The Correlation Between Fluctuations in the Fluxes of Energetic Protons and Cosmic Rays During Forbush Decrease Events

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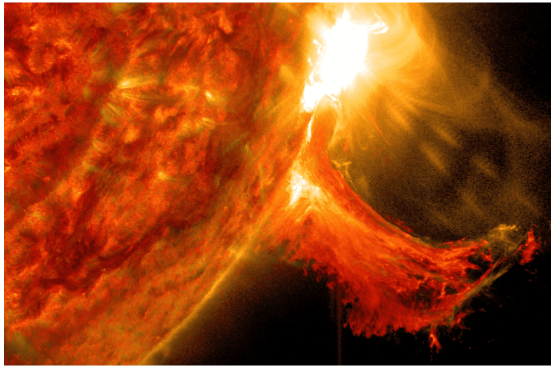
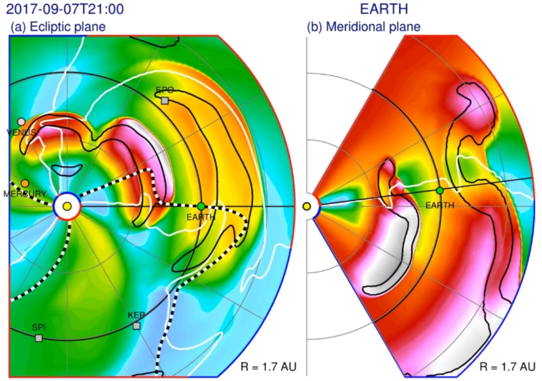
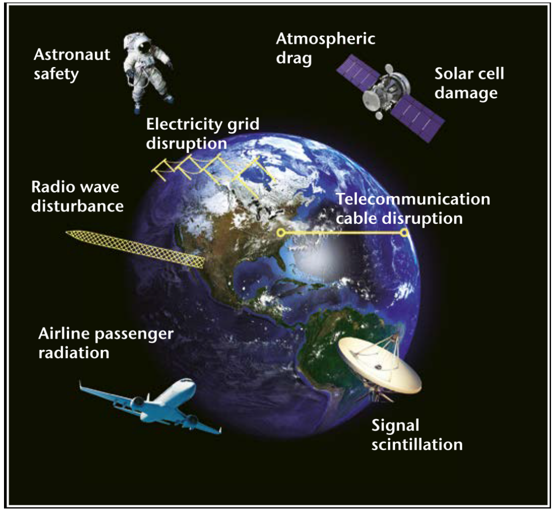
Extreme Space Weather Events and Their Impact



- Intense magnetic activity on the Sun can result in the sudden release of energy as solar flares (SF)
- The primary mechanism for the formation of solar flares is magnetic reconnection, which involves the reconfiguration of the Sun's magnetic field lines
- Solar flares are a significant source of energetic particles accelerated from the Sun

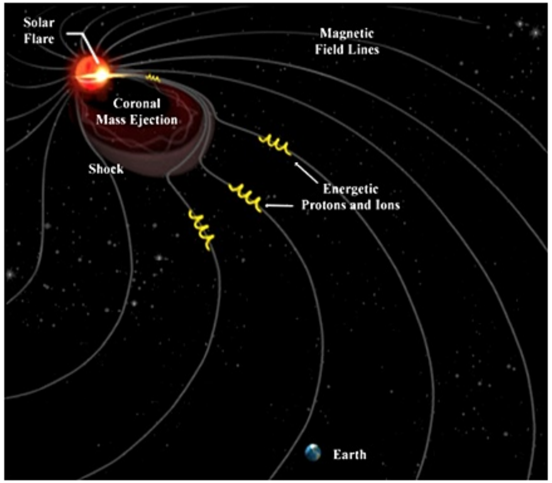
- Solar flares are frequently followed by ejection of coronal plasma and embedded magnetic field
- This phenomenon is known as coronal mass ejection (CME).
- Many CMEs enter interplanetary space, at which point are referred to as interplanetary coronal mass ejections (ICMEs)





- Directed toward Earth, SFs and CMEs can have significant effects on near-Earth environment
- These effects include potentially hazardous impacts on many man-made systems and technologies widely used today

