RADIAL AND LATITUDINAL GRADIENTS OF ANOMALOUS COSMIC-RAY OXYGEN AND HELIUM AND GALACTIC COSMIC RAYS IN THE OUTER HELIOSPHERE

A. C. Cummings[a], E. C. Stone[a], F. B. McDonald[b], W. R. Webber[c], and N. Lal[d]

a) California Institute of Technology, Pasadena, CA 91125 USA
b) NASA Headquarters, Washington, D.C. 20546 USA
c) University of New Hampshire, Durham, NH 03824 USA
d) NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA

Abstract

We have used measurements from instruments on Voyagers 1 and 2 and Pioneer 10 to derive simultaneous latitudinal and radial gradients of anomalous cosmic-ray helium and oxygen and galactic cosmic rays during the latter part of 1986. We find that the negative latitudinal gradients that first appeared in 1985 when Voyager 1 reached heliolatitudes in excess of the current sheet continue to be observed, with an increased magnitude probably related to the decreasing tilt of the current sheet. The sign of this gradient is opposite to that reported during the last solar cycle when the solar magnetic field polarity was reversed, as predicted by propagation models in which curvature and gradient drifts are important. Although during the 1985-1986 time period radial gradients in the outer heliosphere appeared to decrease, the ratios of the radial and latitudinal gradients remained similar for both anomalous and galactic particles as predicted by drift theory. These observations indicate that the particles move inward preferentially at low latitudes from the heliospheric boundary during the current phase of the solar cycle.

1. Introduction. Recently we have used measurements from instruments on Voyagers 1 and 2 (V1 and V2) and Pioneer 10 (P10) to derive simultaneous radial and latitudinal gradients of anomalous cosmic-ray (ACR) oxygen and helium and galactic cosmic rays (GCR) in the outer heliosphere during the latter part of 1985 [1]. We found substantial negative latitudinal gradients for all of these components. The appearance of these latitudinal gradients is presumably related to the fact that the tilt of the current sheet decreased from ~45° to ~20° in early 1985 [2] thus enabling Voyager 1, which was at a heliolatitude of 27°, to directly measure this latitudinal gradient for the first time in the current solar cycle. At a similar time in the previous cycle, McKibben et al. [3] and Bastian et al. [4] reported a positive latitudinal gradient in 1975 when Pioneer 11 reached a maximum heliographic latitude of 16°N. The opposite sign of the latitudinal gradient in the two cycles when the solar magnetic polarity was also reversed suggests that curvature and gradient drifts are important for the propagation of cosmic rays. Theories based on drifts also lead to predictions of the ratios of the radial and latitudinal gradients. Using measurements of these ratios one can estimate values of $\kappa_\perp/\beta$ and its rigidity dependence.

Obviously, interplanetary conditions are evolving with time as the tilt of the current sheet changes and the cosmic-ray intensity increases throughout the heliosphere towards a maximum value expected in 1988. We have therefore extended our earlier study to a period in late 1986 when the current sheet tilt decreased further to ~10° [5] and the intensity of anomalous helium and oxygen at Voyager 2 increased by a factor ~4. Substantially larger negative latitudinal gradients were observed during this later time period. These new data will be presented and discussed in this paper.

2. Observations. The energy spectra for ACR oxygen in late 1986 from V1, V2, and P10 are shown in Figure 1a. Similar data for ACR helium is shown in Figure 1b. The Voyager He and O spectra and the Pioneer He spectrum have been corrected for

