GRADIENTS AND ANISOTROPIES OF HIGH ENERGY COSMIC RAYS
IN THE OUTER HELIOSPHERE

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Introduction Two cosmic rays which pass through the same point going in opposite directions will, in the absence of scattering and inhomogeneities in the magnetic field, trace helices about adjacent flux tubes, whose centerlines are separated by one gyrodiameter. A directional anisotropy at the point suggests a difference in the number of cosmic rays loading the two flux tubes; that is, a density gradient over the baseline of a gyrodiameter. The anisotropy produced by such a gradient can be written

$$\xi = \rho_g \ \hat{B} \ X \ G = P/B^2 \ B \ X \ G \tag{1}$$

where ξ is the anisotropy, ρ_g the gyroradius, P the rigidity, B the field, and G the gradient. It is convenient to express ξ in %, G in %/AU, B in nT, and P in nT-AU.

Previous studies at lower energies have shown that the cosmic ray density gradients vary in space and time [1], and many authors currently are suggesting that the radial gradient associated with solar cycle modulation is supported largely by narrow barriers which encircle the sun and propagate outward with the solar wind. If so, the anisotropy is a desirable way to detect spatial gradients, because it can be associated with the local solar wind and magnetic field conditions.

With this in mind we are studying the anisotropy measurements made by the UCSD Cerenkov detectors on Pioneers 10 and 11. This is a progress report in which we show that the local anisotropy varies greatly, but that the long-term average is consistent with the global radial gradient measured between two spacecraft over a baseline of many AU.

Instrumentation Our Cerenkov detectors register cosmic rays with velocity > 3/4c, corresponding mainly to hydrogen and helium above an energy of ~500 MeV/nucleon. In this study we will consider only protons. Alpha particles are counted, in proportions exceeding their abundance, because the solid angle of the acceptance lobe is larger for multiply charged particles. However, for the same reason, the alpha particle response is less directional than the proton response, and so these particles do not have a great effect on the anisotropy measurements.

Integrating the cosmic ray proton spectra of Meyer et al [2] above our threshold, we estimate that the detector responds to protons with a mean rigidity, P, of 0.14 nT-AU at solar maximum and 0.10 at solar minimum. For a normal Parker spiral field with magnitude of 6 nT at one AU, the average gyroradius for a proton in our counter is then R*0.032

(AU) and R*0.023, respectively, and the expected north-south anisotropy, for a gradient of 2%/AU as measured over a two-spacecraft baseline, is R*0.064% and R*0.046%. Statistically we can resolve an anisotropy of 10% in 10 minutes, 1% in 18 hours, and 0.1% in 75 days, when the telemetry coverage is good. Thus it takes many days to resolve the expected effect.

As the Cerenkov detector is mounted perpendicular to the spacecraft spin axis, which points at earth, we obtain the unidirectional flux of high energy cosmic rays in a plane perpendicular to the spacecraft-earth line. When the gradient effect is dominant, a north-south anisotropy normally represents a radial gradient, and an east-west anisotropy reflects a latitude gradient.

<u>Method</u> The east-west and north-south components of equation (1) give usable relationships between the radial gradient and its contribution to the anisotropy.

$$\xi_{EW} = G_r * P * B_z / B^2 - [G_z * P * B_r / B^2] \tag{1a}$$
$$\xi_{NS} = -G_r * P * B_y / B^2 + [G_y * P * B_r / B^2] \tag{1b}$$

We expect the last terms to be negligible, because, as G_y is the longitudinal and G_z the latitudinal gradient, they tend to cancel themselves when averaged over a solar rotation or longer. Besides, B_r is small in the outer heliosphere, and also tends to cancel itself over a number of magnetic sector reversals.

