grains larger than the interstellar norm [see for example (18)]. Our numerical simulations also indicate that interstellar particles are not strongly deflected from the upstream direction.

We favor the third possibility: interplanetary particles originating in the inner zodiacal cloud. Submicrometer particles are a natural product of collisions between zodiacal dust particles, which are found from 3 AU inward to within a few radii of the sun. These submicrometer grains are electromagnetically dominated and depart the solar system along trajectories that, during the current phase of the solar cycle, reach high latitudes (19). Our numerical investigations indicate that even particles that started on circular zero-inclination orbits are capable of reaching the high latitudes traversed by Ulysses. Furthermore, it is difficult for these particles to reach Ulysses when the spacecraft is farther from the sun and at lower heliocentric latitudes; by the time they reach Ulysses' distance, particles originating in the zodiacal cloud have typically risen well out of the ecliptic plane.

One of the major goals of the Ulysses dust experiment is the investigation of the latitudinal distribution of dust particles in the zodiacal cloud. Until now, this goal has remained elusive because Ulysses' out-of-ecliptic path was first too far from the sun and then too far from the ecliptic to see strong indications of an interplanetary flux. From the data obtained during Ulysses' descent beneath the ecliptic plane, we have improved our understanding of the interstellar flux penetrating the solar system and identified a population of tiny particles at high latitudes. These results will assist us in characterizing the interplanetary population during Ulysses' rapid return to the ecliptic in March 1995.

REFERENCES AND NOTES

1. E. Grün *et al.*, *Geophys. Res. Lett.* **19**, 1311 (1992).
2. E. Grün *et al.*, *Science* **257**, 1550 (1992).
3. E. Grün *et al.*, *Nature* **362**, 428 (1993).
4. E. Grün *et al.*, *Astron. Astrophys.* **286**, 915 (1994).
5. M. Baguhl, E. Grün, D. Linkert, G. Linkert, N. Siddique, *Planet. Space Sci.* **41**, 1085 (1993).
6. M. Baguhl *et al.*, *Space Sci. Rev.* **72**, 471 (1994).
7. D. H. Humes, *J. Geophys. Res.* **85 (A11)**, 5841 (1980).
8. E. Grün *et al.*, *Planet. Space Sci.*, in press.
9. M. Witte, personal communication.
10. E. Grün *et al.*, *Astron. Astrophys. Suppl. Ser.* **92**, 411 (1992).
11. M. Witte, H. Rosenbauer, M. Banaszkiewicz, H. Fahr, *Adv. Space Res.* **13**, (no. 6) 1 (1993).
12. P. Bertin, R. Lallement, R. Ferlet, A. Vidal-Madjar, *J. Geophys. Res.* **98 (A9)**, 15193 (1993).
13. P. C. Frisch, *Science* **265**, 1423 (1994).
14. J. Geiss, G. Gloeckler, U. Mall, *Astron. Astrophys.* **182**, 924 (1994).
15. J. A. M. McDonnell and O. E. Berg, *Space Research* (Academie Verlag, Berlin, 1975), vol. 15, pp. 555–563.
16. E. Igenbergs *et al.*, in *Proceedings of Origin and Evolution of Interplanetary Dust*, A. C. Levasseur-Regourd and H. Hasegawa, Eds. (Kluwer, Dordrecht, 1990), p. 15.
17. H. Svedham, personal communication.
18. J. M. Greenberg, in *Cosmic Dust*, J. A. M. McDonnell, Ed. (Wiley, Chichester, United Kingdom, 1978), p. 187.
19. G. E. Morfill, E. Grün, C. Leinert, in *The Sun and the Heliosphere in Three Dimensions*, R. G. Marsden, Ed. (Kluwer, Dordrecht, 1986), p. 455.

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Cosmic Ray and Solar Particle Investigations Over the South Polar Regions of the Sun

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Observations of galactic cosmic radiation and anomalous component nuclei with charged particle sensors on the Ulysses spacecraft showed that heliospheric magnetic field structure over the south solar pole does not permit substantially more direct access to the local interstellar cosmic ray spectrum than is possible in the equatorial zone. Fluxes of galactic cosmic rays and the anomalous component increased as a result of latitude gradients by less than 50% from the equator to −80°. Thus, the modulated cosmic ray nucleon, electron, and anomalous component fluxes are nearly spherically symmetric in the inner solar system. The cosmic rays and the anomalous nuclear component underwent a continuous, ~26 day recurrent modulation to −80.2°, whereas all recurring magnetic field compressions and recurring streams in the solar wind disappeared above ~55°S latitude.

