The Impact of Coronal Mass Ejection on Small-Amplitude Forbush Events

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DASP WORKSHOP

UNIVERSITY OF CALGARY

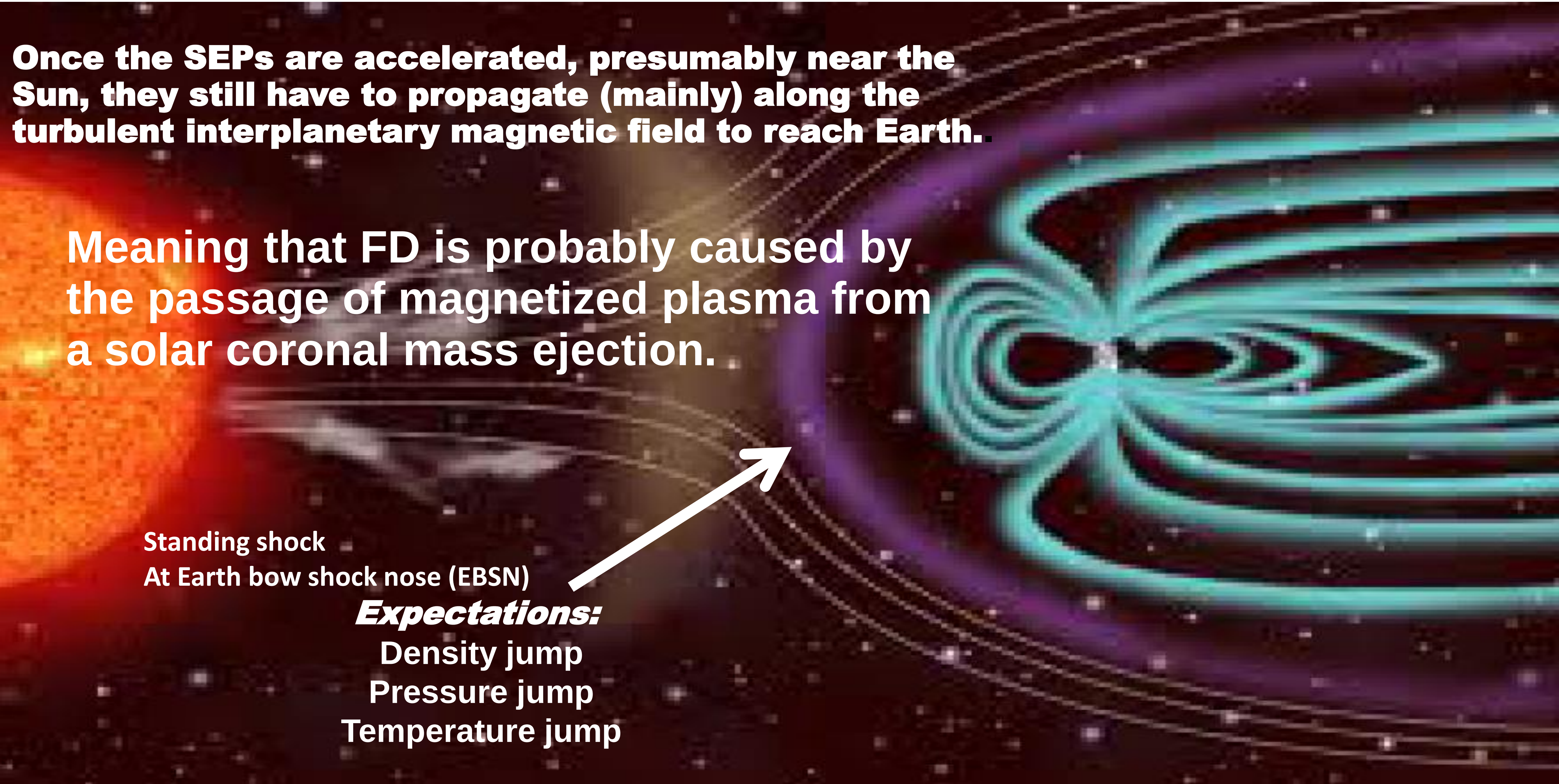
Introduction: Forbush Decrease

A cosmic ray Forbush decrease is a transient suppression of galactic cosmic ray intensity measured at Earth.

Introduction cont.

Once the SEPs are accelerated, presumably near the Sun, they still have to propagate (mainly) along the turbulent interplanetary magnetic field to reach Earth.

Meaning that FD is probably caused by the passage of magnetized plasma from a solar coronal mass ejection.



Expectations:

Density jump

Pressure jump

Temperature jump

Definition: Major and Minor FDs

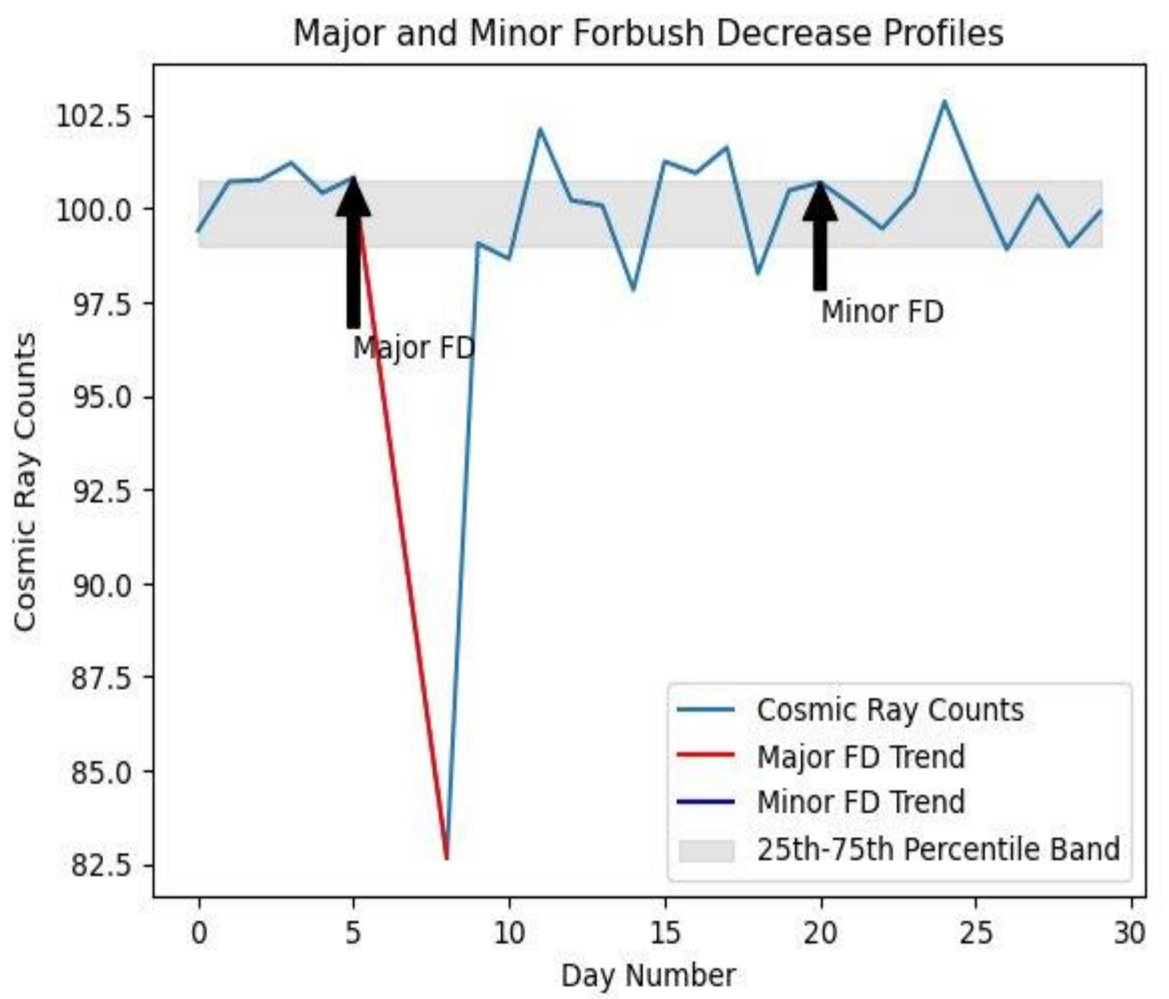
•**Major FDs**

Nevertheless, the focus has generally been on high-magnitude FDs (CR (%) >= 3).

