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Observations of galactic cosmic rays and the anomalous helium during Ulysses passage from the south to the north solar pole*

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Abstract. We compare observations of the modulated intensities and spectra of galactic cosmic ray nuclei and anomalous helium above 30 MeV/n measured by the COsmic and Solar Particle INvestigations (COSPIN) High Energy Telescope (HET) on Ulysses with similar observations from the IMP-8 earth-orbiting satellite between September 1994 and August 1995. During this interval Ulysses made a rapid scan of solar latitude from 80.22°S latitude to 80.22°N latitude at radial distances between 2.2 and 1.3 AU in a period of slowly decreasing solar modulation. The observations confirm our previous conclusions from measurements in the southern hemisphere that solar modulation is remarkably spherically symmetric in the inner heliosphere. Flux increased towards the poles by less than a factor of two for all species measured with no significant changes in the spectra of galactic cosmic ray nuclei and anomalous components. Fluxes over the north pole were in general slightly higher (∼10-20%) than fluxes over the south pole. As reported by Simpson et al. (1996), the modulation was symmetrical about a surface at latitude 10°S. At the boundaries of the equatorial zone defined by low speed solar wind the solar wind speed increased by a factor of two within 5 degrees of latitude with no effect on the modulated cosmic ray and anomalous component spectra. This suggests that typical cosmic ray trajectories are not tightly confined in heliographic latitude and freely cross the boundary between the polar and equatorial zones during the modulation process. At the highest latitudes (>∼50° from the symmetry surface at ∼10°S) latitudinal gradients in the cosmic ray intensity were significantly smaller than at lower latitudes.

Key words: interplanetary medium – solar wind – cosmic rays

1. Introduction

As part of its mission to investigate the 3-dimensional structure of the heliosphere, a principal objective of the Ulysses mission is to study the variation of the modulated intensities of galactic cosmic rays and the anomalous nuclear components as a function of heliographic latitude. Since the solar modulation of cosmic rays is determined by the paths of the cosmic ray particles through all of the interplanetary magnetic field structures that lie between the observer and the boundary of the heliosphere, such studies provide information about the magnetic structure of the heliosphere and the connection of heliospheric magnetic field lines with the interstellar magnetic fields far beyond the reach of direct measurements. Prior to Ulysses' ascent to high latitudes, models based on the standard Parker spiral configuration of the interplanetary magnetic fields suggested that a large increase in the cosmic ray flux in the inner heliosphere might be observed at high solar latitudes (e.g. Potgieter and Haasbroek 1993) as a result of the looser winding of the interplanetary spiral field over the poles. On the other hand, theoretical models of the growth of transverse irregularities in the polar fields (Jokipii and Kóta 1989) during outward convection of the field by the solar wind suggested that modulation might be nearly as strong over the poles as near the equatorial zone of the heliosphere, where all previous measurements had been made. In this study we examine the spectra and fluxes of galactic cosmic rays, which should be uniformly distributed over the heliospheric boundary, and of the anomalous helium component, which may be accelerated preferentially at certain regions of the termination shock. For the present polarity of the solar dipole (positive fields in the northern hemisphere) Pesses et al. (1981) have suggested that the singly charged anomalous nuclear component should be accelerated primarily near the polar regions of the termination shock, so that the flux observed at Ulysses may reflect both the effects of a latitudinal dependence of the modulation and the non-uniform nature of the the source.

For this investigation we use simultaneous measurements from the Ulysses COsmic and Solar Particle Investigations (COSPIN) High Energy Telescope (HET), described by Simpson et al., 1992, and from the University of Chicago Cosmic Ray Experiment on the earth satellite IMP-8, described by Garcia-Munoz et al. (1975). Study of these questions is one of the

* The Ulysses cosmic ray data on which this analysis is based are available on the World-Wide Web at file://odysseus.uchicago.edu/WWW/Simpson/Ulysses.html.

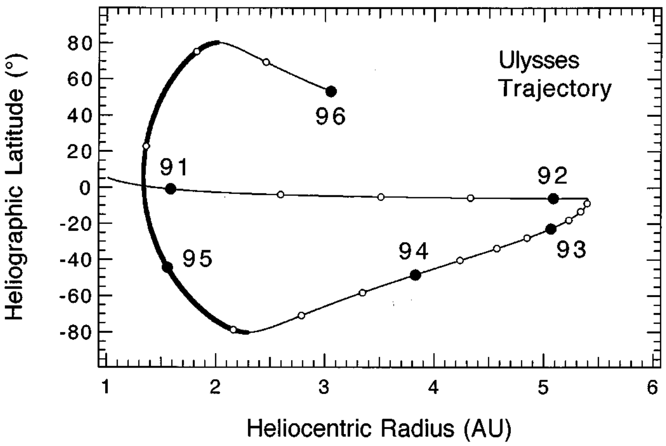

Fig. 1. Trajectory of Ulysses from launch in October 1990 through the end of 1995. Large dots mark the start of each year, and small circles indicate three month intervals. The period of the fast latitude scan is indicated by the heavy line

