Composition, Gradients, and Temporal Variations of the Anomalous Cosmic-Ray Component

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Paper to Appear in
Solar Wind VI Proceedings
NCAR/TN-306+PROC
V. J. Pizzo, Editor
1988

SRL 87-22

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Abstract

Recent measurements in the outer and inner heliosphere have provided new information on the composition, spatial distribution, and temporal variations of the anomalous component. Two additional elements, carbon and argon, are now found to be enhanced, and a method has been developed to derive the abundances of the neutral gas flowing into the heliosphere. In addition, latitudinal gradients recently observed in the outer heliosphere for both the anomalous and galactic cosmic-ray components are negative, opposite to the positive latitudinal gradients reported during the 1976 period when the solar magnetic field was reversed, as expected if the latitudinal gradients are due to effects of curvature and gradient drift in the solar magnetic field. Although the radial gradient remains positive in the outer solar system, there is evidence that the gradient decreases with distance from the Sun. Finally, recurrent 26-day variations in the flux of anomalous cosmic-ray oxygen are large and regular in 1986-1987 at Voyager 1 at ~30° latitude but not at Voyager 2 near the ecliptic plane. We suggest that these variations may result from the combination of a latitudinal gradient with respect to magnetic latitude and the excursion of the spacecraft in latitude caused by a wavy current sheet.

Introduction

The anomalous cosmic-ray component is characterized by anomalous enhancements in the fluxes of helium, nitrogen, oxygen, and neon with energies of ~5 to ~50 MeV/nucleon [Garcia-Munoz et al., 1973; McDonald et al., 1974; Hovestadt et al., 1973; von Rosenvinge and McDonald, 1975]. 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].

At the Solar Wind 5 Conference, Voyager measurements were presented of the energy spectra, composition, and temporal variations of the anomalous component [Webber and Cummings, 1983; Cummings and Webber, 1983]. The time period included in those reports was from launch of the Voyagers in 1977 to early 1982, from minimum to maximum solar modulation.

Since 1982, solar modulation has decreased and the Voyagers have moved beyond 20 AU, making possible several key observations about the composition, temporal variations, and radial and latitudinal gradients of the anomalous component. In this paper we will focus on these recent findings.

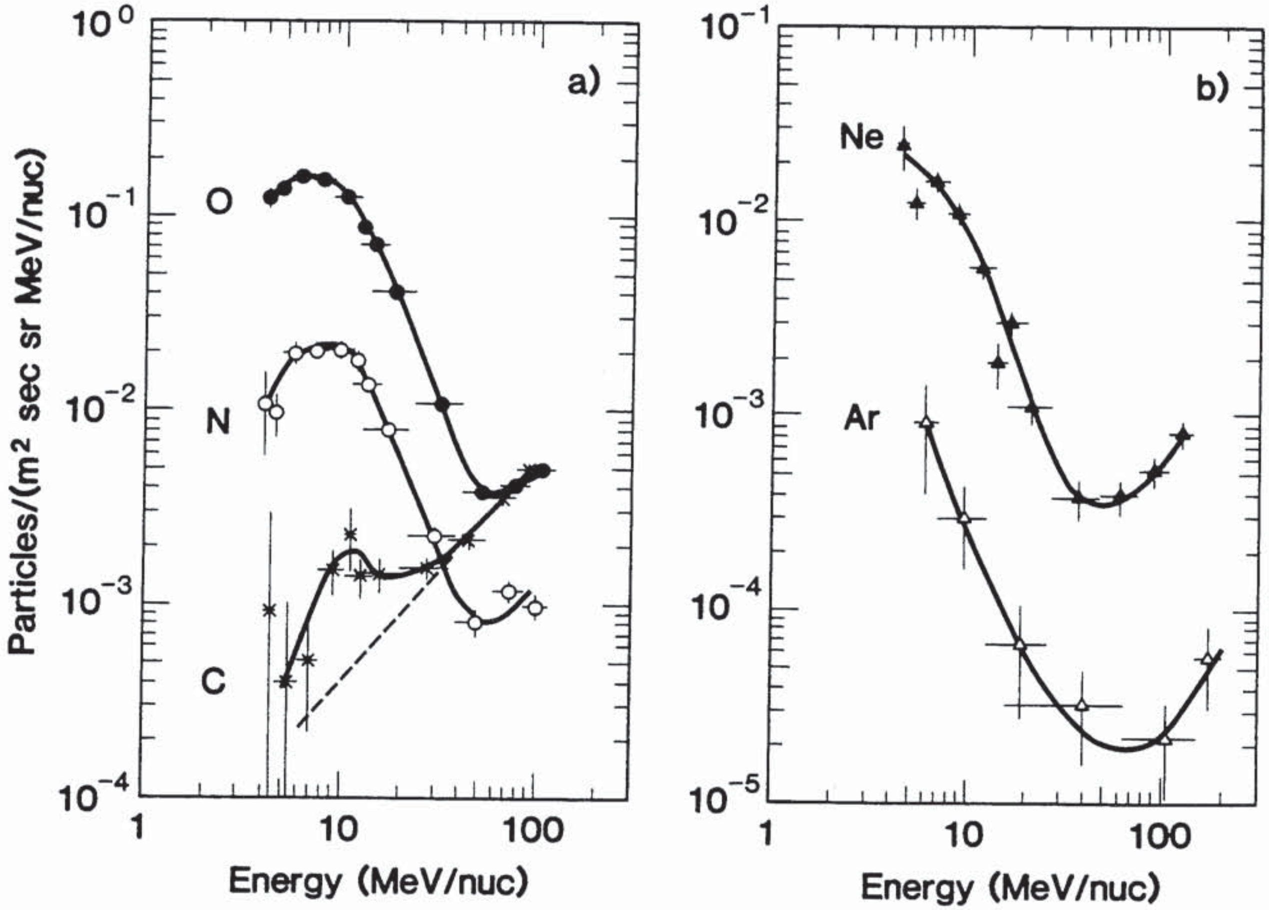

Fig. 1. (a) Observed energy spectra of C, N, and O for the period 1985/274 to 1986/254 from the Voyager 1 and 2 cosmic-ray instruments. The smooth curves are intended to guide the eye and are not fits to the data. The dashed line indicates the estimated galactic cosmic-ray spectrum of C below ~25 MeV/nuc. (b) Energy spectrum of Ne and Ar for the same period as in (a). Note the different intensity scales in panels (a) and (b).

