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Radial and latitudinal gradients of anomalous cosmic ray oxygen in the inner heliosphere

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[1] We use data from the Ulysses, Advanced Composition Explorer, and Solar Terrestrial Relations Observatory spacecraft to determine the radial and latitudinal gradients of anomalous cosmic ray oxygen in two energy ranges from 4.5–15.6 MeV/nuc in the inner heliosphere for the first time during an A<0 part of the solar cycle. Using measurements from early 2007 to mid-2008, we find that the radial gradient is ∼48 ± 13%/AU, consistent with previous inferences for A<0 and larger than that determined in the inner heliosphere for A>0. The latitudinal gradient is consistent with zero and in the range −0.3 to 0.4%/degree, suggesting that during A<0 these particles are not able to propagate into the inner heliosphere by rapid drift along the heliospheric current sheet if the tilt of the sheet is as large as 30 degrees. **Citation:** Cummings, A. C., C. Tranquille, R. G. Marsden, R. A. Mewaldt, and E. C. Stone (2009), Radial and latitudinal gradients of anomalous cosmic ray oxygen in the inner heliosphere, *Geophys. Res. Lett.*, *36*, L18103, doi:10.1029/2009GL039851.

1. Introduction

[2] Anomalous cosmic rays (ACRs) are a sample of the interstellar medium, having originated as interstellar neutral gas, entered the heliosphere, become ionized and picked up by the solar wind, and carried to the outer heliosphere where they are accelerated to MeV energies [*Fisk et al.*, 1974]. The site and mechanism of the acceleration is still to be determined [*Stone et al.*, 2008; *Fisk and Gloeckler*, 2008]. The particles reach the inner heliosphere, here defined to be <5 AU, by a combination of diffusing and drifting in the large-scale interplanetary magnetic field. The drift motions change with the change in polarity of the Sun's magnetic dipole, which reverses approximately every 11 years. In the A>0 part of the 22-year solar magnetic cycle, when the field northward of the heliospheric current sheet (HCS) is directed outward, positively charged particles originating in the outer heliosphere tend to drift towards the heliographic equator from the polar regions [*Jokipii et al.*, 1977]. Many measurements during A>0 periods have confirmed that the latitudinal gradients of ACRs are positive in both the inner and outer heliosphere during such times [see, e.g., *McKibben*, 1989; *Cummings et al.*, 1995; *Trattner et al.*, 1977; *Marsden et al.*, 1999] (and references therein). In the A<0 part of the cycle, which began in ∼2001, the drift patterns are reversed and positive particles drift inward along the HCS. In this case, the particles should exhibit a negative latitudinal gradient, which has been observed in the outer heliosphere [*Cummings et al.*, 1987b; *McDonald et al.*, 1992; *Cummings and Stone*, 1998] but has not yet been established in the inner heliosphere due to the lack of spacecraft positioned in the appropriate locations. The purpose of this paper is to report the first observations of the radial and latitudinal gradients of ACR oxygen within the inner heliosphere during an A<0 period.

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2. Observations

[3] In this study we use three data sets to determine radial and latitudinal gradients between spacecraft near Earth and Ulysses in two energy bands. For ACR O with 4.5–15 MeV/nuc, we use intensities obtained from the Cosmic Ray and Solar Particle Investigation (COSPIN) Low Energy Telescope (LET) on the Ulysses spacecraft [*Simpson et al.*, 1992] and from the Low Energy Telescopes on the Solar Terrestrial Relations Observatory (STEREO) spacecraft [*Mewaldt et al.*, 2008]. For ACR O with 7.3–15.6 MeV/nuc, we use data from COSPIN LET on Ulysses and from the Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE) spacecraft [*Stone et al.*, 1998]. The period chosen for the study is from 2007 day 57 through 2008 day 150 (2007/57–2008/150). The period includes most of the third fast-latitude scan of the Ulysses mission, in which the spacecraft traversed from 80°S heliographic latitude to 80°N from 2007/39 to 2008/15. Ulysses crossed the heliographic equator once during this period on 2007/223 at a radial location of 1.4 AU.