The heliosphere is the region of space in the local galactic arm that encompasses the solar system and is dominated by plasmas and magnetic fields originating at the sun. Within the heliosphere, solar magnetic fields from the corona are frozen into the solar wind plasma and carried outward at supersonic velocities to an as yet undiscovered shock transition, probably at a radius of ~100 astronomical units (AU) from the sun. There, as a result of the confining pressure of the local interstellar magnetic field and plasma, the solar wind is slowed to subsonic velocities and, ultimately, is swept away by the flow of the interstellar medium around the heliosphere. Before the Ulysses mission, in situ observations of the solar wind, magnetic fields, and energetic charged particles most relevant to investigations of heliospheric structure have been restricted to regions of the heliosphere less than about ~35° from the ecliptic plane. Ulysses has now provided data from near the heliospheric equator at 5.4 AU in February 1992 to ~80°S latitude (−80°) in September 1994 at 2.2 AU (1).

To carry out the measurements of energetic charged particles over the large energy range from below 10^6 electron volts (1 MeV) to more than 10^9 eV (1 GeV), and to identify and study the electrons and various nuclear species in the particle population, the international cosmic ray and solar particle investigations (COSPIN) consortium (Table 1) provided five sensor systems on the Ulysses spacecraft (2). Here, we report measurements from these sensors to the maximum latitude attained by Ulysses (−80°) and from the northward return to −45° by the end of December 1994 and correlations of results with solar wind (3) and magnetic field (4) measurements.

The outward sweeping action of the solar wind with its embedded magnetic field strongly reduces or modulates the intensity of low-energy cosmic rays observed near the ecliptic in the heliosphere compared to the

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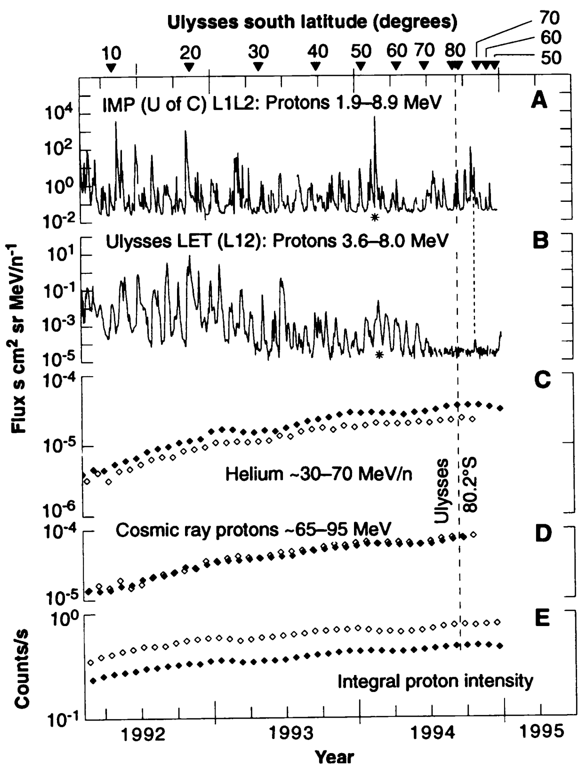
intensity believed to exist in the local interstellar medium. Even though the Pioneer 10 spacecraft is currently beyond 60 AU near the equatorial plane, the low-energy galactic cosmic ray spectrum observed there remains strongly suppressed because of the modulating effects of the still more distant heliospheric magnetic fields beyond Pioneer 10 out to the heliospheric boundary. Whereas the magnetic field lines near the ecliptic are wound into a tight spiral by the sun's rotation, the field over the poles should be far less tightly wound. Thus it might be expected that the magnetic field structure over the poles of the solar system would permit Ulysses' sensors to have a more direct access to the interstellar cosmic ray spectrum. For the solar magnetic dipole polarity prevailing during Ulysses' climb toward the south solar pole in 1994, modulation models that include gradient drifts predicted that positively charged cosmic ray nuclei would preferentially drift inward and downward from the heliospheric poles toward the equatorial zone (5). The nuclei then drift outward along a wavy and inclined current sheet that extends from the coronal streamer belt and divides positive from negative magnetic polarities in the heliosphere. Negatively charged electrons, on the other hand, were predicted to drift inward along the current sheet and then upward toward the poles. Thus intensities of nuclei were predicted to increase and intensities of electrons to decrease as Ulysses traveled toward the poles.

From 1992 to 1994, solar activity rapidly decreased, and as a result, the observed cosmic ray intensity increased globally. At lower energies, <10 MeV, the low level of solar activity led to less frequent and less intense injections into the heliosphere of solar energetic particles, which are accelerated by solar flares associated with coronal mass ejections (CMEs). To separate these temporal variations from spatial changes as Ulysses changed latitude and moved from 5.2 to 2.2 AU we used as a baseline reference measurements from two University of Chicago charged particle telescopes on IMP-8 (6) in Earth orbit, as well as from the Climax neutron intensity monitor for the highest energy nuclei.

