Precursors to Forbush Decreases and Space Weather Prediction

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Abstract

Recent improvements in data analysis, as well as the first numerical solutions of a pitch-angle transport equation for mildly relativistic charged particles crossing an oblique shock, permit important information to be extracted from precursors to Forbush decreases as observed by the worldwide neutron monitor network. We provide detailed calculations of the expected pitch angle distribution of such particles near the shock, including the enhanced diurnal anisotropy and loss cone effects. We compare the observed and calculated intensity and anisotropy of galactic cosmic rays before the onset of interplanetary shocks, including the anisotropy components parallel and perpendicular to the interplanetary magnetic field. Prospects for short-term prediction of space weather effects will be discussed.

1 Observations:

Coronal mass ejections (CMEs) and CME shocks are typically accompanied by strong enhancements of the cosmic ray anisotropy (Lockwood 1971; Duggal & Pomerantz 1976). Such anisotropies represent a key mechanism by which information about the presence of a disturbance can be transmitted to remote locations, including upstream of the shock. Because cosmic rays are fast and have large scattering mean free paths ($\sim$ 1 AU) in the solar wind, this information travels rapidly and may prove useful for space weather forecasting.

Precursor anisotropies — those present in the upstream region — can result from kinetic interactions of cosmic rays with the approaching shock (Belov et al. 1995; Bieber & Evenson 1998). Precursor decreases may result from a "loss cone" effect, in which the observing station is magnetically connected to the cosmic ray depleted region behind the shock. Precursor increases may result from particles that have received a small energy boost by reflecting from the approaching shock (Dorman et al. 1995).

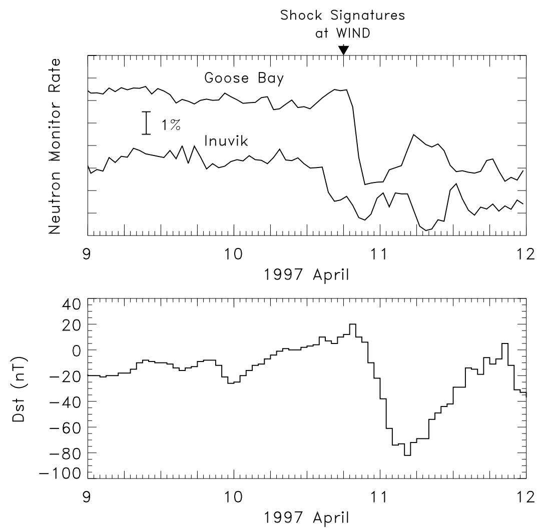

Figure 1: Cosmic ray precursors of the April 1997 CME were quite different at our two Canadian neutron monitor stations. Goose Bay observed a precursor increase from possible shock–reflected particles, while Inuvik observed a possible loss cone effect leading directly into the main part of the Forbush decrease.

A possible example of such kinetic effects appears in Figure 1, which displays neutron monitor observations from Inuvik and Goose Bay, Canada, around the time of an April 1997 CME which produced geomagnetic activity with a peak Kp value of 7- and a Dst variation of 100 nT. Goose Bay observed a precursor increase beginning 5 h before shocked material was detected by the WIND spacecraft (source: ISTP Website), which is consistent with detection of particles reflected from the approaching shock. Inuvik decreased sharply 3 h before the shock, a possible example of a loss cone leading directly into the main phase of the decrease. From a trajectory code, we find that at 15:30 UT both stations were viewing towards the Sun, but Inuvik had a better magnetic connection. Although firm conclusions must await detailed modeling, this geometric configuration seems consistent with the interpretation that Goose Bay was observing reflected particles, while Inuvik was observing penetrating particles from behind the shock.

Another proposed mechanism for precursor anisotropy is disruption of the steady state anisotropy. Bieber et al. (1999) report that precursor anisotropy is frequently manifested as an enhanced flux of particles coming from the direction of $0° - 90°$ GSE longitude, typically beginning about 12 h before the shock arrives. They suggest that such anisotropies might result when CME–related structures move onto the Sun–Earth field line and disrupt the normal steady state flow of cosmic rays by altering the inner boundary conditions.

The potential for neutron monitors to contribute to space weather forecasting is also indicated by statistical results of Kudela et al. (1997), who found correlations at the 40% level between cosmic ray "fluctuations" and Dst values measured ~10 hours later. The source of the effect may well be precursor anisotropy, because anisotropy causes enhanced variability in single station data.

