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Latitudinal and radial variation of >2 GeV/n protons and alpha-particles at solar maximum: ULYSSES COSPIN/KET and neutron monitor network observations

A. V. Belov[1], E. A. Eroshenko[1], B. Heber[2], V. G. Yanke[1], A. Raviart[3], R. Müller-Mellin[4], and H. Kunow[4]

[1]IZMIRAN, Troitsk, Moscow region, 142190, Russia
[2]Fachbereich Physik, Universität Osnabrück, 49069 Osnabrück, Germany
[3]DAPNIA/Service d'Astrophysique, C. E. Saclay, 91191 Gif-sur-Yvette, France
[4]Institut für Experimentelle und Angewandte Physik, Universität Kiel, 24098 Kiel, Germany

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Abstract. Ulysses, launched in October 1990, began its second out-of-ecliptic orbit in September 1997. In 2000/2001 the spacecraft passed from the south to the north polar regions of the Sun in the inner heliosphere. In contrast to the first rapid pole to pole passage in 1994/1995 close to solar minimum, Ulysses experiences now solar maximum conditions. The Kiel Electron Telescope (KET) measures also protons and alpha-particles in the energy range from 5 MeV/n to >2 GeV/n. To derive radial and latitudinal gradients for >2 GeV/n protons and alpha-particles, data from the Chicago instrument on board IMP-8 and the neutron monitor network have been used to determine the corresponding time profiles at Earth. We obtain a spatial distribution at solar maximum which differs greatly from the solar minimum distribution. A steady-state approximation, which was characterized by a small radial and significant latitudinal gradient at solar minimum, was interchanged with a highly variable one with a large radial and a small – consistent with zero – latitudinal gradient. A significant deviation from a spherically symmetric cosmic ray distribution following the reversal of the solar magnetic field in 2000/2001 has not been observed yet. A small deviation has only been observed at northern polar regions, showing an excess of particles instead of the expected depression. This indicates that the reconfiguration of the heliospheric magnetic field, caused by the reappearance of the northern polar coronal hole, starts dominating the modulation of galactic cosmic rays already at solar maximum.

Key words. Interplanetary physics (cosmic rays; energetic particles) – Space plasma physics (charged particle motion and acceleration)

Correspondence to: B. Heber
(bheber@uni-osnabrueck.de)

1 Introduction

Cosmic ray measurements within a wide range of heliographic latitudes in the inner heliosphere were performed by detectors on board the Ulysses spacecraft in 1994–1996. This time period was characterized by low solar activity and weak modulation of cosmic rays. As displayed in Fig. 1 Ulysses reached a maximum heliographic latitude of 80.2° in the Southern and Northern Hemispheres, and has an orbital period of about half a solar cycle. As a consequence, solar activity was high when Ulysses performed the second rapid pole to pole transition in 2000 and 2001. Figure 1 shows the heliolatitude and radial distance of Ulysses from 1993 to 2004. Black and blue solid circles mark the start of each year during the first and second out-of-ecliptic orbit. The red and green histograms show the evolution of the maximum latitudinal extent of the heliospheric current sheet α during the first – solar minimum – and second – solar maximum – orbit. Hoeksema (http://quake.stanford.edu/~wso/) calculates α using two different magnetic field models: (1) The "classical" model uses a line-of-sight boundary condition at the photosphere and includes a significant polar field correction. (2) The newer 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 Fig. 1 we used the "classical" model. Note that the figure would not be altered qualitatively by using the newer model, whereas the absolute numbers would be different.

For the purpose of this paper, the exact value of α is not crucial, as α is used as a proxy for solar activity. It is low and high during solar minimum and maximum, respectively. All large modulation effects in solar cycle 22 during the first Ulysses orbit occurred while the spacecraft was at low latitudes in 1990 to 1993. Ulysses was again close to the heliographic equator by the time of the onset of solar activity

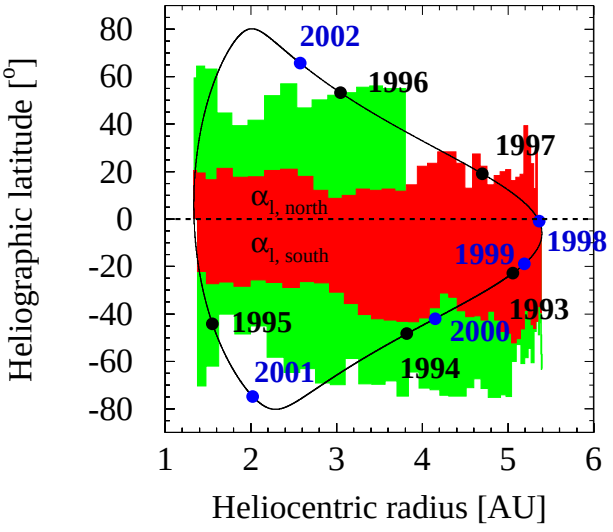

Fig. 1. Ulysses' heliographic latitude as a function of radial distance. Black and blue solid circles mark the start of each year during the first and second out-of-ecliptic orbit. The red and green histograms show the evolution of the maximum latitudinal extent of the heliospheric current sheet α during the first, solar minimum and second, solar maximum orbit.

