Remote Sensing of Plasma Conditions in the Heliosphere Using Neutron Monitor Measurements of Cosmic Rays

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Introduction

- Neutron monitors (NMs) are ground-based detectors of primary cosmic ray ions via their showers in Earth's atmosphere. They are sensitive to particles that exceed an atmospheric cutoff energy (~1 GeV), for their showers to be detectable, and a local geomagnetic cutoff rigidity (varying from near zero in polar regions to ~17 GV in parts of Southeast Asia).
- Detecting atmospheric showers provides a much larger effective area than is available for space instruments, allowing high-precision cosmic ray measurements from a stable platform for nearly continuous, long-term data.
- As charged particles, cosmic ray ions can be deflected by magnetic fields and scattered by magnetic fluctuations in the solar wind. The ions detected at a given time and location have collectively traveled or diffused across large volumes of the heliosphere.
- Plasma conditions in the heliosphere vary strongly with time: with the ~11-year sunspot cycle, ~22-yearsolar magnetic cycle, 27-day solar rotation, and solar storms, including coronal mass ejections (CMEs) and the shocks they drive before them. All of these are reflected in time variations of the cosmic ray flux, spectrum, and anisotropy.
- We briefly describe four specific examples of how neutron monitor observations provide unique remote sensing of plasma conditions and processes elsewhere in the heliosphere.

Fitting Solar Energetic Particle Profiles

- A neutron monitor always detects Galactic cosmic rays (GCRs) above its cutoff rigidity (energy).
- In addition, during each sunspot cycle there are some solar storm events that accelerate ions to relativistic energies at a flux detected above the GCR background for hours or days, which are termed ground level enhancements (GLEs).
- By precision modeling of the interplanetary transport of relativistic solar particles, we have inferred special magnetic configurations in interplanetary space, such as magnetic bottlenecks [1] and magnetic loops [2].
- We have also determined the scattering mean free path of relativistic ions, which can validate models of magnetic turbulence between the Sun and the Earth.

Figure 1(a): A steady solar wind should generate a Parker spiral magnetic field configuration. Figure 1(b): For the GLE of 2000 July 14, we infer from NM observations that a bottleneck configuration affected solar particle transport. Figure 1(c) & Figure 2: The best fit to NM data on 1989 Oct 22 implies transport of energetic particles along both legs of a closed interplanetary magnetic loop.

