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Radial and Latitudinal Gradients of Anomalous Oxygen During 1977-1985

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We find that the radial gradient of anomalous O remains constant during 1977-85 at ~10-15%/AU although the intensity changes by more than a factor of 100. These results can be used to deduce that most of the modulation of the intensities of these particles is occurring beyond 27 AU. We also find evidence for a latitudinal gradient of ~+3%/degree at low energies (7.1-10.6 MeV/nuc).

1. Introduction. In this analysis we make use of measurements of the spectrum of O nuclei from the Cosmic Ray Subsystem (CRS) on the Voyager 1 (V1) and 2 (V2) spacecraft [*Stone et al.*, 1977] and from the Goddard-University of New Hampshire experiment on Pioneer 10 [*McDonald et al.*, 1977] to study the radial and latitudinal gradients and temporal variations of anomalous O. Quiet-time data from 1977 to 1985 are utilized.

2. Observations. The general features of the 11-year cosmic-ray modulation cycle may be examined by using the counting rate of particles which penetrate the high-energy telescope on V1 as shown in Fig. 1 (curve "P", mainly protons > 75 MeV). A change in this rate by a factor ~2 is observed between 1977 and the minimum in 1981-82. This change is mainly due to solar modulation; however, some gradient effects are present in the data as well since V1 is moving outward from 1 to ~22 AU during this time period. Figure 1 also shows a similar plot for 40-106 MeV/nuc C+O nuclei for 24 quiet-time intervals between 1977-85 (curve "C+O"). Here the change in intensity between 1977 and the minimum in 1981 is a factor ~5. Finally, in Fig. 1 the temporal variations for 5.6-17.2 MeV/nuc anomalous O are shown for the same 24 quiet-time intervals (curve "O"). All three components show a similar pattern of variations but for the anomalous O the overall intensity variation is larger than the others, approaching a factor ~100.

In order to minimize contamination by solar and interplanetary particles and to help separate temporal and radial variations, six quiet-time intervals labeled A-F in Fig. 1 were selected by setting limits to the maximum low-energy helium flux, in a manner similar to that described in *Cummings et al.* [1984]. The anomalous O spectrum is derived from the observed total O spectrum for a particular time interval by subtracting both a low-energy solar or interplanetary component and the high-energy galactic cosmic-ray component [*Cummings et al.*, 1985].

In Fig. 2a, b, c we show the differential intensities of anomalous O nuclei in three separate energy intervals for each of the six quiet-time intervals at each of the spacecraft as they moved outward from the sun. The solid lines are least-squares fits to the data points, except for the lowest energy interval for periods E and F when V1 is at ~24 degrees north heliographic latitude. (V1 left the ecliptic plane after encounter with Saturn in 1980.) In these two cases the V1 points, connected by the dashed lines, are significantly above the straight lines (representing a constant radial gradient) connecting the V2 and P10 points. We attribute the deviation to a latitude gradient at low energies having a weighted average value of 3.0 ± 1.0%/degree for the combined two periods E and F.

In Fig. 3 we show the calculated radial gradient (slope of solid lines in Fig. 2) for each of the three energy intervals. In the lowest energy interval (7.1-10.6 MeV/nuc) the spectrum of anomalous O is changing with time [*Cummings et al.*, 1985], which may contribute to the observed variation in the radial gradient. Above 10.6 MeV/nuc no such energy spectral changes are found and the resulting gradient is remarkably constant. In the 10.6-17.1 MeV/nuc interval the average value of the gradient is 10.7 ± 0.6%/AU, somewhat lower than the 15 ± 3%/AU found by