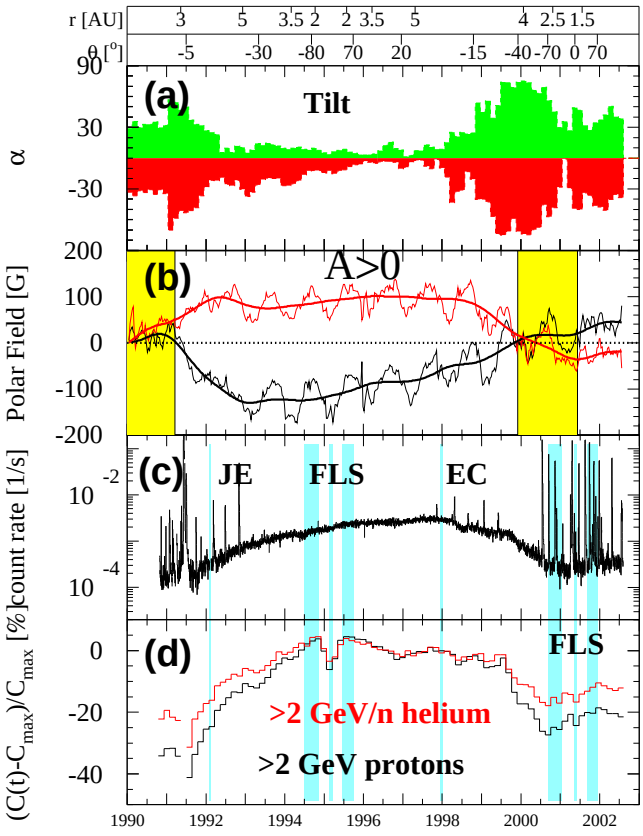

Fig. 2. (a) Evolution of the maximum latitudinal extent of the heliospheric current sheet α. **(b)** Solar polar magnetic field strength for the Southern (black) and Northern Hemisphere (red). The smoothed curves display the 20 nHz low pass filtered values; both are from http://quake.stanford.edu/~wso/. **(c)** Daily averaged count rate of 100–125 MeV (0.3 GV) and **(d)** 26-day "quiet time" count rates of >2 GeV protons and >2 GeV/n alpha-particles. Ulysses' distance to the Sun and its heliographic latitude are shown on top.

in solar cycle 23, at the end of 1997 and beginning of 1998. Since then α and also solar activity remained high.

The evolution of the maximum latitudinal extent of the heliospheric current sheet α (a) and the solar polar magnetic field strength for the Southern and Northern Hemisphere (b) are displayed in Fig. 2 (from http://quake.stanford.edu/~wso/), together with the daily averaged count rate of 100–125 MeV protons (c) and the 26-day averaged "quiet time" count rates of >2 GeV protons and >2 GeV/n alpha-particles (d) from Ulysses' launch in 1990 to mid 2002. In panel (b) the corresponding 20 nHz smoothed solar polar magnetic field strength is superimposed. The 20 nHz low pass filter is used by the Wilcox Solar Observatory to eliminate yearly geometric projection effects. From the time profiles it follows that the two hemispheres reversed their polarities in 1990 and 2000. Hence, the heliospheric magnetic field is expected to reverse its polarity accordingly. In 2001 the northern polar coronal hole was formed (McComas et al., 2001a), showing the corresponding signatures in the heliospheric magnetic field (Smith et al., 2001), indicating the decline towards solar minimum. It is important to note that such interplanetary signatures have not been observed by Ulysses in 2000, when the spacecraft was at 80° S heliographic latitude.

The 26-day averaged "quiet time" counting rates in panel (d) of Fig. 2 are presented as percentage changes with respect to the maximal rates C_{max} measured in mid 1997 at solar minimum. "Quiet time" profiles have been determined by using only time periods when the 100–125 MeV proton channel (panel (c) of Fig. 2) showed no contribution of solar or interplanetary particles (Heber et al., 1999). Marked by shading in (c) and (d) are the Jovian flyby in 1992 (JE), the two rapid pole to pole passages in 1994/1995 and 2000/2001 (FLS), and the ecliptic crossing in 1998 (EC). The observed variations in the particle intensities are caused by temporal and spatial variations due to the Ulysses trajectory. Therefore, the variation from solar minimum to solar maximum in 2000 does not reflect the total modulation amplitude at these rigidities. The two rapid pole to pole transitions at ∼1.5 AU should provide the best "snapshot" of the spatial distribution of cosmic rays in the inner heliosphere at solar minimum and maximum, respectively.

