L1, measured ground–level cosmic ray muon flux and selected parameters of associated Interplanetary coronal mass ejections can improve analysis of violent energetic events on Sun and how Sun affects space weather.
- Worldwide network of small, modular ground muon detectors is planed to study space and terrestrial weather.
- Space weather related Serbian CUBESAT project, still in the initial phase, is planned with goal to study solar activity from LEO and to correlate acquired data with VLF measurements of the ionosphere and CR measurements conducted at the Institute of Physics.
- These two projects will have strong educational and outreach components because of the necessity to develop research capacity in study of the integrated Sun-Earth system.

BACKSLIDES

A&M DATA AsSpectro23

universe
an Open Access Journal by MDPI

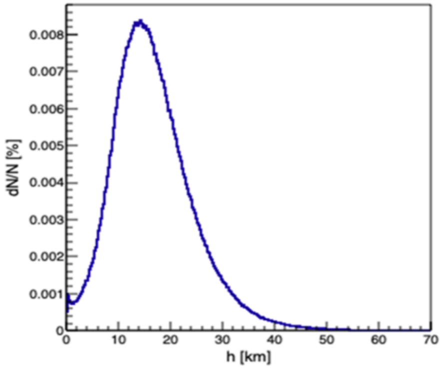
Special Session: "Astronomy and Earth Observations: multi-instrumental approach and theory“

Dedicated to new research insights, theoretical and observational, related to magnetosphere, ionosphere, radiative transfer and influence of space weather climate on biosphere, with the focus on the research of solar-influenced extreme events in the atmosphere, ionosphere and magnetosphere and space weather related interactions and scope to address these topics as a multidisciplinary field of research, important in diversified areas of physics like plasma physics, atomic physics, meteorology, stellar and astroparticle physics.

