The GRAPES-3 cosmic ray instrument as a space weather tool

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- The large (560 m^2) muon detector makes it capable of detecting changes in cosmic ray proton intensity of $\sim 0.1\%$
- This makes it a sensitive space weather instrument, well adapted to detecting changes in cosmic ray intensity due to transients in the near-Earth solar wind (arising from Coronal Mass Ejections, and shocks driven by them)

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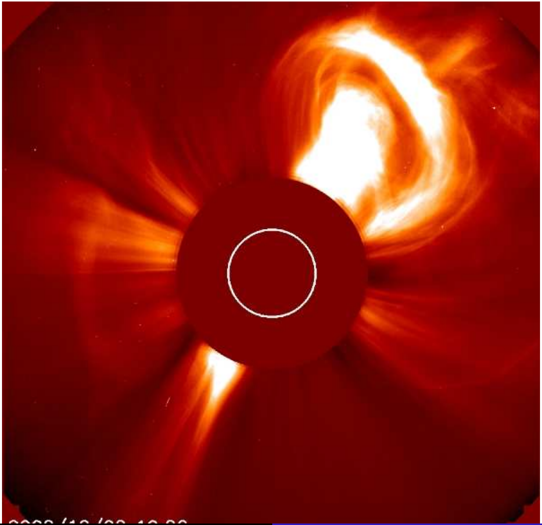
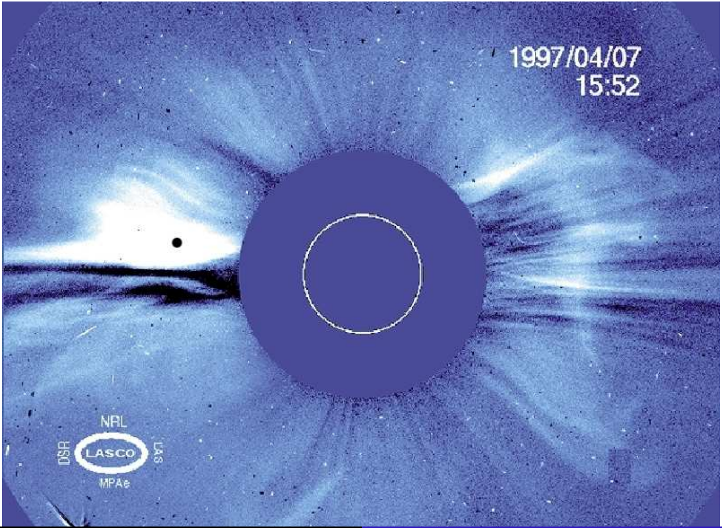
- They frequently drive shocks ahead of them
- CMEs are frequently directed towards the Earth
- Earth-directed CMEs and their shocks affect the Earth's magnetosphere in a variety of ways; taken together, these effects describe "space weather"

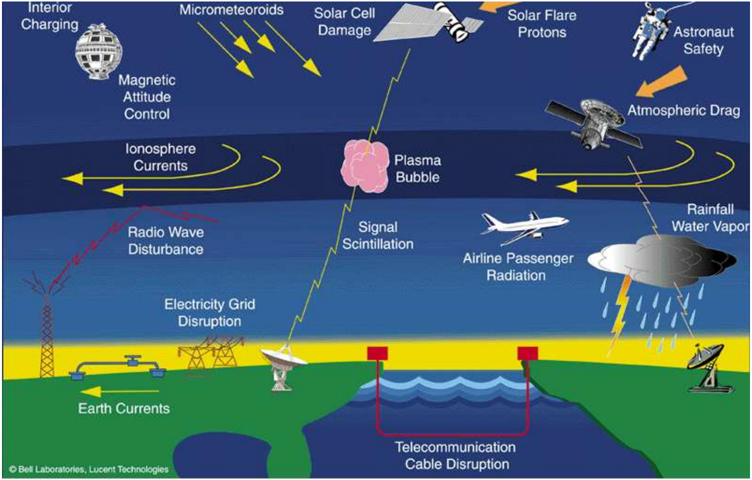
Coronal Mass Ejection (CME): example 1



Coronal Mass Ejection (CME): example 2



"Space Weather"



The effects of magnetic storms - what scientists call space weather - extend from the ground to geostationary orbit and beyond.

