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Charge sign dependent modulation of galactic cosmic rays along the Ulysses trajectory: COSPIN/KET observations

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Abstract. Ulysses, launched in October 1990, began its second out-of-ecliptic orbit in September 1997 and its second fast latitude scan in November 2000. At the time of the submission (May 2001) the spacecraft was located close to the heliographic equator at a radial distance of 1.3 AU. In contrast to the first orbit with the Sun declining to low activity, we are now at solar maximum conditions. The latitudinal gradient ($\sim$0.3 %/degree for $>$100 MeV protons) as well as the charge sign dependent variation of 2.5 GV protons and electrons observed during the previous Ulysses solar minimum orbit can be understood in terms of modulation models taking into account larger perpendicular diffusion to the mean heliospheric magnetic than previously thought. In this paper we present Ulysses COsmic ray and Solar Particle INvestigation Kiel Electron Telescope data at high southern heliographic latitudes and during the first period of the fast latitude scan investigating temporal and spatial modulation around solar maximum and during the solar magnetic field reconfiguration. In contrast to the observation at solar minimum Ulysses observes no or only small latitudinal gradients for galactic cosmic ray protons. While the electron to proton-ratio during the 1994/1995 latitude scan reflected clearly the proton latitudinal distribution, only small variation were found until May 2001 for the current fast latitude scan, hinting that drift is again beginning to play a role in galactic cosmic ray modulation.

1 Introduction

Galactic Cosmic Rays (GCRs) are scattered by irregularities in the heliospheric magnetic field as they enter the heliosphere. They also undergo convection and adiabatic deceleration in the expanding solar wind (Parker, 1965), while the large-scale heliospheric magnetic field causes gradient and curvature drifts. When the field is directed outward from the Sun in the north polar region (denoted by A$>$0) as in the 1990's, drift models predict that positively charged particles drift predominantly inward through the solar polar regions and then outward through the equatorial regions along the heliospheric current sheet (Jokipii et al., 1977). In contrast, electrons drift mainly into the inner heliosphere along the heliospheric current sheet and then outward through the polar regions (Potgieter and Moraal, 1985). When the field polarity is reversed (A$<$0) the drift pattern of electrons and protons also reverses. Good indicator for drift effects in modulation are 1) the difference in the latitudinal dependence of oppositely charged particles during the same polarity epoch and 2) the different temporal variation of different charged cosmic rays caused by the variation of the heliospheric current sheet in a solar cycle (see e.g., Potgieter et al. (1997); Heber (2001)). With Ulysses at polar latitudes in the inner heliosphere around solar minimum in 1994/1995 of the A$>$0 magnetic solar cycle 22, the expected positive latitudinal gradients for protons were observed (Heber et al., 1996a; McKibben et al., 1996). In contrast, the electron latitudinal gradients were consistent with zero (Heber et al., 1999). In the next A$<$0 solar magnetic cycle, the proton latitudinal gradients are expected to become negative. Such negative latitudinal gradients have been observed in the outer heliosphere (McDonald et al., 1997). Evenson (1998) and Heber et al. (1999) could show that the temporal variation was charge sign dependent around solar minimum in an A$<$0 and A$>$0-solar magnetic cycle. In his paper Evenson (1998) emphasized the different recovery of the 1.2 GV electrons and helium shortly after solar maximum in 1989. At that time no simultaneous measurements at high heliographic latitudes were available. Of special interest are therefore the time profiles measured by Ulysses at high heliographic latitudes at solar maximum during the solar magnetic field reversal and the latitudinal variation of these profiles during the ongoing fast latitude scan in 2001: the spacecraft reached its highest southern heliographic latitude of 80.2°in November 2000, and returned to the heliographic equator in May 2001. In this paper we report COSPIN/KET observations of galactic cosmic ray protons as well as electrons in different

