Proceedings of ICRC 2001: 3996 © Copernicus Gesellschaft 2001

ICRC 2001

Latitudinal and radial variation of $>$2 GeV/n protons and α-particles in the southern heliosphere at solar maximum: ULYSSES COSPIN/KET and neutron monitor network observations.

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Abstract. Ulysses, launched in October 1990, began in its second out-of-ecliptic orbit in September 1997 and its second fast latitude scan in November 2000. In contrast to the first orbit with the Sun declining to low activity, we are now at solar maximum conditions. The Kiel Electron Telescope (KET) on-board Ulysses measures proton and alpha-particles in the energy range from 5 MeV/n to $>$2 GeV/n. To derive radial and latitudinal gradients, data from the Chicago instrument on board IMP-8 and the neutron monitor network have been used. To determine the time profile of $>$2 GeV/n proton and alpha-particles at Earth further data reduction,as described in our previous work, is necessary.The latitudinal gradient obtained during the time period from 1997 to 2001 revealed a big difference between those found during Ulysses' first latitude scan in 1994 and 1995 during solar minimum activity. An approximation by a steady-state cosmic ray spatial distribution is characterized by a small radial and large latitudinal gradients, was interchanged with a highly variable one with a large radial and a small - consistent with zero - latitudinal gradient.

1 Introduction

Cosmic ray (CR) measurements within a wide range of heliographic latitudes 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 CR. All large modulation effects in the 22-nd solar cycle during the first Ulysses orbit occurred while the spacecraft was at relatively low latitudes in 1990 to 1993. Ulysses was again close to the heliographic equator by the time of the onset of solar activity in solar cycle 23, at the end of 1997and beginning of 1998.

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. 2) The heliospheric current sheet, the thin layer separating both magnetic polarities of the heliospheric magnetic field (HMF) 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 HMF pointed outwards and inwards in the northern and southern hemisphere, respectively. 3) The latitudinal distribution of high energy cosmic rays measured by Ulysses showed the expected behavior at solar minimum (Paizis et al., 1995; Heber et al., 1998): The count rate of $>$2GeV/n protons and helium increased towards high latitudes, and was nearly symmetric with respect to the equator (Heber et al., 1997, and 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 and not by the radial CR distribution (Belov et al., 1999)

6 years and two months later Ulysses came back to the same heliographic latitudes and distances and found itself under different heliospheric conditions: There are no polar coronal holes. Short living and highly variable coronal holes at low latitudes were observed. The heliospheric current sheet was much more complex around solar maximum and reached latitudes of $>70^o$ (Forsyth, 2001, private communication). This situation got even more complicated due to the fact of the increasing number of coronal mass ejections (CMEs) and their influence on CR. This work is intended to determine, the latitudinal and radial distribution of high energy CR in the inner heliosphere. The result will be compared with the distribution determined during the first Ulysses orbit, characterizing the solar minimum heliosphere.

2 Data Analysis

Fig. 1 displays daily averaged count rates of $>$2 GeV/n protons and α-particles from the Kiel Electron Telescope (KET)

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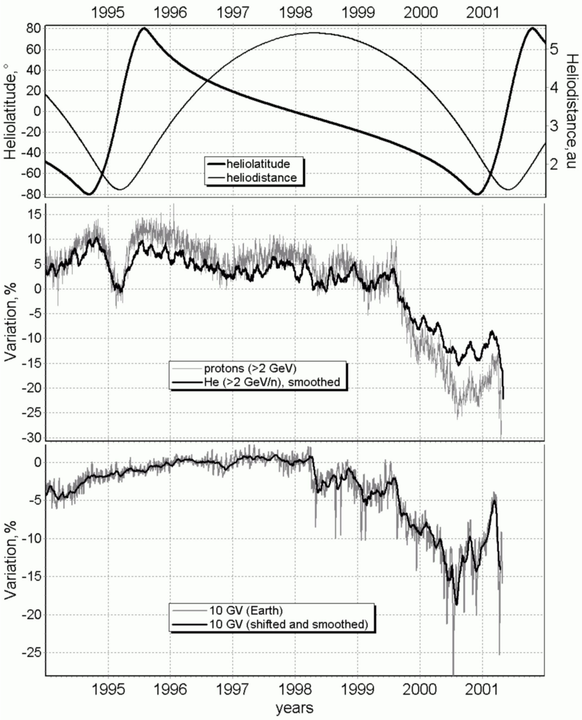