•**Minor FDs**

the ability of small-amplitude FDs (CR (%) <= 3) depressions over ~1 day to prompt small-scale scattering signatures remains less understood:

Ø **CMEs produce major cosmic ray changes -but relationship with minor effects uncertain; Small Forbush decreases (FDs) lack clear origin**



When intercepting the Earth, CMEs produce Forbush decreases (FDs)

Observations and Datasets

Multi-instrument analysis

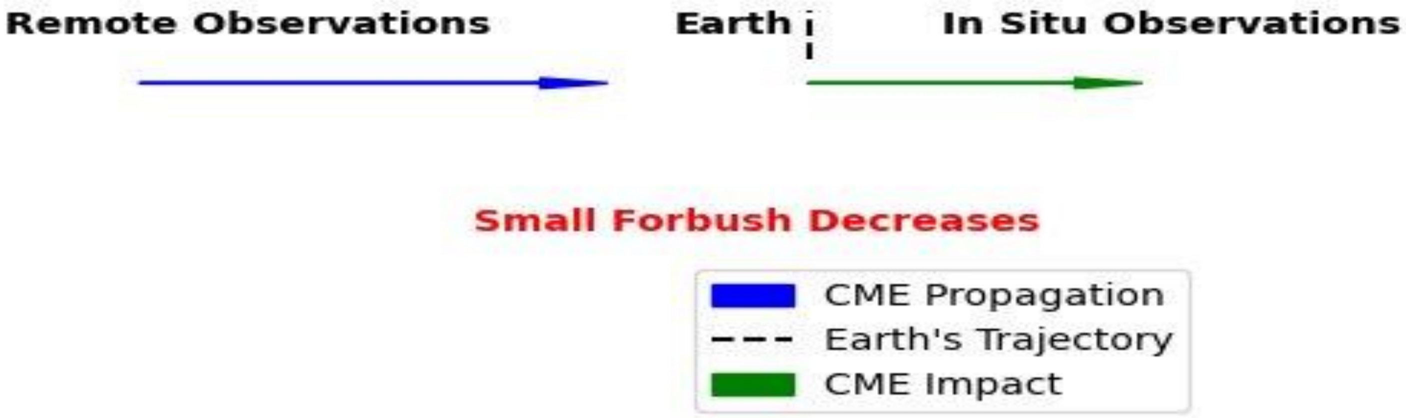
- Identify CME launch to 1 AU propagation including shock fronts responsible

To identify Earth-directed CMEs, we utilized white light coronagraph observations from the:

Large Angle Spectroscopic Coronagraph (LASCO) instrument aboard the Solar and Heliospheric Observatory (SOHO) spacecraft

OMNI is a time--shifted Wind/SWE plasma definitive database that provides more accurate plasma parameters, including density irregularities.

cosmic ray intensity from the Calgary neutron monitor was analyzed surrounding the established CME impact times.



We tracked the propagation of these CMEs to Earth using plasma parameters provided by OMNI database.

Tracking Earth-directed Eruptions

Event selection and cleaning

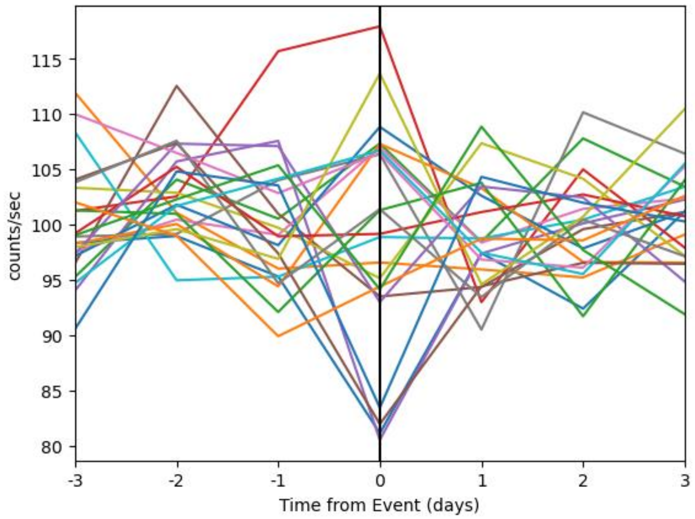
- Identify halo CMEs probable to impact Earth
  - Must be fronted Hallo (i.e directed towards the Earth)
- Sets initial conditions for heliospheric propagation
  - ±1 day of the ICME arrival
  - < 3% amplitude
  - Density jump >1 ($^{ncm-3}$) at onset

Event selection and cleaning

- **From identified 51 front-side full halo CMEs during 1996-2023 based on events listed in the SOHO/LASCO**

A subset of 23 halo CME events during where clear signatures of ejecta passage at Earth was evident based on the set conditions

Due to this recurrence, FD is amenable to superposed epoch analysis (SEA).



Event	FD Time [a]	ICME Speed (km/s)	Density jump	FD_{SEA} (%)[b]
1	1998-04-23	1255	39.20	-0.45
2	1998-12-14	1300	2.40	0.22
3	1998-06-03	1150	19.30	0.19
4	1999-02-23	1319	3.20	-0.18
5	1999-12-19	1208	1.90	-1.03
6	2000-02-02	1091	3.20	0.2
7	2001-03-13	1185	4.20	0.19
8	2002-02-15	1309	4.40	0.17
9	2004-05-15	1283	6.40	-0.12
10	2004-12-15	1135	8.20	0.18
11	2005-03-07	1311	10.40	-0.1
12	2005-06-13	1241	6.50	0.19
13	2005-12-31	1292	3.10	-1.65
14	2006-01-01	1283	15.20	0.19
15	2022-10-01	1134	2.50	0.18
16	2023-01-02	1285	1.80	-0.13
17	2023-01-31	1189	2.20	0.18
18	2023-02-10	1404	2.50	-0.14
19	2023-02-23	1322	6.00	-0.11
20	2023-03-08	1254	7.30	-0.16
21	2023-04-20	1151	5.20	0.19
22	2023-05-15	1255	1.90	0.21
23	2023-07-14	1265	25.40	-0.23