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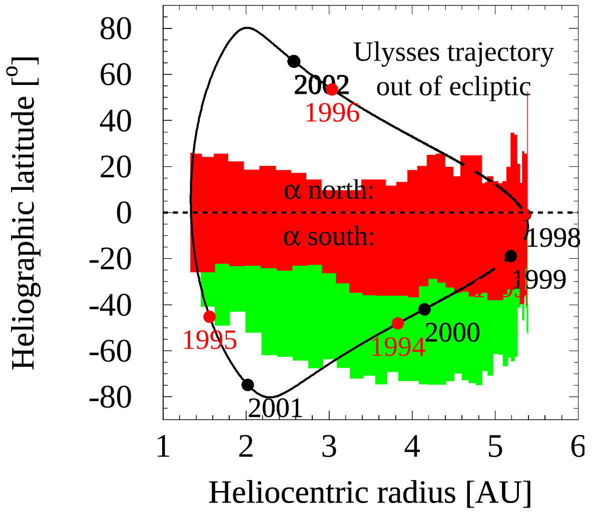

Fig. 1. Ulysses trajectory from beginning of 1993 to 2002. Solid circles mark the start of each year. The dark and light histograms show the evolution of the maximum latitudinal extent α of the heliospheric current sheet as a function of time during the first and second orbit of Ulysses.

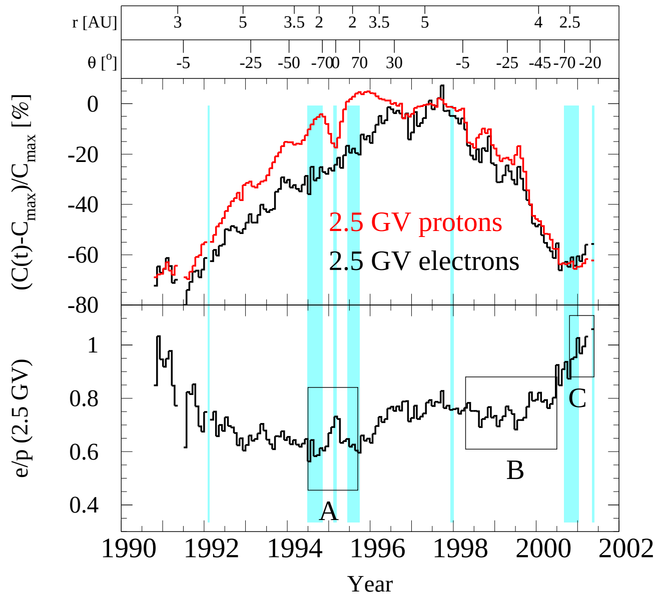

Fig. 2. The 26-day averaged quiet time variation $(C(t) - C_m)/C_m$ of 2.5 GV protons and electrons from launch in 1990 to end of 2000. The 2.5 GV correspond to the 0.25 to 2 GeV proton and 0.9 to 4.6 GeV electron channels. The lower panel displays the time profile of the e/p-ratio along the Ulysses trajectory. 'A', 'B', and 'C' correspond to time periods investigated in this paper. Marked by shading are time periods when Ulysses was above 70° heliographic latitude, when it crossed the heliographic equator in 1995, 1998 and 2001, and when it encountered Jupiter in 1992. Ulysses' distance to the Sun and its heliographic latitude are shown at the top.

channels.

2 Instrumentation and Observations

The observations were made with the Cosmic and Solar Particle Investigation Kiel Electron Telescope KET aboard Ulysses. The KET measures protons and helium in the energy range from 6 MeV/n up to and above 2 GeV/n and electrons in the energy range from 3 MeV to a few GeV (Simpson et al., 1992). Ulysses was launched on October 6, 1990, in the declining activity phase of solar cycle 22. A swing-by manoeuvre at Jupiter in February 1992 placed the spacecraft into a trajectory inclined by 80° with respect to the ecliptic plane. Ulysses completed its first out-of-ecliptic orbit in the beginning of 1998. Fig. 1 displays the first and second out-of-ecliptic orbits of Ulysses. The dark and light histograms show the evolution α of the heliospheric current sheet for these orbits. Hoeksema (http://quake.stanford.edu/∼wso/) calculates α using two different magnetic field models: (1) The "classic" model uses a line-of-sight boundary condition at the photosphere and includes a significant polar field correction. (2) The newer, probably more accurate, model uses a radial boundary condition at the photosphere, has a higher source surface radius (3.25 solar radii), and requires no polar field correction. In our analysis we used the latter one. Note that our qualitative conclusions will not be altered when using the "classical" model, whereas the absolute numbers would be different. Inspection of Fig. 1 shows that α was below 40° during most of the first orbit, but since the beginning of 2000 values above 60° have been observed; thus the second pass is performed during very different solar modulation conditions compared with the previous one.