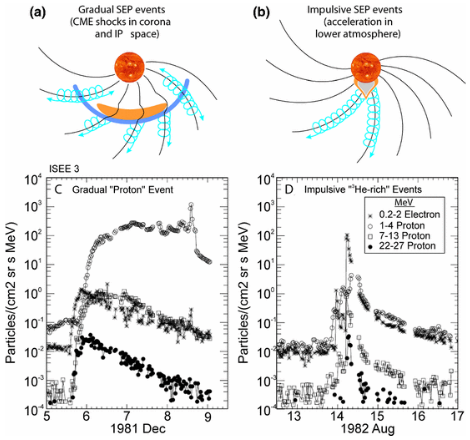
Sources of Solar Energetic Particles



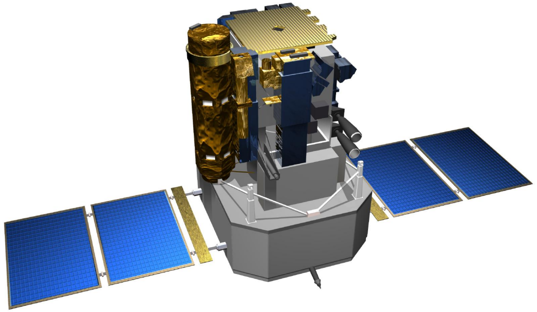
http://spaceweather.uma.es

- Both SF and CME can result in acceleration of solar protons
- Depending on their properties and acceleration mechanism we distinguish two classes of solar energetic particle (SEP) events

- Impulsive SEP events are observed in the absence of CME related shock waves
- Gradual SEP events are associated with CME driven shock acceleration
- Additionally, energetic storm particles (ESP) can be accelerated by shock locally



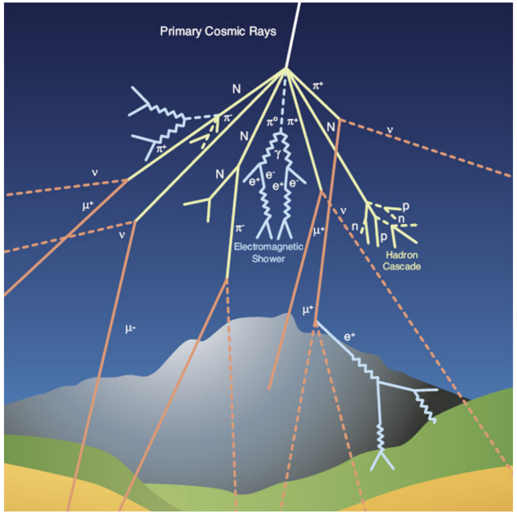
Desai and Giacalone (2016)



https://soho.nascom.nasa.gov/

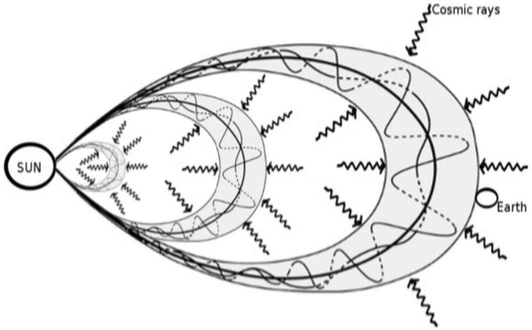
- Many spaceborne probes are conducting in-situ monitoring of protons, ions, and electrons fluxes
- For our analysis, we have utilized data from the SOHO/ERNE instrument situated at L1
- Proton fluxes are available in 20 energy channels, covering the range from 1.3 MeV to energies above 130 MeV

