Cosmic Ray Studies Out of the Ecliptic

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COSMIC RAY STUDIES OUT OF THE ECLIPTIC

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Abstract

Since early 1985, negative latitudinal gradients in the fluxes of anomalous and galactic cosmic rays have been observed by Voyager 1, which is now ~28° above the ecliptic. The latitudinal gradients are larger than the radial gradients, indicating that particles are streaming into the heliosphere preferentially at low latitudes during this solar minimum. The sign of the latitudinal gradients appear to have reversed since the last solar minimum, consistent with the presence of gradient and curvature drifts.

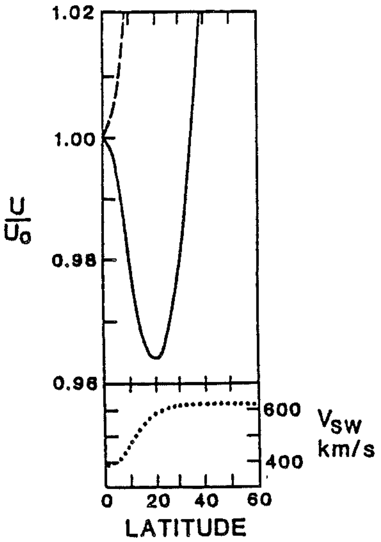
Introduction. The three dimensional distribution of cosmic rays in the heliosphere has been of interest for more than a decade. Although we will have to wait for the launch of Ulysses in 1990 to gain our first look at the high latitude heliosphere, the Voyager and Pioneer spacecraft are already providing glimpses at lower latitudes that reveal how limited our view has been from in the ecliptic. It is those glimpses and their implications that are the subject of this invited paper. Although the results will be discussed in the context of specific quantitative models for solar modulation, the discussion is not intended to identify the definitive modulation model. Rather, the discussion is intended to investigate and illustrate the role of diffusion, convection, and gradient and curvature drifts in particle propagation.

Several properties of the interplanetary medium might be expected to produce latitudinal gradients. If the principal mode of cosmic ray propagation is diffusion parallel to the magnetic field which is wrapped in an Archimedean spiral as the Sun rotates, then a large positive latitudinal gradient would be expected because the decreasing tightness of the spiral with increasing latitude results in a decreasing distance along the field line to the modulation boundary and a corresponding decrease in the modulation level (Fisk, 1976).

In such diffusion dominated transport, the observed increase in solar wind velocities at higher latitudes will modify the latitudinal gradient in a way that depends on the radial dependence of the diffusion coefficient. For example, if the parallel diffusion coefficient is independent of radius, then the latitudinal gradient remains positive as shown in Figure 1 from Newkirk and Fisk (1985). In this case, the increased rate of outward convection at higher latitudes is more than balanced by the increase in inward diffusion that results from the less tightly wrapped Archimedean spiral that is produced by higher solar wind velocities (Jokipii, private communication).

It is possible, however, to choose a diffusion coefficient such that the increased convective losses dominate and negative latitudinal gradients appear at low latitudes. In particular, if the parallel diffusion coefficient varies in such a way as to compensate for the radial dependence of the spiral angle of the field, so that the radial diffusion coefficient is independent of radius in the ecliptic, then a negative latitudinal gradient results at low latitudes as shown in Figure 1.

Figure 1. Calculated latitude dependence of the flux U of 5 GeV cosmic rays, normalized to unity at the ecliptic (Newkirk and Fisk, 1985). The diffusion-convection model includes a latitude variation in the solar wind speed shown in the lower panel. The dashed line in the upper panel indicates the expected latitude dependence if $K_{|}$ is assumed constant. The solid line results if K_{rr} is assumed constant in the ecliptic and $K_{\Theta} \sim 7 \times 10^{19}$ cm^2 s^{-1}.



Although the diffusion-convection calculations in Figure 1 ignore the three-dimensional character of the wavy neutral sheet, they do suggest that negative latitudinal gradients could result from the observed latitude dependence of the solar wind velocity. If the latitudinal gradients are produced by diffusion-convection effects, however, they would be expected to have the same sign each solar cycle, independent of the polarity of the solar magnetic field.

Alternatively, latitudinal gradients could be produced by gradient and curvature drifts which do depend on the polarity of the interplanetary magnetic field. During the last solar minimum, positive particles would drift down from the polar regions of the heliosphere and radially outward along the neutral sheet separating the two magnetic hemispheres as shown in Figure 2 from Pesses *et al.* (1981). With the source of particles at high latitudes, a generally positive latitudinal gradient would be expected. During the current solar minimum, the field polarity is reversed, so that positive particles would drift radially inward along the current sheet and from low to high latitudes. As a result, a negative latitudinal gradient would be expected, at least near the neutral sheet.