Fluxes of low-energy (≲10-MeV) protons (Fig. 1, A and B) increased quasi-periodically about every 26 days. Near the ecliptic these variations are produced by solar wind magnetic field structures that corotate with the sun, known as corotating interaction regions (CIRs). The charged particles are accelerated in the forward and reverse shocks associated with the CIRs (7). Although the variations observed at IMP-8 continued throughout the period reported here, at Ulysses they disappeared for latitudes above about −70° (8). Ulysses observed no shocks in the solar wind after April 1994, when the spacecraft was at a latitude of −60° (3). Thus, the recurrent enhancements of low-energy particles persisted to higher latitudes than the shocks by which the particles are presumably accelerated, but were absent over the pole.

In addition to particles accelerated in CIRs, low-energy particles may also be produced in association with solar flares (or their associated shocks) and CMEs in the solar wind. Two interesting examples of such events were observed by Ulysses at high latitude. The first, on about day 300, 1994, at −73° (vertical line in Fig. 1B), was apparently associated with a large increase in in-



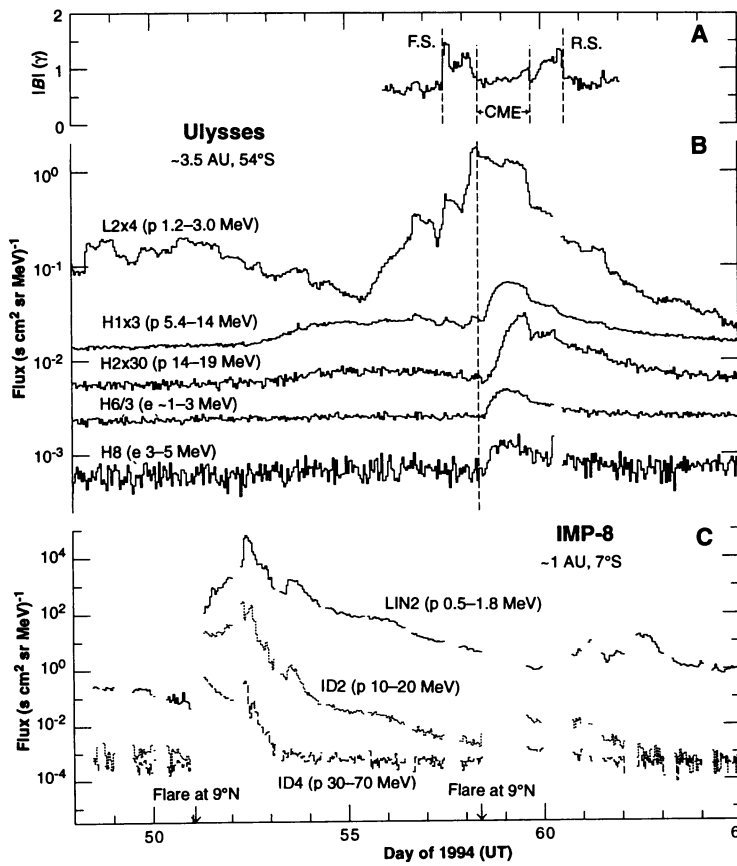


Fig. 1 (left). Daily average fluxes of **(A)** low-energy protons measured on IMP-8 and **(B)** low-energy protons measured by the COSPIN LET on Ulysses. **(C)** Twenty-seven-day average quiet time selected fluxes of ~30–70 MeV/n He nuclei (including contributions from the anomalous helium component) measured by IMP-8 (open symbols) and the COSPIN HET (solid symbols). **(D)** Same as (C) for ~65- to 95-MeV protons. **(E)** Twenty-seven-day average counting rates for the integral intensities of protons ≳100 MeV as measured by the COSPIN KET (solid symbols) and IMP-8 (open symbols). The offset between the curves reflects the differing geometrical factors, the slightly different energy thresholds, and, possibly, the different efficiencies for the two instruments. Maximum south solar latitude −80.2° is marked by a vertical dashed line through all panels. Asterisks and a short dashed line in panels (A) and (B) indicate the times of the solar flare–CME events discussed in the text. **Fig. 2 (right).** The solar flare–CME event of February 1994 as observed in the ecliptic plane by the Ulysses' LET (L) and HET (H) instruments **(B)** and IMP-8 **(C)**; p, protons; e, electrons. The locations of the forward (F) and reverse (R) shock pair associated with the CME and the magnetic field strength **(A)** are from (9).

tensity in the IMP-8 low-energy telescope (LET) several days earlier (one of the largest increases observed in 1994). The solar event that produced the particles was not identified, but if these enhanced fluxes have a common source, it would imply that particles from a single event have access to a large range in latitude.

