SH 3.2.09

Variations of anomalous and galactic cosmic ray fluxes in the northern hemisphere: ULYSSES EPAC and KET observations.

B. Heber[1,2], E. Keppler[1], M. Fraenz[3], and H. Kunow[2]
[1]*MPI für Aeronomie, Germany,*
[2]*Universität Kiel, Germany,*
[3]*Queen Mary and Westfield College, UK*

Abstract

From beginning of 1995 to the end of 1997 the Ulysses spacecraft scanned a heliographic latitude range of 80 degrees in the northern hemisphere. In this paper we will discuss Ulysses Energetic Particle Composition Experiment (EPAC) and Ulysses COsmic and Solar Particle INvestigation Kiel Electron Telescope (KET) observations of different anomalous cosmic ray species and compare our results with the variation of galactic cosmic rays at approximately the same rigidities. The latitudinal gradients determined in the northern hemisphere are in agreement with Ulysses measurements during the rapid pole to pole passage in 1994/1995.

1 Introduction

The intensity of galactic and anomalous cosmic rays (GCRs, ACRs) energetic charged particles are modulated as they traverse the turbulent magnetic field embedded in the solar wind. The observation of the spatial modulation of GCRs and ACRs is one of the major scientific goals of the joint ESA/NASA Ulysses mission. Launched on 6 October 1990 in the declining phase of solar cycle 22 the spacecraft encountered the planet Jupiter in February 1992, and using a gravity assist began its journey out of the ecliptic plane. On 13 September 1994, Ulysses reached the highest southern latitude of 80.2° S. Then the spacecraft moved rapidly to the heliographic equator and climbed to the highest northern latitude, 80.2° N, on 31 July 1995. At present, March 1999, during the rising phase of solar cycle 23, Ulysses is at ∼20° South and heading again to high southern latitudes. Fig. 1 displays Ulysses heliographic latitude as a function of radial distance, when Ulysses was in the northern hemisphere. The histogram shows the evolution of maximum latitudinal extend of the heliospheric current sheet, as calculated by Hoeksema (http://quake.stanford.edu/∼wso/Tilts.html). Thick lines indicate time periods when Ulysses was embedded in the streamer belt dominated region. At higher latitudes Ulysses observed the fast solar wind stream originating from the northern coronal hole.

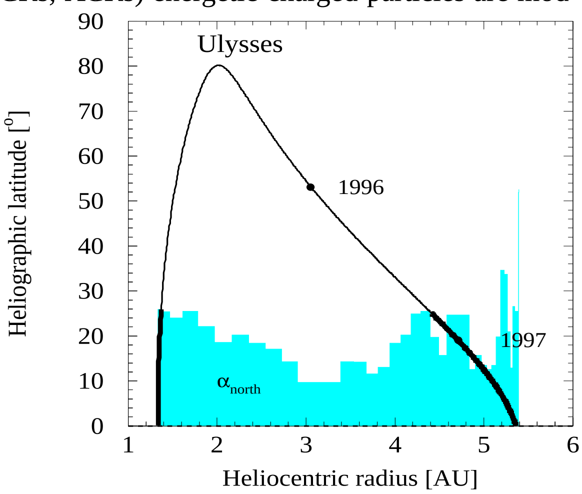

Figure 1: Ulysses heliographic latitude θ as function of radial distance r. Thick lines mark the time periods, when Ulysses is embedded in the streamer belt dominated area, as indicated by the histogram (see text).

2 Observations

In this paper we determine latitudinal gradients for ACR helium and oxygen and GCR protons using different energy channels from the Ulysses EPAC (Keppler et al., 1992) and KET instruments (Simpson et al., 1992). In detail these are the KET 38-125 MeV, 125-250 MeV, 250-2000 MeV and >2 GeV proton as well as the KET 250-2000 MeV/n and >2 GeV/n α-particle channels for determining temporal and spatial variation of GCRs. The KET 6-25 MeV/n and 38-70 MeV/n α-particle channels and the EPAC 2.2-6.8 MeV/n oxygen channel are dominated by ACRs and can be used as a measure for spatial gradients and temporal variation of ACRs.

