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LATITUDINAL AND RADIAL GRADIENTS OF ANOMALOUS AND GALACTIC COSMIC RAYS IN THE OUTER HELIOSPHERE

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Abstract. We have used measurements from instruments on Voyagers 1 and 2 and Pioneer 10 to derive simultaneous radial and latitudinal gradients of anomalous cosmic-ray oxygen during the latter part of 1985. We find that in the energy interval from 7.1-30.6 MeV/nucleon the latitudinal gradient is -3 to -4 %/deg. The sign of the latitudinal gradient is opposite to that reported for the last solar cycle when the solar magnetic field polarity was reversed, as predicted by propagation models in which curvature and gradient drifts are significant. The ratios of the radial and latitudinal gradients of anomalous oxygen, anomalous helium, and galactic cosmic rays are similar, also in agreement with drift theory predictions. Based on drift theory, these observed ratios, which are near unity, lead to estimates of $\kappa_\perp/\beta$ in the range of $3\text{-}8 \times 10^{22}$ cm^2/sec at 24.9 AU for particles with rigidities of ~2-3 GV.

Introduction

Although the role of curvature and gradient drifts in the solar modulation of cosmic rays has been theoretically studied for some time (see, e.g., Jokipii et al. [1978]), it has been difficult to provide a clear experimental demonstration of the importance of drift effects. Among the most specific predictions of drift theory are that the sign of the latitudinal gradient should reverse with the reversal of the solar magnetic field. The theory also makes specific predictions about the ratio of the latitudinal and radial gradients of cosmic rays and its relationship to the perpendicular diffusion coefficient [Levy, 1978]. Because the tilt of the current sheet decreased abruptly in mid-1985 from ~45° to ~20° [Christon et al., 1986], it is now possible to measure the radial and latitudinal gradients for a variety of species in order to address these predictions.

The first observations of persistent large-scale negative cosmic-ray latitudinal gradients have recently been reported by Christon et al. [1986] for >70 MeV protons and helium and by McDonald and Lal [1986]. In this Letter we present measurements of the spectra of anomalous cosmic-ray (ACR) oxygen from the Cosmic Ray System (CRS) on V1 and V2 (described by Stone et al. [1977]) and from the Goddard-University of New Hampshire cosmic-ray experiment on Pioneer 10 (P10) (described by McDonald et al. [1977]) for the period 1985 day 208 to 1986 day 52. The location of these spacecraft during this time period permits a separation of the radial and latitudinal gradients. We also perform a similar three-spacecraft analysis for galactic cosmic-ray (GCR) nuclei with >70 MeV/nuc using penetrating particle rates (dominated by protons), so that a similar determination of both the radial and latitudinal gradients of these particles can be obtained.

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Observations

The energy spectra of ACR oxygen from the V1, V2, and P10 measurements are shown in Figure 1. The Voyager spectra have been corrected for interplanetary and GCR contributions by a method described in Cummings et al. [1986a]. The P10 spectrum shown in Figure 1 is the uncorrected observed spectrum of oxygen. Since the radial position of P10 is much larger than that of the Voyager spacecraft, the low-energy interplanetary and GCR corrections are expected to be smaller than for the Voyager data.

The striking feature of Figure 1 is that the V1 intensities are ~30-40% lower than those of V2 even though V1 is 6.5 AU farther from the Sun than V2. The P10 intensities are larger than those at V2 as would be expected for a positive radial gradient. Since V1 is out of the heliographic equatorial plane (~27° N) and V2 and P10 are near the plane, the data of Figure 1 indicate that there is a negative latitudinal gradient for ACR oxygen from 7.1-30.6 MeV/nuc.

In deriving radial and latitudinal gradients we assume that the particle intensities are not a function of heliolongitude and that the radial and latitudinal gradients are independent of radius and latitude between V2 and P10. With these assumptions, the following two equations relate the ratio of the fluxes (f_i where i denotes the spacecraft) in a particular energy interval to the radial (G_r) and latitudinal (G_Θ) gradients:

$$\ln\frac{f_1}{f_2} = G_r(r_1-r_2) + G_\Theta(\Theta_1-\Theta_2) \qquad (1)$$

$$\ln\frac{f_{10}}{f_2} = G_r(r_{10}-r_2) + G_\Theta(\Theta_{10}-\Theta_2) \qquad (2)$$

where r_i and Θ_i denote the radial and latitudinal positions of spacecraft i.