The second event (* in Fig. 1, A and B) was a consequence of a solar particle event and a CME observed at a radius of ~3.5 AU and latitude −54° at a time when IMP-8 was within ~10° in longitude from Ulysses relative to the sun. A solar flare occurred at 9°N on 20 February 1994 (day 52), and protons accelerated to energies >70 MeV were observed at IMP-8 (Fig. 2C). The flux of >10 MeV protons at IMP-8 increased by more than a factor of 10^5. The intensity increase at Ulysses, beginning later on day 52 for protons from 5 to 14 MeV was initially much smaller, and although evidence is not conclusive, some channels displayed an energy-dependent dispersion in particle arrival times, consistent with propagation of the accelerated particles from the sun to Ulysses. Several days after the event, a CME, probably associated with this same solar event, was observed at Ulysses (9). This CME (Fig. 2) was enclosed within a forward (F)-reverse (R) shock pair that provided a defining example of a new class of CMEs in the heliosphere (9). Entry into the CME was associated with a further intensity enhancement of nucleons and electrons at Ulysses. No clear dispersion as a function of particle energy was observed in the onset times during the CME. This result suggests entry of Ulysses into a region of enhanced flux, rather than, as in the initial onset, propagation of particles to Ulysses from a distant acceleration site. It is not clear whether the particles observed were accelerated in the flare on 20 February that generated the CME, or were more recently produced. Possible sources include the large solar event at about 0900 on day 58 off the west limb of the sun marked by an x-ray burst and a radio event (whose location suggests an origin in the same active region at 9°N that produced the 20 February event) or, less likely, smaller east limb events recorded early on day 58 (*10*). While this event is complex and requires further study (*10*), our interpretation is that many of the nuclei and electrons accelerated in this event were contained by and carried across ~63° of solar latitude by the CME.

For higher energy particles (Fig. 1, C, D, and E), the most important change in fluxes was a result of the changing level of solar modulation. However, the changes in the modulated intensities were nearly identical at IMP-8 and Ulysses. Differences between Ulysses and IMP-8 would be expected as a result of both radial gradients and latitude gradients in the fluxes. The apparent small size of the latitude effects, coupled with the large temporal changes in the total flux level during Ulysses' climb from the ecliptic to high latitude makes accurate measurement of these effects difficult.

To discover whether there was a significant latitude effect we assumed that the flux is a separable function of radius and latitude and then subtracted the radial effect. While this assumption may not be completely valid, it offers a simple way of estimating the effects of latitude as Ulysses climbed toward the south pole while traveling inward from ~5.4 to 2.2 AU. Ideally it would have been possible to measure the radial gradient during Ulysses' outward in-ecliptic trip to Jupiter. However the high level of solar activity and extremely rapid trajectory during that period resulted in there being too few periods free of solar energetic particles to make an accurate measurement.

An alternative approach to determining the radial gradient is justified by observations in Fig. 3A, which contains measurements made after Jupiter flyby of the apparent radial gradient (*11*) for ~30 to 70 MeV per nucleon (MeV/n) helium versus heliographic latitude. While Ulysses was rising from −10° to −20°, a period of about 6 months, the radius decreased by less than 0.2 AU. During this period (bar in Fig. 3A) there was also almost no change in the apparent radial gradient. We found this to be the case as well for all other particle species for which we have attempted to determine a latitude gradient. Thus we take as our measure of the radial gradient the average apparent gradient determined for latitudes between −10° and −20° after the Jupiter flyby. Using this value for the radial gradient and the simultaneously observed flux at IMP-8, we computed the flux that would be expected for a spacecraft at the radius of Ulysses and compared it to the measured flux at Ulysses. The ratio of the observed flux to the expected flux measures the added flux at Ulysses resulting from latitude effects, a quantity we have called the latitude excess (Fig. 3, B to D).

Up to ~−30° latitude, which corresponds to the region swept by the heliospheric current sheet at that time, there was no clear flux increase with latitude for any species. Above latitudes of ~−30°, for all

Table 1. Cosmic Ray and Solar Particle Investigations (COSPIN) sensor systems (*2*). *Z*, atomic number; *n*, nucleon; *E*, energy; MeV, million electron volts.

