Spatially dependent turbulence and particle diffusion in an interplanetary magnetic flux rope

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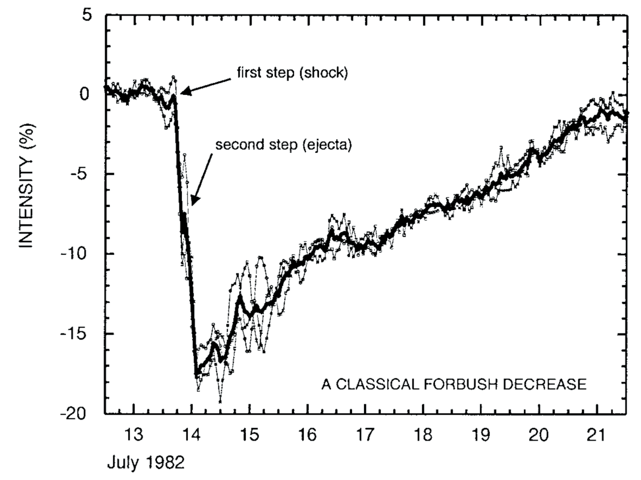
1.Introduction

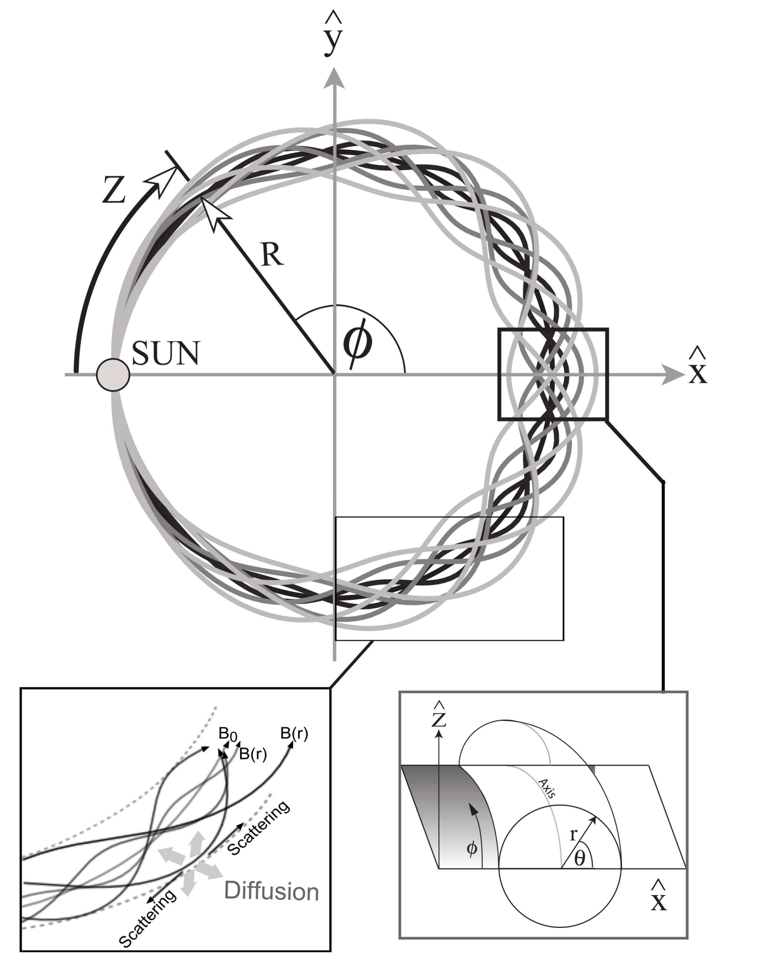
- Interplanetary Coronal Mass Ejections (ICMEs) are large-scale plasma bubbles and magnetic field structures expelled from the Sun into space.
- Some ICMEs have large and smooth rotation of magnetic field lines, implying an "interplanetary magnetic flux rope (IMFR)."
- When an IMFR sweeps past Earth, it deflects away some Galactic Cosmic Rays (GCRs) that would otherwise strike our planet from all directions, then the GCRs have a lower density inside the IMFR and the ground-based detectors experience the sudden drops in the signal called "Forbush Decreases (FDs).
- We consider how GCRs fill the flux rope until the signal comes close to its ambient level.

