RADIAL AND LATITUDINAL GRADIENTS OF ANOMALOUS COSMIC-RAY OXYGEN AND HELIUM FROM 1 TO ~41 AU

A. C. Cummings[a], R. A. Mewaldt[a], E. C. Stone[a], and W. R. Webber[b]

a) California Institute of Technology, Pasadena, CA 91125 USA
b) University of New Hampshire, Durham, NH 03824 USA

Abstract

We have used data from the IMP 8, Voyager 1 (V1), Voyager 2 (V2), Pioneer 11 (P11), and Pioneer 10 (P10) spacecraft to determine the radial and latitudinal gradients of anomalous cosmic ray oxygen in the energy range ~7 - 25 MeV/nuc and anomalous cosmic ray helium in the energy range ~20 - 25 MeV/nuc for a time period near minimum solar modulation in 1987. We find that the radial gradients of both species are decreasing functions of radial distance, r, approximately $\propto r^{-1}$ for oxygen and $\propto r^{-0.7}$ for helium. The latitudinal gradient is large and negative, implying significant spherical asymmetry in the heliospheric distribution of these particles.

Introduction. The anomalous cosmic ray (ACR) component is characterized by anomalous enhancements in the fluxes of hydrogen, helium, nitrogen, oxygen, neon, and argon with energies of ~5 to ~50 MeV/nucleon (Christian et al., 1988, and references therein). Recognition that these elements have high first ionization potentials and are therefore neutral in the local interstellar medium led to the widely held model in which anomalous cosmic rays originate as neutral interstellar atoms that drift into the heliosphere (Fisk et al., 1974), become singly-ionized near the Sun, and are then convected outward by the solar wind to the outer heliosphere where the ions are accelerated to higher energies (Pesses et al., 1981; Jokipii, 1986).

The radial gradients of ACR helium and oxygen, the two most abundant species, have been measured since the launch of the planetary probes, P10 in 1972, P11 in 1973, and V1 and V2 in 1977. In previous studies of data from the last solar minimum in 1972-77 it was difficult to separate radial and temporal dependences, as indicated by early suggestions of a radial dependence of the radial gradient of ACR oxygen (Webber et al., 1975; Webber et al., 1979), which were subsequently revised to suggest a near constant radial gradient of ~15%/AU from 1-15 AU (Webber et al., 1981). Analyses of ACR helium fluxes from the University of Chicago experiments on IMP 8, P11, and P10 in 1976 when P11 reached 16° N latitude indicated a positive latitudinal gradient of ~2%/degree (Bastian et al., 1979a) and a radial gradient of ~14%/AU (Bastian et al, 1979b).

More recently, in a study carried out using 5 spacecraft (IMP 8, V1, V2, P11, and P10), Stone et al. (1987) (see also Cummings and Stone, 1988) found that the latitudinal gradient of ACR oxygen was negative during 1986/156 - 1987/53 and the radial gradient showed a definite radial dependence, being much smaller in the outer heliosphere (20 - 40 AU) than in the inner heliosphere. In a companion paper given at this conference, Cummings et al. (1990) show that the radial and latitudinal gradients for ACR oxygen in the outer heliosphere (>20 AU) are correlated and appear to be functions of the tilt angle of the neutral sheet, reaching a minimum of ~2%/AU for the radial gradient and a maximum of ~-5.5%/deg for the latitudinal gradient during the solar minimum period in mid-1987 when the tilt reached its minimum value of ~9° (Hoeksema, 1989).

Observations. In this analysis we present data for both ACR oxygen and helium from 1 to 41 AU using the 5-spacecraft approach. We concentrate on a half-year period near solar minimum in 1987 when the tilt of the neutral sheet was at its minimum value.