The radial and latitudinal gradients derived from these equations using the spacecraft positions and measured flux ratios are displayed in Table 1. The latitudinal gradient for ACR oxygen is negative with a magnitude in the range of 3-4%/deg. The radial gradient

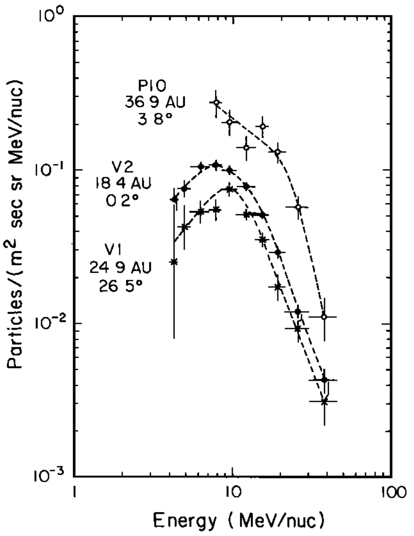

Fig. 1. Energy spectra of anomalous oxygen at V1 (×), V2 (●), and P10 (○) for the time period 1985/208-1986/52. The dashed lines are drawn to guide the eye. The heliographic radius and latitude of the spacecraft are also shown. The heliographic longitudes are 332°, 2°, and 175° for V1, V2, and P10, respectively.

for the same particles is positive, ~5-9%/AU, somewhat smaller than that observed during the period 1977-1985 [Webber et al., 1985]. The latitudinal gradient for the >70 MeV/nuc nuclei, -0.34 ± 0.08%/deg, is in good agreement with the value of -0.36 ± 0.05%/deg derived for >70 MeV protons by Christon et al. [1986] for a slightly different time period. We also show in Table 1 our calculation of the latitudinal and radial gradients of protons and helium based on the measurements of McDonald and Lal [1986], which were made at almost the same radial position (25.5 AU).

It is useful to express the latitudinal gradient in terms of the perpendicular distance $|z|$ from the heliographic equator. This quantity, $G_{|z|}$, and the ratio $G_r/G_{|z|}$ at the radial position of V1 (~25 AU) are shown in Table 1 and plotted versus median rigidity in Figure 2a. It is striking that this ratio is approximately the same for the wide variety of particle types and energies shown in Table 1, including ACR oxygen, GCR and ACR helium, GCR protons, and high-energy GCR nuclei. Furthermore, the value of this ratio is of order unity, indicating a significant deviation from spherical symmetry in the distribution of particles in the outer heliosphere with both galactic and anomalous cosmic-ray components penetrating inward preferentially at low latitudes.

Discussion

The ACR component consists of enhanced fluxes of He, N, O, and Ne with energies below ~50 MeV/nuc [Garcia-Munoz et al., 1973; Hovestadt et al., 1973; McDonald et al., 1974], which are thought to be interstellar neutrals which drift into the heliosphere, become singly ionized, and are then convected to the outer heliosphere where they are accelerated [Fisk et al., 1974].

There have been two other measurements of latitudinal gradients of the ACR component. McKibben et al. [1979] and Bastian et al. [1979] reported a positive latitudinal gradient of ~1-2%/deg for 11-67 MeV/nuc ACR helium for an extended period in 1976 when Pioneer 11 reached a maximum heliographic latitude of 16°N. Cummings et al. [1986a] and Webber et al. [1985] reported a positive latitudinal gradient of ~3%/deg for 7.1-10.6 MeV/nuc ACR oxygen for a two-year period from 1983-1985. The measurements reported here are the first observation of negative latitudinal gradients for the ACR component.

The positive gradient reported by Webber et al. [1985] was obtained during a period when the energy spectra of ACR oxygen at V1 and V2 differed only at the lowest energies [Cummings et al., 1986a], leading to an apparent positive latitudinal gradient in the low-energy interval. By the time of the period considered here, the spectra had evolved so that they have similar shapes (see Figure 1), and the latitudinal gradients in all three energy intervals have the same sign. Unlike the previous measurement, which was made when the tilt of the current sheet was large and V1 was sampling from both sides of the current sheet, the present measurement is derived when the estimated current sheet tilt is less than the heliographic latitude of V1 [Christon et al., 1986] so that differences in long-term averages of intensity measured at the Voyager spacecraft can be directly related to latitude for the first time.

