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Populating an inner heliosphere reservoir (<5 AU) with electrons and heavy ions

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Abstract. Heavy ion ($Z > 2$) and electron measurements were made on the ACE (1 AU) and Ulysses (3.2 AU) spacecraft in the inner heliosphere during the July 14, 2000 solar events. Following the last interplanetary shock event at ~1437 UT on July 15, the heavy ion fluxes at 1 AU began to decay with an e-folding decay time for both O and Fe ions (0.5–1 MeV/nucl) of ~1 day. In contrast, the heavy ion fluxes at Ulysses (heliolatitude ~62^oS; $\sim 90^o$ in longitude from the ACE-Sun line) abruptly increased in intensity on July 14, and continued to increase slowly thereafter. The ion and electron fluxes were essentially equal at both locations on July 21, indicating that the inner heliosphere (to ~3.2 AU) then contained an approximately uniform reservoir of charged particles in a volume of $\sim 10^2 \mathrm{AU}^3$ (~$3.4{\cdot}10^{24}\mathrm{km}^3$). The equality of the decaying fluxes at the two locations persisted for more than two weeks, at times modulated more noticeably at 1 AU by solar activity.

1 Introduction

The distribution of solar-produced energetic particles in the heliosphere, and its evolution with time after major solar events – flares, CMEs, etc. – is a topic of continuing interest. Early in the spacecraft era it was recognized that solar occurrences across the visible disk, as well as behind the limbs, could result in particle events being observed at Earth. Considerable research was devoted to possible understanding of this under the general topic of azimuthal particle propagation in the solar corona (e.g., Reid, 1964; Lanzerotti, 1973). Using the Pioneer 6 and 7 spacecraft spaced azimuthally around the Sun near 1 AU and IMP4 at Earth, McKibben (1972) showed that, within a rather short time (a few days) following many solar-produced events, the heliosphere within about 1 AU became filled nearly uniformly with particles. In this era, the emphasis of the research was on the means by which solar particles could spread azimuthally around the Sun, and whether the processes involved propagation in the corona or the interplanetary medium or both. While these issues remain open, the principal interest in this paper is on the radial distance to which the inner heliosphere is filled.

The launch of several spacecraft to other planets and of Ulysses out of the ecliptic provided the possibility of examining the distributions of energetic particles, and their evolution, over an extensive range of helioradii. For example, as Ulysses (ULS), following its launch in 1990 traveled in the ecliptic plane to Jupiter, a large solar event was measured at ULS at ~ 3.5 AU and some months later at Voyager 2 (~ 35 AU) and Voyager 1 (~ 47 AU) (Maclennan *et al.*, 1996). The measured fluxes of ions ($Z > 2$; 0.5 - 6.0 MeV/nucl) differed between ULS and the two Voyagers by a factor of $\sim r^{-2}$. An examination of ULS data and data acquired near Earth during this solar activity demonstrated that ~ 5 days following the onset as measured at Earth, the fluxes at Earth and at ULS became approximately equal (Roelof *et al.*, 1992). The equality persisted for 5 or 6 days, until the onset of another solar event. A charged particle reservoir filled the inner heliosphere out to ~ 3.5 AU following the solar activity, with the reservoir slowly decaying with time.

We take advantage of the out-of-ecliptic orbit of Ulysses to investigate the nature of an inner heliosphere particle reservoir in three dimensions. Measurements made by essentially identical instrumentation on the ACE and the Ulysses spacecraft following the large solar activity of 14 July 2000 are used. At this time ACE was at the L1 libration point upstream of the Earth and Ulysses was at ~ 3.2 AU and at a heliolatitude of $\sim 62^o$S. It was separated by $\sim 90^o$ in longitude from the ACE-Sun line. Data and observations from this event have been presented by several groups (e.g., Smith *et al.*, 2001; Tylka *et al.*, 2001; Reames *et al.*, 2001).