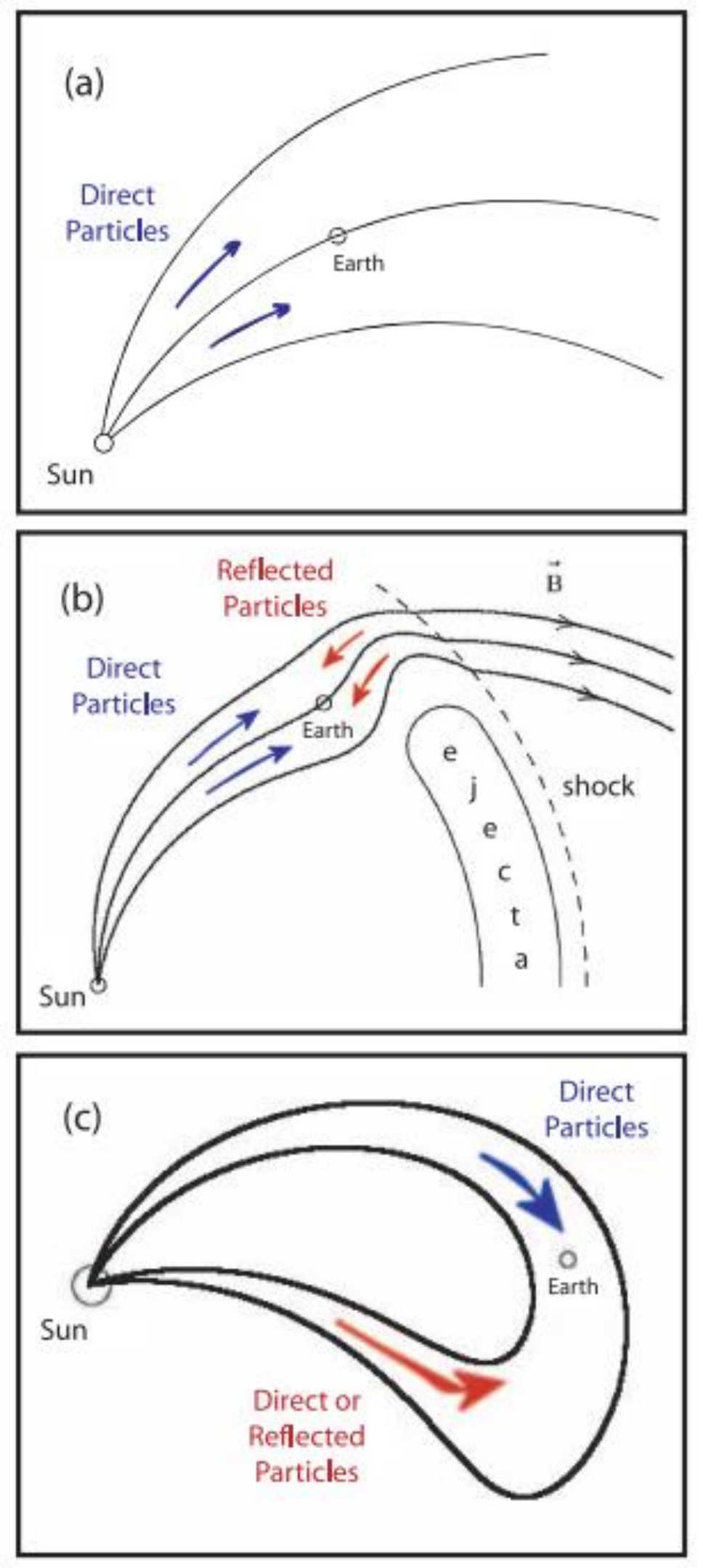


Figure 1