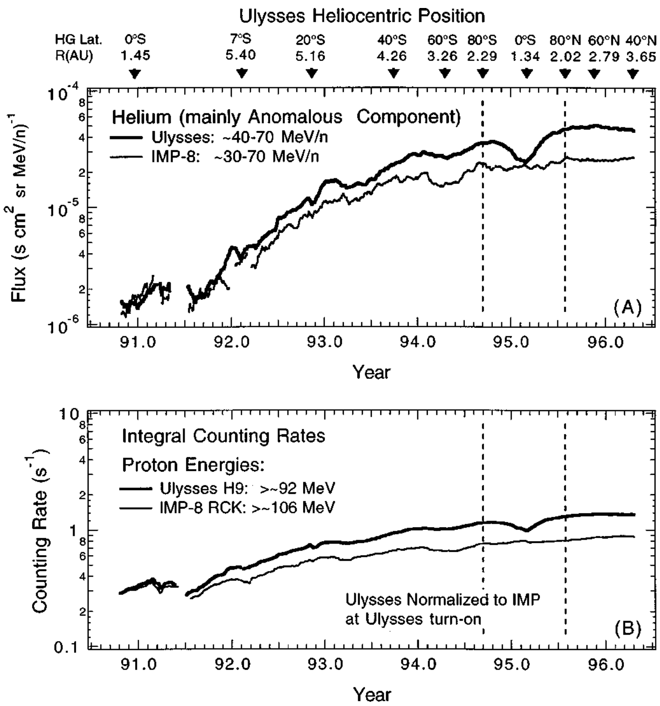

Fig. 2a and b. Ulysses and IMP-8 observations for low energy anomalous helium (**a**) and the integral flux of protons above $\sim$100 MeV (**b**) from launch through 1995, illustrating the large changes in modulation over the course of the Ulysses mission, and the relative stability of modulation during the period of Ulysses' fast latitude scan in 1994-95. The observations are shown as 27 day running averages of quiet-time-selected measurements

objectives for which the HET was proposed for the Ulysses mission (Simpson et al. 1992).

We have previously reported on the variations in the modulated intensities of galactic cosmic rays and anomalous helium above about 30 MeV/n observed during Ulysses' initial climb from the equatorial zone to maximum southern latitude (Simpson et al. 1995a) and during the transition from the south solar polar regions of the heliosphere back to the equatorial zone (Simpson et al. 1995b). Similar reports, based on the Kiel Electron Telescope (KET) portion of the COSPIN experiment have been given by Kunow et al. (1995a) and by Heber et al. (1995a,b,c). The variation of lower-energy anomalous component fluxes, based on measurements with the COSPIN Low Energy Telescope, has been reported by Trattner et al. (1995). The conclusion of all of these reports has been that the modulated intensities of both cosmic rays and anomalous components display a remarkable near-spherical symmetry in the inner heliosphere, with increases of intensity towards the poles of less than a factor of two between the equator and 80° south heliographic latitude.

Ulysses reached its highest south heliographic latitude of 80.2° at a radius of 2.3 AU in mid-September, 1994. Less than a year later, in July-August, 1995 Ulysses reached 80.2° north heliographic latitude at a heliocentric radius of 2.0 AU, thus completing the first scan of solar latitude from the south polar regions of the sun to the north. This period, shown as the heavy portion of the Ulysses trajectory in Fig. 1, has become known as the fast latitude scan to distinguish it from the very much slower climb to high southern latitudes after Jupiter flyby in February of 1992. Conditions during the fast latitude scan were ideal for determining the latitudinal variations in the modulation. As shown in Fig. 2, measurements from the IMP-8 satellite in orbit about the earth showed that there was little change in the 11-year solar cycle modulation in the inner heliosphere during this period. On the other hand, as shown also in Fig. 2, during the initial long climb to high latitude after Jupiter flyby the modulation decreased dramatically as solar activity declined after its maximum in 1990, so that confusion of time-dependent effects with latitude-dependent effects was a constant problem for this earlier analysis.

In this report we extend the analysis reported by Simpson et al. (1995a,b) to include observations from the HET through the end of 1995, including the time of Ulysses' highest northern latitude of 80.2° and the beginning of its descent from the polar regions back to a crossing of the heliographic equatorial plane near the orbit of Jupiter in late 1997 (cf. Fig. 1). Heber et al. (1996a,b) have recently reported similar observations derived from the COSPIN KET instrument. Our present measurements through the north polar pass are consistent with our previous conclusions, but with the entire scan of latitudes available additional features are apparent that may prove important for understanding the cosmic ray modulation, the structure of the heliosphere at high solar latitudes, and the propagation of high energy charged particles through the heliosphere.

