rona and, in particular, into the dynamic processes and structures that are associated with the acceleration of the solar wind.

The transition between the two different regimes varied along the orbit of Ulysses (Fig. 6): Closer to the sun, at higher latitudes, the transition between unevolved fluctuations and turbulence occurs at higher frequencies, consistent with the slow evolution of fluctuations with heliocentric distance. In this interpretation, a population of fluctuations with an essentially $1/f$ spectrum close to the sun evolves, through the intermediary of small velocity fluctuations in the solar wind, toward a fully developed turbulence with a power spectral exponent of $-5/3$. This model is likely to be somewhat simplistic, as shown by the more detailed study based on structure function analysis, that includes correlations higher than second order (*21*). Although the evolution and mix of the fluctuations observed in the fast solar wind flows at polar latitudes is thus significantly different from that near the ecliptic plane, the interpretation of the observations in terms of detailed processes on the microscales and mesoscales of the solar wind remains to be completed.

Fluctuations in the magnetic field in any case cannot be fully described in terms of conventional spectrum analysis. While structure function analysis provides a more complete understanding into the statistical nature of the fluctuations, the study of discontinuities provides a complementary approach into aspects of the microstructure of the polar flows. The rate of occurrence of discontinuities, as measured using criteria defined previously for in-ecliptic measurement, has been found to increase significantly (up to 100 to 200 per day) in the high-speed polar solar wind (*25*), when compared to rates found near the ecliptic. The presence of discontinuities appears to be strongly correlated with the presence of Alfvén waves. When individual examples of discontinuities are examined, it is found that the discontinuity is part of the Alfvén pulse train, and corresponds to the phase-steepened edge of the wave.

A feature of the microscale structure is the frequent occurrence of nulls (or holes) in the magnetic field (*26*). These events, in which the strength of the magnetic field drops to a value close to zero (without a change in the direction of the field), are of short duration (of the order of tens of seconds) and represent a significantly different state of the solar wind plasma. Although such events had been noted in the ecliptic (*27*), their rate of occurrence is significantly enhanced at high latitudes. Their relation to the mirror-mode instability first identified in the Earth's magnetosheath (*28*) is at present unclear, as is their frequent association with tangential discontinuities. There is evidence of plasma (Langmuir) wave activity associated with the magnetic holes (*29*), possibly caused by streaming energetic electrons. Another feature of the short time-scale magnetic field observations is the presence of current-sheet-like features, characterized by dropouts in the magnitude of the magnetic field, associated with sharp deflections of the field direction. Taken together, the collection of small-scale phenomena in the high-speed and relatively uniform solar wind characteristic of the polar region represent new classes of plasma processes for use as diagnostics of coronal and heliospheric processes.

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Over the Southern Solar Pole: Low-Energy Interplanetary Charged Particles

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The heliosphere instrument for spectrum, composition, and anisotropy (HISCALE) recorded the fluxes of low-energy ions and electrons (>50 kiloelectron volts) when Ulysses crossed the southern solar polar region and revealed that the large-scale structure of the heliosphere to at least ~−75° was significantly influenced by the near-equatorial heliospheric current sheet. Electrons in particular were accelerated by the current sheet–produced and poleward-propagating interplanetary reverse shock at helioradii far from the Ulysses location. At heliolatitudes higher than ~−75° on the Ulysses ascent to the pole and ~−50° on the descent, small, less regular enhancements of the lowest energy electron fluxes were measured whose relations to the current sheet were less clear. The anomalous component of low-energy (~2 to 5 megaelectron volts per nucleon) oxygen flux at the highest heliolatitudes was found to be $\sim 10^{-8}$ [per square centimeter per second per steradian (per kiloelectronvolt per nucleon)]; the anomalous Ne/O ratio was ~0.25.

The HISCALE investigation (*1*) on the Ulysses spacecraft provided three-dimensional measurements of the distributions of low-energy charged particles (electrons and ions with energies between 50 keV and 5 MeV) in the heliosphere. These low-energy particles are accelerated from lower energy plasmas by magnetohydrodynamic processes in the solar corona and photosphere, as well as in interplanetary shock waves. HISCALE also measured the composition of the low-energy [$E > 0.5$ MeV per nucleon

(MeV/n)] interplanetary particles, including the anomalous component of cosmic rays—ions whose origin is believed to be the interstellar neutral gas that penetrates the heliosphere. The HISCALE measurements of low-energy charged particles at high heliolatitudes thus provide information on the structure and dynamics of the three-dimensional heliosphere.