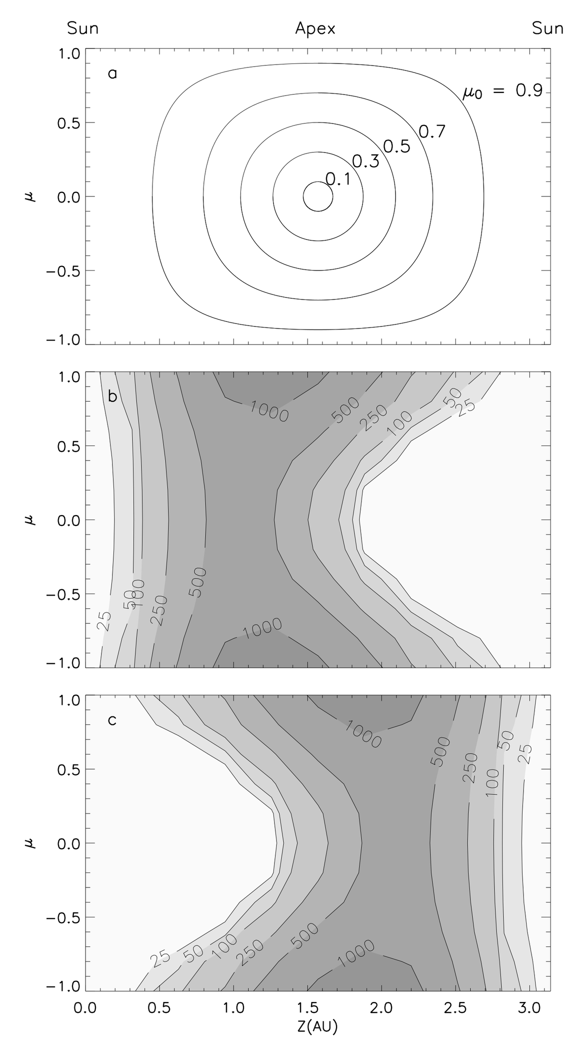


[*left*] Figure 1: Forbush Decrease and recovery to ambient intensity in July 1982 detected by Deep River, Mt.Wellington, and Kerguelen neutron monitors (from Cane [1]).

2.Systematic physical processes of GCR transport

- Parallel to the mean magnetic field: streaming and focusing, conserving the first adiabatic invariant.
- Perpendicular to the mean magnetic field: gradient drift (v_g) and curvature drift (v_c).
- The equation of the motion of the guiding center is $d\mathbf{r}/dt = \mu v\hat{\mathbf{b}} + \mathbf{v}_g + \mathbf{v}_c$ where the pitch angle cosine is $\mu = \mathbf{p}\cdot\mathbf{B}/|\mathbf{p}||\mathbf{B}|$ and $\mathbf{p}$ is the particle's momentum.
- An analytic IMFR model developed by [2] in quasi-toroidal coordinates (r,ϕ,θ) relative to a circle of radius R, which is the axis of flux rope. A flux surface is defined by $r = a\cos(\phi/2)$, where a is the radius of the flux surface at the apex of the rope ($\phi = 0$) (see Fig. 2).
- Examples of some trapped-particle trajectories (Fig. 3a) in terms of μ, and the distance from the Sun along the loop $Z = R(\pi-\phi)$, for varying initial μ_0 at the apex. These trajectories exhibit magnetic mirroring.
- The drift velocity across the flux rope surface, $v_n = (v_g + v_c)\hat{n}$, where $\hat{n}$ is the outward normal to the surface, yields an inflow rate (Fig.3b) and outflow rate (Fig.3c) averaged over the flux rope surface (averaged over θ) as a function of μ and Z. The drifts across the flux rope boundary are predominantly inward along one leg of the loop and predominantly outward along the other.
- During a Forbush decrease, this should contribute a unidirectional anisotropy and net flow of GCRs. The flow direction is determined by the poloidal field direction [2].