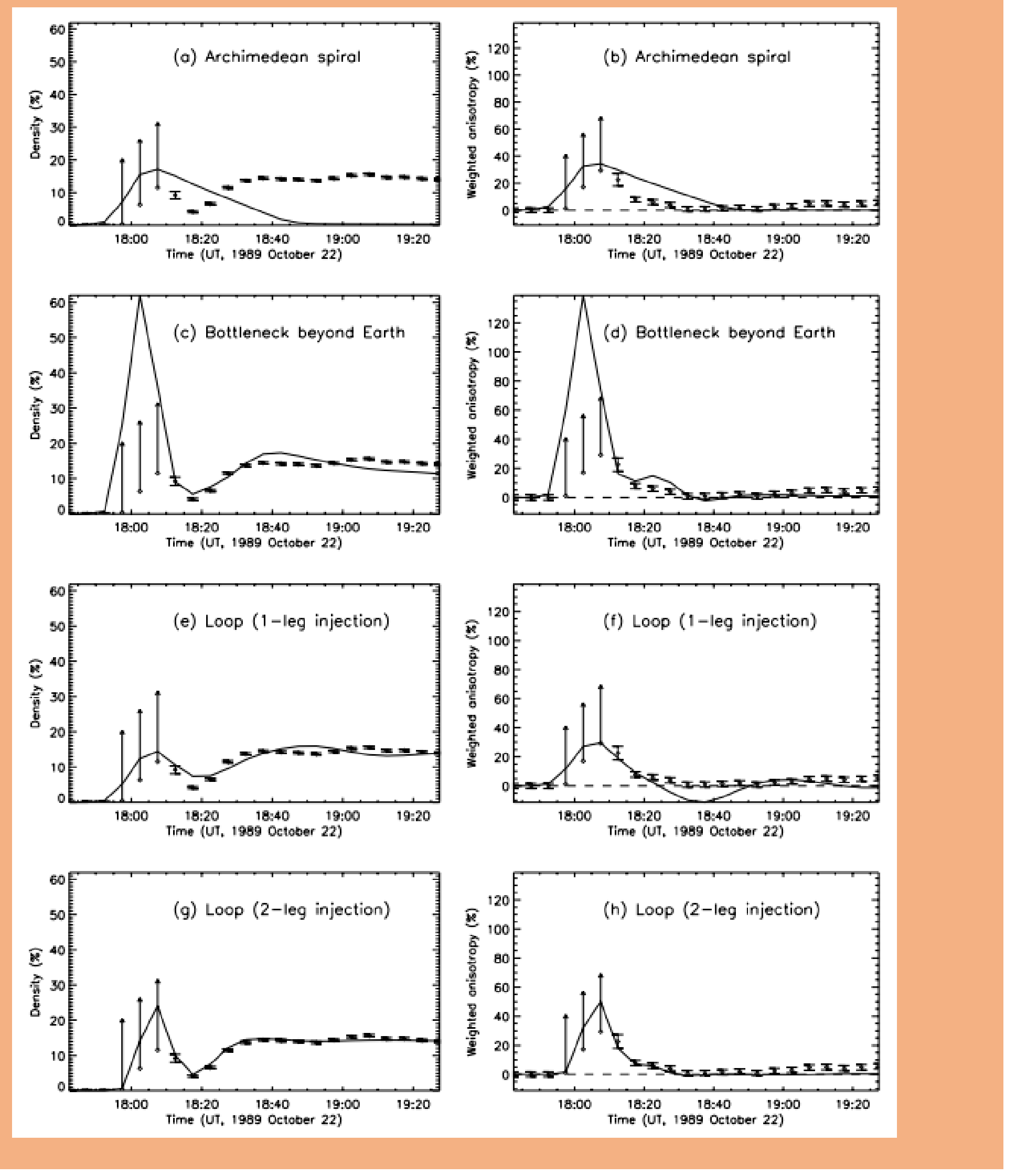
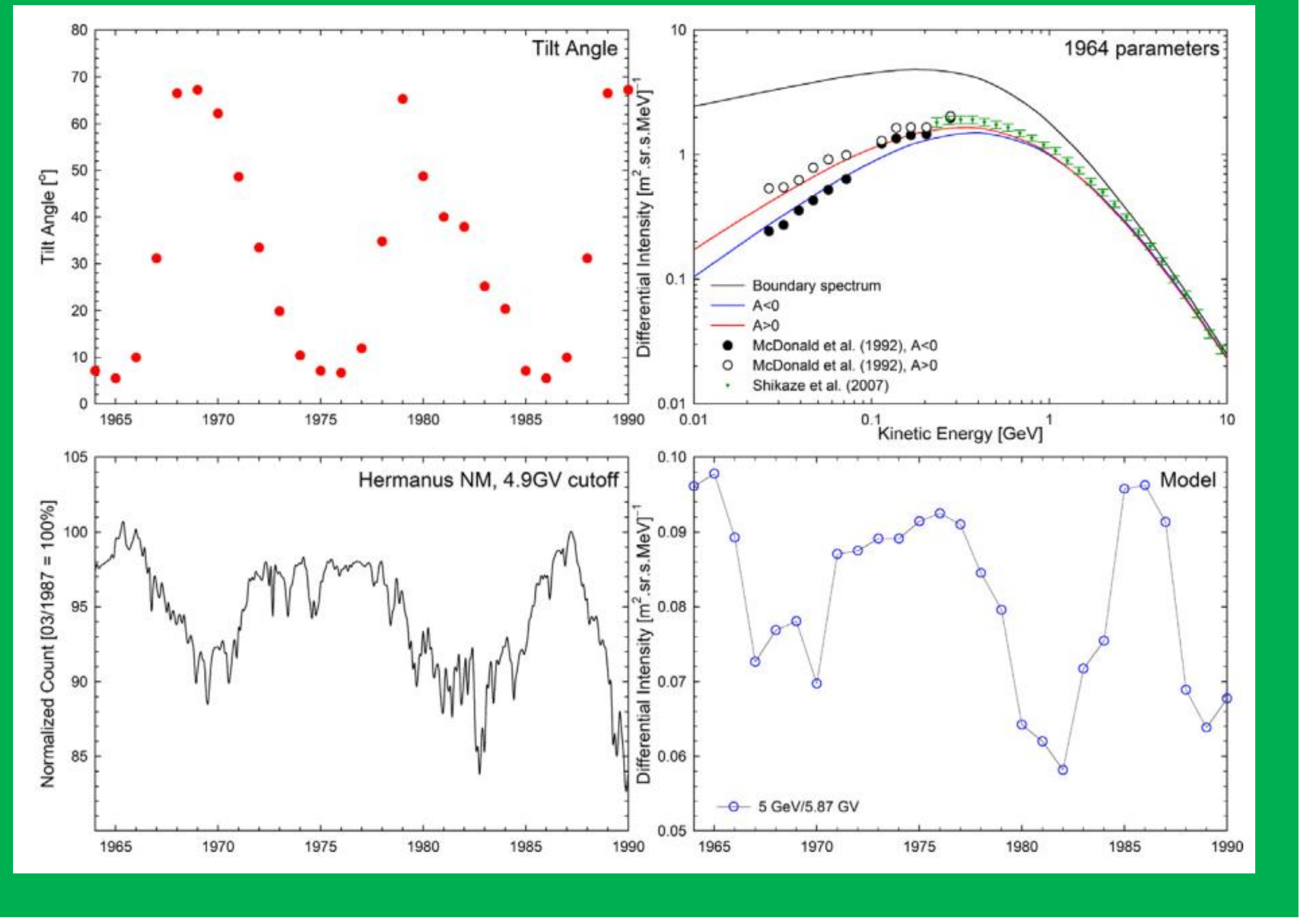


