SH 3.2.04

Charge sign dependent modulation: Ulysses COSPIN/KET results

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Abstract

According to drift dominated modulation models galactic cosmic ray protons and electrons respond differently to the latitudinal extension of the heliospheric current sheet. In an A>0 solar magnetic cycle intensities of positively charged particles should vary only weakly with the latitudinal extension, whereas electrons should show a much stronger response. In this paper we investigate the charge sign dependent modulation in the 1990s using measurements of 2.5 GV protons and electrons of the Cosmic and Solar Particle Investigation Kiel Electron Telescope (COSPIN/KET) on board Ulysses from the beginning of 1992 to the end of 1998. Only close to solar minimum, when the maximum latitudinal extend is below ∼30°, differences in the temporal variation of electrons and protons are observed.

1 Introduction

Galactic Cosmic Rays (GCRs) enter the heliosphere where they are scattered by irregularities in the heliospheric magnetic field and undergo convection and adiabatic deceleration in the expanding solar wind. The large-scale heliospheric magnetic field (Parker, 1965) leads to gradient and curvature drift (Jokipii *et al.*, 1977). When the heliospheric magnetic field is directed outward from the Sun in the north polar region (denoted by A>0, e.g. the present cycle), models predict that positively charged particles drift in over the solar poles and outwards along the heliospheric current sheet (HCS). In contrast, electrons drift into the inner heliosphere along the HCS and outward through polar regions. When the magnetic field polarity is reversed (denoted by A<0) the behaviour of electrons and protons is also reversed. Jokipii and Thomas (1981), Kota and Jokipii (1983), and Potgieter and Moraal (1985) developed steady-state modulation models and Le Roux and Potgieter (1990) a time dependent modulation model taking into account the "tilt angle" α of the HCS. They predicted that due to drift effects the proton (electron) time profile should be depending less on α in an A>0 (A<0) magnetic cycle than in an A<0 (A>0) cycle (see also Burger & Potgieter, SH 3.1.04; Ferreira *et al.*, SH 3.1.14). Such a charge sign dependent behaviour was observed during solar minimum in the previous A<0 magnetic cycle (Evenson, 1998) and in the present A>0 magnetic cycle (Heber *et al.*, 1999).

In this paper we extent the analysis of the 2.5 GV proton and electron time profiles at solar minimum, as described in Heber *et al.* (1999), to the time period from mid 1992 to the end of 1998. For the values of α we use the maximum latitudinal extent of the HCS (Hoeksema, http://quake.stanford.edu/∼wso/Tilts.html). Note, that α is not only directly connected to the magnetic configuration of the heliosphere, it is also correlated to solar activity (e.g. Haasbroek *et al.*, 1995).

2 Instrumentation and Observations

The GCR intensity measured along the Ulysses orbit results from a combination of temporal and spatial variations. The observations were made with the Kiel Electron Telescope (KET) aboard Ulysses, which measures protons and helium nuclei in the energy range from 6 MeV/n to above 2 GeV/n and electrons in the energy range from 3 MeV to a few GeV (Simpson *et al.*, 1992). The time profiles of 2.5 GV electrons (filled symbols) and protons (solid line) from 1991 to end 1998 are displayed in Fig. 1 (left). Channels are normalised in March 1995, when Ulysses crossed the heliographic equator at ∼1.3 AU. Radial distances and latitudes are