1.1 The 3-dimensional heliosphere at solar minimum

Around solar minimum there is a clear separation between low and high latitudes: (1) While the region close to the heliographic equator is embedded in slow solar wind, polar regions are dominated by the high speed solar wind, originating from the polar coronal holes (McComas et al., 2001a). (2) The heliospheric current sheet, the thin layer separating both magnetic polarities of the heliospheric magnetic field,

is embedded in the slow solar wind regime and stable around solar minimum (McKibben et al., 1998). In an $A > 0$ solar magnetic cycle, like in the 1990's, the heliospheric magnetic field pointed outwards and inwards in the Northern and Southern Hemispheres, respectively. In that case drift models predict that positively charged cosmic rays drift predominantly inward through the solar polar regions and then outward through the equatorial regions along the heliospheric current sheet (Jokipii et al., 1977). (3) The latitudinal distribution of high energy cosmic rays measured by Ulysses showed the expected behavior (Paizis et al., 1995; Heber et al., 1998): The count rate of >2 GeV/n protons and helium increased towards high latitudes, and was nearly symmetric with respect to the equator (Heber et al., 1997; Belov et al., 1999). The observed time profile at these rigidities during Ulysses' first fast latitude scan in 1994/1995 is dominated by the latitudinal gradient (Belov et al., 1999).

1.2 The 3-dimensional heliosphere at solar maximum

The second fast latitudinal scan in 2000/2001 was the first exploration of the inner 3-dimensional heliosphere around solar maximum. The heliosphere was completely different from the first rapid pole to pole passage in 1994/1995. A relatively quiet, stable and well-structured heliosphere was interchanged with a highly variable solar wind and heliospheric magnetic field showing a large number of irregularities (McComas et al., 2001a; Smith et al., 2001). At solar minimum a clear separation exists between low-latitude slow solar wind and fast solar wind. The heliospheric current sheet, which had a "simple" and stable configuration during solar minimum, became a much more complex structure and was observed at polar regions (Smith et al., 2001) (see Fig. 1). During Ulysses' second out-of-ecliptic orbit, the polar coronal holes disappeared and were interchanged with short-lived coronal holes originating at low latitudes. This situation became even more complex due to (1) the increasing number of coronal mass ejections, causing large Forbush effects, which were nearly absent during solar minimum, and (2) the reversal of the solar magnetic field, as described above.

2 Data analysis

As described in the previous section, Fig. 2 displays the daily averaged count rates of 100–125 MeV protons and 26-day "quiet time" averages of >2 GeV/n protons and alpha-particles from the Kiel Electron Telescope (KET) on board Ulysses. Figure 3 shows the high energy KET channels with higher time resolution along with a 1-AU baseline measurement, which is derived from neutron monitor and IMP-8 observations. A simple inspection of Figs. 2 and 3 shows the differences between the first (solar minimum) and the second (solar maximum) orbit. While the spatial variation dominates the temporal variation during Ulysses' first orbit from 1994 to fall of 1997, the observed count rate variation from 1998 to 2001 is determined by the increasing temporal modulation in the inner heliosphere, reaching solar maximum conditions in 2000/2001. Although numerous solar particle events have been observed, the "quiet time" count rates of galactic cosmic ray protons and alpha-particles are continuously increasing during the second fast latitude scan, indicating that none of these events give rise to a modulation barrier, like the March to July activity in 1991 (McDonald et al., 2000).

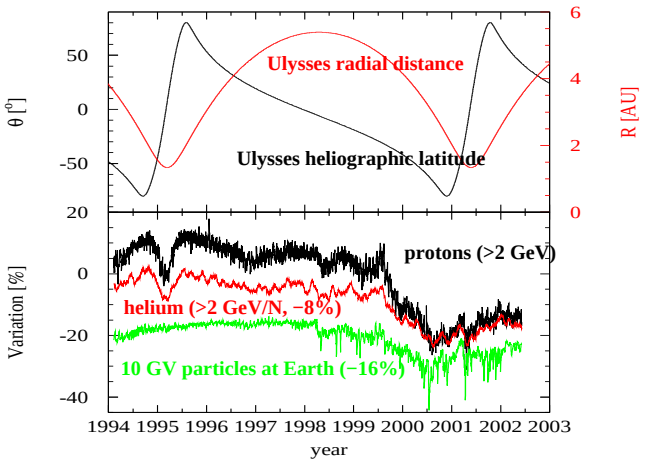

Fig. 3. Ulysses' heliographic latitude and radial distance to the Sun. Daily and 26-day running mean averaged variations >2 GeV/n protons and helium as measured by the KET and 10 GV cosmic ray variation at Earth. The latter is inferred from neutron monitor and IMP-8 observations.