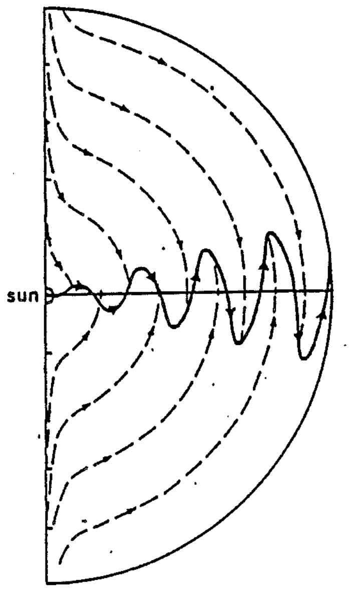


Figure 2. The lines of the flow inward from the polar regions and outward along the wavy current sheet for 70 MeV/nuc He^+ during a period of positive polarity such as the last solar minimum (Pesses *et al.*, 1981).

The wavy nature of the neutral sheet somewhat complicates the expected gradients as shown in Figure 3 from Kota and Jokipii (1983). For example, the calculated isointensity curves for the last solar cycle exhibit a positive latitudinal gradient at latitudes above the maximum latitude reached by the current sheet. However, at lower latitudes the gradients are modified by an assumed cross-field diffusion such that the minimum does not occur at the neutral sheet. As a result, the calculated gradient is weakly negative on the side of the neutral sheet near the local minimum, although the positive gradients on the opposite side are much larger.

Isointensity contours for the current magnetic polarity exhibit significant negative gradients on both sides of the neutral sheet as expected. However, diffusion in from the polar region results in a positive latitudinal gradient at high latitudes. Thus for both magnetic polarities, the sign and magnitude of the expected gradients will depend on the latitudinal region being observed and on the relative importance of drifts and diffusion, so that care must be exercised in drawing conclusions from a set of observations.

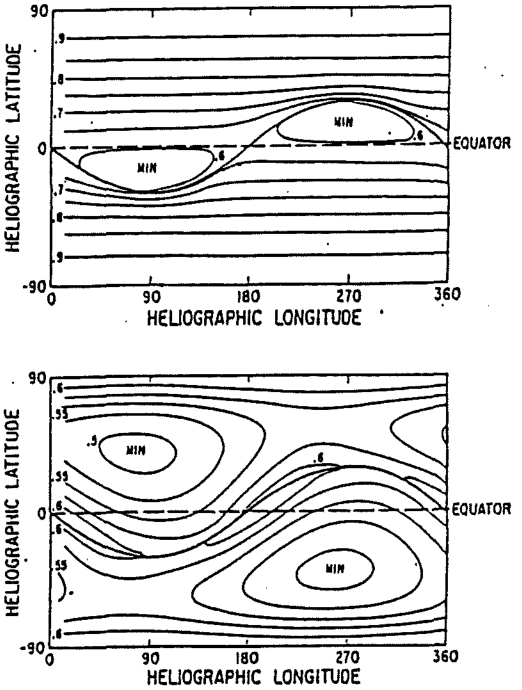


Figure 3. Calculated isointensity contours at 1 AU for 1.06 GeV protons (Kota and Jokipii, 1983). The top panel is for positive magnetic polarity, the bottom for negative, with the current sheet indicated by the heavy line.

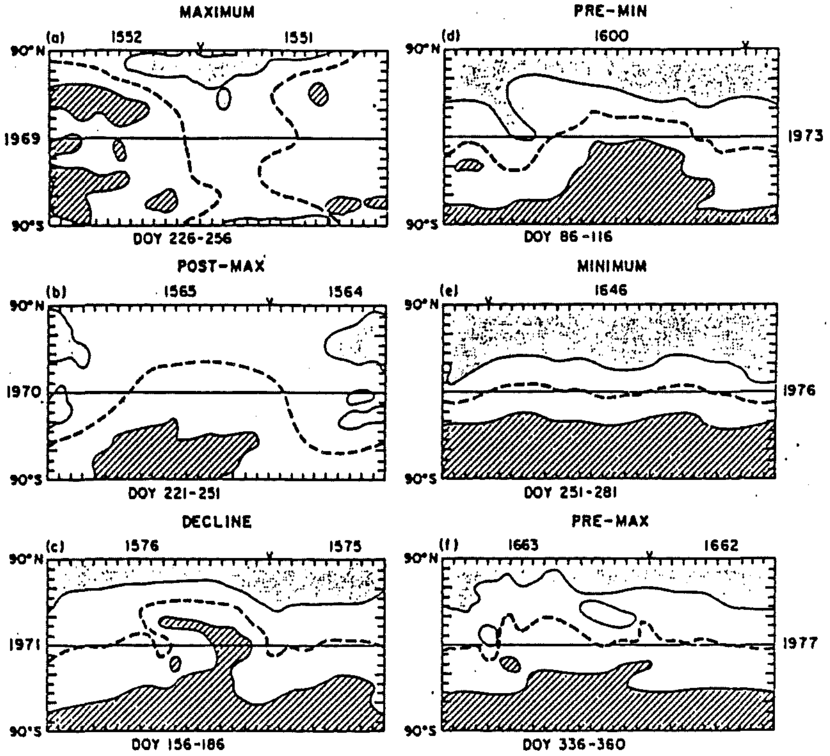


Figure 4. Map of the coronal magnetic field at 1.5 R_S for different phases of the solar cycle (Newkirk and Fisk, 1985). Hatched areas are coronal holes with positive polarity, stippled are negative. The inferred coronal current sheet is shown by the dashed line.