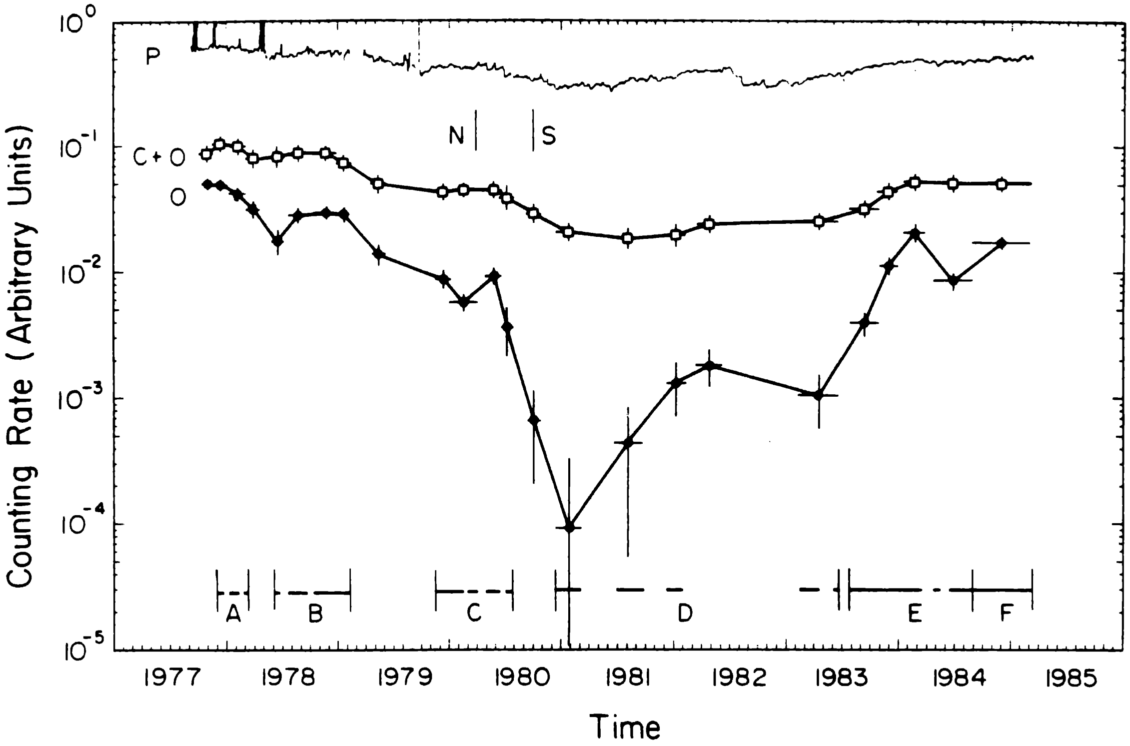

Fig. 1. Counting rates of three particle types from Voyager 1 telescopes. P labels the penetrating rate from the high-energy telescope (mainly protons > 75 MeV), C+O labels the rate of 40-106 C+O, and O labels the rate of 5.6-17.2MeV/nuc anomalous oxygen. The approximate times of the solar magnetic field reversal in the northern (N) and southern (S) polar regions are indicated by the vertical bars [*Webb et al.*, 1984]. The horizontal bars represent quiet-time intervals as discussed in the text.

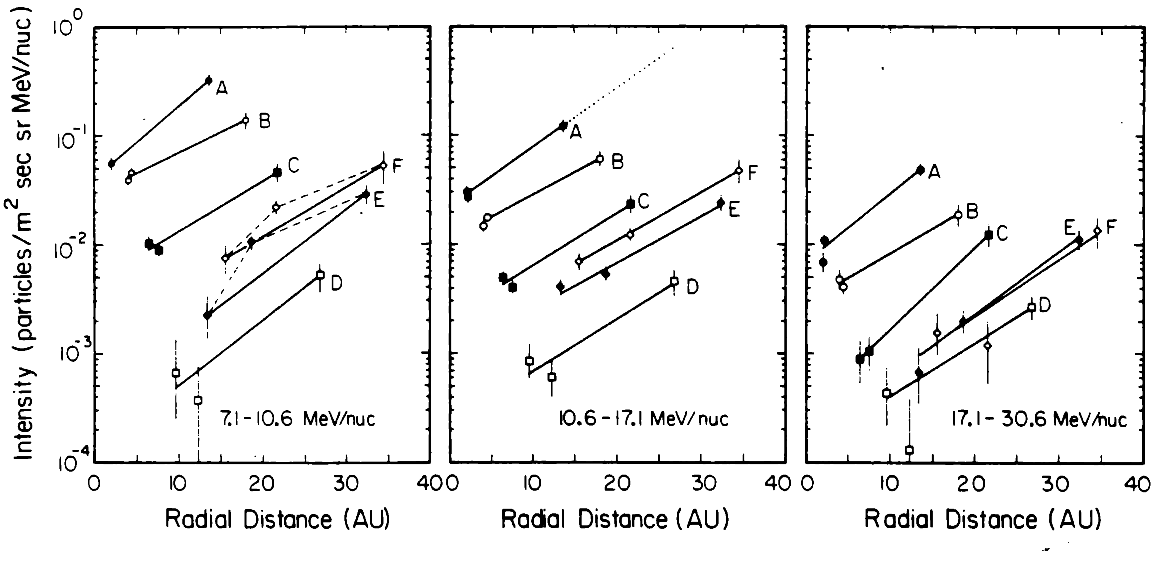

Fig. 2. Intensity of anomalous O versus heliocentric radial distance in three energy intervals from the V1, V2, and P10 cosmic-ray instruments. The labels A-F refer to the six quiet-time intervals chosen for analysis. The lines are described in the text.

Webber et al. [1981] for the period 1972-79. It is clear from Figs. 2 and 3 that the radial gradient for all three energy intervals has not changed appreciably with time or radial distance, maintaining a value between ~10-15%/AU despite the fact that the intensity has varied by more than a factor of 100.

