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Intensities of galactic cosmic ray nuclei from the ecliptic to the south solar polar regions near solar maximum: Observations from the Ulysses COSPIN HET and KET instruments

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Abstract. Ulysses reached its maximum south heliographic latitude of $80.2°$S in late November 2000, near the maximum in the solar activity cycle and is now embarked on a fast latitude scan that will bring it to a perihelion at 1.34 AU near the solar equator by mid-May 2001. Throughout the period of increasing solar activity since Ulysses left the ecliptic in 1998, the variations of modulation observed at Ulysses and at IMP-8 near Earth have been closely similar despite the significant radial and latitudinal separations between the spacecraft. Thus latitudinal and radial gradients have remained small during the approach to maximum solar activity. A surprise is that at some energies, especially for protons with energies ˜35-70 MeV, the latitudinal gradients appear to have reversed even before the reversal of the solar magnetic dipole was complete. For this paper observations are available from the fast latitude scan to latitudes as low as ˜$37°$S. Even at these low latitudes, the Ulysses/IMP flux ratios remain well below one. Observations through perihelion when Ulysses is in the ecliptic near 1.3 AU will be crucial to determining whether the apparent negative gradients are real or the result of instrumental effects.

1 Introduction

In its continuing exploration of the 3-Dimensional heliosphere, Ulysses has recently passed over the south polar regions of the sun for the first time in solar maximum conditions, spending the period from September, 2000 to January, 2001 at latitudes above $70°$S (see Fig. 1B). In Ulysses' previous pass over the sun's poles in 1994-95, solar activity was at near minimum levels, and the magnetic structure of the heliosphere was particularly simple, with a low inclination current sheet near the equator separating positive and negative magnetic polarities in the interplanetary magnetic field. On either side of the current sheet, magnetic fields originating from the well-developed polar coronal holes filled the heliospere with and displayed a nearly uniform radial component as a function of latitude (Forsyth et al., 1996). In this simple solar minimum heliosphere, with a positive polarity for the solar dipole, Ulysses found that latitude gradients for galactic cosmic rays and anomalous components were small. In some cases they were in fact unmeasurable. In all cases where they could be measured, the gradients were less than ˜1% per degree and positive for positively charged particles (McKibben et al., 1996). While smaller than had been expected, the sign of the gradients was consistent with models in which gradient and curvature drifts in the non-uniform interplanetary magnetic field play a significant role in propagation of cosmic rays through the heliosphere (e.g. Potgieter, 1998). The positive gradients were also consistent with observations made 20 years earlier for the same sign of the solar dipole when Pioneer 11 reached $17°$N latitude in the inner heliosphere near solar minimum (Bastian et al., 1979; McKibben, 1989).

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During the recent passage over the south pole, the polarity of the solar magnetic dipole, as measured by the Wilcox Solar Observatory, was in transition from positive to negative state (see Fig. 1A). At the same time, the magnetic structure of the heliosphere, as measured by the inclination of the current sheet deduced from solar coronal magnetic fields (see Fig. 1B), was complex and was continually disrupted by Coronal Mass Ejections (CME's) associated with high levels of solar activity. The study of modulation of galactic cosmic rays in this environment was made doubly difficult by the near continuous presence of low energy solar energetic particles (SEP's) in the interplanetary medium, and by the frequent transient modulations produced by CME's propagating through the solar wind. Elsewhere in this conference (McKibben et al., 2001) we have reported observations of solar energetic particles over the south polar regions of the sun. In this paper we present a first report of observations of galactic cosmic rays over the south polar regions and through the first stages of the fast latitude scan.

