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Low energy charged particles in the high latitude heliosphere

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Abstract. Low energy ion and electron measurements made over the south and north polar regions of the sun by the HI-SCALE instrument on the Ulysses spacecraft during its solar minimum polar passages are summarized. The polar flux levels were considerably reduced in comparison to fluxes in the vicinity of the heliospheric current sheet. Flux variations with a period of $\sim$26 days were seen to nearly 80°S but were not observed over the northern pole. Solar particle events originating from near-equatorial activity were seen at high southern latitudes, but not at high northern latitudes. Comparisons with in-ecliptic measurements made during the same time interval on the IMP8 spacecraft suggest that the polar differences are largely spatial and not temporal. The flux of low energy ($\sim$ 0.8–5.0 MeV/nucl) anomalous oxygen was measured to be $\sim$ 50% higher over the northern polar region than in the south. The flux of solar wind iron, measurable because of its convection into the instrument by the high speed polar solar wind, is estimated to be about a factor of two larger over the south pole than over the north.

Key words: interplanetary medium – Sun: particle emission

1. Introduction

The Ulysses spacecraft provided the first opportunity to measure the characteristics of the heliosphere at high latitudes. The extensive complement of instrumentation supplied by teams of European and U.S. investigators has provided data on all aspects of the sun's polar environment. This paper describes measurements made by the HI-SCALE instrument over both solar poles, and compares and contrasts the low energy particle population in the two polar regions. The HI-SCALE instrument measures electrons (E $\gtrsim$ 50 keV) and ions (E $\gtrsim$ 50 keV) in four two-element semiconductor detector telescopes. A fifth, three-element telescope (with a 5μ thick first detector) is used to measure the composition of ions with energies in the range $\sim$ 0.5–10 MeV/nucleon. A priority scheme is used to enhance the statistics of ions with Z$>$ 2. The instrument and its operation have been described in Lanzerotti et al. (1992).

2. Electron and ion measurements

The color spectrogram of Fig. 1 provides an overview of the HI-SCALE electron measurements during the interval day 85 (March 26), 1994, to day 360 (December 26), 1995. The heliolatitude coverage is shown along the top of the figure. At the beginning of this interval the Ulysses spacecraft was at a south heliolatitude of 57° ascending to the south solar pole. Large, quasi-periodic (approximately 26-day period) variations in the electron fluxes are prominent in the left hand portion of the figure, and were measured to a heliolatitude of $\sim$ 75°. Electrons from solar events were measured over the south pole at heliolatitudes of 54° (day 57, 1994) and 74° (day 299, 1994) (e.g., Pick et al, 1995a,b). Descending from the south pole, the electron fluxes were enhanced in the region of the near-equatorial heliospheric current sheet (approximately days 52–87, 1995; R.J.Forsyth, private communication). For latitudes above $\sim$ 50°, the northern region was relatively barren of electron enhancements compared to the southern region, as is discussed in more detail below.

Plotted in Figs. 2a and b are electron and ion fluxes, respectively, from two HI-SCALE energy channels for northern (upper panel) and southern (lower panel) heliolatitudes above 60°. Because the background in the detectors due to galactic cosmic rays changes as a function of heliolatitude, no "background" has been subtracted from the data. This provides a basis for judgments that do not require the difficult and uncertain step of background correcting the relatively low measured fluxes.

The data obtained in the passage of Ulysses over the poles depends on three major variables: time, heliolatitude, and helioradius. The relationships between these quantities differed in the two regions. In order to compare the two polar regions, a format was chosen for Figs. 2-4 that plots the fluxes vs helioradius: for the south polar pass (lower panel of each figure) this corresponds to reverse time (i.e. time – days 108–335, 1994 – runs from right to left); for the north polar pass (upper panel of each figure) time (days 150–322, 1995) runs in the conven-