[*left*] Figure 2: Global, analytic magnetic flux rope model [2].
[*right*] Figure 3: (a) Particle trajectories in terms of μ, and Z (b) Inflow rate and (c) outflow rate averaged over the surface of the flux rope(averaged over θ) as a function of μ and Z in units of AU km s^{-1}.

3.Stochastic processes and spatial dependence of turbulence

- Magnetic turbulence described by the 2D+Slab model of [3]: $\mathbf{B} = B_m\hat{z} + \mathbf{b}(x,y,z) = B_m\hat{z} + \mathbf{b}_{2D}(x,y) + \mathbf{b}_{SL}(z)$, where $B_m\hat{z}$ is the mean magnetic field, and $\mathbf{b}_{2D}(x,y)$ and $\mathbf{b}_{SL}(z)$ are transverse fluctuation fields.
- Field Line Random Walk (FLRW): Particles diffuse because they undergo no parallel scattering and are tied to a field line, which undergoes a random walk.
- The Non-Linear Guiding Center (NLGC)theory is based on the FLRW, parallel diffusion along the mean field, and diffusion of guiding center [4,5].
- Pitch angle scattering: particles scattered by parallel force $\mathbf{F}_{\parallel} = q\mathbf{v}_{\perp}\times\mathbf{b}$, which randomly changes the pitch angle.
- Assumption: flux rope originally had uniform turbulence, but during expansion and stretching of the ICME, at relative speeds faster than the Alfvén speed, turbulence properties became non-uniform.
- Assumption: 2D correlation length l_{2D}, expands as a perpendicular length scale proportional to the flux rope radius: $l_{2D} = l_{2D,Apex}\cos(\phi/2)$.
- Assumption: Slab correlation length, l_{SL}, is stretched along with the loop like the field line winding: $l_{SL} = l_{SL,Apex}/\cos(\phi/2)$.
- Assumption: Spatial dependence of turbulent energy density b^2 is related to local expansion/stretching of the volume, giving $\mathbf{b} = \mathbf{b}_{Apex}/\sqrt{\cos(\phi/2)}$.