2. Observations

The spectra of protons and helium nuclei measured at Ulysses near maximum north and south latitudes and near the equator during the fast latitude scan are shown in Figs. 3a and 3b, respectively. The proton spectra at all three locations are well described by the T^{+1} spectral form characteristic of a balance between adi-

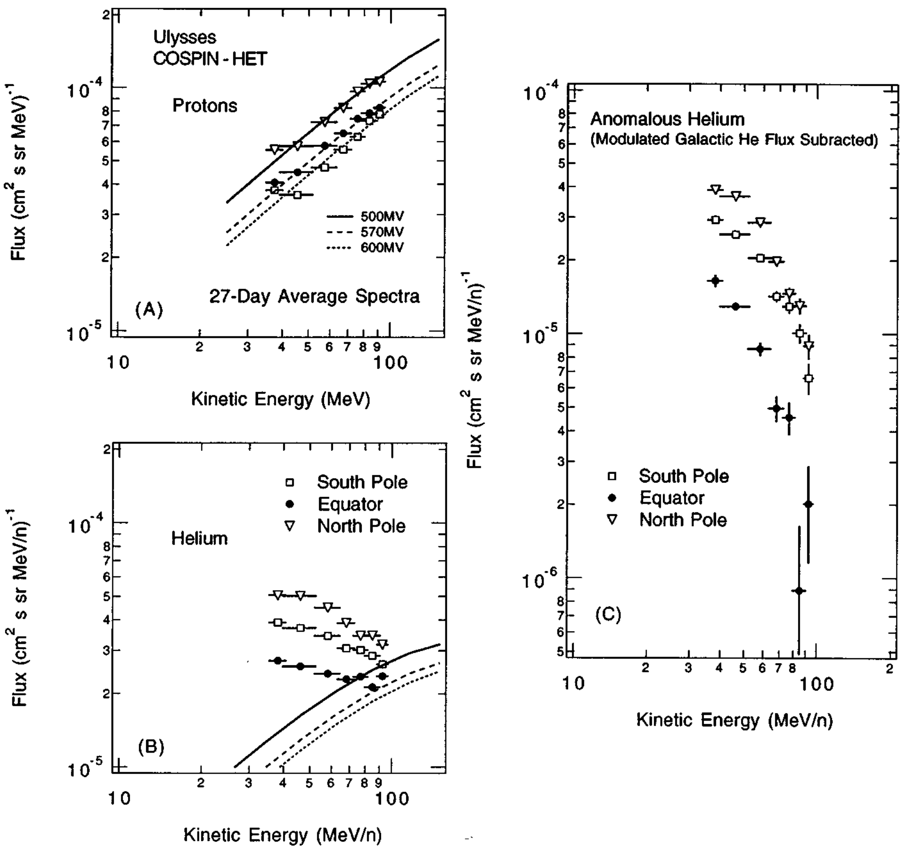

Fig. 3a–c. 27-day average spectra for protons (**a**), combined galactic and anomalous component helium (**b**), and pure anomalous helium (**c**) derived by subtracting from the spectra in (**b**) model galactic helium spectra predicted by a modulation model which produces satisfactory fits to the proton spectra in **a**. Spectra are shown for periods when Ulysses was near its maximum South latitude (squares, days 241-267 of 1995, south latitudes 79.8°-80.2°-79.7°), near the heliographic equator (filled circles, days 38-65 of 1995, latitudes 19.9°S-0.8°N) and near its maximum North latitude (inverted triangles, days 200-227, 1995, north latitudes 79.2°-80.2°-79.1°). The model spectra shown in **a** and **b** are derived from a standard, spherically symmetric modulation model (Evenson et al., 1983) using the values of the force-field modulation parameter, Φ, indicated in the figure

abatic deceleration and outward convection at low energies in standard modulation models, and show a steady increase in intensity from the south polar pass through the north polar pass. The lines through the observations are model spectra derived from a standard spherically symmetric model of the solar modulation (Evenson et al. 1983) for the values of the modulation parameter, Φ, shown. The agreement between model spectra and the observations is clearly satisfactory both at the poles and at the equator.

Even though the change in modulation level as a result of declining solar activity was small during the fast latitude scan, the steady increase in the proton intensity implies that for low energy ($<\sim$100 MeV) protons the temporal variation in modulation was still larger than any effect attributable to the changing latitude of Ulysses during this period. This will be demonstrated more conclusively below by examination of the Ulysses/IMP flux ratios as a function of Ulysses latitude.