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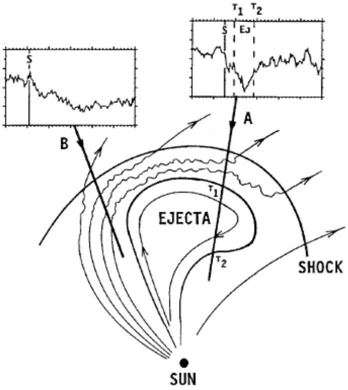
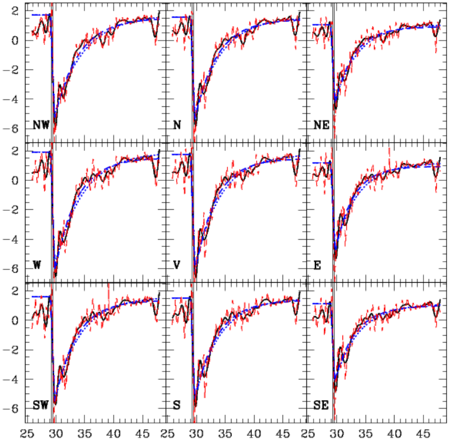
- Specifically, magnetic clouds/near-Earth CME manifestations and their associated shocks are known to cause Forbush decreases in the galactic cosmic ray intensity.
- More interestingly, precursors to Forbush decreases in galactic cosmic rays at the Earth provide advance information about parameters of the CME-associated shock, and hence the impending geomagnetic storm

FDs are due to near-Earth CME/shock



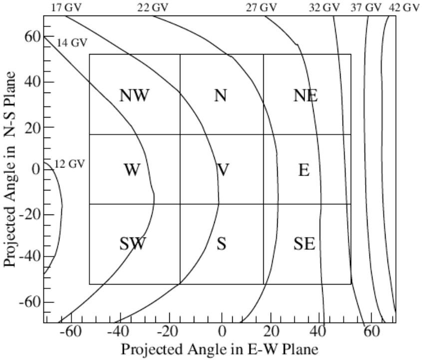
Shock (magnetic "umbrella" against cosmic rays) + CME (low density cavity)

Forbush decrease: GRAPES-3 data



Decrease in galactic cosmic ray intensity@Earth

GRAPES-3 muon detector directional bins



GRAPES-3 can observe in 9 directions/rigidities/energies

Forbush Decrease studies with GRAPES-3

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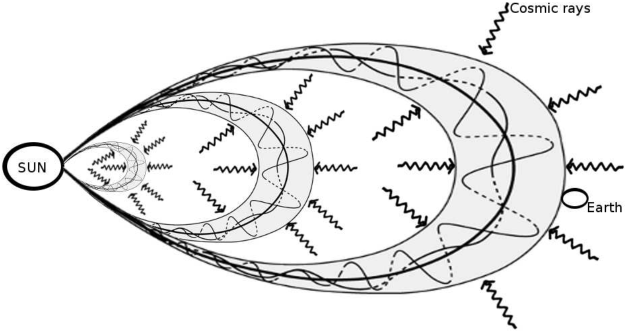
- At GRAPES-3 energies ($\approx 14 - 42$ GeV) we have shown (Subramanian et al 2009; Arun Babu, PhD thesis) that the relatively empty magnetic bottle (the CME) is the primary cause of the Forbush decrease.
- We have derived tight constraints on the turbulence level (amplitude) in the vicinity of the CME (sheath region), especially with multi-rigidity data (Arun Babu, PhD thesis). We are also elucidating the role of cross-field diffusion in the presence of MHD turbulence.

