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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at its leading edge.

After day 120 of 1993, the ratio between fast and slow solar wind speed dropped from 2 to 1.4, while the maximum speed remained at about 800 km $s^{-1}$ (*4*). Ulysses had reached $-29°$, the maximum latitude to which the heliographic streamer belt extends (*4*), which is thought to surround the heliospheric current sheet (*6, 7*). At that time, the sector structure of the interplanetary magnetic field disappeared. The CIR-related forward shocks propagating toward the equator also disappeared (*8*) and with them the signature (double peak, spectral slope) of the two shocks in the energetic particle data (Fig. 1, peak 18 and higher). Reverse shocks were regularly observed until $-41.5°$ (*9*).

The particle fluxes rose by several orders of magnitude in all species in association with the forward-reverse shock pairs ahead of and behind the CIR interface (Figs. 1 and 2) [shocks identified according to (*10*)]. This is evidence that the shocks that accompany the CIR accelerated the energetic particles. Such a pattern was seen throughout 1992 and into mid-1993. Typical features of accelerated particles known for CIR-related shock pairs in lower latitudes were also observed in the higher latitudes. These include a short rise time in front of the forward shock and a first peak in ion intensity at the forward-shock surface, followed by a decay toward the stream interface, followed by an even larger increase in intensity at the reverse shock and a slow decay after the reverse shock had passed beyond the spacecraft. At the forward shocks, the intensity of particles increased by more than four orders of magnitude from near background levels [background: $10^{-4}$ $cm^{-2}$ $sr^{-1}$ $s^{-1}$ $(MeV/n)^{-1}$ for He]. This increase suggests that the particles were accelerated by the shocks, even those above solar wind energies. This result is supported by the observed acceleration of interstellar pickup ions to megaelectron volt energies (*11*) by an interplanetary shock. The flux increases at higher latitudes could no longer be correlated with the solar wind speed, which became quasi-constant above $-35°$. However, the particle beams returned every solar rotation until June 1994.

The particles show no energy dispersion and have, after correction for convection, an anisotropy directed inward. The rise time to the maximum of the observed accelerated beams did not change throughout the period of observation, including the period at lower latitudes when the shocks and accelerated particles were directly observed. The particles must have originated in a ongoing acceleration process [for example, by the recurrent CIR-related (*12*) poleward-propagating reverse shock] in the distant heliosphere that continuously injected particles of all energies into the inner heliosphere (*13, 14*). The particles seem to be guided by magnetic flux tubes from the shock, thus we do not think diffusion normal to the magnetic field is a major effect. Particles propagating toward the sun in flux tubes would be scattered and reflected somewhere in the increasing field. So in a flux tube, we expect a net inward flow in which all energies would be present at any time. The residual anisotropy (in a solar wind frame) would then be directed inward once Ulysses became immersed in such an environment, as observed.

The CIR-related shock is continuously generated at low latitudes; with each solar rotation, a portion of it rotates into the magnetic flux tubes that directly connect to

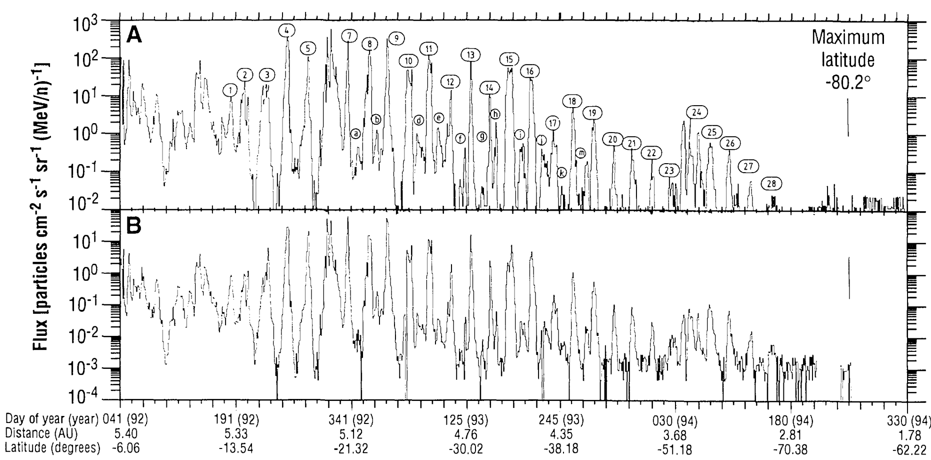


**Fig. 1.** Fluxes of (**A**) energetic protons and (**B**) helium between 0.5 and 1 MeV/n from day 41 of 1992 until day 330 of 1994, while Ulysses passed from $-6°$ through $-80.2°$ heliocentric latitude; the satellite's distance from the sun is also given. Peaks of CIR-associated accelerated particle beams are identified by numbers; interevents by letters.