The helium spectra, on the other hand, show the rising spectral form characteristic of the singly charged anomalous helium component at all three locations. The galactic cosmic ray helium spectra predicted by the modulation model for the same modulation levels that provided satisfactory fits to the proton spectra in Fig. 3a are shown as the lines in Fig. 3b. Clearly the anomalous helium component dominates or at least makes important contributions to the measured helium flux at all energies that we measure. If we assume that the model spectra provide a reasonably accurate estimate of the contribution of galactic cosmic rays to the observed spectra, we can obtain spectra of the pure anomalous component helium by subtracting the model spectra from the observed helium spectra. The results of this subtraction are shown in Fig. 3c. If this separation of the anomalous and galactic cosmic ray helium components is correct, then the form of the anomalous component helium spectrum does not change dramatically from the pole to the equator in either hemisphere. Furthermore, the lower intensity observed at the equator than at either pole indicates a latitudinal variation in the modulation for the anomalous component between the pole and the equator significantly larger than the magnitude of the temporal decrease in modulation during this period. This conclusion is especially robust for the lowest energy anomalous helium shown, where because anomalous component spectrum rises steeply towards low energies the uncertainty in the proper galactic flux to be subtracted is less significant.

To address the latitudinal dependence of the cosmic ray and anomalous component fluxes with greater accuracy corrections must be made for temporal changes in modulation. By taking the ratio of fluxes measured by the COSPIN HET on Ulysses to those measured by the University of Chicago cosmic ray experiment on IMP-8, which remains at 1 AU in the ecliptic, we can minimize any influence from global time-dependent effects in the modulation that would affect both IMP and Ulysses. In this manner we isolate latitudinal effects as Ulysses scans through the latitude range from 80°S to 80°N. The basic observations we use consist of 27 day running averages of the fluxes of protons, helium, and heavy nuclei in several energy ranges measured at Ulysses and simultaneously in nearly identical energy ranges

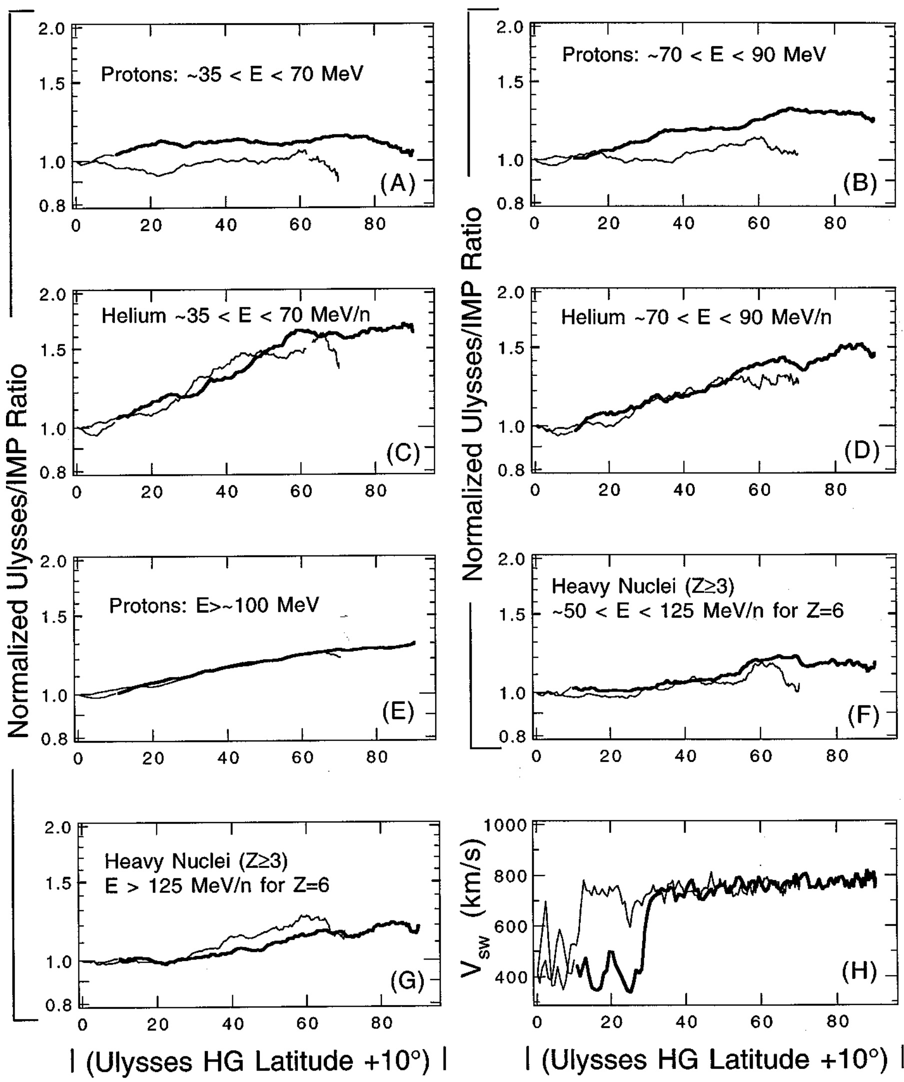

Fig. 4. a-g The ratio of Ulysses fluxes to IMP fluxes measured simultaneously in nearly identical energy intervals, as a function of latitudinal distance from heliographic (HG) latitude 10°S, which was found by Simpson et al. (1996) to be a symmetry surface for the modulation. Thus the value of "0" on the abscissa of each plot corresponds to 10°S heliographic latitude. The ratios are formed from 27 day running averages of quiet-selected measurements. For uniformity and to make immediately apparent the magnitude of the increase towards the poles, the ratios have been normalized to 1.0 at 10°S. Heavy lines indicate northern hemisphere measurements. **h** Daily average solar wind speeds, plotted in the same format as panels **a-g**. The observations were kindly provided by J. L. Phillips of the Ulysses solar wind team (private communication, 1996)