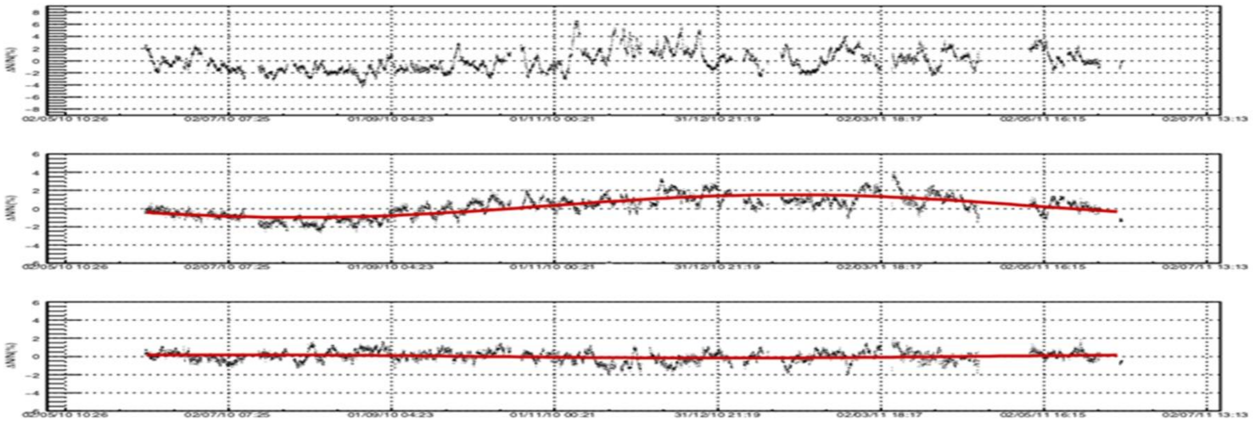
http://asspectro2023.ipb.ac.rs/

Meteorological effects on muon component

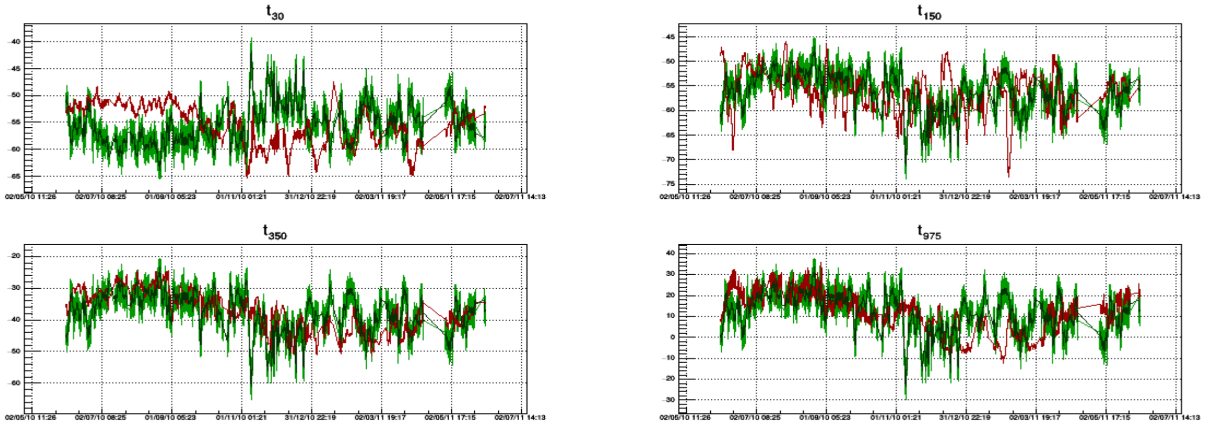
Flux of secondary CR as well as VLF signals measured by ground-based detectors are affected by changing conditions in the atmosphere. The flux of muon component of secondary CR is affected, primarily by the variations of atmospheric pressure (*barometric effect*) and atmospheric temperature (*temperature effect*). Other than correction of such modulation, precise modelling of atmospheric effects utilizing multivariante analysis techniques like PCA and machine learning allows for inverse diagnostic, where parameters of the atmosphere can be predicted based on the above mentioned detector measurements.



$$\frac{\Delta I}{I} = \beta \Delta p + \int \alpha(h) \Delta T(h) dh$$



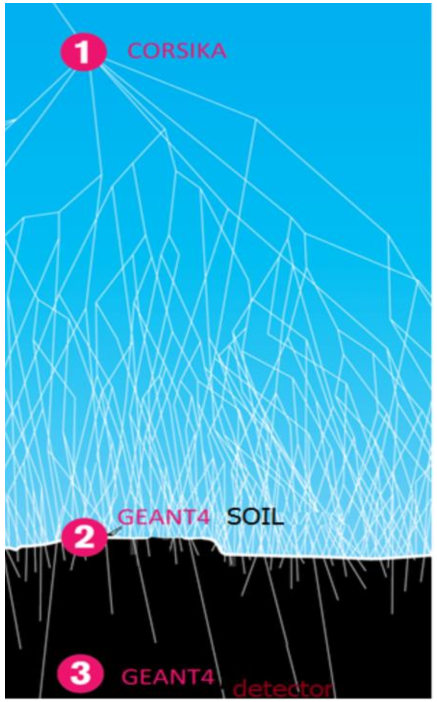
Muon count rate time series : raw data (top), pressure corrected data (middle), data PT corrected using selected multivariate methods.