Forbush decrease due to magnetic bottle



CME starts out almost devoid of CRs. CRs (cross-field) diffuse into it, but its still a depleted (CR) cavity @ Earth

Some details - I

- Flux of protons entering CME:

$$F\,(\mathrm{cm}^{-2}\,\mathrm{s}^{-1}) \;=\; D_{\perp}(\rho\,,\sigma^{2})\,\frac{\partial N_a}{\partial r}\,, \tag{1}$$

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- Total # of high energy protons that will have diffused into CME after time T:

$$U_i = \int_0^T A(t)\,F(t)\,dt = \int_0^T D_{\perp}(\rho\,,\sigma^{2})\,A(t)\,\frac{\partial N_a}{\partial r}dt\,, \tag{2}$$

Some details - II

- The density inside the near-earth magnetic cloud

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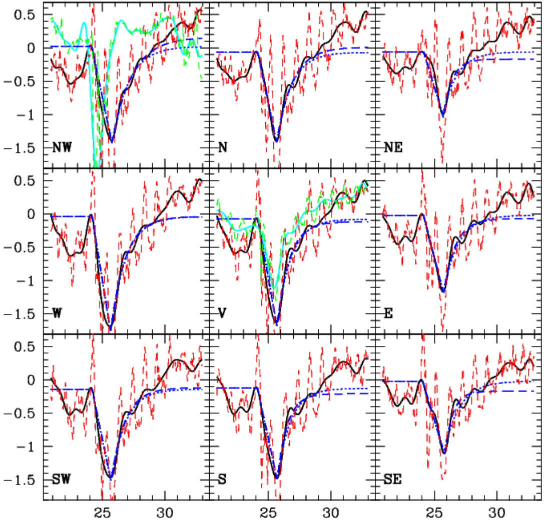
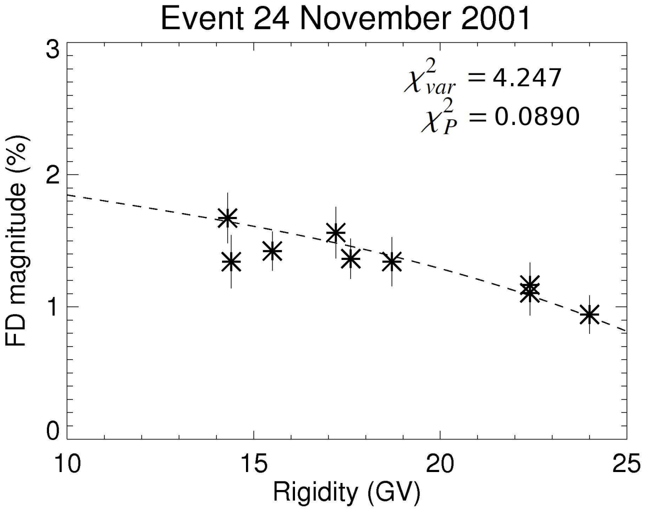
- can be related to the magnitude M of Forbush decrease:

$$\alpha\, M = \frac{N_a - N_i}{N_a} = \frac{\Delta N}{N_a} = 1 - \frac{4\,\pi\, \int_0^T D_{\perp}(\rho\,,\sigma^2)\, H(t)\, dt}{R^2(T)\, L(T)}\,, \tag{4}$$

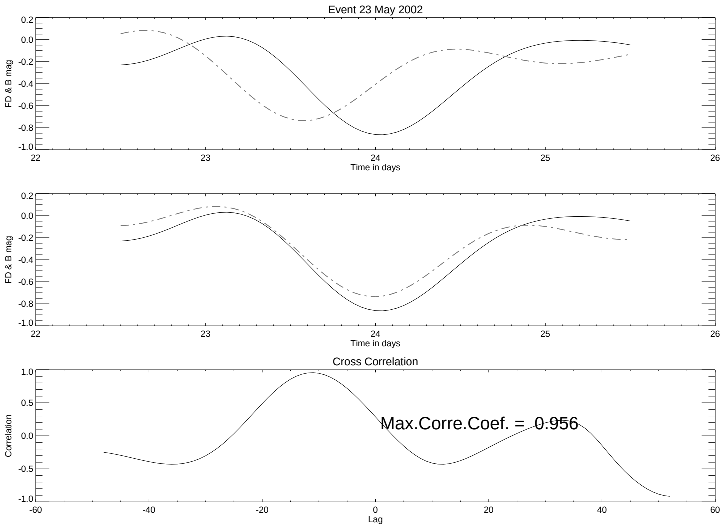
Results: multi-rigidity data Nov 24 2001