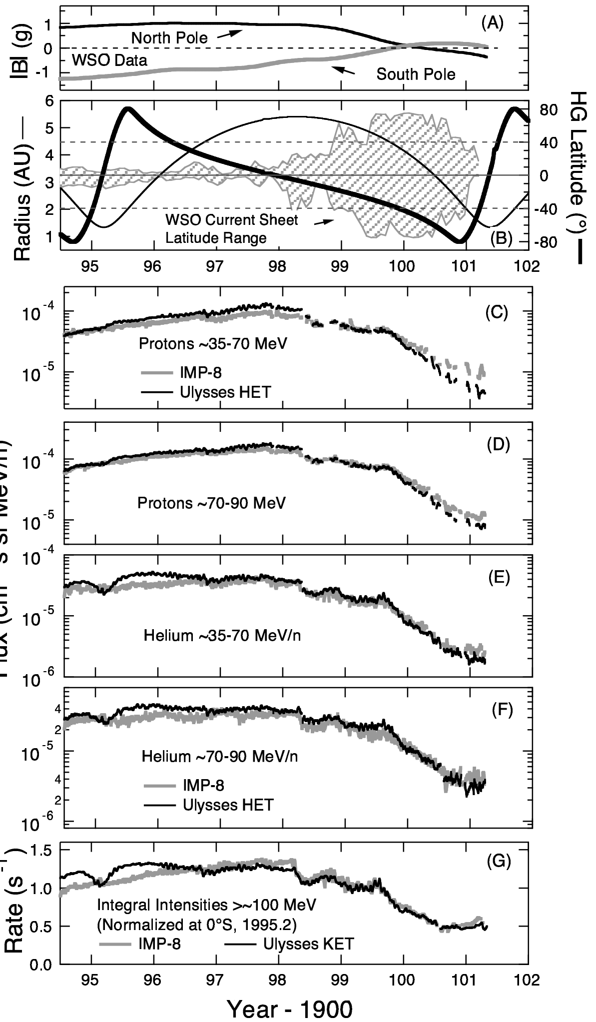

Fig. 1. A) Solar polar magnetic fields from the Wilcox Solar Observatory (WSO); B) Ulysses trajectory and WSO "radial model" current sheet tilt; C-G) IMP-8 and Ulysses 9-day running averages of cosmic ray protons and helium fluxes and of the integral intensity above 95 MeV (IMP-8) and 106 MeV (Ulysses).

2 Observations

2.1 Overview

Figure 1(C-G) gives an overview of observations of galactic cosmic rays made by IMP-8 in Earth orbit and simultaneously by the Ulysses COSPIN HET and KET telescopes during the period since Ulysses last visited the south polar regions of the heliosphere in 1994. The COSPIN instrumentation has been described by Simpson et al. (1992).

From Fig. 1 it appears that the time of Ulysses aphelion in early 1998 coincides approximately with the beginning of increasing solar modulation leading to the current solar maximum. In most cases shown in Fig. 1 the maximum cosmic ray intensities at Earth were reached early in the 3rd quarter of 1997, but the first major decrease in intensity occurred in the Spring of 1998. Since then the cosmic ray intensities

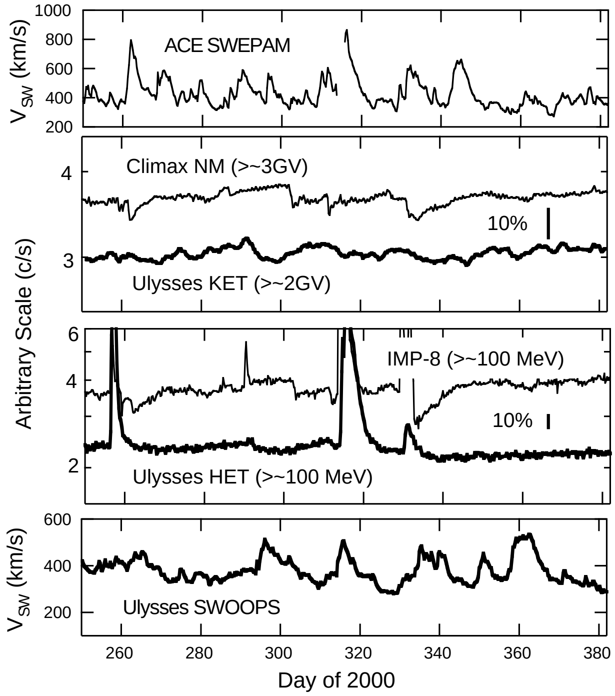

Fig. 2. Six hour average high energy counting rates and solar wind speeds measured at Ulysses and near Earth while Ulysses was over the south polar regions of the sun.

have been decreasing, by more than an order of magnitude for some species, at both Ulysses and IMP. Several points follow immediately from inspection of Fig. 1.

Despite significant radial and increasing latitudinal separations between Ulysses and IMP, the overall time structure of the increasing modulation is nearly identical at Ulysses and IMP. However this holds only on the large scale. Fig. 2 shows 6 hour averages of high energy counting rates, relatively unaffected by SEP's, from Ulysses and from IMP-8 and the Climax Neutron Monitor at Earth for the period when Ulysses was at latitudes $> 70°$S. This period is also discussed briefly by McKibben et al. (2001) elsewhere in these proceedings. The detailed records of intensity variations are very different at Ulysses and Earth, indicating response to very different interplanetary environments. Particularly striking is the period 290-305, where Ulysses observed a significant Forbush-like decrease, possibly associated with a solar event with halo CME that went off on day 290 (McKibben et al., 2001), for which IMP saw a particle increase, but no Forbush decrease. However on day 302, IMP and the Climax neutron monitor observed a sharp decrease, while Ulysses saw no effect.