The positive latitudinal gradient of ACR helium reported by McKibben et al. [1979] and Bastian et al. [1979] was derived for the last solar minimum period when the solar field polarity was opposite to what it is during the selected period. Because the sign of the helium gradient at that time was opposite to that of ACR oxygen reported here, it suggests that curvature and gradient drifts, which are field-polarity dependent, are important in the propagation of cosmic rays as suggested by Jokipii et al. [1977].

Using drift theory and assuming that the latitudinal gradient is symmetric about the heliographic equator, Levy [1978] derived the following relationship between the ratio of the gradients and $\kappa_\perp$, the perpendicular diffusion coefficient, at the heliographic equator (see also Jokipii and Kopriva [1979]):

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

where R is particle rigidity, βc is the particle velocity, ψ ($=\tan^{-1}(r\Omega/V)$) is the angle of the magnetic field with the Sun-spacecraft line (~90° for the outer heliosphere), and $|B|$ is the magnetic field strength. (The - sign is taken for the current magnetic field cycle, the + sign for the last and next.) Using an Archimedean spiral magnetic field with solar wind velocity, V, of 400 km/sec, $|B|$ at 1 AU = 5×10^{-5} gauss, and solar angular rotation rate, Ω, of 2.92×10^{-6}/sec, we obtain:

$$\kappa_\perp = 9.9\times10^{20}\beta R r^2 \sin(\psi)\cos(\psi)|G_r/G_{|z|}| \tag{4}$$

TABLE 1. Radial (G_r) and Latitudinal (G_Θ and $G_{|z|}$) Gradients and Corresponding Estimates of $\kappa_\perp/\beta$ at ~ 25 AU from Voyager and Pioneer data [a]

Particle Type	Energy (MeV/nuc)	G_r (%/AU)	G_Θ (%/deg)	$G_{|z|}$ (%/AU)	$G_r/G_{|z|}$	Median R (GV)	$\kappa_\perp/\beta$ (cm^2/sec)
ACR O[b]	7.1-10.6	5.0±0.8	-2.9±0.4	-6.6±0.9	-0.75±0.12	2.1[d]	$(3.5\pm0.6) \times 10^{22}$
ACR O[b]	10.6-17.1	5.7±0.7	-3.0±0.3	-6.8±0.7	-0.84±0.08	2.5[d]	$(4.7\pm0.5) \times 10^{22}$
ACR O[b]	17.1-30.6	9.1±0.8	-3.7±0.6	-8.6±1.3	-1.06±0.17	3.3[d]	$(7.8\pm1.2) \times 10^{22}$
GCR nuclei[b]	>70	0.95±0.12	-0.34±0.08	-0.79±0.17	-1.20±0.28	1.9	$(5.0\pm1.2) \times 10^{22}$
Protons[c]	130-210	3.3±0.1	-0.9±0.1	-2.0±0.3	-1.63±0.23	0.6	$(2.2\pm0.3) \times 10^{22}$
Helium[c]	10-21.7	5.3±0.6	-2.2±0.7	-5.0±1.6	-1.06±0.32	0.6[e]	$(1.7\pm0.5) \times 10^{22}$
Helium[c]	30-56	5.0±0.4	-1.6±0.3	-3.7±0.8	-1.37±0.27	0.9[e]	$(3.6\pm0.7) \times 10^{22}$
Helium[c]	140-350	2.1±0.1	-0.8±0.1	-1.8±0.2	-1.21±0.09	1.4	$(4.0\pm0.3) \times 10^{22}$

[a]Uncertainties shown are statistical and do not include any systematic uncertainty arising from the latitudinal and radial averaging. [b]This work. [c]Derived from observations of McDonald and Lal [1986]. [d]Assumes particles are singly charged. [e]Assumes 60% of particles are singly charged.

where r is in AU and R is in GV. For the position of V1 (r = 24.9 AU) where these measurements are inferred, $\psi = 87.89°$.