The latitudinal gradients might also be expected to depend on the tilt of the current sheet which varies with the solar cycle. The inferred latitude of the coronal neutral sheet is shown in Figure 4 for six phases in the solar cycle (Newkirk and Fisk, 1985). Only during periods of solar minimum is the current sheet tilt small and reasonably regular.

The effect of current sheet tilt for the current magnetic polarity is illustrated in Figure 5 from Christon *et al.* (1986a). The two horizontal lines indicate the range of fluxes observed in the ecliptic and at 30° north. If the current sheet tilt is 30°, the 26-day average flux at 30° is about 3% smaller than that observed in the ecliptic. Hence in this case the gradient relative to the ecliptic has the same sign as that relative to the neutral sheet. However, if the tilt is increased to 60°, the flux minimum is near the ecliptic and a positive latitudinal gradient would be observed between the ecliptic and 30° N, opposite in sign to the gradient relative to the neutral sheet.

Although particle drifts result in gradients relative to the neutral sheet rather than relative to the ecliptic, observations are necessarily carried out at essentially fixed ecliptic latitudes and thus directly measure gradients relative to the ecliptic. As illustrated above, the observed gradients may reflect the gradients relative to the current sheet only if the tilt of the current sheet is small, i.e., only during solar minimum.

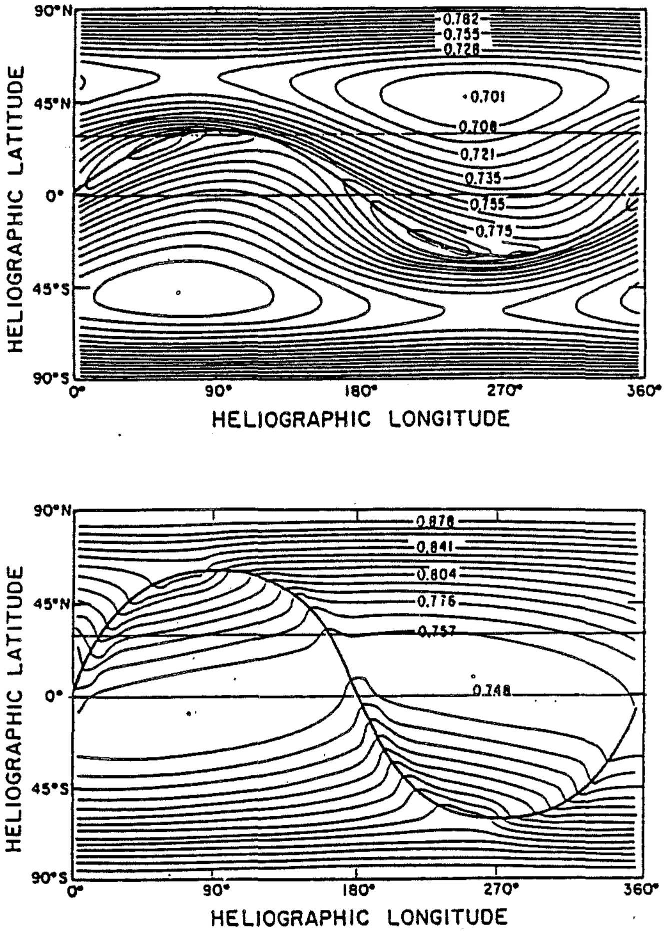


Figure 5. Calculated isointensity contours at 5 AU for 1.6 GeV protons during periods of negative polarity such as the present solar minimum (Christon *et al.*, 1986). The current sheet tilt is assumed to be 30° in the top panel and 60° in the lower. The horizontal lines indicate the range of fluxes that would be observed by spacecraft in the ecliptic and 30° north.

<u>Probes in the Outer Heliosphere.</u> During the current solar minimum there are four spacecraft in the outer heliosphere, all with functioning cosmic ray instruments. The spacecraft trajectories are shown mapped onto the ecliptic plane in Figure 6. Pioneer 11 and Voyager 1 and 2 are headed in the general direction of the solar apex toward the nose of the heliosphere, while Pioneer 10 is headed in the opposite direction down the heliospheric tail.