Fig. 1. Variations of Ulysses' heliospheric latitude and distance from the Sun along from 1994 to 2001 (upper panel); daily and 26-day running mean averaged variations of Ulysses >2GeV/n protons and helium (mid panel); variation of 10 GV CR at Earth, inferred from the neutron monitor network. 26-day running mean averages have been shifted in time to take into account the propagation time of a disturbance from Earth to Ulysses (lowest panel).

on board Ulysses in the time period from 1994 to 2001. Inspection of Fig. 1 clearly show 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 changing temporal modulation conditions in the inner heliosphere. Under such conditions Ulysses measurements alone are not sufficient to infer a concept about the CR space distribution and its time variations. However, it is possible to compare the observations with theoretical distributions and check for it consistency. In our model we assume that temporal, radial and latitudinal dependencies of the CR intensities are separable:

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

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 α-particles). Since Ulysses' radial variation is small, we can write $f_r^i(t,r) = \exp(g_r^i(t) \cdot (r - r_0))$ with $g_r^i(t)$ a time dependent radial gradient. Although Ulysses covers the whole latitude range from the heliographic equator to southern polar regions 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. It is common 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. Unfortunately, there are no identical baseline instruments for KET CR measurements available. Therefor 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 (NM) from the world wide network on the Earth. From these data a rigidity spectrum of the CR density variations for every day can be derived (Heber et al., 1997; Belov et al., 1999) for quiet time periods - periods when no particles of solar or interplanetary origin contaminates the CR fluxes. In those papers the obtained rigidity spectra have been used to calculate the expected variations of the >2 GeV/n protons and α-particles at Earth. The determination of the temporal variation of >2 GeV/n particles from the neutron monitor network relies on the exact determination of the temporal variation at higher rigidities (typically 10 to 20 GV) and its extrapolation to lower rigidities (~6 GV). While such an Ansatz is useful during solar minimum it is not reliable around solar maximum because of the large uncertainties due to the extrapolation. In order to determine the temporal modulation for >2 GeV/n protons and α-particles we assume 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 equation (1) as following:

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

Herein the explicit time dependence of the five parameters but especially for g_θ have been neglected. We used the "ls-method" to obtain the five unknown parameters in eq. (2) from the observations. It is important to note, that the CR space distribution during high solar activity is more complicated than at solar minimum. E.g. during Ulysses' fast latitude scan in 1994/1995 the CR observations were dominated by 1) the latitudinal, 2) radial, and 3) temporal variation. Therefore we could determine a) the latitudinal gradient, when Ulysses was at high heliographic latitudes and during its fast latitude scan, and b) the radial gradient, when Ulysses was back to the heliographic equator in 1997 with high precision (Belov et al., 1999). When going from solar minimum to solar maximum conditions one should take into consideration that the parameters in eq. (2) might become dependent on time, radial distance and heliographic latitude too. The CR time variation, which is not related to Ulysses spatial position, correlates occasionally with the spacecraft distance and latitude. Such a correlation can be essentially high on relatively small time interval's (less than a year). To obtain reliable and stable approximations of eq. (2) to the data and with it a mean radial and latitudinal gradient, we

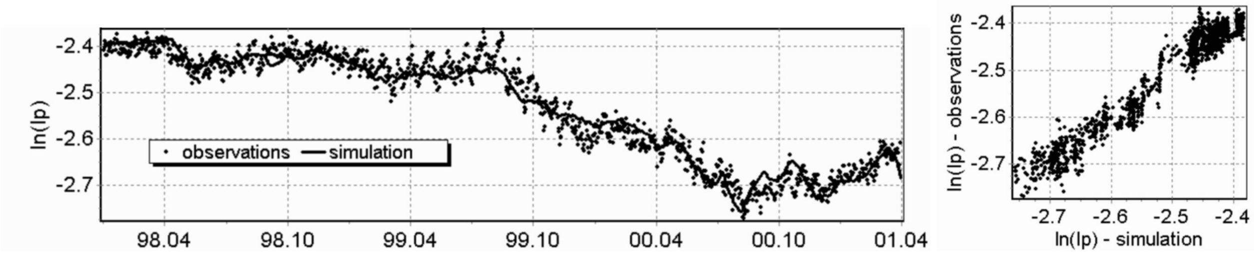

Fig. 2. Daily averaged variation of >2 GeV Ulysses protons (dots) and its approximation by eq. (2). For the parameters in eq. (2) see text.

need to analyze both (Ulysses and 10 GV particle) data sets for a long time period.