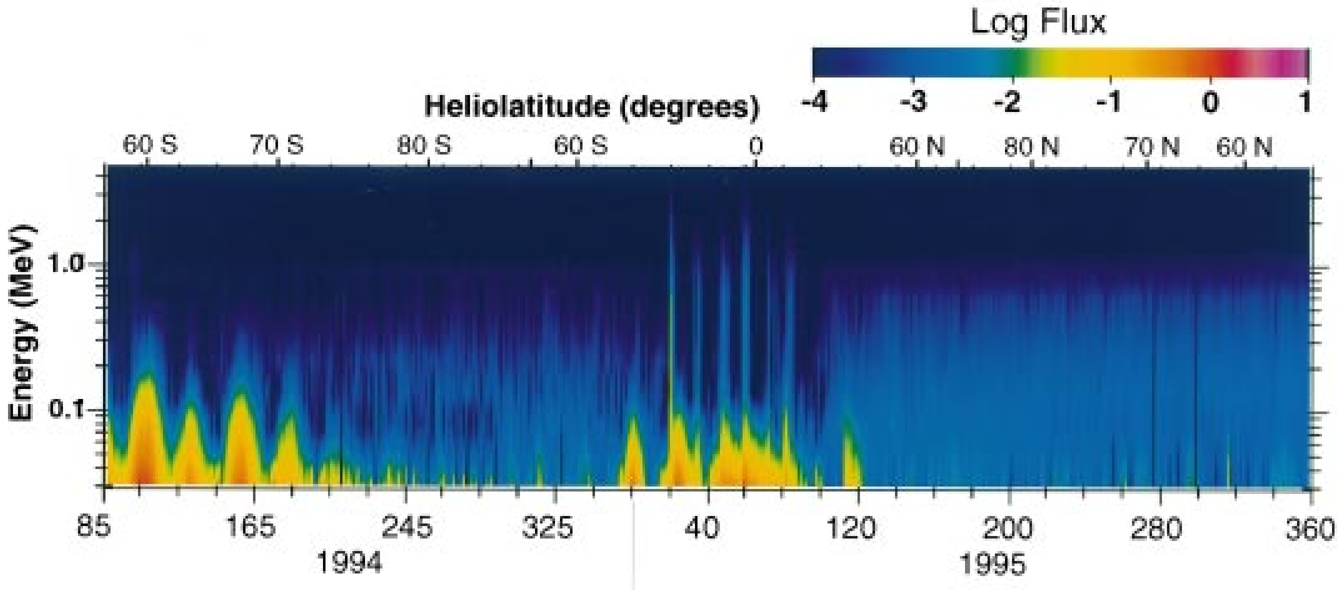

Fig. 1. Color spectrum overview of electron fluxes (from the HI-SCALE LEFS150 telescope) for the interval March 26, 1994 (day 85), through December 26, 1995 (day 360). Some background has been subtracted. Major tick marks are at 80-day intervals, and minor tick marks are at 20-day intervals. During this time Ulysses moved from 57°S towards the southern solar pole, passing approximately over the south pole, then through the heliospheric equator, and over the north pole to 55°N.

tional sense, from left to right. The plots cover the periods when Ulysses was poleward of 60°. This format brings out the fact that the helioradius was considerably different for a given heliolatitude in the two hemispheres.

Fig. 2a shows that over the southern solar pole large, sinusoidal enhancements, with a period of ∼ 26 days, were seen in the electron fluxes to a latitude of ∼75° at a helioradius as close as ∼2.6 AU. At smaller helioradii at higher latitudes the electron fluxes were less regular in appearance. Together with some evidence for a 26-day period at the smaller helioradii, solar electron events from near-equatorial solar source regions were also observed at high southern latitudes to at least 74° latitude (Pick et al., 1995b).

In the northern polar region (Fig. 2a), the appearance of the electron fluxes was different. Note first that in the upper panel of Fig. 2a, the flux scale is linear with a zero-suppressed scale because the northern fluxes showed much less variability than did the fluxes in the southern hemisphere. At the smaller helioradii, the electron fluxes exhibited far less structure than over the southern pole. There was no evidence of recurring electron events at all. There were two apparently solar-associated northern hemisphere electron enhancements at ∼ 72° and ∼ 64° (helioradii of ∼ 2.38 and ∼ 2.62 AU, respectively) which occurred approximately 36 days apart.