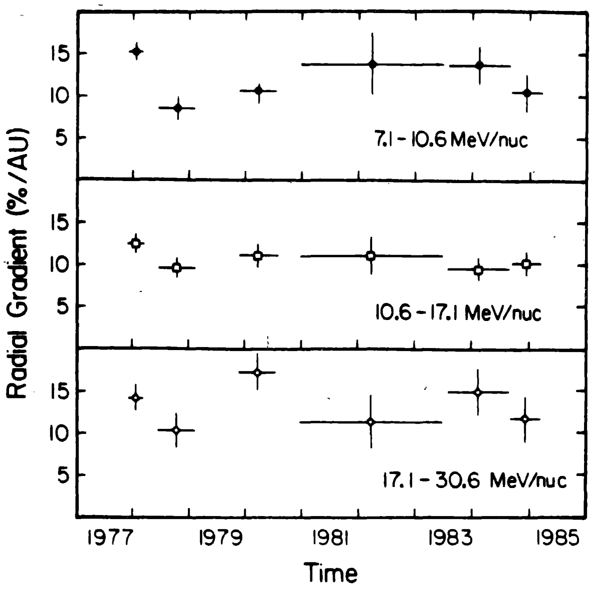

Fig. 3. Measured radial gradients of anomalous O versus time for the three energy intervals of Fig. 2.

3. Discussion. We believe that the constancy of the gradient with respect to time both before and after the solar magnetic field reversal in 1980, and during a period when the intensity change was a factor ~100 is an important clue and constraint on the solar modulation process. In conventional modulation theory, if the effects of particle streaming in the interplanetary medium can be neglected, then the radial gradient, G_r, and the radial diffusion coefficient, κ_r, are related by $G_r = CV/\kappa_r$. The average solar wind velocity, V, and κ_r change only slightly over a solar cycle (see *Hedgecock* [1974] and *Feldman et al.* [1979]). Also the Compton-Getting coefficient C, which is related to the spectral shape, does not change appreciably since the spectral shape remains similar above ~10 MeV/nuc. Thus, if the gradient can be described by these local parameters, it would be expected to be constant as observed.

In this simple conventional modulation model in which κ_r is independent of radial distance r, the particle intensity j at r is given by $j = j_b \exp[CV(r-r_b)/\kappa_r]$, where j_b is the intensity at the modulation boundary. Since C, V, and κ_r are not changing appreciably with time, and assuming j_b is constant, the large modulation at a given position would require a time variation in the boundary location r_b. The magnitude of the required change in the boundary distance can be estimated from Fig. 2b. The dotted line is an extrapolation of the intensity in the 10.6-17.1MeV/nuc energy range during the time of solar minimum to the position of P10 (27AU) during the solar maximum period of interval D. The implied intensity change from period A to D at 27AU is a factor of 136 ± 52, indicating that most of the modulation during period D is occurring beyond 27AU. Using the average radial gradient for this energy interval we find that the required change in the boundary distance r_b is 46 ± 4AU. A similar boundary shift has been suggested by *Evenson et al.* [1979] to explain electron observations.

Such a boundary shift would also produce changes in the intensity of other particle species. For example, the penetrating particle rate (P) in Fig. 1 shows a variation from solar minimum to solar maximum of a factor ~2. The median rigidity of the particles dominating this rate is ~1.8GV, the same rigidity as 7MeV/nuc anomalous O if O is singly charged (as expected if they are freshly-ionized neutrals [*Fisk et al.*, 1974]). The spectral shapes of the anomalous O (above 10MeV/nuc) and high-energy protons are similar (spectral index ~-2) implying they have similar values of C. Since $\kappa_r \propto \beta f(R)$, where β is the particle velocity and R is the rigidity, the expected gradient for the P rate can be scaled from the gradient of anomalous O by $G_r(P) = G_r(O)(\beta_O/\beta_P) \sim 10(.12/.89) = 1.5$%/AU, a value in approximate agreement with observations by others (see *McKibben et al.* [1982] and *Lockwood and Webber* [1984]). The intensities at two different times are related by $j_1/j_2 = \exp(G_r(\delta r_b))$ Therefore, a boundary change of 46AU and a radial gradient of 1.5-3%/AU would result in $j_1/j_2 = 2\text{-}4$ for the penetrating particles, similar to what we observe.

An alternative way to accomplish the same modulation without changing the boundary distance is to decrease κ_r, and thus increase the gradient, in a localized shell of turbulence in the outer heliosphere, as suggested by *Burlaga et al.* [1984]. The observed change in modulation would require, for example, an increase in the anomalous O gradient from 11%/AU to 44%/AU in a shell 15 AU thick.

It is also possible that variations in the source of the anomalous O may contribute to the observed solar cycle variation. We note that *Jokipii* [1985], using a model of the anomalous component in which the particles are accelerated at the polar termination shock and drift to the solar equatorial regions, has calculated spectra of anomalous O that depend on the polarity of the magnetic field and which are in reasonable agreement with observations of changes in the spectra associated with the magnetic field reversal (see *Cummings et al.* [1985]). However, we find no evidence of a change in the gradient of the anomalous O at the time of the solar magnetic field reversal as would presumably be expected from such a model.

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