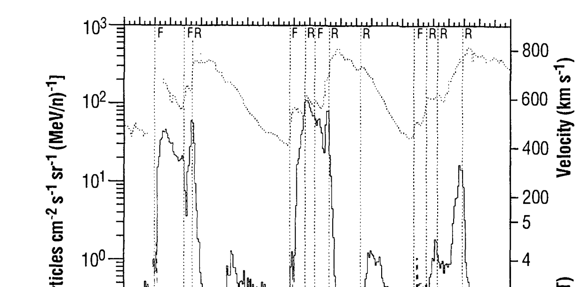


**Fig. 2.** Proton fluxes (solid line) together with solar wind velocity and magnetic field strength (dotted and dashed lines) during events 10, 11, and 12 (Fig. 1A). Interevents d and e are also shown. Forward and reverse shocks are designated by F and R, respectively.

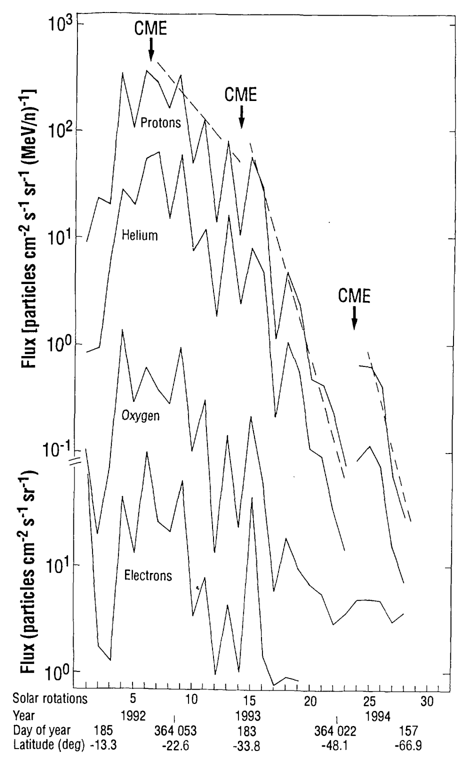


**Fig. 3.** Variations of observed peak intensities of protons (0.6 to 0.8 MeV), helium (0.4 to 0.8 MeV/n), oxygen (0.5 to 6.8 MeV/n), and electrons (0.1 to 3.38 MeV) during the high-latitude path of Ulysses. Bottom scale for electrons only.

Ulysses, so that the accelerated particles can reach the instrument. The interplanetary magnetic field at high latitudes appears to follow an approximated Archimedean spiral bound to a conical surface (*15*). The declining peak intensity of the accelerated particle beams (Fig. 3) could be tentatively attributed to the continuous weakening of that shock whenever it connects to Ulysses. An exponential decay of the peak fluxes would be quite natural. We also conclude that such a connection was no longer possible above about −65°, where the particle increases were no longer observed.

A modulation of the energetic particle streams that was probably associated with coronal mass ejections (CMEs) was observed during the high-latitude pass. The peaks of the accelerated energetic particles (~1 MeV/n) decreased in a systematic manner (Fig. 3) with a time constant of about 35 days. This decay was apparently interrupted when a new CME appeared, and subsequently, the intensity of the energetic particle streams lifted; however, it again decayed exponentially as before. All three cases observed were well correlated with major CMEs, which cause major disturbances in the inner heliosphere (*7*, *8*).

In many cases, a CME drives a shock ahead of it, which could accelerate charged particles, as suggested by the observations for November 1992, when the CME-driven shock arrived at Ulysses at nearly the same time as the CIR shock (*16*). It might even intensify the shocks associated with the CIR.

