Charged particle composition in the inner heliosphere during the rise to maximum of Solar Cycle 23

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Abstract. Flux distributions and abundances relative to oxygen of interplanetary ions ($Z > 1$) are statistically studied and compared for measurements made at 1 and at ~ 5 AU on the ACE and the Ulysses spacecraft near the ecliptic plane. Over the nearly two year interval studied, the distributions of the relative abundances and the fluxes of particles at the two locations are found to be approximately log normal. The statistical distributions of the relative abundances are found to be similar at the two helioradii. On a statistical basis, the fluxes at Ulysses times the distance of the measurements appear to be proportional to the fluxes at ACE. This radial dependence of the fluxes is consistent with the interpretation that, statistically, the ion parallel diffusion coefficient is large.

INTRODUCTION

Between the launch of the ACE spacecraft in late 1997 and mid-1999, the Ulysses (ULS) spacecraft (launched in October 1990 into a polar orbit of the Sun) was within about 30° of the ecliptic plane and at $\sim 4.5 - 5$ AU distance from the Sun. Ulysses was just ending its Solar Minimum Mission and beginning its Solar Maximum Mission. The essentially identical low energy charged particle instrumentation (EPAM on ACE and HI-SCALE on Ulysses: (1, 2)) that is flying on the two space probes provides an ideal opportunity to study the near-ecliptic distribution of interplanetary particles in the inner heliosphere during the beginning of the rise of solar cycle 23.

The charged particle detectors on the two space probes each consist of five solid state detector telescopes that are oriented to cover almost 4π steradians of the sky on the spin-stabilized spacecraft (spin rate of 5 rpm on both ACE and ULS). Of central relevance to the study reported herein is the composition aperture (CA) telescope of each instrument system. Each CA is a three element solid state telescope that consists of a 5μm first detector followed by two 100μm second and third detectors. Particle atomic species (hydrogen to iron) and energies (~ 0.5–8 MeV/nucl) are identified by energy loss and total energy measurements. A priority scheme is included to enhance the counting statistics of less abundant atomic species.

The Earth (and thus ACE, located sunward along the Earth-Sun line near the Lagrangian point) traveled nearly two complete orbits of the Sun during the time interval examined herein. That is, ULS only infrequently occupied a region of space that included a flux tube that might connect it to the ACE spacecraft near Earth. Therefore, this study of atomic species at 1 and 5 AU is made on a statistical, rather than an event-by-event, basis.

A number of spacecraft (most significantly Pioneers 10 and 11 and Voyagers 1 and 2) have traveled between the Earth and the orbit of Jupiter (~ 5 AU). Several investigators have used instrumentation on these space probes to measure the helioradius distribution of particle fluxes. Generally, past investigations have studied the propagation of protons from distinct solar events, e.g. (3), or anomalous cosmic rays, e.g. (4, 5). A few papers have determined a radial dependence for ions, with values ranging from $r^{-.5}$ to r^{-2}, depending on factors such as location and solar activity. We concentrate here on the statistical abundances at these two helioradial distances for atomic species with Z between 1 and 26.

MEASUREMENTS

Plotted in Figure 1 are oxygen (O) fluxes measured at ~1 and ~5 AU for the interval day 244, 1997, to day 190, 1999. The upper two panels show the O fluxes in the range 0.57–1.0 MeV/nucl for ACE and 0.5–1.0 MeV/nucl for ULS. The lower two panels contain the fluxes for 2.8–6.0 MeV/nucl oxygen. All sectors sampled by the spin of the spacecraft are averaged over one day intervals, which are themselves plotted as sliding 5-day averages every one day. The heliolatitude of ULS throughout the interval is given at the top of the Ulysses data panels; this latitude

CP528, *Acceleration and Transport of Energetic Particles Observed in the Heliosphere: ACE 2000 Symposium*,
edited by Richard A. Mewaldt, et al.