Composition

The general spectral features of the anomalous component are shown in Figure 1a, which displays the observed energy spectra of carbon, nitrogen, and oxygen for the period 1985 day 274 to 1986 day 254. Each spectrum is an unweighted average of independent spectra obtained from the Cosmic Ray System (CRS) on Voyagers 1 and 2 (see Stone et al. [1977] for a description of the CRS instrument).

The carbon and oxygen fluxes in Figure 1a are in close agreement near 100 MeV/nuc, as is expected since the galactic cosmic-ray component, which dominates at this energy, has a C/O ratio of ~1 (see, e.g., Simpson [1983]). The large increases in the intensity of the spectra of oxygen and nitrogen below ~50 MeV/nuc are due to the anomalous component. The carbon spectrum has only a small increase near 10 MeV/nuc, which we ascribe to anomalous carbon at about the 1% level of oxygen (see

Cummings and Stone [1987]). We believe that this is the first observation of anomalous carbon and is made possible because the Voyagers are far enough removed from the Sun so that the low-energy solar or interplanetary component, which dominated this energy region in previous measurements, is absent.

In Figure 1b we show the observed neon and argon spectra for the same period. The intensity ratio between the two is about 20, which is the same ratio reported at the Solar Wind 5 Conference [Webber and Cummings, 1983], and which led to a suggestion that anomalous argon might be present. With this new spectrum, which is free of solar contamination and of much better statistical accuracy, we believe there is no longer any ambiguity.

Thus six elements are now known to comprise the anomalous component: helium, carbon, nitrogen, oxygen, neon, and argon. Assuming the model of Fisk et al. [1974] for the origin of the anomalous component, we have inferred the abundances of the inflowing neutral gas relative to oxygen from the anomalous component measurements [Cummings and Stone, 1987].

We considered each step in the process of converting the neutrals into the observed spectra. The cross sections for charge exchange with the solar wind and for photoionization by solar ultraviolet radiation are reasonably well known. We calculated correction factors for these ionization processes together with estimates of their uncertainties.

In order to estimate the effect of acceleration on the observed abundances of particles with different A/Z, we used the analysis of Dröge and Schlickeiser [1986] for second-order Fermi acceleration. Although their approximation of first-order Fermi acceleration as a distributed process yields the same A/Z dependence, it is not clear that such an approximation is applicable. Thus the extent to which the following estimate reflects the A/Z dependence of shock acceleration is unknown. In addition, the parameters involved in the acceleration process are rather poorly understood. In order to gauge the uncertainty introduced in the relative abundances, we calculated two sets of acceleration correction factors by making two widely different assumptions regarding the injection mode of the particles. Therefore, in Figure 2 we show two estimates of the local interstellar medium neutral gas abundances relative to oxygen, corresponding to injection at common velocity and common momentum, respectively. Also shown are various estimates from other measurements.

We find that the ratio of our estimate based on the common velocity injection mode to that based on common momentum for a particle with mass number A is proportional to $(16/A)^2$. Thus the injection assumption is not very important for elements with mass number near the reference element oxygen, e.g., nitrogen and neon. However, for elements such as hydrogen and helium the uncertainties are large enough that further work is needed before we can be confident of the neutral abundances of these elements.

For elements other than hydrogen and helium it is possible to quantitatively address some issues with the data in Figure 2. Consider first the nitrogen, oxygen, neon, and argon. These atoms all have first ionization potentials larger than that of hydrogen and might be expected to be predominantly neutral in the interstellar medium. The abundances we derive for nitrogen and neon are in excellent agreement with the Anders and Ebihara [1982] solar system abundances, indicating that there is no large depletion of