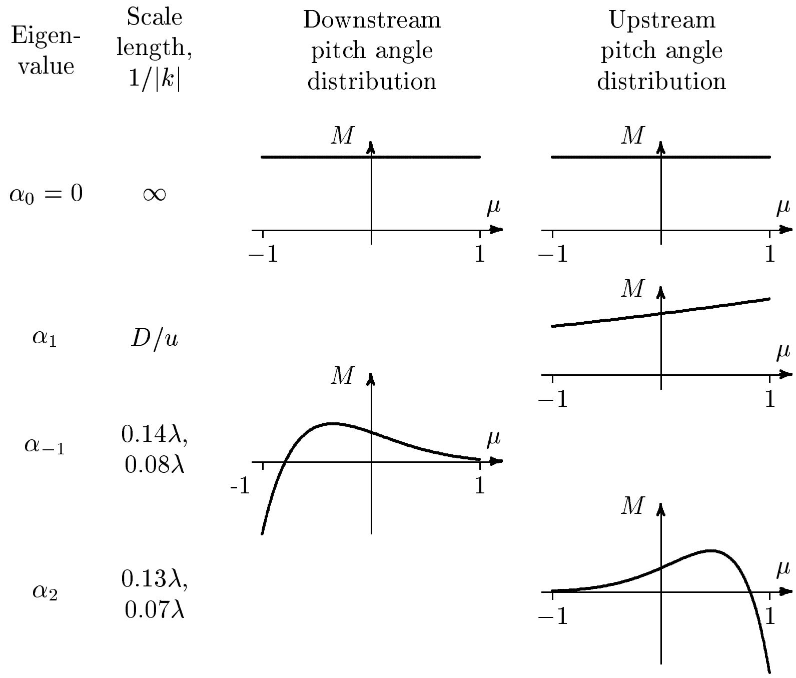

Figure 2: Separable solutions of the transport equation in the steady state on the downstream and upstream sides of a shock at $z = 0$. For each solution, $F_w = e^{kz}M(\mu)$, so $1/|k|$ represents the scale length over which the solution decays upstream or downstream of the shock. $D = v\lambda/3$ is the spatial diffusion coefficient. Where two scale lengths are given, they are for $q = 1$ and 1.5, respectively.

2 Transport Equation and Numerical Solutions:

The strong anisotropies in GCR that are observed shortly before the impact of an interplanetary shock are clearly outside the framework of diffusive transport. We can make substantial progress in understanding these observed effects of an interplanetary shock on the distribution of cosmic rays by numerically solving a Fokker-Planck equation of focused transport that includes the effects of interplanetary scattering and solar wind convection to first order in the solar wind speed (Ruffolo 1995), and by incorporating the changes in pitch angle and momentum as a particle crosses or is reflected by a shock.

It turns out that both precursory increases and decreases can be interpreted in terms of a simple model of a plane-parallel shock with straight magnetic field lines on either side. For this configuration, the transport equation simplifies to

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

where $F(t, z, \mu, p) \equiv d^3N/(dpd\mu dz)$ is the particle distribution function, t is the time in the shock frame, z is the distance along the magnetic field in the shock frame, μ is the cosine of the pitch angle in the local wind frame, p is the momentum in the local wind frame, v is the particle speed in the local wind frame, u is the wind speed relative to the shock, and $\varphi(\mu)$ is the pitch angle scattering coefficient, which we assume to have the form $A|\mu|^{q-1}(1-\mu^2)$. Here we use $q = 1$, corresponding to isotropic scattering, and $q = 1.5$, in the range of 1.3-1.7 inferred from observations (Bieber, Evenson, & Pomerantz 1986).

Following Kirk & Schneider (1987), who considered ultrarelativistic particles, in the steady state it is possible to find separable solutions if we restrict the z domain to only one side of the shock. We set $\partial F/\partial t = 0$ and $F_w = (1 - \mu uv/c^2)F$ as the distribution function in the wind frame, and use the separation of variables, $F_w(\mu, z) = M(\mu)Z(z)$, yielding $Z \propto e^{kz}$ and

$$\frac{\partial}{\partial\mu}(1-\mu^2)|\mu|^{q-1}\frac{\partial M}{\partial\mu} - \alpha\left(\mu + \frac{u}{v}\right)M = 0, \qquad (2)$$

where $\alpha \equiv 2kv/A$ is an eigenvalue of the equation. To avoid divergence as $z \to \pm\infty$, we must have $k \leq 0$ (≥ 0) for $z > 0$ (< 0), so separable solutions for $\alpha \neq 0$ are only valid on one of the two sides of the shock. For q and u/v values of interest, Ruffolo (1999) evaluated eigenvalues and eigenfunctions using the Mathematica software package (Wolfram Research, Inc.).

Figure 2 shows pitch angle distributions for low-order separable solutions on either side of the shock for $q = 1$. The α_0 and α_1 solutions correspond to the solution in the diffusive approximation (e.g., Krymskii 1977), while higher-order separable solutions can appear closer to the shock. Note that this mathematical analysis refers to the restricted domain of one side of the shock or the other; numerical simulations are necessary to find the amplitudes of the separable solutions for the steady state, or to address a time-dependent situation. Our numerical technique is described in these proceedings by Nutaro & Ruffolo (1999).