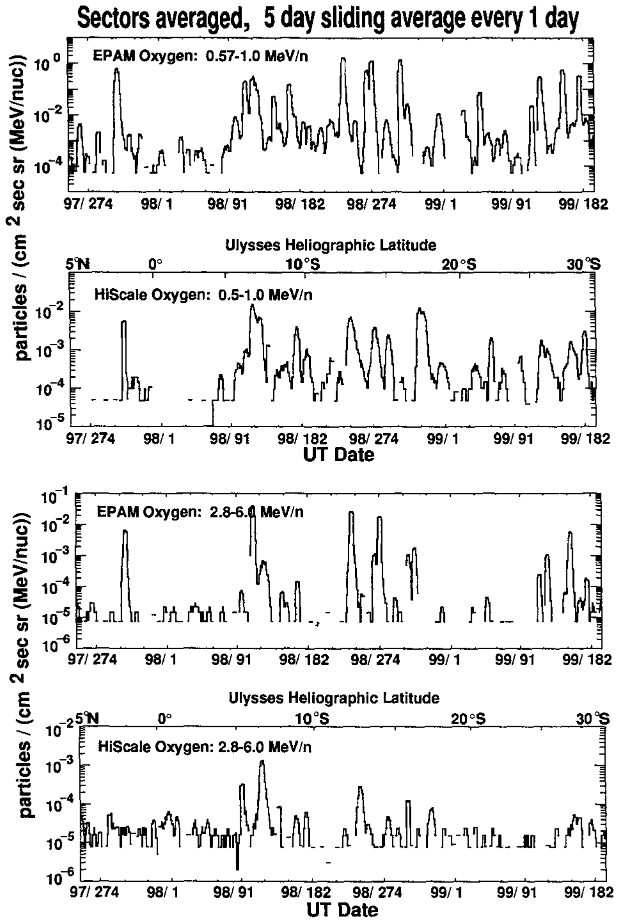

FIGURE 1. ACE and Ulysses oxygen fluxes in two energy ranges

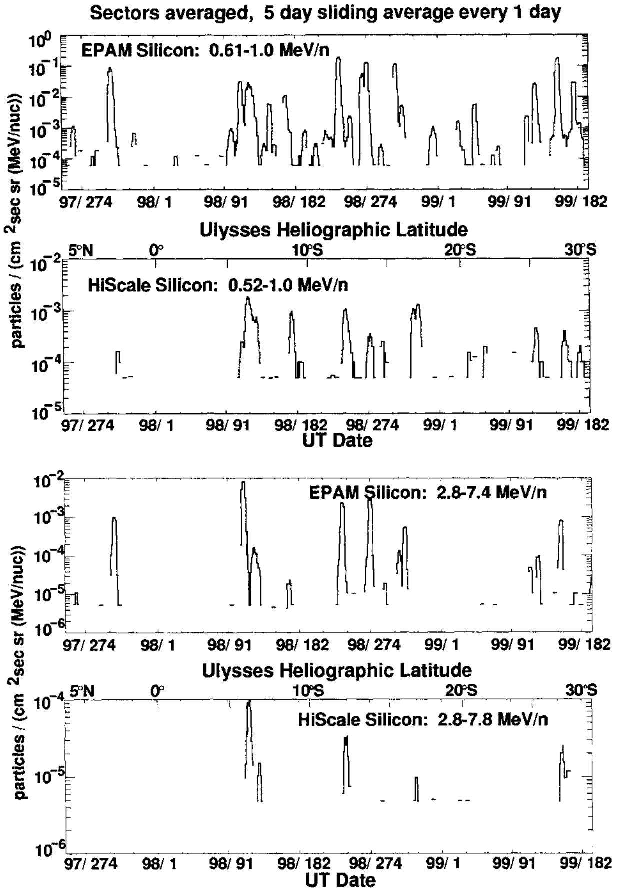

FIGURE 2. ACE and Ulysses silicon fluxes in two energy ranges

changes from ~ 5° N to ~ 30° S over the time shown as ULS passed through its aphelion distance of ~ 5.4 AU from the Sun.