Figure 2

Solar Modulation of Galactic Cosmic Rays

- GCRs undergo significant flux variations over the sunspot cycle, a phenomenon known as solar modulation.
- A polar neutron monitor may observe a flux variation of ~15%.
- Data have been collected from numerous NMs for several solar cycles [3].
- In parallel, there have been great advances in 1) models of solar wind turbulence and its transport through the heliosphere, as informed by spacecraft measurements along certain trajectories (mostly near the Ecliptic plane), and 2) theories of cosmic ray transport [4]. While many challenges remain, NMs provide important constraints on modeling of solar wind turbulence and transport theories.

Figure 3: In this example, data from the Hermanus NM help indicate which plasma parameters are more responsible for solar modulation [5], which has practical implications for the cosmic radiation environment during long-distance manned space missions. The interplanetary magnetic field is often anti-correlated with cosmic ray intensity, but not during Solar Cycle 20 (1964-1976). Physics-based modeling can explain the apparent discrepancy, confirming that other parameters such as the heliospheric current sheet tilt angle play a major role.



Anisotropy during Forbush Decreases in Galactic Cosmic Rays

- As a shock and/or CME pass Earth, neutron monitors may see a so-called Forbush decrease in the GCR flux.
- While Earth is inside the magnetic flux rope of a CME, plasma turbulence can be weak and relativistic particles may have a mean free path of ~1 AU [2,6]. Therefore, the GCR anisotropy inside a flux rope can provide direct information about distant plasma processes.
- There was a prediction that cosmic rays drift into a CME flux rope along one leg and out the other, which should generate a unidirectional anisotropy [7]. Such anisotropy was observed from NM data [8], providing remote evidence for this process.

Figure 4: Because a CME flux rope's width increases with distance from the Sun, the flux rope is not cylindrical and particles drift inward along one leg and outward along the other [7].
Figure 5: This picture is confirmed by NM observations that measured the dipole anisotropy of GCRs perpendicular and parallel to the magnetic field during the passage of a CME flux rope [8].