at IMP-8. In this paper we limit our discussion primarily to observations made during the fast latitude scan since the interpretation of these observations is more straightforward than that of the earlier observations made during the passage from Jupiter flyby to the south polar regions. Since the focus of this investigation is on the variation of the long-term solar-cycle modulation with heliographic latitude, we use 27 day running averages to smooth over the effects of corotating intensity variations and other short-term effects which have been found to extend to the highest latitudes sampled by Ulysses (McKibben et al. 1995). The amplitudes of these recurrent intensity variations and their correlations with latitudinal intensity gradients from pole to pole have recently been discussed by Zhang (1996). Looked at another way, averaging over a 27-day period, corresponding approximately to one complete solar rotation, provides a measure of the modulation averaged over solar longitude. Since at the time of Ulysses' crossing of the ecliptic IMP and Ulysses were nearly on opposite sides of the Sun, such analysis effectively removes any effects due to longitudinal dependences in the modulation which might otherwise have to be considered.

The basic results of this paper are given in Fig. 4 and in Table 1. Panels a-g in Fig. 4 show ratios of the Ulysses to IMP 27-day running average fluxes for various energy ranges and particle types. The ratios are normalized to 1.0 at a latitude of 10°S, reflecting the recent report by Simpson et al. (1996) that the plane of symmetry of the modulation of relativistic galactic cosmic rays and anomalous helium is shifted 10° south of the heliographic equator. Because of this southward shift in the symmetry surface, the ratios in Fig. 4 are shown as a function of the absolute value of the quantity $\Delta\theta$ = (Ulysses latitude + 10°). Latitudes in the southern heliographic hemisphere are assigned negative values, so that the range of $\Delta\theta$ sampled by Ulysses extends from −70° to +90°. Flux ratios measured in the southern hemisphere are shown as light lines, and those in the northern hemisphere as heavy lines.

In forming the ratios displayed in Fig. 4, no account has been taken of the variation of IMP-8's heliographic latitude with time [Simpson et al. (1996) investigated the effect of such corrections, and found that they did not significantly affect the results of their analysis], nor has any correction been made for radial

Table 1. Best fit latitude gradients within 60° of heliographic latitude of the symmetry surface at 10°S latitude. Assumed form: Ulysses/IMP=$A_0 e^{(g_\theta * \Delta\theta)}$†

Particle type	Energy (Rigidity)	g_θ (%/deg) 70°S-10°S	g_θ (%/deg) 10°S-50°N	g_θ (%/deg) 70°S-50°N
Protons	∼35-70 MeV (∼260-370 MV)	0.10	0.14	0.10
Protons	∼75-90 MeV (∼370-430 MV)	0.15	0.39	0.25
Protons	>∼100 MeV (>∼400 MV)	0.37	0.38	0.37
Helium	∼35-70 MeV/n (∼1.0-1.5 GV)	0.77	0.89	0.83
Helium	∼70-95 MeV/n (∼1.5-1.7 GV)	0.52	0.59	0.55
Heavy Nuclei	∼50-125 MeV/n (620-1000 MV) [for Z=6]	0.22	0.24	0.23
Heavy Nuclei	>∼125 MeV/n (>∼1000 MV) [for Z=6]	0.44	0.22	0.36

† The exponential function used to describe the latitudinal variation is chosen for convenience and because the variation of ln((Ulysses flux)/(IMP flux)) vs. latitude appears reasonably linear (cf. Fig. 4) over the range of the least squares fits used to derive values of the gradient. Parameters allowed to vary in the fit are A_0, the intensity normalization between IMP and Ulysses, and the latitudinal gradient, g_θ. $\Delta\theta$ is the latitude difference between IMP and Ulysses, taken to be simply the heliographic latitude of Ulysses. Uncertainties on the gradient values are dominated by the time variations visible as irregularities in the curves in Fig. 4, and can reasonably be estimated as ±0.1%/degree. Formal errors on the gradients derived from the fitting algorithm are of order ±0.01%/degree, which is unrealistically small.

gradients as Ulysses' heliocentric radius varied from 2.2 AU at 80°S latitude to 1.3 AU at the heliographic equator and back to 2.0 AU at 80°N latitude. No current measurements of the radial gradient between 1 and 2 AU are available for the particle species and energy ranges of interest. Measurements made in the previous solar minimum period with positive solar magnetic polarity showed that radial gradients for the particle species and energies considered here were generally of the order of a few percent per AU near 1 AU. [A comprehensive review of available observations from that period has been given by McKibben (1975).] Thus contributions to variations in the ratios from radial gradients could decrease slightly the size of the latitude gradients deduced from our current measurements. However such corrections would not affect the fundamental conclusions which we shall draw from our observations. From use of 27 day averages, the statistical counting errors on the individual flux measurements from each spacecraft are in all cases of the order of or less than 1-2 percent. Thus we make no attempt to show error bands in Fig. 4.