Effects of Coronal Mass Ejections on Primary Cosmic Rays

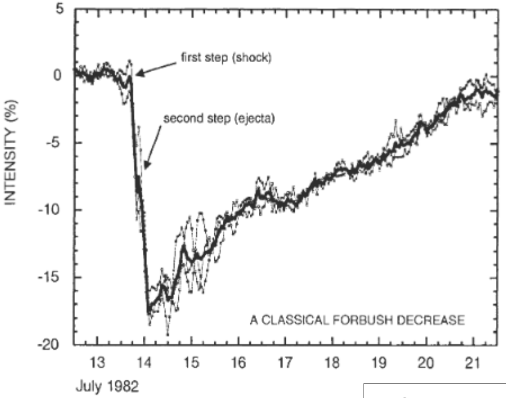


- Primary cosmic rays (CRs) are a flux of particles of mainly galactic origin
- In interactions with our atmosphere, they generate showers of secondary particles that are detected by ground-based detectors

- Passage and the shock of an ICME following an extreme solar event modulate the flux of primary cosmic rays in the heliosphere
- The resulting sudden reduction in CR intensity, followed by a gradual recovery phase as a Forbush Decrease (FD).



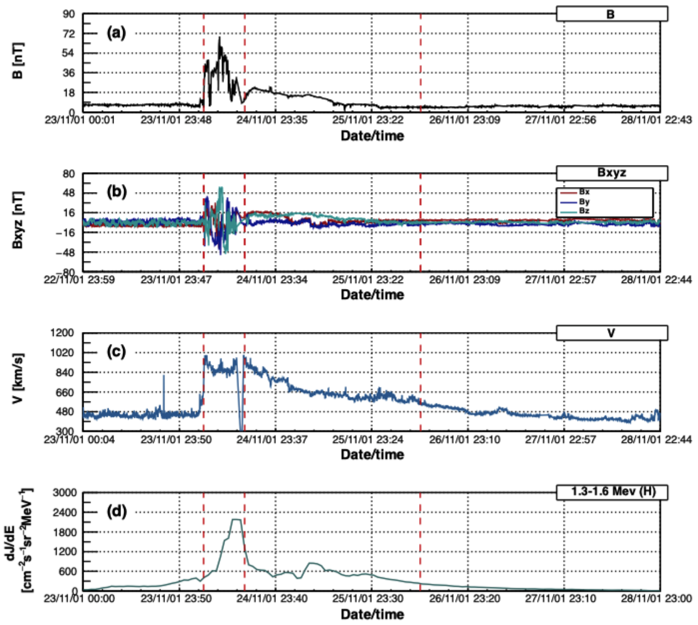
Arunbabu et al. (2022)



Cane (2000)

- FDs are clearly observable in the flux of secondary CR particles, particularly if an ICME is directed toward Earth, and can be detected by ground-based detectors
- The two most commonly used types of instruments for monitoring secondary cosmic rays are neutron monitors and muon detectors.

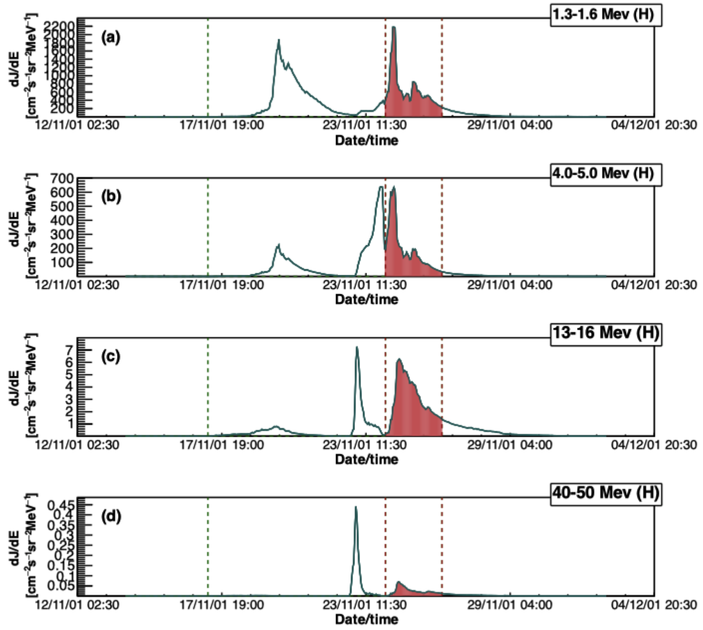
Determination of Energetic Proton Fluence