Instrumentation	Responses
High-energy telescope (HET) University of Chicago	Nuclei, Z = 1–28 $30 \leq E \leq 500$ MeV/n Electrons ~1–10 MeV
High-flux telescope (HFT) Herzberg Inst. of Astrophys., Canada	Protons, $0.3 \leq E \leq 10$ MeV He, CNO, Fe groups
Low-energy telescope (LET) Space Science Department, ESA	Protons and He $0.9 \leq E \leq 20$ MeV/n $1 \leq Z \leq 20$
Kiel electron telescope (KET) University of Kiel and Centre d'Etudes Nucléaires de Saclay	Electrons $2 \leq E \leq 6000$ MeV Protons and He $3 \leq E \leq 2100$ MeV/n
Anisotropy telescopes (ATs) Blackett Laboratory, Imperial College	Protons and He $1 < E < 7$ MeV

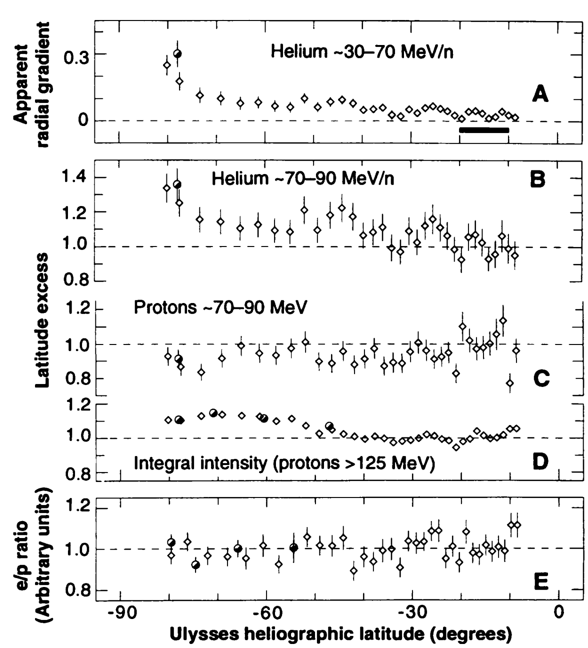


Fig. 3. (**A**) Apparent radial gradients as a function of Ulysses latitude based on 27-day average Ulysses HET/IMP-8 flux ratios for ~30 to 70 MeV/n helium nuclei. Bar indicates the period used to determine the average radial gradient (0.03 AU^{-1} in this case) for use in calculating the latitude excess (see text). (**B**) Latitude excess (see text) for 70 to 90 MeV/n helium nuclei measured by the HET with G_r = 0.03 AU^{-1}, determined as in (A). (**C**) Latitude excess for ~70- to 90-MeV protons measured by the HET with G_r = −0.03 AU^{-1}, determined as in (A). (**D**) Latitude excess for protons >125 MeV measured by the KET with G_r = 0.03 AU^{-1}, determined as in (A). (**E**) Ratio of the flux of ~2-GV magnetic rigidity electrons (and positrons) to the flux of protons of the same rigidity versus latitude.

species except protons ~70 to 90 MeV (and ~30 to 70 MeV, not shown) there was a modest increase in flux toward high latitudes, leading to a positive latitude excess (*12*). This is consistent with reports from Voyager (*13*) in the previous solar minimum, where the negative latitude gradients, appropriate for the solar magnetic polarity at that time, were observed clearly only while the maximum current sheet latitude was less than Voyager's latitude.

The above analysis depends upon continuous comparison between Ulysses measurements and equivalent simultaneous measurements from IMP-8. For electrons measured by the COSPIN Kiel electron telescope (KET), there are no equivalent in-ecliptic measurements available. However, because current models predict that, under the assumption that the bulk of the electron flux is composed of negative electrons, the latitude variation of the electron flux should be opposite to that of protons; that is, decreasing toward high latitudes, a decrease in the electron to proton flux ratio at the same magnetic rigidity would be expected as Ulysses climbs in latitude. However, no variations in the electron to proton ratio at a rigidity of ~2 GV are apparent (Fig. 3E).

In summary, the increase in flux toward the poles was modest for most nuclei, much smaller than had been hoped based upon ideas of magnetic field lines open to the interstellar medium that were current prior to the launch of Ulysses (*2*). More recent predictions (*14*), taking into account drifts and the possibility of reduced diffusion coefficients over the poles, produced predictions that, where direct comparison is possible, agree reasonably well with the magnitude of the increases we observed. However, there is no obvious explanation for the lack of a latitude variation for protons at energies less than ~90 MeV. The lack of variation of the electron-to-proton ratio with latitude appears to be in clear contradiction to the predictions of models which include a significant role for gradient and curvature drifts (*5*). Because the modulation over the south pole in the inner heliosphere is comparable in magnitude (within about 50% of equatorial) to the extensively studied modulation at low latitudes, we conclude that the three-dimensional distribution of the modulated galactic cosmic ray flux is nearly spherically symmetric in the inner solar system.