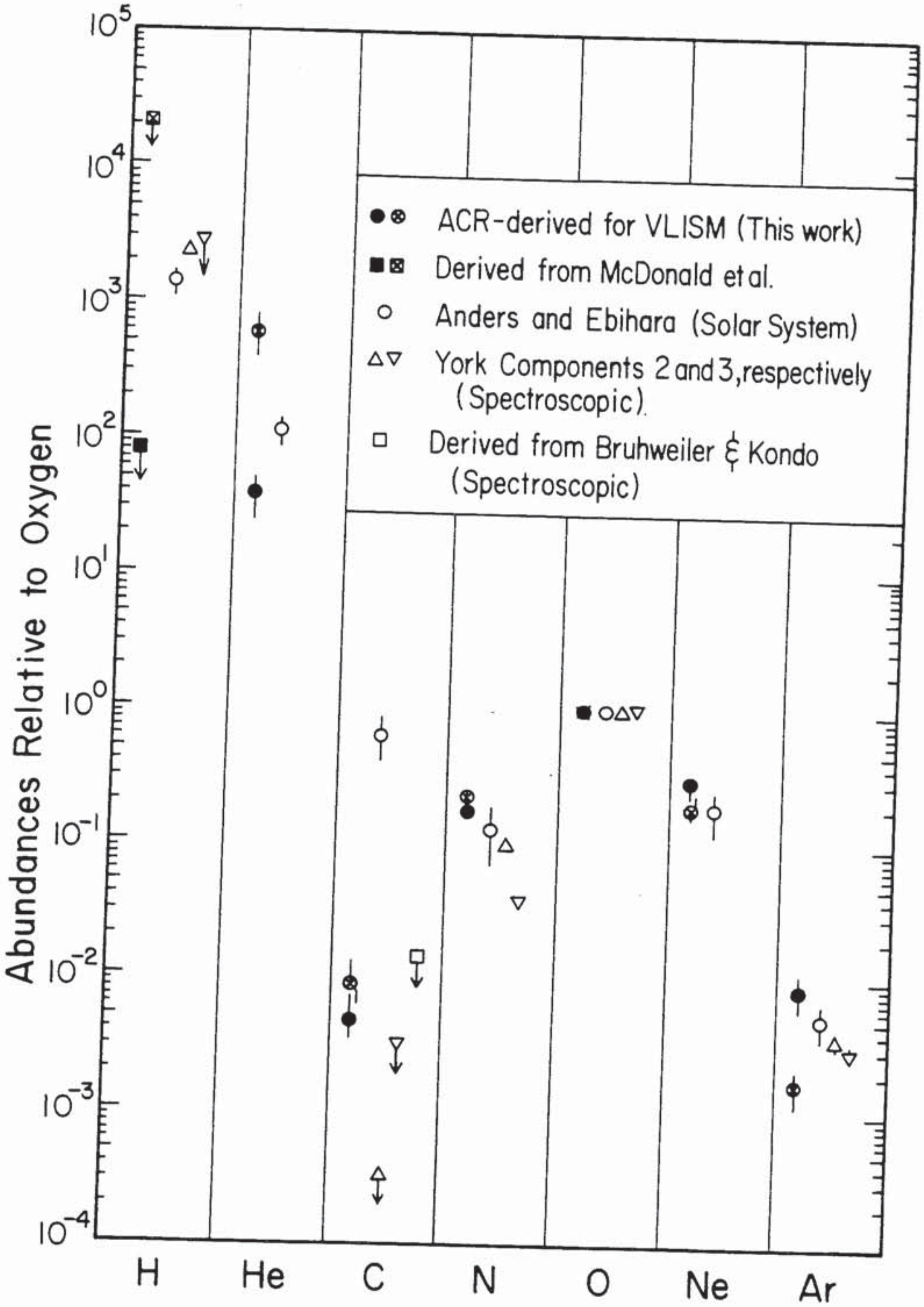

Fig. 2. Relative abundances (to O) of neutral gases in the local interstellar medium. The ● and ■ are derived assuming injection at common momentum for all species; the ⊗ and ⊠ assume injection at common velocity. The hydrogen upper limit is derived from McDonald et al. [1986] assuming all the protons at ~200 MeV are anomalous protons. (Note: This figure is from Cummings and Stone [1987] with revised values for □, △, and ▽ for C).

these atoms in the very local interstellar medium. The abundance of argon is also in general agreement with the solar system compilation, although the derived abundance is somewhat dependent on the injection mechanism assumed.

We note that since the charge-exchange cross section for neon is much smaller than that of oxygen, the fact that Ne/O is normal suggests that significant charge-exchange processes are not occurring at the heliospheric interface, contrary to the suggestion of Fahr and Ripken [1984]. Also, our abundance of nitrogen is significantly greater than that of both components 2 and 3 of York [1983], which have recently been proposed as being representative of the local and the very local interstellar medium, respectively [Vidal-Madjar et al., 1986].

The relative abundance we derive for carbon is a factor of $\sim$100 below that of Anders and Ebihara. This is consistent with the expectation that most of the carbon is ionized in the interstellar medium because of its lower first ionization potential. A local spectroscopic measurement of neutral carbon was made by Bruhweiler and Kondo [1982] along a 7 parsec line of sight. Our measurement is consistent with the upper limit we derive from their spectroscopic observations. Our measurement is greater than the upper limit from York component 2, but marginally consistent with the York component 3 upper limit. However, as noted above, the York component 3 nitrogen abundance is significantly below our measurement, suggesting that neither of the two York components can likely be identified with the very local interstellar medium.

Gradients

Voyager 1 began to climb out of the ecliptic plane after its encounter with Saturn in 1980. By the beginning of 1987 it had reached 28°N heliographic latitude. Several investigations, based on the high-latitude Voyager 1 data, have recently found negative latitudinal gradients in anomalous and galactic cosmic rays [Christon et al., 1986a,b; McDonald and Lal, 1986; Cummings et al., 1987a; Decker et al., 1987].

In Figure 3 we show the flux of anomalous oxygen as observed by Voyagers 1 and 2 in the energy region from 5.6 - 17.2 MeV/nuc from 1983 to 1987. Note that the Voyager 1 flux drops below that of Voyager 2 in early 1985 even though Voyager 1 is farther out from the Sun. Christon et al. [1986b] found a similar crossover in the $>$70 MeV/nuc nuclei rate and ascribed it to the fact that the near-Sun current sheet tilt dropped below the latitude of Voyager 1, so that Voyager 1 presumably began to sample from only one side of the current sheet. In the inset to Figure 3 we show the near-Sun current sheet tilt data shifted in time to account for the propagation delay to the position of Voyager 1, using a solar wind speed of 500 km/sec. The crossover in fluxes corresponds to the time when the predicted current sheet tilt drops below the latitude of Voyager 1, in agreement with the suggestion of Christon et al.

In order to separate radial and latitudinal gradients, we need more than just two spacecraft. Recently, data from Pioneer 10, Pioneer 11, and IMP-8, which is at 1 AU, has been added to the Voyager data in order to derive both the radial and latitudinal gradients [Stone et al., 1987].

We will suggest later that heliomagnetic coordinates may well be the most natural set of coordinates to use for describing the gradients (see also Newkirk and Lockwood

