TIME VARIATION OF RADIAL AND LATITUDINAL GRADIENTS OF ANOMALOUS COSMIC RAY OXYGEN IN THE OUTER HELIOSPHERE

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Abstract

We have used data from the Voyager 1 (V1), Voyager 2 (V2), and Pioneer 10 (P10) spacecraft to monitor the radial and latitudinal gradients of anomalous cosmic ray oxygen in the energy range 7.1 - 17.1 MeV/nuc from 1984 to 1989. We find that the latitudinal gradient varies from near zero value in 1984-85 to -5.5%/deg in mid-1987, returning to near zero value by the end of 1988. The magnitude of the latitudinal gradient is inversely correlated with the radial gradient. The variations in the radial and latitudinal gradients are correlated with the tilt of the neutral sheet for tilts $\lesssim 30^\circ$, as expected from a simple model of particle propagation which includes curvature and gradient drifts in the large-scale heliospheric magnetic field.

Introduction. Several studies of anomalous cosmic ray (ACR) oxygen gradients in the outer heliosphere have revealed that after the middle of 1985 the latitudinal gradient of these particles is negative and the radial gradient is relatively small (Cummings et al., 1987a; Cummings et al., 1987b; Cummings and Stone, 1988). Cummings et al. (1987b) observed that the latitudinal gradient was more negative during the period 1986/206-310 than during 1985/208-1986/52 and suggested that the decreasing tilt of the neutral sheet was responsible. In this paper we extend these previous observations for ACR oxygen to 26 time periods between 1984 and 1989. We note that Smith and Thomas (1986) have previously pointed out a correlation between cosmic ray modulation level and neutral sheet tilt angle.

Observations. The fluxes of ACR oxygen at V2, V1, and P10 in the energy range 7.1 - 17.1 MeV/nuc are shown in Figure 1. The average radial positions of the spacecraft corresponding to the periods shown are: V2 13.4 - 28.3 AU; V1 18.6 - 36.6 AU; and P10 32.4 - 45.6 AU. V1 is well above the heliographic equatorial plane throughout the period, increasing from 21.9° in 1984 to 30.2° N latitude at the end of 1988 (see Figure 2b), whereas V2 and P10 remain close to the equator ($\lesssim 4^\circ$).

A comparison of the P10 and V2 fluxes in Figure 1 indicates that the radial gradient is always positive, gradually decreasing from 1984 to mid-1987 and increasing thereafter. The latitudinal gradient varies in magnitude as well, as indicated from a comparison of the V1 and V2 flux profiles.

In order to derive quantitative latitudinal and radial gradients for each time period we follow the method of Cummings et al. (1987a), in which the fluxes at the three spacecraft are used to determine two parameters: the average radial and latitudinal gradients. The latitudinal gradients so derived are shown in the top panel of Figure 2.

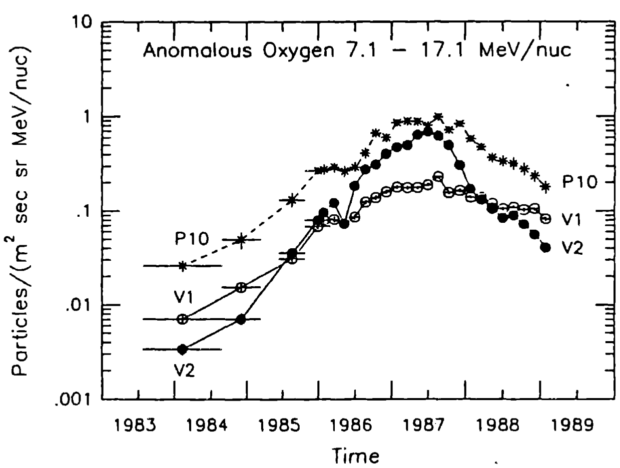

Figure 1. Fluxes of ACR oxygen at three spacecraft versus time.