Consistent with this conclusion, the modulated spectrum for cosmic ray protons over the south polar region showed an approximately E^{+1}-type spectrum below 100 MeV (Fig. 4A)—namely, the spectrum that results from a near balance between outward convection by the solar wind and intensive adiabatic deceleration (cooling) of the protons from interstellar space in the irregular and expanding heliospheric magnetic fields. This is the same spectral form observed by IMP-8 in equatorial zones of the inner heliosphere.

The helium spectrum measured in the south polar region (Fig. 4B) shows a maximum flux at approximately 20 MeV/n, which can be understood as the result of a significant contribution from the anomalous helium component, believed to consist of singly ionized helium ions accelerated at the solar wind termination shock. Although there remains a systematic difference in the flux computation between IMP-8 and Ulysses (Fig. 1C), the spectral maximum at IMP-8 was significantly higher in energy than for Ulysses near −80° latitude (Fig. 4). From comparison of the spectra it would appear that the latitude excess of ~11 to 20 MeV/n anomalous helium must be comparable to that for the higher energy helium. This surprisingly small latitude effect (*15*) was not expected from experiments at lower latitudes (*16*) or from models (*17*) where the anomalous helium is accelerated at

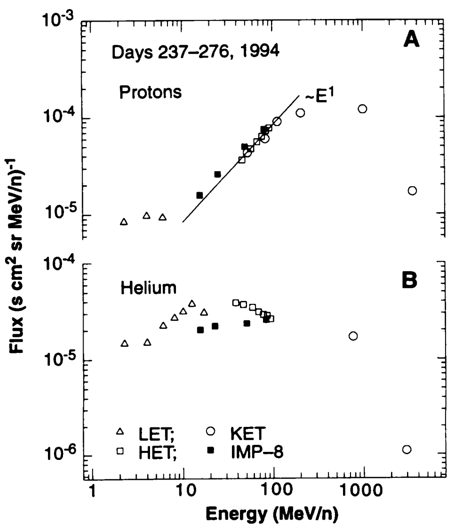


Fig. 4. (**A**) The proton differential energy spectra near −80° (LET, HET, KET) and in the ecliptic (IMP-8). The solid line represents the slope of heavily modulated cosmic rays at the equator (∝ E^{+1}). (**B**) Helium differential energy spectra. Anomalous component helium dominates the spectra near −80° latitude with a flux maximum at ~20 MeV/n.