Low energy (56–78 keV) ions measured over both poles are shown in Fig. 2b, plotted in the same format as Fig. 2a. These ions are an average of two of four spin sectors of the LEMS30 telescope that do not view directly the sun (the other two spin sectors in this telescope, which is pointed in the approximate solar direction, had responses to sunlight and solar x-rays as well as to charged particles). The vertical scale is the same for each panel. The fluxes in the southern hemisphere have substantially more variability than the northern fluxes. Similar energy ion fluxes measured in the LEMS120 telescope, which views ∼ 120° to the solar direction, do not show this type of variability. Indeed, measurements by LEMS120 in the two polar regions are at the background of the instrument. As noted in the Discussion section (below) and suggested in Roelof et al. (1996), the LEMS30 detector response in Fig. 2b can be accounted for by heavy solar wind ions that acquire enough total energy to trigger the detector threshold as they convect with the polar high speed solar wind.

Low energy ion (0.5–0.96 MeV) and electron (0.22–0.5 MeV) data measured near Earth in the ecliptic plane by the Charged Particle Measurement Experiment (CPME) on IMP8 are shown in Figs. 3a and b. Since IMP 8 is located at 1 AU, the data are plotted as a function of time for the same time intervals as in Fig. 2 when Ulysses was at latitudes above 60°. Thus, the lower trace in each of Figs. 3a and b has time plotted from right to left to correspond to the southern latitude pass shown in Figs. 2a and b. Since the Ulysses helioradius is roughly linear with time, a fair comparison can be made.

The IMP8 electrons as shown are a composite of foreground and background fluxes. The flux equivalent of background in Fig. 3a increases from about 1.7/(cm^2 s sr) beginning in 1994 to about 2/(cm^2 s sr) at the end of the interval plotted. This background is due to the penetrating component of the galactic cosmic rays, which was recovering during this time as solar minimum approached. The increases, which last from one to several days, are solar electron events that are typically associ-

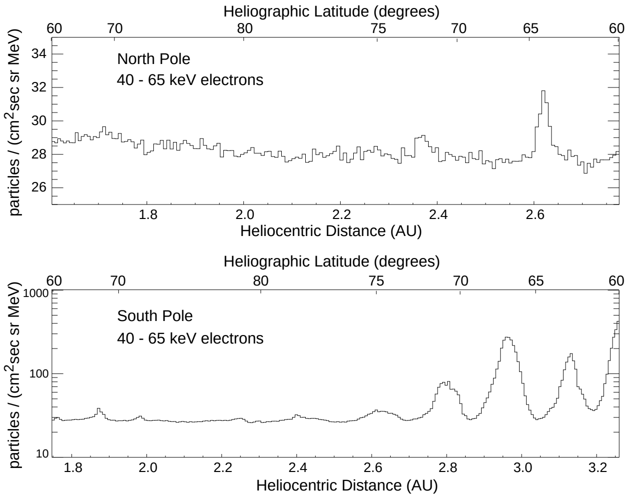

Fig. 2a. Daily average electron fluxes at latitudes $> 60°$ over the north solar pole (upper panel) and the south solar pole (lower panel) plotted as a function of the helioradius of the measurements. In this representation, time runs from right to left in the lower panel.

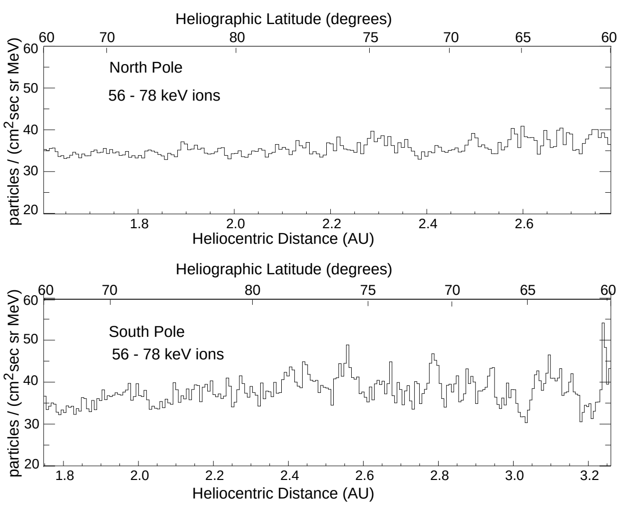

Fig. 2b. Same as Fig. 2a, for a low energy ion channel (HI-SCALE LEMS30 telescope).