In Table 1 we show the values of $\kappa_\perp/\beta$ deduced from the values of $G_r/G_{|z|}$, assuming the ACR oxygen particles are singly ionized. These values for ACR oxygen are in the range $3\text{-}8 \times 10^{22}$ cm^2/sec for median rigidities of ~2-3 GV. We also show $\kappa_\perp/\beta$ for the >70 MeV/nuc nuclei and for the measurements of McDonald and Lal [1986]. In order to assign a rigidity to the helium particles in the 10-56 MeV/nuc interval, we had to estimate what fractions were singly-charged ACR and doubly-charged GCR helium. To do so, we normalized the GCR ^{4}He energy spectrum from Cummings et al. [1986b] to the observed ^{4}He intensity at 100 MeV/nuc. This normalized GCR spectrum accounted for ~40% of the flux in the 10-56 MeV/nuc interval and is thus doubly ionized. We have used this same fraction in calculating the median rigidities for the 10-21.7 and 30-56 MeV/nuc intervals. It should be noted that the values of $\kappa_\perp/\beta$ in Table 1 should be regarded as estimates because the gradients are averaged over ~ 40° in latitude and ~ 20 AU in radius, whereas Equation 3 is strictly valid only locally at the current sheet.

Since $\kappa_\perp/\beta$ is proportional to the scattering mean free path, $\lambda_\perp$, it should be independent of particle type, varying as $\lambda_\perp$ depends on rigidity. In Figure 2b we plot the values of $\kappa_\perp/\beta$ versus median rigidity. These data are reasonably well represented by a power-law relationship with $\kappa_\perp/\beta \propto R^{0.6\pm0.1}$.

Assuming that $\kappa_\perp/\beta$ varies inversely with the magnetic field strength [Jokipii and Davila, 1981] leads to a radial scaling $\propto r^2(1+(r\Omega/V)^2)^{-1/2}$. Using this scaling for the range of $\kappa_\perp/\beta$ in Table 1 of $1.7\text{-}7.8 \times 10^{22}$ cm^2/sec at ~25 AU, we obtain $\kappa_\perp/\beta = 0.5\text{–}2 \times 10^{21}$ cm^2/sec at 1 AU, consistent with the range of values summarized by Palmer [1982].

Latitudinal gradients may also result from a latitudinal variation in the solar wind velocity (see, e.g., Newkirk and Fisk [1985] and McDonald and Lal [1986]). During periods of low solar activity the solar wind speed increases from ~350 km/sec near the heliographic equator to a plateau of ~600 km/sec at latitudes of ~30°-40° (see Newkirk and Fisk [1985] and references therein). Using a simple spherically-symmetric model of modulation we find that an increase of ~50 km/sec in the solar wind velocity can produce the observed depression of the V1 flux. However, such a simple model predicts a negative latitudinal gradient during both solar magnetic cycles, contrary to the observations.

Our observations, taken together with those of McKibben et al. [1979] and Bastian et al. [1979], imply that the sign of the latitudinal gradient changes with

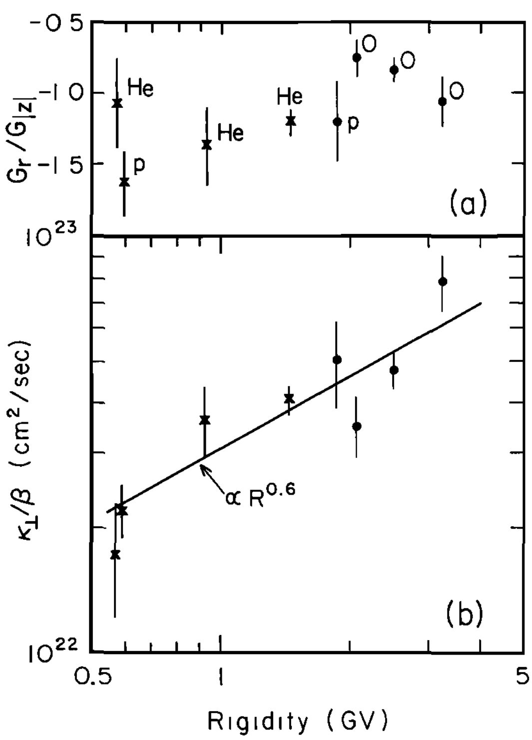

Fig. 2. (a) Values of $G_r/G_{|z|}$ from our measurements (●) and from those of McDonald and Lal [1986] (×) versus median rigidity for p, He, and O. (b) Estimates of $\kappa_\perp/\beta$ as deduced from the measurements. The straight line is a least-squares fit to the data.

solar magnetic field polarity, in agreement with a major prediction of drift theory. We also find that the observed ratios of the radial and latitudinal gradients are essentially the same for both the anomalous and galactic cosmic ray components. These measurements can be used to make estimates of $\kappa_\perp$ within the framework of drift theory.

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