3 Results and Discussion

To determine the mean latitudinal gradients we analyzed the time period from January 1998 to March 2001. This period was characterized by high high solar activity, including maximum activity of solar cycle 23, as well as the reversal of the HMF, leading to a significant CR modulation from April 1998 to its maximum in July 2000; the daily averaged 10 GV variation at Earth exceeded 30%. During this time Ulysses was in the southern hemisphere,starting from 01^o S (January 1998), reaching it's maximum southern latitude of 80^o S in November 2000, and returning to $\sim$30^o in March 2001, while its distance to Sun was gradually decreasing from 5.4 to 1.5 AU. Although Ulysses scanned the whole latitude range the CR measurements are dominated by the large temporal variation, leading to a high correlation in CR behavior measured at Earth and on-board Ulysses over the last two years. 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 even better correlated. Due to the different heliographic latitudes and longitudes of both spacecraft, not all short term CR decreases caused by e.g. CMEs or corotating interaction regions are seen at Earth and at Ulysses. The influence of these short term decreases can be minimized when using solar rotation (26 day) averaged running mean averages. These averages are determined by also taking into account the time lag due to the propagation of the solar wind from Earth to Ulysses and are displayed in Fig. 1. For >2 GeV/n protons and α-particles the best approximation of eq. (2) to the observations are obtained when using the following parameter: $g^p_{0,r} = 4.1 \pm 0.2$ %/AU, $g^p_{1,r} = -0.07 \pm 0.02$ %/AU, $g^p_\theta = -0.01 \pm 0.01$ %/^{o}, $b^p_\delta = 1.60 \pm 0.07$ %/AU and $g^h_{0,r} = 2.6 \pm 0.4$ %/AU, $g^p_{1,r} = -0.07 \pm 0.04$ %/AU, $g^h_\theta = -0.05 \pm 0.02$ %/^{o}, $b^p_\delta = 1.17 \pm 0.14$ %/AU. The result of these approximation is displayed for >2 GeV protons in Fig. 2 left. Fig. 2 right shows the correlation of the calculated and measured l^p_{mod}. The corresponding correlation coefficient is 0.974, indicating that our approximation by eq. 2 is a good fit to the observations.

As a result the radial gradient of >2 GeV protons and α-particles is increasing from 4.0%/AU to 5.3%/AU and 2.5%/AU to 3.8%/AU, respectively. The latitudinal gradients found are consistent with zero, indicating that the CR distribution is in contrast to solar minimum nearly spherical symmetric around solar maximum. The temporal variation of > 2 GeV/n protons and α-particles exceeded the CR modulation depth of 10 GV particles by a factor of 1.6 and 1.17, respectively. At this point we would like to emphasize, that we have not taken into account a temporal or spatial dependence of all parameters in eq. (2). Therefore the uncertainty of each value is larger than the statistical one, given above. Nevertheless, we argue that the second Ulysses out-off ecliptic orbit is characterized by large radial and small latitudinal gradients. In contrast the gradients were $g^p_r = 0.5$%/AU and $g^p_\theta = 0.19 \pm 02$%/^{o} for the first Ulysses' orbit (Belov et al., 1999 and Heber et al., 1997). The latitudinal gradient was small only within the narrow belt of the streamer belt (Belov et al., 1999 and Heber et al., 1997).

To visualize the differences between the mean CR distribution obtained by Ulysses and the neutron monitor network at solar minimum in 1994 to 1996 and around solar maximum from 1998 to 2001, Fig. 3 (a) and Fig. 3 (b) display these distributions within a sphere of 5 AU around solar minimum and solar maximum, respectively. To obtain the solar minimum distribution in Fig. 3 (a) we used $g_r = 0.5$ %/AU, $g_\theta = 0$ for 15^o S $< \theta <$ 15^o N, $g_\theta = 0.19$ %/^{o}, gradually decreasing to zero above 70^o. In Fig. 3 (b) we displayed the corresponding proton distribution around solar maximum from 1998 to 2001. For the radial gradient a constant value of 4.4%/AU has been applied. A simple inspection of Fig. 3 (a) and Fig. 3 (b) show the differences of both distributions clearly. In contrast to solar minimum our analysis indicates a spherical symmetric distribution of CR around solar maximum. The intensities in the inner heliosphere are depending on the radial distance from the sun only, while in 1994 to 1996 the latitude dependence outside of the streamer belt ($\sim$15^o) dominates the observations at solar minimum. Since the radial gradient was increasing in 1998 (Belov et al., 1999) we suggest that the transformation from the minimum to the maximum distribution must have occurred before mid 1999, when the spacecraft was well below the heliographic equator, allowing a good determination of latitudinal effects.