Figures 1a and b show ACR oxygen and helium spectra at the 5 spacecraft. In order to compute the radial and latitudinal gradients we have used the following approach. We have computed the least-squares fit factor, A, in the expression

$$(dJ/dE)_i = A(dJ/dE)_{V2}$$

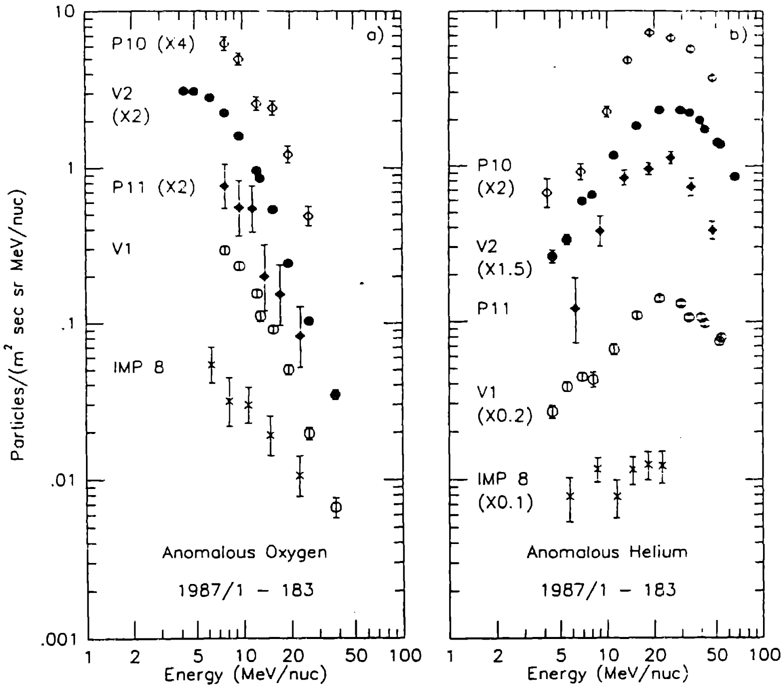

Figure 1. (a) Energy spectra of ACR oxygen at the position of 5 spacecraft for the period 1987/1-183. The heliographic radial and latitudinal positions of the spacecraft are given in Table 1. (b) Same as in (a) but for ACR helium.

where $(dJ/dE)_i$ is the energy spectrum at the i^{th} spacecraft and $(dJ/dE)_{V2}$ is the energy spectrum at V2, which is taken to be a "reference" spectrum. The fit was done by assuming the V2 spectrum could be approximated by power-law segments between the data points. Systematic uncertainties of 5% (1-σ) were assumed in the knowledge of the geometry factors for IMP 8, V1, and V2 and 10% for P10 and P11.

Table 1: Gradient parameters for 1987/1-183

S/C	Heliographic Radius (AU)	Lat. (deg)	ACR O[a] Flux Factor	ACR He[a] Flux Factor
IMP 8	1.0	4.6[b]	0.05 ± 0.01	0.08 ± 0.02
V2	22.5	2.0	1.00 ± 0.05	1.00 ± 0.05
P11	22.9	15.4	0.39 ± 0.08	0.74 ± 0.10
V1	29.9	28.5	0.31 ± 0.02	0.46 ± 0.03
P10	40.7	3.6	1.62 ± 0.18	2.18 ± 0.23

Notes:
a - Includes estimate of systematic uncertainties.
b - Average of absolute value of lat. over time period.

The energies sampled by the oxygen spectra shown in Figure 1a are mostly above the peak energy of 4-5 MeV/nuc (shown for the V2 spectrum), whereas the energies represented by the IMP 8 ACR helium spectrum (Figure 1b) are at the peak energy and below. Since the region of the spectrum below the peak energy is dominated by particles which have been decelerated from higher energies, we have used only the ACR helium data in the peak energy region of ~20-25 MeV/nuc in calculating the helium flux factors. On the other hand, all oxygen data shown in Figure 1a were used in the gradient calculations.