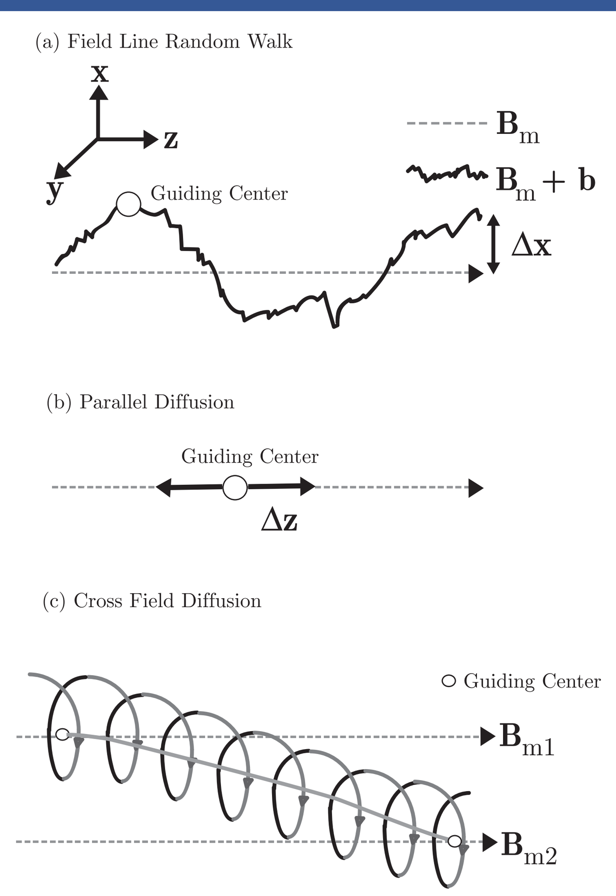
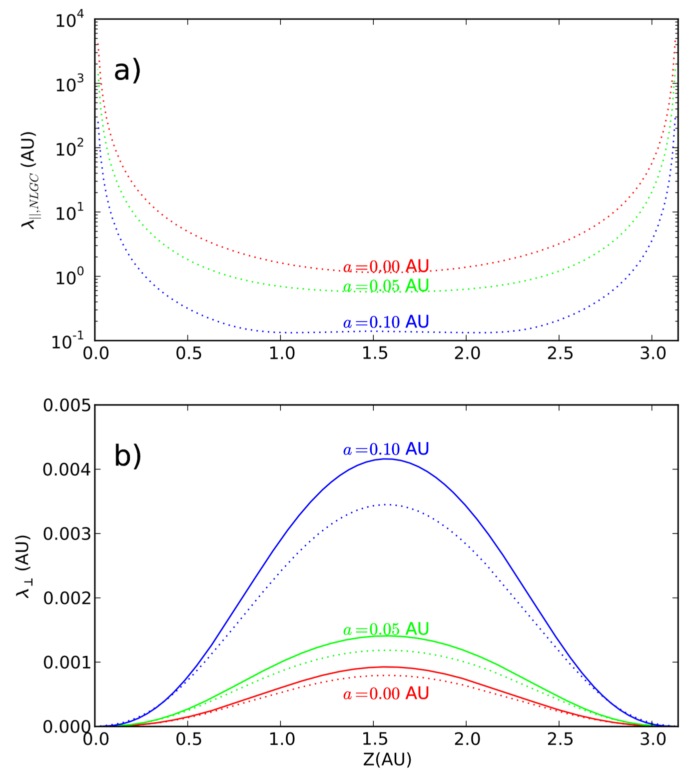
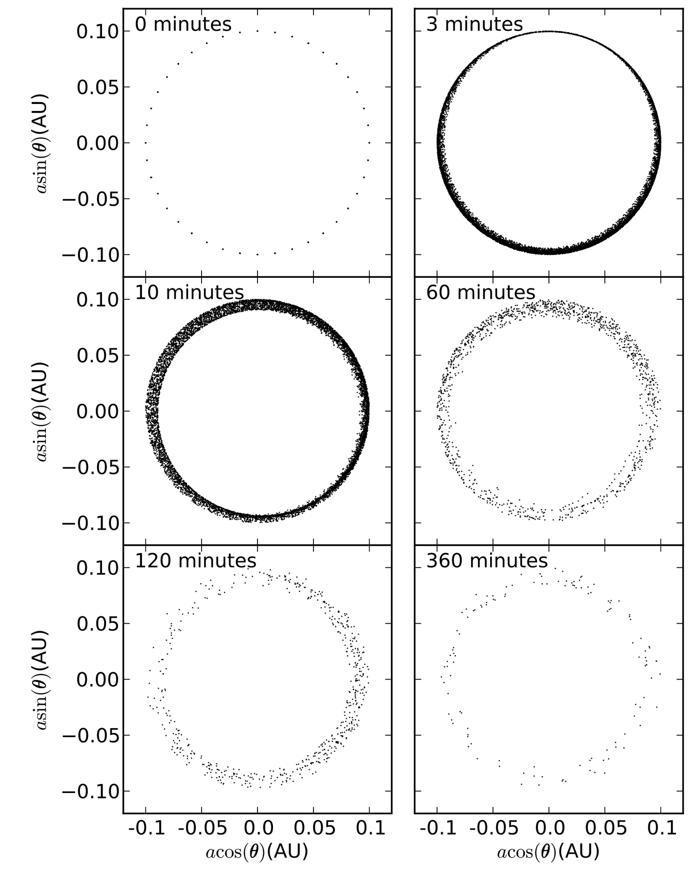