2 Data

The heavy ion ($Z > 2$) data that are presented in this paper are taken from the essentially identical WART detector

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telescopes in the HI-SCALE instrument on ULS (Lanzerotti *et al.*, 1992) and in the EPAM instrument on ACE (Gold *et al.*, 1998). The electron data are from the DE (deflected electron) telescope on each spacecraft. 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 detectors. Particle atomic species (hydrogen to iron) and energies ($\sim$ 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.

3 Electron fluxes

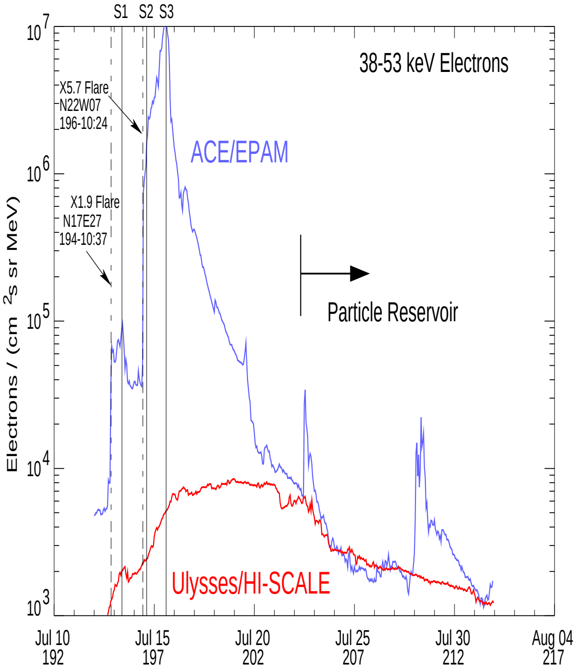

Fig. 1. Electron fluxes (38-53 keV) measured on ACE by EPAM (blue) and on Ulysses by HI-SCALE (red) from July 10 to August 4, 2000. Times of the two large X-flares at 1037 UT on July 12 and at 1024 UT on July 14 and of three interplanetary shock waves measured on ACE are shown.

Plotted in Figure 1 are the electron fluxes (38-53 keV) measured by EPAM on ACE and by HI-SCALE on Ulysses from July 10 to August 4, 2000. Indicated in the Figure are the times of the two large X-flares on July 12 (1037 UT) and 14 (1021 UT) as well as the times of three interplanetary shock waves as measured on ACE.

Upstream of Earth at 1 AU, after the peak fluxes of $\sim 10^7$ (cm^2 s ster MeV)$^{-1}$ were reached on July 15, the ACE-measured electrons tended to decrease approximately exponentially to July 19. During this decrease, several small increases in the electrons also occurred. The fluxes dropped by a factor of about two on the 19th, after which an about two day exponential decrease again occurred. Then on July 22, another electron event was measured that increased the fluxes by a factor of about two. This impulsive electron event decayed rapidly over about a day, with the fluxes decreasing to values that might be expected if the flux decay on July 20-21 were extrapolated through the injection event on July 22.