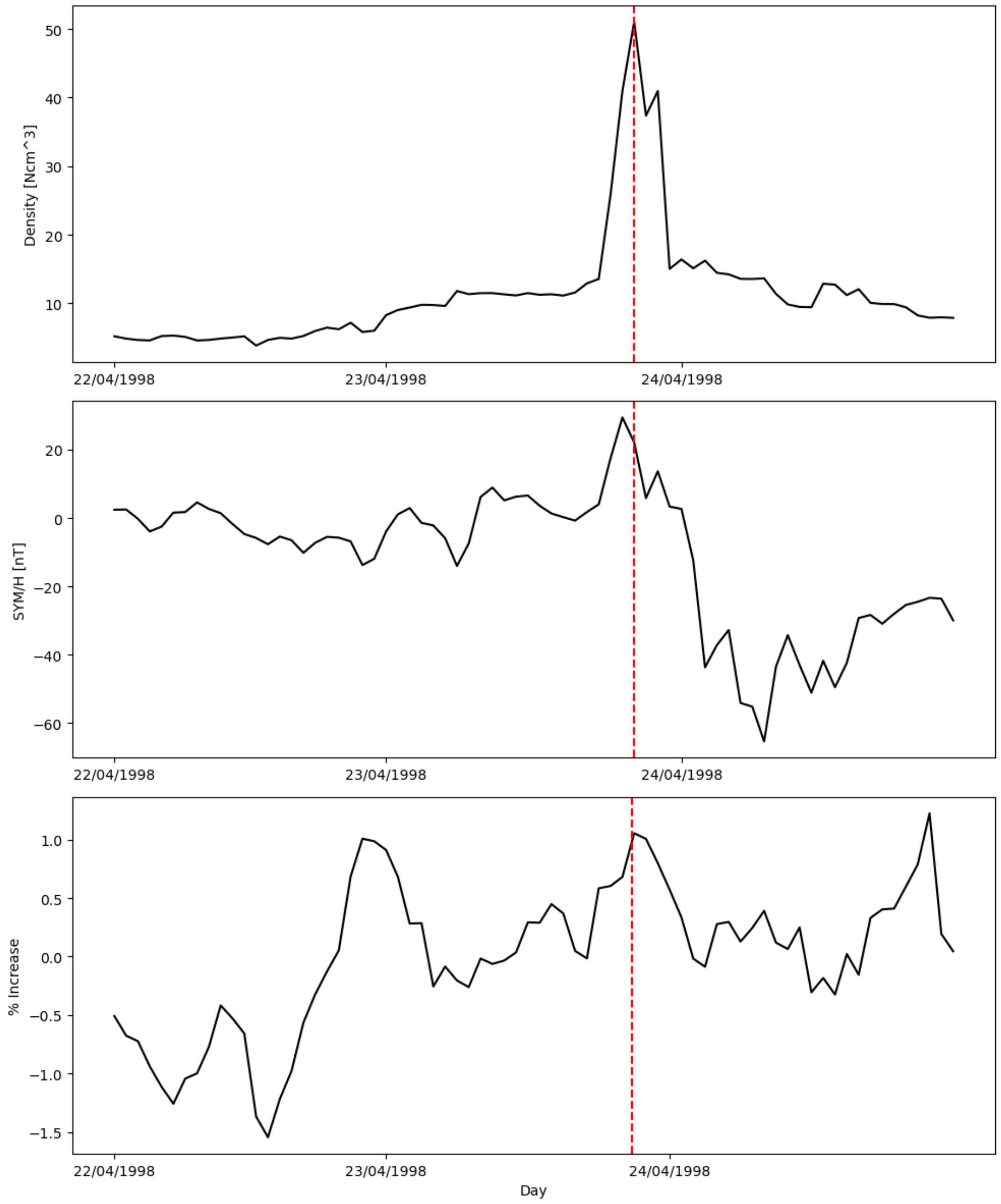
[a] at ±1 day ICME arrival Earth.
[b] Based on medidan average of CALG NM.

Case Study Event Diagnosis: Calgary NM

Case 1

- Calgary NM: minor FD event on 23 March 1998

Density jump reveals a modulated drop in galactic ray accessibility within hours of the estimated shock front encounter



When a CME propagates through the interplanetary medium, it compresses the solar wind plasma, resulting in an enhanced magnetic field and increased particle density (see Ogunjobi et. al. 2014, 2016, 2017).

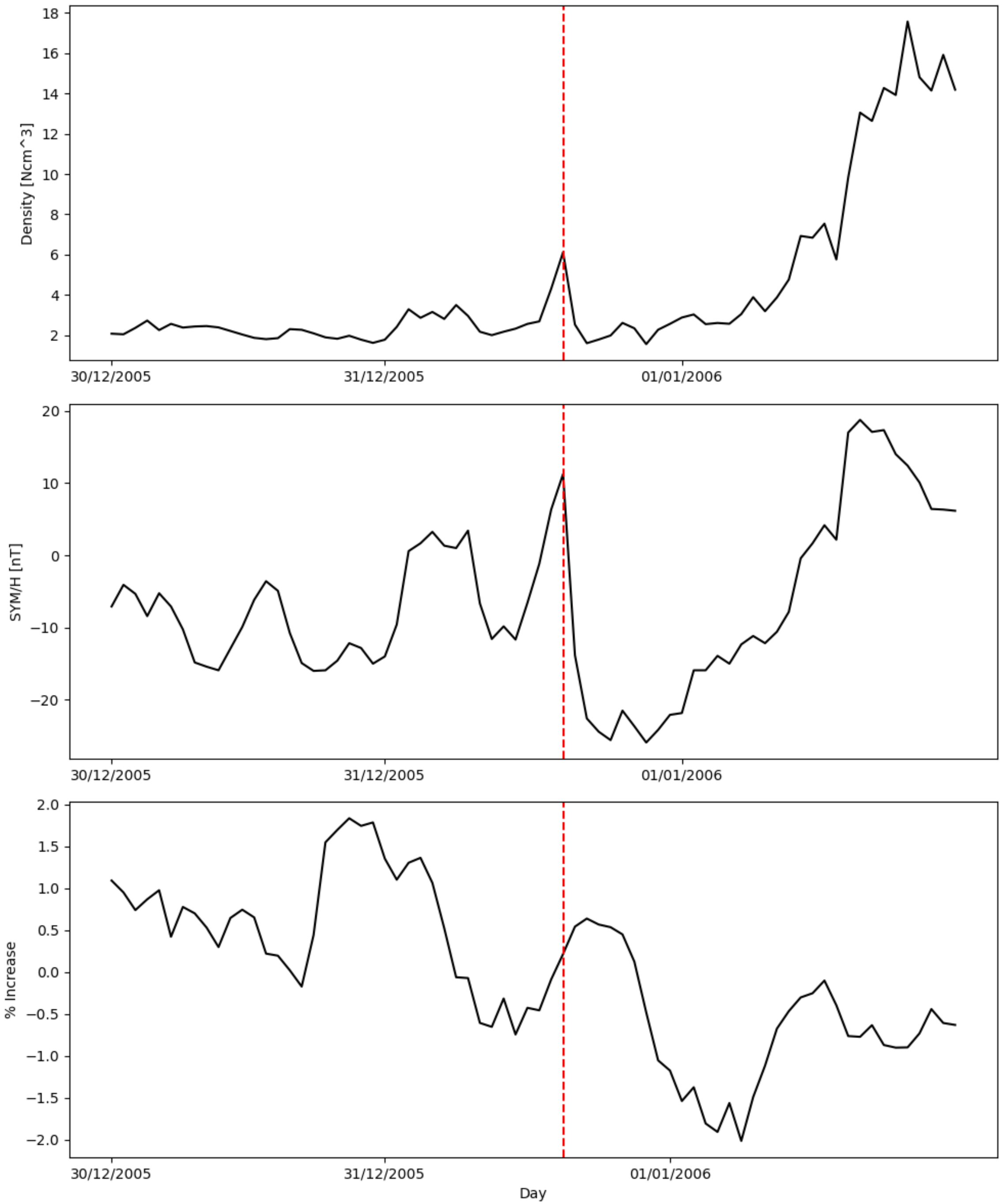
There is evidence that the intensity of cosmic rays temporarily decreases due to this compression, shielding the Earth.

Case Study Event Diagnosis: Calgary NM

Case 2

- **Calgary NM: minor FD event on 31 December 2005**
    - **Timing, amplitude, duration align expectations**