After its encounter with Jupiter in early February 1992, Ulysses swung out of the ecliptic plane on its trajectory to high heliolatitudes. After about the middle of 1992, at a heliolatitude of ~15°, Ulysses entered an interplanetary region where it began to periodically encounter a recurrent high-speed solar wind stream. This stream appeared to originate in a south latitude coronal hole that formed corotating interaction regions (CIRs) in the interplanetary medium. The interplanetary plasma and magnetic field signatures of the CIRs largely disappeared when Ulysses passed above ~−35° and entered a permanent high-speed solar wind stream issuing from the south polar coronal hole (*2*).

Low-energy charged particles were found to vary with a periodicity of ~26 days, even above ~−35° when the spacecraft no longer regularly encountered the CIRs. These low-energy ions probably originate (are accelerated) at the reverse shock of the CIRs at larger radial distance than the spacecraft (*3*).

The intensities of the quasiperiodic enhancements (periods on the order of 26 days) in the electron fluxes tended to decrease with time from about mid-1993 to the beginning of 1994 (Fig. 1, B and C). After the beginning of 1994, large enhancements were measured for several ~26-day intervals in the periodic electron appearances. After about day 190 (latitude ~−70°), the periodic increases became much smaller. The increases in ion flux (Fig. 1A) at these latitudes appear to have been a mixture of direct solar and CIR-related particles, especially during the first part of 1994.

On the descent from the maximum latitude, large increases in the fluxes of electrons were not encountered until ~−45° [helioradius 1.58 astronomical units (AU); Fig. 1C]. This is a lower latitude than the latitude of the termination of the largest periodic enhancements on the ascent (~−70°; helioradius 2.83 AU). Although a helioradius dependence on the effectiveness of the shock acceleration might produce some of this difference, the finding suggests that at least the inner heliosphere was pumped up with low-energy solar and CIR particles during approximately the first third of 1994 (*4*). Some of the differences between the ascent to, and descent from, the polar region may also have been produced by the decreasing inclination of the heliosphere current sheet during this declining phase of the solar cycle.

The first third of 1994 also corresponded to a time of enhanced geomagnetic activity with an ~26-day period at Earth. The intensities of interplanetary electron and ion data recorded by the Charged Particle Measurement Experiment (CPME) on the IMP-8 spacecraft (*5*) in the ecliptic plane were much more variable than those seen at the highest solar latitudes. The IMP-8 intensity measurements of 0.2 to 0.5 MeV electrons typically exhibited ~20% variation over time scales of a solar rotation or two, and their recurrence pattern was less coherent than that at high latitudes in the HISCALE data (Fig. 1). This is because the in-ecliptic electrons originated in solar active regions as well as from CIRs. At high latitudes at this time, the coronal source had largely disappeared; hence, the virtual lack of correlation between the in-ecliptic and the HISCALE measurements at the time that Ulysses traversed the southern solar polar region.

The ~26-day period seen in the electron intensities is a frequency that can be associated with the near-equatorial heliospheric current sheet. However, the rapid change in Ulysses' heliocentric longitude during the polar pass and the known differential rotation of the sun implies that the electron reappearance frequency should not be constant in time. Exploratory data analyses using conventional complex-demodulation methods confirmed that the frequency of the electron increases changed at the highest latitudes and also showed that the changes were not simple. Thus a more elaborate demodulator whose center frequency tracked the rotational frequency was designed. At the low signal-to-noise flux ratios encountered near the pole, a tracking filter is necessary in order to avoid serious bias of the frequency estimates (*6*).

Initially, the magnetic rotational frequency corresponding to Ulysses' heliographic latitude, less the time derivative of Ulysses' right ascension, was tried (dashed curve in Fig. 2B). Analysis of the demodulates so obtained with the harmonic F-test (*7*) showed that whereas the shape of the curve was reasonable, the average frequency detected by HISCALE was higher, about 443 nHz, which is more typical of heliographic latitudes near 30°, as was expected from the CIR particle acceleration process. Consequently, the filtering process was started with the use of the offset curve. Projection filters (*8*) centered on this offset frequency curve

