SPATIAL VARIATION OF COSMIC RAYS NEAR THE HELIOSPHERIC CURRENT SHEET

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ABSTRACT. We report a quantitative comparison between theoretical predictions and observations of the intensity of galactic cosmic rays near the interplanetary current sheet. Comparison of our model calculations is made with a statistical analysis of observations of galactic cosmic rays at Earth and the simultaneous position of the current sheet. We use an ensemble of different current sheet inclinations, in order to make the analysis of the computations approximate the method used to analyse the data.

1. INTRODUCTION. The transport of cosmic rays in the interplanetary magnetic field is the consequence of four basic effects - diffusion, convection, cooling and gradient and curvature drifts. The resulting transport equation for the distribution function f may be written:

$$\frac{\partial f}{\partial t} = \nabla\cdot(\underset{\sim}{K}\cdot\nabla f) - \underset{\sim}{V}\cdot\nabla f + \frac{1}{3}\nabla\cdot\underset{\sim}{V}\,\frac{\partial f}{\partial \ln P} \quad (1)$$

where P is momentum, $\underset{\sim}{V}$ is wind velocity and $\underset{\sim}{K}$ is the diffusion tensor.

A variety of solutions of this equation has appeared in the literature. A straightforward application of the equation leads to a situation in which the particle drifts play a very important and perhaps dominant role in the modulation of galactic cosmic rays (see, e.g. Jokipii and Kopriva, 1979, Jokipii and Davila, 1981, and Kota and Jokipii, 1982). The problem of the intensity near the interplanetary current sheet was first addressed observationally by Newkirk and Lockwood (1981). Subsequently, Kota and Jokipii (1982) showed that the Newkirk and Lockwood results were consistent with their three-dimensional code.

More-sophisticated analyses of the observations were reported by Newkirk and Fisk (1985) and Newkirk, Asbridge and Lockwood (1985). Here we determine the agreement of these observations with our model.

2. The Model Calculations. We have developed a 3-dimensional code to solve the full transport equation. We use a straightforward extrapolation of observations taken near the ecliptic plane. The model is static in a coordinate frame corotating with the Sun. The numerical technique and details of the model are described elsewhere (Kota and Jokipii 1982). The interplanetary magnetic field is the same as that used by Jokipii and Thomas (1981). The field at the solar surface is assumed to be uniform and radial, with opposite signs on either side of a magnetic equator. This magnetic equator is a tilted plane at the sun, which is a wavy neutral sheet at larger heliocentric radii in interplanetary space (see Figure 2 of Jokipii and Thomas 1981). The degree of waviness increases from a minimum near solar minimum to a large value near 90 near sunspot maximum. The field on either side of the current sheet is an Archimedean spiral. The case in which the northern hemisphere field is outward corresponds to the field parameter A being positive. The solar wind speed was taken radial and constant in magnitude at 400 km s^{-1}. We are not yet able to use a spatially-varying solar wind speed.

The parallel diffusion coefficient, $K_{\parallel}$, was assumed to be inversely proportional to the magnetic field strength, B ,

$$K_{\parallel} = K_0 P^{\frac{1}{2}} \beta \left(B_{earth}/B\right) \quad (2)$$

with P being the particle rigidity in GV, is the particle velocity in units of velocity of light, and K_0 is a normalization constant in the range 10^{21} - 10^{23} if is expressed in cm^2/sec (see, eg., Jokipii and Davila, 1981). The ratio of perpendicular and parallel diffusion coefficients was kept constant at $K_\perp/K_\parallel$ = 0.05-0.10. To reduce computing requirements the outer boundary was set at r = 15 AU, with some runs carried out for a 30 A.U. boundary. The general features of the solutions have been discussed in detail elsewhere (Kota and Jokipii, 1982), and their discussion will not be repeated here, except to reiterate that the solutions are clearly affected by the particle drifts. Of most interest here is the dependence of the intensity on the structure of the interplanetary current sheet illustrated in the contour plot in figure (1). It is clear that the magnetic field organizes the cosmic-ray intensity in a characteristic manner relative to the current sheet, and that this organization is different for the two signs of the interplanetary magnetic field. Note also, for future reference, that the intensity is not simply dependent on the distance from the current sheet.