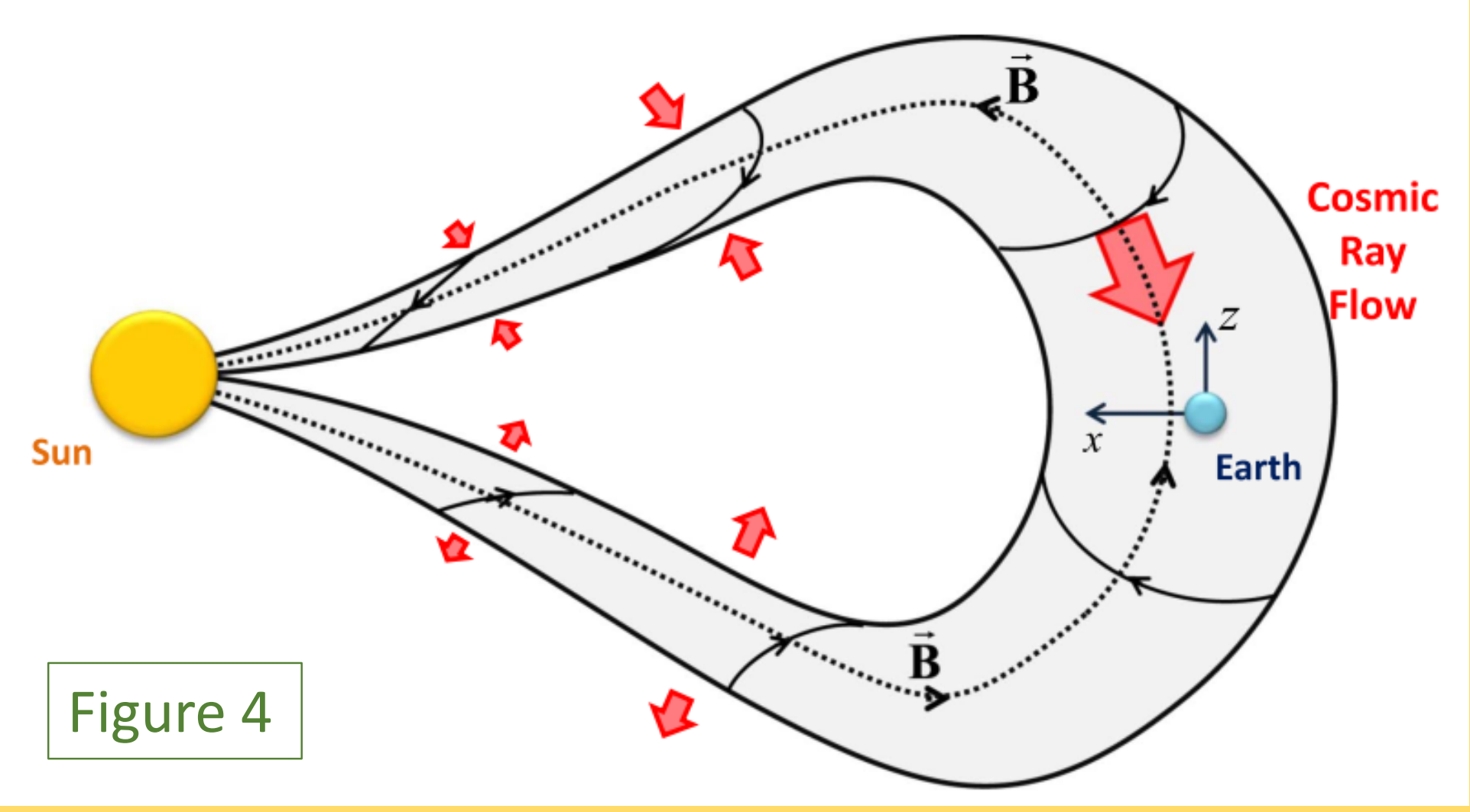


Figure 4

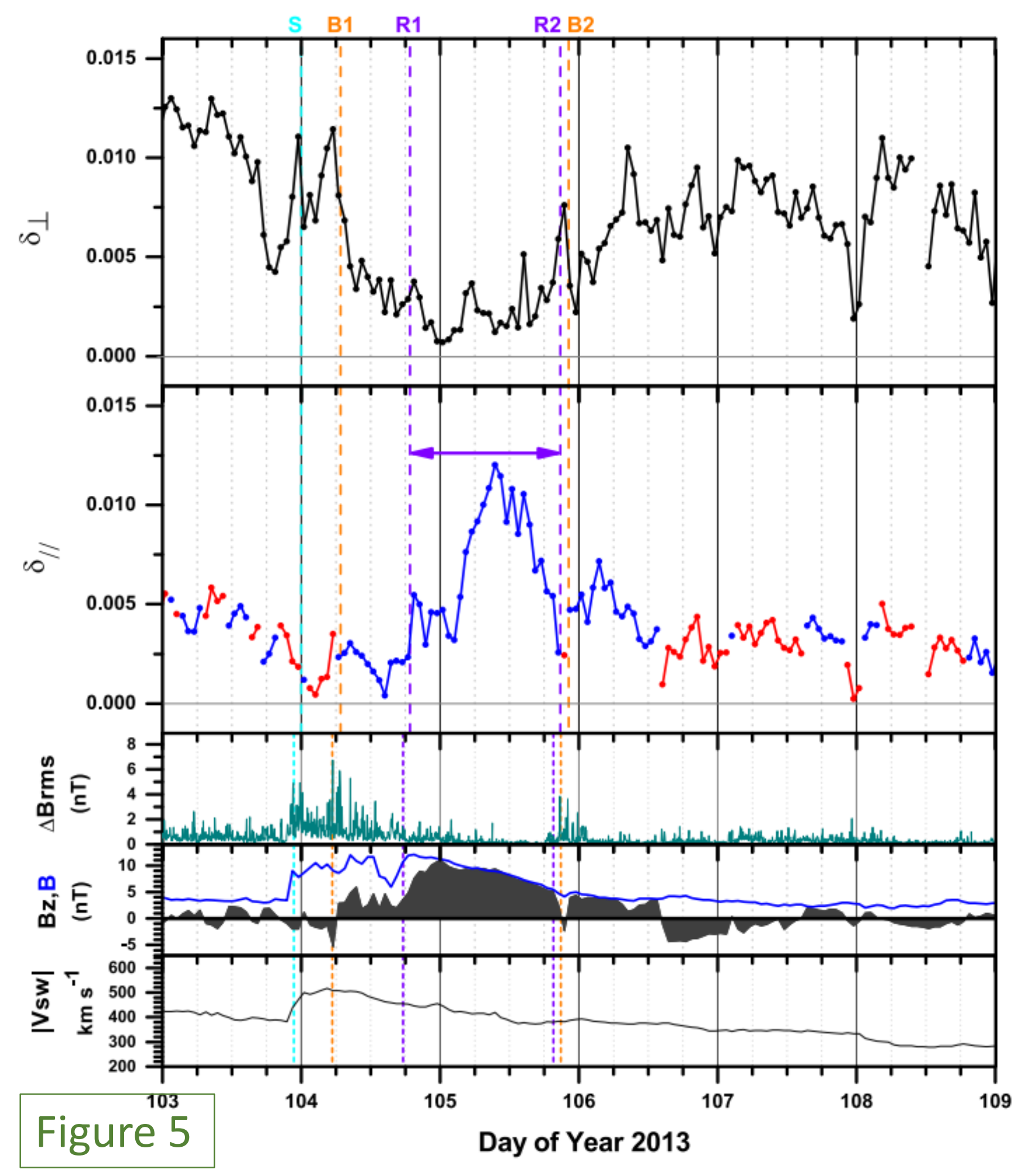


Figure 5

Two-Week Modulation Events

- In contrast with a Forbush decrease in the GCR flux at the time of a shock and/or CME, with a rapid onset and slower recovery over a few days, recent work has noted two time periods in 2012 with a slow decrease in the GCR flux and similarly slow recovery, over a total of two weeks, along with a remarkably strong anisotropy [9].
- This can be explained as the non-local effect of a shock or sequence of shocks that already passed the Earth as they block GCR access for this extended period of time.
- The anisotropy indicates diffusive inflow of cosmic rays perpendicular to the large-scale magnetic field, with a mean free path similar to that estimated from an existing theory of perpendicular diffusion [10].