***This scenario is as in case 1, but effect of Solar cycle is noticeable.**



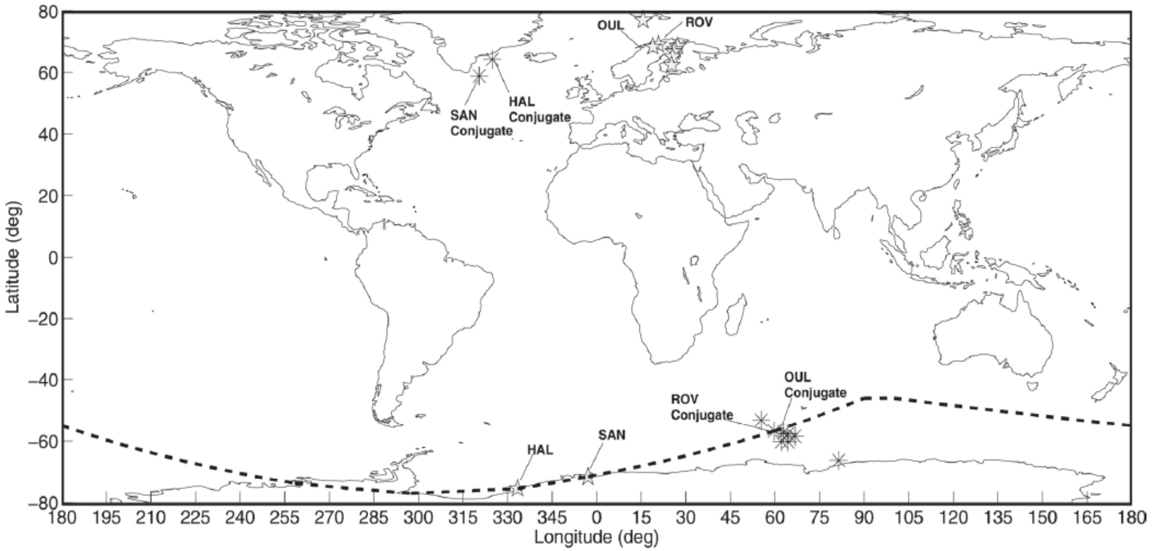
Case Study Event Diagnosis: Oulu NM

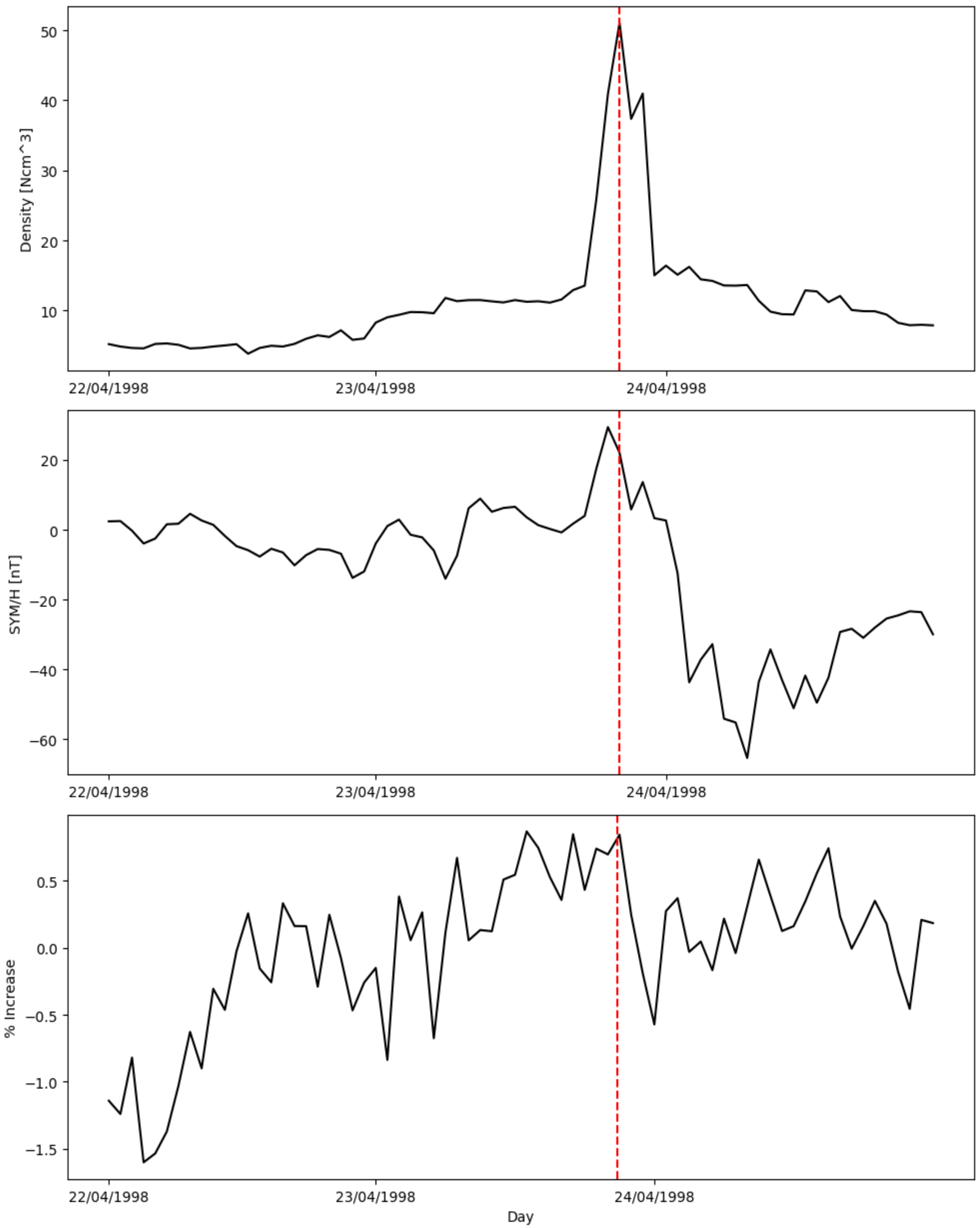
Case 1

•Oulu NM: minor FD event on 23 March 1998

*This scenario is as in Calgary case studies with similar magnitude;

meaning that they observe CRs arriving from approximately the same range of angles above the horizon.



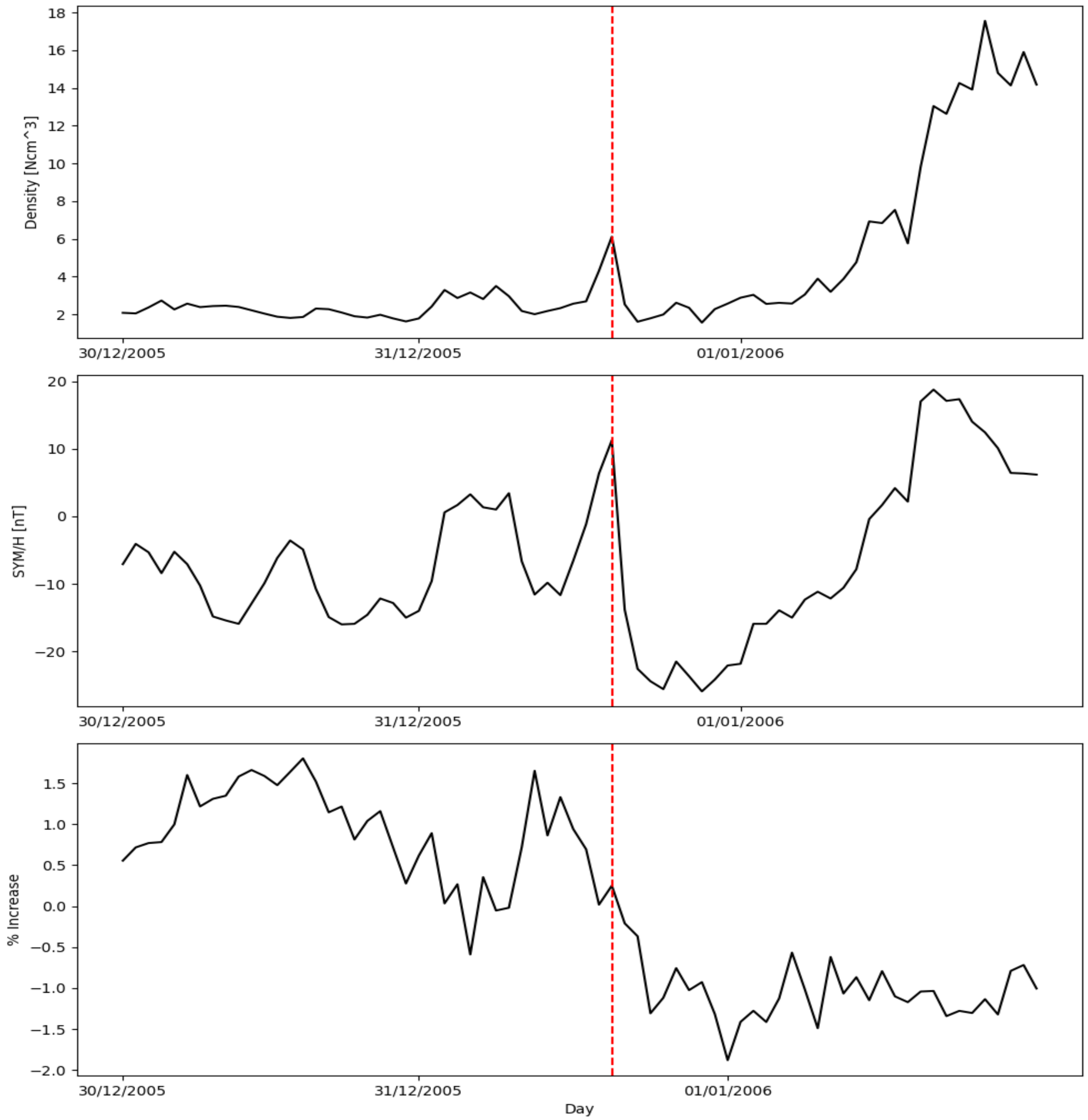


Case Study Event Diagnosis: Oulu NM

Case 2

•Oulu NM: minor FD event on 31 December 2005

Similarly to Calgary, density jumps reveal a modulated drop in galactic ray accessibility within hours of a shock front encounter.