The latitudinal locations of the spacecraft are shown in Figure 7. Voyager 2, which will encounter Neptune in August 1989, is essentially in the ecliptic plane, as is Pioneer 10 which has remained at relatively low latitudes. In contrast, Pioneer 11 and Voyager 1

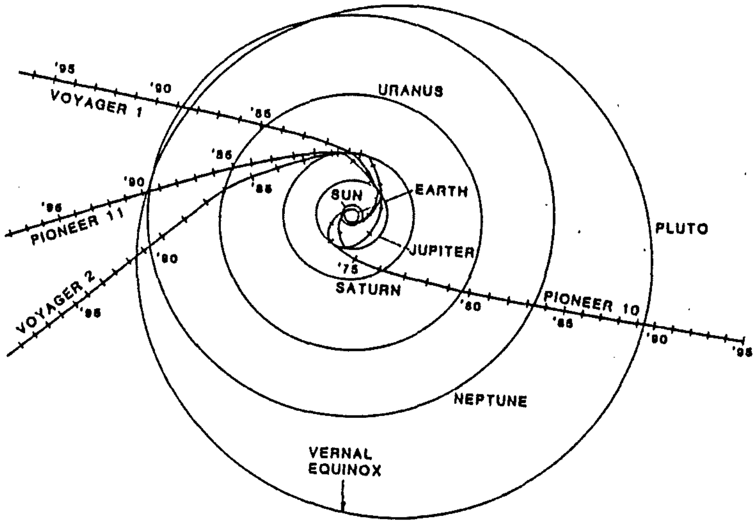


Figure 6. Spacecraft trajectories projected onto the ecliptic plane.

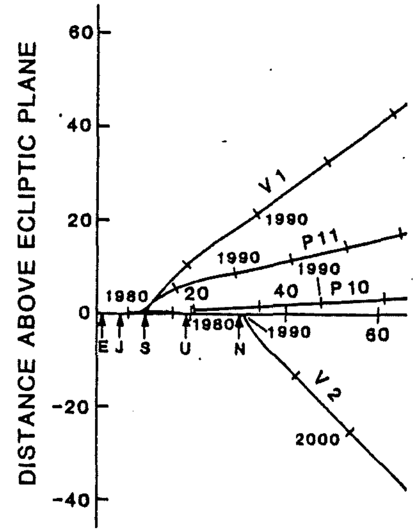


Figure 7. Spacecraft trajectories mapped into a common meridian plane. The horizontal axis is the ecliptic plane. Distances are in astronomical units.

have been climbing above the plane ever since their encounters with Saturn in 1979 and 1980, respectively. This combination of spacecraft, along with IMP 8 and ISEE 3 at 1 AU, provide a unique opportunity for studying the latitudinal and radial gradients of anomalous and galactic cosmic rays.

Galactic Cosmic Rays. Although comparisons of the integral counting rates of >70 MeV protons observed by Voyager 1 and 2 had indicated the presence of a negative latitudinal gradient relative to the current sheet during restricted periods in 1981 through 1983 (Christon *et al.*, 1986a), it wasn't until early 1985 that a durable latitudinal gradient was observed (Christon *et al.*, 1986b, McDonald and Lal, 1986, and Decker *et al.*, 1987). Since that time, the counting rate of >70 MeV protons and >70 MeV/nuc alpha particles observed by Voyager 2 exceeded that observed by Voyager 1, even though Voyager 1 is more than 6 AU further from the Sun. This inversion in the relative counting rates corresponds to an apparent negative radial gradient as shown in Figure 8. However, Voyager 1 was at ~25° latitude during this time and the inversion of the counting rates is actually an indication of negative latitudinal gradients since there is other evidence from Pioneer 10 and IMP 8 that the radial gradients have remained positive.