Table 1 shows the heliographic radius and latitude of all 5 spacecraft during this period and the flux factors. The flux factors for ACR oxygen and the latitudinal positions of the spacecraft are plotted versus radial position in Figures 2a and b, respectively. The radial gradient apparently decreases with distance, as shown by the dashed line connecting the flux values from IMP 8, V2, and P10, all of which are near the heliographic equator. The average radial gradient from 1 to 22 AU is ~14%/AU, consistent with measurements in the inner heliosphere in the last half of the solar cycle (Webber et al., 1981; Bastian et al., 1979b). In the outer heliosphere, from 22 to 40 AU, the gradient is much smaller,

~3%/AU. During the last solar minimum all spacecraft were inside 20 AU, so there are no outer heliospheric data with which to compare.

The abrupt change in the gradient at ~20 AU, as depicted by the dashed lines in Figures 2b and c, is rather unlikely. We have explored several smooth functions that have some physical basis. For example, Figures 3a and b show least-squares fits to the oxygen data assuming a constant latitudinal gradient and a differential radial gradient, $g_r = (1/f)(\partial f/\partial r)$, which is proportional to r^n. Figure 3a shows the radial dependence of the flux after correcting for the latitudinal gradient, and Figure 3b shows the latitudinal dependence of the flux corrected to 30 AU. The best-fit value of n is -0.96 and the latitudinal gradient is -5.6%/deg. The sign and magnitude of the latitudinal gradient are quite insensitive to the assumed radial dependence of the radial gradient.

Figures 2c and 4 show the ACR helium data analyzed in the same way as the oxygen. A large negative latitudinal gradient (-4.3%/deg) is clearly present for ACR helium. The radial dependence of the radial gradient is somewhat different from that of ACR oxygen, with the best-fit power-law index being -0.67. This dependence is very sensitive to the value of the flux at 1 AU. We have carefully corrected the observed helium spectrum at 1 AU for galactic cosmic ray (GCR) and solar energetic particle contributions to arrive at the ACR helium spectrum, as in Cummings et al. (1986). The solar contributions are negligible, while the GCR ^{4}He flux is found to range from 20 to 40% of the observed flux, based on the observed flux of GCR ^{3}He.

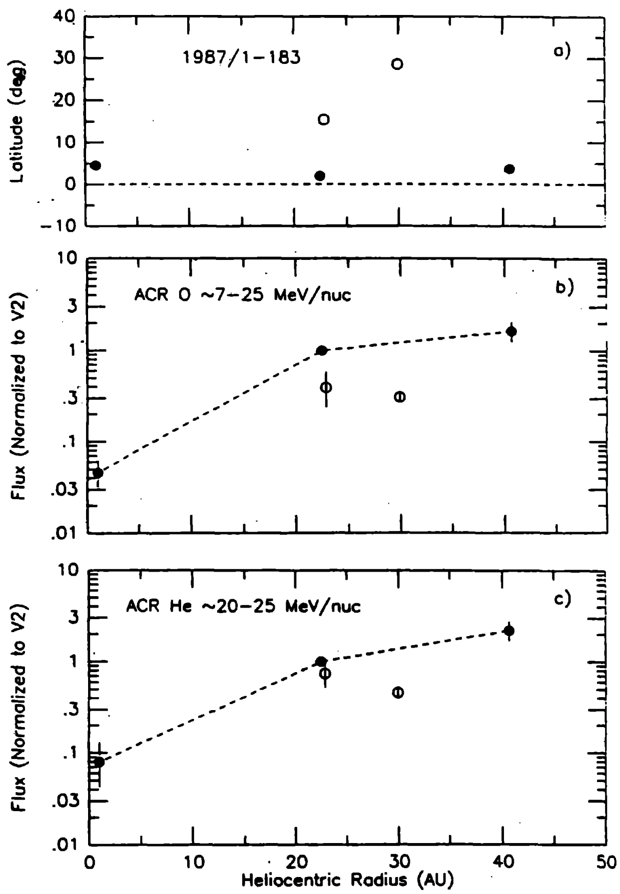

Figure 2. (a) Heliographic latitude of each spacecraft versus radius. The open circles denote spacecraft (V1 and P11) that are significantly north of the heliographic equatorial plane. (b) Flux of ACR O normalized to that measured at V2 versus radius. The dashed line represents one possible radial dependence. (c) Same as (b) but for ACR He.

