GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 4, PAGES 333-336, FEBRUARY 15, 1995

Measurement of anomalous cosmic ray oxygen at heliolatitudes ~25° to ~64°

L.J. Lanzerotti[1], C.G. Maclennan[1], R.E. Gold[2], T.P. Armstrong[3], E.C. Roelof[2], S.M. Krimigis[2], G.M. Simnett[4], E.T. Sarris[5], K.A. Anderson[6], M. Pick[7], and R.P. Lin[6]

Abstract. We report measurements of the oxygen component (0.5 – 22 MeV/nucl) of the interplanetary cosmic ray flux as a function of heliolatitude. The measurements reported here were made with the Wart telescope of the HI-SCALE low energy particle instrument on the Ulysses spacecraft as the spacecraft climbed from ~24° to ~64° south solar heliolatitude during 1993 and early 1994. As a function of heliolatitude, the O abundance at 2–2.8 MeV/nucl drops sharply at latitudes above the heliospheric current sheet. The oxygen spectrum obtained above the current sheet has a broad peak centered at an energy of ~2.5 MeV/nucl that is the anomalous O component at these latitudes. There is little evidence for a latitude dependence in the anomalous O fluxes as measured above the current sheet. Within the heliospheric current sheet, the O measurements are composed of both solar and anomalous origin particles.

Introduction

In-ecliptic studies of the anomalous component of several species of the cosmic ray fluxes have been conducted since their first discovery near 1 AU [e.g., Garcia-Munoz, Mason, and Simpson, 1973; Hovestadt et al., 1973; McDonald et al., 1974, 1976]. These measurements have now been made near the ecliptic plane to helioradii distances of several tens of A.U. with the Voyager and Pioneer spacecraft [e.g., recent reports by Cummings et al., 1993a,b; Lopate and Simpson, 1993]. Current theory on understanding the existence of these cosmic rays is centered on the ionization of interstellar neutral atoms by solar UV or the solar wind [Fisk et al., 1974; Fisk 1986], the convection of these particles to the outer heliosphere, and their acceleration to higher energies at the solar wind termination shock [Pesses et al., 1981]. The accelerated nuclei re-enter the inner heliosphere. Recently, Luhmann [1994] has discussed and modeled possible solar system sources for the neutrals.

[1] AT&T Bell Laboratories, Murray Hill, NJ.
[2] Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD.
[3] Department of Physics, University of Kansas, Lawrence.
[4] University of Birmingham, UK.
[5] University of Thrace, Xanthi, Greece.
[6] Space Sciences Laboratory, University of California, Berkeley.
[7] Observatoire de Paris, Meudon, France.

Paper number 94GL03210
0094-8534/95/94GL-03210$03.00

The fluxes of the anomalous component increase with increasing radial distance [e.g., Cummings et al., 1987; Mewaldt et al., 1993a; Cummings, Stone, and Webber, 1993a,b; Lopate and Simpson, 1993]; in addition, the anomalous component is not detectable above the interplanetary background fluxes near 1 A.U. during solar maximum conditions [e.g., Mewaldt et al., 1993b] when the solar modulation is largest. Recent results from combined measurements from the SWICS and HI-SCALE instrumentation on Ulysses show that the anomalous hydrogen component (at least) is also accelerated at interplanetary co-rotating interaction regions (CIRs) at distances $\lesssim$5A.U. [Gloeckler et al., 1994]. Ferrando et al. [1993] reported the measurements of anomalous He (34 – 125 MeV/nucl) from the KET instrument on Ulysses at ~5 A.U.

The Ulysses spacecraft provides an opportunity to investigate the anomalous component at heliolatitudes much higher than any examined to date by any spacecraft. In particular, during the current solar minimum conditions, Ulysses instruments can examine the spectra of the anomalous component above the heliospheric current sheet and the direct effects of the corotating interaction regions on particle acceleration. We have analyzed the HI-SCALE data to study the variation of the O nuclei during the first transit of Ulysses to high solar latitudes.