It is instructive to compare the variation in the gradients with the variation in the tilt angle of the neutral sheet, averaged over the region between V2 and P10. The tilt angle midway between V2 and P10 was estimated from the coronal neutral sheet tilt value, kindly provided for each solar rotation by Hoeksema (1989), taking into account the delay time corresponding to an outward propagation at 400 km/sec. In order to account for variations in the neutral sheet tilt in the region between V2 and P10, a 3-solar rotation moving average has been used. This averaging period closely matches the ~80-day solar wind propagation time between the two spacecraft. The resulting average tilt of the neutral sheet between V2 and P10 is shown in Figure 2b.

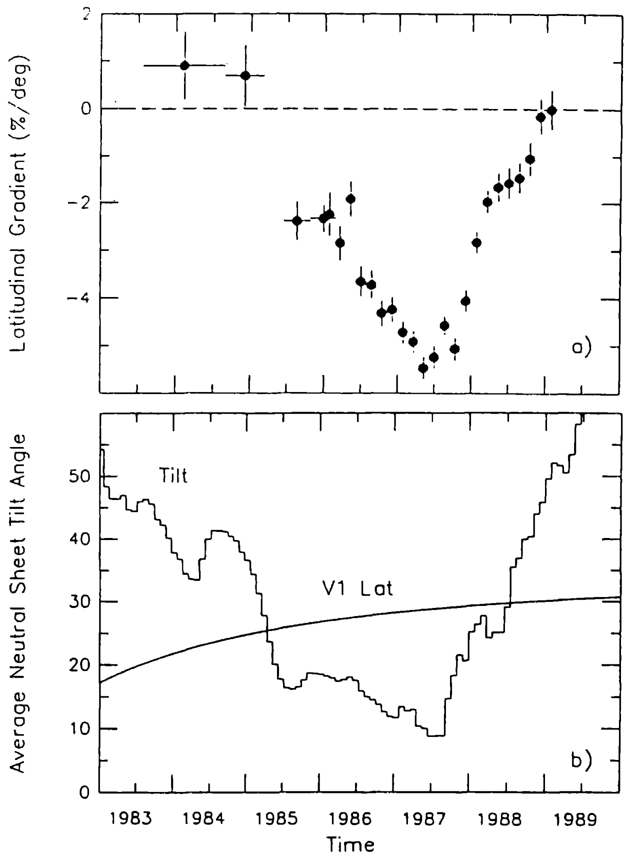

Figure 2. (a) Latitudinal gradients of ACR oxygen in the energy range 7.1 - 17.1 MeV/nuc computed from V1, V2, and P10 data versus time. (b) Time-shifted and time-averaged neutral sheet tilt angle (as described in the text) versus time (histogram). The solid line is the heliographic latitude of V1.

From Figure 2 we note that there appears to be a good correlation between the tilt of the neutral sheet and the magnitude of the latitudinal gradient. The latitudinal gradient first becomes negative in mid-1985 when the neutral sheet tilt drops below the latitude of V1 (shown in Figure 2b), an observation that has been reported earlier for both anomalous and galactic cosmic rays (Christon et al., 1986; Cummings et al., 1987a). The latitudinal gradient reaches a maximum value of -5.5%/deg in the time period 1987/105-157. At 30 AU, the average radial position of V1 at that time, this latitudinal gradient, when expressed as a spatial gradient perpendicular to the heliographic equatorial plane (G_z), is -10.3%/AU. The observed radial gradient at the same time is only 2.2%/AU, indicating the large spherical asymmetry of the distribution of these particles. As the tilt of the neutral sheet increases after mid-1987 the latitudinal gradient returns to near zero values by the end of 1988.

In Figure 3 we display the radial gradients determined for the 26 time periods as a function of the average tilt from Figure 2b. The radial gradient is well-correlated with the tilt of the neutral sheet for tilts $\lesssim 30°$. Above 30° the gradient appears to "saturate" at ~8 - 10%/AU.

In Figure 4 we plot the latitudinal gradient, G_z, at the radial position of V1 versus the radial gradient for all 26 data points. The radial and latitudinal gradients are well-correlated for all tilt angles, ~9 - 50°. There appears to be no "hysteresis" in this correlation, as indicated by the good agreement in the measurements before and after the mid-1987 period. In paper SH6.4-12 of this conference, Moraal (1990) uses this correlation to make quantitative estimates of diffusion coefficients in the outer heliosphere.