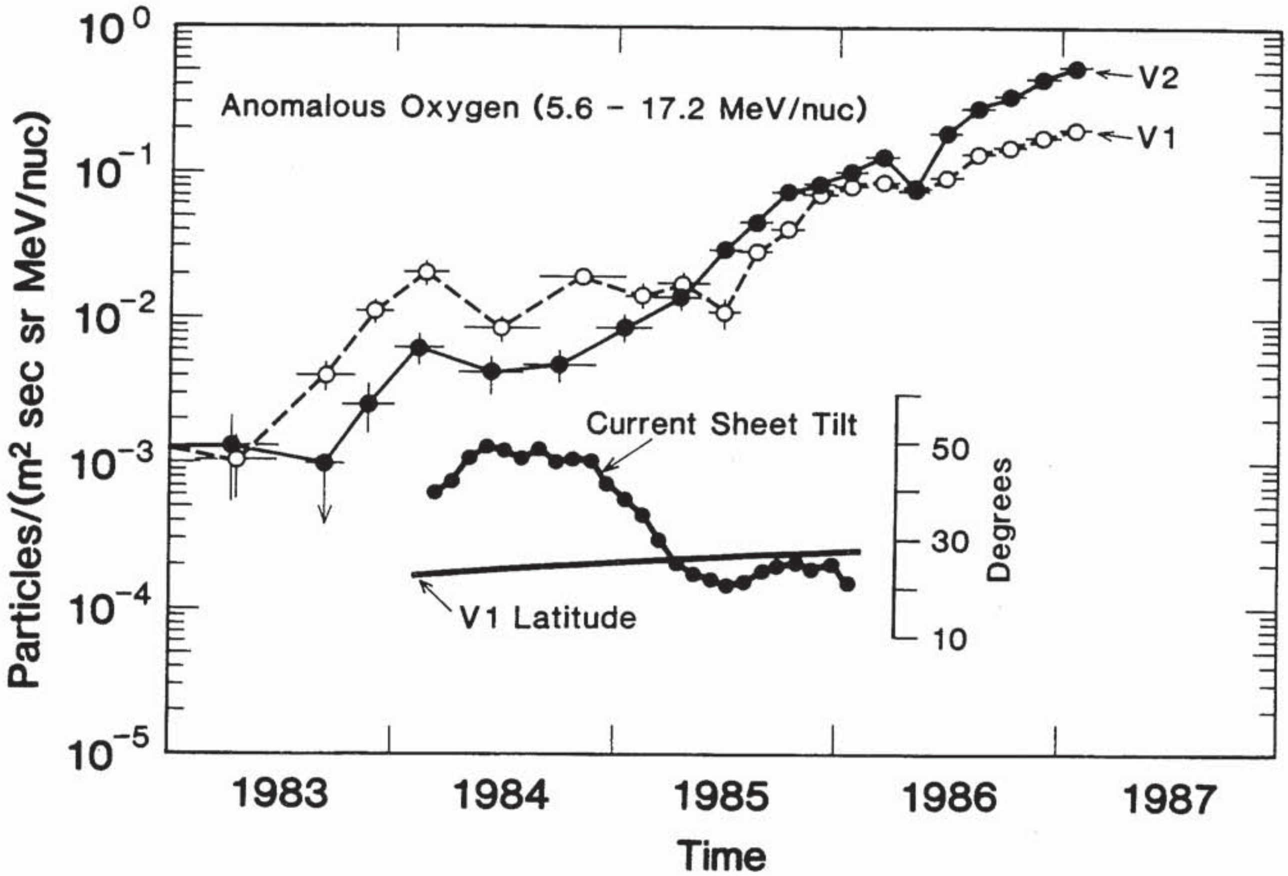

Fig. 3. Intensity of anomalous cosmic-ray oxygen at Voyager 1 and 2 versus time. Also shown is the predicted tilt of the current sheet from Christon et al. [1986b], time-shifted as described in the text, and the heliographic latitude of Voyager 1 versus time.

[1981], Newkirk and Fisk [1985], and Christon et al. [1986a]). However, we have no direct measure of the heliomagnetic latitude of the spacecraft, and so in what follows we use heliographic coordinates instead. Note, however, that a change in the tilt of the current sheet results in a change in the heliomagnetic latitude of the spacecraft which could lead to a change in the derived heliographic gradient. Indeed, there is already some evidence for this effect [Cummings et al., 1987b].

The data for the period 1986 day 156 to 1987 day 53 are shown in Figure 4. The radial gradient apparently decreases with distance, as shown by the dashed line connecting the flux values from IMP-8, Voyager 2, and Pioneer 10, all of which are near the heliographic equator. The gradient from 1 to 20 AU is ~16%/AU, consistent with measurements in the inner heliosphere in the last half of the solar cycle [Webber et al., 1981]. In the outer heliosphere, from 20 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.