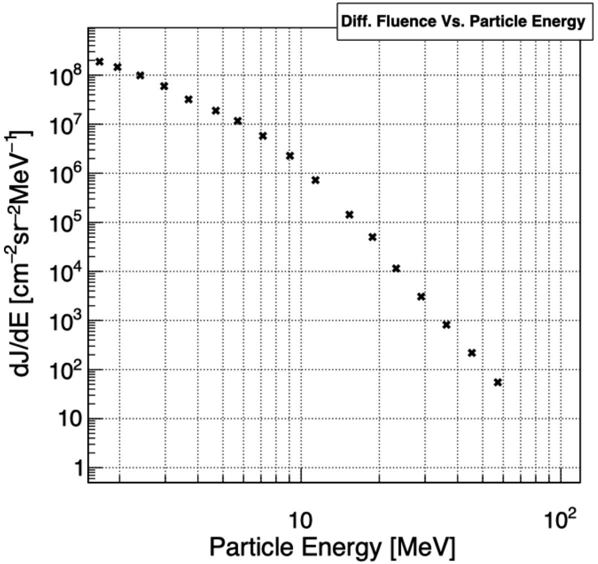
- As CME can simultaneously be responsible for both the increase in energetic proton flux and the FD, we investigate the potential connection between the two induced phenomena

- To describe the effect on energetic particles we focused on the shape of fluence spectra.

- To precisely determine the time intervals associatted with the passage of the specific CME fluence spectra inteplanetary magnetic field (IMF) and CME data (provided by the WIND satellite) were used



Energetic Proton Models



- Fluence spectra have a shape that may involve a characteristic “knee” or a “bend” in the spectrum
- We present three models developed that describe this shape

- **Ellison-Ramaty model**
- Developed to describe particle acceleration in interplanetary shocks
- Involves exponential roll-over

$$\frac{dJ}{dE} = AE^{-\gamma} \exp\left(-\frac{E}{E_0^{ER}}\right)$$

- **Weibull model**
- Has the form of a two-parameter stretched exponential
- Successfully used to describe SEP spectra

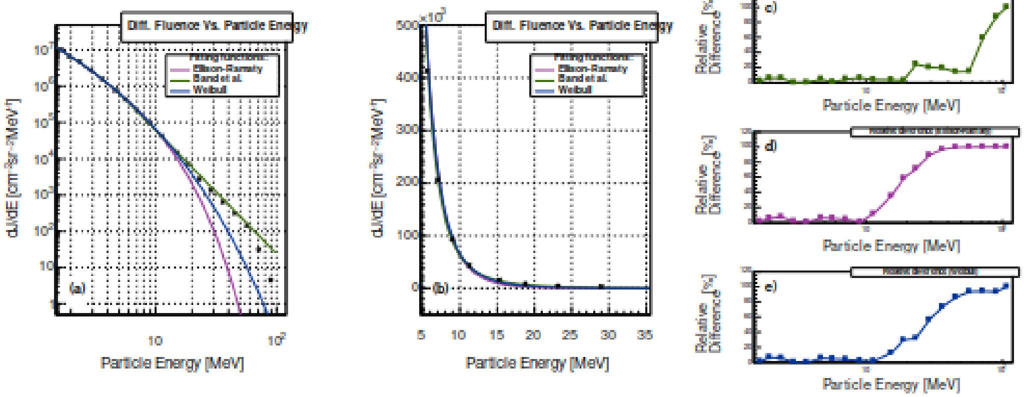
$$\frac{dJ}{dE} = AE^{b-1} \exp\left(-\frac{E}{E_0^{W}}\right)^{b}$$

- **Band et al. model**
- Developed to describe gamma ray burst spectra
- Explicitly treats the “knee” feature

