MAGNETIC FLUCTUATIONS AND COSMIC RAY DIURNAL VARIATIONS

J. W. Bieber and M. A. Pomerantz
Bartol Research Foundation of The Franklin Institute
University of Delaware, Newark, Delaware 19716

ABSTRACT

A unified theory of cosmic ray diurnal variations has been proposed in which the first 3 harmonics of the cosmic ray daily variation all result from a single anisotropy produced by the combined effects of adiabatic focusing and anisotropic pitch angle scattering. The purpose of the present report is twofold: (1) to simplify and improve the theoretical description of steady-state cosmic ray anisotropies, and (2) to present and discuss, in light of the theory, preliminary results of a study of correlations between cosmic ray diurnal variations and the fluctuation characteristics of the interplanetary magnetic field.

1. Theory. Several theoretical investigations of energetic particle anisotropies (Roelof, 1969; Kunstmann, 1979; Earl, 1981) suggest that observed anisotropies may appropriately be cast in the form of a simple analytic solution of the steady-state Boltzmann equation, which, according to Earl (1981), is given by

$$f = c_0 + c_1 \, B \, \exp\left\{ \frac{(4-q)\lambda}{3\,L} \, \mu \, |\mu|^{1-q} \right\} . \qquad (1)$$

Here, f is the phase space density, c_0 and c_1 are constants, B is the magnetic field magnitude, q is a parameter characterizing the anisotropy of pitch angle scattering, λ is the scattering mean free path, L is the focusing length (~ 0.94 AU for the nominal Parker field at Earth), and μ is the cosine of the particle pitch angle. The property of (1) relevant to the present work is that it has a non-sinusoidal form, and hence will naturally contribute higher order harmonics to the cosmic ray daily variation observed by ground-based instrumentation.

For reasons connected with geomagnetic correction of neutron monitor observations (Yasue et al., 1982), it is convenient to express the free space anisotropy as a Legendre series. Figure 1 shows the relationship between the parameters λ/L and q and the coefficients a_i of the Legendre expansion of (1). Note that a measurement of the 3 coefficients a_1, a_2, and a_3 serves to determine uniquely the values of both λ/L and q. Figure 1 thus allows values of interplanetary scattering parameters to be inferred from measurements of cosmic ray diurnal variations.

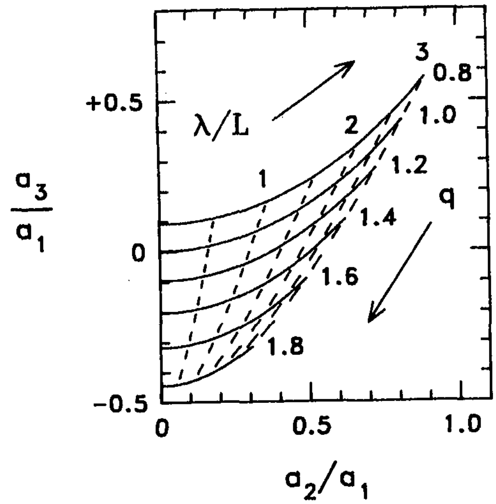

Fig. 1. Lines of constant λ/L (dashed) and constant q (solid) are plotted in a coordinate system representing ratios of the coefficients a_i of a Legendre series expansion of the exponential anisotropy (1). The coefficients a_1, a_2, and a_3 are closely related to the first, second, and third harmonics, respectively, of the cosmic ray diurnal variation.

Bieber and Pomerantz (1983) used essentially this procedure to infer values for λ and q from an analysis of 12 years of neutron monitor data. However, that earlier analysis expressed the anisotropy as a first-order focusing eigenfunction, which is closely related to the exponential (1), but which differs somewhat in the quantitative prediction of harmonic amplitudes. Because the exponential anisotropy is derived from the steady-state Boltzmann equation which includes the effect of a field-aligned density gradient, as well as the effects of focusing and scattering, it should be the more accurate approximation to actual cosmic ray anisotropies in most circumstances. If the observational results of Bieber and Pomerantz are re-interpreted in terms of the exponential anisotropy, then the long-term average of the scattering mean free path at 10 GV changes from 0.5 to 0.3 AU, while the long-term average of q remains unchanged at 1.1.

2. Magnetic Fluctuations and Diurnal Variations. In light of the theory described above, it might be expected that cosmic ray diurnal variations would be correlated with the fluctuation characteristics of the interplanetary magnetic field. In particular, one might expect the amplitude of the second harmonic relative to the first to decrease as the fluctuation level increases, since an increase in fluctuations should correspond to a decrease in λ and, according to Figure 1, a decrease in a_2/a_1.