3. Discussion

General conclusions that can be drawn immediately from examination of Fig. 4 are:

A) As demonstrated by the good agreement of the southern and northern hemisphere observations for all species except low energy protons when referred to a surface at 10°S latitude, the 10° southward offset of the surface of symmetry of modulation reported by Simpson et al. (1996) for the high energy integral flux of cosmic rays and for 30-70 MeV/n anomalous helium is a general characteristic of the modulation of galactic cosmic rays and the anomalous helium during this period.

B) Consistent with the report by Simpson et al. (1996), we find that for all energies of protons and helium examined (Fig. 4a-e) the maximum Ulysses/IMP flux ratios measured in the northern hemisphere were higher than those in the southern hemisphere by from ∼5-∼20%. On the other hand for the two energy ranges of heavy nuclei examined (Figs. 4f,g) the maximum flux ratios measured in the north and south hemispheres were comparable in magnitude. The magnitude of the northern hemisphere flux excesses does not correlate strongly with the size of the observed latitudinal gradients as might be expected if the excess were simply a result of the greater latitudinal distance of the north polar regions from the symmetry surface at 10°S latitude.

C) Where a significant latitudinal dependence can be observed, all gradients are positive towards the poles of the sun, as would be expected from standard modulation models for the current sign (north pole positive) of the solar dipole magnetic field.

D) Latitudinal gradients are small, with the largest (Fig. 4c for ∼35-70 MeV/n helium) leading to a flux at high northern latitudes only 1.7 times that observed at 10° south latitude, corresponding to a latitudinal gradient of <1%/degree. See Table 1 for a summary of the best fit latitude gradients for the various species shown in Fig. 4, calculated for the southern, northern, and combined hemispheres between latitudes of 70°S and 50°N (see point F below).

E) for low-energy protons shown in Figs. 4a and b essentially no latitudinal effect was observed from the south polar regions of the heliosphere to the heliographic equator. This is consistent with our earlier report (Simpson et al. 1995b). In the northern hemisphere, however, the proton flux increased toward the polar regions. For 35-70 MeV Protons (Fig. 4a) the increase occurred in a more or less step-wise fashion between 10° S and 10° N, whereas for 70-90 MeV protons (Fig. 4b) the increase occurred gradually over a latitude range up to 50-60° north latitude.

F) The increase towards the polar regions for all species and energies is for the most part confined to latitudes less than 60° from the plane of symmetry at 10° S. This is most clearly seen for the low energy anomalous helium in Fig. 4c, but in all panels a-g the rate of increase at latitudes more than 60° from the plane of symmetry is significantly lower than at lower latitudes.

G) During the climb towards the south pole after Jupiter flyby no clear latitudinal gradients were observed in the near-equatorial region swept by the current sheet (Simpson et al. 1995a). During the fast latitude scan, however, if we take the region of slow solar wind within 20° of the heliographic equator to correspond to the equatorial zone affected by the current sheet, the increase of flux towards the north solar pole began well within this region for most of the species shown in Figs. 4a-g. Figs. 4a-g shows 27-day running averages plotted at the midpoints of the intervals, which are influenced by observations 13 days on either side of the plotted position. However examination of daily average ratios, while limited by poorer statistical accuracy, confirms the conclusion that a significant variation in the fluxes with latitude began within the equatorial zone. Thus, suppression of latitude effects in the region swept by the current sheet appears not to be a general characteristic of the modulation.

H) Since the anomalous helium is singly charged its rigidity for the energies considered here is in all cases $>\sim 1$ GV. The heavy nuclei shown in Figs. 4f,g also have rigidities > 0.6 GV and >1 GV respectively, while the protons in Figs. 4A, B have rigidities <0.4 GV. Thus our observations (Figs. 3, 4a-g) are consistent with the interpretation that latitudinal effects are organized by particle rigidity, and are strongest for particles with rigidities of order 1 GV, decreasing both at lower and higher rigidities (cf. Table 1). This may help to explain the apparent discrepancy between our observations and those of Trattner et al. (1995), who reported an absence of latitudinal effects for lower energy (11-20 MeV/n, 0.6-0.8GV) anomalous helium. Such a rigidity dependence would be similar to that reported for the amplitude of the 26-day variations by McKibben et al. (1995; see also Zhang 1996).