The fluxes of the higher energy (2.8–6.0 MeV/nucl) O measured by Ulysses from the beginning of the time plot to about day 91, 1998, are anomalous oxygen at 5 AU. Beginning about day 91, 1998, to about day 1, 1999, the oxygen fluxes measured at both spacecraft became significantly more variable, especially in the lower energy range plotted. These continuing changes in the fluxes with time are produced by the increasing solar activity.

The abundance of the higher energy O particles in the time interval around day 91, 1999 (at a time of lower solar activity), is significantly lower than in the interval leading up to day 91, 1998. A discussion of these data in the context of anomalous cosmic ray oxygen and the implications for their removal from the inner heliosphere is contained in (6).

Shown in Figure 2 are the fluxes of silicon (Si) as measured at both spacecraft in approximately the same energy ranges as in Figure 1. This Si should be largely of solar origin, although some contributions from the sputtering of interplanetary grains from comets and other sources cannot be ruled out entirely. The fluxes of Si are larger at 1 AU than at 5 AU. The increases in the fluxes due to the increase in solar activity are clearly evident, especially at the lower energies and beginning around day 91, 1998.

COMPOSITION COMPARISONS

Plotted in Figure 3 are statistical comparisons of the fluxes of hydrogen and helium (0.5–1.0 MeV/nucl) that were measured at the two spacecraft locations for the time interval day 100, 1998 to day 262, 1999 (ACE fluxes as heavy solid lines; ULS fluxes as light lines). This time interval excludes the interval from day 244, 1997, to day 99, 1998, when most, if not all, of the O measured at 5 AU was anomalous oxygen (see discussion of Figure 1). The fluxes in each bin are normalized to the total number of daily averages for each spacecraft. The top two pan-

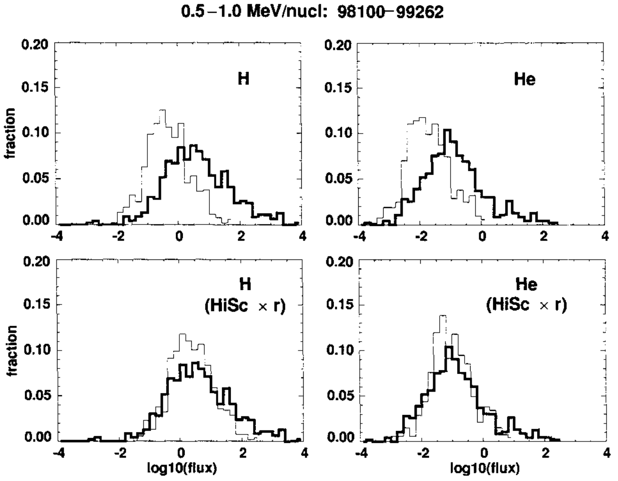

FIGURE 3. Distributions of 0.5–1.0 MeV/nucl H and He for ACE and Ulysses (heavy and light lines, respectively)

els contain the distributions of measured flux values; the lower two panels contain the distributions after multiplying each ULS daily flux value by the radial distance of ULS on that day. Thus, the ACE fluxes are the same in the upper and the lower panels.

The hydrogen and helium flux distributions in Figure 3 are seen to be approximately log-normal. (Lanzerotti et al. (7) remark on the log normal distribution of Voyager-measured hydrogen particles in the heliosphere beyond the orbit of Jupiter.) It is also evident that, on a statistical basis, the fluxes at each location are comparable when the ULS-measured flux values are scaled by the radial distance at the time of the measurement.

Figure 4 shows a comparison of the fluxes of atomic abundances (0.7–1.0 MeV/nucl) for carbon, nitrogen, oxygen, neon, magnesium, silicon, sulfur, and iron. The ACE distributions are plotted as heavy dark lines; the ULS distributions are the light lines and have been multiplied by the radial distance of the measurements before compiling the statistics. The distributions are seen to be similar at the higher flux levels. The $Z > 2$ fluxes are not log normally distributed, having low flux intensity cutoffs of the distributions that correspond to the measurement (or not) of a single count during an averaging interval. For this reason, the distributions are not similar at the lowest fluxes.