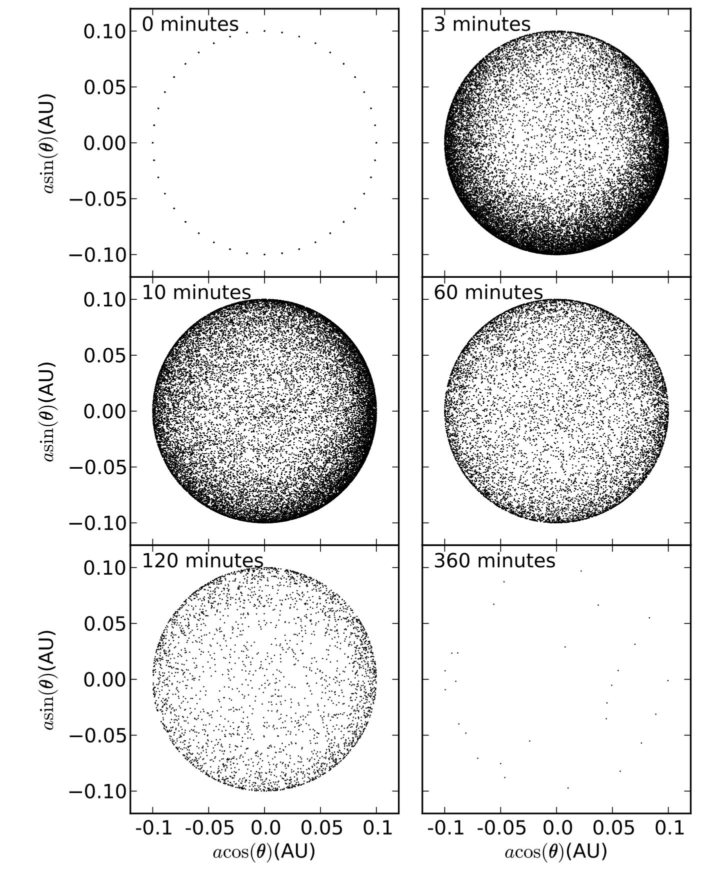
Figure 4: The basis of NLGC theory.

4.Results

- We use an energy ratio $E_{SL}/E_{2D} = 10.0/90.0$, $\langle b_{SL}^2\rangle/\langle b_{2D}^2\rangle = 0.18$, $b^2/B_m^2 = 0.05$, $l_{2D,Apex} = 0.006$ AU, and $l_{SL,Apex} = 0.003$ AU.
- The particles' perpendicular mean free path and diffusion coefficients calculated from the NLGC theory compared with the results from the FLRW theory are shown in Fig.5.
- We simulate GCR motion by initially placing the guiding centers of protons of 1 GeV kinetic energy at flux rope surface. Then we trace the trajectories due to systematic and stochastic processes. as mentioned before. The results are shown in Figs. 6 and 7 by plotting the positions of particle guiding centers in a cross-section of the flux rope ($a-\theta$ space), integrating over the entire rope (integrate over ϕ) as a function of time.







[*left*] Figure 5: (a) Comparison of parallel diffusion mean free path calculated from quasilinear theory at various flux surfaces $a = 0.0$, 0.05, and 0.10 AU. (b) Perpendicular mean free paths calculated from FLRW (solid lines) and NLGC theory (dashed lines). Because the difference is not great, and FLRW is much faster to compute, we employ this theory in the simulations.

[*center*] Figure 6: The position of guiding centers in integrated cross-section of flux rope at various times from a simulation with systematic processes only (streaming, focusing, and drifts).

[*right*] Figure 7: Same as Fig.6 but adding stochastic processes to the simulation.

5.Conclusions

- The drifts alone cannot transport the GCRs into the inner portion of the rope.
- The drifts alone do not are not sufficient to fill the flux rope with GCRs to come close to an ambient level over a time scale of several hours.
- In a weak turbulence environment such as that inside a magnetic cloud, the particles' perpendicular mean free path and perpendicular diffusion coefficient can be similar for FLRW & NLGC theories (see also [5]).
- The perpendicular mean free path at the center of the IMFR is short, and becomes longer away from the flux rope axis.
- The parallel mean free path is very long in the loop leg regions, and then shorter at the flux rope's apex.
- The perpendicular mean free path is short at the loop leg regions, and then longer at the flux rope's apex.
- When adding stochastic processes such as perpendicular diffusion and pitch angle scattering, the particle is able to travel into the center region of an IMFR.

6.References

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