Discussion. The negative latitudinal gradients of -5.6%/deg for ACR oxygen and -4.3%/deg for ACR helium reported in this study correspond to spatial gradients perpendicular to the heliographic equator of -10.8%/AU and -8.3%/AU, respectively, at 30 AU. This latitudinal gradient is therefore much larger than the ~3%/AU radial gradient observed in the outer heliosphere and implies a large spherical asymmetry of the particle distribution. This finding is consistent with previous reports of large negative latitudinal gradients in the outer heliosphere for both anomalous and galactic cosmic rays (see Stone, 1987, for a review of recent observations).

A radial gradient which decreases with radius might be plausible if the particles are drifting in along the neutral sheet and diffusing perpendicular to the sheet with a perpendicular diffusion coefficient, $\kappa_\perp$, which varies inversely with the magnetic field strength (see, e.g., Jokipii and Davila [1981] and Newkirk and Fisk [1985]). The difference in the radial dependence of the radial gradient of ACR helium and oxygen may be related to the different region of the energy spectra sampled, as discussed above.

We note that with the r^{-1} dependence for ACR oxygen, the gradient would be 37%/AU from 1 to 5 AU, somewhat larger than observed in the previous solar minimum. However, it is also possible that the gradient from 1 - 22 AU more nearly resembles the dashed line in Figure 2b, possibly reflecting a change in the structure in the interplanetary medium, such as the merging of interaction regions beyond ~10 AU (Burlaga et al., 1985).

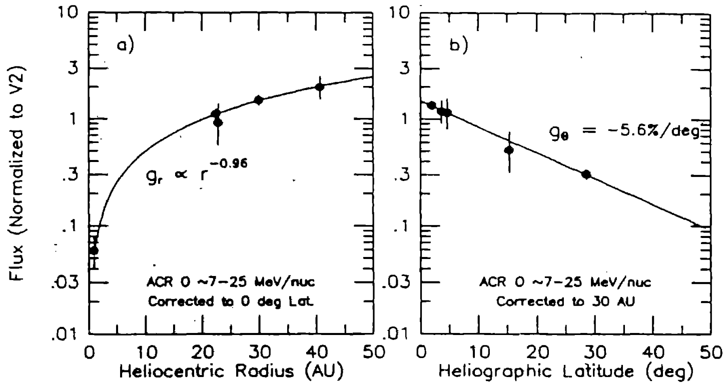

Figure 3. (a) Flux of ACR oxygen versus radial distance for the time period of Figure 2. The fluxes have been normalized to the flux at V2 and have been corrected to 0° latitude using a latitudinal gradient of -5.6%/deg. The solid line is a least-squares fit to the data as described in the text. (b) Fluxes as in (a), except plotted versus heliographic latitude and corrected to 30 AU using parameters from the least-squares fit to the data shown as the solid line.

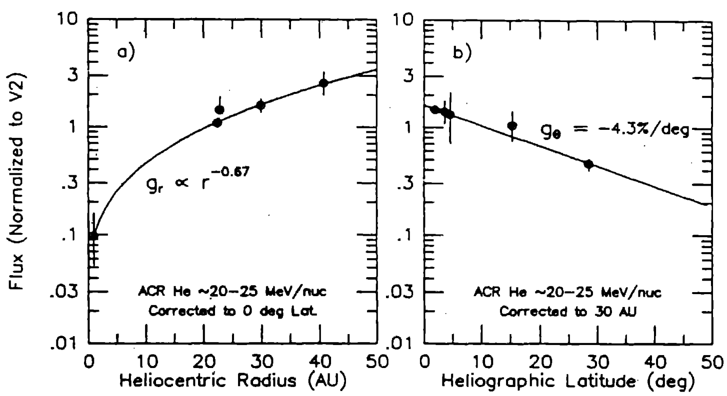

Figure 4. Same as Figure 3a and b except for ACR helium.

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