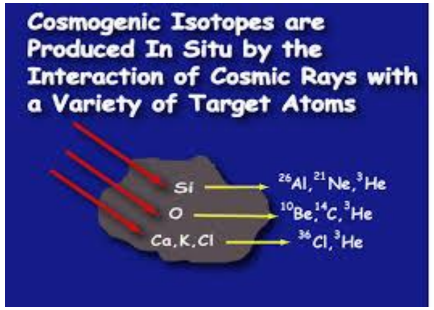


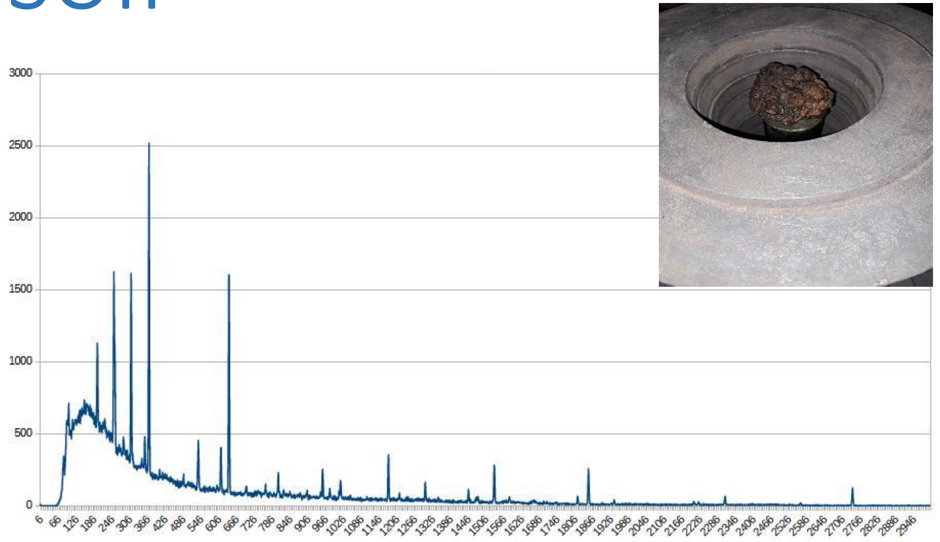
Savić M. et al. *Space Weather,* 19, (**2021**) https://doi.org/10.1029/2020SW002712
as presented at ICRC2021,Berlin,Germany

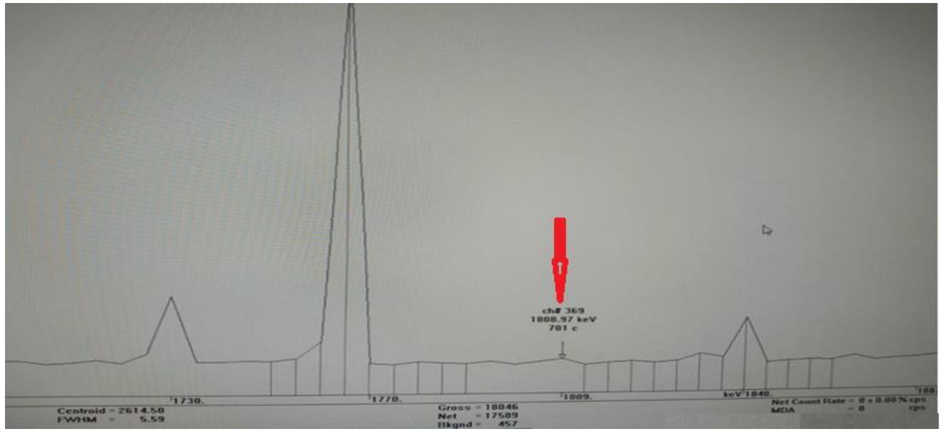
Space weather related activity – THE WAY FORWARD: Meteorites and soil

Cosmogenic radionuclides are created when cosmic rays interact with Earth's atmosphere and ground. Cosmogenic nuclides are proxy for ancient Solar activity. Production of cosmogenic nuclides in soil due to fast secondary nucleons happens near to ground surface Production due to interaction of soil with muons which penetrate more deeply are very important for determine paleo-erosion. Also meteorites and asteroids can be additional way of determining ancient space climate.