Superposed Epoch Analysis

Superposed epoch analysis (SEA) is a statistical technique used to study the average behavior of a time series around specified key events. The key aspects of superposed epoch analysis are:

- Superposed epoch peak alignments
- Lag correlation significance evaluation
- Low false coincidence probability value

The time series data has N total key events at times (t1, t2, ..., tN).
For each key event i, we define a window spanning from L time steps before to M time steps after the event:

$$w\_i(t) = x(t + ti)$$
$$\text{for } -L \leq t \leq M$$

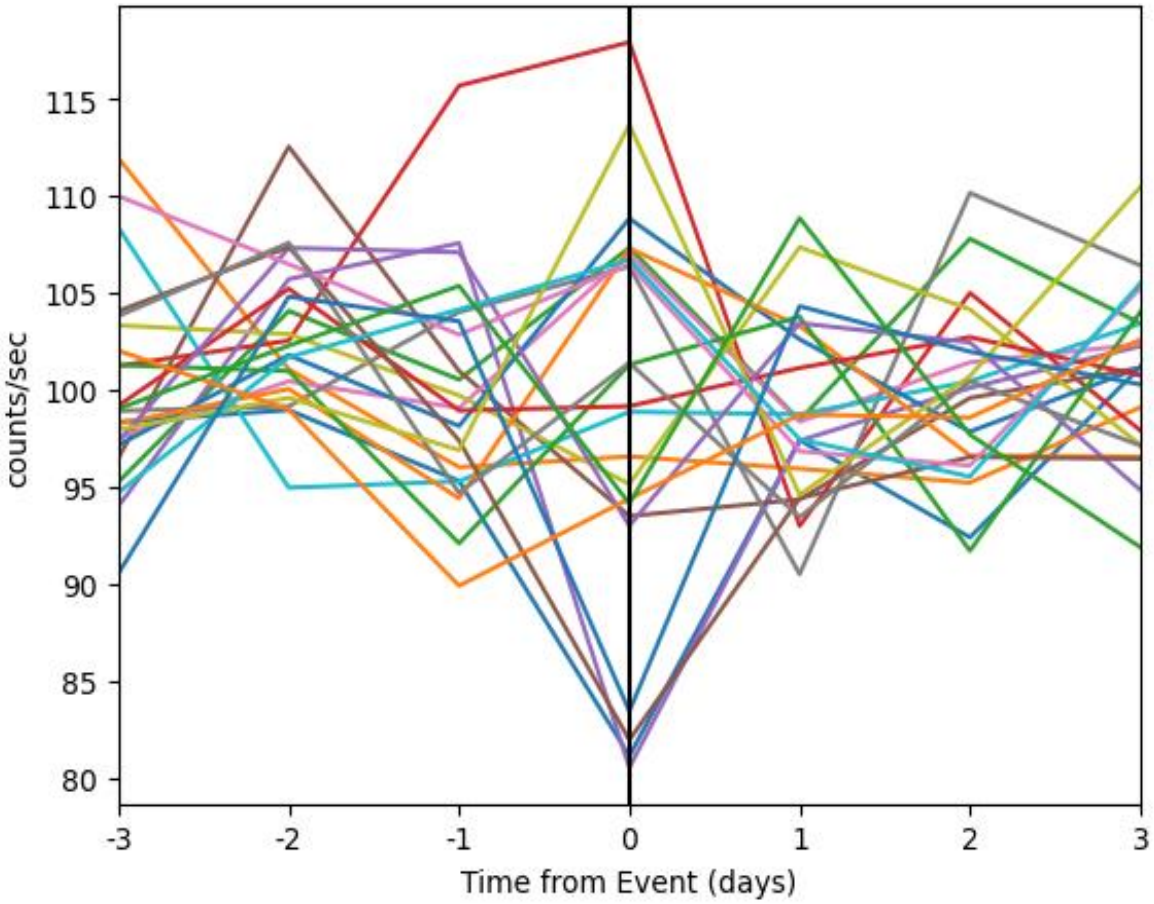
Where x(t) is the time series data.

Each window w_i contains the segment of x(t) centered on each key event i. These event epochs are superposed (overlapped) based on aligning the key event times.

The superposed epoch z(t) for -L ≤ t ≤ M
is calculated by taking the average over all N epochs:

$$z(t) = (1/N) \sum w\_i(t)$$
$$= (1/N) \sum x(t + ti)$$

Standard error and significance testing can also be calculated based on the distribution of epochs.



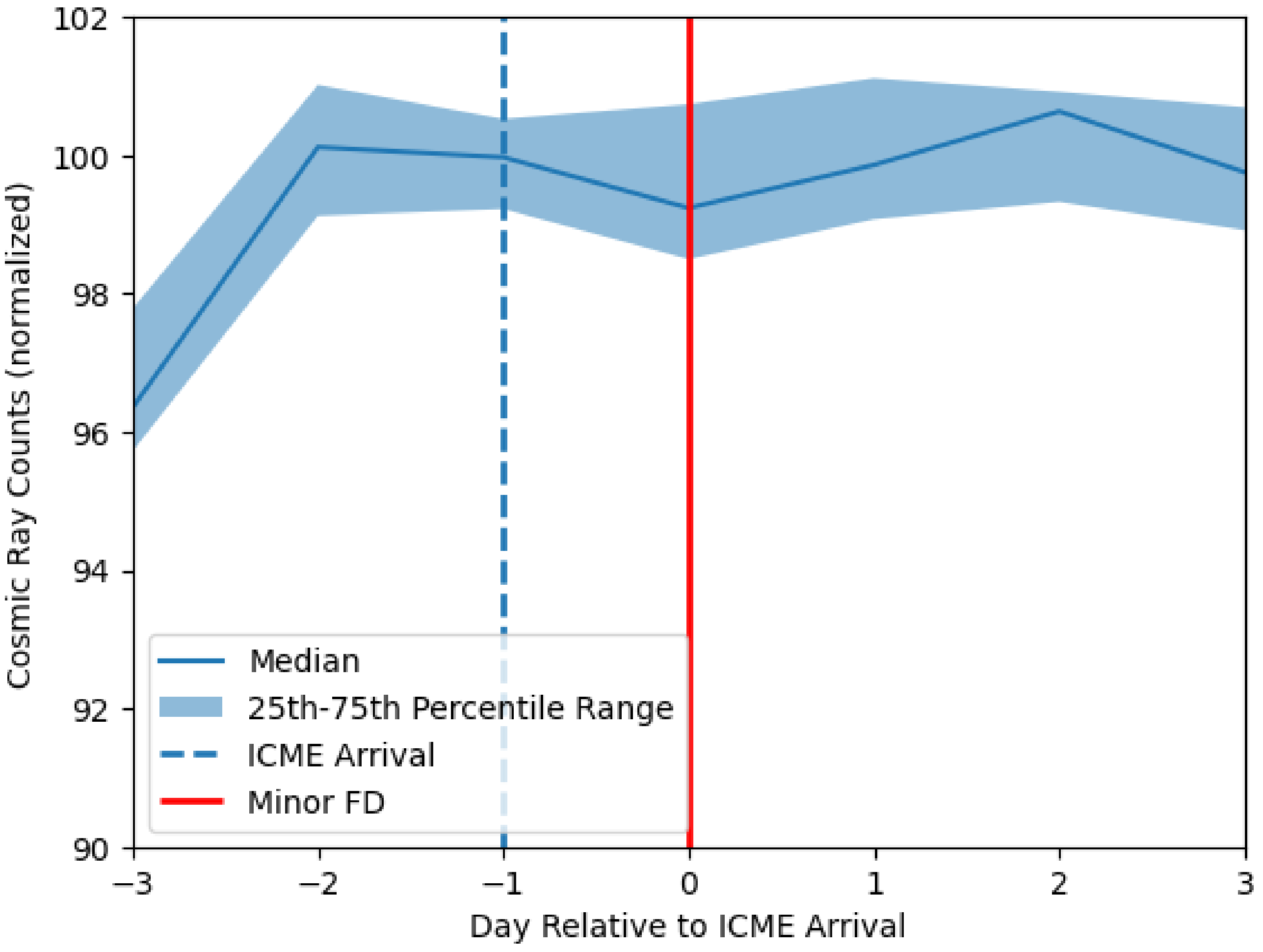
Epoch Synthesis Reveals Consistent Depletion