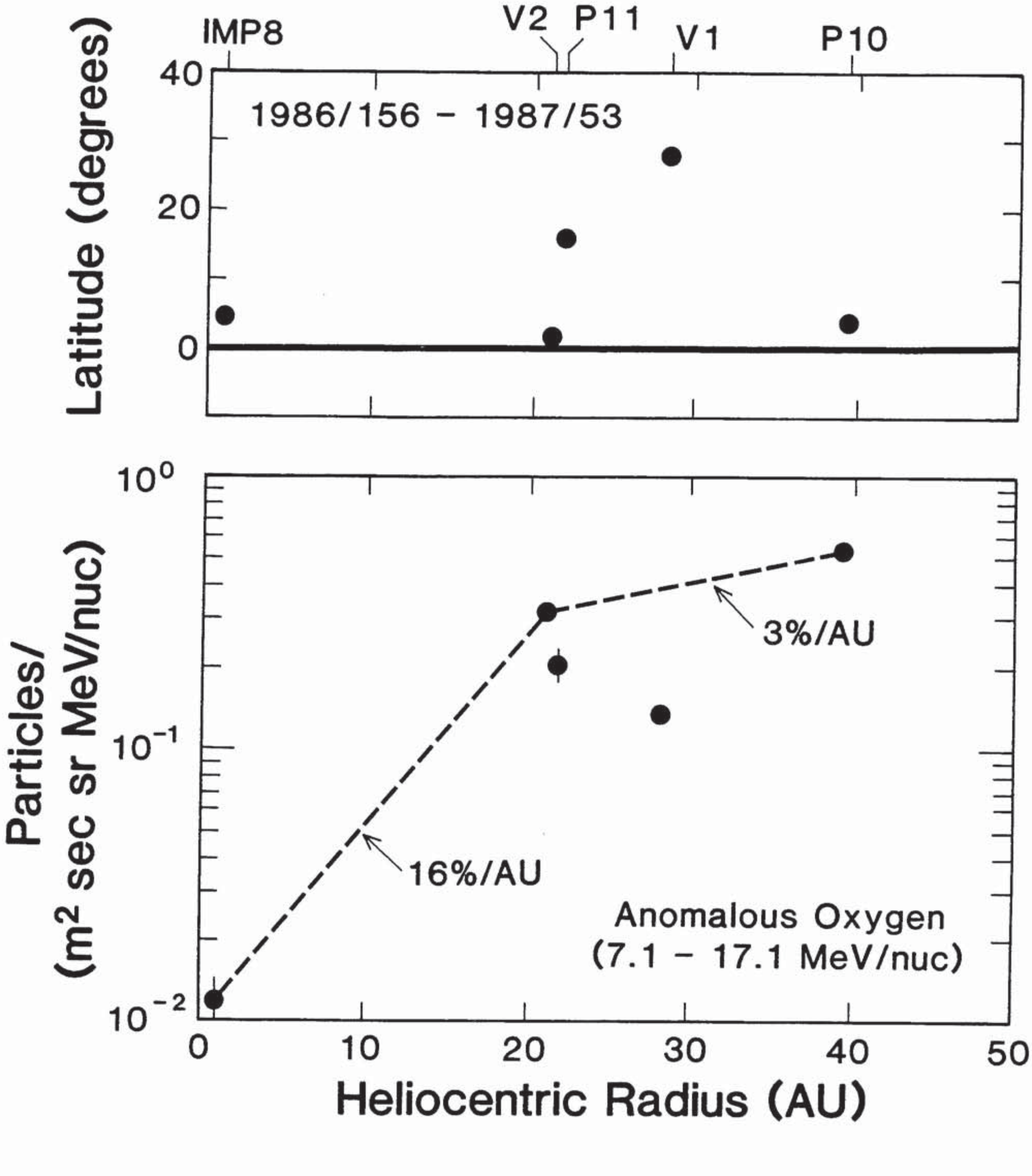

Fig. 4. The flux of anomalous oxygen (7.1 to 17.1 MeV/nuc) observed on different spacecraft versus heliocentric radius (bottom panel). The top panel indicates the heliographic latitude of each spacecraft. The dashed line represents one possible radial dependence for the flux. (After Stone et al. [1987].)

The abrupt change in the gradient at ~20 AU, as depicted in Figure 4, is rather unlikely. We have explored several smooth functions that have some physical basis. For example, Figures 5a and b show least-squares fits to the data assuming a constant latitudinal gradient and a radial gradient which is proportional to r^n. Figure 5a shows the radial dependence of the flux after correcting for the latitudinal gradient, and Figure 5b shows the latitudinal dependence of the flux corrected to 20 AU. The best-fit value of n is -1.0 and the latitudinal gradient is -4.3%/deg. We find that this value of the latitudinal gradient is essentially independent of the assumed radial gradient function. A nonlinear latitude dependence, such as that shown by the dashed line in Figure 5b, cannot be ruled out, however.

The 1/r dependence for the radial gradient might be plausible if the particles are drifting in along the current sheet and diffusing perpendicular to the sheet (see discussion of Equation 1 below) with a $\kappa_\perp$ which varies inversely with the magnetic field strength (see, e.g., Jokipii and Davila [1981] and Newkirk and Fisk [1985]). With this radial dependence, the gradient would be ~ 60%/AU from 1 to 3 AU, much larger than observed in the previous solar minimum. However, it is also possible that the gradient more nearly resembles the dashed line in Figure 4, 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].