2.1 KET-observations

Fig. 2 shows the 26-day quiet time variation $(C(t)-C_m)/C_m$ of the counting rate $C(t)$ of 2.5 GV electrons (0.9 to 4.6 GeV) and protons (0.25 to 2 GeV) from the end of 1990 to May 2001, when Ulysses crossed the heliographic equator. C_m is the count rate measured in fall 1997 at solar minimum. Quiet time profiles have been determined by using only time periods, when the 38-125 MeV proton channel showed no contribution of solar or interplanetary particles (Heber et al., 1999). It is important to note that the observed variations in the 2.5 GV particle fluxes are caused by temporal variation as well as by spatial variation due to Ulysses trajectory. The spacecraft was close to the ecliptic close to solar maximum in mid 1991 and spring 2001 and at solar minimum in fall 1997, when KET registered minimum and maximum intensities, respectively. Since electrons as well as protons are normalized to their maximum count rates in 1997, the upper panel of Fig. 2 shows a modulation amplitude of about $60-70\%$ for both "species" at 2.5 GV. The lower panel shows the e/p-ratio at 2.5 GV along the Ulysses trajectory, indicating three time periods, to be discussed in this paper. If we assume that the radial gradient for both charge signs is the same, then the different values at solar minimum (~ 0.8) and close to solar maximum (1) close to the ecliptic are a good indication of charge sign dependent modulation, as predicted by current modulation models Potgieter et al. (2001).

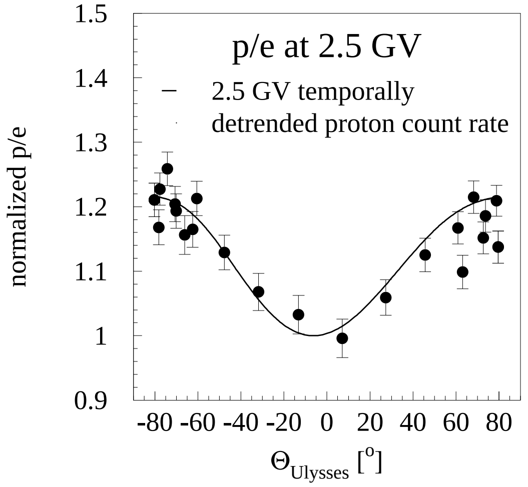

Fig. 3. 2.5 GV p/e ratio as function of Ulysses heliographic latitude θ from day 110 of year 1994 (60° S) to day 320 of 1995 (60° N). The solid line is the latitudinal variation of 2.5 GV protons as determined by Heber et al. (1996b).

