# LARGE-SCALE RADIAL GRADIENT OF ANOMALOUS COSMIC-RAY OXYGEN FROM 1 TO ~30 AU

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Abstract

The cosmic-ray instruments on IMP 8 and Voyagers 1 and 2 have been used to measure the energy spectrum and large-scale radial gradient of anomalous cosmic-ray oxygen with ~5-30 MeV/nuc for the period 1986/206-310. We find that the flux of anomalous oxygen at 1 AU is continuing to recover, with an average intensity that is a factor of ~4 lower than the 1974-78 solar minimum spectrum. The data from the three spacecraft are consistent with a constant radial gradient at ~10 MeV/nuc of ~15%/AU from 1 to 28 AU, similar to that for the previous solar minimum period, but a factor of ~4 higher than that for the 21-39 AU region. These results suggest that the radial gradient decreases with radial distance or that there is a longitudinal gradient of ~1%/AU. Under either assumption we find negative latitudinal gradients which, at the position of Voyager 1 (~28 AU), are comparable in magnitude to the radial gradients.

1. Introduction. The anomalous cosmic-ray (ACR) component is thought to have its origin in the inward drift of interstellar neutrals into the heliosphere [1]. These neutrals become singly ionized by solar ultraviolet radiation and charge exchange with the solar wind and are then swept into the outer heliosphere by the solar magnetic field frozen into the expanding solar wind. The particles are presumed to be accelerated to the MeV/nuc energy region in the outer heliosphere, possibly at the solar wind termination shock [2,3].

Recently, several investigations using cosmic-ray instruments on the Voyager 1 and 2 (V1 and V2) and Pioneer 10 (P10) spacecraft have revealed the presence of substantial negative latitudinal gradients of both ACR and galactic cosmic-ray (GCR) particles in the outer heliosphere [4,5,6]. Christon et al. [4] showed that these gradients began to appear in 1985, possibly because the heliospheric current sheet tilt decreased to a value below that of the latitude of V1 (~27°N). Cummings et al. [6] showed that the similarity in the ratio of the radial to latitudinal gradients for both ACR and GCR particles was in agreement with drift theory predictions and permitted specific estimates of the perpendicular diffusion coefficient. These results have recently been extended to the time period 1986/206-310 for the radial regime 21-39 AU [7] and indicate that as the near-Sun current sheet tilt has continued to decrease, even larger latitudinal gradients and smaller radial gradients are observed in the outer heliosphere.

In this paper we present spectra of ACR oxygen for the same 1986 time period for a different radial regime of the heliosphere (1-28 AU) using data from cosmic-ray instruments on the IMP 8, V1, and V2 spacecraft. These results are compared to those from the outer heliosphere. We make a plausible argument for the existence of longitudinal gradients of order 1%/deg, although it does not appear possible to distinguish this possibility from a radial gradient which decreases with radial distance.

2. Observations. The observed energy spectra of ACR oxygen from the Cosmic Ray System (CRS) experiments on V1 and V2 (described in [8]) are shown in Fig. 1 for the period 1986/206-310. These data have been corrected for GCR and interplanetary contributions by a method similar to that described in Cummings et al. [9].

Also shown is the oxygen energy spectrum from the Caltech Electron/Isotope Spectrometer on IMP 8 (described in [10]). Although ACR oxygen was essentially unobservable at 1 AU from 1979 to ~1984 due to modulation effects, by early 1986 it was clearly present above the level of ~10 MeV/nuc GCR oxygen, and the observed 5-15 MeV/nuc C/O ratio was ~0.1 during the first 10 months of 1986, compared to the GCR ratio of C/O≃1. Although the IMP 8 spectrum in Fig. 1 has not been corrected for GCR oxygen contributions, we have made such corrections before calculating intensity gradients. The corrections, based on the observed He spectra at IMP 8 and V2, range from 12% at 5.4-8.5 MeV/nuc to 40% at 14-28 MeV/nuc. Solar contributions to the IMP 8 spectrum are negligible.

The dashed-line oxygen spectrum in Fig. 1 is taken from Fig. 1 of Mewaldt et al. [11] and represents the solar minimum spectrum at 1 AU obtained from IMP 8 during 1974-78. The increase in this spectrum above ~40 MeV/nuc is due to the GCR component. The recent IMP 8 spectrum is a factor of ~4 lower in intensity than this solar minimum spectrum, indicating that as of the latter part of 1986 the fluxes were well on their way to recovery to solar minimum levels.