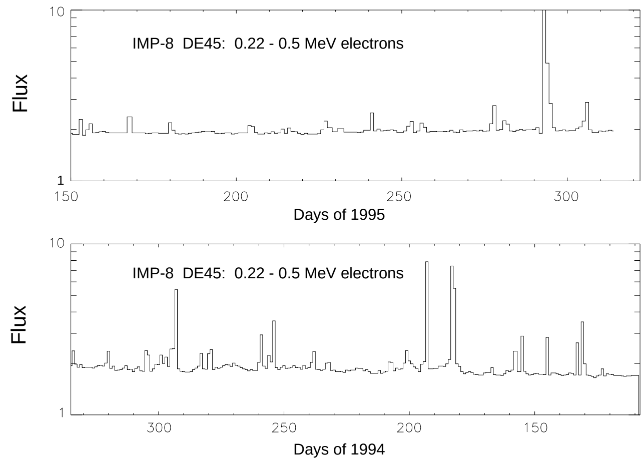

Fig. 3a. Daily average electron measurements from the IMP8 spacecraft in orbit around Earth during the same time intervals as shown in Figs. 2a and b. Time runs from right to left in the lower panel, to correspond to the lower panels in Figs. 2a and b.

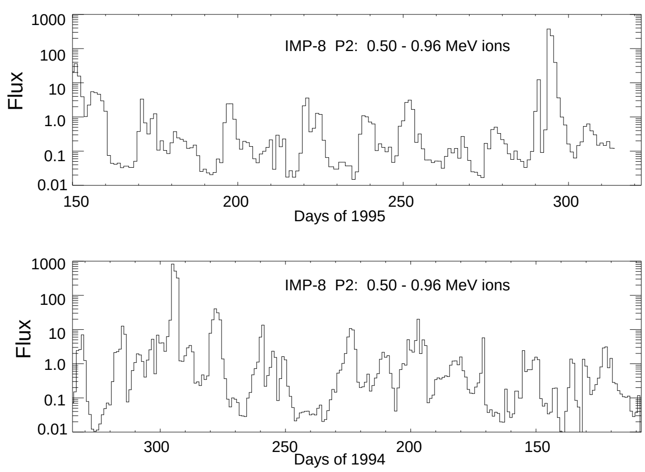

Fig. 3b. Same as Fig. 3a, for ion measurements made on the IMP8 spacecraft.

ated with flares and other solar activity. Note that 1994 was more active than 1995. The small, recurring increases that are apparent in 1995 are due to magnetospheric electron bursts that occur mainly when IMP8 passes through the magnetotail plasma sheet at about 12-day intervals. There is an obvious 26-day recurrent electron increase pattern in these higher energy electrons at 1 AU in the ecliptic that resembles the recurrent increases observed by Ulysses (right hand side of lower panel of Fig. 2a). The solar event at about day 293, 1995, is not seen by HI-SCALE over the north pole (Fig. 2a).

The IMP8 ion fluxes shown in Fig. 3b demonstrate much larger variability than do the IMP8 electrons or any of the Ulysses ion or electron observations. The 1 AU in-ecliptic ion fluxes are dominated by flare sources, interplanetary shock-associated events, and other solar-generated events. Although the 1995 enhancements tend to be slightly smaller and fewer in number, it is clear that, for these ions in the ecliptic, solar and interplanetary activity persisted in 1995 to nearly the level evident in 1994. From the persistence of variations observed with IMP8 and the interhemispheric differences of electron and ion fluxes observed with Ulysses one can plausibly infer that the Ulysses-measured flux variations were spatial rather than temporal.

3. Polar particle composition

As noted in the Introduction, at energies greater than about 0.5 MeV/nucl, the WART telescope of HI-SCALE can be used to study individual ion species. Shown in Figs. 4a and b are daily average fluxes of protons (0.48–1.2 MeV) and helium