Table 1. Rates of increase and decrease in the inner heliosphere

S/C	Species	Energy (MeV/nucl)	Days fit	E-folding time (hours)
ACE	e	0.038–0.053	199.0–201.0	$-26.2\,^{-0.8}_{+0.7}$
ACE	e	0.053–0.103	199.0–201.0	$-25.0\,^{-0.6}_{+0.5}$
ACE	e	0.103–0.175	199.0–201.0	$-24.1\,^{-0.5}_{+0.4}$
ACE	e	0.175–0.315	199.0–201.0	$-23.6\,^{-0.4}_{+0.4}$
ACE	e	0.038–0.053	202.0–204.4	$-79.3\,^{-4.8}_{+4.3}$
ACE	e	0.053–0.103	202.0–204.4	$-76.0\,^{-4.0}_{+3.6}$
ACE	e	0.103–0.175	202.0–204.4	$-72.6\,^{-3.1}_{+2.8}$
ACE	e	0.175–0.315	202.0–204.4	$-71.9\,^{-2.5}_{+2.4}$
ACE	H	0.7–1.4	199.0–201.0	$-23.0\,^{-1.0}_{+0.9}$
ACE	C	0.55–5.24	199.0–201.0	$-21.4\,^{-1.4}_{+1.2}$
ACE	O	0.57–6.05	199.0–201.0	$-22.4\,^{-0.9}_{+0.8}$
ACE	Fe	0.25–8.15	199.0–201.0	$-22.3\,^{-1.4}_{+1.3}$
ACE	H	0.7–1.4	202.0–204.5	$-32.7\,^{-2.3}_{+2.0}$
ACE	C	0.55–5.24	202.0–204.5	$-43.0\,^{-10.1}_{+6.9}$
ACE	O	0.57–6.05	202.0–204.5	$-62.7\,^{-15.6}_{+10.4}$
ACE	Fe	0.25–8.15	202.0–204.3	$-31.9\,^{-9.2}_{+5.9}$
ULS	H	0.7–1.0	197.0–203.0	$249.2\,^{+60.9}_{-40.9}$
ULS	C	0.47–5.20	197.0–203.0	$195.3\,^{+124.2}_{-54.7}$
ULS	O	0.49–6.00	197.0–203.0	$134.4\,^{+33.2}_{-22.2}$
ULS	Fe	0.23–10.71	197.0–203.0	$104.6\,^{+27.2}_{-17.5}$

At 3.2 AU, the electron fluxes began a slow, approximately four day, increase to a peak value of $\sim 6 \times 10^4$ (cm^2 sec ster MeV)$^{-1}$. After about July 16, the fluxes at Ulysses remained approximately constant at this value for ~ 5 days. The fluxes at Ulysses began to decrease on July 22 at about the time that the impulsive event was measured on ACE. With the exception of the impulsive event at 1 AU, beginning at about the beginning of July 22, the fluxes at both locations were approximately equal, and they remained approximately equal through July 27. At this time, another large, three day, impulsive event was recorded at 1 AU. However, by July 31, after the impulsive event, the fluxes at both locations were again measured to be approximately the same. This interval beginning on July 22 is indicated in the Figure as the ”Particle Reservoir”.

Listed in each of the top two panels (Panels 1 and 2) in Table 1 are the four electron energy channels on ACE. Also listed are the exponential decay times (and uncertainties) of the electron fluxes for two different time intervals following the largest fluxes at the time of the July 15 shock. Panel 1 gives the decay times for the two-day interval day 199 (July 17) and day 200 (July 18), and Panel 2 gives the decay times for the interval from day 202 (July 20) to hour 10 UT, day

204 (following the factor of two drop in flux on July 19). In the first interval, the e-folding decay time is of the order of 25 hours whereas in the second interval the decay time is about a factor of three longer, ~ 75 hours. In both time intervals, the decay times vary with energy, with the decays decreasing with increasing electron energy. While the uncertainties are such that the decay time between any two adjacent energy channels is not statistically significant, the differences between the shortest and the longest times are significant, and thus it can be concluded that the overall trend is valid.