- Isolates real signal above random fluctuations
- Precisely timed post-ICME arrival
- Verifies intermittent modulation source

Cosmic ray flux measurements aligned with transient interplanetary shock passage times show a highly robust depletion feature.

verifies Earth-impacting ICME structures cause Forbush decreases instead of stochastic variation

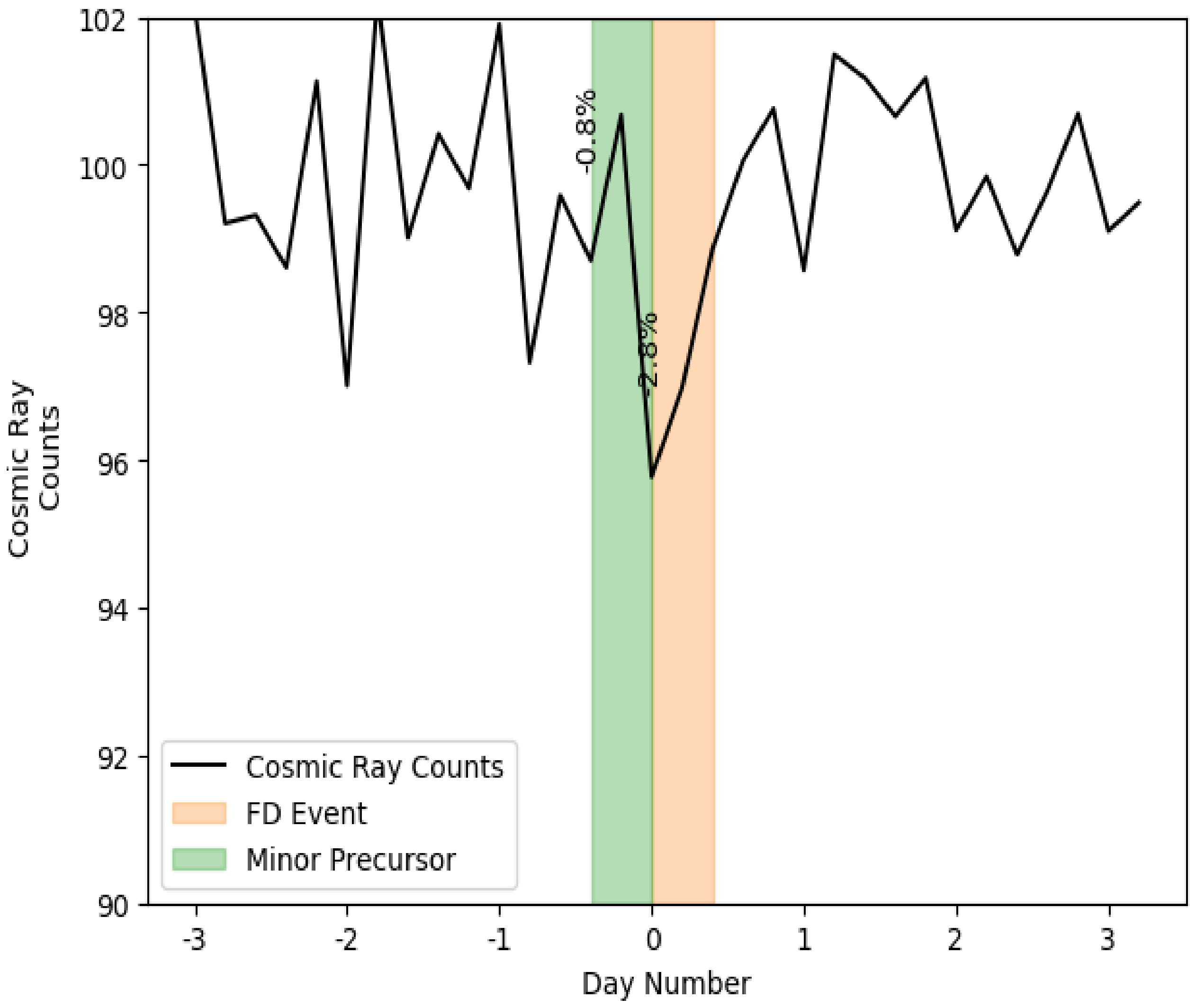
Overlayed epoch analysis of cosmic ray data aligned to ICME arrival times



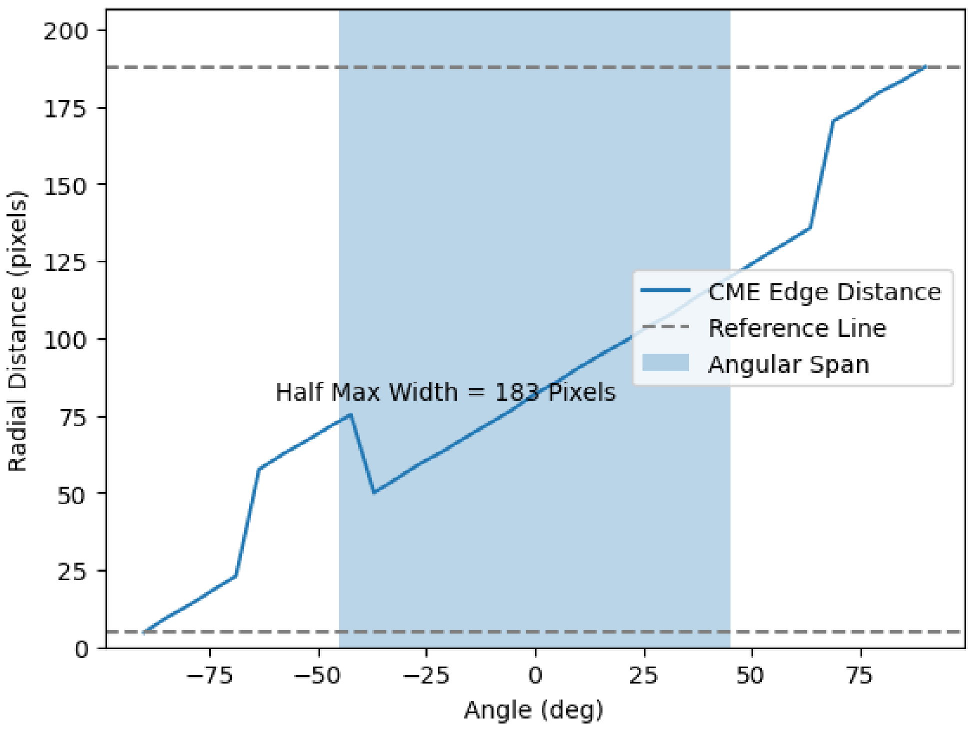
Trends in the Superposed Epoch Analysis

- ➢ Distinct, transient decrease in cosmic ray intensity preceding Forbush effect onset;

- ➢ which statistically supports scattering by an approaching coherent structure.



