INTENSITY GRADIENTS OF ANOMALOUS COSMIC RAY OXYGEN THROUGHOUT THE HELIOSPHERE

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ABSTRACT

We use anomalous cosmic ray oxygen energy spectra collected from five different locations in the heliosphere during three time periods to estimate the radial and latitudinal gradients of the particle intensities at three energies. The three periods include the two high-latitude passes of Ulysses over the solar poles and the last few months of the cosmic ray oxygen data from Pioneer 10. The radial gradient is modeled as a power law in radius and the latitudinal gradient is assumed to be constant. The gradients are analyzed in two ways: the first uses the actual average spacecraft latitudes and the second assumes the symmetry plane of the heliosphere is at 10° S in heliolatitude. Reasonable fits are obtained under either assumption concerning the location of the symmetry plane, although the latitudinal gradients are smaller by a factor of ~2 if the symmetry plane is offset by 10° S. The radial gradient exhibits a radial dependence of $\sim r^{-1}$ or r^{-2} depending on whether the symmetry plane is the helioequator or not, respectively. The r^{-2} dependence is not consistent with the gradient measured in a similar part of the solar cycle ~20 years ago, suggesting that the helioequator is the likely plane of symmetry for these particles. The only significant difference in oxygen flux between polar passes occurs at <10 MeV/nuc and is similar to that observed one year earlier in the outer heliosphere due to decreasing solar modulation.

INTRODUCTION

Anomalous cosmic rays (ACRs) are energetic particles which are thought to be accelerated from the pickup ion distribution at the solar wind termination shock (Pesses et al. 1981). The termination shock has not been crossed by any of the outer heliosphere spacecraft and the radial gradient of these particles has always been positive since the first reports in the late 1970s. The latitudinal gradient of ACRs has been measured as generally positive in the so-called A>0 portion of the solar cycle (the current period) (Cummings et al. 1995*b*, Trattner et al. 1996) and negative in the A<0 portion (Cummings et al. 1987, McKibben 1989). This is thought to be due to the change in direction of the drifts of the particles in the Sun's magnetic field when the solar field reverses (Jokipii et al. 1977).

Most studies of three-dimensional particle distributions in the heliosphere have assumed that the helioequatorial plane is a plane of symmetry for the particle distributions. Recently, studies from Ulysses high-latitude pass data showed that larger fluxes of low energy cosmic rays were observed in the northern polar region as compared to the southern polar region and that the plane of symmetry of the particle distributions appears to be located at ~ 10° S in heliolatitude (Simpson et al. 1996, McKibben 1997). In this study of the radial and latitudinal gradients of cosmic ray oxygen, we use data from six spacecraft at five different locations in the heliosphere to estimate the gradients assuming either that the plane of symmetry is the helioequator or assuming it is at 10° S. We select three

