Radial and Latitudinal Gradients of Anomalous Cosmic Ray Oxygen Throughout the Heliosphere

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Abstract

We have used data from the SAMPEX, Ulysses, Voyager 1 (V1), Voyager 2 (V2), and Pioneer 10 (P10) spacecraft to determine the radial and latitudinal gradients of anomalous cosmic ray oxygen at 10 MeV/nuc during 1994 days 209 - 313. These five spacecraft cover radial distances from 1 AU (SAMPEX) to 61 AU (P10) and latitudes to 80° S (Ulysses) and 33° N (V1). We find that the radial gradient is a decreasing function of radial distance, $\sim r^{-n}$, with $n = 0.7 \pm 0.7$. The large-scale radial gradient between the inner and outer heliosphere is much smaller than it was during the last solar minimum period in ~1987. The latitudinal gradient is small and positive, 2.1 ± 0.6 %/deg, as opposed to the large and negative latitudinal gradients found during 1987, but similar to the small positive latitudinal gradient reported in a similar study for 1993 and also similar to that measured during 1976 for anomalous cosmic ray helium. These observations confirm that effects of curvature and gradient drift in the large scale magnetic field of the Sun are important for establishing the three-dimensional intensity distributions of these particles in the heliosphere during periods of solar minimum conditions.

1. Introduction

Anomalous cosmic rays (ACRs) are thought to be interstellar neutrals [1] which flow into the heliosphere, become ionized by either solar UV or solar wind protons in the interplanetary medium, and are then accelerated in the outer heliosphere, probably at the solar wind termination shock [2]. There are seven known elements that comprise the ACR component: H, He, C, N, O, Ne, and Ar.

According to the theories of particle acceleration and transport which include curvature and gradient drifts in the large-scale heliospheric magnetic field, the spatial distribution of ACRs near solar minimum should depend on the orientation of the Sun's field. When the Sun's magnetic field is directed inward at its North pole, the so-called $A < 0$ period, which last occurred during the 1987 solar minimum and recurs each 22 years, positive particles gain access to the inner heliosphere via rapid inward drift along the neutral sheet. However, during $A > 0$ periods, appropriate to the current study, the particles flow down onto the heliographic equatorial plane from the polar regions [3]. This leads to two predicted effects: a latitudinal gradient which reverses sign between the two periods and a radial gradient which is smaller in the $A > 0$ phase than in the $A < 0$ phase of the solar cycle. During $A < 0$ periods, the latitudinal gradient should be negative, as was observed in 1987 [4], and during A > 0 periods, the latitudinal gradient should be positive.

This is the third in a series of reports using the SAMPEX, Ulysses, V1, V2, and P10 spacecraft to investigate the radial and latitudinal gradients of 10 MeV/nuc ACR oxygen in the heliosphere. In the first study [5] we reported that the latitudinal gradient for the period 1993/183-365 was small and positive, 1.3 ± 0.3 %/deg, with the maximum latitude coverage being 41° S. In the second study [6] we repeated the measurements for the period 1994/152-212 which included data from Ulysses at ~70° S. A small positive latitudinal gradient was also found in that period, 1.6 ± 0.4 %/deg. In this study we use data from the period 1994/209-313 during which Ulysses passed over the southern pole of the Sun, varying in heliolatitude from 75° S to a maximum of 80° S and back to 69° S. We assume symmetry of the particle distributions about the heliographic equator, in accordance with the drift theory.

2. Observations

Figure 1 shows the energy spectra of ACR oxygen at V1, V2, P10, Ulysses, and SAMPEX for the period 1994/209-313. (See [5] for references to instrument papers.) Where appropriate, subtractions for GCR and low-energy components, similar to those described in [5], have been made before plotting. We have chosen 10 MeV/nuc as the energy for comparing fluxes at the 5 spacecraft because the overlap in spectral coverage is approximately optimum there. For all energy spectra, except for the one from Ulysses, the flux at 10 MeV/nuc was interpolated by using a power law.