[4] During this period the >4.5 MeV/nuc oxygen data were not significantly contaminated by either enhancements from corotating interaction regions or solar energetic particle events. Restricting the energy range below 250 MeV total energy reduces contamination from galactic cosmic rays (GCRs) and ensures the bulk of the particles are singly charged [*Klecker et al.*, 1995; *Mewaldt et al.*, 1996; *Jokipii*, 1996]. The energy spectra of O from Ulysses, STEREO, and ACE are shown in Figure 1 for the period 2008/43–150, where the portion of the spectrum dominated by GCRs is evident above ∼35 MeV/nuc. ACR O dominates the spectrum below that energy. From ∼4–20 MeV/nuc, the energy dependence of the spectrum at Ulysses is similar to the near-Earth spectra, implying the gradients are approximately independent of energy.

[5] In order to separate radial and latitudinal gradients, we adopt a method first used by *Bastian et al.* [1979] and *McKibben et al.* [1979], in which we fit the ratio of 27-day

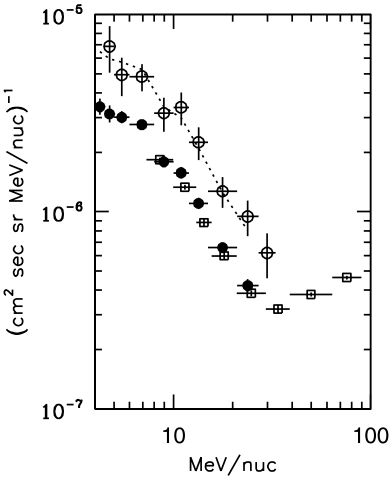

Figure 1. Energy spectra of oxygen from Ulysses (open circles), STEREO (solid circles), and ACE (open squares) for the period 2008/43–150. During this period the radial position of Ulysses varied from 2.35 AU to 2.89 AU and the heliographic latitude ranged from 74.0°N to 58.7°N. The dotted line represents the STEREO spectrum multiplied by a constant factor and indicates that the gradient is independent of energy.

averaged intensities of O with 4.5–15 MeV/nuc at Ulysses and STEREO, for example, to the following equation:

$$ln(I_U/I_S) = G_r\Delta r + G_\Theta\Delta|\Theta| + C \quad (1)$$

where I_U and I_S are intensities at Ulysses and STEREO, respectively, G_r is the radial gradient, Δr is the radial separation of the two spacecraft, G_Θ is the latitudinal gradient, and C represents a normalization constant. The logarithmic dependence in equation (1) is a solution of a simple diffusion convection model in which G_r and G_Θ are constant [see, e.g., *Jokipii*, 1971]. G_Θ is assumed to be symmetric about the heliographic equator and $\Delta|\Theta|$ is $|\Theta_U| - |\Theta_S|$. By using the ratio of intensities in this way we reduce the impact of long-term temporal changes on the deduced spatial gradients. A similar fit using Ulysses and ACE intensities of O with 7.3–15.6 MeV/nuc was done separately.

[6] We first consider the analysis of the Ulysses and STEREO observations. For STEREO we average the O intensities with 4.5–15 MeV/nuc from the two spacecraft (A and B) and we show those intensities for 17 Bartels rotations in Figure 2a along with the O intensities from the Ulysses spacecraft. Radial locations and heliographic latitudes of the spacecraft are shown in Figures 2b and 2c, respectively. For STEREO we show the average of the absolute values of the STEREO A and B coordinates. The natural logarithms of the intensity ratios are shown in Figure 2d. Figure 2e shows that the tilt of the HCS remained in the range ~30–35 degrees during the period of analysis.

[7] The solid line shown in Figure 2d is the result of the least-squares fit to equation (1). The best-fit parameters are: G_r = 45 ± 12 %/AU, G_Θ = 0.18 ± 0.24%/degree, and C = −0.19 ± 0.11. The normalization parameter, C, of −0.19 implies a normalization factor of 0.83 ± 0.09 between the Ulysses and STEREO instruments. The chi square of the fit was 12.2 for 14 degrees of freedom, indicating an excellent fit.