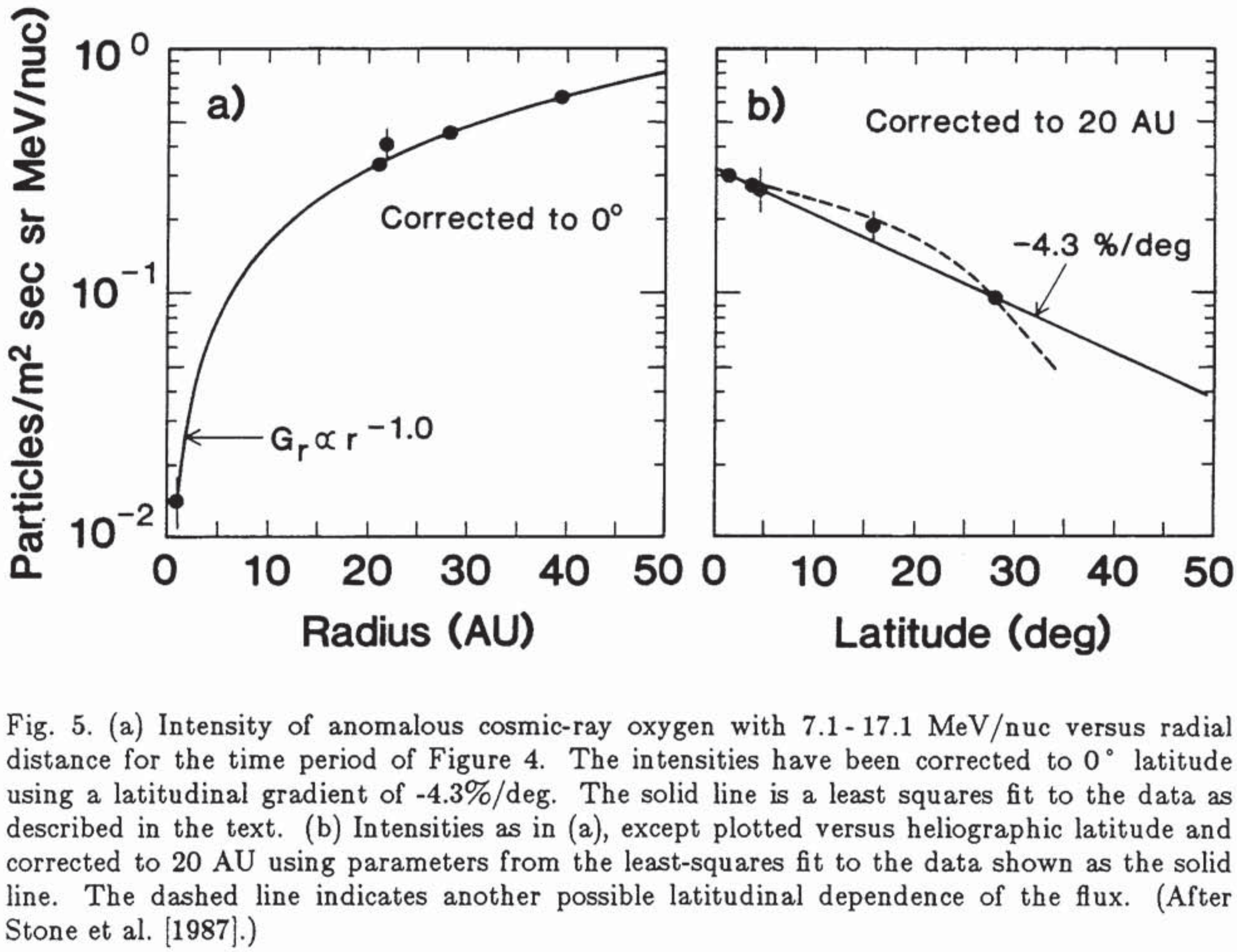

Fig. 5. (a) Intensity of anomalous cosmic-ray oxygen with 7.1 - 17.1 MeV/nuc versus radial distance for the time period of Figure 4. The intensities have been corrected to 0° latitude using a latitudinal gradient of -4.3%/deg. The solid line is a least squares fit to the data as described in the text. (b) Intensities as in (a), except plotted versus heliographic latitude and corrected to 20 AU using parameters from the least-squares fit to the data shown as the solid line. The dashed line indicates another possible latitudinal dependence of the flux. (After Stone et al. [1987].)

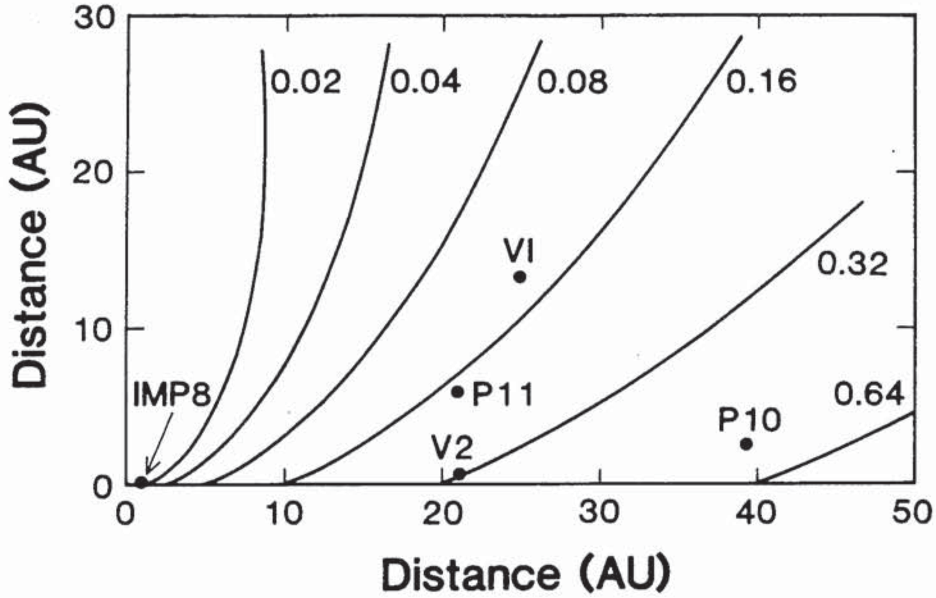

Fig. 6. Intensity contours of 7.1 - 17.1 MeV/nuc anomalous oxygen (labeled in units of $m^{-2}sec^{-1}sr^{-1}(MeV/nuc)^{-1}$) derived from the least-squares fit described in the text. The ordinate is distance above the heliographic equator. The solid circles show the positions of the 5 spacecraft used in the fit. (After Stone et al. [1987].)

As an illustration, we show in Figure 6 the flux contours in the heliosphere that would result from a 1/r dependence for the radial gradient and a latitudinal gradient of -4.3%/deg. The contours emphasize the large deviation from spherical symmetry and the need for non-spherically symmetric modulation models to describe the distribution of particle intensity in the heliosphere.

Two suggestions for the origin of the negative latitudinal gradient have been discussed recently. The first is that the decreased flux at Voyager 1 is due to increased convective effects resulting from a positive latitudinal gradient in the solar wind speed [McDonald and Lal, 1986]. Newkirk and Fisk [1985] noted, however, that a positive latitudinal cosmic ray gradient would result unless special assumptions were made concerning the radial dependence of the diffusion coefficient. The second suggestion is that the latitudinal gradient is a natural consequence of the boundary condition at the neutral current sheet derived by Levy [1978] assuming that drift effects are important in cosmic-ray propagation [Cummings et al., 1987a].

It is difficult to distinguish between these two possibilities during the current half-cycle because both could lead to negative latitudinal gradients. However, during the last half of the solar cycle the drift gradient should have been positive due to the reversed magnetic polarity, while a solar wind induced gradient would have again been negative. A positive latitudinal gradient in the anomalous helium flux was observed in 1976 when Pioneer 11 reached 16° latitude [Bastian et al., 1979; McKibben et al., 1979] and was above the current sheet most of the time [Smith et al., 1978]. Thus a gradient reversal appears to have occurred with the reversal of the solar magnetic field, as expected if the gradient arises from drifts.

Levy [1978] pointed out that particle drifts would result in a latitudinal gradient near the current sheet that was related to the radial gradient by the following expression (see also Jokipii and Kopriva [1979]):

$$\frac{G_{|z|}}{G_r} = \pm \frac{R\ \beta c \sin(\psi)}{3\ |B|\ \kappa_\perp} \tag{1}$$

where $G_{|z|}$ is the latitudinal gradient expressed in %/AU, G_r is the radial gradient in %/AU, R is particle rigidity, βc is the particle velocity, ψ is the angle of the magnetic field with the Sun-spacecraft line (~90° for the outer heliosphere), $|B|$ is the magnetic field strength, and $\kappa_\perp$ is the perpendicular diffusion coefficient. (The - sign is taken for the current magnetic field cycle, the + sign for the last and next.) This relationship holds for any kind of charged particle, anomalous component or galactic cosmic-ray component. In fact, negative latitudinal gradients are observed in both of these components [Cummings et al., 1987a].