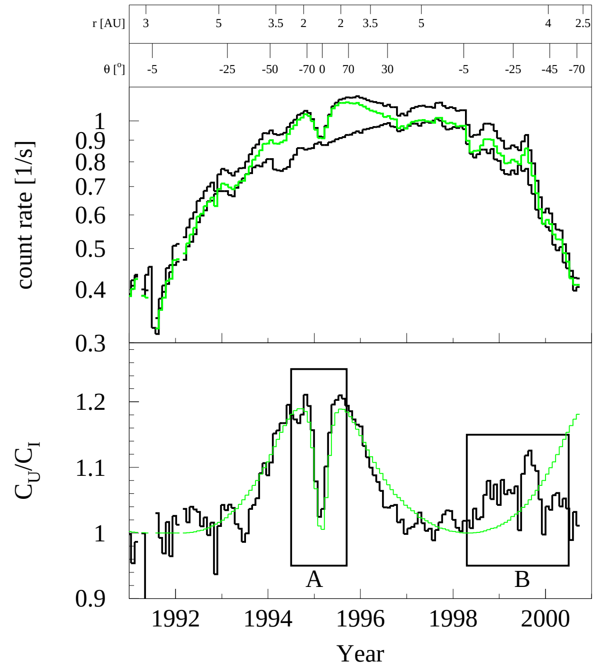

Fig. 4. Upper panel: 26-day averaged quiet time count rates of Ulysses' >250 MeV protons (upper curve) and the guard detector from the GSFC instrument on board IMP (C_I, lower curve) from 1991 to 2001. The grey curve displays the >250 MeV proton count rate C_U, corrected for Ulysses radial variation by using a radial gradient of 2 %/AU. The lower panel displays the ratio of the corrected Ulysses protons to the guard detector and its expected variation (grey curve). For details see text. 'A', and 'B' are defined as in Fig. 2. Ulysses' distance to the Sun and its heliographic latitude are shown at the top.

3 Data Analysis

Period 'A' corresponds to the time period of the fast latitude scan in 1994 and 1995. Detailed discussions of the results can be found in Heber et al. (1996b); Ferrando et al. (1996). Fig. 3 from Heber et al. (1999) displays the proton to electron ratio during the period 'A' as a function of Ulysses' heliographic latitude. The solid curve in Figure 3 represents the variation of the temporally detrended 2.5 GV proton count rates only (from Figure 5 in Heber et al. (1996b)). As this curve is almost a perfect fit to the p/e data, one has to conclude that the contribution of electron latitudinal gradients to this ratio is negligible. Within the uncertainties, a possibly larger electron gradient in comparison with the protons would have no influence on this ratio, as long as the difference is only a few %/AU. Fuji and McDonald (1997) determined a radial gradient for 180–450 MeV/n protons of ~3%/AU and ~1%/AU for an A>0 and A<0, repectively, at a radial distance of 10 AU. In Heber et al. (1999) we rejected the possibility of a significant latitudinal gradient of electrons, which is exactly compensated by the temporal variations, because the temporal variations would have to be symmetric relative to the time when Ulysses crossed the heliographic equator. We conclude therefore that the electrons show no significant latitudinal gradient, in agreement with model predictions (Potgieter et al., 2001).

To investigate period 'B' we display in Fig. 4 the time profile of >250 MeV protons (upper black curve) at Ulysses and the time profile of the guard anticoincidence detector (courtesy H. V. Cane and F. B. McDonald) of the Goddard Space-Flight Center instrument on board IMP (lower black curve). Both channels have been normalized in November 1990, when Ulysses was close to Earth. It is important to note that the count rates are approximately the same in February 1995, when Ulysses crossed the heliographic equator at 1.3 AU, indicating that both channels respond equally to the temporal modulation of galactic cosmic rays. The grey curve in Fig. 4 displays the Ulysses count rate, corrected for the radial movement of the spacecraft with a radial gradient of 2%/AU. In Heber et al. (1993) we determined a slightly larger radial gradient of 3.2 ± 0.8%/AU for the time period from launch in 1990 to September 1992 in the declining phase of solar cycle 22. Comparing the time profile C_I at Earth and the radially corrected Ulysses time profile C_U it is evident that for periods with Ulysses at low latitudes both curves track each other from launch 1990 to mid 1993 and from 1997 to mid 1998. The lower panel shows the corresponding count rate ratio. This ratio is consistent with one during the time periods mentioned. From mid 1993 to 1997 and from 1998 to late 1999 the ratio is correlated with Ulysses' latitude (Heber et al., 1996b, 2001). The grey curve superimposed displays the expected time profile of this ratio by approximating a Gaussian law in time during the fast latitude scan in 1994/1995 (Period 'A'); for details on the fit see Heber et al. (1996b). During period 'B' the ratio is first increasing but then suddenly dropping to 1. Heber et al. (2001) argue that this drop in the ratio has been caused by the reconfiguration of the heliospheric magnetic field from a well ordered dipole like structure to a more complex one. In comparison to the extrapolation from the first fast latitude scan the observed ratio indicates a nearly spherical symmetric distribution of