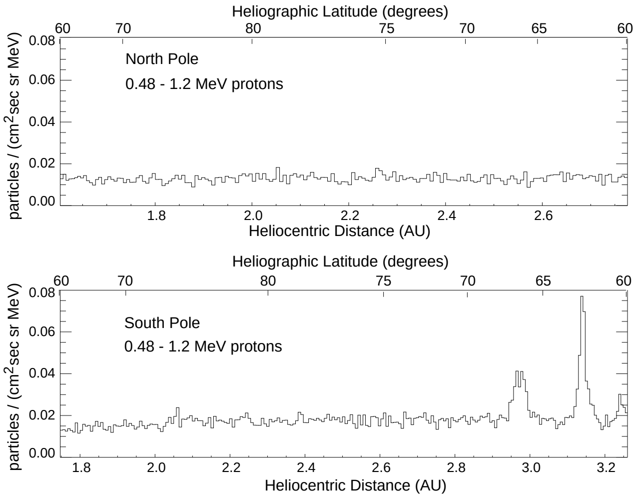

Fig. 4a. Daily average protons measured by the HI-SCALE Wart telescope over the north (upper panel) and south (lower panel) poles of the sun at latitudes $> 60°$ plotted as a function of helioradius. Time in the lower panel runs from right to left, as for Figs. 2 and 3.

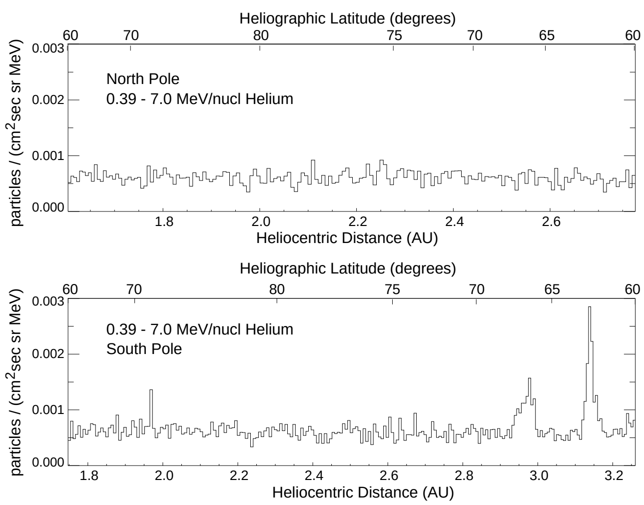

Fig. 4b. Same as Fig. 4a, for helium ions.

ions (0.39–7.0 MeV/nucl), respectively. While enhancements in both ion species were seen to heliolatitudes as high as $\sim 67°$ (helioradius ~ 2.95 AU) in the southern hemisphere, none were seen at similar heliolatitudes in the northern hemisphere. The interval between the two southern hemisphere enhancements is about 26 days, and these are the last measurements, during ascent to the southern pole, of the string of CIR-related particle enhancements first discussed in Lanzerotti et al. (1995).

The He/proton ratios for particles of energy $\sim$ 0.4–1.2 MeV/nucl are shown in Fig. 4c. In the southern hemisphere, inside about 2.1 AU, the relative abundance of He particles increased for latitudes below $\sim 74°$. Similar high ratio values in the He/proton abundances were seen for most of the northern hemisphere observations.

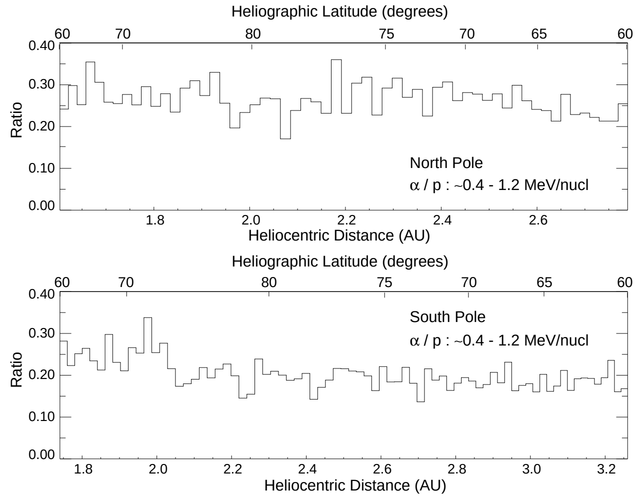

Fig. 4c. Three-day average He/H ratios for heliolatitudes $> 60°$ in the north (upper panel) and south (lower panel) solar poles plotted as a function of helioradius. Time runs from right to left in the lower panel.

Ten-day average fluxes of CNO ions (carbon, nitrogen, and oxygen; $E > 0.47$ MeV/nucl) are shown in the upper panel of Fig. 5 for 1994–1995. The heliolatitude coverage, indicated along the top axis, shows the data interval to be from 55°S, over the southern pole, across the helioequator, and across the northern pole to 55°N. As the spacecraft approached the southern solar pole, the lower energy CNO fluxes decreased in intensity and the higher energy fluxes increased. The opposite was seen as the helioequator region was crossed. Across the northern pole, the flux levels in both energy channels were somewhat larger than in the south polar region.