At a heliographic latitude of −30°, after day 120 of 1993, the rates in the ELH channels of each of the four telescopes rose continuously, and the signals were superimposed by a modulation with a period of about 26 days that was not seen in the ELL channel (Fig. 4). Before this date, the high-energy and low-energy electron channel rates showed similar variations caused by solar electrons. After that date, low-energy electrons were no longer observed. We exclude electrons as a cause of the higher rates (Fig. 4). The modulated ELH rates attributed to protons ($E > 230$ MeV) and the megaelectron volt ion fluxes were anticorrelated: Maxima in the ELH channels occurred during the minima in the ion channels and vice versa, except during the CMEs after days 170 and 335 of 1993 and day 54 of 1994. During the latter event, low-energy electrons were also present, so that the large peaks in Fig. 4 are believed to be caused by electrons. Otherwise, these events were of a different nature. We conclude that the increase and the 26-day variation of the ELH rates were caused by galactic cosmic rays and that the rise in Fig. 4 is a signature of the recovery of the solar modulation of the galactic flux, partly due to time variations and partly due to a latitudinal gradient [also observed by others (*17*)], whereas the three peaks mentioned above are due to electrons. The 26-day modulation (Fig. 5) is attributed to the presence of the CIR in near-ecliptic latitudes. The energetic particles accelerated in the CIR-related shocks appeared in the minima of the modulation. Apparently the CIR blocks the propagation of a fraction of the high-energy cosmic rays. Once the CIR has moved to the opposite side of the sun, the CIR appears under a somewhat smaller solid angle and the shadowing is correspondingly smaller, that is, the flux increases. However, there is still a significant and real variation in the amplitudes of the modulation (statistical error of the rates ~6%). There also seems to be a trend in these variations: After a CME, the amplitude was enhanced and then decayed until the next CME arrived. We suggest that two independent transient mechanisms are operating: one that causes the 26-day modulation and one that causes the decreasing modulation of the observed flux. We tentatively associate the 26-day modulation with the low-latitude CIR and associate the decreasing modulation depth with the CME, which might also affect the CIR.

To determine the relative composition of the particles, we separated the observations into three different types: (i) the accelerated periodic CIR-related beams (identified by

**Fig. 4.** Rates of (**top**) protons, ELH, and (**bottom**) ELL. Note linear scale for electrons. Peaks in protons coincide with minima in ELH. Electron events are off the scale.

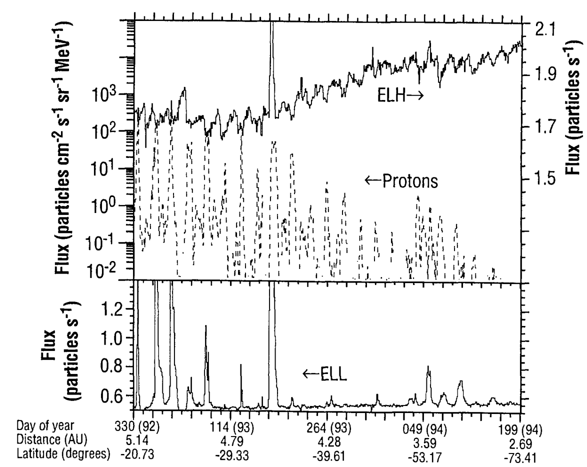


**Table 1.** Elemental abundances of ions relative to oxygen from measurements obtained during November 1992 and June 1994 and interevents. Numbers are sums of all measurements during CIRs, interevents, and quiet-time periods. Errors refer to the error of measurement and do not give the variations within the periods.

| Element | EPAC | | | Literature | |
|---|---|---|---|---|---|
| | CIRs† | Quiet times‡ | Interevents† | Solar minimum CIRs (*19*) | ACR (*20*) |
| p/He | 14 ± 2* | 85 ± 40* | 18 ± 2* | 17 ± 5 | |
| He | 162 ± 16* | 263 ± 26* | 240 ± 24* | 160 ± 50 | 0.95 |
| C | 0.8 ± 0.1 | 0.05 ± 0.02 | 0.47 ± 0.09 | 0.89 ± 0.10 | 0.004 |
| N | 0.12 ± 0.01 | 0.08 ± 0.02 | 0.14 ± 0.07 | 0.140 ± 0.10 | 0.125 |
| O | 1.0 ± 0.02 | 1.0 ± 0.1 | 1.0 ± 0.16 | 1.0 | 1.0 |
| Ne | 0.16 ± 0.01 | 0.10 ± 0.02 | 0.10 ± 0.03 | 0.20 ± 0.04 | 0.08 |
| Mg | 0.12 ± 0.01 | 0.02 ± 0.01 | 0.08 ± 0.03 | 0.13 ± 0.03 | |
| Si | 0.086 ± 0.008 | | 0.05 ± 0.02 | 0.08 ± 0.02 | |
| S | 0.033 ± 0.004 | | 0.03 ± 0.02 | 0.06 ± 0.01 | |
| Fe | 0.11 ± 0.01 | | 0.08 ± 0.03 | 0.10 ± 0.05 | |

*For protons and helium: 0.5 to 1 MeV/n. †Heavier ions: 0.6 to 2.5 MeV/n. ‡Heavier ions: 2.0 to 6.0 MeV/n.