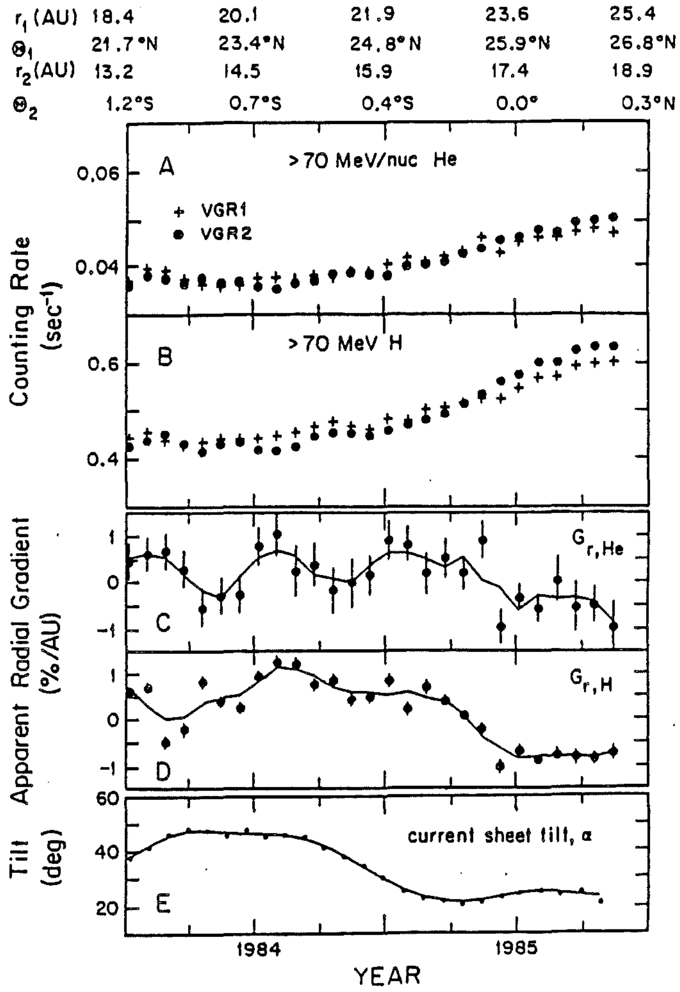


Figure 8. Twenty-six day averages of the H and He counting rates observed by Voyager 1 (pluses) and Voyager 2 (circles) as reported by Christon *et al.*, (1986). The apparent radial gradients are indicated in Panels C and D, and the tilt of the coronal current sheet is shown in Panel E.

As discussed above, negative latitudinal gradients arising from drifts are expected to be observable when the tilt of the current sheet drops near or below the latitude of one of the spacecraft. An estimate of the tilt of the current sheet derived from coronal data similar to that in Figure 4 is shown in the bottom panel of Figure 8. When account is taken of the delay of ~70 days between the solar observations and the arrival of the solar wind at 20 AU, the inversion of the counting rates is well correlated with the decrease in the latitude of the current sheet below that of Voyager 1, as expected. The spectra in Figure 9 from McDonald and Lal (1986) illustrate that negative latitudinal gradients are observed over a wide energy range.

The correlation of the appearance of the latitudinal gradients with the reduced tilt of the current sheet is consistent with that expected if the gradients arise from particle drifts. Unfortunately a direct correlation with changes in the solar wind velocity cannot be investigated because the plasma instrument on Voyager 1 is no longer working.

The Anomalous Component. The anomalous cosmic ray component is believed to originate as interstellar neutral atoms which flow into the heliosphere, become singly ionized as they near the Sun, and are then convected back out to the edge of the heliosphere where they are accelerated to ~10 MeV/nuc. These newly accelerated particles subsequently diffuse and drift back into the solar system as cosmic ray particles, but with rigidities and velocities differing from those of galactic cosmic rays which are fully ionized. Thus the anomalous particles provide a different probe for studying the role of drifts and diffusion in interplanetary propagation.

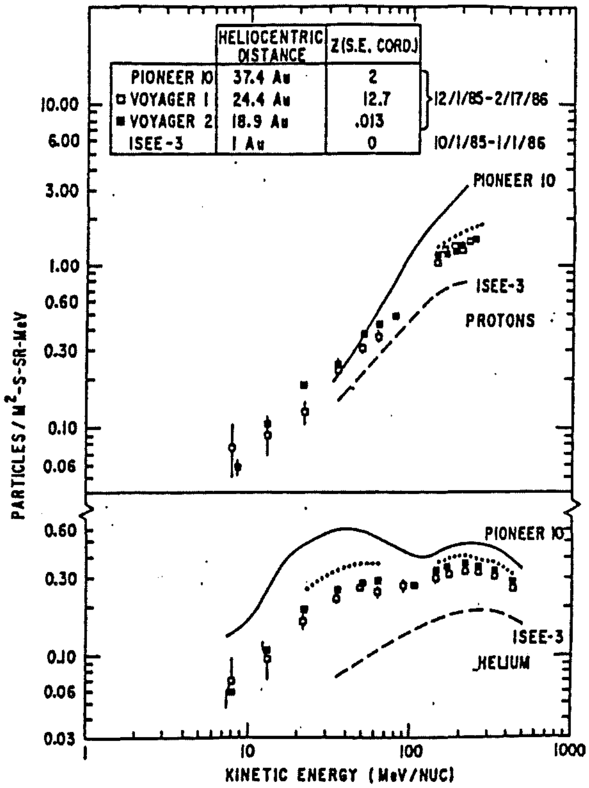


Figure 9. Hydrogen and helium spectra observed in the outer heliosphere and at 1 AU (McDonald and Lal, 1986). The dotted line indicates the predicted Voyager 1 spectrum interpolated from the Pioneer 10 and Voyager 2 spectra assuming no latitudinal gradient.