The spectral index for the CNO fluxes, derived from the two energy channels assuming power law energy spectra, is shown in the lower panel of Fig. 5. This index indicates quite hard energy spectra across the polar regions, with substantially softer spectra near the helioequator. The spectral indices are approximately the same over the two poles. The harder spectral indices over the poles probably exist because most of the detected CNO ions in these regions are anomalous O ions which, in the energy range covered by the WART telescope, have an almost flat spectrum (see below; also, Lanzerotti & Maclennan, 1995).

Details of the energy spectra for ions measured in the two polar regions are presented in Figs. 6a-d. Figs. 6a and b contain spectra of hydrogen, helium, oxygen, and nitrogen for the north and south polar regions, respectively, for heliolatitudes above 65°. The H and He spectra show power law dependence on energy in the energy range of the Wart sensitivity. The peak in the He spectrum is from the detection in the telescope of a calibration source that is located on the open cover of the telescope (the telescope does not view the source directly; it is not as yet understood what the specific interplanetary field configuration must be for a detection at these low levels to occur). Within the statistics, the H and He fluxes are approximately the same in each hemisphere.

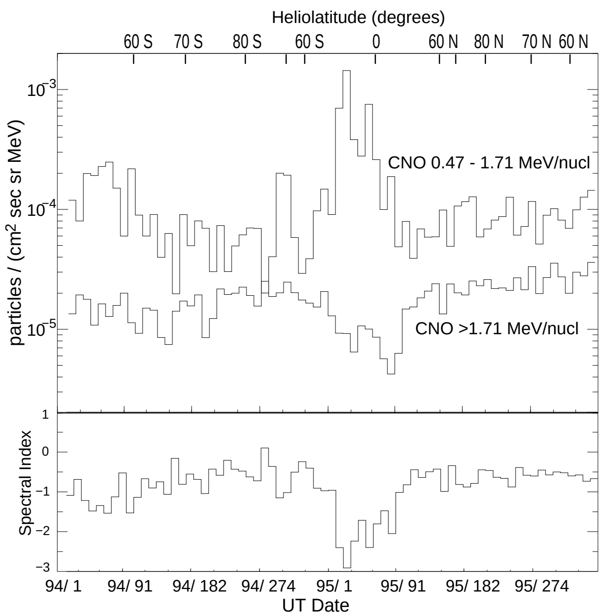

Fig. 5. Upper panel: Ten-day average fluxes of CNO ions measured in two Wart energy channels as a function of time (heliolatitude along upper axis). Lower panel: Spectral index of CNO ion fluxes assuming a power law dependence for the energy spectrum.

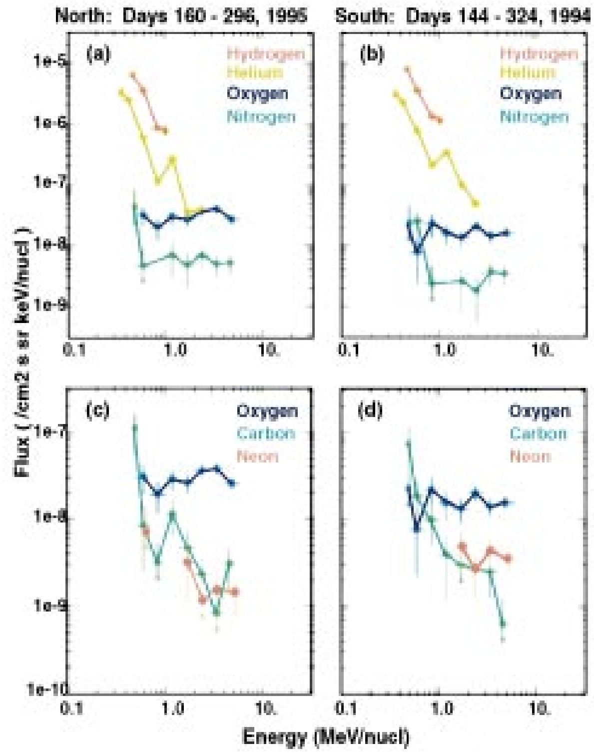

Fig. 6. a Spectra of H, He, N, and O ions for heliolatitudes $> 65°$N; **b** Same as **a** for heliolatitudes $> 65°$S. **c** Spectra of C, O, and Ne ions for heliolatitudes $> 65°$N; **d** Same as **c** for heliolatitudes $> 65°$S