Although Equation 1 strictly applies only at the current sheet, Cummings et al. [1987b] used it to estimate values of $\kappa_\perp$ from their measurements, as shown in Figure 7. The resulting rigidity dependence of $\kappa_\perp$ is reasonable, nearly proportional to rigidity, as is its magnitude when scaled back to Earth [Cummings et al., 1987a], although $\kappa_\perp$ is very uncertain experimentally (see Palmer [1982]).

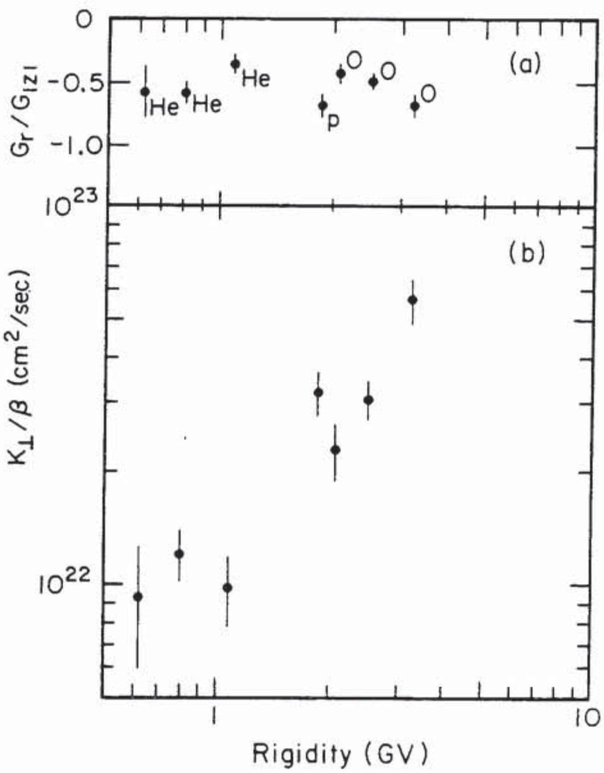

Fig. 7. (a) Values of $G_r/G_{|z|}$ versus rigidity for p, He, and O for the period 1986 day 206 to 310 appropriate for ~28 AU. (b) Estimates of $\kappa_\perp/\beta$ versus rigidity for the same particles. (From Cummings et al. [1987b].)

Temporal Variations

Recurrent variations in the Voyager 1 counting rates may also indicate that the latitude gradient is with respect to the current sheet, rather than the heliographic equator. In Figure 8a we show the Voyager 1 and 2 counting rates of nuclei with >70 MeV/nuc for 1986 and 1987. After the large Forbush decrease in early 1986, there are large recurrent 26-day variations in the Voyager 1 rate that are absent or much smaller in the Voyager 2 rate. Even larger recurrent variations are present in the Voyager 1 fluxes of anomalous oxygen, shown in Figure 8b, which are again much larger than in Voyager 2.

Recently such variations in the >70 MeV/nuc rate, along with the general recovery profile of the rate from 1981 through 1984, have been attributed to the passage of enhanced magnetic field regions past the spacecraft [Perko and Burlaga, 1987; Burlaga et al., 1985]. These regions are presumed to contain enhanced turbulence, leading to a decreased diffusion coefficient from the position of the observer to the modulation boundary. Perko and Burlaga [1987] used the force-field approximation for the cosmic-ray transport equation to predict the recovery profile of the Voyager 2 cosmic-ray rate based on the measured magnetic field profile at the spacecraft. Although this approach resulted in general agreement of the predicted and measured cosmic-ray rate profiles, it remains to be seen whether such a technique will be able to account for the very different profiles at the two spacecraft observed in 1986-1987 as shown in Figure 8a.

An alternate explanation for the variations seen in Figures 8a and b is that they reflect a combination of a gradient in magnetic latitude together with a variation in the latitude caused by a wavy current sheet. The amplitude of the intensity variations is determined by the magnitude of the tilt of the current sheet, α, and the magnitude of the local latitudinal gradient in the vicinity of the spacecraft. If we define the amplitude of the intensity variations, M_i, as the ratio of maximum to minimum fluxes observed on the ith spacecraft, then we have:

$$\frac{\ln(M_i)}{\Delta\Theta_i} = G_{\Theta_i} \qquad (2)$$

where $\Delta\Theta_i$ is the maximum variation in magnetic latitude and G_{Θ_i} is the local latitudinal gradient. For the case of Voyager 1, which is at ~28°N latitude and hence expected to always be above the maximum excursion of the current sheet, $\Delta\Theta_1 = 2\alpha$.

For example, in early 1987 the Voyager 1 anomalous oxygen variations are observed to be a factor of $M_1 \approx 2$ in Figure 8b. Using the latitudinal gradient of -4.3%/deg from Figure 5b results in a current sheet tilt of ~8° to account for the amplitude of the Voyager 1 variations. If the gradient at Voyager 1 is larger, as illustrated by the dashed line in Figure 5b, a smaller current sheet tilt would be needed.

The situation is likely different for Voyager 2 which was at ~1.8°N latitude in early 1987, near the heliographic equator. Consider the case where the current sheet is centered on the spacecraft. The magnetic latitudes sampled by Voyager 2 would be in the range of $\pm\alpha$. Since drift theory would predict latitudinal gradients which are symmetric about the current sheet, $\Delta\Theta_2 = \alpha$ in Equation 2, resulting in a flux variation ratio $M_2 = \sqrt{M_1} \approx \sqrt{2}$ if the gradient is constant (i.e., if $G_{\Theta_1} = G_{\Theta_2}$).