Discussion. The negative latitudinal gradients shown in Figure 2a for the period 1985-1989 contrast with the positive latitudinal gradients reported for anomalous and galactic cosmic rays in 1976 (McKibben et al., 1979, and Bastian et al., 1979). Because the polarity of the Sun's magnetic field reversed in ~1980, such a reversal in the sign of the latitudinal gradient is expected if curvature and gradient drifts (Jokipii et al., 1977), which are field-polarity dependent, are important in the propagation of cosmic rays during periods of minimum solar activity and minimum neutral sheet tilt. According to drift theory, positive particles would drift rapidly inward from the boundary along the neutral sheet during the current solar minimum period (~1987). The particles scatter off the neutral sheet via perpendicular diffusion and drift toward the poles, leading to a negative latitudinal gradient, as observed. During the previous solar minimum period (1972-77), positive particles would have the opposite drift pattern, entering the observable regions of the heliosphere by drifting toward the equator from the poles, leading to a positive latitudinal gradient.

The correlation of the radial gradient with the tilt as shown in Figure 3 adds new support to the drift theory. If the particles are rapidly drifting in along the neutral sheet, and if the neutral sheet is deformed as indicated by the tilt, then one would expect that the distance along the neutral sheet between two spacecraft would be an important parameter in analyzing the radial gradient. As the tilt decreases, the spacecraft are closer together as measured along the sheet and hence the observed radial gradient would appear to decrease. This is just the correlation shown in Figure 3.

It is likely that this simple picture would break down for large tilts. For example, for a tilt of 30° and assuming that the neutral sheet is a sine wave with wavelength 6.3 AU, the distance along the neutral sheet between radial positions 30 and 36 AU is ~70 AU. If the perpendicular diffusion coefficient, $\kappa_\perp$, is large enough, the drifting particles would tend to "short-circuit" the large waves of the neutral sheet and propagate in primarily by diffusion. From Figure 3, this effect may be responsible for the saturation of the radial gradient for tilts $\gtrsim 30°$.

From the preceding discussion we construct a simple model of particle propagation in which we specify the differential spatial gradient along the neutral sheet (spatial

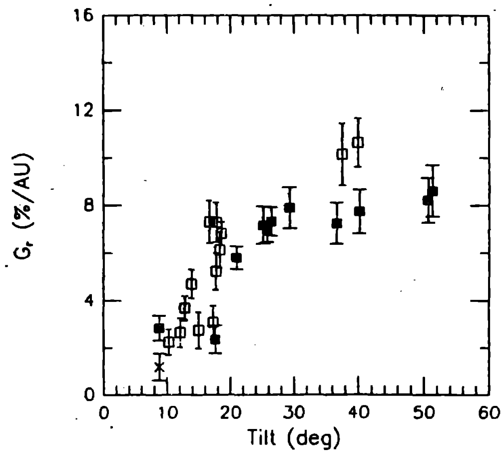

Figure 3. Radial gradient of ACR oxygen between the radial positions of V2 and P10 versus neutral sheet tilt angle (from Figure 2b) for the 26 time periods of Figure 1. The open squares refer to data before 1987.5, the filled squares to data after 1987.5, and the cross to data at 1987.5.

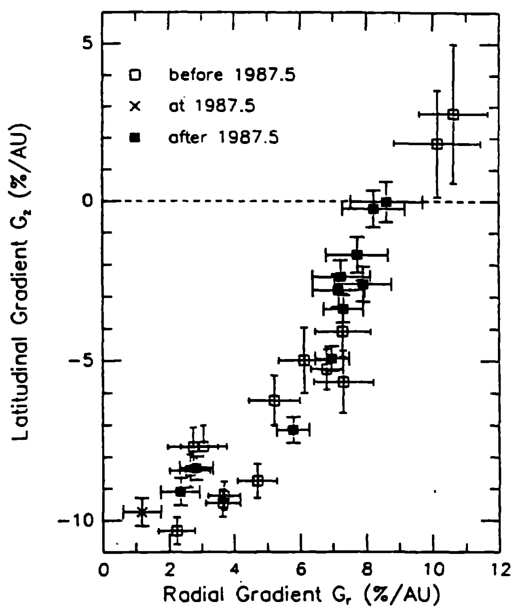

Figure 4. Latitudinal gradient perpendicular to the heliographic equator at the radial distance of V1 versus radial gradient for the 26 time periods of Figure 1.