4 Ion fluxes

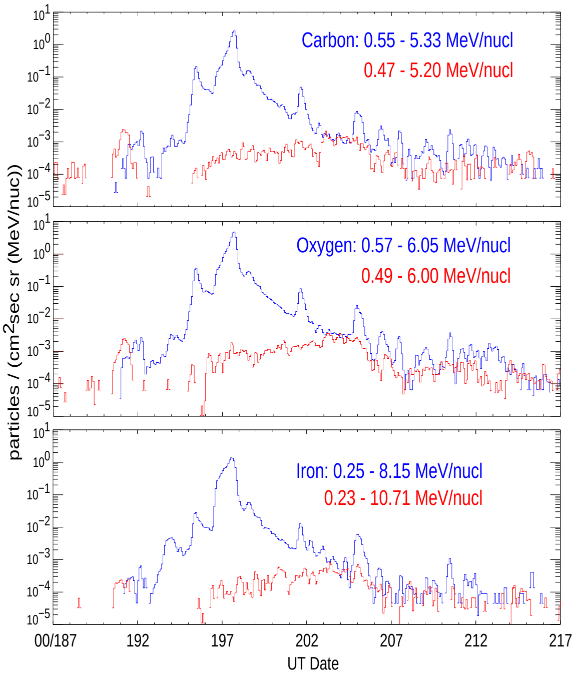

Fig. 2. Heavy ion C, O, and Fe fluxes measured on both ACE (blue) and Ulysses (red) in the July 2000 event.

The heavy ion ($Z>2$) carbon, oxygen, and iron fluxes measured on both ACE and Ulysses in the July 2000 event are shown in Figure 2. Following the peak ion fluxes as measured at ACE, the ion fluxes at 1 AU decayed approximately exponentially until the occurrence of the flux enhancement on day 201 (July 19). This enhancement was produced by an interplanetary shock (and was evidenced in the ACE electron fluxes – Figure 1 – by a small enhancement and then a sharp, about a factor of two, drop). An approximately exponential decay also occurred on days 202 and 203. From the end of day 204 to the end of the time interval plotted, numerous fluctuations in the ion fluxes were observed.

At $\sim$ 3.2 AU at Ulysses, the ion fluxes increased sharply by more than a factor of ten on day 196 and then slowly increased exponentially with time until about day 204. At this time, the heavy ion fluxes at both locations in the heliosphere became essentially equal, and remained this way until the end of the interval shown. The particle reservoir for heavy ions, with approximately equal fluxes at 1 and 3.2 AU, began on about day 203 (July 21). This was about a day earlier than for the electron fluxes (Figure 1).

Listed in Panels 3 and 4 of Table 1 are the ACE-measured decay times for the H, C, O, and Fe fluxes for two separate time intervals following the peak fluxes, days 199 and 200 (July 17 and July 18) and day 202 to day 204.5 (July 20 to July 22.5). In the first interval, the e-folding decay time is of the order of 22 hours. In the second interval, the e-folding decay times are of the order of 40 hours, within the large uncertainties (the uncertainties are large because the flux levels have significant variability).

Panel 5 of Table 1 contains the e-folding times for the heavy ion increases measured at Ulysses for the six-day interval days 197–day 203 (July 15–July 21). Again, because the variations of the fluxes are appreciable, the uncertainties are large. Nevertheless, one can conclude that the e-folding times for the flux increases are of the order of 4 to 8 days.

5 Discussion

The foregoing electron and heavy ion data presentations show that following the solar particle event on 14 July 2001 there were significant differences in particle onsets at 1 and at 3.2 AU. Despite these differences, after about 7–8 days, there was a near equality of fluxes at ACE near Earth and at Ulysses. This near equality persisted for the entire interval shown in the figures and, in fact, for nearly a complete solar rotation (not shown here). This occurred despite the large radial and latitudinal separation between the two spacecraft.

As noted above, McKibben (1972) and Roelof *et al.* (1992) had shown earlier that such a reservoir could exist in the ecliptic plane following large events. However, these Ulysses measurements establish that such reservoirs are truly a three-dimensional phenomenon in the inner heliosphere.

Further, the three-dimensional reservoir is now shown to exist not only for electrons and protons, but for heavy ions as well. Indeed, the data in Figures 1 and 2, as well as the parameters in Table 1, show clearly that the buildup of the reservoir and the subsequent leakage of the particles from the reservoir are dependent upon species as well as on particle energy – and possibly rigidity. The energy dependence of the electron decays at 1 AU prior to the reservoir are statistically significant between the lowest and highest energy channels. The electron increase at Ulysses occurred over $\sim$3 to 4 days. After this time the electron fluxes as measured at ULS were nearly constant for 5 to 6 days, at which time the reservoir became established. Once the electron reservoir is established, the loss rate is essentially uniform across the reservoir. Also, once the reservoir is established, there is no field-aligned gradient in the fluxes between 1 and 3.2 AU.