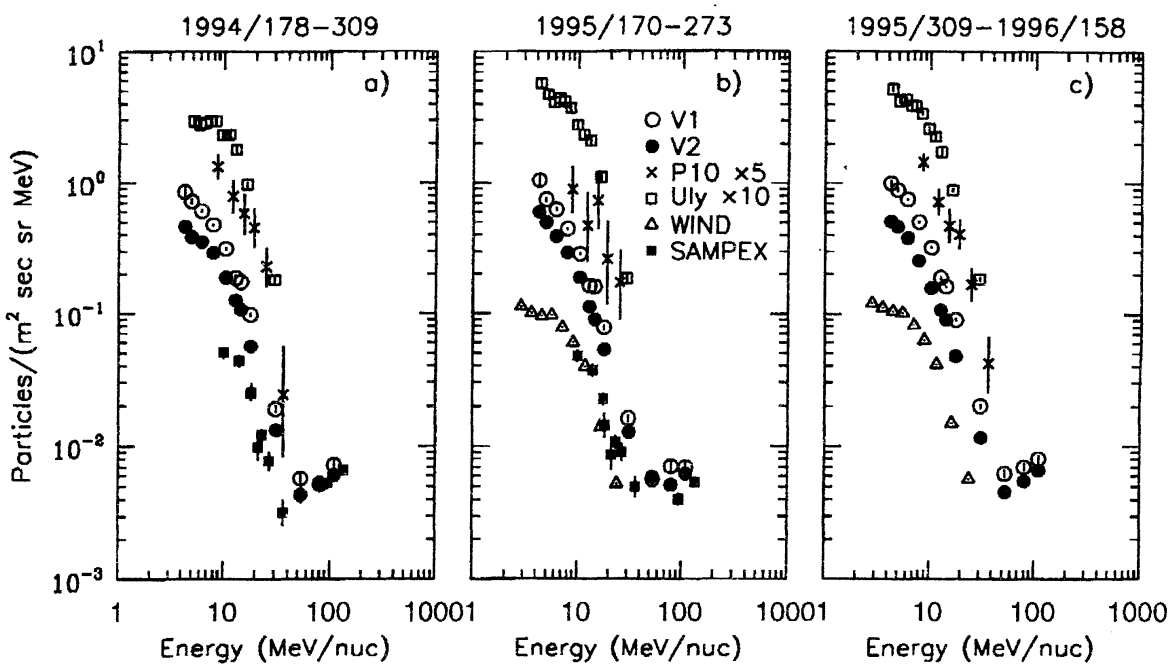

Fig. 1: a) Energy spectra of oxygen at the positions of five spacecraft for the period 1994/178-309. The symbol table is shown in b). For clarity, the Ulysses and P10 fluxes have been multiplied by the factors shown before plotting. b) Same as a) except for period 1995/170-273. Six spectra are shown. c) Same as a) except for period 1995/309-1996/158.

time periods, two of which are for the times when Ulysses was within 20° of the Sun's poles, and the other is for the last of the Pioneer 10 (P10) cosmic ray oxygen data (see Table 1).

Table 1: Average locations of the spacecraft for three time periods

S/C	1994/178-309		1995/170-273		1995/309-1996/158	
	r	Θ	r	Θ	r	Θ
	AU	deg	AU	deg	AU	deg
Voyager 1	56.9	32.6	60.3	32.8	62.2	32.9
Voyager 2	43.8	-12.3	46.5	-14.3	47.2	-15.3
Pioneer 10	60.4	3.1	62.8	3.0	64.2	3.0
Ulysses	2.4	-76.2	2.1	76.1	3.3	47.2
"1 AU"	1.0	5.8	1.0	5.6	1.0	-3.5

OBSERVATIONS

The energy spectra are shown for three time periods in Figure 1. These were fit with an exponential in energy/nucleon in order to interpolate fluxes at three common energies: 5, 10, and 20 MeV/nuc. For SAMPEX and Pioneer 10 the fit was used to extrapolate down to 5 MeV/nuc.

We use the same techniques to estimate the radial and latitudinal gradients as in previous multi-spacecraft studies (Cummings et al. 1990, Cummings et al. 1995*a*, Cummings et al. 1995*b*). The latitudinal gradient is assumed to be constant and the differential radial gradient $g_r = (1/f)(\partial f/\partial r)$ is assumed to be proportional to r^{-n}. A 5% systematic error was added in quadrature to the statistical error for each flux value to account for normalization uncertainties between the spacecraft.

In Figure 2 we show representative least-squares fits for two cases. For the case with an offset

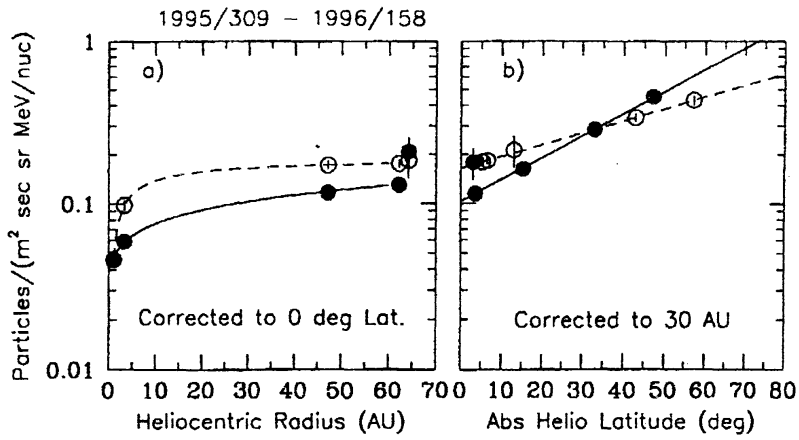

Fig. 2: a) Flux of oxygen at 10 MeV/nuc versus heliographic radial distance for the time period 1995/309 - 1996/158. The fluxes have been corrected to 0° *using the latitudinal gradients (solid and dashed lines) in b). The solid circles and solid line refer to the nominal case wherein the plane of symmetry is the helioequator. The open circles and dashed line are for the plane of symmetry located at* 10° *S. The radial gradient power-law indices are -0.84 and -1.60 for the nominal and offset cases, respectively. b) Fluxes as in a), except plotted versus heliographic latitude and corrected to 30 AU using parameters from the least-squares fits to the radial dependence of the radial gradient shown as the solid and dashed lines in a). The values of the latitudinal gradients are +3.1%/deg and +1.7%/deg for the nominal and offset cases, respectively.*

symmetry plane in the fit, 10° was added to the nominal spacecraft latitudes before fitting. For this particular period and energy, the fit with the offset spacecraft latitudes appears to be better than that with the nominal latitudes. However, the overall average reduced χ^2 of the 9 fits (3 time periods and 3 energies) is $\sim$ 1 for both plane-of-symmetry assumptions, so there is no statistical basis for preferring one or the other.