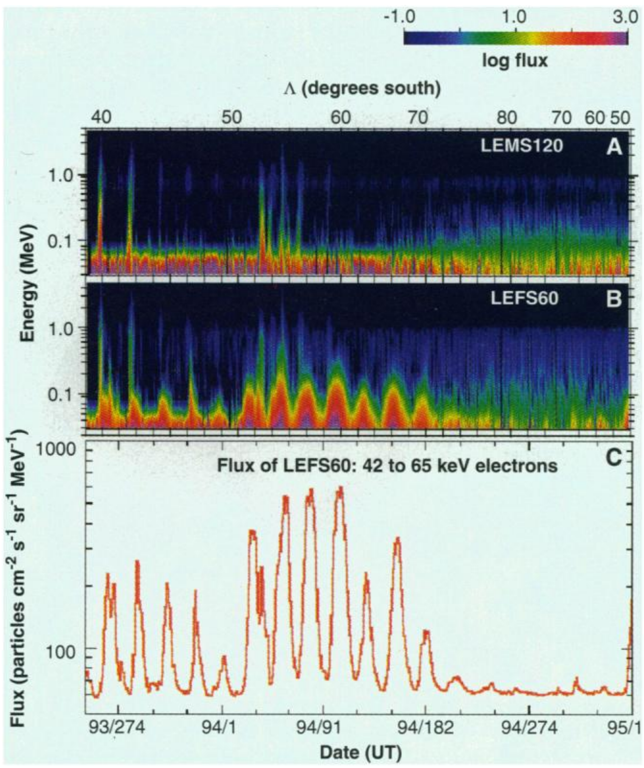

Fig. 1. (**A**) Spectrogram of Ulysses HISCALE measurements of low-energy interplanetary ions (as measured by the LEMS120 telescope) from ~−38° across the southern solar pole to ~−45°. During this interval, the distance of Ulysses from the sun ranged from 4.4 AU at day 245 of 1993, to 2.3 AU at the highest latitude, to 1.6 AU at day 1 of 1995. The orange-red band across the bottom of the spectrogram is due to detector background not removed entirely in the processing. The color scale for the flux levels is shown at the top of the figure. (**B**) Spectrogram as in (A) for HISCALE electrons (as measured by the LEFS60 telescope). (**C**) Time-intensity plot of one HISCALE electron channel.

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were used on 1-hour averaged electron data from two electron telescopes. As initial analysis had shown that the frequency varied rapidly, especially as the polar region was reached, the bandwidth of the filter was set at 300 nHz—as wide as was possible without suffering serious leakage problems from frequencies at 0 or the first harmonic of rotation. Two passes through the data were made, and the results obtained from the initial pass were used to adjust the center frequencies of the filters for the second pass.

It was also found useful to subtract a time-varying average from the data, and to vary the "gain" so that the amplitude was approximately constant. As a first approximation, 800-hour (33-day) overlapping blocks of data were sorted. The average of the center 20% was used as an average, and the range between the high and low 10 percents were used for the gain. Both the raw center and gain estimates were made at 4-day increments, smoothed, and splined to give the initial center and gain functions. On the second pass, the initial gain was further scaled by the average power of the filter output (Fig. 2A). Estimation of the gain and offsets independently on both channels does not change the results significantly.

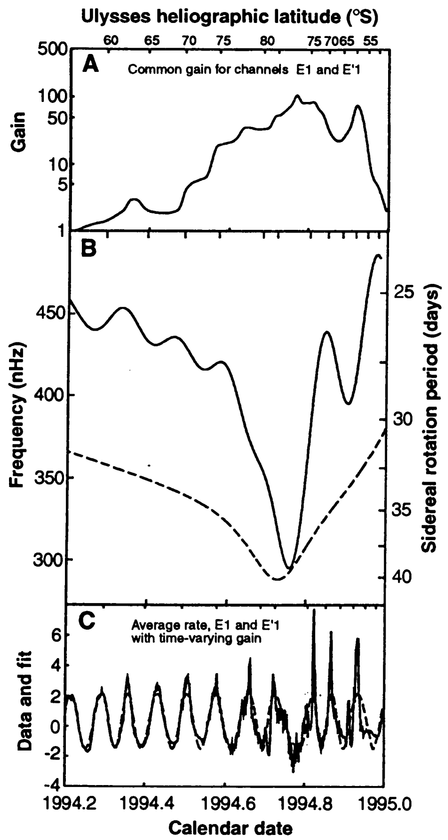

Fig. 2. (**A**) Common gain used for analysis of electron fluxes in two energy channels as measured over the southern solar pole. (**B**) The dashed line shows the solar rotation rate at the latitude of Ulysses as it passed over the southern solar pole, taking into account the change with time of the right ascension of the spacecraft as well. The solid line shows the power-weighted average estimate of the reappearance rate of the electron flux enhancements detected by HI-SCALE as the polar region was crossed. (**C**) The solid line shows the arithmetic average of HI-SCALE electron data after application of the common gain shown in (A). The dashed line shows the predicted time variation of electron rates with the use of derived frequency variation with time [solid line in (B)] and phase (9).