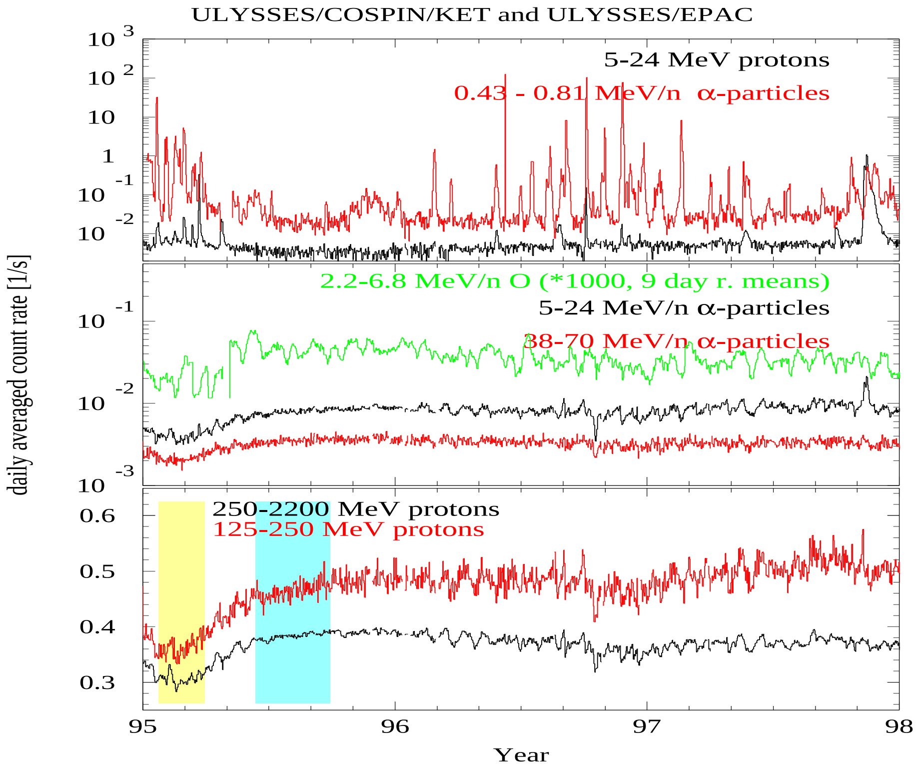

Figure 2: Overview plot of selected energetic particle data from the beginning of 1995 to fall 1997 (see text).

Fig. 2 displays from top to bottom the daily averaged 5.4-25 MeV protons and 9 day running mean averaged 0.43-0.81 MeV/n α-particles; 6-25 MeV/n, 34-70 MeV/n helium and 9-day running mean averaged 2.2-6.8 MeV/n oxygen; and daily averaged 125-250 MeV and 250-2000 MeV COSPIN/KET protons. Marked by shading are the time periods when Ulysses is above 70° N and when the spacecraft crossed the heliospheric equator in 1995. The first panel shows the daily averaged count rates of 5.4-24 MeV protons and 0.43-0.81 MeV/n α-particles. The proton channel has been used to determine time periods, when the GCR and ACR flux may be influenced by major solar or interplanetary particle events. The helium channel is mainly dominated by locally accelerated particles. We conclude therefore that the full data set from fall 1995 to November 1997 could be used to determine the spatial and temporal variation of ACRs and GCRs.

3 Data Analysis and Discussion

In order to separate spatial from temporal variations in the GCR nuclei flux, a baseline measurement at 1 AU is necessary. In what follows we assume that the count rates at a given rigidity P measured by KET and EPAC $C_P(r,\theta,t)$ can be determined by the count rate measured at Earth $f_P(t)$ by:

$$C_P(r,\theta,t) = f_P(t) \cdot g_P(r) \cdot h_P(\theta) \tag{1}$$

herein are

$$\text{the radial dependence } g_P(r) = \exp\left(G_r(P)\cdot\Delta r\right) \quad \text{with the radial gradient } G_r(P)$$
$$\text{the latitude dependence } h_P(\theta) = \exp\left(G_\theta(P)\cdot\Delta\theta\right) \quad \text{with the latitude gradient } G_\theta(P)$$

Unfortunately 1 AU data are not available for all KET/EPAC particle channels. Therefore reasonable assumptions have to be made: Heber et al. (1998) found that significant latitudinal gradients are only observed when

Ulysses was in the fast solar wind dominated regime. During these time periods the count rates are dominated by the temporal variation and changes in Ulysses's radial distance.