Nevertheless, despite the difference in detailed modulation history, on the larger scale as shown in Fig. 1G, the variation in the long term modulation was nearly identical at IMP and Ulysses, suggesting that individual disturbances have little effect on the long-term modulation. Indeed, throughout the rise to solar maximum, and despite their very different locations in the inner heliosphere, Ulysses and IMP fluxes

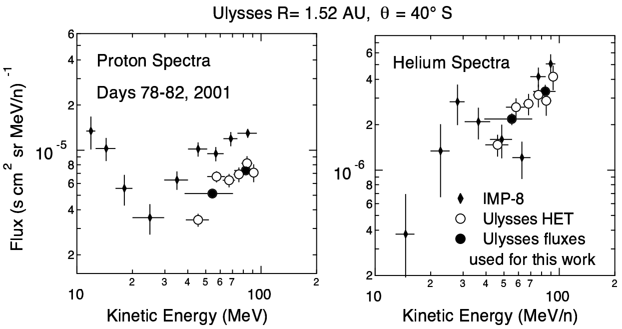

Fig. 3. Proton and helium spectra obtained from the Ulysses HET and IMP-8 instruments during one of the rare "quiet" periods identified in 2001. The energy ranges used for the Ulysses fluxes in Fig. 1 are identified using filled circles. Similar energy intervals are extracted from the IMP-8 data.

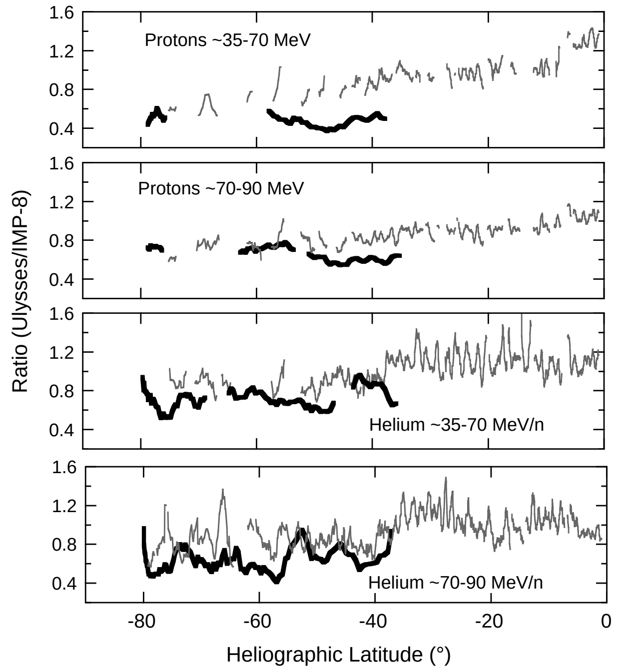

Fig. 4. Ulysses/IMP flux ratios measured during the Aphelion-Pole (1998-2000, light line) and during the subsequent fast latitude scan (2001, heavy line) using data available to date. Data are presented as 9 day running averages of quiet-selected fluxes.

remained equal to within a factor of about 2, and were usually much more closely equal than that. Thus we may also conclude that radial and latitudinal gradients remained small even at solar maximum.

As is most clearly seen in Fig. 1G there were three major turning points in the increasing modulation, occurring at both Ulysses and IMP in early 1998, late 1998, and the middle of 1999, respectively. The large decrease in early 1998 was roughly coincident with a significant outburst of solar activity, but close inspection of more detailed data shows that the decrease actually began before the large solar events that marked the increase in activity. Similarly, no convincing correlation with solar activity or solar wind events is apparent for the late 1998 or mid-1999 changes. As discussed previously by McKibben et al., (2001a), the best correlation may be with episodic increases in the tilt of the current sheet (Fig. 1B) with possibly a lag of 2-3 months from a significant tilt increase until the effect is seen in the modulated intensities. Such a correlation has previously been suggested and documented by Smith and Thomas (1986) and Smith (1990). Consistent with this suggestion is that, following the decline in tilt of the current sheet beginning in late 2000, there are indications of recovery of the cosmic ray intensities, especially at high energies, even though solar activity continued at very high levels as measured by the frequency of SEP events.

Below 100 MeV (Fig. 1C-F) fluxes at Ulysses were steadily larger than at IMP before 1999, consistent with positive radial and latitudinal gradients. However, by 2000 Ulysses fluxes had decreased to become equal to or less than those measured at IMP. (We do not discuss the integral intensities in Fig. 1G since questions of possible energy dependent response of the integral channels make definitive comparison of intensities questionable for small intensity differences.) The reversal in the flux ratios between Ulysses and IMP suggests development of a negative latitudinal gradient in the cosmic ray intensities even before clear reversal of the dipole polarity (Fig. 1A). While a negative gradient is expected once the negative polarity for the solar dipole is established, the early appearance of the effect is the most surprising observation to be reported here.