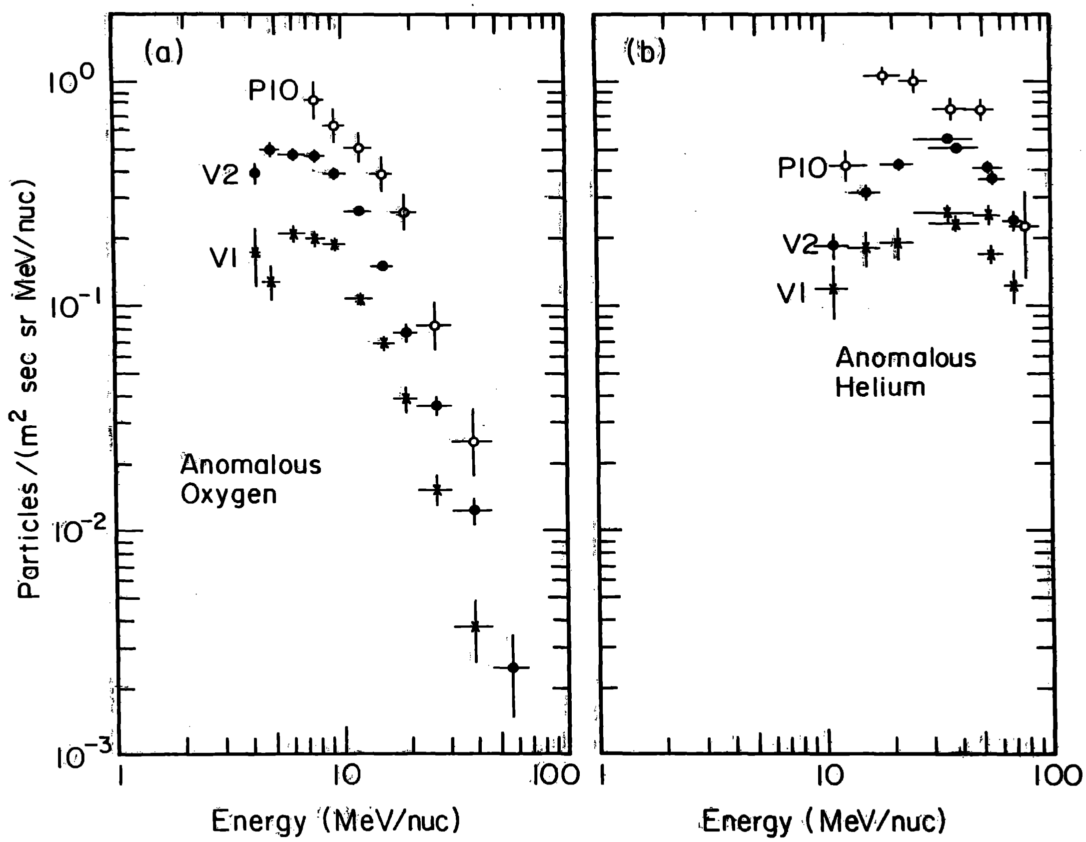

Fig. 1. (a) Energy spectra of anomalous oxygen at V1 (×), V2 (•), and P10 (O) for the time period 1986/206 to 1986/310. The heliographic radius and latitude of the spacecraft are given in Table 1. The heliolongitudes for V1, V2, and P10 are 335°, 9°, and 176°, respectively. (b) Same as in (a) but for anomalous helium

interplanetary and GCR contributions by a method similar to that described in Cummings et al. [6,7]. The large increase in intensity of ACR oxygen over that measured in late 1985 at all spacecraft can be seen by comparing with Figure 1 in Cummings et al. [1]. It should also be noted that the V2 intensities of both ACR helium and oxygen are a factor ~2 larger than those at V1, in contrast to a difference of ~30% observed in late 1985, indicating that the negative latitudinal gradient has increased substantially in the 1 year time interval between measurements.

In the interpretation of measurements made on the V1, V2, and P10 spacecraft we shall assume that the particle intensities are to first order not a function of heliolongitude and that the radial and latitudinal gradients are independent of radius and latitude. With these assumptions the first order radial and latitudinal gradients may be derived following Cummings et al. [1]. These gradients, as derived from the measured flux ratios and the spacecraft positions, are displayed in Table 1. It is observed that the latitudinal gradient for ACR oxygen has increased from ~-3%/deg to ~-4.5%/deg in the one year period through the end of 1986. The gradients for GCR nuclei >70 MeV and ACR helium have also increased by comparable amounts to ~-0.67%/deg and ~-4%/deg, respectively. At the same time the average radial gradients, as determined between V2 and P10, have decreased in all cases from their values one year earlier. In fact, these radial gradients are now only one half of their values two years earlier in 1984 [8,9].

TABLE 1. Radial (G_r) and Latitudinal (G_θ and $G_{|z|}$) Gradients and Corresponding Estimates of $\kappa_\perp/\beta$ at ~ 28 AU from Voyager and Pioneer data.[a,b]