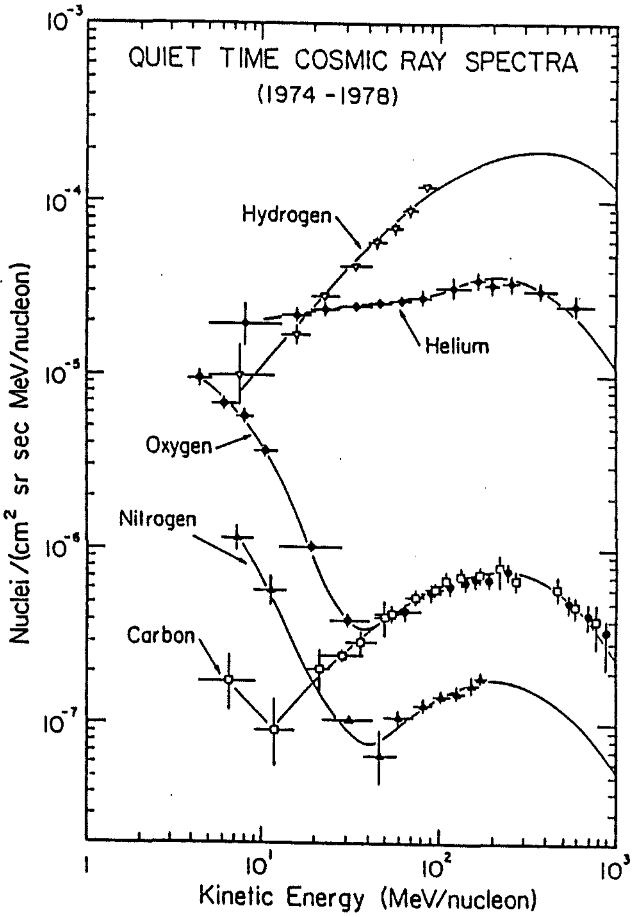


Figure 10. Quiet time energy spectra from the last solar minimum illustrating the anomalous enhancements in helium and oxygen at ~10 MeV/nuc (Mewaldt *et al.*, 1984).

The anomalous component is recognizable by an unusual, or anomalous, composition dominated by species with high first ionization potential, such as He, N, and O, which are primarily neutral in the interstellar medium (Fisk *et al.*, 1974). As shown by the energy spectra in Figure 10, at ~10 MeV/nuc the flux of He exceeds that of H and the fluxes of N and O are much larger than that of C (Mewaldt *et al.*, 1984).

Figure 11 displays the fluxes of anomalous oxygen observed by the two Voyager spacecraft as a function of time. Here, too, an inversion occurs in early 1985, just as the tilt of the current sheet drops below the latitude of Voyager 1. The positive radial gradient and negative latitudinal gradient are confirmed by comparing the spectra in Figure 12. Even though Voyager 1 is located radially between Pioneer 10 and Voyager 2, it observes a lower flux at all energies.

With three spacecraft it is possible to derive both the radial and latitudinal gradients, if a simple functional dependence is assumed. For example if it is assumed that the gradients G_r and G_Θ are constant, then the fluxes f_1 and f_2 measured at locations separated by Δr and $\Delta\Theta$ are related by

$$\ln(f_1/f_2) = G_r\Delta r + G_\Theta\Delta\Theta \,. \tag{1}$$

Typical gradients as reported by Cummings *et al.*, in SH 6.4-3 are included in Table 1.