[8] In Figure 3 we show similar data for the 7.3–15.6 MeV/nuc energy interval using Ulysses and ACE measurements. In this case, the best-fit parameters are: G_r = 51 ± 14 %/AU, G_Θ = 0.03 ± 0.29 %/degree, and C = −0.01 ± 0.13. The normalization factor between Ulysses and ACE measurements in this case is 0.99 ± 0.13. The chi square of the fit was 13.5 for 14 degrees of freedom, The results are shown in Table 1 for the two energy ranges and are consistent with each other. Combining the two measurements, the radial gradient is ~48 ± 13%/AU and the latitudinal gradient is consistent with zero and in the range −0.3 to 0.4 %/degree.

3. Discussion

[9] Although this is the first direct measurement of the radial gradient of ACR O inside 5 AU during an A<0 period, there have been other inferences. *Stone and Cummings* [1999; see also *Cummings and Stone*, 1999] developed a

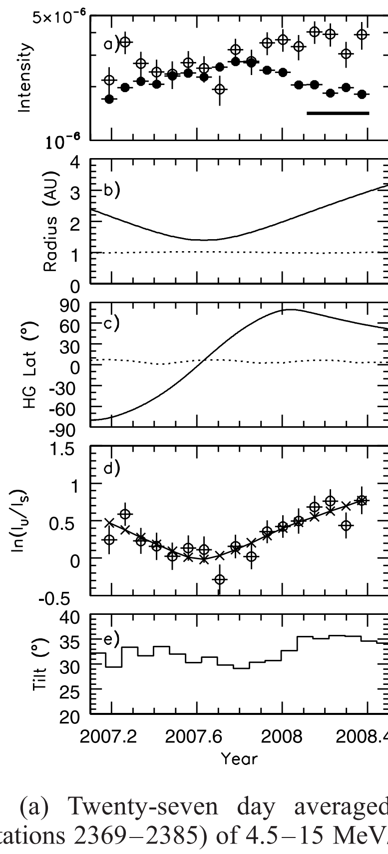

Figure 2. (a) Twenty-seven day averaged intensities (Bartels rotations 2369–2385) of 4.5–15 MeV/nuc O from Ulysses (open circles) and STEREO (solid circles) versus time. The units are (cm^2 s sr MeV/nuc)$^{-1}$. The horizontal bar shows the time period for the energy spectra shown in Figure 1. (b) Radial position of Ulysses (solid line) and STEREO (A,B average) (dotted line) versus time. (c) Heliographic latitude of Ulysses (solid line) and STEREO (A,B average) (dotted line) versus time. (d) Ratio of intensities (open circles) in Figure 2a versus time. The solid line connects best-fit points (×) as described in the text. (e) Tilt ("classic" line-of-sight method) of heliospheric current sheet from the Wilcox Solar Observatory versus time.

tilt model for the time variation of the 7.1–17.1 MeV/nuc ACR O intensity near the heliographic equator at the radial positions of 1 AU, Voyager 1, Voyager 2, Pioneer 10, and Pioneer 11 for the period 1973 to 1999. The model was based on the time history of the tilt of the HCS, gradient versus tilt and gradient versus radial distance relationships, and a source intensity at a radial distance at the heliographic equator that varied from A<0 to A>0. The model fits the data reasonably well. For the 1980.5 to 1990.5 period with A<0, the radial gradient assumed in the model for the region from 1 to 4.5 AU was 48%/AU and invariant with time. In addition, multi-spacecraft studies produced estimates of the radial gradient in the inner heliosphere during the previous A<0 period, even though the only spacecraft inside ~20 AU were at 1 AU [*Cummings et al.*, 1987a, 1990a]. For example, from the approximate 1/r dependence of the radial gradient deduced for the outer heliosphere, the gradient for 7–25 MeV/nuc ACR O from 1–3 AU was 49%/AU, estimated from *Cummings et al.* [1990a, Figure 3]. Both of these indirect determinations are in excellent agreement with the more direct measurement presented here of 48 ± 13 %/AU. This radial gradient value for A<0 is larger than previous determinations made for A>0, which are 25 ± 5 %/AU [*Webber et al.*, 1977, 1979] and 18.0 ± 2.4 %/AU [*Marsden et al.*, 1999] for ~10 MeV/nuc O.