A further conclusion derived from comparison of the variations of the Ulysses/IMP ratios (Figs. 4a-g) with the solar wind velocity profile (Fig. 4h) is that the modulated intensity at Ulysses was remarkably insensitive to the dramatic change of the local solar wind velocity across the boundary of the equatorial zone, where the solar wind speed increased by a factor of two within about 5 degrees of latitude, corresponding to about 7 days along Ulysses trajectory. One might have expected significant variations across the boundary since, among the processes believed responsible for the solar modulation the solar wind velocity controls outward convection and the rate of adiabatic deceleration, and, through its effect on the pitch of the spiral interplanetary magnetic field, the gradient and curvature drift velocities as well. The only major modulation process not directly dependent on the solar wind velocity is inward diffusion. Reports from the Ulysses magnetometer experiment (Forsyth et al. 1996) show that the variances of the transverse magnetic field components, which are directly related to the spectrum of magnetic field irregularities responsible for diffusion, also undergo a significant increase at the boundaries of the equatorial zone.

Thus there were significant changes in all of the parameters thought to be important for modulation at the boundaries of the equatorial zone. Nevertheless, there was no discernible effect on the modulated intensities of the cosmic rays and anomalous components on crossing the boundary of the equatorial zone during the fast latitude scan. For particles whose propagation is strongly guided by the interplanetary magnetic field, which in the ideal Parker model is drawn out from the sun in spirals at constant heliographic latitude, a significant effect might have been expected.

In a previous period when Ulysses crossed repeatedly between the polar and equatorial solar wind zones, significant effects on the modulated intensities were observed. In 1992-1993, Ulysses spent an extended period at radii near 5 AU in a latitude range where during each solar rotation it spent part of the time in the high speed polar solar wind flow and part of the time in the low speed equatorial solar wind. Strong variations in the cosmic ray flux were observed in correlation with this 26-day periodic alternation between regions (McKibben et al. 1995; Kunow et al. 1995b; see also Zhang 1996). However as is apparent from Fig. 2 of McKibben et al. (1995), the periodic increases in modulation at mid-latitudes in 1992-93 were most closely associated with the enhanced magnetic field in the interaction regions between fast and slow solar wind, in a manner consistent with the model for local variations in modulation proposed by Burlaga et al. (1985). Thus the lowest intensities were observed in the high speed solar wind after passage of the interaction regions, and the highest intensities were observed in the low speed equatorial solar wind, contrary to the sense of the latitudinal gradients that we observe (see Zhang [1996] for an extensive discussion of the relationship between the latitudinal gradients and the 26-day intensity variations).

During the fast latitude scan in 1995, Ulysses was at radii where interaction regions had not yet fully formed. Furthermore, based on the source surface maps computed from the Wilcox Solar Observatory magnetograms[1] the inclination of the current sheet and thus presumably of the equatorial wind region was much smaller than in 1992-93. As pointed out by Pizzo (1991) the strength of the interaction between the fast polar and slow equatorial wind is weaker and develops more slowly with increasing heliocentric radius for smaller inclinations of the current sheet region.

[1] Source surface maps are available on the World Wide Web at http://quake.stanford.edu/˜wso/coronal.html, and are published monthly in Solar Geophysical Data by NOAA, Boulder, CO. Computational methods and assumptions are discussed by Hoeksema (1995) and by Wang and Sheeley (1992). Hoeksema (1995) also discusses selected observations during Ulysses climb towards the south pole.

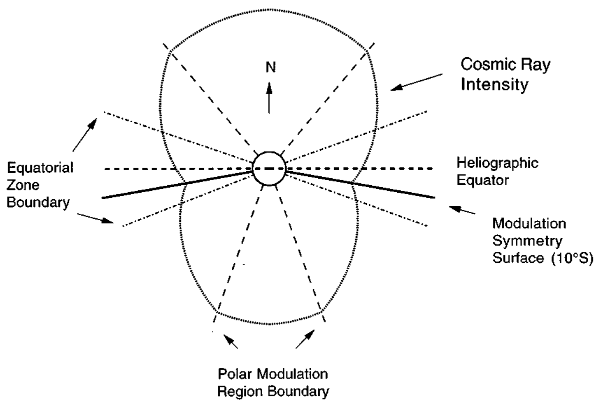

Fig. 5. Schematic meridional cross-section of the variation of the modulated intensity as a function of heliographic latitude suggested by our observations and those of Simpson et al. (1996). The radial distance of the dotted curve from the sun at the center indicates the cosmic ray intensity. A variation of the flux with latitude, θ, as $e^{(g_\theta * \Delta\theta)}$ is assumed, where $\Delta\theta$ is measured from 10°S latitude and g_θ =1.0%/degree for $|\Delta\theta|<60°$ and g_θ = 0.1%/degree for $|\Delta\theta| > 60°$

Thus in 1995 observations at Ulysses were relatively unaffected by interaction regions and provided a cleaner isolation of the effect of variations in the solar wind velocity on the modulation level. The observations show that at the position of Ulysses, changes in solar wind velocity had little effect on the modulation.