To check for possible contamination of the fluxes by solar energetic particles, we have constructed proton and helium spectra from Ulysses and IMP for a period in 2001 (days 78-82) corresponding to some of the last data included in Fig.1. The spectra for this interval are displayed in Fig. 3, and, while the statistical accuracy is poor, they show no sign of solar contamination in the energy intervals used. As in Fig. 1, the Ulysses protons are significantly lower in intensity than those observed at IMP, while the helium fluxes are nearly equal.

2.1.1 Fast latitude scan

After reaching its maximum latitude of $80.2°$S in Nov. 2000, Ulysses began a rapid transit from the south to the north poles. This phase of the mission is of crucial importance for verifying the conclusions about latitudinal structure derived from the slow climb after aphelion from the equator to polar latitudes. As can be seen from Fig. 1, the period since Ulysses' aphelion in 1998 has been one of strong temporal variations, with a time scale comparable to the time scale for Ulysses transit from the equatorial to polar regions. Thus confusion between temporal and spatial effects is a clear danger.

During the fast latitude scan, however, within a short period of approximately 6 months Ulysses travels from $80°$S at a radius of 2.3 AU to the equator at a radius of 1.34 AU. This rapid transit provides a snapshot of the latitudinal profile of the cosmic ray intensity, and a normalization check with near-Earth observations while near the equator and perihelion. This is of particular importance for checking the surprising result of a negative latitude gradient even in advance of the reversal of the solar polar fields.

In Fig.4 we show the Ulysses/IMP flux ratios measured as Ulysses was rising from the equator toward the south pole in 1998-2000, and those measured in 2001 as Ulysses began its return to the equator in the fast latitude scan. If the low ratios over the poles are truly a result of a variation with latitude in the cosmic ray flux, we should expect the ratios to increase as Ulysses' latitude decreases, and to reach a value near 1 as Ulysses passes through perihelion in the equatorial zone, only 0.34 AU further from the sun than Earth.

The results from the fast latitude scan so far, reaching from the pole to latitudes of ˜37°S, are mixed. The latitude range is limited not only by the availability of data, but also by the presence of large fluxes of SEP's after day 86, 2000, which prevent measurement of the modulated cosmic ray intensity. The low energy protons, which showed the largest apparent depression at high latitudes, do not appear to be retracing the variation in the ratio observed during the slow climb to the poles in 1998-2000. The helium ratios, on the other hand, which showed a smaller depression at high latitudes, are reasonably consistent with ratios observed in the same latitude range during the rise to high latitude.

If the ratios do not return to near 1 as Ulysses crosses the equator, we must continue to search for instrumental or other causes for the effect. As shown in Fig.3, contamination of IMP fluxes by SEP's does not seem to be an adequate explanation for the low ratios. However at the very low flux levels observed in solar maximum conditions, measurements become increasingly susceptible to alteration by background subtraction, and techniques that are appropriate for higher flux levels may be inappropriate at the very low levels now being observed. We have so far found no evidence of distortion, but it remains a concern. As a result, we must still consider the apparent early development of negative latitude gradients as a preliminary result, to be confirmed or not as the fast latitude scan progresses.

3 Summary

During the evolution of solar modulation from solar minimum to solar maximum, and during Ulysses climb from the equator to the poles, comparison of measurements at Earth and Ulysses has shown little difference between the cosmic ray fluxes measured at Ulysses and IMP, regardless of the radial and latitudinal separations of the spacecraft. The largest differences measured, approximately a factor two for the lowest energy protons considered (˜35-70 MeV), if not the result of instrumental effects, still require that radial and latitudinal gradients remain small in the inner heliosphere even at solar maximum. Latitudinal gradients in particular are of the order of 1%/degree or less.

During the development of the modulation, short-term intensity variations were often significantly different at Ulysses and Earth, but the long-term intensity variations resulting from the solar modulation were nearly identical at the two observation points. Three significant steps or changes in trend in modulation were observed during the passage from solar minimum to maximum, and the best correlation with other heliospheric observables appears to be with abrupt changes in the inclination of the heliospheric current sheet, with perhaps a delay of 2-3 months from a change in inclination until the effect is observed in the modulation, consistent with suggestions by Smith and Thomas (1979) and Smith (1990).

Ulysses is now embarked on its second fast scan of solar latitude, and will be over the north polar regions of the Sun in October 2001, while we may still expect modulation to be near maximum levels. We may expect that many of the questions and uncertainties still surrounding the observations will be made clear and resolved by the time observations from the north polar regions are available.

All of the observations to date are consistent with the general conclusion derived from studies of solar minimum gradients, solar energetic particles, and CIR-accelerated particles, that the energetic charged particle populations of the inner heliosphere are remarkably homogenous as a function of latitude. This conclusion now extends to solar maximum as well as solar minimum.

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