Ulysses' measurements alone are not sufficient to infer a concept about the spatial distribution of the cosmic ray phase space density during the rising phase of the solar cycle because of its temporal variation. However, Fig. 2 indicates that because of the continuous increase during the rapid pole to pole passage in 2000/2001, no significant latitudinal gradients at solar maximum could be present. If such latitudinal gradients would have been present, then the temporal and Ulysses' radial variation must have canceled them exactly. We find such a symmetric temporal variation, centered around day 136 of 2001, unlikely, and, therefore, reject this scenario. Since Ulysses moved from a distance of ∼2 AU at southern polar regions inward to 1.34 AU close to the heliographic equator and then back to ∼2 AU over the north pole, a radial gradient of ∼3%/AU would lead to a 1.021 times higher flux at polar regions. A negative latitudinal gradient of the order of 0.026%/degree might be masked by the radial variation.

In order to derive mean radial and latitudinal gradients around solar maximum, a model describing the temporal and time dependent spatial parameters is applied. The temporal variations can be described by appropriate 1 AU observations, as given by the neutron monitor network, and displayed together with the Ulysses observations in Fig. 3. The radial and latitudinal gradients are then derived from a fit to the KET data using Ulysses' trajectory parameters as displayed in the upper panel of Fig. 4. We assume that temporal, radial

and latitudinal dependencies of the cosmic ray intensities are separable, so that the cosmic ray intensity at Ulysses can be described as:

$$I^i(t,r,\theta) = I_0^i(t_0,r_0,\theta_0)\cdot(1+\delta^i(t))\cdot f_r^i(t,r)\cdot f_\theta^i(t,\theta)\,, \quad (1)$$

where $I_0^i(t_0,r_0,\theta_0)$ is the particle intensity at time t_0 at a distance r_0 from the Sun and at a heliographic latitude θ_0; $\delta^i(t)$ is the intensity variation at a time (t). Note that $\delta^i(t) < 1$. The index i is used for the type of particle (p for protons and h for alpha-particles).

2.1 Radial variation

Since Ulysses' radial variation is small, we can write $f_r^i(t,r) = \exp(g_r^i(t)\cdot(r-r_0))$ with $g_r^i(t)$ as a time dependent radial gradient. It is reasonable to relate $g_r^i(t)$ with the depth of modulation $\delta^i(t)$: $g_r^i(t) = g_{0,r}^i + g_{1,r}^i\delta^i(t)$, where $g_{0,r}^i$ describes the radial gradient at solar minimum and $g_{1,r}^i$ its changes within the solar cycle. In what follows we will use both, the stationary and time dependent approximation of the radial gradient.

2.2 Latitudinal gradient

Although Ulysses' observations over the whole latitude range from the heliographic equator to southern and northern polar regions indicates that two different modulation regions exist, with different latitudinal gradients in the fast and "slow" solar wind regime (Heber et al., 1998, 2002), we assume that $f_\theta^i(t,\theta) = \exp(g_\theta^i(t)\cdot(\theta-\theta_0))$. Herein is $g_\theta^i(t)$ the time dependent latitudinal gradient.

2.3 Temporal variations

Unfortunately, there is no 1-AU baseline instrument for the KET cosmic ray measurements available. The time variation $I_0^i(t_0,r_0,\theta_0)$ has to be estimated by observations of high energy particles by the neutron monitors from the world-wide network on Earth. From these data a rigidity spectrum of the cosmic ray density variations can be derived on a daily basis (Heber et al., 1997; Belov et al., 1999, 2001). Since a simple power law rigidity spectrum is not sufficient to describe the long-term variations, we assumed a rigidity dependence $f(R) = 1/(\beta+R^\gamma)$. The expected neutron monitor counting rate variation is $\delta = a_0c_0 = a_0\int_{R_c}^{\infty} W(R)f(R)/f(R_0)dR$, where a_0 and c_0 are amplitude and coupling coefficients of the isotropic cosmic ray variation, respectively, R_c is the geomagnetic cutoff rigidity, $R_0 = 10\,\mathrm{GV}$. The parameters a_0, β, and γ can be found for every day by comparing the expected variations and the real variations observed by the neutron monitor network (more than 30 stations). While the approach of deriving the rigidity spectrum of the temporal variation is useful at solar minimum (Heber et al., 1997; Belov et al., 1999), it is not reliable around solar maximum because of the large uncertainties as described by Belov et al. (2001). In this paper we determine the temporal modulation for >2 GeV/n protons and alpha-particles, assuming that the modulation depth $\delta^i(t)$ is proportional to the modulation depth $\delta_{10}(t)$ at 10 GV. The latter can be determined from the neutron network observations with high accuracy. Taking into account all the assumptions listed above and introducing $l_{mod}^i = ln(I^i(t,r,\theta))$, we can rewrite Eq. (1):

$$l_{mod}^i = ln(I^i(t,r,\theta)) = a^i + b_\delta^i\delta_{10} + g_\theta^i\theta + (g_{0r}^i + g_{1r}^1\delta^i)\cdot r. \quad (2)$$