3.1 Temporal recovery from 1995 to 1998

Fig. 3 shows 9-day running mean averages of 250-2200 MeV protons ($P\sim$2.5 GV) measured by the KET onboard Ulysses and >100 MeV protons ($P\sim$2 GV) measured by the University of Chicago Instrument on board IMP8. The line fitted to the IMP data shows the approximation of the count rates by an exponential law in time: $f_P(t) = f_P(t_0) \cdot \exp\left(\gamma \cdot (t - t_0)\right)$ using the mean values during the two marked time periods. As pointed out by Heber *et al.* (1998) latitudinal variations are small, when the spacecraft is embedded in the streamer belt dominated area. From Fig. 3 it is evident, that the approximation fits the temporal recovery at Earth reasonably good. Fig. 4 (left) shows the approximation for all channels analyzed. For GCRs and ACRs the recovery towards solar minimum modulation conditions, as expressed by γ, is decreasing with increasing rigidity. ACRs seem not to recover at the same rate as GCRs. However, as we will discuss below, this observation is influenced by different radial gradients for ACRs and GCRs and the change of radial distance of Ulysses from the Sun. Within these constraints we conclude that γ is the same for GCRs and ACRs.

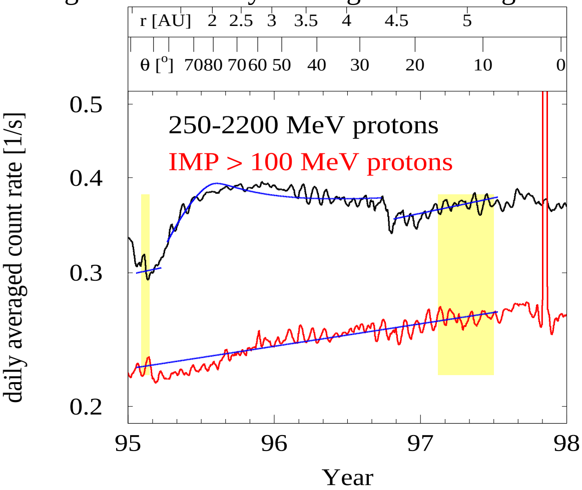

Figure 3: 9-day running mean averages of 250-2200 MeV protons measured by the KET and >100 MeV protons measured by the University of Chicago Instrument at Earth.

3.2 Radial gradients

During the time period of interest Ulysses moved from $\sim$2.5 to $\sim$4.2 AU outward. Since radial gradients are expected to be positive, the intensities in each energy channel increase with radial distance depending on the individual radial gradients. McDonald (1998) and references therein found that the radial gradient is larger for ACRs than for GCRs. They determined a mean radial gradient of 3–>5%/AU and $\sim$1%/AU for 10-22 MeV/n helium and 130-240 MeV protons. In the previous section we did not correct the measured count rates for the increasing distance of Ulysses. Since both time periods are $\sim$2 years apart, and the spacecraft moved in that time from $\sim$1.3 AU to $\sim$5.3 AU a radial gradient G_r would be misinterpreted in our approach as a temporal recovery rate of $\gamma = G_r \cdot \Delta r / \Delta t$. The values γ for >2 GeV/n protons and α-particles might be dominated by this effect. Belov *et al.* (1998) find a radial gradient of 0.5–1%/AU for >2 GeV protons. Such a gradient would lead to a recovery rate γ, which is of the same order as we have found by our procedure. However, the radial gradient of low energy protons is of the order of <3%/AU (McDonald, 1998), leading to the conclusion, that their time profile is dominated by the temporal recovery. To estimate the differences in γ found for low rigidity GCRs and ACRs in the previous section, we calculate the difference in γ assuming a radial gradient difference of 3%/AU . Such a difference would lead to $\gamma \sim$ 6%/year, which is comparable to our analysis. Thus we conclude, that different radial gradients of ACRs and GCRs are the main cause of our observation of different γ's for ACRs and GCRs.