The O energy spectrum from Ulysses extends only up to 6 MeV/nuc. As was done in [5] we extrapolated the flux to 10 MeV/nuc using a power-law fit to the three measured points as an upper limit and a factor relating the flux at 10 to that at 6 MeV/nuc from model calculations [7] as a lower limit. (See [5] for more discussion).

Table 1 shows the average heliographic radii and latitudes of all 5 spacecraft during this period and the fluxes of ACR oxygen at 10 MeV/nuc at each position. The fluxes are plotted versus radial position in Figure 2. Note that the flux at Ulysses is the largest of the five, likely the result of the high southerly latitude of the spacecraft.

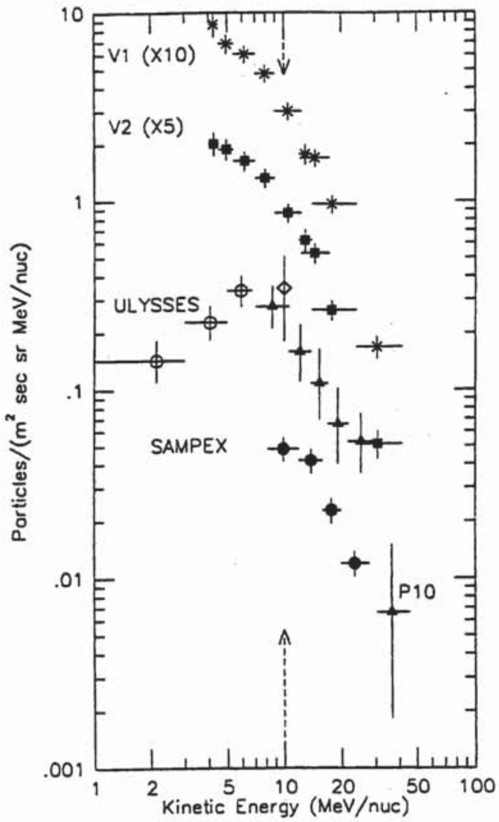

Figure 1. Energy spectra of ACR oxygen at the positions of 5 spacecraft for the period 1994/209-313. The two vertical dashed lines with arrows drawn at 10 MeV/nuc indicate the energy of comparison between the 5 spacecraft. An estimate of the flux of ACR O at 10 MeV/nuc from Ulysses is shown as the open diamond symbol and its derivation is described in the text.

Figure 3a and b shows least-squares fits (based on the Levenberg-Marquardt method [8]) to the ACR oxygen fluxes assuming a constant latitudinal gradient and a differential radial gradient, $g_r = (1/f)(\partial f/\partial r)$, which is proportional to r^{-n}. This is the same form used by [4] to describe the 1987 data, which is reproduced in Figure 3c and d. Panels a and c of Figure 3 show the radial dependence of the flux after correcting for the latitudinal gradient, and panels b and d show the latitudinal dependence of the flux corrected to 30 AU. The best-fit value of n for 1994 is 0.7 ± 0.7 and the latitudinal gradient is 2.1 ± 0.6 %/deg. The average large-scale radial gradient in 1994 between 1 and 61 AU is small, 2.6 ± 0.5 %/AU, compared to 8.8 ± 0.6 %/AU observed in 1987 between 1 and 41 AU.

Table 1: Gradient parameters for 1994/209-313

S/C	Heliographic Radius (AU)	Heliographic Lat. (deg)	ACR O Flux[a] at 10 MeV/nuc $(m^2\ s\ sr\ MeV/nuc)^{-1}$
SAMPEX	1.0	6.3	0.048 ± 0.007
Ulysses	2.3	-77.1	0.347 ± 0.166
V2	43.9	-12.5	0.185 ± 0.022
V1	57.1	32.6	0.324 ± 0.036
P10	60.6	3.2	0.219 ± 0.055

Notes:
a - Includes estimate of systematic uncertainties.