We can derive spatial gradients in the intensity of ACR oxygen if we assume that the fluxes, f, measured at two different locations (r, Θ, and ϕ) in the heliosphere are related by an equation of the form:

$$\ln(f_i/f_j) = G_r(r_i - r_j) + G_\Theta(\Theta_i - \Theta_j) + G_\phi(\phi_i - \phi_j) \quad (1)$$

where the subscripts denote the spacecraft number, and $G_r$, $G_\Theta$, and $G_\phi$, the radial, latitudinal, and longitudinal gradients, respectively, are assumed to be constants. The recent measurements of $G_r$ and $G_\Theta$ in the outer heliosphere [4,5,6,7] assumed that the heliolongitudinal gradients were negligible. With this same assumption we display in Table 1 the radial and latitudinal gradients we calculate for three energy intervals for ACR oxygen from the two flux ratios we can form among the IMP 8, V1, and V2 spacecraft measurements. This table is modeled after those in [6] and [7] and includes an estimate of the latitudinal gradient expressed as a function of distance from the current sheet, $G_{|z|}$, at the position of V1. The absolute value of the ratio of $G_{|z|}/G_r$ is near unity, very similar to the findings in the outer heliosphere which used data from V1, V2, and P10. However, the radial gradient for ~10 MeV/nuc ACR oxygen is ~15%/AU, which is the same as that reported during the previous solar minimum [12,13], but a factor of ~4 higher than that reported for this same 1986 period in the outer heliosphere [7]. The latitudinal gradients we derive are ~−7%/deg at ~10 MeV/nuc, rather than ~−4.5%/deg reported in [7].

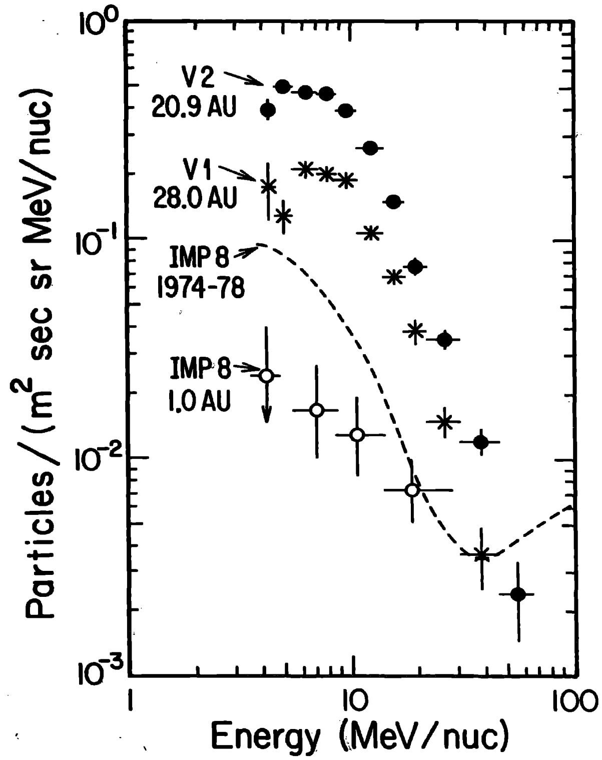


Fig. 1. Energy spectra of oxygen at IMP 8 (○), V1 (×), and V2 (•) for the time period 1986/206 to 1986/310. The heliographic radial positions of the spacecraft are shown. The dashed line is the solar minimum spectrum at 1 AU from Mewaldt et al. [11]. Note that the intensity at V1 is less than that at V2 because of the negative latitudinal gradient

3. Discussion. The radial gradients of ~15%/AU reported during the last solar minimum period for ACR oxygen were determined with spacecraft within ~15 AU of the Sun, not very much different from the current IMP 8, V1,

TABLE 1. Radial ($G_r$) and Latitudinal ($G_\Theta$ and $G_{|z|}$) Gradients of ACR Oxygen Assuming Zero Longitudinal Gradient ($G_\phi$).[a,b]

| Energy (MeV/nuc) | $G_r$ (%/AU) | $G_\Theta$ (%/deg) | $G_{\|z\|}$ (%/AU)[c] | $G_r/G_{\|z\|}$ |
|---|---|---|---|---|
| 5.4-8.5 | 15.5±2.1 | -7.3±0.6 | -14.9±1.3 | -1.04±0.07 |
| 8.5-13.9 | 15.3±2.0 | -7.1±0.6 | -14.6±1.2 | -1.05±0.07 |
| 13.9-30.6[d] | 12.3±2.3 | -6.2±0.7 | -12.7±1.4 | -0.97±0.09 |

[a]For period 1986 day 206 - 1986 day 310. Average spacecraft positions: V2 at R = 20.9 AU, $\theta$ = 1.3°, $\phi$ = 9°; V1 at R = 28.0 AU, $\theta$ = 27.9°, $\phi$ = 335°; IMP 8 at R = 1.0 AU, $\theta$ = 6.3°, $\phi$ = 97°. [b]Uncertainties shown are statistical and do not include any systematic uncertainty arising from the latitudinal and radial averaging. [c]Calculated at the position of V1. [d]This energy interval is for the Voyager data; the IMP 8 energy interval is 13.9-28.3.

V2 radial regime. Since we now observe the same gradient in this same radial region and since the outer heliospheric radial gradient appears now to be only ~4%/AU, we might conclude that the radial gradient is a decreasing function of distance.