For the heavy ions, prior to the establishment of the reservoir, the loss rate from the Ulysses orbit was less than the decay rate of particles measured at 1 AU – that is, the population of heavy ions at 3.2 AU continued to build for 7 to 8 days after the solar event. Once the reservoir was established in the inner heliosphere, out to ~ 3.2 AU, the over-all loss of the ions was essentially uniform across the reservoir. That is, beginning on about 21 July, the inner heliosphere (to ∼3.2 AU) contained an approximately uniform reservoir of heavy ions in a volume of $\sim 10^2 \mathrm{AU}^3$ ($\sim 3.4 \cdot 10^{24} \mathrm{km}^3$).

In summary, solar particle – electron and ion – reservoirs can exist in the inner heliosphere following solar events. The interplanetary conditions that contribute to the establishment and maintenance of these reservoirs require further explanation.

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References

Gold, R. E., Krimigis, S. M., Hawkins, S. E., Haggerty, D. K., Lohr, D. A., Fiore, E., Armstrong, T. P., Holland, G., and Lanzerotti, L. J. (1998). Electron, proton, and alpha monitor on the advanced composition explorer spacecraft. *Space Science Reviews*, **86**, 541–562.

Lanzerotti, L. J. (1973). Coronal propagaion of low-energy solar protons. *J. Geophys. Res.*, **78**, 3942.

Lanzerotti, L. J., Gold, R. E., Anderson, K. A., Armstrong, T. P., Lin, R. P., Krimigis, S. M., Pick, M., Roelof, E. C., Sarris, E. T., Simnett, G. M., and Frain, W. E. (1992). Heliosphere instrument for spectra, composition, and anisotropy at low energies. *Astron. and Astrophysics Suppl.*, **92**, 349–363.

Maclennan, C. G., Lanzerotti, L. J., Decker, R. B., Krimigis, S. M., Collier, M. R., and Hamilton, D. C. (1996). Helioradius dependence of interplanetary carbon and oxygen abundances during 1991 solar activity. *Astrophys. J.*, **468**, L123–L126.

McKibben, R. B. (1972). The azimuthal propagation of low energy solar flare protons as observed from spacecraft very widely separated in solar azimuth. *J. Geophys. Res.*, **77**, 3957–3984.

Reames, D. V., Ng, C. K., and Tylka, A. J. (2001). Heavy ion abundances and spectra and the large gradual solar energetic particle event of 2000 july 14. *Astrophys. J.*, **548**, L233–L236.

Reid, G. C. (1964). A diffusive model for the initial phase of a solar proton event. *J. Geophys. Res.*, **69**, 2659.

Roelof, E. C., Gold, R. E., Simnett, G. M., Tappin, S. J., Armstrong, T. P., and Lanzerotti, L. J. (1992). Low-energy solar electrons and ions observed at Ulysses February-April, 1991: The inner heliosphere as a particle reservoir. *Geophys. Res. Lett.*, **19**, 1243–1246.

Smith, C. W., Ness, N. F., Burlaga, L. F., Skoug, R. M., McComas, D. J., Zurbuchen, T. H., Haggerty, D. K., Desai, M. I., Mason, G. M., Dwyer, J. R., Cohen, C. M. S., and Leske, R. A. (2001). Ace observations of the Bastille Day 2000 interplanetary disturbances. *ICRC*, **this volume**, submitted.

Tylka, A. J., Cohen, C. M. S., Dietrich, W. F., Maclennan, C. G., McGuire, R. E., Ng, C. K., and Reames, D. V. (2001). Evidence for remnant flare suprathermals in tha source population of solar energetic particles in the 2000 Bastille Day event. *Astrophys. J.*, **532**, submitted.