Herein the explicit time dependence of the five parameters especially for g_θ, has been neglected. We used the least-square root method to obtain the four or five unknown parameters in Eq. (2) from the observations. It is important to note that the cosmic ray spatial distribution during high solar activity is more complicated than at solar minimum. For example, during Ulysses' solar minimum orbit in 1994 to 1997 the cosmic ray observations were dominated by (1) latitudinal, (2) radial, and (3) temporal variations. Therefore, we could determine the latitudinal gradient, during Ulysses' fast latitude scan, and the radial gradient, when Ulysses was back to the heliographic equator in 1997 (Belov et al., 1999).

At solar maximum one should take into consideration that the parameters g_r, g_θ in Eq. (2) become dependent on time, radial distance and heliographic latitude (McDonald et al., 1997; Fujii and McDonald, 1997) The cosmic ray time profile, which should not be related to Ulysses' position, correlates occasionally with the spacecraft distance and/or latitude. Such a correlation can be essentially high on relatively small time intervals (less than a year). To obtain a reliable and stable fit of Eq. (2) to the data we need to analyze the data sets for long time periods.

3 Results and discussion

To determine the mean radial and latitudinal gradients we analyzed the time period from January 1998 to mid 2002. This period is characterized by (1) increasing solar activity from 1998 to 2000, (2) solar maximum activity of cycle 23 in 2000/2001, and (3) declining activity in 2002. It is important to note that the latter period includes the reversal of the heliospheric magnetic field. The total observed cosmic ray modulation for 10 GV particles at Earth exceeded 30%. In what follows we will discuss the observations, excluding the time period of the heliospheric magnetic field reversal, which corresponds to the times when Ulysses was in the Southern Hemisphere, the observations during the second fast latitude scan, and the latest data, taken in the Northern Hemisphere.

3.1 Cosmic ray gradients during the rising and maximum phase of the solar cycle

From January 1998 to May 2001 Ulysses was in the Southern Hemisphere, reaching its maximum southern latitude of 80° S in November 2000, and returning to the heliographic equator in May 2001. In that time period its distance to the Sun was gradually decreasing from 5.4 to 1.4 AU. Although Ulysses scanned the whole latitude range, the cosmic

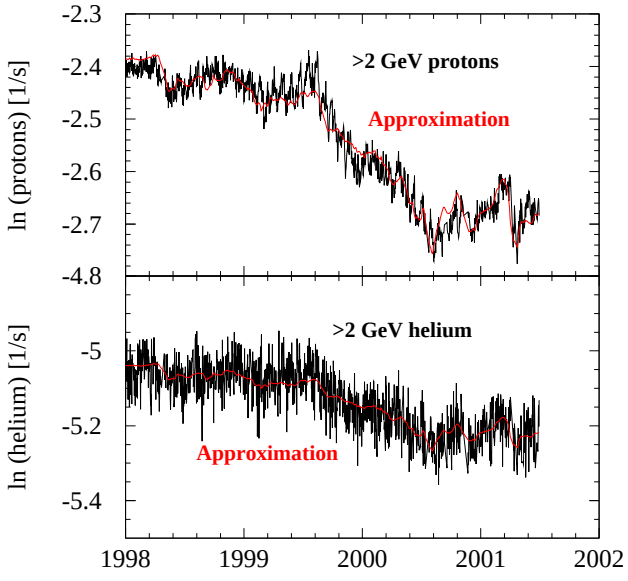

Fig. 4. Daily and 26 day running mean averages >2 GeV Ulysses protons (upper) and helium (lower panel) and the fit of Eq. (2) to the data. For the parameters in Eq. (2) see text.

ray measurements are dominated by the large, temporal variation, leading to a high correlation in cosmic ray behavior measured at Earth and on board Ulysses.