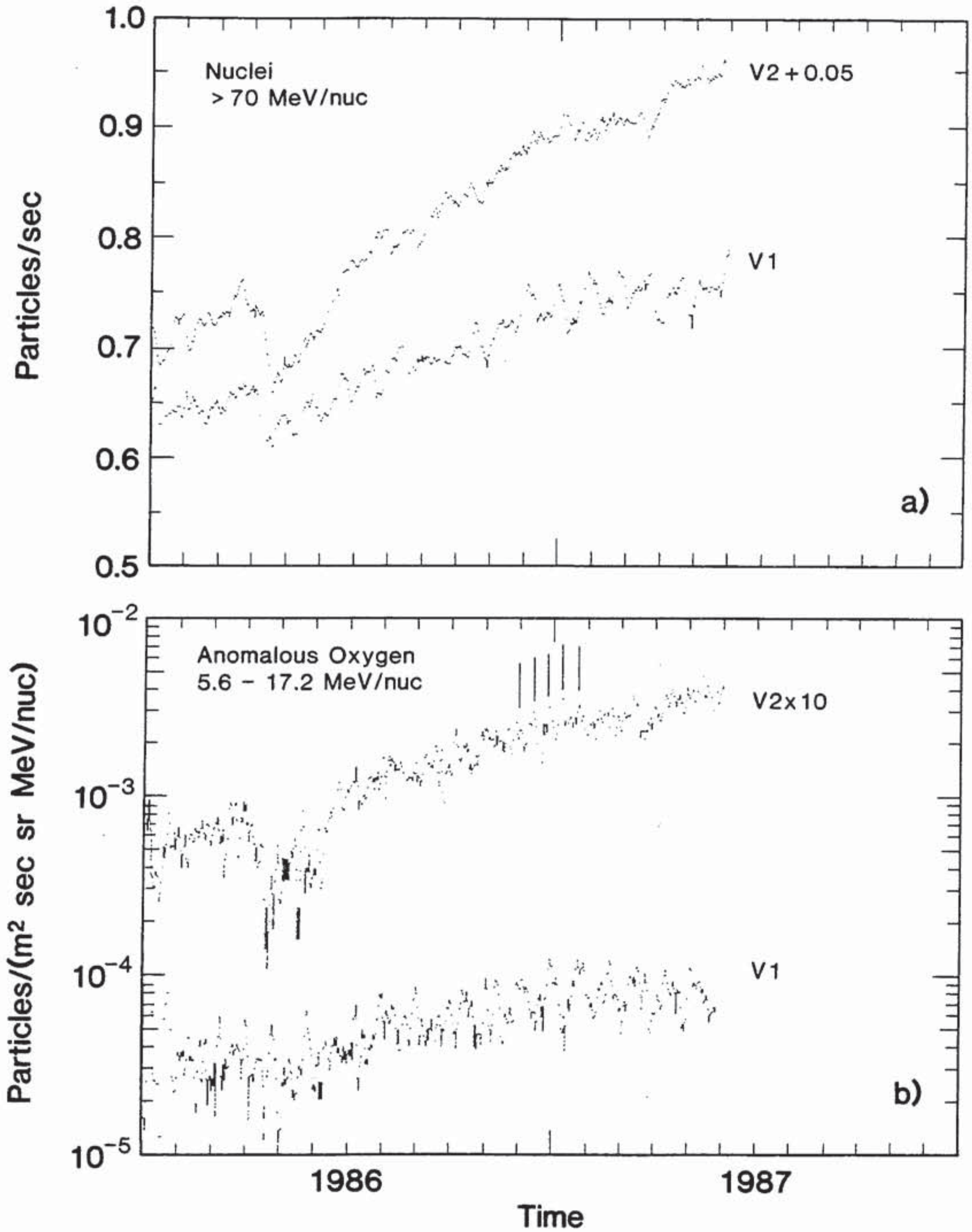

Fig. 8. (a) Three-day moving averages of the counting rate of nuclei with >70 MeV/nuc as measured on Voyager 1 and 2 in 1986-1987. The Voyager 2 rate has been offset for clarity. (b) Three-day moving averages of the flux of anomalous cosmic-ray oxygen with 5.6 - 17.2 MeV/nuc as measured on Voyager 1 and 2. The Voyager 2 flux has been offset for clarity. The vertical bars indicate five 13-day recurrent variations as discussed in the text.

The frequency is also different on Voyager 2 than on Voyager 1, since a maximum in intensity is reached each time the current sheet is crossed. In early 1987, five 13-day variations of approximately this magnitude are observed (see Figure 8b). If $G_{\theta_2} < G_{\theta_1}$, as illustrated by the dashed curve in Figure 5b, then even smaller variations in the Voyager 2 flux would be expected.

We also note that Equation 2 can be used to predict the relative local latitudinal gradients of two different particle populations. From Equation 2 the ratio of the logarithm of the amplitudes is proportional to the ratio of the latitudinal gradients. From Figures 8a and b we infer that in the vicinity of Voyager 1 the local latitudinal gradient of the anomalous oxygen is a factor of ~12 larger than that of nuclei with >70 MeV/nuc. This factor is somewhat larger than that reported for the large-scale latitudinal range 0 - 28° (~6 in Cummings et al. [1987b] and ~9 in Cummings et al. [1987a]), which may indicate that the latitudinal gradients of these two components have different latitudinal dependences.

In order to establish which of the two mechanisms discussed here are responsible for the latitudinal gradients of cosmic rays, it will be necessary to correlate plasma, magnetic field, and cosmic-ray data. If enhanced magnetic fields associated with merged interaction regions account for the variations, then the flux minima should be correlated with the current sheets which are embedded in such regions [Burlaga et al., 1985]. On the other hand, if heliomagnetic latitude is the relevant organizing parameter, as suggested here, then current sheet crossings on Voyager 2 should be correlated with maxima in the cosmic-ray intensity.

Summary

The recent measurements of the anomalous cosmic-ray component have revealed the presence of carbon for the first time and have confirmed anomalous argon. The abundances of these and other elements of the anomalous component have been used to infer the abundances of the interstellar neutral atoms in the local interstellar medium. During solar minimum, the anomalous component exhibits large negative latitudinal gradients and a positive radial gradient which decreases with radius. Finally, there is evidence that the latitudinal gradient is with respect to the current sheet, rather than the heliographic equator.

Acknowledgements

We are grateful to R.E. Vogt for his contributions during his tenure as Principal Investigator for the Voyager CRS. We appreciate contributions from M. Allen who supplied some of the photoionization cross sections and to E. Christian who helped compile and analyze the cross section data. We acknowledge many helpful conversations with R. Mewaldt. We also appreciate the contributions of the other Voyager CRS team members at Caltech, Goddard Space Flight Center, and the University of New Hampshire. This work was supported in part by NASA under contracts NAS 7-918 and NAG5-727, and grant NGR 05-002-160.

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