Both the O and the N spectra at the high latitudes are approximately flat over the energy range ~ 0.8 to ~ 5 MeV/nucl. Each species shows larger fluxes in the northern hemisphere than in the southern by a factor of ~50%. The N/O ratio over both poles is ~ 0.16 for energies of 2–4 MeV/nucl.

Figs. 6c and d plot the energy spectra for oxygen, carbon, and neon for latitudes above 65°. Both of the C spectra fall steeply with increasing energy, attaining values comparable to those of Ne at the highest energies that the Wart measures. The fluxes of the six species in the two polar regions and the north/south pole ratios are given in Table 1 for two different energy ranges. The abundances relative to O for the ion species are provided in Table 2 for the two energy ranges.

4. Discussion

The above presentation of low energy electron and ion data obtained in the two polar regions of the sun shows that during solar minimum conditions the polar regions are devoid (compared to near-ecliptic regions) of high fluxes of particles. The lowest energy ion and electron fluxes, as shown in Figs. 2a,b, were different in the two hemispheres, with more variability seen in the southern polar region. Comparisons with fluxes measured at 1 AU on the IMP8 spacecraft suggest that this difference was a spatial and not a temporal effect. In addition, other than an event at 40°N (Buttighoffer et al. 1996), no solar electron events were seen at high northern latitudes, unlike the case over the south polar region (Pick et al. 1995a,b).

The reason(s) for the hemispheric asymmetry in the lowest energy ions and electrons remains unclear, as it is not as yet agreed upon as to the reason(s) for the enhancements in the electron fluxes at high southern heliolatitudes at a period approximately that of the near-equatorial current sheet. The model of Jokipii (1995) invokes cross-field diffusion of the electrons from the near-equatorial CIRs to produce the recurrent electron enhancements. In this case, our observations would imply that the particle perpendicular diffusion coefficient is larger in the southern hemisphere than in the north.

Alternatively, Simnett & Roelof (1995), propose that the electrons are accelerated by CIRs at the boundaries of the streamer belt. The acceleration occurs at the poleward edge of the expanding reverse shock at some large distance from the spacecraft; the electrons are detected when magnetic flux tubes connect the acceleration site to the satellite. This scenario could explain the CIRs being most effective in the southern hemisphere because of a basic asymmetric tilt in the heliospheric current sheet during this epoch.

Finally, it has been proposed by Fisk (1996) that the polar magnetic field lines do not extend radially outward but are bent toward the steamer belt. The offset of the solar dipole with respect to the solar rotation axis would cause a polar spacecraft to find itself on field lines that would tend to intersect the CIR acceleration regions once each approximately 26-day interval. This explanation could alleviate a problem inherent in the Simnett & Roelof (1995) work that requires the poleward propagating reverse shock to maintain its acceleration capability to quite high latitudes. According to the Fisk (1996) suggestion,

Table 1. Comparisons of North/South Pole Fluxes[a]

	0.5–1.0 MeV/nucl.			2.0–4.0 MeV/nucl.		
	South Pole	North Pole	N/S Ratio	South Pole	North Pole	N/S Ratio
H	5.00e-6	4.52e-6	0.90±0.04	–	–	–
He	9.97e-7	7.19e-7	0.72±0.07	4.47e-8[b]	3.54e-8[b]	0.79±0.18[b]
C	2.88e-8	1.16e-8	0.40±0.27	2.46e-9	3.04e-9	1.24±0.95
N	2.71e-8	4.43e-9	0.16±0.17	5.3e-9	1.14e-8	2.15±0.98
O	2.99e-8	5.08e-8	1.70±0.76	3.42e-8	7.52e-8	2.20±0.41
Ne	3.35e-9	4.43e-9	1.3±1.6	6.9e-9	2.7e-9	0.39±0.26

[a] Fluxes in particles/cm^2 s sr keV measured at heliolatitudes $> 65°$.
[b] He fluxes for 2.0–2.4 MeV/nucl.
– The WART does not measure H at this energy.