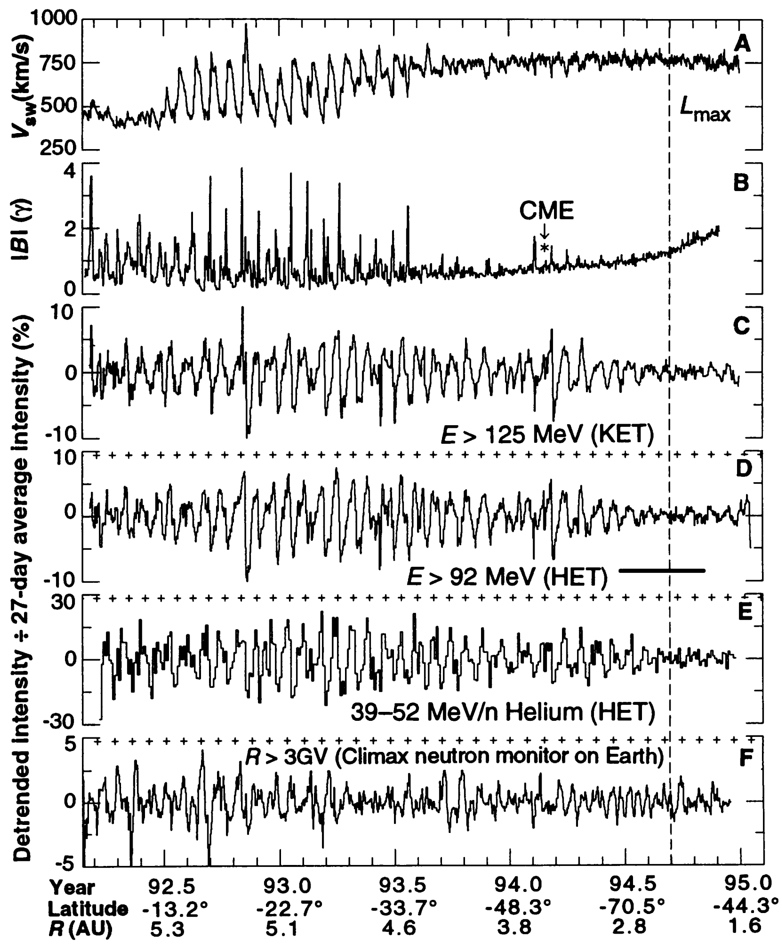


Fig. 5. (**A**) 6-hour averages of solar wind speed from (*3*). (**B**) Daily averages of magnetic field |B| from (*4*). (**C** and **D**) Daily average intensity after detrending to remove the long-term increase in cosmic ray intensity for the integral intensity of cosmic rays as measured by the KET (see also Fig. 2E) and the HET. (**E**) Three-day average detrended helium flux measured by the HET, consisting of a mixture of cosmic ray and anomalous helium. (**F**) Daily average detrended Climax, Colorado, neutron monitor intensity variations from primary protons with energy >3 × 10⁹ eV.

the termination shock near the pole and, for the current solar magnetic polarity, diffuses and drifts downward toward the heliospheric equator.

The low fluxes at the poles imply that, although the relative importance of the various processes that produce the solar modulation of cosmic rays in the heliosphere may be different at high latitudes than near the equator, their summed effect is nearly the same at all latitudes in the inner heliosphere. A significant part of the high-latitude modulation can probably be ascribed to the polar magnetic field irregularities that have been observed (*4*, *18*) with the Ulysses helium vector magnetometer. Continuously present waves were found to be propagating outward from the sun. They have the characteristics of Alfvenic fluctuations and may significantly reduce the diffusion coefficient for cosmic rays on the polar field lines. These waves and the long period (10-hour) waves also observed (*4*) may correspond to the transverse irregularities proposed (*19*) as a possible cause of increased polar modulation.

The ~26-day recurrent modulation of cosmic ray and anomalous nuclear component intensities by CIRs is clearly present in the Ulysses plasma, magnetic field, and charged particle measurements up to ~−35° (Fig. 5). However, CIR compressions in the recurrent magnetic field and enhancements of the recurrent solar wind velocity gradually disappear with increasing latitude above ~−40°, whereas the cosmic ray intensity continued to undergo recurrent modulation all the way to −80° latitude.

The sun is known to exhibit differential rotation as a function of latitude, with the rotation period ranging from ~26 days at the equator to ~36 days at the poles (*20*). Although the recurrent modulation at low latitudes corresponded to the near-equatorial solar rotation of 26 to 28 days, our autocorrelation analysis of the >92 MeV proton counting rate (Fig. 6)—in the polar regions where no CIRs were observed—also showed the same equatorial recurrence period.

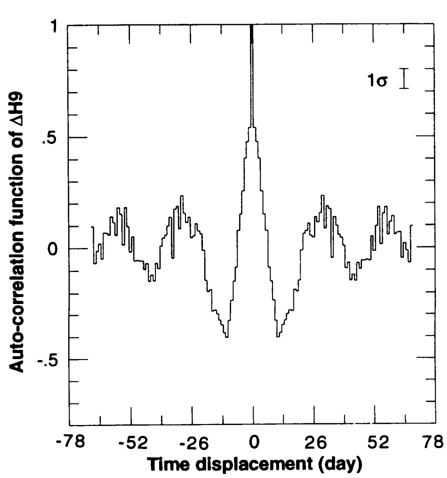


Fig. 6. Determination of the average recurrence period of cosmic ray >92 MeV per proton intensity modulation near −80° latitude (bar interval in Fig. 5D), representing days 178 to 310, 1994, and latitudes from −70° to −80° and back to −70°.

Neither the tilted heliospheric current sheet nor the solar magnetic field variations correlate with these observations. The magnetic field intensity was remarkably constant in azimuthal intensity over the south polar pass (*4*, *18*). None of the magnetic field components displayed variation that could be attributed to an inclined dipole field component (*21*), which, if combined with the cosmic ray latitude gradient (~1% per degree) could produce recurrent intensity variations at Ulysses.

The detrended recurrent modulation of the high-energy telescope (HET) proton flux (Fig. 5D) displays an occasional second, but smaller, recurrent modulation sequence displaced in time from the main recurrent sequence by approximately 15 and 11 days. This spacing is the same as between the two CIRs observed simultaneously at 1 AU by IMP-8 (*22*). During the Ulysses mission these dual CIR sequences were also observed at low and intermediate latitudes in magnetic fields (*23*) and by their acceleration of low-energy charged particles (for example, *24*). Thus, it is becoming clear that the two spatially separated CIRs, probably through their expansion in latitude in the more distant heliosphere, modulated the cosmic ray and anomalous nuclear component observed in the high-latitude inner heliosphere by Ulysses. It is not obvious to what extent rapid cross-field diffusion may contribute or how magneto-hydrodynamic processes (*25*) or latitudinal motion of the heliospheric current sheet (*26*) may connect the low-latitude CIR phenomena with the new, south polar latitude discoveries.