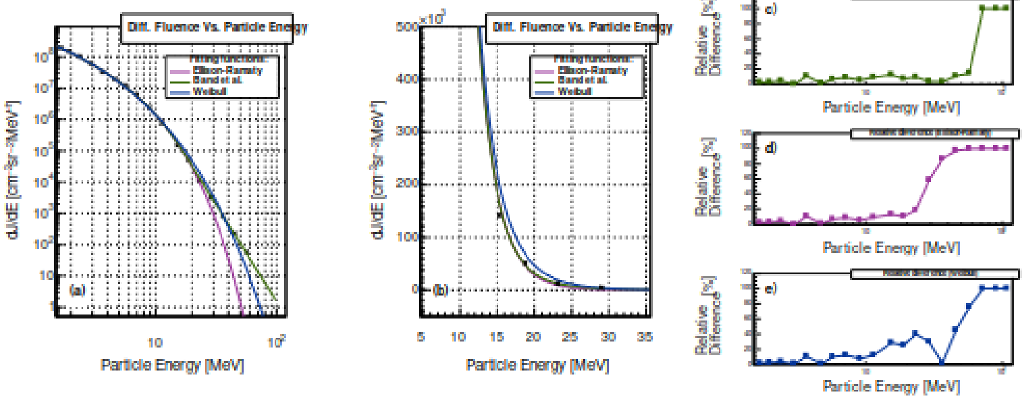
$$\frac{dJ}{dE} = \begin{cases} AE^{-\alpha} \exp\left(-\frac{E}{E_B}\right), & E \leqslant (\beta-\alpha) E_B \\ AE^{-\beta}\left[(\beta-\alpha) E_B\right]^{\beta-\alpha} \exp(\alpha-\beta), & E > (\beta-\alpha) E_B \end{cases}$$

Model Comparison

November 2003 event

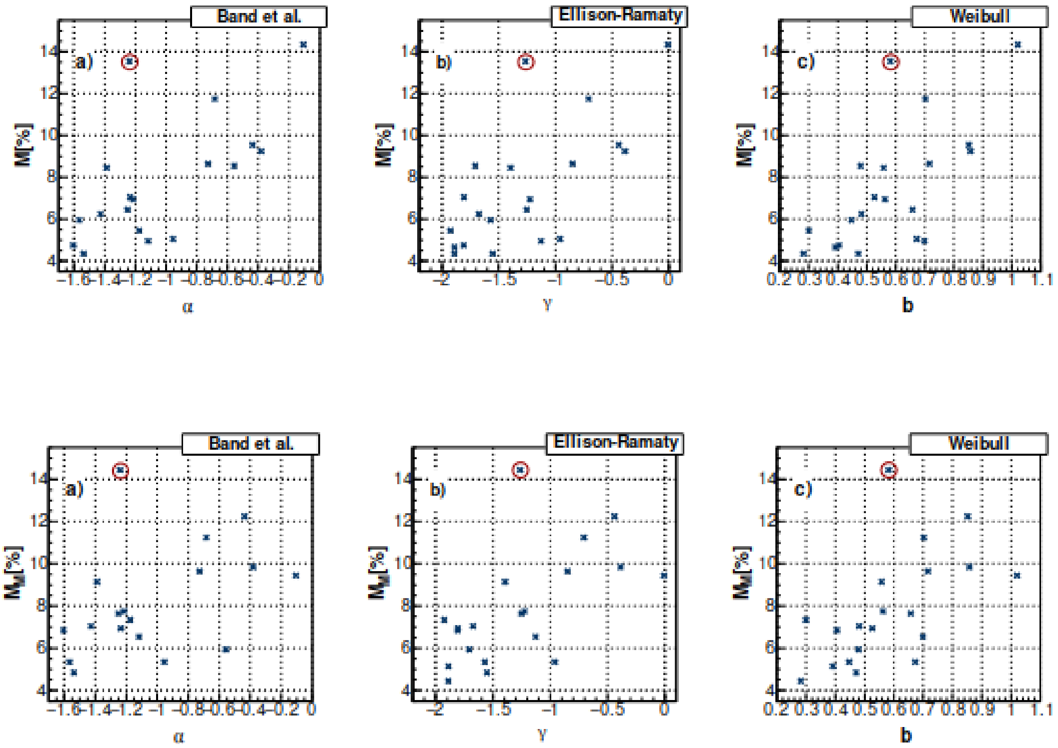


June 2015 event



- We have made a selection of 20 events in total that cover a period from 2001 to 2017 that involved a distinct FD and a concurrent increase in energetic proton detected
- Events were fitted with all three functions
- Two events are shown to illustrate the performance of different models
- Band function was found to describe the spectra very well, especially the region around the “knee”
- Ellison-Ramaty and Weibull model are overall comparable, where individual better performance depends on the specific event