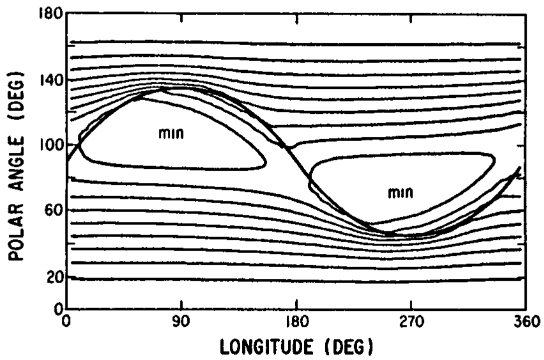

Fig. 1 Computed contours of equal intensity at a radius of 1 A.U., for protons of energy 2.36 GeV. Inclination of current sheet = 45°. $K_0=1.0\times10^{22}$ cm^2/sec, and the outer boundary was at 15 A.U. All other parameters as in Jokipii and Kota, 1982.

3. Comparison With Observations

a. The Data.

Given the above, it is of interest to study observationally the relationship between the current sheet and cosmic rays. The analyses carried out by Newkirk and Lockwood (1981) and Newkirk and Fisk (1985a) and Newkirk, Asbridge and Lockwood (1985) attacked this problem statistically, in order to minimize the problem of transient, time-dependent effects. They studied the dependence of the intensity of the Mt. Washington neutron monitor (to protons of about 5.3 GeV energy) on the distance from the current sheet, for data obtained in the years 1973-1978. Data from the years around sunspot maximum were not included. The determined the position of the current sheet from coronal white light data, which has been determined to be quite accurate. Their figure (9) shows a scatter plot of the daily intensity vs. the heliomagnetic latitude at the point of observation (defined as the angular distance in degrees along a meridian to the current sheet, which defines the heliomagnetic equator). The data show considerable scatter, which is to be expected since effects of transient disturbances, etc. may be expected to disrupt the pattern. Nontheless, there is a clear trend in the data, and the solid line gives the best fit of the function

$$I = a_0 + a_1 \sin^2(\lambda_{mg}) \qquad (3)$$

to the data, where λ_{mg} is heliomagnetic latitude. The fit to the data, with a_0 = 2407 and a_1 = -117 is quite well-determined. In a subsequent paper, Newkirk, Asbridge and Lockwood examined the energy dependence of the ratio a_1/a_0 by analysing data from a variety of other sources. These data show that the effect depends inversely on energy, scaling approximately as $T^{-0.8}$. It should be noted, however, that this observational result is still consistent with there being no instantaneous latitudinal gradient. For, since all of the observations are taken near the solar equatorial plane, the large values of λ_{mg} occurred when the current sheet was far from the equatorial plane, and the inclination of the current sheet was large. Hence, if the intensity of cosmic rays <u>globally</u> were small when the current-sheet inclination was large, then a scatter plot of $_{mg}$ vs intensity would tend to be lower at large $_{mg}$, as is observed. We will not discuss this possibility any further here, as it does not affect the analysis.

b. The Model Calculations.

In order to compare these data with the model, it is important to simulate the methods used to analyse the data very accurately.

First, we note that the inclination of the current sheet varied considerably over the time period spanned by the data set, so it would not be appropriate to use only one simulation, with one current sheet inclination. Second, the orbit of the Earth carries the point of observation sinusoidally seven degrees above and below the heliographic equator. Since the maximum value of $_{mg}$ in the data set shown in figure (9) of Newkirk and Fisk is approximately 55^o, a maximum current sheet inclination of 45^o would give a maximum λ_{mg} of 52^o. The work of Jokipii and Thomas (1981) suggests a minimum inclination of the order of 15^o Hence, three different inclinations, 15, 30, and 45 degrees were computed for each parameter set. A fourth inclination of 0 degrees was also used in some of the runs, with little change in the results. Then, to simulate the motion of the Earth in its orbit, the intensity was determined at a number of points, which were spaced in heliographic latitude and longitude just as the Earth is in its orbit. For each such point, in addition to the computed intensity, j, the heliomagnetic latitude $_{mg}$ as defined by Newkirk and Fisk was calculated.