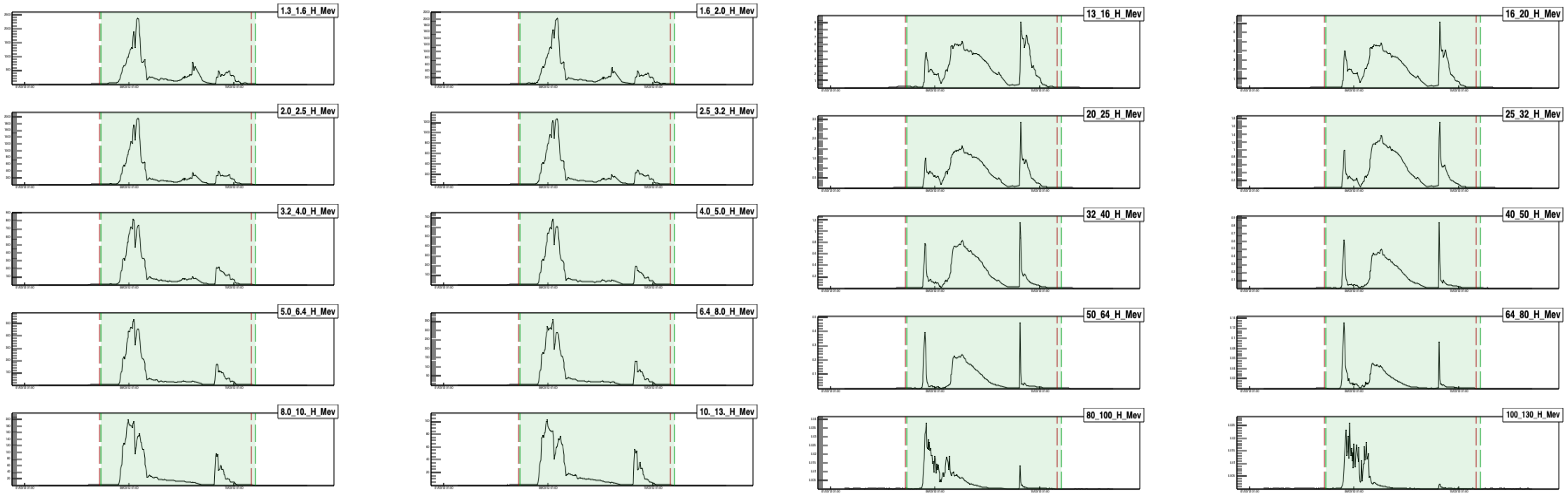
Correlations

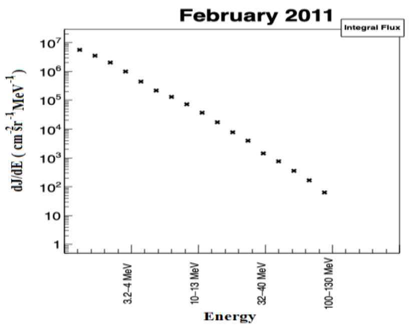
$$\frac{dJ}{dE}=\begin{cases}E^{-\alpha}\exp\left(-\frac{E}{E_b}\right) & E\leq(\beta-\alpha)E_b,\\ E^{-\beta}\left[(\beta-\alpha)E_b\right]^{\beta-\alpha}\exp(\alpha-\beta) & E>(\beta-\alpha)E_b,\end{cases}$$

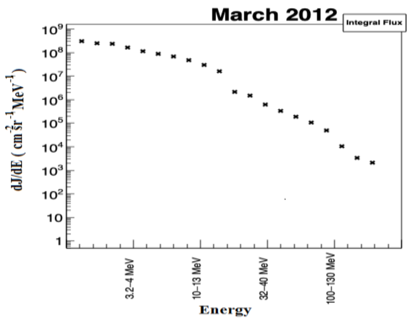
	α	β	M	M_M	V_{meanC}	V_{mean}	V_{max}	Kp_{max}	Ap_{max}	Dst_{min}
α	1.00	0.96	0.67	0.64	0.77	0.75	0.66	0.40	0.53	-0.40
β	0.96	1.00	0.67	0.67	0.72	0.70	0.60	0.44	0.50	-0.38
M	0.67	0.67	1.00	0.84	0.79	0.79	0.79	0.53	0.65	-0.41
M_M	0.64	0.67	0.84	1.00	0.57	0.57	0.53	0.69	0.69	-0.46
V_{meanC}	0.77	0.72	0.79	0.57	1.00	1.00	0.92	0.61	0.77	-0.58
V_{mean}	0.75	0.70	0.79	0.57	1.00	1.00	0.92	0.62	0.78	-0.60
V_{max}	0.66	0.60	0.79	0.53	0.92	0.92	1.00	0.49	0.71	-0.58
Kp_{max}	0.40	0.44	0.53	0.69	0.61	0.62	0.49	1.00	0.94	-0.78
Ap_{max}	0.53	0.50	0.65	0.69	0.77	0.78	0.71	0.94	1.00	-0.97
Dst_{min}	-0.40	-0.38	-0.41	-0.46	-0.58	-0.60	-0.58	-0.78	-0.87	1.00