Table 2. Abundance ratios above 65°

	0.5–1.0 MeV/nucl.		2.0–4.0 MeV/nucl.	
	South Pole	North Pole	South Pole	North Pole
He/H	0.20±0.07	0.16±0.04	–	–
He/O	27.6±9.9	13.0±3.7	2.2±0.6[a]	0.97±0.24[a]
C/O	0.84±0.42	0.22±0.14	0.09±0.05	0.04±0.02
Ne/O	0.1±0.1	0.1±0.1	0.22±0.08	0.04±0.02

[a] He/O ratio for 2.0–2.4 MeV/nucl.
– The WART does not measure H at this energy.

the observations over the two poles by HI-SCALE indicate that the polar fields are not bent equatorward as much in the north as in the south polar region.

The ion composition measurements indicate that the oxygen spectra are quite hard over the poles. In the Wart energy range, they are essentially flat, independent of energy, in both polar regions, as are the nitrogen and the neon spectra. In contrast, the carbon spectra fall quite steeply as a function of energy. Comparisons of the intensity ratios of these spectra indicate that the N, O, and Ne ions are anomalous ions (the C/O ratios, at energies $\gtrsim$ 1.5MeV/nucl, are $\lesssim$ 0.2. If the C ions at the highest energies measured with the Wart are "anomalous", then their relative (to O) abundance is less than that of Ne. The steep rise in the C spectrum to the lowest energies is notable in that such an increase is not seen at all in the O fluxes. This increase at the low energy suggests that there may be a source of low energy C in the inner high latitude solar system, additional to the source(s) of the N, O, and Ne. Such a source could be grains from the interstellar medium and/or the helioequator dust belt that produces the zodiacal light. Other solar system sources would be comets and asteroids. Solar wind energy carbon measurements with the SWICS instrument on Ulysses (Geiss et al. 1995) support such a speculation. This point requires further investigation. The spectral comparisons of Fig. 6 as well as the flux values in Table 1 show that while the low energy H and He fluxes were slightly larger over the south pole than over the north, the opposite is the case for the N, O, and Ne fluxes. Indeed, the O fluxes are more than 50% larger over the north pole than they are over the south. This is surprising in the context of the CIR-related effects (the ∼26-day periodicity in the electron fluxes), which were observed to higher latitudes in the south than in the north. Hence, if the CIRs that accelerate electrons are also accelerating a portion of the anomalous O, then higher fluxes would be expected in the southern polar region than in the north. This asymmetry in the N, O, and Ne fluxes might argue for easier access (less scattering) of the anomalous ions from the outer heliosphere to the northern polar cap.

An alternative explanation might be based upon a radial gradient, as the ion measurements over the north pole were made closer to the sun than were the measurements over the south pole (see Fig. 5 horizontal axes). At 80°N the distance was $\sim$ 2.0 AU while at 80°S the distance was $\sim$ 2.3 AU. However, assuming equal fluxes in each hemisphere gives an unrealistically large negative value, $\sim$ 150% per AU, for the radial gradient. No other measurements by HI-SCALE in its traversal of the polar regions would support this magnitude of polar radial gradient. Hence, the first of the possibilities, easier access of anomalous ions approaching the sun from the distant northern heliosphere, is a more viable explanation.

As noted in the discussion of the ion measurements shown in Fig. 2b, it is likely that the variations seen in the non-sun-viewing sectors of the ion channel are the detector response to thermal Fe ions in the high speed solar wind in the polar coronal holes in the south and north hemispheres. The more significant fluctuations occurred in the southern hemisphere, an indication that the Fe/H abundances were larger over the south pole than over the north. The analysis of the HI-SCALE measurements by Roelof et al. (1996), using daily averages of the low energy HI-SCALE ion measurements and of the solar wind velocity and density, conclude that $[Fe/H]_{north}/[Fe/H]_{south}$ is $\sim 1/2$. Until comparable Fe/H measurements are available in the ecliptic (e.g., from WIND), Roelof and colleagues must leave open whether this abundance difference is a temporal effect (between

1994 and 1995) and/or whether it is due to different solar wind structures encountered at comparable high latitudes in the southern and northern hemispheres.

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