This recurrent modulation of the cosmic radiation has been shown (*27*) to extend to neutron monitor energies on Earth, affecting particles with energies in excess of $\sim 3 \times 10^9$ eV (Fig. 5F) and even 13×10^9 eV (from the University of Chicago neutron monitor on Haleakala, Maui). Since these variations have the same phase as the lower energy Ulysses observations, it is clear that the heliospheric recurrent modulation mechanism must be a global, large-scale phenomenon extending from the inner heliosphere to well beyond Ulysses to account for the lower energy modulation observed in the south polar region.

These discoveries by the COSPIN collaboration will be tested during the rapid scan of latitude now being performed by Ulysses, and during the period when it is in the north solar polar region in June through September 1995. The modulation level at that time should be even lower than during the Ulysses south polar pass as a result of the still declining level of solar activity with the same solar magnetic field polarity.

REFERENCES AND NOTES

1. E. J. Smith, R. G. Marsden, D. E. Page, *Science* **268**, 1005 (1995).
2. J. A. Simpson *et al.*, *Astron. Astrophys. Suppl. Ser.* **92**, 365 (1992).
3. J. Phillips *et al.*, *Science* **268**, 1030 (1995).
4. A. Balogh and E. J. Smith, personal communication; A. Balogh *et al.*, *Science* **268**, 1007 (1995).
5. J. R. Jokipii *et al.*, *Astrophys. J.* **213**, 861 (1977).
6. M. Garcia-Munoz, G. M. Mason, J. A. Simpson, *Astrophys. J. (Lett.)* **201**, L145 (1975).
7. J. A. Simpson, E. J. Smith, B. T. Tsurutani, in *The Sun and the Heliosphere in Three Dimensions*, R. Marsden, Ed. (Reidel, Dordrecht, Netherlands, 1986), pp. 319 and references therein.
8. T. R. Sanderson *et al.*, *Space Sci. Rev.* **72**, 291 (1995); T. R. Sanderson *et al.*, in preparation.
9. J. T. Gosling *et al.*, *Geophys. Res. Lett.* **21**, 2271 (1994).
10. V. Bothmer *et al.*, in preparation; M. Pick *et al.*, in preparation.
11. We define the apparent radial gradient as the logarithm of the Ulysses/IMP flux ratio (corrected for normalization errors determined by comparison of Ulysses to IMP soon after Ulysses launch) divided by the radial distance between them. Absolute relative normalization of the flux measurements from IMP and Ulysses was determined in the period after launch while Ulysses was still close to 1 AU.
12. For the low-energy protons, essentially no latitude effect was found, and, using the same analysis as for other species, a slightly negative radial gradient was found. This is opposite to the expected positive radial gradient, and may be an effect of contamination of the measured fluxes by solar energetic particles early in the mission when Ulysses and IMP were close together and the relative normalizations of the IMP and Ulysses instruments were determined.
13. S. P. Christon *et al.*, *Geophys. Res. Lett.* **13**, 777 (1986); A. C. Cummings *et al.*, *ibid.* **14**, (1987).
14. M. S. Potgieter and L. J. Haasbroek, *Proc. 23rd Int. Cosmic Ray Conf.*, Calgary, **3**, 457 (1993).
15. K. J. Trattner *et al.*, in preparation.
16. R. B. McKibben, *J. Geophys. Res.* **94**, 17021 (1989); ______, K. R. Pyle, J. A. Simpson, *Astrophys. J. (Lett.)* **227**, L147 (1979).
17. M. E. Pesses, J. R. Jokipii, D. Eichler, *Astrophys. J.* **246**, L85 (1981).
18. E. J. Smith *et al.*, *Space Sci. Rev.* **72**, 165 (1995).
19. J. R. Jokipii and J. Kóta, *Geophys. Res. Lett.* **16**, 1 (1989).
20. R. Howard and J. Harvey, *Solar Phys.* **12**, 23 (1970).
21. E. J. Smith, personal communication.
22. J. A. Simpson and M. Zhang, unpublished data.
23. E. J. Smith *et al.*, *Geophys. Res. Lett.* **20**, 2327 (1993).
24. G. M. Simnett *et al.*, *Space Sci. Rev.* **72**, 327 (1995).
25. V. Pizzo, *J. Geophys. Res.* **99**, 4185 (1994).
26. J. R. Jokipii and J. Kóta, *Space Sci. Rev.* **72**, 379 (1995).
27. R. B. McKibben *et al.*, *ibid.*, p. 403.

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