coordinate "s") and calculate for each time period the expected radial gradient we should observe, derived from the radial positions of V2 and P10 and the tilt of the neutral sheet. By analogy with the relationship derived by Levy (1978) for a flat neutral sheet, we assume that $(1/f)(\partial f/\partial s) \sim (1/f)(\partial f/\partial\theta)\kappa_{\perp}/r^2$, where r is heliographic radius, θ is latitude, and f is flux. With the usual assumption that $\kappa_{\perp}\sim r$ and assuming that $(1/f)(\partial f/\partial\theta)$ is independent of r, this approach suggests that $(1/f)(\partial f/\partial s) \sim 1/r$. (The results are not very sensitive to the exact form assumed for this radial variation.) We then compute the expected radial gradient, G_r, from

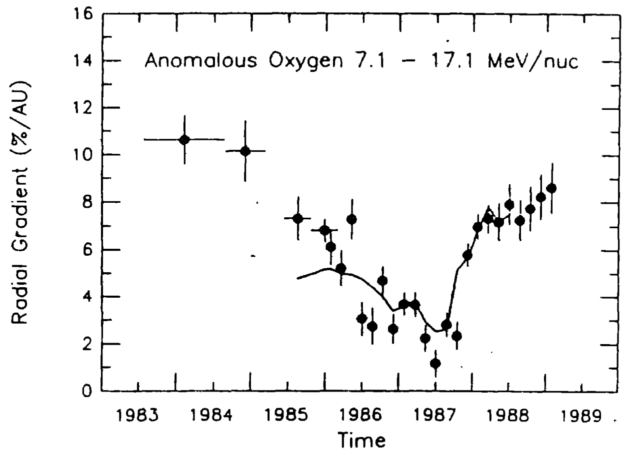

Figure 5. Radial gradient of ACR oxygen from V1, V2, and P10 data versus time (filled circles) and model fit as described in the text (solid line).

$$G_r = \frac{\int_{r_{V2}}^{r_{P10}} \frac{1}{f}\frac{\partial f}{\partial r}dr}{(r_{P10} - r_{V2})} = \frac{\int_{r_{V2}}^{r_{P10}} \frac{1}{f}\frac{\partial f}{\partial s}\frac{ds}{dr}dr}{(r_{P10} - r_{V2})} = \frac{\int_{r_{V2}}^{r_{P10}} \frac{A}{r}\frac{1}{\cos\beta}dr}{(r_{P10} - r_{V2})}$$

where β is the angle between the neutral sheet and the radius vector and is given by (see Jokipii and Thomas, 1981):

$$\beta = \tan^{-1}\left\{\frac{2\pi r}{\lambda}\sin\alpha\cos\left(\frac{2\pi r}{\lambda}\right)\left[1 - \sin^2\alpha\sin^2\left(\frac{2\pi r}{\lambda}\right)\right]^{-1/2}\right\}$$

where α is the tilt of the neutral sheet and λ is the wavelength. The parameter A (= 23.6%/AU at 1 AU) is determined from a least-squares fit to the data, including only those time periods for which the tilt $< 30°$.

Figure 5 shows the observed radial gradients for all 26 time periods (filled circles) and the expected values from the simple model (solid line). The model reproduces the variation of the radial gradient surprisingly well considering its simplicity, suggesting that for tilt angles $\lesssim 30°$, gradient and curvature drifts and the neutral sheet play important roles in the propagation of particles in the outer heliosphere.

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