The self-cancellation of unwanted terms becomes the basis of a powerful detection method, because, as the gradient-related anisotropy does change sign with B, we can average the data in such as way as to preserve this effect alone. Multiply equations (1a and b) by B_z and B_y.

$$B_z * \xi_{EW} = G_r * P * (B_z/B)^2 + \text{self-cancelling terms} \tag{2a}$$
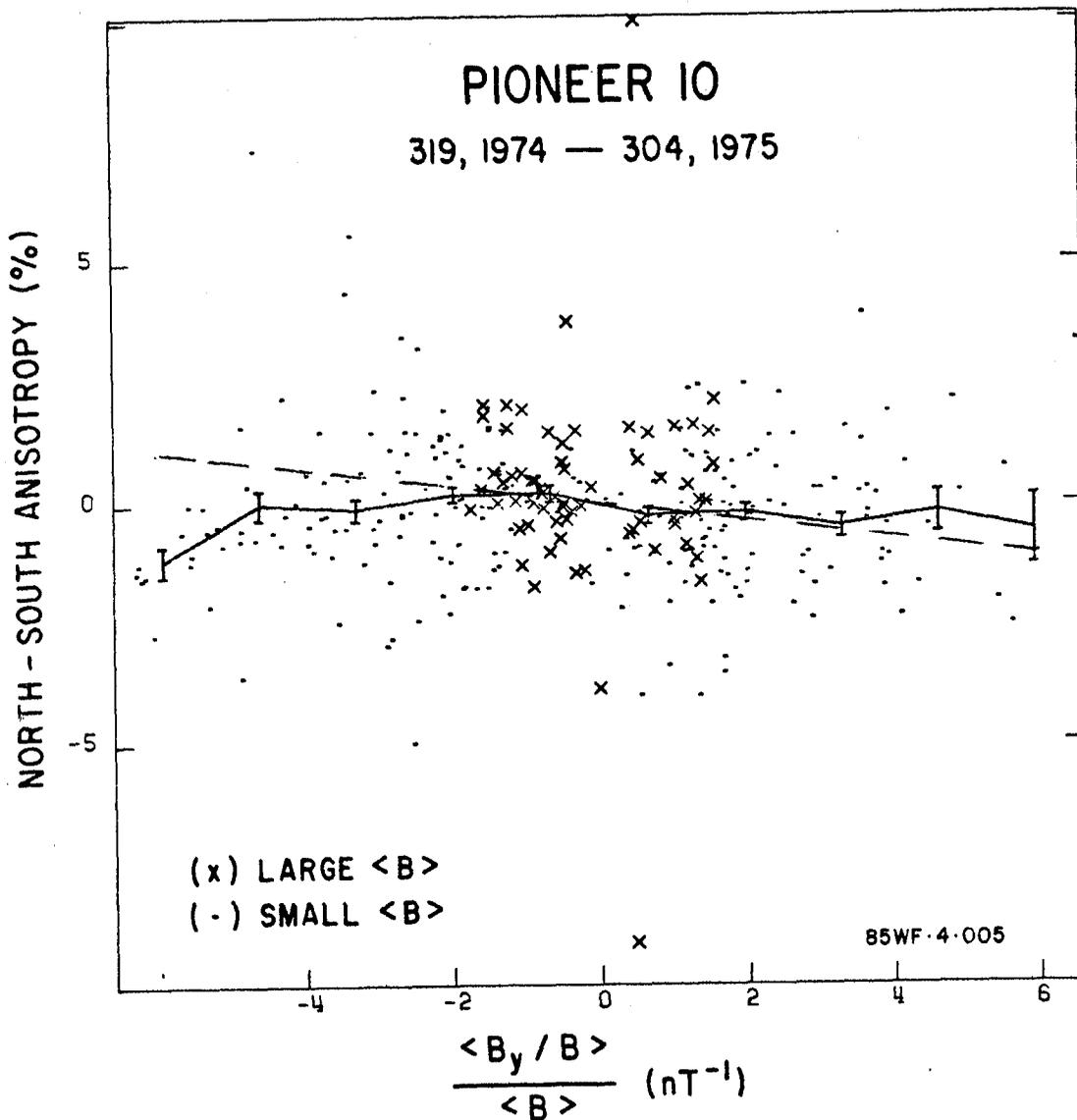$$-B_y * \xi_{NS} = G_r * P * (B_y/B)^2 + \text{self-cancelling terms} \tag{2b}$$

Adding (2a) and (2b) produces an expression relating the radial gradient, G_r, to its associated anisotropy in the scan plane.

$$B_z * \xi_{EW} - B_y * \xi_{NS} = G_r * P * (B_\perp/B)^2 + \text{self-cancelling terms} \tag{3}$$

We recognize the LHS of (3) to be $(\xi \times B)_r$. From a general expression for ξ, it can be shown [3] that $(\xi \times B)_r = (G_\perp P)_p$ + a scattering term that is proportional to the inverse of the diffusion tensor. The differences between this and equation (3) are negligible when we average over sufficiently long intervals and assume weak scattering.