Figure 6: Data from the Princess Sirindhorn Neutron Monitor (PSNM) at Doi Inthanon, Thailand, with the world's highest cutoff rigidity (~17 GV), in comparison with solar wind parameters. For cosmic ray protons, this corresponds to a threshold energy of ~16 GeV. At high cutoff (threshold), cosmic ray anisotropy is relatively more prominent. (a-b) Vector anisotropy (flow) in GSE coordinates, inferred from the daily cosmic ray flux variation, in which Earth's rotation carries the NM look directions across the sky. (c) Phase and (d) magnitude of diurnal anisotropy. (e) NM count rate, indicating the cosmic ray flux. (f-h) Solar wind magnetic fluctuation, magnitude, and speed from the *Wind* spacecraft.

Yellow shading indicates two 2-week modulation events, in contrast with the five Forbush decreases (gray shading). The 2-week modulation events have a much longer duration of flux decrease and very strong diurnal anisotropy, including the strongest of the entire solar cycle.

Figure 7: The flow of GCRs along the −y direction due to diffusion perpendicular to the magnetic field as CME-driven interplanetary shocks beyond the Earth inhibit the GCR access via parallel transport.

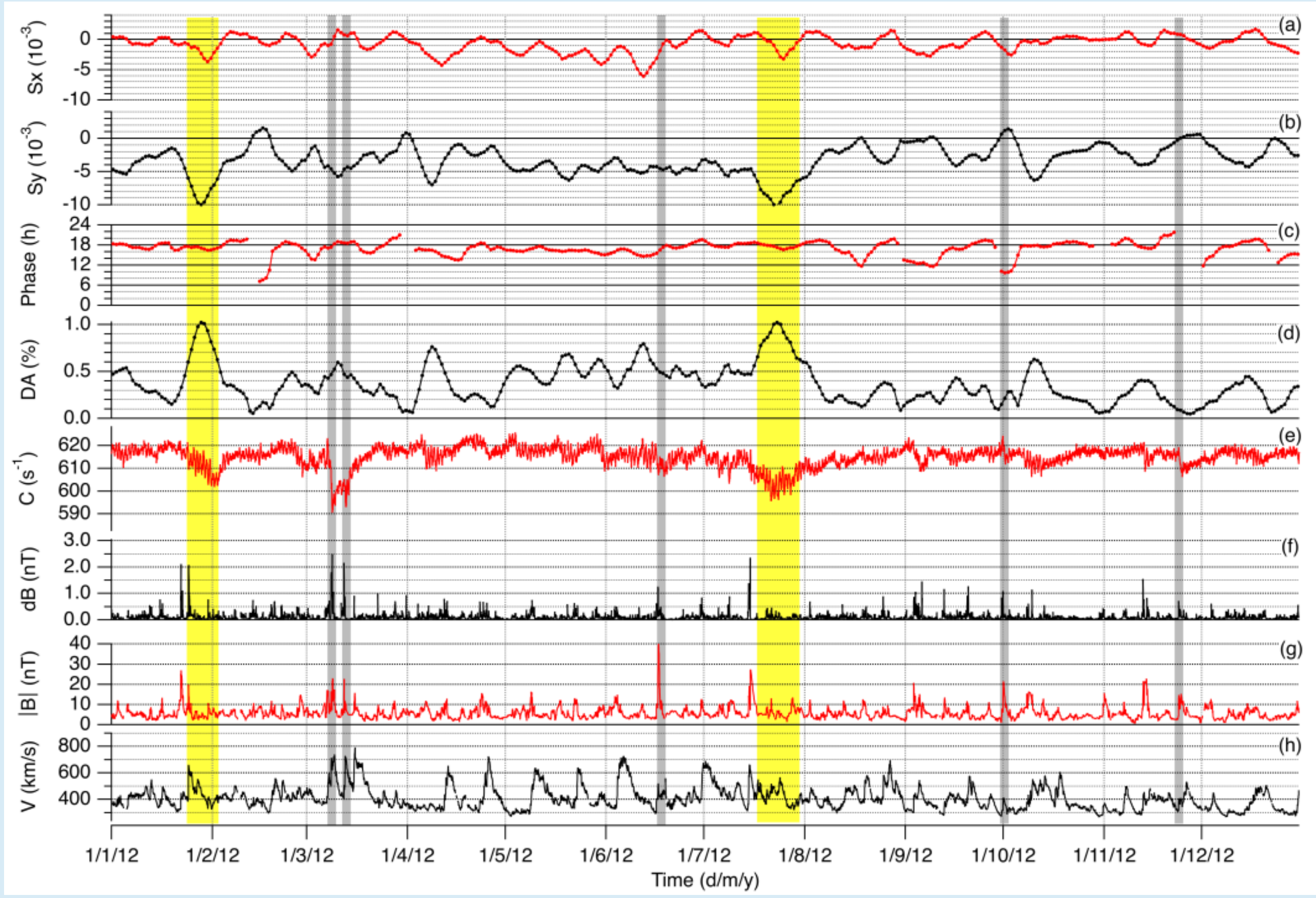


Figure 6

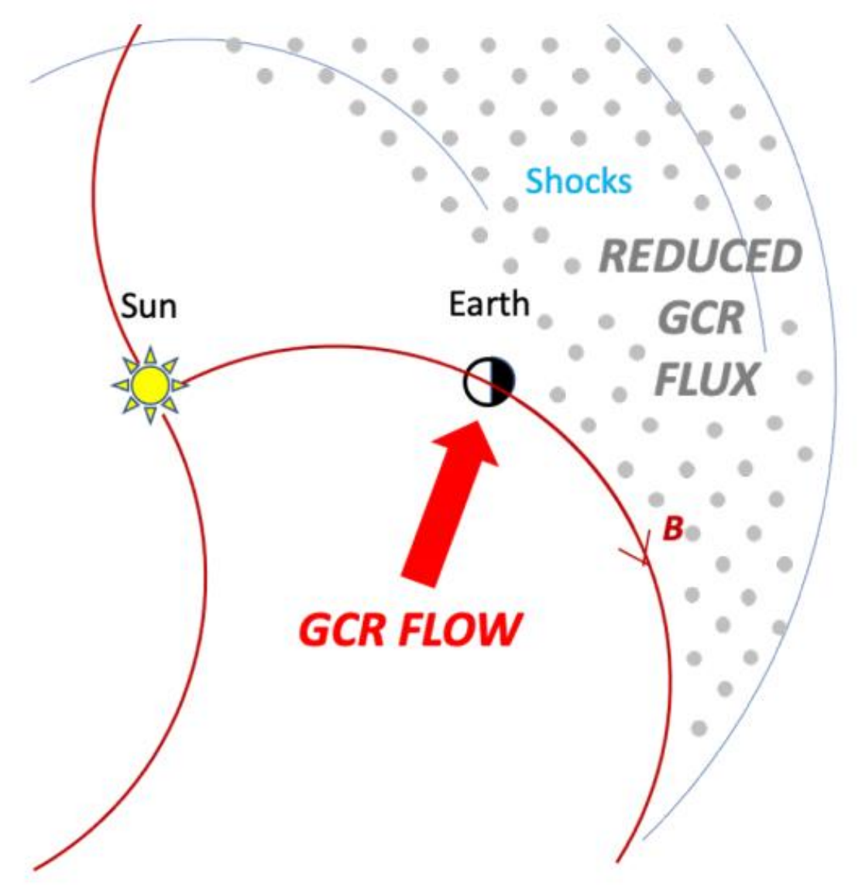


Figure 7

Acknowledgments

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