Our numerical simulations can also be applied to the time-dependent case of GCR near an oblique, interplanetary shock, in order to address the observations. Physically, we consider that the Forbush decrease downstream of the shock results because fresh plasma emitted along with a CME has a relatively low density of GCR. Therefore, we assume f is initially 0 downstream and constant upstream, with a constant inflow far upstream. Figure 3 shows the phase space density f vs. μ and z (in units of $\lambda_{||}$), where the shock-field angle is 45° upstream, $q = 1.5$, and $f \propto BF$ is normalized to have a pitch-angle averaged value of one just upstream of the shock. Pitch angle distributions are shown in Figure 4 for $z = \lambda_{||}$, far upstream of the shock, and $z = 0.05\lambda_{||}$, immediately upstream of the shock.

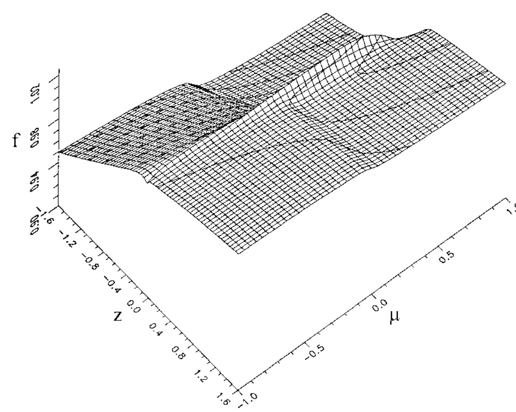

Figure 3: Simulated phase space distribution of galactic cosmic rays vs. μ, the pitch angle cosine, and z, the distance from an oblique, interplanetary shock along the magnetic field (in units of $\lambda_{||}$).

3 Discussion and Conclusions:

Although the precursors of Forbush decreases are time-dependent phenomena, features corresponding to the steady-state separable solutions are still apparent in Figures 3 and 4. In particular, the simulations exhibit an enhanced anisotropy far upstream, roughly corresponding to α_1, as in neutron monitor observations. Closer to the shock, the pitch angle distribution shows 1) an enhancement (relative to the far upstream solution) of particles reflected from the shock, which gain energy from the shock encounter, and 2) a sharp depletion in a loss cone corresponding to particles coming from downstream. These two features correspond nicely to the precursory increases and decreases observed in neutron monitor observations and also to the steady-state separable solution for α_2 (Figure 2). In fact, the simulations verify that the distance scale over which these features are found is close to that expected for the separable solution, $\approx 0.07\lambda_{||}$ along the field. This distance scale is robust in that it does not depend on the shock-field angle and depends only weakly on the shock speed.

For short-term space weather forecasting, the objective is to accurately determine the time at which a major shock will impact the Earth's environment, or the distance to the shock as it approaches. While it has been recognized for some time that upstream precursors of Forbush decreases are harbingers of upcoming space weather effects, this work represents the first detailed explanation of the loss-cone and reflection precursors, and predicts a robust distance scale over which they can be found, i.e., $\approx 0.1\lambda_{||}$ along the magnetic field from the shock. Enhanced diurnal anisotropies far upstream of the shock give advanced warning of the likely onset of space weather, and strong anisotropy features can indicate its imminent onset. These results underline the usefulness of the worldwide neutron monitor network and its characterization of the cosmic ray anisotropy.

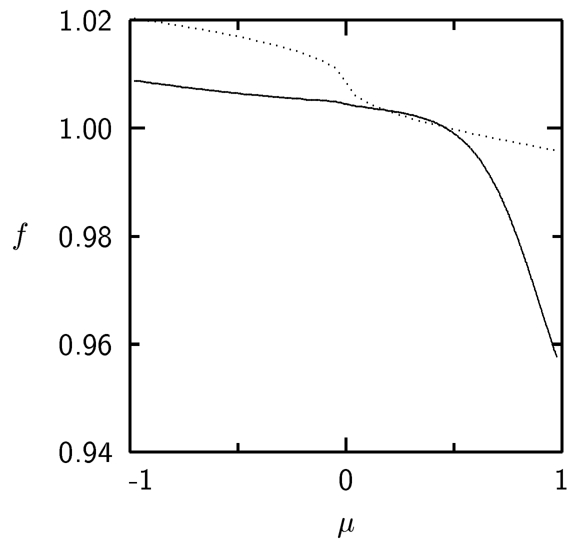

Figure 4: Simulated phase space distribution of galactic cosmic rays vs. μ near an oblique, interplanetary shock at $z = 0.05\lambda_{||}$ (solid line) and $z = \lambda_{||}$ (dashed line), representing near upstream and far upstream precursors of a Forbush decrease.

What is needed to translate this result into more precise short-term space weather prediction? There is some dependence of the above distance scale on the parameter q, which for the foreseeable future represents an inherent uncertainty in this approach. The scattering mean free path parallel to the magnetic field is also difficult to estimate. There are prospects for better determination of the shock geometry, e.g., to convert the distance to the shock along the magnetic field into a distance along the shock normal, particularly with future space missions, e.g., STEREO. Further work is also needed to clarify the origin of the precursory anisotropies.

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