The power-weighted average estimate of the frequency of the electron fluctuations from the two detectors as a function of time and, implicitly, of heliolatitude shows that the electron reappearance rate decreased to nearly the solar polar rotation rate at the highest latitude. Results for the two electron channels individually (9) are similar with the exception that the minimum period in one of them occurs a few days earlier than for the average. There is, in addition, a hint that there may be a low-amplitude signal in this band that changes phase by 180° near the maximum latitude, which may be evidence of a solar g-mode oscillation (*10*).

The results from the analysis of the electron variations (Fig. 2) confirm that at heliolatitudes $\lesssim -75°$ on the ascent to the pole, the variations in the electron fluxes have a periodicity close to that of the solar equatorial region. This is because the detected particles are being accelerated by the reverse shock from the heliospheric current sheet at some large distance from the spacecraft. However, above this latitude, the frequency of appearance of the electron enhancements decreases, reaching, just after the highest latitude, essentially a level corresponding to the local solar latitude of Ulysses at the time. This analysis suggests that during the Ulysses southern polar pass, the effect of the remote acceleration by the heliocurrent sheet was not readily evident above heliolatitudes of $\sim -75°$ on the ascent in the coronal hole and to latitudes as low as $\sim -45°$ on the descent. Therefore, above those latitudes to the highest latitude that Ulysses attained, the precise relations of the small and irregular electron enhancements to lower latitude CIRs and poleward-propagating reverse shocks are uncertain. There is undoubtedly contribution to the electron fluxes from CIR-produced reverse shocks, as was seen at the lower latitudes. This is one way in which such variations might be produced in the fluxes. If so, the magnetic connections to the shock would occur at large distances from the spacecraft location. Because these fluxes are quite isotropic, the electrons, whatever their origins, are undoubtedly significantly scattered, and may even be trapped within the inner heliosphere by the turbulence that is found in the magnetic field fluctuations in the polar coronal hole (*11*).

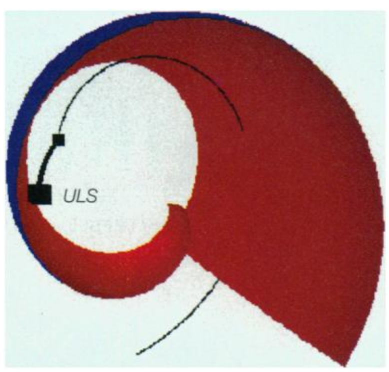

Fig. 3. Schematic illustration, in reference frame corotating with the sun, of an interplanetary reverse shock intersecting the Ulysses spacecraft (ULS). The light solid line is an interplanetary magnetic field line connecting the Ulysses orbit (heavy solid line) to the shock at a larger helioradius.

By removing the common gain, it can be seen that the polar electron increases are somewhat different in character from those at lower latitudes (Fig. 2). In addition to being closer to the instrument background, the electron increases at the highest latitudes have a less regular structure than do the rates at the lower latitudes at the beginning of 1994 (which are more sinusoidal in appearance). Further, small differences are evident in the rates at the highest latitudes from the two electron sensors.

Initial modeling of the mid- to high-heliolatitude observations with reference to interplanetary shock structures has been carried out. The geometry of the shock structure relative to the spacecraft observations is quite complex. An interplanetary reverse shock structure (*12*) viewed in a reference frame corotating

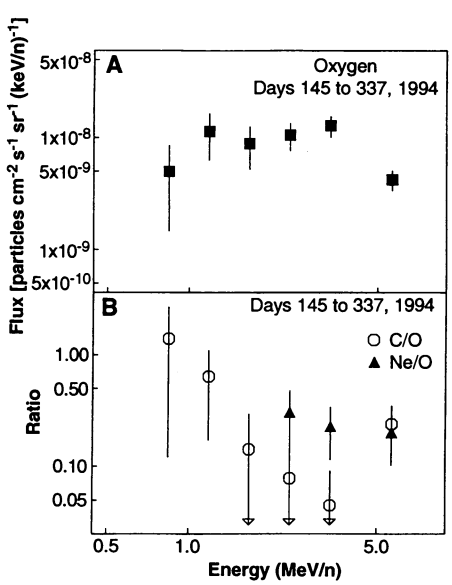

Fig. 4. (**A**) Interplanetary oxygen particle spectrum measured in south solar pole region. (**B**) Abundance measurements of carbon and neon as ratios to oxygen.

with the sun is shown as the smooth surface in Fig. 3. The leading edge of the shock, propagating to the south (away from the viewer into the page) has just intersected the Ulysses spacecraft (ULS in the figure). The plasma pressure gradients are weakest in the region where the shock intersects Ulysses, and thus particle acceleration is weakest. However, as Ulysses transits its orbit (in the corotating frame; heavy, short solid line), some 3 to 4 days later it will be on a magnetic field line (light solid line extending away from the Ulysses orbit in the figure) that will intersect a much stronger region of the shock at a greater helioradius where particle acceleration is enhanced. Accelerated particles, and electrons in particular, can propagate to the spacecraft. As Ulysses progressed to the highest latitudes, it is likely that the field lines did not intersect the propagating shock at all, which provides an explanation for the low fluxes over the pole.