Results: (multi-rigidity) model fitting



FD profile - B field compression profile



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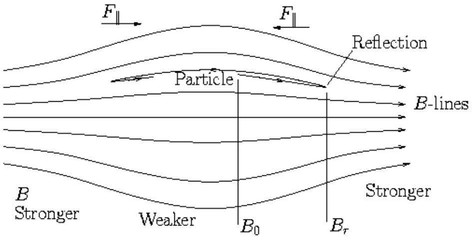
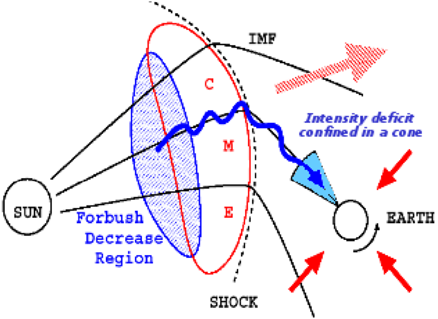
- Use GRAPES-3 data to identify precursor decreases
- Theoretical understanding of FD precursors in terms of loss cone decreases
- A thorough understanding of FD precursors will result in predictive capability ($\sim$ 3 - 4 hours) wrt the strength of/turbulence level near the shock that is due to hit the Earth's magnetosphere

FD precursors: general understanding



The B field compression near the shock is like a magnetic mirror. Since $v_\perp \uparrow$ with $B \uparrow$, $v_{||}$ can $\rightarrow 0$ at the mirror point for energy to be conserved.



If $v_{\|}/v_{\perp} \gg 1$ (low pitch angle), the mirror effect is minimal, and these particles can "leak" through the mirror. This "loss cone" of particles can propagate (at speeds $\approx c$) ahead of the shock, forming a FD precursor.
Cartoon: Nelson Schuch, Brazil

FD precursors: physics

- Cosmic ray particles undergo resonant pitch angle scattering with turbulent irregularities near the shock. This alters the loss cone/precursor characteristics (Ruffolo et al 1999; 2003)

$$\frac{\partial F}{\partial t} = -\frac{\partial}{\partial z}\left[\mu\, v + \left(1 - \mu^2\, \frac{v^2}{c^2}\right) u\right] F + \frac{\partial}{\partial \mu}\left[\frac{\phi}{2}\, \frac{\partial}{\partial \mu}\left(1 - \mu\, \frac{u\, v}{c^2}\right) F\right]$$

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- F: particle distribution function, z: distance from shock, μ: (cosine) pitch angle. So we have pitch angle diffusion due to resonance with turbulent eddies [embodied in the term $\phi \equiv A\,|\mu|^{q-1}\,(1-\mu^2)$: crucial!]

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- Characteristics of loss cone precursors will yield information on $\phi \rightarrow$ turbulence amplitude, strength of shock

FD precursors: lead times

- Net effect 1: Loss cone precursors for higher energy cosmic rays generally precede the FD by a longer time (complication: it also depends upon the geometry of the large-scale magnetic field/Parker spiral connecting the observer with the shock)

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- Net effect 2: Precursor lead time can also provide information about turbulence level near the shock/strength of shock (important!)

FD precursors: data analysis

- There has been some work in the past on FD precursors (Nagashima et al) and a flurry of recent work from the global muon detector network (e.g., Munakata et al 2000; Fushishita et al 2010; Rockenbach et al 2011)

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- This could enable prediction of impending shock strengths

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- Multi-rigidity data fitting has shown that (for FDs associated with magnetic clouds) CMEs/magnetic clouds are the primary contributors to the decreases (not the shocks)
- Forbush decrease precursor data from GRAPES-3 offers significant promise for diagnostics of turbulence levels near shocks/shock strengths with lead times of at least a few hours.

Thank you for your attention!