Observations

The interplanetary oxygen ion measurements reported herein were made with the Wart (W) telescope of the HI-SCALE instrument [Lanzerotti et al., 1992] on the Ulysses spacecraft. The Wart is a three element solid state telescope consisting of a 5μ first (D) detector followed by two 200μ second (C) and third (B) detectors used in coincidence and anti-coincidence to define the mass and energy of the detected particles. Two fixed energy channel windows identify the CNO group of elements, and all particles satisfying the coincidence/energy requirements are counted. A pulse height analysis (PHA) is applied to individual events in order to get better species and energy resolution at the expense of statistical precision (two events are so analyzed each spacecraft spin period of 12 seconds duration). A rotating, four level priority scheme is used in order to increase the statistics of the PHA analysis of less abundant species.

Shown in the left panel of Figure 1 are the spectra of the interplanetary C (open diamonds) and O (open triangles) fluxes measured by the HI-SCALE W for the 212-day interval 93023 – 93235. These days correspond to Ulysses heliolatitudes of ~24° – 38° and helioradii of ~5AU – 4.5 AU. Both spectra are similar in functional form; the power law line drawn through the O points corresponds to an exponent in energy of ~−3. The C/O ratios vary slightly from energy bin to energy bin, but over-all, the ratio is of the order of 0.5 – 0.6. At an energy of ~1.7 MeV/nucl, the ratio is the lowest: ~0.4

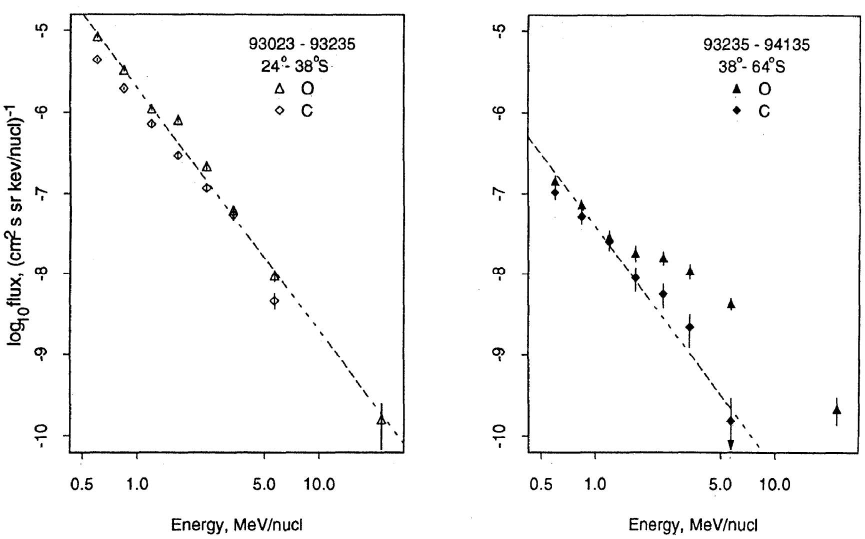

Figure 1. Left side: Oxygen (open triangles) and carbon (open diamonds) spectra measured over the heliolatitude range ~24° – 38° S, within the range of the heliocurrent sheet. Right side: Oxygen (solid triangles) and C (solid diamonds) spectra measured over the latitude range ~38° to ~64° S, above the heliocurrent sheet. The dashed line in both panels is a power law with exponent -3 fit through the three lowest energy O flux values. Error bars are shown based upon the counting statistics.

Plotted in the right panel of Figure 1 are C (solid diamonds) and O (solid triangles) spectra for the 265–day interval 93235 – 94135. This interval covers the latitude range ~38° to ~64° S. Ulysses left the heliospheric current sheet at a latitude ~30° S [Smith et al., 1993], so these spectra were obtained above the current sheet. The helioradius range for the time period was ~4.5 AU to ~3.1 AU.

The O spectrum in the right hand panel of Figure 1 departs significantly from a power law, and is distinctly different in shape than the C spectrum, particularly at energies above ~1.5 MeV/nucl. For the three lowest energies, the C/O ratio is ~0.7 to ~0.8. The ratio then decreases essentially monotonically with increasing energy, with values of ~0.2 and ~0.04 at the two highest energies. The power law line drawn through the three lowest energy O values has a slope of ~ –3, as for the spectra in the left hand panel of the Figure. The C spectrum is somewhat less soft across the entire energy range, particularly if the highest energy point is omitted.