Another important conclusion can be made by the comparison of the spatial distribution displayed in Fig. 3 (a) and Fig. 3 (b). Since latitudinal gradients were positive at solar minimum in the last cycle and vanishing to zero, the total

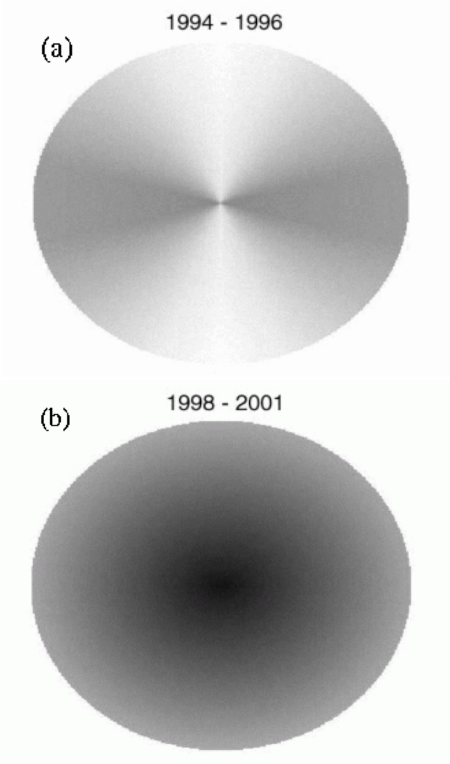

Fig. 3. Meriodinal cut of the >2 GeV/n protons spatial distribution in a sphere of 5 AU during solar minimum (a) and solar maximum (b). Dark and light regions corresponds to low and high intensities, respectively. For details see text

modulation is higher at polar latitudes than in the ecliptic. While the observations at solar minimum in an A$>$0 solar magnetic cycle confirms the results from advanced modulation models (Potgieter et al., 2001), the distribution obtainable by Ulysses during the next solar A$<$0 solar minimum will be a crucial test for such models.

4 Summary and Conclusion

In this paper we determined important modulation parameter like the radial and latitudinal gradient as well as the modulation depth for solar minimum and solar 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 2001. While the positive latitudinal gradient dominates the picture at solar minimum this distribution is spherical symmetric around solar maximum, with large radial gradients in the inner heliosphere. The increase of solar activity is accompanied by an increase of the radial gradient. When Ulysses was at high heliographic latitudes above 30^o S from mid 1999 on, no significant latitudinal structure could be found. As mentioned above the heliospheric conditions were very different for Ulysses during the first and second out-off ecliptic orbit. During the first one the spacecraft was embedded in the fast solar wind stream of the polar coronal hole. In contrast the plasma instruments measured slow highly variable solar wind during the second orbit only (McComas et al, 2001). 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 of the streamer belt to high heliographic latitudes lead to a strong increase in modulation at heliographic latitudes below the maximum extend (tilt) of the heliospheric current sheet. The latter increases simultaneously with the expansion of the streamer belt towards higher latitudes. Indeed, monthly averaged tilt angles of the heliospheric current sheet increased from $<15^o$ in 1997 to above 50^o in the beginning of 1998 (http://quake.stanford.edu:80/∼wso), indicating the importance of the heliospheric current sheet tilt for CR modulation. Both the modulation depth and form of the CR space distribution in the inner heliosphere are related to its changing configuration. It is interesting to note that as consequences of the global reconstruction for CR the magnitude of the 11-year CR cycle is essentially bigger at polar regions than close to the heliospheric equator, in particular near Earth. Since the tilt angle is now decreasing again towards the solar minimum our concept of a close correlation of the CR modulation with the HMF configuration can be tested in the near future.

Acknowledgements. This work is supported by RFFR, grants 99-02-18003 and 01-02-17580. We are grateful to the Bartol Research Institute (U.S.NSF grant ATM-0000315), to University of Chicago (U.S. NSF grant ATM-9912341) and to all other contributors of the NM data. The ULYSSES/KET project is supported under grant No. 50 ON 9103 by the German Bundesminister für Bildung und Forschung (BMBF) through the Deutsches Zentrum für Luft- und Raumfahrt (DLR).

References

Belov A., et al., Adv. Space. Res., 23(3), 443-447, 1999.
Heber, B. et al., 25th Int. Cosmic Ray Conf., 2, 85-88, 1997.
Heber, B., et al., J. Geophys. Res., 103, 4809–4816, 1998.
McComas et al., Geophys. Res. Lett., in press, 2000.
McKibben, R. B., et al., Space Sci. Rev., 83, 188–193, 1998.
Paizis, C., et al., 24th Int. Cosmic Ray Conf., 4, 756-760, 1995.
Potgieter, M. S., Burger, R. A., and Ferreira, S. E. S., Proc. ESLAB 34, in press, 2001.