Evidence of CME and magnetosphere interaction



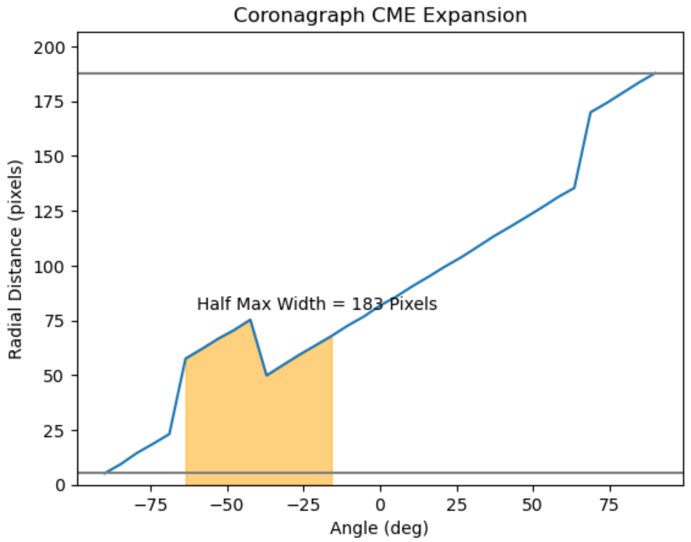
- **Superposed CME expansion images show its radial extent. At various azimuthal angles, the half-maximum intensity lead edge of the CME is traced, providing insight into the dynamic behavior during the selected FD.**

- **The narrow width of the CME during a Forbush Decrease event implies a more focused and localized interaction with the Earth's magnetosphere.**

- **While this may lead to a weaker Forbush Decrease modulation, it also results in a more modest increase in cosmic rays, with potential implications for space weather forecasting and the impact on satellite operations and communication systems.**

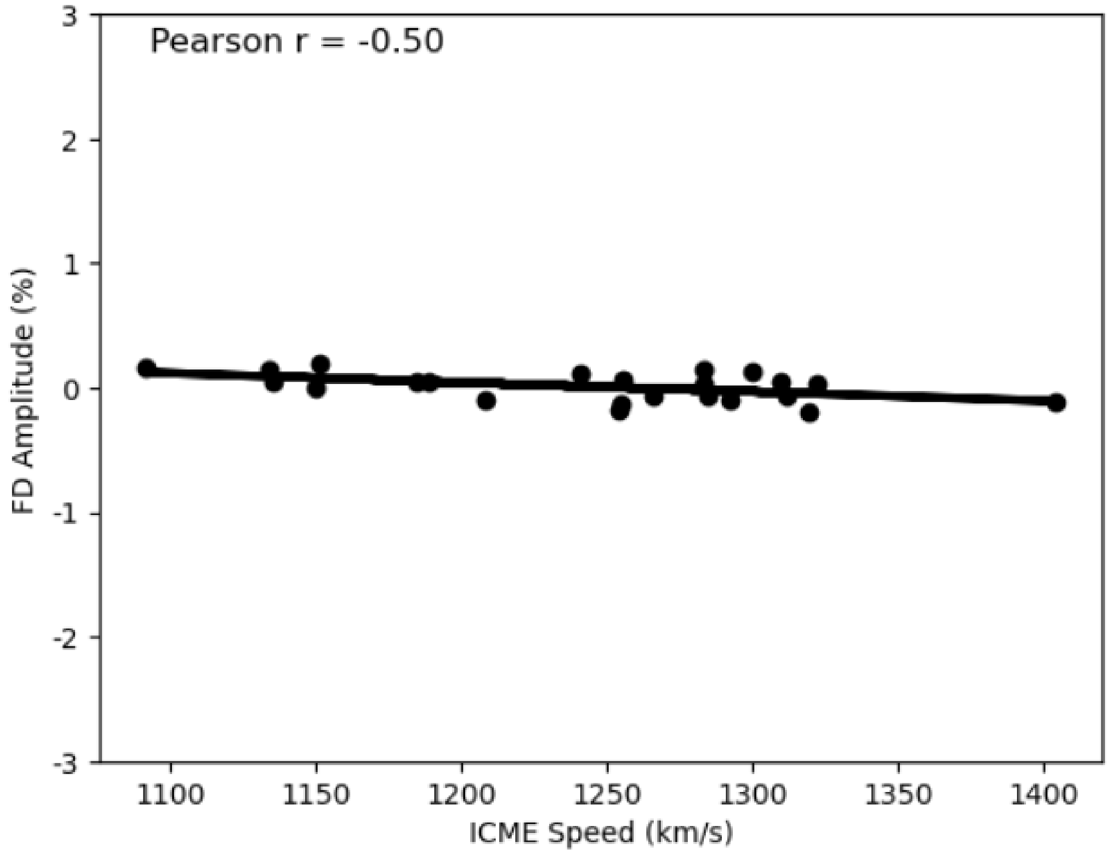
LASCO C2 is a coronagraph that observes the solar corona in the visible light wavelength range and is capable of capturing the dynamics of CMEs.

*we obtained CME radial distance (halfway between its minimum and maximum values.)



It measures less than 30 pixels wide, indicating a compact angular width. This is consistent with a relatively confined CME path to intersect Earth.