Any of several methods might be used to attempt to quantify the nature of the anomalous O fluxes in the recorded data. Detailed examination of the intensity-time plots of HI-SCALE ion data during the interval when the spacecraft was encountering the heliospheric current sheet shows that in the intervals between the large flux enhancements associated with corotating interaction regions (CIRs) there were often smaller solar-related events (termed "interevents") that could be mapped back to a dwell region [Nolte and Roelof, 1973] on the sun [E. C. Roelof et al., in preparation]. Hence, it was decided that instead of confining the analysis of the O fluxes within the current sheet to the intervals between the CIR events, all O fluxes would be analyzed and the spectra of the O and C would be compared.

The difference between the power law fit (exponent -3) through the three lowest O spectral values and the remainder of the O spectral points is shown in Figure 2 by solid and open triangles for the time intervals in Figure 1. For the latitude range outside the current sheet the differenced spectra show that there is a broad peak in the O spectrum at an energy of ~2 – 3 MeV/nucl. (the error bars shown correspond to counting statistics). This is the anomalous O spectrum at mid to high heliolatitudes. No evidence of a maximum in the fluxes is seen for the differenced spectrum for the latitudes within the current sheet.

The solid diamond values in Figure 2 correspond to the difference between the C spectrum in the right hand panel of Figure 1 and a power law line (with exponent -3) through the three lowest energy C values. In this figure, the C/O ratio outside the current sheet is ~0.2 at an energy ~2.5 MeV/nucl. This is only an upper limit to the actual anomalous abundance ratio. A

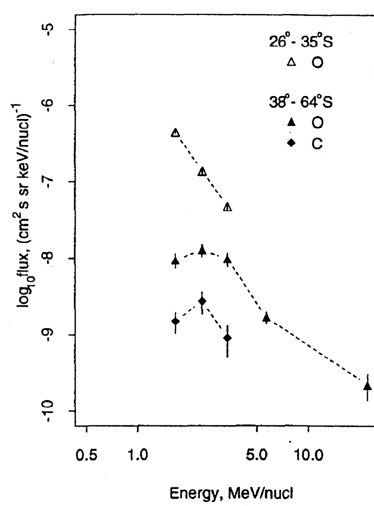

Figure 2. Solid and open triangles correspond to O fluxes obtained by subtracting power law fits (exponential -3 to the lowest three energy channel fluxes) from the measured spectra for the spectra measured above and within the heliocurrent sheet latitudes, respectively. The solid diamonds correspond to C fluxes obtained in the same way for latitudes above the current sheet.

power law with a smaller exponent can be fit to all of the C energy channels save the highest energy one. If this is done, then there are essentially no residual C fluxes above the over-all fit line. Hence, the C/O ratio of 0.2 is an upper limit.

Discussion

The results of Figures 1 and 2 show clearly that the low energy interplanetary O spectra are quite different at heliolatitudes above the heliocurrent sheet from those at latitudes within the sheet. However, even though the fluxes of the O and C nuclei are found to be larger within the latitudes of the current sheet than above the sheet, the power law dependence of the flux values of the three lowest energy channels measured is approximately the same in both latitude range locations. Above the current sheet, at energies $\geq$1.5 MeV/nucl, the interplanetary O spectrum deviates sharply from the power law fit. The anomalous O spectrum above the current sheet has a broad peak in the vicinity of 2.5 MeV/nucl.

The C/O ratio of ~0.2 is probably an upper limit to the anomalous flux abundance ratio since, as noted above, a power law fit through all of the C flux values except the highest energy value produces essentially no residual C fluxes. This is consistent with the results of Cummings and Stone [1990], who found an anomalous C/O of $\leq$0.01.

Plotted in Figure 3 are the flux values for 2.0 – 2.8 MeV/nucl O nuclei as a function of heliolatitude. These values are taken for 53-day intervals during the latitude range covered. The flux values plotted are derived by subtracting a power law fit through the three lowest O energy spectral points from the actual measured flux values (as was done to obtain the spectra in Figure 2). The fluxes measured within the current sheet are undoubtedly a mixture of solar and anomalous origin O nuclei. The relatively high value at a latitude of ~35° arises from the occurrence of a solar particle event during this interval. This latitude plot of the fluxes shows clearly that the mean flux levels drop sharply (by a factor of 5 or more) as the spacecraft latitude increases above the heliosphere current sheet.