Correlation Analysis (1)



- To establish the assumed connection between the shape of energetic proton fluence spectra and Forbush decreases we studied the relationship between spectral indices from three selected models and FD magnitudes
- Magnitude *M* is the FD magnitude for 10GV particles calculated using the GSM method (developed by the IZMIRAN research group) using the measurements by the world-wide network of neutron monitors
- Magnitude M_M is the FD magnitude for 10GV particles corrected for magnetospheric effects
- Plots show dependencies of FD magnitudes M and M_M spectral indices α, γ and b
- July 2004 event (circled in red) was excluded from the analysis

Correlation Analysis (2)

- Correlation analysis was used to quantify the observed relationship
- Other than *β* which showed negligible correlation, other spectral indices are significantly correlated with FD magnitudes
- Correlation coefficient between *α*, *γ* and *b* and *M* are comparable with ones for selected CME and solar wind parameters
- Correlation coefficient between *α*, *γ* and *b* and M_M are more significant than for any other parameter
- Roll-over and cut-off parameters exhibit modest to low correlation with spectral indices and/or FD magnitudes with, the exception of E_0^W (Weibull function)

	α	β	E_B	E_B^*	γ	E_0^{ER}	b	E_0^W	V_C	V_{max}	Kp_{max}	M	M_M
α	1.00	-0.18	-0.46	0.04	0.83	-0.47	0.84	0.82	0.68	0.69	0.40	0.83	0.71
β	-0.18	1.00	0.21	-0.61	-0.44	0.47	-0.53	-0.27	-0.08	-0.10	-0.04	-0.07	-0.20
E_B	-0.46	0.21	1.00	0.52	-0.19	0.86	-0.37	-0.09	0.00	-0.05	-0.33	-0.23	-0.32
E_B^*	0.04	-0.61	0.52	1.00	0.47	0.18	0.37	0.42	0.37	0.28	-0.10	0.15	0.12
γ	0.83	-0.44	-0.19	0.47	1.00	-0.42	0.96	0.95	0.78	0.74	0.46	0.77	0.73
E_0^{ER}	-0.47	0.47	0.86	0.18	-0.42	1.00	-0.61	-0.27	-0.14	-0.14	-0.32	-0.33	-0.38
b	0.84	-0.53	-0.37	0.37	0.96	-0.61	1.00	0.90	0.72	0.70	0.45	0.76	0.70
E_0^W	0.82	-0.27	-0.09	0.42	0.95	-0.27	0.90	1.00	0.87	0.82	0.47	0.84	0.70
V_C	0.68	-0.08	0.00	0.37	0.78	-0.14	0.72	0.87	1.00	0.94	0.55	0.81	0.54
V_{max}	0.69	-0.10	-0.05	0.28	0.74	-0.14	0.70	0.82	0.94	1.00	0.48	0.80	0.52
Kp_{max}	0.40	-0.04	-0.33	-0.10	0.46	-0.32	0.45	0.47	0.55	0.48	1.00	0.47	0.66
M	0.83	-0.07	-0.23	0.15	0.77	-0.33	0.76	0.84	0.81	0.80	0.47	1.00	0.78
M_M	0.71	-0.20	-0.32	0.12	0.73	-0.38	0.70	0.70	0.54	0.52	0.66	0.78	1.00

Conclusions

- We investigated the assumed connection between the concurrent CME-induced variations in energetic proton and cosmic ray fluxes
- Intervals in energetic proton time series directly related to the passage of CME were established using WIND satellite data and used to calculate the proton fluence spectra
- Three different models used to describe the energetic proton spectra were compared, with spectral indices obtained from the fits used to parameterize the spectra
- The correlation between spectral indices and FD magnitudes was studied to establish the relationship
- A significant correlation, comparable to other parameters known to have large correlation with FD magnitude, was established for several spectral indices
- Correlation found between spectral indices and FD magnitude corrected for magnetospheric effects was more significant than for any other parameter