[10] Previous studies of latitudinal gradients of ACR O in the inner heliosphere were acquired during A>0 periods and suggested there is likely a latitude dependence, with the gradient varying from 0.6%/degree in the 0° to 20° latitude range [*Marsden et al.*, 1999] to as much as 3%/degree at higher latitudes [*Trattner et al.*, 1977]. *Marsden et al.* [1999] suggest that the smaller latitudinal gradient at lower latitudes is due to an erosion of the gradient within the streamer belt.

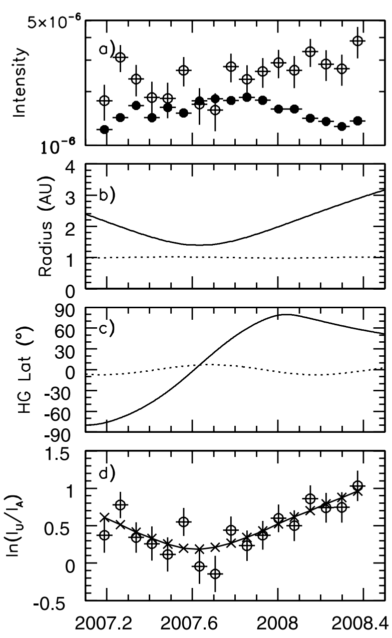

Figure 3. Similar to Figure 2 except for O with 7.3–15.6 MeV/nuc using Ulysses and ACE measurements. The units of intensity in Figure 2a are (cm^2 s sr MeV/nuc)$^{-1}$.

Table 1. Radial and Latitudinal Gradients of ACR O

Energy Range (MeV/nuc)	G_r (%/AU)	G_θ (%/degree)
4.5–15	45 ± 12	0.18 ± 0.24
7.3–15.6	51 ± 14	0.03 ± 0.29

[11] The latitudinal gradients determined here for the current A<0 period, 0.18 ± 0.24%/degree for the 4.5–15 MeV/nuc energy range and 0.03 ± 0.29 %/degree for the 7.3–15.6 MeV/nuc energy range represent an average gradient over the full range of the Ulysses latitude excursion. The small values are consistent with the very small latitude gradient reported for the same time period for GCRs with about the same rigidity (~2–2.5 GV) [*Heber et al.*, 2008]. They are also consistent with the negligible latitudinal gradient determined for 2.5 GV electrons in the inner heliosphere during the first Ulysses fast latitude scan in 1994/1995 during an A>0 period [*Heber et al.*, 1999a, 1999b]. At the same time there was observed a small positive latitudinal gradient for 2.5 GV protons. In both periods when the determinations were made, 1994/1995 and 2007/2008, the average tilt of the HCS was about 25–30 degrees. Thus, taken together, the results of the latitudinal gradients of ACR O and GCR protons and electrons in both A<0 and A>0 solar minimum periods in the inner heliosphere indicate that when the particles drift from the poles downwards towards the heliographic equator, positive latitudinal gradients are observed. However, when the tilts are >25 degrees, negative latitudinal gradients are not observed for positive particles during A<0 periods or for negative particles during A>0 periods. This is the tilt value below which the GCR electron to proton ratio first started to show the effects of drift in the last A>0 period (mid 1990s) [*Heber et al.*, 1999a, 1999b]. This is also consistent with observations in the outer heliosphere during A<0 periods, where it is found that both radial and latitudinal gradients are strong functions of the tilt angle of the HCS [*Cummings et al.*, 1990b], with larger negative latitudinal gradients appearing as the tilt declines below ~30 degrees.

[12] Thus, if the tilt angle continues to evolve to lower values in the coming months or years, we expect that the intensity of ACR O in the inner heliosphere will grow and that negative latitudinal gradients are likely to be established [see, e.g., *Jokipii*, 1989]. It appears that when the tilt is greater than 25–30 degrees, particles with the charge polarity that drift inward along the HCS cannot drift all the way into 1 AU to establish an effective source of particles at low latitude. This is perhaps because the pathlength along the sheet is large enough that diffusion is the dominant transport mechanism.

[13] **Acknowledgments.** We thank the Wilcox Solar Observatory for making the heliospheric current sheet data available. This work was supported by NASA at Caltech under grant NNX8AI11G and contract NAS5-03131. We acknowledge the use of the Ulysses Data System in the preparation of this paper.

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