In Figure 3 we show the latitudinal gradients and radial gradient power-law indices for all three fits. For the latitudinal gradients, there is no statistically significant energy dependence to the gradient during any of the time periods. The latitudinal gradient during the most recent period is $\sim$1.5 times larger than in the earlier periods, which may be a result of the smaller tilt of the heliospheric current sheet in the later period at 1 AU. The gradients are smaller by a factor of $\sim$2 if one invokes the offset plane of symmetry. The values of the gradients, $\sim$1-3 %/deg, are in reasonable agreement with earlier estimates for the A>0 portion of the cycle (Cummings et al. 1995*b*, Trattner et al. 1996).

For the radial gradient power-law indices, there appears to be a tendency for the index to be more negative at higher energies, especially in the offset case. The indices are smaller, $\sim$ -1, for the nominal S/C latitude case than for the offset latitude case ($\sim$ -2).

DISCUSSION

During the last A>0 period $\sim$22 years ago, radial gradients of ACR O were reported to be $\sim$25%/AU between 1 and 5 AU and $\sim$10%/AU between 5 and 10 AU (Webber et al. 1979). Such a dependence would imply a radial gradient power-law index in our model of -0.87, similar to the values derived above for a helioequatorial symmetry plane. From inspection of the Ulysses energy spectra in Figures 1a and b, corresponding to the southern and northern high-latitude passes, respectively, it is clear that the asymmetry in fluxes is present only below $\sim$10 MeV/nuc. There is approximately a one year difference in the polar passes and it is likely that the flux difference below 10 MeV/nuc represents the unfolding of the energy spectrum with decreasing modulation. A similar unfolding during a 1 year period from 1993/184-365 to 1994/184-365 is evident in the V1 and V2 energy spectra in the

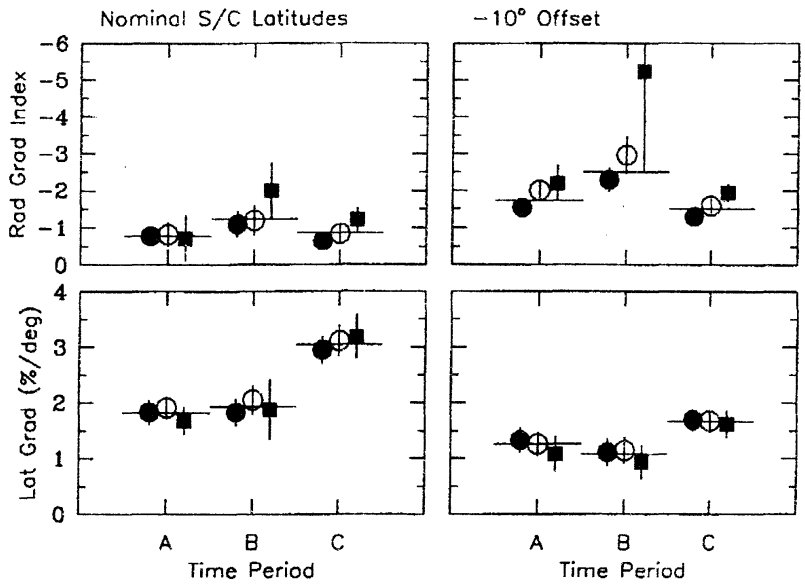

Fig. 3: Latitudinal gradients (bottom) and radial gradient power-law indices (top) for three time periods (A = 1994/178-309; B = 1995/170-273; C = 1995/309-1996/158) and three energies (5 MeV/nuc = solid circle; 10 MeV/nuc = open circle; 20 MeV/nuc = solid square). The fits using actual S/C latitudes are shown on the left; the fits in which 10° *was added to the S/C latitudes are shown on the right. The solid lines are weighted averages.*

outer heliosphere (Stone et al. 1997). Thus, we feel that it is more likely that the plane of symmetry for ACR O is the helioequator and is not offset south by 10°.

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