Plotted in Figure 5 are comparisons of the abundances of atomic species relative to oxygen (0.7–1.0 MeV/nucl) as measured at ACE (heavy dark lines) and ULS (light lines) for the same time interval as in Figure 3. These abundance distributions are approximately log normal and are similar at the two helioradii. That is, the statistical abundances do not appear to be affected by any

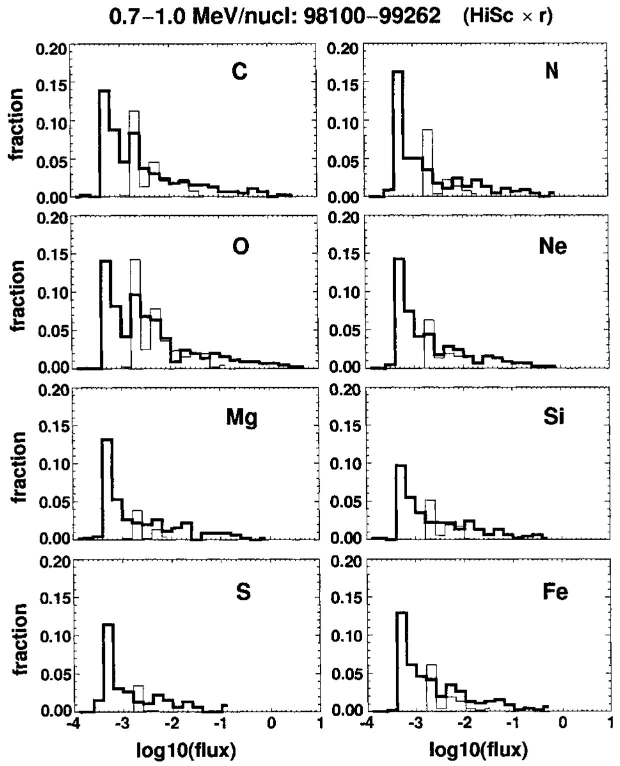

FIGURE 4. Distributions of heavy elements (0.7–1.0 MeV/nucl) for ACE and Ulysses (heavy and light lines, respectively). HiScale measurements are multiplied by the radial distance of the spacecraft

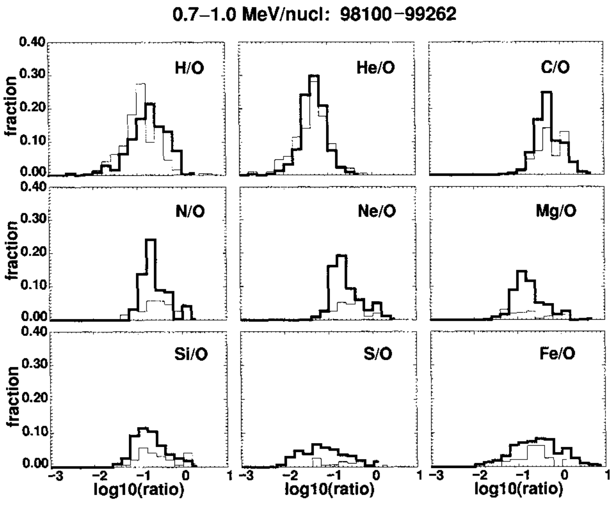

FIGURE 5. Abundance ratios to oxygen (0.7–1.0 MeV/nucl) for ACE and Ulysses (heavy and light lines, respectively)

interplanetary dynamics that might occur between 1 and 5 AU.

The suggestion of double peaks in the N/O, Ne/O, and Fe/O abundance distributions (Figure 5) also appears in other energy ranges (not shown), and may provide information to distinguish solar flare and CME particles from those accelerated by CIRs. This will be discussed in more detail elsewhere.