Particle Type	Energy (MeV/nuc)	G_r (%/AU)	G_θ (%/deg)	$G_{|z|}$ (%/AU)	$G_r/G_{|z|}$	Median R (GV)	$\kappa_\perp/\beta$ (cm^2/sec)
ACR O	7.1-10.6	3.4±0.7	-3.8±0.3	-7.9±0.6	-0.43±0.08	2.1[c]	$(2.3\pm0.4)\times10^{22}$
ACR O	10.6-17.1	4.5±0.6	-4.6±0.3	-9.3±0.5	-0.49±0.06	2.5[c]	$(3.1\pm0.4)\times10^{22}$
ACR O	17.1-30.6	6.4±0.8	-4.6±0.5	-9.4±0.9	-0.68±0.09	3.3[c]	$(5.6\pm0.8)\times10^{22}$
GCR nuclei	>70	0.94±0.09	-0.67±0.04	-1.37±0.09	-0.69±0.09	1.9	$(3.2\pm0.4)\times10^{22}$
ACR He	9.2-18.0[d]	3.4±1.0	-2.8±0.8	-5.7±1.6	-0.59±0.21	0.6[c]	$(0.9\pm0.3)\times10^{22}$
ACR He	18.0-25.2[e]	5.5±0.5	-4.5±0.6	-9.2±1.3	-0.59±0.09	0.8[c]	$(1.2\pm0.2)\times10^{22}$
ACR He	29.4-48.6[f]	2.7±0.6	-3.6±0.3	-7.4±0.7	-0.36±0.08	1.1[c]	$(1.0\pm0.2)\times10^{22}$

[a]For period 1986 day 206 - 1986 day 310. Voyager 2 located at R = 20.9 AU, θ = 1.3°; Voyager 1 at R = 28.0 AU, θ = 27.9°; Pioneer 10 at R = 39.2 AU, θ = 3.7°. [b]Uncertainties shown are statistical and do not include any systematic uncertainty arising from the latitudinal and radial averaging. [c]Assumes particles are singly charged. [d,e,f]These energy intervals are for the Voyager data; the Pioneer 10 energy intervals are: d = 10.0 – 15.3, e = 15.3 – 29.0, f = 30.7 – 43.4.

It is useful to express the latitudinal gradient in terms of the perpendicular distance $|z|$ from the heliographic equator. This quantity $G_{|z|}$ and the ratio $G_r/G_{|z|}$ at the radial position of V1 (~28 AU) are shown in Table 1 and plotted versus median rigidity in Figure 2a. This ratio is approximately the same for all the particle types and rigidities shown in Table 1. However this ratio is now ~ 0.5 in contrast to a value ~ 1 obtained one year earlier. These values indicate an increasing deviation from spherical symmetry in the distribution of particles in the outer heliosphere with both galactic and anomalous cosmic-ray components penetrating inward preferentially at low latitudes.

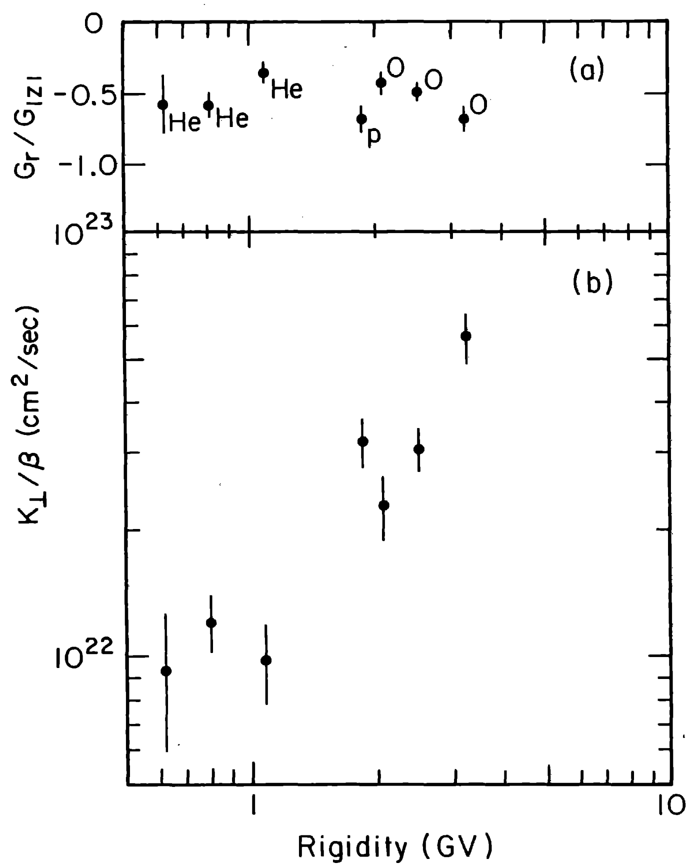

Fig. 2. (a) Values of $G_r/G_{|z|}$ versus rigidity for p, He, and O as shown. (b) Estimates of $\kappa_\perp/\beta$ versus rigidity for the same particles