Due to the different heliographic latitudes and longitudes of Ulysses and Earth, not all short-term cosmic ray decreases caused by, for example, coronal mass ejections or corotating interaction regions are seen at Earth and at Ulysses. Since Ulysses is at a larger radial distance than Earth, an outward moving disturbance will reach the spacecraft later. In order to account for these effects, we applied the following two corrections to the data:

1. Measurements at Earth have been "shifted" to the Ulysses position. If we take into account a propagation speed of 400 km/s for a disturbance moving from 1 AU to Ulysses at a radial distance r_u, the time profiles at Earth and at Ulysses are better correlated; the correlation coefficient increased from 0.954 to 0.972;

2. Solar rotation averaged running means have been used to minimize the longitudinal differences.

If we assume that the radial gradient is constant over the time period of interest (from January 1998 to May 2001), $g_{1,r} = 0$, the fit of Eq. (2), as displayed in Fig. 4, leads to the following results for >2 GeV/n protons and alpha-particles (for comparision the values obtained at solar minimum have been given too; Belov et al., 1999):

	solar maximum	solar minimum
g_r^p	$= (3.9 \pm 0.1)\%/AU$	$(0.5 \pm 0.1)\%/AU$
g_θ^p	$= (0.02 \pm 0.01)\%/^\circ$	$(0.17 \pm 0.02)\%/^\circ$
b_δ^p	$= 1.37 \pm 0.04$	$n.a.$

	solar maximum	solar minimum
g_r^h	$= (2.4 \pm 0.2)\%/AU$	$(0.5 \pm 0.2)\%/AU$
g_θ^h	$= (-0.01 \pm 0.01)\%/^\circ$	$(0.12 \pm 0.01)\%/^\circ$
b_δ^h	$= 0.93 \pm 0.07$	$n.a.$

Using these parameters we obtain for protons and alpha-particles correlation coefficients of 0.972 and 0.81. Note that the poor correlation coefficient for the alpha-particles results from the large statistical uncertainties. If we take into account the variation of the radial gradient with the modulation depth, we find for >2 GeV protons that the radial gradient is varying between 3.4 and 4.2%/AU. However, in that case the correlation coefficient is statistically not significant, and it is important to note that no temporal dependence of the latitudinal gradient has been taken into account; therefore, our results are not in contradiction with the result at lower rigidities from Heber et al. (2002), who attributed the higher count rates of the data compared to the expectation in mid 1999 to the existence of latitudinal gradients. These gradients vanish later. It is important to keep in mind that Ulysses was below 20° S before 1999 and around 30°, when this latitudinal gradient has been observed. In Heber et al. (1997, 1998) it was shown that latitudinal gradients are significantly smaller close to the heliographic equator than at higher latitudes, so that a significant contribution of the latitudinal gradient is not expected to occur before 1999. If we attribute the excess of the observations in mid 1999 in Fig. 4 to a latitudinal gradient, then we find $g_\theta \sim= 0.17\%$/degree. This value is in good agreement with the value $g_\theta = 0.17 \pm 0.02\%$/degree found by Belov et al. (1999) at solar minimum.

In what follows we will neglect the latitudinal dependence, because the mean latitudinal gradient was found close to zero for the high latitude observations (see Fig. 4). We can rewrite Eq. (2) to:

$$l^i_{mod} = ln(I^i(t,r,\theta)) = a^i + b^i_\delta \delta_{10} + g^i_{r,0} r \,. \quad (3)$$

Our analysis showed that the approximation is even valid until July 2001, and we can extent our analysis to that period. We obtain the following parameters for >2 GeV/n protons and alpha-particles:

$$g_r^p = (3.7 \pm 0.1)\%/AU$$
$$b_\delta^p = 1.49 \pm 0.03$$

$$g_r^h = (2.2 \pm 0.2)\%/AU$$
$$b_\delta^h = 0.92 \pm 0.06$$

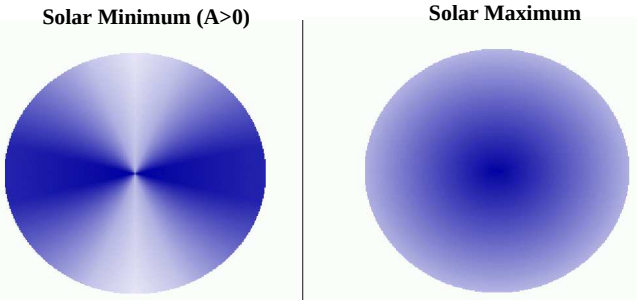

Fig. 5. Meridional cut of the >2 GeV/n protons spatial distribution in a sphere of 5 AU radius during solar minimum **(a)** and solar maximum **(b)**. Dark and light regions correspond to low and high intensities, respectively. For details see text.