<u>Observations</u> The scatter in the data is amply demonstrated in Figure 1, where we test for the linear relationship between ξ_{NS} and B_y/B^2 given by equation (1b). The data points are one-day accumulations, and so their accuracy is limited statistically to $\pm$ 1%. Clearly the variability of the data points exceeds this measurement limit by a large factor. We interpret this result as evidence that either the gradient is not uniform and homogeneous (it might be time dependent, or localized spatially), or the density gradient effect does not always dominate the anisotropy.

PIONEER 10

319, 1974 — 304, 1975

(x) LARGE <B>

(·) SMALL <B>

85WF·4·005

NORTH - SOUTH ANISOTROPY (%)

$$\frac{<B_y/B>}{<B>} \quad (nT^{-1})$$

Nevertheless, the radial gradient does produce a trend which is discernible with enough data. The abscissa was divided into ten intervals, and the anisotropies averaged over each interval, as shown by the ten points with error bars. The five points at the center fall close to the expected relationship, given by the dashed line for 1.8 %/AU [4], and it is only the fringe intervals that deviate from expectations. As these intervals represent days when B is low, a possible interpretation is that the gradient is small inside rarefaction regions.

Although the gradient-related anisotropy is submerged in highly variable data, it is a robust effect. Figure 2 demonstrates how this signal persisted for 1000 days during an interval when we had adequate data coverage. Here we have solved equations (2b) and (3) for the gradient, and plotted this quantity vs time. We used equation (2b) before January, 1975 because Jovian electrons were present up to that
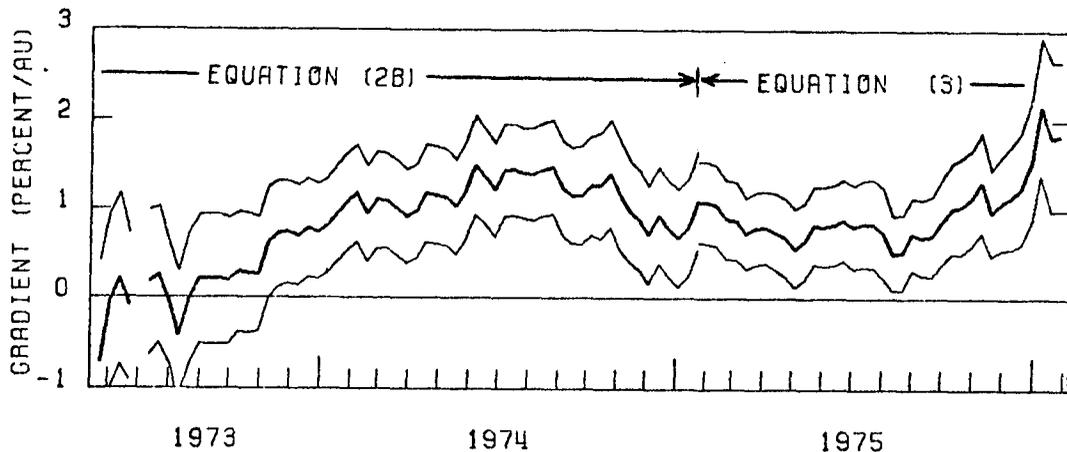
time in the east-west anisotropy, and affected the results from equation (3). These equations were evaluated every 10 days using 300 day boxcar averages to beat down the statistics and allow the extraneous effects to cancel.

Discussion   The gradient values of 1-2 %/AU in Figure 2 are close to those obtained by comparing omnidirectional counting rates on two widely separated spacecraft [4,5]. Thus, the anisotropy method works for obtaining the radial gradient from a single spacecraft. This method was anticipated by Ip et al [6], but the present application is the most successful yet.
    It is clear that other effects are present, over and above statistical errors, which cause the microscopic measurement to deviate from the global value. We hope to learn more about these effects with further study.

References
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