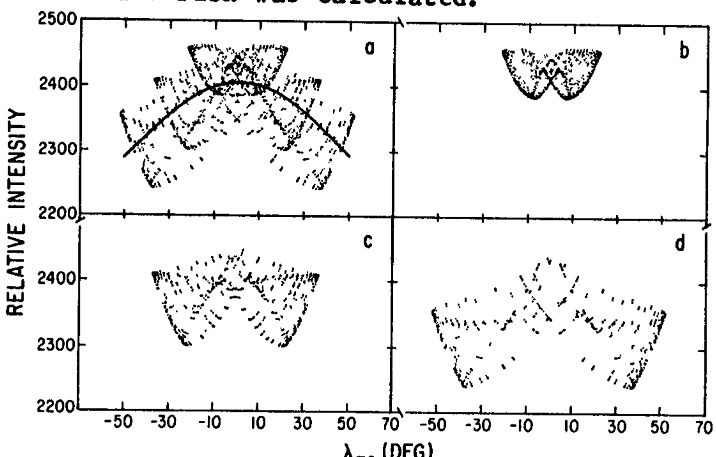

Fig. 2 a. Scatter plot of intensity vs λ_{mg} summed over three inclinations 15, 30 and 45 degrees, for the parameters of fig 1. b,c,d give the individual contributions for the three inclinations.

The resulting set of points (j, λ_{mg}), for three inclinations and along the Earth's orbit is illustrated in figure (2a) for one set of parameters. Note that there is considerable scatter in the points, reflecting the fact that the computed intensity depends on other parameters as well as λ_{mg}. Nontheless, the calculated values show a trend toward decreasing intensity as λ_{mg} increases, similar to that found in the data by Newkirk and Fisk. Figures (2 b,c,d) show the scatter plot obtained for the individual inclinations.

Finally, a least squares fit of equation (3) to the synthesized scatter plot was made to obtain the "theoretical value" of the coefficients a_0 and a_1 for each given set of parameters. This procedure was repeated for each set of parameters (diffusion coefficient normalization, energy, etc). As mentioned above, the absolute values are irrelevant, so the ratio a_1/a_0 is used in what follows. Illustrated in figure (3) gives the variation of this ratio for a range of diffusion-coefficient normalizations for particles of energy 2.36 GeV, together with the value for this energy given by Newkirk, Asbridge and Lockwood (1985). Clearly, there is a broad range of plausible diffusion coefficients for which the computed value is close to that observed.

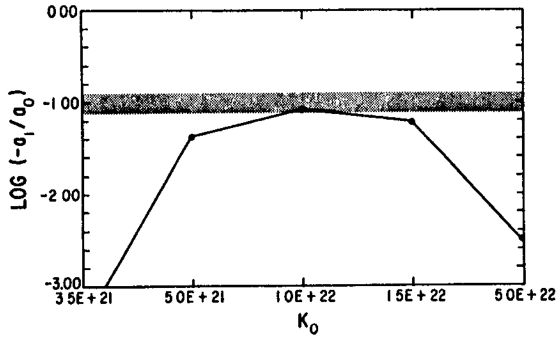

Fig. 3 Dependence of computed a_1/a_2 on K_0 for the parameters in figures 1 and 2. Horizontal band is observed value.

We also studied the energy dependence of the ratio a_1/a_0. We found that although the calculated value does indeed decrease with increasing particle energy, and agrees well with the data at a few GeV energy, the functional dependence is not the simple power law seen in the data. We expect that changing the energy dependence of the diffusion tensor could improve agreement here, but have not been able to verify this.

4. Summary and Interpretation The analysis presented above demonstrates that a model of modulation, in which the dominant physical effect is the large-scale structure of the interplanetary magnetic field, is quantitatively consistent with the analysis of the data reported by Newkirk and Lockwood (1981) and Newkirk and Fisk (1985a,b). At present the only significant discrepancy appears to be in the somewhat different energy dependences obtained from the data and from the model, and it appears likely that modifying the diffusion coefficient may improve this. Taken together with other comparisons of the theory with data, including the prediction of 22-year solar magnetic cycle effects (Jokipii and Thomas, 1981, and Kota and Jokipii, 1982), and detailed comparison with the inclination of the current sheet (Smith and Thomas, 1985), this suggests that many features of the solar-cycle modulation of galactic cosmic rays are a consequence of the model, and that drifts may well be a dominant process in solar modulation.

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