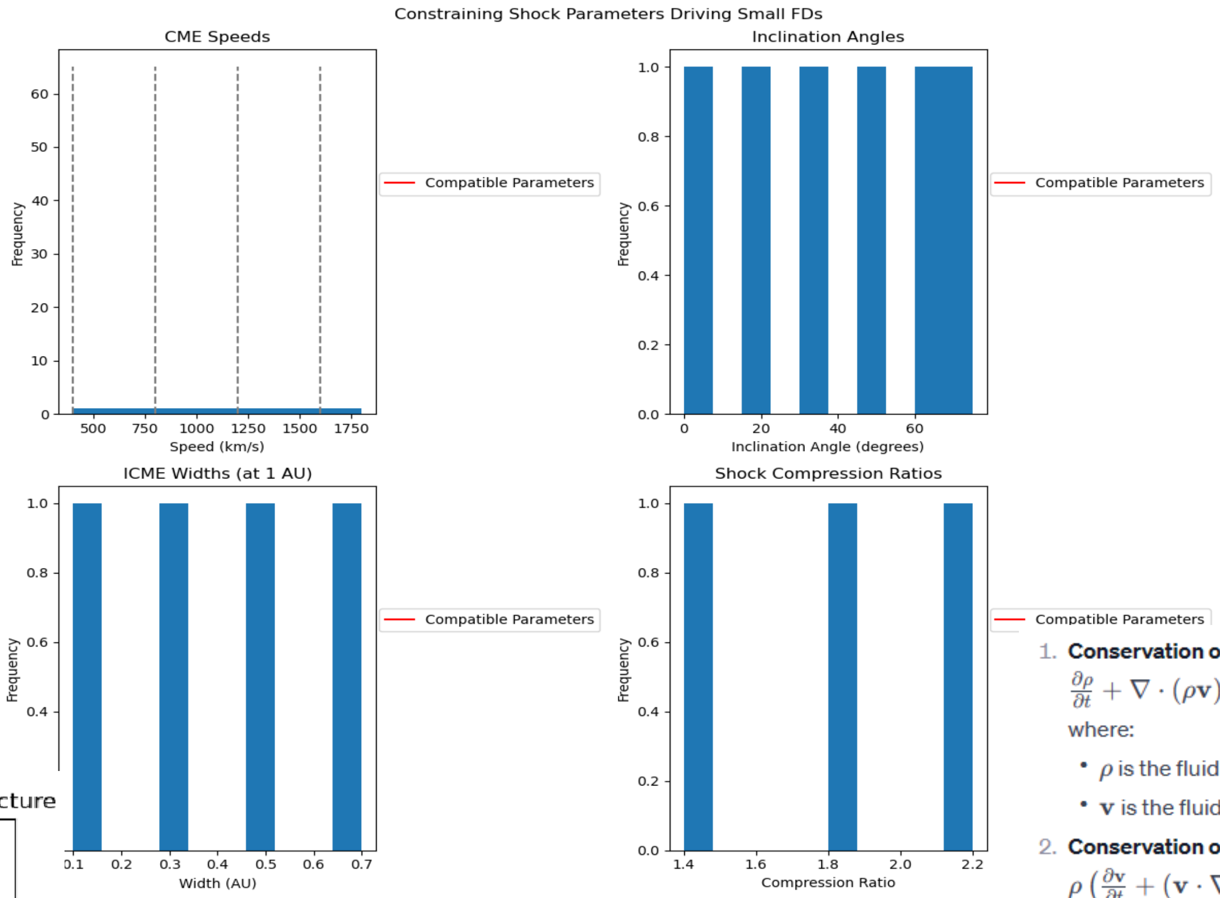
Speed & Amplitude Correlations



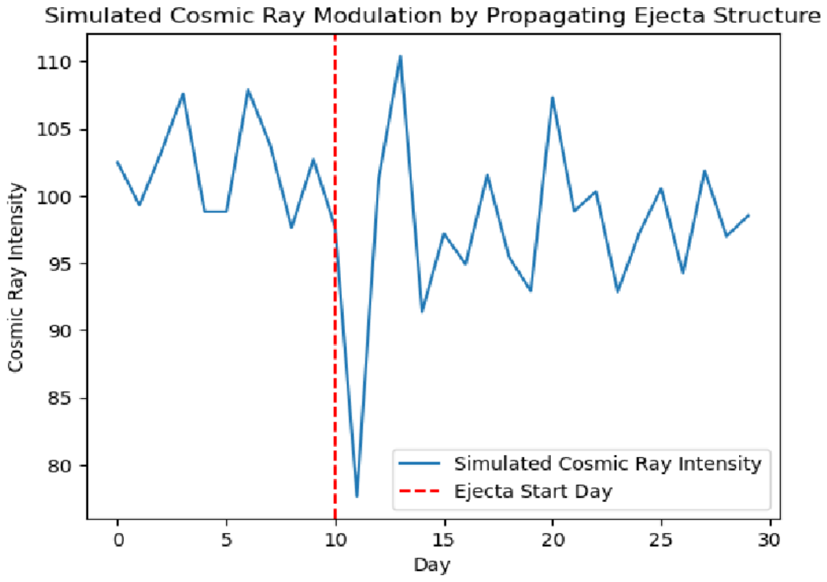
- **There is a correlation (non-random) relationship between the magnitude of the FDs and the launch velocity (ICME speed);**
- **which further confirms events are not spurious.**

Parameter Constraints

An advanced magnetohydrodynamic computational procedure is used to develop realistic shock morphologies for driving small cosmic ray reductions.



Shock parameter space constraints at 1 AU



Time series of cosmic ray modulation by propagating ejecta structure

WSA-ENLIL Solar Wind Prediction | NOAA / NWS Space Weather Prediction Center

1. **Conservation of Mass:**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

where:

- ρ is the fluid density.
- $\mathbf{v}$ is the fluid velocity.

2. **Conservation of Momentum:**

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} \right) = -\nabla p + \nabla \cdot \sigma + \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B}$$

where:

- p is the fluid pressure.
- σ is the stress tensor.
- μ_0 is the permeability of free space.
- $\mathbf{B}$ is the magnetic field.

3. **Conservation of Energy:**

$$\rho \left(\frac{\partial e}{\partial t} + (\mathbf{v} \cdot \nabla) e \right) = -p(\nabla \cdot \mathbf{v}) + \nabla \cdot (\sigma \cdot \mathbf{v}) + \frac{1}{\mu_0} \mathbf{B} \cdot (\nabla \times \mathbf{B})$$

where:

- e is the specific internal energy.

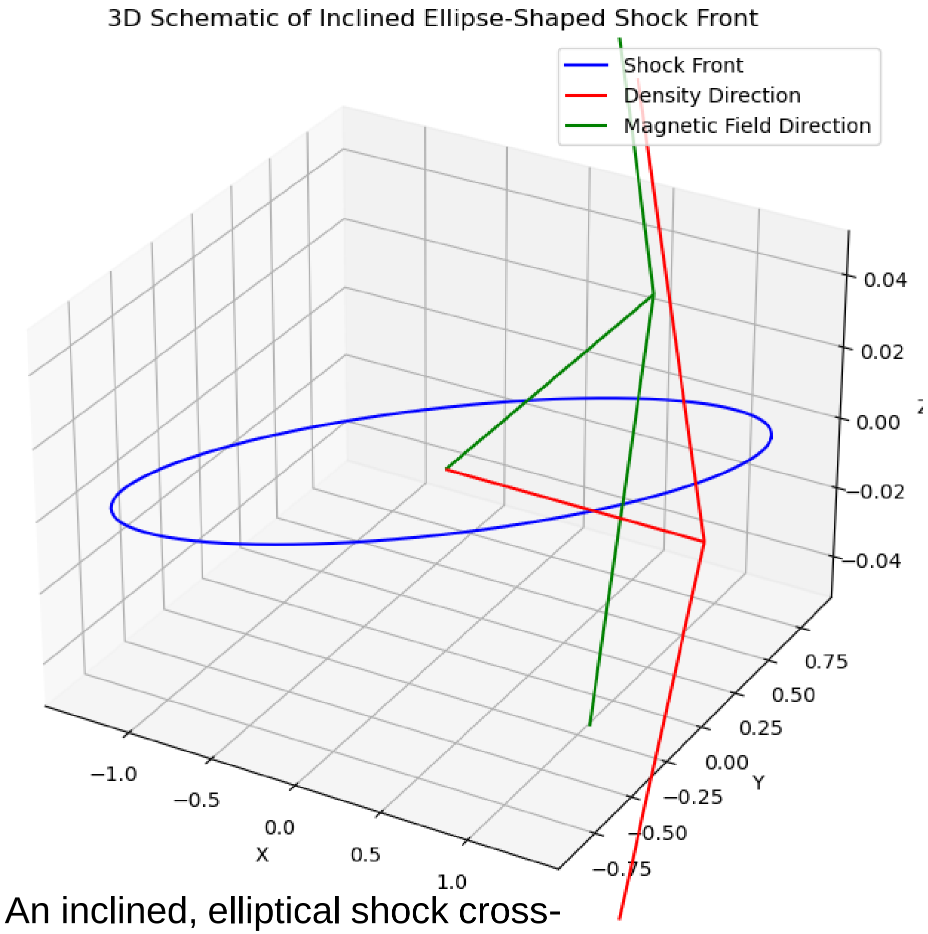
4. **Magnetic Induction Equation:**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

where:

- η is the magnetic diffusivity.

Model scenario for shock geometry and density jump consistent with minor FD properties



An inclined, elliptical shock cross-section approaching Earth

Despite a limited angular mass surface area, the compressed plasma and electromagnetic perturbations achieve moderate magnetosonic amplification factors.

The experimental measurements of density compression waves and turbulent magnetic deflections modulated cosmic rays implicitly restrict the transient barrier intensity, orientation, and spatial locality needed to shed only a small fraction of the intensity

Next focus: Dealing with current limitations

Looking at:

Location-dependent diurnal anisotropy of cosmic rays and small-amplitude FDs: An empirical analysis

Specific aim/objective:

To develop catalogs of small-amplitude FDs from all the functional neuron monitors across different locations using extremely sensitive automatic functional harmonic analysis.

Step 1: filtering techniques and location algorithms

$CR = \{(CR - CR_k) / CR_k)\} * 100\%$

*for any chosen period, CR_k will represent the mean value of CR data

Step 2: Harmonic analysis

Extremely sensitive to plasma density, pressure and /or temperature

Step 3: Diurnal waves and Fourier transforms

Good for BSc/MSc student project in:

-Physics
-Applied Mathematics
-Computer science

Summary

• Small-amplitude Forbush decreases (FDs), cosmic ray intensity drops of ≲3% over ~1 day, are definitively linked to the arrival of Earth-directed coronal mass ejections (CMEs).

• Timing and efficiency signatures reveal the FDs probably originate from transient shock passages at CME ejecta fronts, specifically in the sheath regions.

• Weak scattering zones are inferred to have elliptical cross-sections preferentially oriented edge-on to Earth based on the short duration and low density compression factors (<2) of the FDs.

• Even moderately fast CMEs are capable of reducing cosmic rays, representing an overlooked category of minor interplanetary perturbations by common solar eruptions.

• Connecting properties of these subtle FDs to remote CME structure and kinematics elucidates inner heliospheric shock physics below major FD thresholds.

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