3. Discussion. The ACR component consists of enhanced fluxes of helium, oxygen, and certain other nuclei with energies below ~50 MeV/nuc, which are thought to be interstellar neutrals which drift into the heliosphere, become singly ionized, and are then convected to the outer heliosphere where they are accelerated [10]. A specific model for the acceleration of these particles at the solar wind termination shock and then their subsequent motion in the heliosphere has been developed by Jokipii and co-workers (e.g., [11]). In this model, drift motions of these particles after their acceleration play an important role in their distribution in the outer heliosphere and lead not only to a

prediction of a reversed sign of the latitudinal gradient as the polarity of the solar magnetic field reverses, but also to specific predictions regarding the radial and latitudinal gradients themselves, as well as changes in the energy spectrum of both ACR oxygen and helium between the two polarity cycles. A positive latitudinal gradient of ACR helium has been reported by McKibben et al. [3] and Bastian et al. [4] for the last cycle when the solar field polarity was opposite to the present cycle when we observe negative gradients.

We note that negative latitudinal gradients may also result from an increase in solar wind speed from ~350 km/sec near the heliographic equator to a plateau of ~600 km/sec at latitudes of ~30°-40° [12,13]. However, this increase in solar wind speed is found for both solar magnetic field polarities. Since the observations imply a reversal of the sign of the latitudinal gradient with changing magnetic field polarity, we assume in what follows that drifts are the dominant mechanism in establishing the latitudinal gradients.

Using drift theory and assuming that the latitudinal gradient is symmetric about the heliographic equator, it is possible to use the relationship between $G_r/G_{|z|}$ to estimate the local value of the perpendicular diffusion coefficient $\kappa_\perp$ at the point of measurement in the outer heliosphere [14]. Following the procedures of Cummings et al. [1] we show in Table 1 the values of $G_r/G_{|z|}$ for GCR nuclei and for ACR helium and oxygen assuming both components are singly ionized. Since $\kappa_\perp/\beta$ is proportional to the scattering mean free path $\lambda_\perp$, it should be independent of particle type, varying as $\lambda_\perp$ depends on rigidity. In Figure 2b we plot the values of $\kappa_\perp/\beta$ versus assigned rigidity. The data are reasonably well represented by a power-law relationship with $\kappa_\perp/\beta \propto R^{1.1\pm0.1}$. This supports the assumption that the ACR particles are indeed singly ionized. In addition, the observed near equality of the ratios of radial and latitudinal gradients for different species, including both the GCR and ACR components, arises naturally from drift effects in particle propagation models.

The strong correlation between the measured latitudinal and radial gradients with the decreasing tilt of the current sheet from ~45° in 1984 to ~10° in late 1986 suggests that this current sheet plays an important role in the movement of the particles inward in the solar system from the heliospheric boundary and that a strongly asymmetric particle distribution exists throughout 1985 and 1986.

4. Acknowledgements. This work was supported in part by NASA under contract NAS-7-918 and grant NGR-05-002-160.

References

1. Cummings A. C., E. C. Stone, and W. R. Webber, *Geophys. Res. Lett.*, in press, 1987.
2. Christon S. P., E. C. Stone, and J. T. Hoeksema, *Geophys. Res. Lett.*, **13**, 777, 1986.
3. McKibben R. B., K. R. Pyle, and J. A. Simpson, *Astrophys. J. Lett.*, **227**, L147, 1979.
4. Bastian T. S., R. B. McKibben, K. R. Pyle, and J. A. Simpson, *Proc. 16th Internat. Cosmic Ray Conf.*, **12**, 318, 1979.
5. Hoeksema J. T., private communication, 1987.
6. Cummings A. C., E. C. Stone, and W. R. Webber, *J. Geophys. Res.*, **91**, 2986, 1986.
7. Cummings A. C., R. A. Mewaldt, and E. C. Stone, *Geophys. Res. Lett.*, **13**, 1043, 1986.
8. Webber W. R., A. C. Cummings, and E. C. Stone, *19th Internat. Cosmic Ray Conf.*, **5**, 172, 1985.
9. Webber W. R., and J. A. Lockwood, *Astrophys. J.*, **302**, 511, 1986.
10. Fisk L. A., B. Kozlovsky, and R. Ramaty, *Astrophys. J. Lett.*, **190**, L35, 1974.
11. Jokipii J. R., *J. Geophys. Res.*, **91**, 2929, 1986.
12. McDonald F. B., and N. Lal, *Geophys. Res. Lett.*, **13**, 781, 1986.
13. Newkirk Gordon, Jr., and Lennard A. Fisk, *J. Geophys. Res.*, **90**, 3391, 1985.
14. Levy E. H., *Geophys. Res. Lett.*, **5**, 969, 1978.