Assuming that our understanding of the basic physical processes of modulation is not in error, two conclusions follow:

First, the continuity across the equatorial zone boundary must imply that little of the total modulation takes place in the radial range sampled by Ulysses. This is perhaps not surprising given the results from the Pioneer-10 (Lopate and Simpson 1993) and Voyager (Fujii and McDonald 1995) spacecraft showing persistence of strong modulation, comparable to that observed at 1 AU, at radial distances beyond 50 AU from the sun in the equatorial zone. Thus, even the large changes in the local wind velocity observed produce by themselves only negligible changes in the total modulation experienced by the particles.

Second, the continuity across the equatorial zone boundary suggests that the cosmic rays and anomalous components, even those observed at low energies, must have sampled a wide range of solar latitudes on their travels from the modulation boundary to the point of observation. If so, the modulation would be determined by the integrated effect of propagation conditions over not only the radial interval from the observer to the boundary, but over a range of latitudes as well. Thus particles observed in the equatorial zone will also have been influenced by modulation conditions in the high speed solar wind at higher latitudes, and vice-versa. Although the path of cosmic rays is strongly guided by the interplanetary magnetic field lines, possible mechanisms for such latitudinal mixing include the random walk of fields (Jokipii and Parker 1969), and randomly oriented gradient and curvature drift velocities in the medium-scale (e.g. MIRs, CIRs, etc.) and small-scale structures (turbulence, CMEs, etc.) in the interplanetary magnetic field which may lead to enhanced diffusion perpendicular to the mean magnetic fields. More recently Fisk (1996) has suggested a mechanism based on solar differential rotation that would provide direct magnetic connection between high and low latitude regions of the heliosphere.

4. Summary and conclusions

The major conclusions based on observations reported in this paper are:

- Proton and helium spectra over the north and south poles of the sun are similar to those observed in the equatorial zone. The difference in modulation observed between the poles and the equator is small compared to the total modulation experienced by these particles in the course of propagating from the heliospheric boundary to the inner heliosphere.
- Latitude gradients in the intensity of all nuclear species are small and positive towards the solar poles in both the northern and southern hemispheres. An exception is for low energy protons, which show no appreciable latitudinal intensity gradient in the southern solar hemisphere.
- For galactic protons at energies below 100 MeV the flux observed at Ulysses increased continuously from the south polar pass through the north polar pass, implying that the difference in modulation from pole to equator was smaller than the temporal variation in modulation during the fast latitude scan.
- No direct information concerning the latitudinal variation of low energy (<100 MeV/n) galactic helium is available because of the dominating presence of the anomalous helium component in the helium flux at these energies at this phase of the 11-year solar activity cycle. Subtracting from the observed helium spectra model galactic helium spectra derived from fits to the proton spectra produces spectra for the anomalous helium component that show a clear increase in intensity from the equator to both the South and North poles, but that have little variation in form from the poles to the equator.
- The observations suggest that latitudinal effects may be ordered by rigidity, with the strongest effects observed for particles of rigidity ∼1GV, decreasing at both lower and higher rigidities.
- The variation of the modulated intensity of galactic cosmic rays and anomalous helium during Ulysses' fast latitude scan is, except for low energy (<∼100 MeV) protons, approximately symmetrical with respect to a conical surface displaced 10°S from the heliographic equator, confirming the report of Simpson et al. (1996) and extending their conclusion to lower energies and to a wider range of particle species.
- Maximum intensities of all species (except for fluxes of heavy nuclei [Figs. 4f,g]) are higher over the north polar regions than over the south polar regions of the sun, perhaps, as suggested by Simpson et al. (1996) reflecting the tighter winding of the most probable direction of interplanetary magnetic field observed in the southern hemisphere (Forsyth et al. 1995).

- The strongest latitude gradients are confined to a region less than 60! from the surface of symmetry at 10°S, resulting in a polar cap region over both poles where there is little variation in the cosmic ray flux as a function of latitude. This change in the latitudinal dependence of modulation at high latitudes occurs in the absence of any obvious changes in solar wind or magnetic field characteristics.
- Suppression of latitude effects within the equatorial zone, apparent during Ulysses' climb to high latitude following Jupiter flyby, is not observed during the fast latitude scan.
- There is no sensitivity of the modulated intensities to the dramatic change of solar wind velocity and magnetic field characteristics at the boundary of the equatorial zone. This suggests that the particles observed at the position of Ulysses must have undergone significant excursions in heliographic latitude in the course of their inward journey through the heliosphere, so that they have been affected by modulation conditions both in the polar and equatorial wind regions by the time they reach the inner heliosphere.

Fig. 5 schematically illustrates the apparent latitudinal structure of the cosmic ray modulation as deduced from our results during the fast latitude scan. Our observations, coupled with the overall small magnitude of the latitudinal variations in modulation appear to provide an interesting challenge for the current models for the modulation process.

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