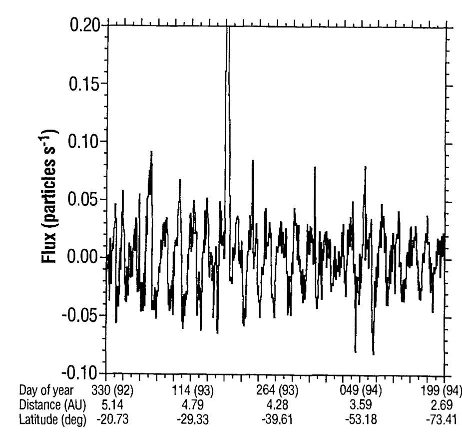


**Fig. 5.** Detrended plot of ELH rates for telescope 2. The apparent period is 26.6 days.

numbers in Fig. 1A), (ii) regularly observed small intensity increases between the beams, called interevents (*14, 18*) (letters in Fig. 1A), and (iii) the quiet periods between the two. We saw 11 interevents, the first following the large CME in November 1992. The composition in these events was consistent with particles of solar origin. However, in other events of clear solar origin, the convected anisotropy (by the fast solar wind) was evident (*2*). The particles in the interevents, in contrast, did not show such anisotropy, and no energy dispersion was observed. Therefore, interevents must have been convected past Ulysses, in corotating flux tubes, for example, within which equilibrium could have been established.

We used the $E$-($dE/dx$) matrix for the composition analysis. These data have been designed to provide a sample of fully analyzed particle events. Because of low count rates in the minima between the periodic events, these data contain all particles that entered the telescopes. Coincidences were checked [whether they lie on the expected $E$-($dE/dx$) ion tracks]. To eliminate periods where (typically larger) fluxes of particles were present, we set a threshold for the observed rates in a He-channel at 0.03 ions $cm^{-2}$ $sr^{-1}$ $s^{-1}$ $(MeV/n)^{-1}$. Rates were accumulated during periods when they fell below this threshold to obtain statistically significant information (Table 1). The relative abundances in the CIR-related events from November 1992 to June 1994 appear to be consistent with earlier observations in CIRs (*19*) (except for the much lower proton to helium ratio). The interevents are characterized by a low fraction of heavy ions. These events are also different from the composition of CMEs even though the C/O ratio was consistent with a CME relation. In the quiet periods, the fluxes were low but not zero. These periods were characterized by a low C/O ratio [but higher than known for the anomalous component of cosmic rays (ACR) (*20*)], which suggests the presence of the ACR probably together with particles of other origin, which is likely in view of the energy range (0.5 to 1 MeV/n) from which the data were taken (*14, 18, 21*). The C/O ratio in the energy range 2 to 6 MeV/n was 0.05 ± 0.02, and the N/O ratio was 0.08 ± 0.02, values that are similar to those observed for the ACR near Earth (*20, 22*). From the abundance ratio of C/O, we conclude that the quiet-time fluxes that underlie all observations are attributable to particles belonging to the ACR. This component seems to be present throughout the inner heliosphere at all latitudes. Because the latitudinal gradient of the ACR was negative during this cycle (*23*) and changed sign in each previous cycle, we assume that the ACR propagates mainly by drifts.

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# Dust Measurements at High Ecliptic Latitudes


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Along Ulysses' path from Jupiter to the south ecliptic pole, the onboard dust detector measured a dust impact rate that varied slowly from 0.2 to 0.5 impacts per day. The dominant component of the dust flux arrived from an ecliptic latitude and longitude of 10° ± 10° and 280° ± 30° which indicates an interstellar origin. An additional flux of small particles, which do not come from the interstellar direction and are unlikely to be zodiacal dust grains, appeared south of −45° latitude. One explanation is that these particles are beta-meteoroids accelerated away from the sun by radiation pressure and electromagnetic forces.


The objective of the Ulysses dust detector is to measure impact directions, velocities, and masses of dust in the solar system. Here we report on results from the orbital arc traversed between March 1992 and September 1994, covering latitudes from 0° to −79° and heliocentric ranges from 5.4 to 2.2 astronomical units (AU). For earlier results see (*1–3*). The Ulysses dust detector (*4*) is a multicoincidence, impact-ionization sensor with 1000 $cm^2$ of area sensitive to incoming submicrometer- to micrometer-sized dust particles (*5*). Measurements by a twin dust detector on the Galileo spacecraft (*6*) serve as an in-ecliptic base line for the dust measurements of Ulysses. The only previous dust measurements in the outer solar system were performed near the ecliptic by the Pioneer 10 and 11 spacecraft (*7*). The Pioneer results predict about five impacts with masses $>10^{-9}$ g for Ulysses during the 3 years that it spent outside 3 AU. During this time, Ulysses recorded three particles with masses larger than $10^{-9}$ g and seven which exceeded $10^{-10}$ g. These results are consistent with the Pioneer findings.

Between March 1992 and September 1994, Ulysses recorded the impacts of 826 dust particles. These particle impacts were


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