The spectrum of the anomalous O measured in the heliolatitude range above the current sheet in this phase of the 22nd solar cycle is centered at an energy nearly a factor of two lower than that reported by Cummings and Stone [1990] in a summary of observations used in a discussion of the composition of the very local interstellar medium. The peak energy in Figure 2 is also lower than that which appears to exist in the O data

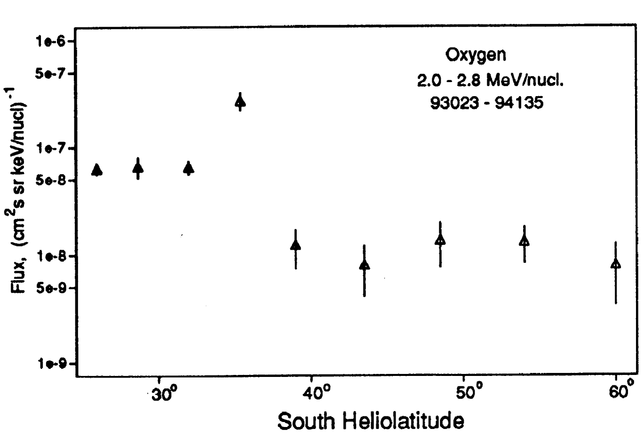

Figure 3. Heliolatitude dependence of fluxes of 2.0 – 2.8 MeV/nucl. interplanetary cosmic ray O.

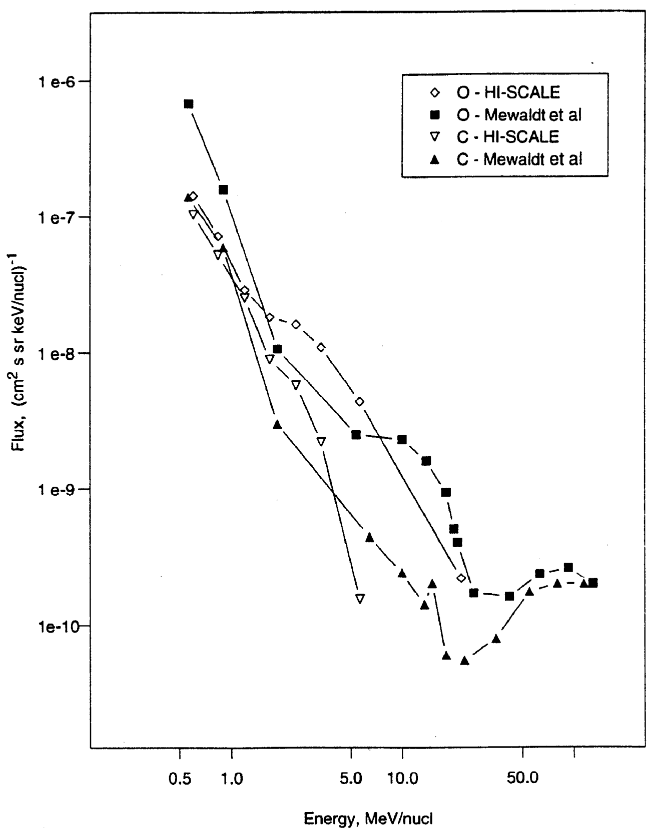

Figure 4. Comparison of oxygen and carbon spectra measured by HI-SCALE above the heliocurrent sheet (from Figure 1) and O and C spectra reported by Mewaldt et al. [1993b] from the SAMPEX satellite in low Earth polar orbit in the declining phase of this (22nd) solar cycle.

reported from measurements made on the SAMPEX satellite, in low Earth polar orbit. Plotted in Figure 4 is a comparison of published SAMPEX O (solid squares) and C (solid triangles) spectra [Mewaldt et al., 1993b] and the HI-SCALE O (open diamonds) and C (open inverted triangles) spectra measured above the heliocurrent sheet (taken from the right panel of Figure 2). Error bars are omitted for clarity. These comparisons of spectra show that the lowest energy SAMPEX oxygen fluxes appear to have a steeper power law slope than do the HI-SCALE fluxes in the same energy range (~0.5 – ~1.5 MeV/nucl). Since the SAMPEX data were collected at magnetospheric latitudes >70°, these low energy O fluxes could be interplanetary in origin. The C spectra from SAMPEX and HI-SCALE are more similar than are the O spectra from the two different locations.