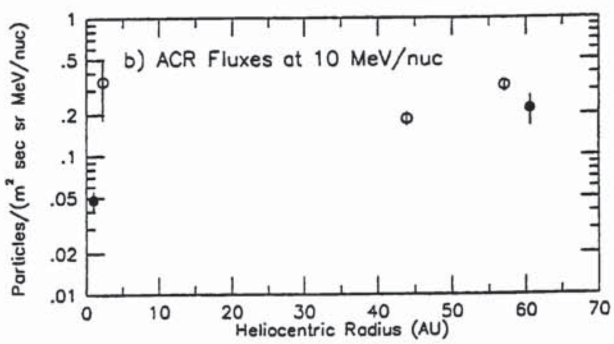

Figure 2. Flux of ACR O at 10 MeV/nuc from Table 1 versus heliographic radius. The open circles denote spacecraft (Ulysses, V1, and V2) that are significantly off the heliographic equator

3. Discussion

The small positive latitudinal gradient observed in this study and in the previous similar studies [5,6] contrasts sharply with the large negative latitudinal gradient observed during 1987 (compare Figure 3b and d). In 1976, however, when the Sun's magnetic polarity was the same as now, a small positive latitudinal gradient of ACR helium, ~2 %/deg, was observed based on P11 observations at 16° N [9]. Thus we now have strong evidence that the latitudinal gradient reverses sign in three consecutive solar magnetic field epochs, giving strong support to theories of particle propagation that include drifts in the large-scale magnetic field [10].

In addition, the magnitude of the average radial gradient from the inner to the outer heliosphere is a factor of ~3 to 4 smaller in 1994 than in 1987. This is also in agreement with predictions based on the drift theory because in the present A > 0 period the particles are expected to be drifting down from the poles onto the heliographic equatorial plane.

In 1995 Ulysses will reach its maximum northerly excursion in latitude (about 80° N). We plan to continue these multi-spacecraft observations as Ulysses rapidly traverses

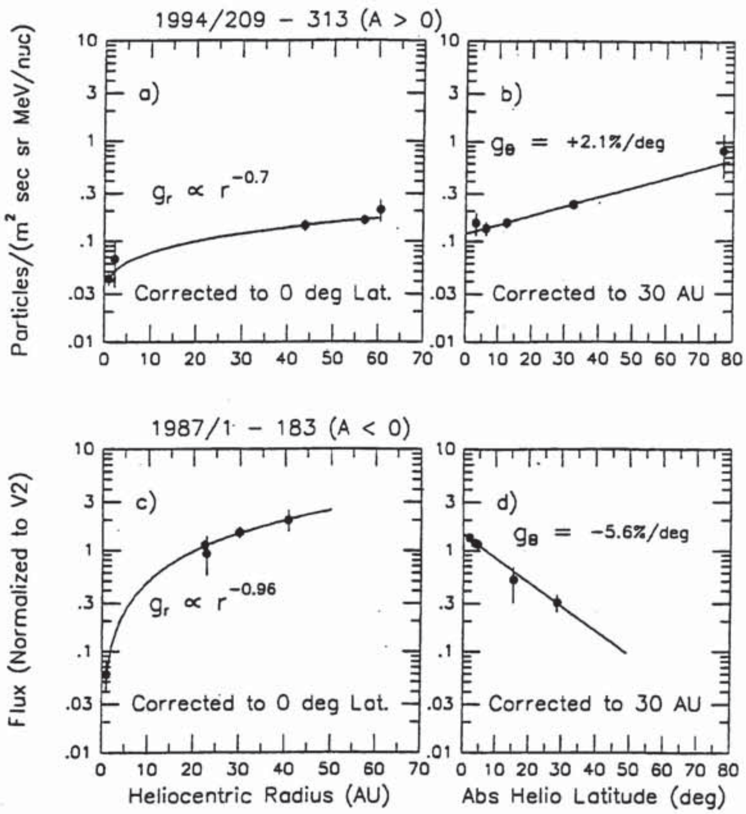

Figure 3. (a) Flux of ACR O at 10 MeV/nuc versus heliographic radial distance for the time period 1994/209 - 313, corresponding to A > 0. The fluxes have been corrected to 0° using a latitudinal gradient of 2.1 %/deg. The solid line is a least-squares fit to the data as described in the text. (b) Fluxes 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. (c) and (d) are reproduced from [4].

~160° in heliographic latitude.

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