We therefore consider a radial gradient of the form

$$\frac{1}{f}\frac{\partial f}{\partial r} \equiv g_r = G_0 - Cr \qquad (2)$$

where f is the flux of particles, r is the radial distance from the Sun, $g_r$ is the local radial gradient, and $G_0$ and C are constants. A similar form was used by Webber and Lockwood [14] to fit observations of high-energy galactic cosmic rays from instruments on IMP 8, V1, V2, and P10 in 1984. We use the 8.5-13.9 MeV/nuc energy range for the IMP 8, V1, and V2 ACR oxygen spectra and estimate the flux at 11.2 MeV/nuc from the P10 spectrum in [7] (~0.54 p/($m^2$ sec sr MeV/nuc)). From the three ratios that can be formed from the four spacecraft measurements we obtain $G_0$ = 23.0%/AU, C = −0.64%/AU/AU, and $G_\Theta$ = −4.9%/deg (assuming $G_\phi$ = 0).

However, the two Voyager spacecraft are moving toward the nose of the heliosphere where the solar wind termination shock and heliopause occur closest to the Sun. Pioneer 10 is traveling in the opposite direction, down the tail of the heliosphere, and in a direction which is perhaps farther removed from the termination shock, the possible site of the acceleration of the ACR component. Therefore, it is possible that the P10 fluxes are reduced because of a heliolongitudinal gradient.

To investigate this possibility we consider a model in which the radial gradient is assumed to remain constant but in which there is a finite longitudinal gradient. The longitudinal position of V2 at the time of our observations is within ~10° of both the solar apex direction and the direction of the inflowing interstellar wind. Thus for illustrative purposes we assume that the distribution of ACR particles is symmetrical in longitude about a line from the Sun to V2. By solving a set of three simultaneous equations from Equation 1 we obtain $G_r$ = 11.8%/AU, $G_\Theta$ = −5.0%/deg, and $G_\phi$ = −0.92%/deg at ~11 MeV/nuc. At the position of V1 (~28 AU) these three gradients when expressed in %/AU are 11.8, −10.2, and −1.9, respectively. Note that we find the magnitude of $G_\phi$ (in %/AU) to be much less than either $G_r$ or $G_\Theta$. This result is reasonable since for particles in the outer heliosphere longitudinal propagation is parallel to the magnetic field, while latitudinal and radial propagation is perpendicular to the field. The gradients we derive under both assumptions are displayed in Table 2. Regardless of whether we assume that there is a longitudinal gradient or that the radial gradient decreases with radial distance, we find that the absolute value of $G_r/G_{|z|}$ at ~28 AU is in the range ~0.5-1, indicating that there is a large deviation from spherical symmetry in the heliosphere.

TABLE 2. Comparison of Radial ($G_r$, $G_0$, C), Latitudinal ($G_\Theta$, $G_{|z|}$), and Longitudinal ($G_\phi$) Gradient Parameters for ACR Oxygen With ~11 MeV/nuc.

| Assumption | $G_0$ or $G_r$ (%/AU) | C (%/AU/AU) | $G_\Theta$ (%/deg) | $G_\phi$ (%/deg) | $G_{\lvert z\rvert}$ (%/AU)[a] | $G_r/G_{\lvert z\rvert}$ |
|---|---|---|---|---|---|---|
| $g_r = G_0 + Cr$, $G_\phi = 0$ | 23.0 | -0.64 | -4.9 | --- | 10.0 | -0.51 |
| $G_r$ = Constant | 11.8 | --- | -5.0 | -0.92 | 10.2 | -1.16 |

[a] Calculated at 28 AU.

The plausibility of a small longitudinal gradient is illustrated by a simple calculation. The time it takes particles to diffuse a distance D is given by $t \propto D^2/\kappa$, where $\kappa$ is the diffusion coefficient. If the acceleration of ACR particles occurs primarily in the upwind region of the heliosphere, then the particles would diffuse radially inward toward V2 by perpendicular diffusion and longitudinally to P10 by parallel diffusion. If we assume that the longitudinal propagation is ~90°, then the ratio of travel times from an upwind region at 40 AU to each of the spacecraft is $t_{10}/t_2 \sim (63/20)^2\ \kappa_\perp/\kappa_\parallel$. If we use an often assumed range for $\kappa_\perp/\kappa_\parallel$ of 0.05-0.10, then $t_{10}/t_2$ ~0.5-1. Thus if the ACR source is asymmetric, then the intensity at P10 and V2 might be comparable, even though P10 is at a greater radial distance than V2. Thus we suggest that longitudinal gradients are not unexpected and could account for the apparent decrease in the radial gradient determined by comparing P10 and V2.

However, we note that the observations themselves do not allow us to distinguish between a longitudinal gradient and a radial gradient which decreases with distance from the Sun. Observations by Pioneer 11 will help resolve this issue, since P11 is in the same radial and longitudinal regime as V1 and V2, with a latitude that is between the two. As a result, we should be able to determine the local spatial gradients in the 20-28 AU region and confirm whether or not there is a radial dependence to the radial gradient.

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