The results obtained above the heliospheric current sheet suggest that the anomalous O fluxes have little if any latitudinal gradient over the range reported in this letter. It is likely that the HI-SCALE mid- to high-latitude O spectrum, particularly at energies $\geq$1.5 MeV/nucl, represents both the accelerated O from the termination shock as well as CIR-accelerated particles diffusing to higher latitudes. It is surely the case that CIRs can accelerate anomalous O, as they do for other nuclear species [e.g., McDonald et al., 1976; Dietrich and Simpson, 1985; Richardson et al., 1993; Maclennan and Lanzerotti, 1994; Gloeckler et al., 1994]. The acceleration efficiency of CIRs decreases strongly with increasing heliolatitude [e.g., Simnett et al, 1994; Franz et al., 1994] such that the reverse shock becomes the dominant source of particle acceleration [Simnett and Roelof, 1994], an effect that seems particularly important for interplanetary electrons.

Acknowledgements. We thank Drs. J.B.Blake, A.C.Cummings, R.E.Mewaldt, and E.C.Stone for comments, discussions, and suggestions. We thank as well the two referees.

References

Bame, S.J., B.E. Goldstein, J.T.Gosling, J.W.Harvey, D.J. McComas, M. Neugebauer, and J.L. Phillips, Ulysses observations of a recurrent high speed solar wind stream and the heliomagnetic streamer belt, *Geophys.Res.Lett., 20*, 2323, 1993.

Cummings, A.C., and E.C.Stone, Elemental composition of the very local interstellar medium as deduced from observations of anomalous cosmic rays, *21st ICRC* , SH6.4-14, 1990.

Cummings, A.C., E.C. Stone, and W.R. Webber, The distance to the solar wind termination shock during 1986-1988, *23rd ICRC, 3*, 411, 1993a.

Cummings, A.C., E.C. Stone, and W.R. Webber, Latitudinal and radial gradients of anomalous and galactic cosmic rays in the outer heliosphere, *Geophys.Res.Lett., 14*, 174, 1987.

Cummings, A.C., E.C. Stone, and W.R. Webber, Estimate of the distance to the solar wind termination shock from gradients of anomalous cosmic ray oxygen, *J.Geophys.Res., 98*, 15165, 1993b.

Dietrich, W.F., and J.A. Simpson, Elemental abundance differences between nuclei accelerated in CIR shocks and solar flares, *19th ICRC, 4*, 277, 1985.

Ferrando, P. et al., The proton and alpha spectra in and out of the ecliptic, and the appearance of the anomalous He component – Ulysses observations, *23th ICRC, 3*, 409, 1993.

Fisk, L.A., B. Kozlovsky, and R. Ramaty, An interpretation of the observed oxygen and nitrogen enhancements in low energy cosmic rays, *Ap.J.Lett., 190*, L35, 1974.

Fisk, L.A., The anomalous component, its variation with latitude and related aspects of modulation, in *The Sun and the Heliosphere in Three Dimensions*, ed. R.G. Marsden, pp.401-411, Reidel, Dordrecht, 1986.

Franz, M., E. Keppler, N. Krupp, M.K. Reuss, and J.B.Blake, The elemental composition in energetic particle events at high heliospheric latitudes, *Space Sci.Rev.*, in press, 1994

Garcia-Munoz, M., G.M. Mason, and J.A. Simpson, *Ap.J.Lett., 182*, L81, 1973.

Gloeckler, G., D. Hovestadt, F.V. Ipavich, and G.M. Mason, Distribution function representation of energy spectra of H, He, C, O and Fe in corotating particle streams, *16th ICRC, 5*, 368, 1979.

Gloeckler, G., J. Geiss, E.C.Roelof, L.A.Fisk, F.M.Ipavich, K.W.Ogilvie, L.J.Lanzerotti, R. von Steiger, and B. Wilken, Acceleration of interstellar pickup ions in the disturbed solar wind observed on Ulysses, J.Geophys.Res., in press 1994.