3.3 Latitudinal gradients in the northern hemisphere:

A mean latitudinal gradient G_θ can be calculated by subtracting the long term trend, as determined from the data:

$$G_\theta(\theta) = \left(\log C_P - \log f_P(t)\right) / \theta \quad . \tag{2}$$

Analyzed are only time periods when Ulysses is embedded in the fast solar wind regime (70° N–25° N). By analyzing the IMP8 data we are able to estimate the systematic uncertainty of our method. The residual G_θ is consistent with 0%/degree. The uncertainty of G_θ has been calculated by dividing the latitude range from 70° N to 30° N into three intervals (not shown here). The minimum and maximum of G_θ has been used as the uncertainty of each channel.

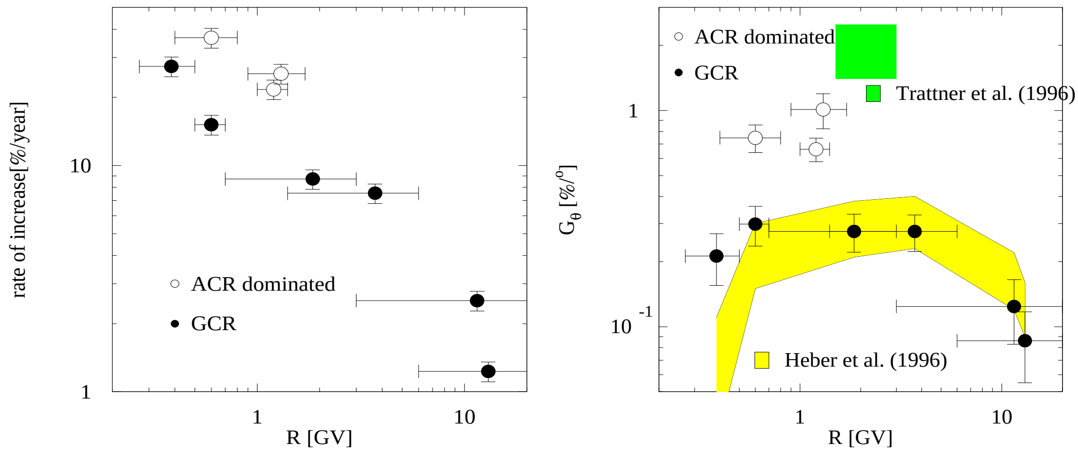

Figure 4: Rigidity dependence of the rate of increase γ and the latitudinal gradient G_θ.

The result of this analysis is shown in Fig. 4 (right) and in Fig. 3. In Fig. 3 the fitted line shows the variation calculated by using eq. 2 taking into account the temporal recovery of 250-2000 MeV protons. Obviously the line is not a perfect fit to the data. However, it represents the measurements very well, if one bares in mind all assumptions made.

Fig. 4 displays the rigidity dependence of G_θ. Marked by shading are latitudinal gradients determined by Trattner *et al.* (1996) and Heber *et al.* (1996) using the data set from the rapid pole to pole passage. The values obtained by our analysis are within the uncertainties consistent with the 1994/1995 values, indicating stable modulation conditions in the inner heliospheric regions dominated by the fast solar wind from the coronal holes. Consequences for the rigidity dependence of the diffusion coefficients for GCR protons are discussed in Burger *et al.* (SH.3.3.02). As for γ G_θ is much larger for ACRs than for GCRs at the same rigidity. In contrast it is also depending on the particle species, as discussed also by Paizis et al. (1997).

4 Summary and Conclusion

In this paper we showed that a simple approximation of Ulysses GCR and ACR count rates by an exponential law in time and latitude represents our data reasonably good. By using this approximation we were able to determine the rigidity dependence of GCRs and ACRs over a vast range. Our results are within the error bars consistent with results obtained during the Ulysses rapid pole-to-pole passage, indicating stable modulation conditions in the inner heliospheric regions dominated by the fast solar wind from the coronal holes.

References

Belov, A., et al., 1999, Adv. in Spac. Res., accepted.
Heber, B., et al., 1996, Astron. & Astrophys., 316, 538.
Heber, B., et al., 1998, J. of Geophys. Res., 103, 4809.
Keppler, E., et al., 1992, Astron. & Astrophys. Suppl., 92, ???.
McDonald, F.B., 1998, Space Sci. Revs., 83, 33.
Paizis, C., et al., 1997, Proceedings 25th ICRC (Durban, South Africa), 2, 93.
Trattner, K.J., 1996, Astron. & Astrophys., 316, 519.
Simpson, J., et al., 1992, Astron. & Astrophys. Suppl., 92, 365.