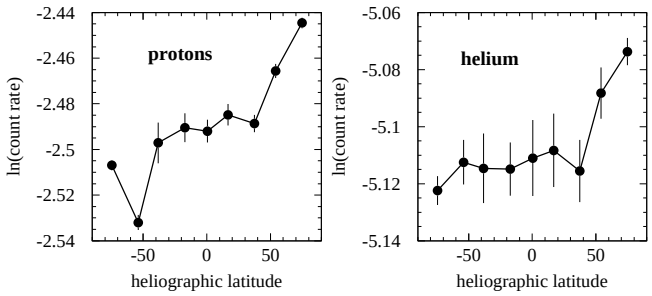

Fig. 6. Twenty-six-day averaged count rates of >2 GeV/n protons and alpha-particles as a function of Ulysses' heliographic latitude from the beginning of February to the end of September 2001 during the second fast latitude scan.

The red curves in Fig. 4 correspond to the result of this spherically symmetric approximation. It is important to note that from mid 1999 to mid 2001, corresponding to 2 years around solar maximum, the cosmic ray distribution is in good agreement with a spherically symmetric one, which is characterized by large radial and nearly no latitudinal gradients. In contrast, Belov et al. (1999) and Heber et al. (1997) determined radial and latitudinal gradients $g_r^p = 0.5\%/\mathrm{AU}$ and $g_\theta^p = 0.19 \pm 02\%/^\circ$ for the first Ulysses orbit. As mentioned above they also found that the latitudinal gradient was small only within the narrow region of the streamer belt.

To visualize the differences between the mean cosmic ray distribution obtained by Ulysses and the neutron monitor network at solar minimum in 1994 to 1996 and around solar maximum from mid 1999 to mid 2001, Fig. 5 (left) and Fig. 5 (right) display these distributions within a sphere of 5 AU radius. To obtain the solar minimum distribution we used $g_r = 0.5\%/\mathrm{AU}$, $g_\theta = 0$ for $|\theta| < 15^\circ$, else $g_\theta = 0.19\%/^\circ$, gradually decreasing to zero above 70°. To obtain the solar maximum distribution, a constant radial gradient of 4%/AU has been applied. In contrast to solar minimum our analysis indicates a spherically symmetric distribution of cosmic rays around solar maximum. The intensities in the inner heliosphere depend on the radial distance from the Sun only, while in 1994 to 1996 the latitude dependence outside of the streamer belt (∼15°) dominates the observations at solar minimum. Since the radial gradient was increasing in 1997/1998 (Belov et al., 1999; McDonald et al., 2001), we suggest that the transformation from the minimum to the maximum distribution must have occurred around mid 1999, when the spacecraft was well below the heliographic equator, allowing for a good determination of latitudinal effects.

Another important conclusion can be made by the comparison of the spatial distributions displayed in Fig. 5. Since latitudinal gradients were positive at solar minimum in the last cycle and vanishing thereafter, the total modulation is higher at polar latitudes than in the ecliptic. While the observations at solar minimum in an $A > 0$ solar magnetic cycle confirm the results from advanced modulation models (Potgieter et al., 2001), the distribution obtained by Ulysses during the next $A < 0$ solar minimum will be a crucial test for such models.

3.2 Cosmic ray gradients around solar maximum in the Northern Hemisphere

The results discussed in the previous section relate to the Ulysses observations in the Southern Hemisphere. The fit of Eq. (2) and (3) to the Ulysses data from mid 2001 to the most recent data were not successful. This might have several causes:

- In contrast to the Southern Hemisphere observations, all observations available were performed during the declining phase of the solar cycle 23;
- In contrast to the high southern latitudes a polar coronal hole was observed in the Northern Hemisphere, indicating the reconfiguration at the Sun. If latitudinal gradients are tied to the fast solar wind region, then the fit by both equations will fail, because of the spatial dependence of the latitudinal gradient;
- As argued by Heber et al. (2002) the temporal change of radial and latitudinal gradients does not occur simultaneously.

In order to determine the gradients by fitting Eq. (2) to the data, more data at low latitudes are needed to determine the radial gradient with better precision. Due to the reconstruction of the heliospheric magnetic field towards a well-ordered structure, the galactic cosmic ray distribution is expected to change (Heber et al., 2003), which might not be expressed by the modulation depth, so that Eq. (2) is not applicable.