Hovestadt, D., O. Vollmer, G. Gloeckler, and C.Y. Fan, *Phys.Rev.Lett., 31*, 650, 1973.

Lanzerotti, L.J., R.E.Gold, K.A.Anderson, T.P.Armstrong, R.P.Lin, S.M. Krimigis, M. Pick, E.C. Roelof, E.T. Sarris, G.M. Simnett, and W.E. Frain, Heliosphere instrument for spectra, composition and anisotropy at low energies, *Astron. Astrophys., 92*, 349, 1992.

Lopate, C. and J.A. Simpson, Recent Pioneer 10 and IMP 8 measurements of the anomalous component and the search for the termination shock, *23rd ICRC, 3*, 415, 1993.

Luhmann, J.G., Oxygen in the heliosphere, *J.Geophys.Res., 99*, 13285, 1994.

Maclennan, C.G., and L.J. Lanzerotti, Elemental abundances in corotating interaction regions at high solar latitudes, *Space Sci.Rev.*, in press, 1994.

McDonald, F.B., B.J. Teegarden, J.H. Trainor, and W.R. Webber, The anomalous abundance of cosmic ray nitrogen and oxygen nuclei at low energies, *Ap.J.Lett., 185*, L105, 1974.

McDonald, F.B., B.J. Teegarden, J.H. Trainor, T.T. von Rosenvinge, and W.R. Webber, The interplanetary acceleration of energetic nucleons, *Ap.J.Lett., 203*, L149, 1976.

Mewaldt, R.A., A.C. Cummings, J.R. Cummings, E.C. Stone, and T.T. von Rosenvinge, The return of the anomalous component to 1 AU in 1992, *23rd ICRC, 3*, 404, 1993a.

Mewaldt, R.A., A.C. Cummings, J.R.Cummings, E.C. Stone, B. Klecker, D. Hovestadt, M. Scholer, G.M. Mason, J.E. Mazur, D.C. Hamilton, T.I. vonRosenvinge, and J.B. Blake, The return of the anomalous cosmic rays to 1 AU in 1992. *Geophys.Res.Lett., 20*, 2263, 1993b.

Nolte, J.T., and E.C. Roelof, Large-scale structure of the interplanetary medium, 1. High coronal source longitude of the quiet-time solar wind, *Solar Phys., 33*, 241, 1973.

Pesses, M.E., J.R. Jokipii, and D. Eichler, Cosmic ray drift, shock acceleration, and the anomalous component of cosmic rays, *Ap.J.Lett., 246*, L85, 1981.

Scholer, M., D. Hovestadt, B. Klecker, and G. Gloeckler, The composition of energetic particles in corotating events, *Ap.J., 227*, 323, 1979.

Simnett, G.M., and E.C. Roelof, Reverse shock acceleration of electrons and protons at mid-heliolatitudes from 5.3–3.8 AU, *Space Sci.Rev.,* in press, 1994.

Simnett, G.M., K.A. Sayle, E.C. Roelof, and S.J. Tappin, Corotating particle enhancements out of the ecliptic plane, *Geophys. Res. Lett., 21* 1561, 1994.

Smith, E.J., M. Neugebauer, A. Balogh, S.J. Bame, G. Erdos, R.J. Forsyth, B.E. Goldstein, J.L. Phillips, and B.T. Tsurutani, Disappearance of the heliospheric sector structure at Ulysses, *Geophys.Res.Lett., 20*, 2327, 1993.

L.J. Lanzerotti and C.G. Maclennan, AT&T Bell Laboratories, Murray Hill, NJ 07974. (email:ljl@physics.att.com)

R.E. Gold, E.C. Roelof, S.M. Krimigis, Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD 20723.

T.P. Armstrong, Department of Physics, University of Kansas, Lawrence, KS 66045.

G.M. Simnett, University of Birmingham, UK.

E.T. Sarris, University of Thrace, Xanthi, Greece.

K.A. Anderson, R.P. Lin, Space Sciences Laboratory, University of California, Berkeley, CA 94720.

M. Pick, Observatoire de Paris, Meudon, France.

(Received August 22, 1994; revised September 30, 1994; accepted November 2, 1994.)