A thorough investigation of this effect would require that the scattering mean free path be calculated from the observed power spectrum of the magnetic field (e.g., Jokipii, 1971). However, for this preliminary study a simpler procedure was chosen in which the fluctuation level is characterized by the relative variance of the magnetic field. Relative variance was calculated on a daily basis by taking the vector variance of observed hourly field vectors and dividing this by the mean-square field. For days in which both toward and away field polarities occurred, the direction of toward vectors was reversed before the variance was taken. Days with fewer than 12 hours of data were excluded from the analysis. The remaining days were then divided into 7 groups according to relative variance, and the first 3 harmonics of the cosmic ray daily variation observed at Swarthmore over the period 1965-1978 were averaged separately for each group.

Results of the analysis appear in Figure 2, where the amplitudes and phases of the first 3 harmonics of the diurnal variation are displayed as a function of relative variance. The only quantity to exhibit a strong dependence upon magnetic fluctuation level is the amplitude of the second harmonic, which decreases significantly at the higher fluctuation levels.

After correction for geomagnetic effects and for the Compton-Getting anisotropy (Bieber and Pomerantz, 1983), the data of Figure 2 may be used to infer values of the interplanetary scattering parameters λ/L and q, as described above. For relative variances in the range 0-0.5, λ/L remains nearly constant at a value ~ 0.35, while for ranges 0.5-0.7 and 0.7-1.0 λ/L decreases to 0.27 and 0.19, respectively. For all values of relative variance the q parameter remains near a value of 1.1.

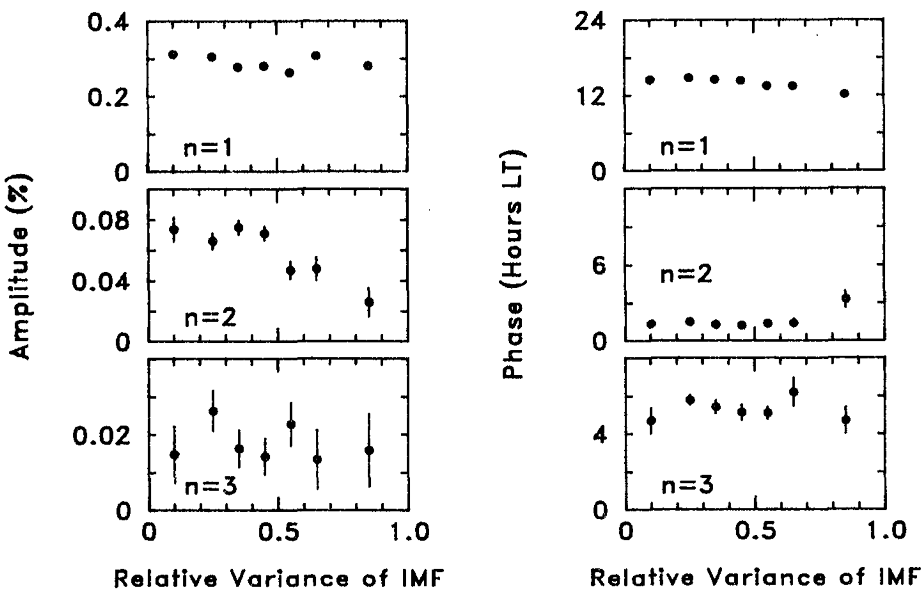

Fig. 2. The amplitudes and phases of the first (top panels), second (middle panels), and third (bottom panels) harmonics of the cosmic ray daily variation observed at Swarthmore are plotted as a function of the relative variance of the interplanetary magnetic field. Data are not corrected for geomagnetic effects or for the Compton-Getting anisotropy. Error bars are ± 1σ.

3. Discussion. The daily variance calculated from hourly-averaged magnetic field vectors will naturally be most influenced by fluctuations with time scales in the range of 1 to 24 hours. This, it turns out, is a very suitable range insofar as the scattering of cosmic rays of neutron monitor energies is concerned, as a cosmic ray of 10 GV rigidity is resonant with waves that have periods ~ 24 hours in the spacecraft frame. Thus, it is reasonable to suppose that the relative variance provides a rough measure of the scattering rate that would be calculated from the actual power spectrum of fluctuations.

Under this hypothesis, the results described above show general agreement with theoretical expectation, in that the mean free path inferred from particle anisotropies decreases at the higher fluctuation levels. There is also a hint of a possible discrepancy, however, in that the inferred mean free path seems to be independent of fluctuation level for relative variances < 0.5.

Further analysis is required to see whether any significance can be attached to this puzzling result. In particular, the characterization of fluctuation level by daily relative variance should be replaced by a careful evaluation of observed magnetic power spectra. This will allow the relationship between interplanetary scattering parameters and the fluctuation characteristics of the magnetic field to be studied quantitatively at a level of detail that has not heretofore been possible.

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