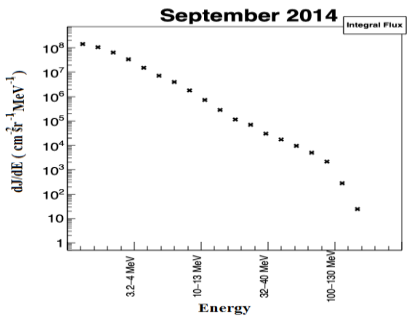
Above table shows correlation between power law exponents α and β and some of the parameters related to cosmic rays, space weather and geomagnetic field typically used in similar analyses. These are: M – FD magnitude, M_M – FD magnitude corrected for magnetospheric effects, V_{mean} – mean CME velocity, Kp_{max} – maximum Kp index and Dst_{min} – minimal Dst index during the event

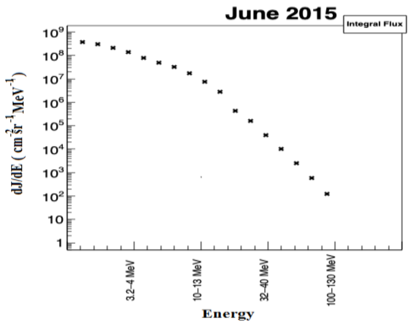
Correlations



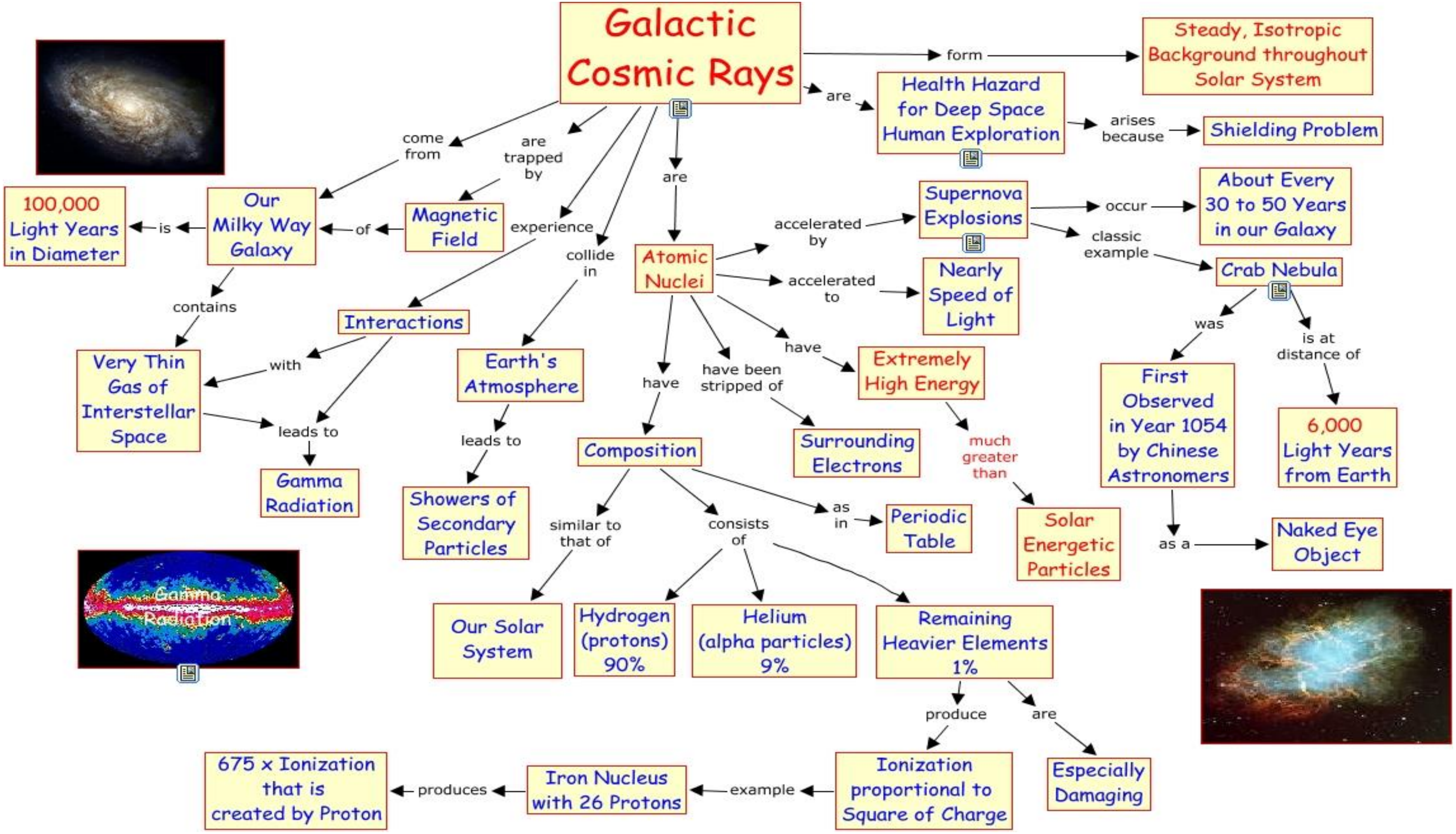








RawGLData	RawGLData	1.3_1.6_H_Mev	1.6_2.0_H_Mev	2.0_2.5_H_Mev	2.5_3.2_H_Mev	3.2_4.0_H_Mev	4.0_5.0_H_Mev	5.0_6.4_H_Mev	6.4_8.0_H_Mev	8.0_10._H_Mev	10._13._H_Mev	13_16_H_Mev	16_20_H_Mev	20_25_H_Mev	25_32_H_Mev	32_40_H_Mev	40_50_H_Mev	50_64_H_Mev	64_80_H_Mev	80_100_H_Mev	100_130_H_Mev
Quit days	1	−0.01	0.01	0.02	0.03	0.04	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.25	0.38	0.15
Dist. days	1	−0.05	−0.05	−0.05	−0.05	−0.05	−0.06	−0.06	−0.06	−0.06	−0.06	−0.06	−0.05	−0.05	−0.05	−0.04	−0.02	0.07	0.08	0.11	0.09



Galactic Cosmic Rays
form
Steady, Isotropic Background throughout Solar System
are
Health Hazard for Deep Space Human Exploration
arises because
Shielding Problem
come from
Our Milky Way Galaxy
is
100,000 Light Years in Diameter
contains
Very Thin Gas of Interstellar Space
are trapped by
Magnetic Field
of
experience
Interactions
with
leads to
Gamma Radiation
collide in
Earth's Atmosphere
leads to
Showers of Secondary Particles
are
Atomic Nuclei
accelerated by
Supernova Explosions
occur
About Every 30 to 50 Years in our Galaxy
classic example
Crab Nebula
was
First Observed in Year 1054 by Chinese Astronomers
as a
Naked Eye Object
is at distance of
6,000 Light Years from Earth
accelerated to
Nearly Speed of Light
have
Extremely High Energy
much greater than
Solar Energetic Particles
have been stripped of
Surrounding Electrons
have
Composition
similar to that of
Our Solar System
consists of
Hydrogen (protons) 90%
Helium (alpha particles) 9%
Remaining Heavier Elements 1%
as in
Periodic Table
produce
Ionization proportional to Square of Charge
are
Especially Damaging
example
Iron Nucleus with 26 Protons
produces
675 x Ionization that is created by Proton
Gamma Radiation