3.3 The solar maximum fast latitude scan

The second fast latitude scan occurred early in the declining phase of solar cycle 23, when the cosmic ray intensities started to recover. Besides the relative short time period – it took Ulysses 11 months from the southern polar cap to the

northern one – the radial variations were small. We selected the part of the Ulysses orbit, when the spacecraft was within 2.5 AU from the Sun, which covers the time period from December 2000 to December 2001, and the whole latitudinal range from 80° S to 80° N. Hence, we used the radial and temporal parameters as determined in the previous section. The residual profile should, therefore, reflect the latitudinal dependence of the cosmic ray fluxes as displayed in Fig. 6 for 2 GeV/n protons and alpha-particles as a function of Ulysses' latitude. A simple inspection of Fig. 6 shows that the proton and helium intensities depend only weakly on latitude with the exception of the increase above $\sim$ 50° N for both species. The drop in the Southern Hemisphere at about 60 ° S is only observed in 2 GeV protons and might be rather caused by the increased solar activity in March 2001, with large short-term cosmic ray variations, rather than by the latitudinal distribution. In contrast, the increase in the Northern Hemisphere is seen in both channels and has a consistent trend. If we attribute this trend to a latitudinal gradient, then a value of $g_\theta \sim 0.12\%$/degree and $g_\theta \sim 0.1\%$/degree for protons and alpha-particles is obtained. It is important to note that this latitudinal gradient is smaller than the one observed at solar minimum in 1994/1996, but it is still positive. At a first view this is a surprise because the solar magnetic field reversed in 2000/2001, and drift should operate in this solar cycle such that positively charged particles are streaming in along the heliospheric current sheet and out in polar directions, leading to negative latitudinal gradients. However, the latitudinal dependence of cosmic rays is not only determined by drifts, but also by diffusion, convection and adiabatic deceleration. These mechanisms depend differently on the heliospheric conditions. In this context it is important to note that significant latitudinal gradients were observed mainly in the fast solar wind regime (Heber et al., 1998; Belov et al., 1999). If the particle transport depends on such structures, one expects no dependence on the solar magnetic epoch. The reappearance of the northern polar coronal hole in 2001 (McComas et al., 2001b) would consequently lead to larger cosmic ray intensities at polar regions than close to the streamer belt. At the same time the structure of the heliospheric current sheet was still very complicated. Thus, drifts, which would cause negative latitudinal gradients, were not fully "operational", leading to positive latitudinal gradients. This is in agreement with the constancy of the e/p-ratio at 2.5 GV as measured by Ulysses (Heber et al., 2003). In order to analyze and interpret the observations, further measurements are needed. A detailed analysis of the Northern Hemisphere data will be possible, when the spacecraft has returned close to the ecliptic plane.

4 Summary and conclusion

In this paper we determined important modulation parameters, like the radial and latitudinal gradient, as well as the modulation depth from solar minimum to maximum, by using Ulysses' KET and neutron monitor network observations. We could show that the mean spatial distribution at solar minimum from 1994 to 1996 is remarkably different from the one at solar maximum from 1998 to mid 2001. While the positive latitudinal gradient dominates the picture at solar minimum this distribution is spherically symmetric around solar maximum, with large radial gradients in the inner heliosphere. The increase in solar activity is accompanied by an increase in the radial gradient. When Ulysses was at high heliographic latitudes above 30° S from mid 1999 on, no significant latitudinal structure could be found until July 2001, when Ulysses was going above $\sim$50° N and the tilt angle α fell down sharply. It is interesting to note that, as a consequence of the reconstruction of cosmic rays from a latitude dominated to a spherically symmetric distribution at solar maximum, the magnitude of the 11-year cosmic ray cycle is essentially bigger at polar regions than close to the heliospheric equator, particularly near Earth.

Unfortunately, the observations during the slow northern descent of Ulysses in 2001/2002 are difficult to interpret, and we have not been successful in determining the gradients and temporal variations independently from each other. However, we investigated the second fast latitude scan, assuming that the radial gradient as well as the parameters describing the temporal variation stay constant during these 11 months. As a result of this analysis we find higher cosmic ray intensities in the northern polar region than close to the heliographic equator. If we interpret these as latitudinal gradients, we can determine g_θ to be 0.12%/degree and 0.1%/degree for 2 GeV/n protons and alpha-particles, respectively, with a lower accuracy for the helium channel. It is important to note that this interval is correlated with the time period when Ulysses is embedded in the recently developing northern polar coronal hole. From mid 1999, when Ulysses was above 30° S to mid 2001, a highly variable and slow solar wind has been observed by Ulysses only (McComas et al., 2001b). In Heber et al. (1998) and Belov et al. (1999) we showed that latitudinal gradients are small in the streamer belt dominated region. Therefore, we argue here that the expansion described by the tilt angle and structure of the streamer belt to high heliographic latitudes leads to a strong increase in modulation and the form of the cosmic ray spatial distribution in the inner heliosphere. As the tilt angle is decreasing towards solar minimum, with the development since 2001 of the northern polar coronal hole, fast solar wind emanating from that hole has been observed by Ulysses. Nearly simultaneously an increase in the particle intensities at high northern polar latitude can be observed. This is in agreement with a concept of a close correlation of the cosmic ray modulation with the HMF configuration.

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