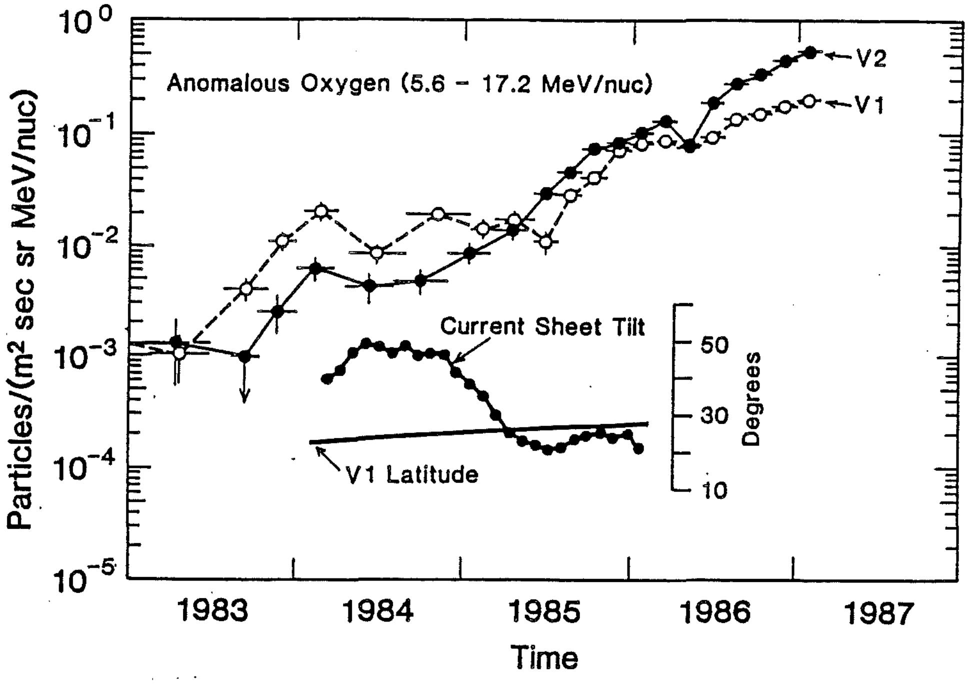


Figure 11. The flux of anomalous oxygen observed by Voyager 1 (V1) and Voyager 2 (V2) reported by Cummings and Stone (1987). The estimated tilt of the current sheet is from Figure 8, shifted to correspond to the travel time of the solar wind from the Sun to the spacecraft.

For all three species, the latitudinal gradient exceeds the radial gradient, indicating that the flow of cosmic rays into the heliosphere is certainly not spherically symmetric, at least during solar minimum conditions.

TABLE 1: TYPICAL GRADIENTS*
(See SH6.4-3)

		E MeV/nuc	Gr %/AU	$G_{\|z\|}$ %/AU
Anomalous	O	11-17	4.5±0.6	-9.3±0.5
Anomalous	He	18-25	5.5±0.5	-9.2±1.3
Galactic	H	>70	0.94±0.09	-1.37±0.09

*For 1986:206 to 1986:310, when Voyager 2 was located at R = 20.9 AU, Θ = 1.3°; Voyager 1 at R = 28.0 AU, Θ = 27.9°; and Pioneer 10 at R = 39.2 AU, Θ = 3.7°

<u>Relationship of the Radial and Latitudinal Gradients.</u> If particle drifts play an important role in the gradients near the neutral sheet, then locally the radial and latitudinal gradients should be related by the following expression (Levy, 1978)

$$\frac{G_{|z|}}{G_r} = \pm \frac{R\ \beta c \sin\psi}{3|B|\kappa_{\perp}} \tag{2}$$

where the sign depends on the magnetic polarity, R is the particle rigidity, βc is the particle velocity, ψ is the angle of the magnetic field (~90° in the outer solar system), $|B|$ the magnetic field strength, and $\kappa_{\perp}$ the perpendicular diffusion coefficient. The gradients at an idealized neutral sheet are related because as the particles drift inward along the current sheet, they also diffuse away from the sheet, thereby creating a radial gradient.

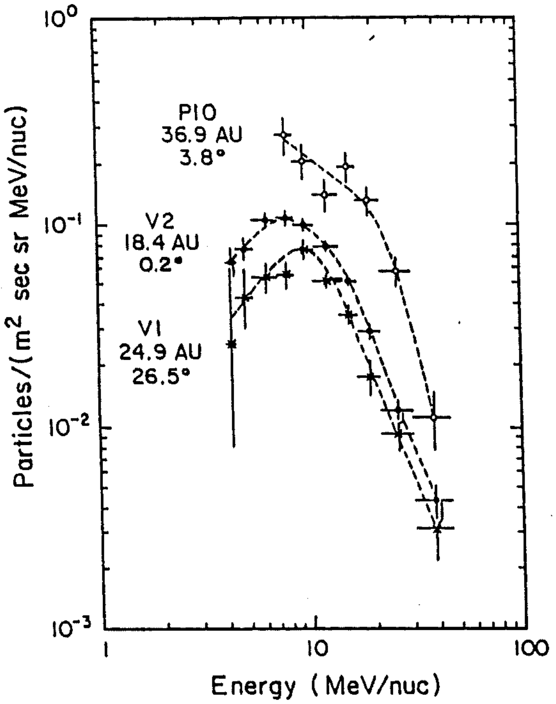


Figure 12. Anomalous oxygen spectra observed by Pioneer 10 (P10), Voyager 1 (V1) and Voyager 2 (V2) for the period 1985/208 to 1986/52 (Cummings *et al.*, 1987).