DISCUSSION

The results presented above show that the ion fluxes at r = 5 AU, j_5, scale as $\sim 1/r$ times the fluxes at Earth, j_1. If we assume ion propagation without diffusion or drift (and no additional sources or losses), the standard transport equation for energetic particles in the solar wind (8), written in terms of the distribution function $f = p^2 j$ reduces to:

$$V\frac{\partial f}{\partial r} = \frac{1}{3r^2}\frac{\partial}{\partial r}[r^2 V]p\frac{\partial f}{\partial p} \tag{1}$$

where V is the solar wind speed (taken to be constant) and p is the ion momentum (non-relativistic in this case). The term on the left describes convection in the solar wind, and the term on the right, adiabatic deceleration. Then (1) becomes

$$\frac{\partial f}{\partial r} = \frac{2}{3r}p\frac{\partial f}{\partial p} \tag{2}$$

which has a solution $f \propto r^a p^b$ where a and b are related as

$$a = \frac{2}{3}b \tag{3}$$

For the case $a = -1$ (results of Figures 3 and 4), $b = -3/2$. Then $j \propto p^{1/2}$, a spectrum rising with energy, which does not describe the measured ion spectra.

For the other extreme of pure ion diffusion,

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \kappa \frac{\partial f}{\partial r}) = 0 \tag{4}$$

where κ is the radial diffusion tensor. For only parallel diffusion $\kappa_{\|}$, $\kappa = \kappa_{\|}(\cos\psi)^2$ where ψ is the angle between the magnetic field and the radial direction. If κ is approximately a constant, as found in reference (3) (or varies only very slowly compared to $1/r^2$), then a solution of (4) is

$$f \propto 1/r \tag{5}$$

Hence the results of Figures 3 and 4 imply rapid ion radial diffusion (long mean free path, order 1 AU) between $r \sim$ 1 AU and 5 AU. This is not an unreasonable description of particle propagation in the inner heliosphere, although the statistical results in (3) reported mean free paths < 0.1 AU between 1 and 5 AU.

The foregoing conclusion of rapid ion diffusion cannot eliminate, however, the possible effect of interplanetary statistical acceleration off-setting the adiabatic deceleration in a pure convection/diffusion regime (which incorporates adiabatic deceleration). A preliminary examination of this possibility shows that statistical acceleration is not significant in the context of the diffusion term. This will be explored further in a future work, as will the implications for possible CIR acceleration.

As shown in Figure 5, on a statistical basis the ion abundances relative to O are found to be similar and approximately log normal at 1 and at 5 AU over the nearly two year interval examined. The similarity of the distributions at both locations indicates that any dynamical processes that are operative in the solar system beyond Earth to the orbit of Jupiter, such as acceleration or deceleration by traveling shock waves and statistical acceleration, operate statistically equally on all ions. On a statistical basis, therefore, this implies that the charge state of the ions examined at the two locations is the same, probably a charge of one.

ACKNOWLEDGMENTS

We thank Dr. B. Klecker for helpful comments and our EPAM and HI-SCALE colleagues for their continuing contributions to the success of these investigations.

REFERENCES

1. Gold, R.E., S.M. Krimigis, S.E. Hawkins III, D.K. Haggerty, D.A. Lohr, E. Fiore, T.P. Armstrong, G. Holland, and L.J. Lanzerotti, *Space Science Reviews* **86**, 541-562 (1998).
2. Lanzerotti, L. J., et al., *Astron. Astrophys.* **92**, 349-363 (1992).
3. Zwickl, R. D., and W. R. Webber, *Solar Physics* **54**, 457-504 (1975).
4. McDonald, F. B., B. J. Teegarden, J. H. Trainor, and W. R. Webber, *Ap. J.* **187**, L105-L108 (1974).
5. Webber, W. R., F. B. McDonald, T. T. von Rosenvinge, and R. A. Mewaldt, *17th Inter. Cosmic Ray Conf.* **10**, 92 (1981).
6. Lanzerotti, L. J., and C. G. Maclennan, *Ap.J.Lett.* in press (2000).
7. Lanzerotti, L. J., R. E. Gold, D. J. Thomson, R. E. Decker, C. G. Maclennan, and S. M. Krimigis, *Ap. J.* **380**, L93-L96 (1991).
8. Parker, E. N., *Planet. Space Sci.* **13**, 9-49, (1965).