The HISCALE instrument also returned data on the composition of the low-energy heavy ions over the southern solar polar region. The spectrum of the oxygen ions measured between the energies of ~0.8 to 6 MeV/n (Fig. 4), covering the heliolatitude range from $-65°$ on ascent to the pole back to $-60°$ on descent, is approximately independent of energy over this decade of energy range, except for the highest energy point, which tends to drop in intensity. The O intensities are on the order of 10^{-8}[cm^{-2} s^{-1} sr^{-1} $(keV/n)^{-1}$]. This value is approximately the same as that measured after the Ulysses spacecraft passed above the heliospheric current sheet at $\sim -35°$ (*13*). Thus, essentially no heliolatitude gradient in the anomalous oxygen fluxes from that latitude to $\sim -80°$ is found (*13*).

The C/O ratios (Fig. 4) decreased sharply with increasing energy. At the two lowest energies, the ratios are not inconsistent with solar abundances, although the statistical uncertainties are large. However, at energies above ~2 MeV/n, the ratios are on the order of 0.2 in one case and are much smaller for three other energy determinations. The low values of the C/O ratios show clearly that above ~1.5 MeV/n, the oxygen abundances measured in the polar region are low-energy anomalous cosmic rays. The Ne/O abundance ratios were ~0.25. The measured Ne particles are also anomalous cosmic rays.

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Observations of Energetic Particles with EPAC on Ulysses in Polar Latitudes of the Heliosphere

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Measurements with the Energetic Particle Composition instrument (EPAC) aboard Ulysses show particles from near the ecliptic that were apparently accelerated by shocks associated with a corotating interaction region. The particles were detected together with the shocks and even when shocks no longer arrived at Ulysses up to $-65°$ of heliographic latitude but not beyond. Particles could have reached these latitudes along magnetic fields; such connections to the outer lower latitude heliosphere evidently do not exist above that latitude. The accelerated streams have composition similar to solar wind abundances, no dispersion, and a net inward anisotropy. The underlying composition between the recurrent stream is similar to the anomalous component of cosmic rays. The channel sensitive to high-energy protons (>230 megaelectron volts) shows a 26-day variation of the flux superimposed on the heliospheric modulation of galactic ions.

There has been much speculation concerning particle propagation in the heliosphere; suggestions have ranged from easy access of low-energy cosmic ray particles along polar magnetic fields to diffusive, meridional flow patterns throughout the heliosphere. We present observations made at high heliocentric latitudes with the EPAC energetic particle composition spectrometer on board Ulysses throughout the period after its Jupiter flyby.

The EPAC instrument consists of four identical three-element semiconductor telescopes mounted at different angles relative to the spacecraft spin axis; by virtue of the spin rotation, about 80% of the sphere can be sampled in 32 bins. By means of the (dE/dx)-E technique, elements as heavy as iron can be separated. The energy ranges covered are 0.3 to 1.5 MeV for protons and 0.4 to 6 MeV per nucleon (MeV/n) for heavier ions. Electrons were measured in two channels [$0.1 < E < 0.38$ MeV (ELL) and $E > 0.18$ MeV (ELH)] and spin-averaged for each telescope. The ELH channels are also sensitive to high-energy ions, which may penetrate the 1.5-mm Pt shield (depending on their direction; protons need $E > 230$ MeV) (*1*).

Near the ecliptic, Ulysses was immersed in an almost ever present flow of solar particles (Fig. 1) (*2*). In contrast, after day 176 of 1992 [heliocentric latitude, $-13.4°$; distance from sun, 5.3 astronomical units (AU)] (peak 1 in Fig. 1), Ulysses no longer detected these frequent and variable solar particle fluxes. It encountered a region where recurrent large energetic particle fluxes were recorded, similar to earlier observations (*3*). A recurrent fast solar wind stream with velocities up to 800 km s^{-1} was observed, whereas outside of the region, the solar wind speed dropped to about 400 km s^{-1} (*4*). The fast stream returned every ~26.6 days. It apparently emerged from an equatorward extension of the southern solar polar coronal hole. Beyond 1 AU, a corotating interaction region (CIR), bounded by a forward-reverse shock pair (*5*), formed

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