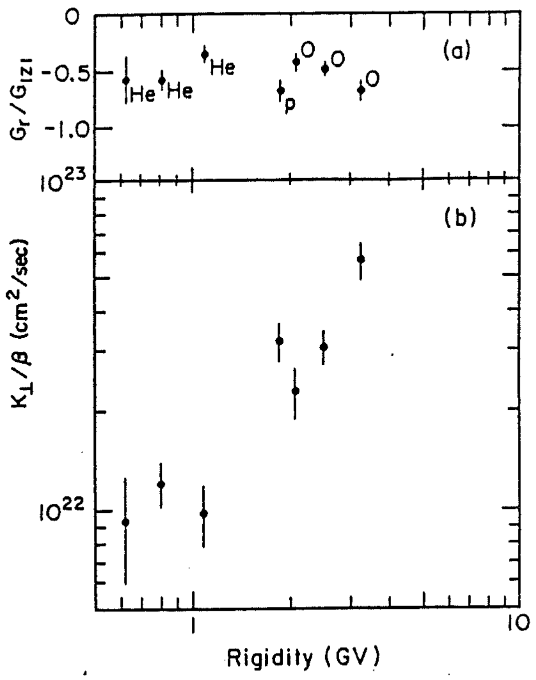


Figure 13. The ratio of the radial (G_r) and latitudinal ($G_{|z|}$) gradients and corresponding estimates of $\kappa_\perp/\beta$ from Equation 2 (Cummings *et al.*, SH6.4-3).

Although Equation 2 strictly applies only at the current sheet, Cummings *et al.*, (1987, SH6.4-3) used it and the observed ratio of $G_{|z|}$ and G_r to estimate $\kappa_\perp/\beta$ for various species of galactic and anomalous cosmic rays having different rigidities. The top panel of Figure 13 illustrates that the ratio of $G_r/G_{|z|}$ is remarkably similar for all of the measured species, while the lower panel shows the corresponding estimates of $\kappa_\perp/\beta$ derived using Equation 2. Although the well-organized character of the results does not prove that Equation 2 is applicable near the current sheet, it is consistent with that possibility. Since $\kappa_\perp/\beta$ should be independent of particle type and vary according to the rigidity dependence of the perpendicular mean free path, the results in Figure 2 suggest that $\lambda_\perp$ is proportional to rigidity. When compared to estimates of $\kappa_\perp/\beta$ at 1 AU, the values in Figure 13 are reasonable if $\kappa_\perp$ scales inversely with magnetic field strength (see, e.g. Jokipii and Davila, 1981, and Newkirk and Fisk, 1985).

Dependence on Magnetic Polarity. Although the above results are consistent with the presence of particle drifts, none provide definitive evidence, since during the present solar cycle negative latitudinal gradients can arise under suitable circumstances from either an increasing solar wind velocity or from drifts. However, the sign of the gradient should reverse with the reversal of the solar magnetic field if drifts are responsible, but not if the latitudinal increase in the solar wind velocity is responsible.

Fortunately, the solar magnetic field reverses from one 11-year cycle to the next, and measurements are available from the last solar cycle when Pioneer 11 was more than 10° above the ecliptic plane for a period of 21 months in 1975-76. During this period of minimum solar activity, the current sheet dropped below Pioneer 11, providing the first direct evidence that the sector structure of the interplanetary field was due to a warped or tilted near-equatorial current sheet (Smith *et al.*, 1978).

As discussed above, observations made above the maximum latitudes reached by the current sheet are expected to provide the most reliable indication of latitudinal gradients. Although there were significant long term variations in the cosmic ray fluxes that had to be taken into account, McKibben *et al.* (1979) and Bastian *et al.* (1979), nevertheless concluded from comparisons of Pioneer 11 with Pioneer 10 and IMP 8 that there were significant positive latitudinal gradients in both the anomalous helium and galactic proton fluxes. Their 1976 results are compared with the 1986 results in Table 2. Both species not only exhibit the sign reversal expected if drifts are responsible, but the magnitudes of the gradients for a particular species are essentially the same in the two cycles.

TABLE 2: LATITUDINAL GRADIENTS AND MAGNETIC POLARITY

		G_Θ(%/Degree)	
Year	Polarity	Galactic Protons	Anomalous Helium
1976	+	+1.2±0.4	+2.0±0.5
1986	-	-0.9±0.1	-2.2±0.7

Sources: 1976 - Bastian *et al.*, 1979; 29-67 MeV protons; 11-20 MeV/nuc He
1986 - Cummings *et al.*, 1987; 130-120 MeV protons (derived from McDonald and Lal, 1986); 10-21.7 MeV/nuc He

Summary. During the current solar minimum, durable negative latitudinal gradients are observed in the fluxes of anomalous helium and oxygen and galactic hydrogen and helium. The latitudinal gradients are larger than the radial gradients, indicating a significant spherical asymmetry in the inward flow, with particles preferentially streaming into the heliosphere at low latitudes. The negative gradients have been observed consistently since early 1985 when the current sheet dropped below the latitude of Voyager 1, suggesting that the gradients are relative to the current sheet rather than the ecliptic plane. The latitudinal gradients during 1985-87 are opposite in sign from those observed by Pioneer 11 in 1976 when the solar magnetic field was also of opposite polarity, as predicted if particle drifts are present during solar minimum conditions when the interplanetary medium is least disturbed, and indicating that particle drifts must be included in models of solar modulation.

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