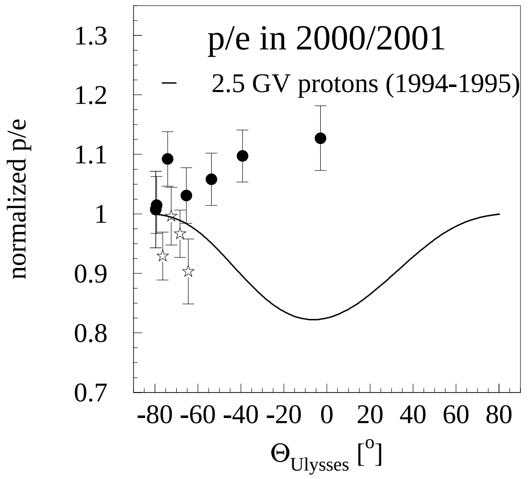

Fig. 5. 2.5 GV p/e ratio as function of Ulysses heliographic latitude θ during the fast latitude scan in 2000 and 2001 (solid points) and during the slow decline from 60° S to 80° S (stars). The solid line is the latitudinal variation of 2.5 GV protons as determined by Heber et al. (1996b) near solar minimum.

galactic cosmic ray protons in the inner three dimensional heliosphere.

In a similar format as in Fig. 3, Fig. 5 displays the proton to electron ratio as a function of Ulysses heliographic latitude from day 180 of year 2000 to day 146. Here, the ratio has been normalized to one for the time period when the spacecraft was above 60° latitude. The solid line superimposed displays in essence the latitudinal variation of 2.5 GV protons as determined by Heber et al. (1996b) near solar minimum. In contrast to the first fast latitude scan the proton to electron ratio shows no obvious correlation with Ulysses' latitude. If there was any variation with Ulysses heliographic latitude, then the data would indicate an increase towards lower latitudes rather than a decrease, as in 1994/1995. As discussed above such a variation is expected in an A$<$0-solar magnetic cycle (Potgieter et al., 2001) for the latitude dependence of the proton to electron if electrons have a positive latitudinal gradient and/or protons have a negative latitudinal gradient. Since the beginning of 2001 the maximum latitudinal extension of the heliospheric current sheet (tilt angle) is decreasing again. In an A$<$0 solar magnetic cycle the e/p-ratio is increasing with decreasing tilt (e.g. Heber, 2001, Potgieter et al., 2001). Therefore Ulysses ongoing observation in the northern hemisphere will be crucial to distinguish between a temporal or a spatial effect. Corresponding data will be presented at the time of the conference. However, the overall latitude profile together with the fact that latitudinal gradients dropped to low values for protons favors the interpretation of a nearly spherical symmetric distribution of galactic cosmic rays around solar maximum (see also Belov et al., 2001).

4 Summary and Conclusion

Ulysses time profiles of 2.5 GV protons and electrons as well as $>$250 MeV protons at Ulysses and Earth have been presented. We find that for the time period from 1992 to mid 1999 the spatial gradients for an integral proton channel in the inner solar system are consistent with values determined until mid 1993. In late 1999 the proton count rate at Ulysses and Earth indicates that the latitudinal gradient drops to small values, at the time of the reconfiguration of the heliospheric magnetic field from a simple dipole like to more complex configuration. This suggests that close to solar maximum activity the cosmic ray distribution is nearly spherical symmetric and that modulation is dominated by diffusion rather than by drifts in the global heliospheric magnetic field. In agreement with this observation the proton to electron ratio also displayed no obvious variation with Ulysses heliographic latitude when it was between 60S and 80S, but since late 2000 sign of a trend in the p/e ratio has developed. Although not as large and well defined yet as during the first fast latitude scan in 1994/1995, it is hinting that drift is beginning to play a role, especially because the tilt angles also dropped significantly since late 2000. However, additional observations are necessary to confirm these trends.

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