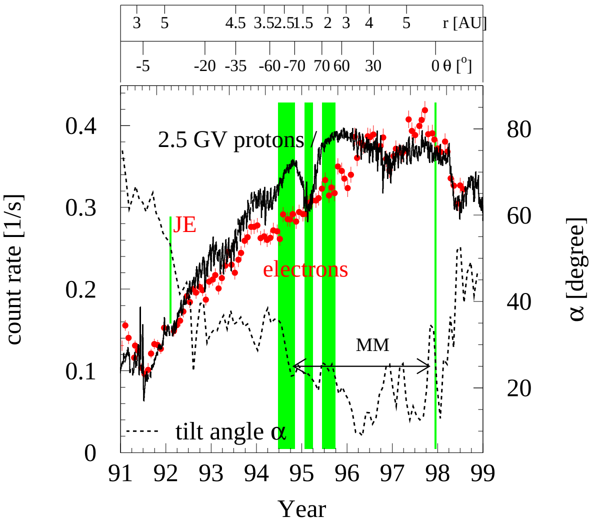

Figure 1: Daily averaged count rates of 2.5 GV protons and 26 day averaged count rates of 2.5 GV electrons from 1991 to mid 1998. The dashed line shows the variation of the maximum latitudinal extent of the heliospheric current sheet α as explained in the text. MM marks the minimum modulation time period.

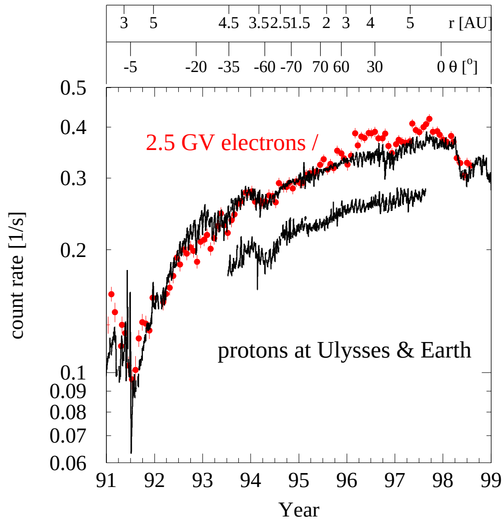

Figure 2: Daily averaged count rates of 2.5 GV protons and 26 day averaged count rates of 2.5 GV electrons corrected for the latitudinal variation of the spacecraft. The lower line shows the daily averaged countrate of >100 MeV protons measured at Earth.

indicated at the top of Fig. 1. Shaded areas indicate the Jovian encounter (JE), the time periods when Ulysses was below 70° S and above 70° N, and when Ulysses crossed the heliospheric equator in 1995 and in 1998. ¿From 1991 to September 1997 the GCR proton and electron intensities increased with decreasing solar activity, but in March/April 1998 the GCR intensity has started to decrease again. Changing solar activity is reflected in the evolution of α, as indicated by the dashed line in Fig. 1 (see also Hoeksema, 1995). During the rapid pole-to-pole passage in 1994/1995, the 2.5 GV proton count rate shows a definite variation with Ulysses heliographic latitude (Heber *et al.*, 1996), whereas no significant latitudinal variation was found for electrons during this period (Ferrando *et al.*, 1996 and Heber *et al.*, 1999).

3 Data Analysis and Discussion

Determination of charge sign dependent temporal modulation by using Ulysses data requires a correction of the observations for the spatial movement of the spacecraft. We assume that in the period of our analysis (mid 1992 to end 1998) the variation of the cosmic ray intensity is separable in time and space, with a latitudinal and a radial dependence. We showed in previous studies (Heber *et al.*, 1996, 1998) that we can determine both the latitudinal and radial gradients of protons by combination with Earth orbiting experiments. Heber *et al.* (1999) approximated the spatial parameters for electrons as follows: (1) The rapid pole-to-pole passage was used in their analysis to determine the latitudinal gradient, which was found to be consistent with zero. (2) The radial gradients of electrons and protons were assumed to be identical, because the variation of Ulysses in distance during the time period of interest was small.

After applying the corrections, as discussed in detail in Heber *et al.* (1999), we derive the ”heliographic equator equivalent” proton (upper solid line) and electron (symbols) intensities as displayed in Fig. 2. Note, that we don't correct the data for Ulysses' radial variation, because previous investigations showed that the radial gradient of >100 MeV protons is not a constant over the whole time period analysed (Heber *et al.*, 1998). In addition the count rates of >100 MeV protons measured by the University of Chicago Instrument on board the IMP spacecraft are shown. Comparing the time profiles of both proton channels, we find a good agreement between the KET ”heliographic equator equivalent” time history and the IMP data. Note, that in

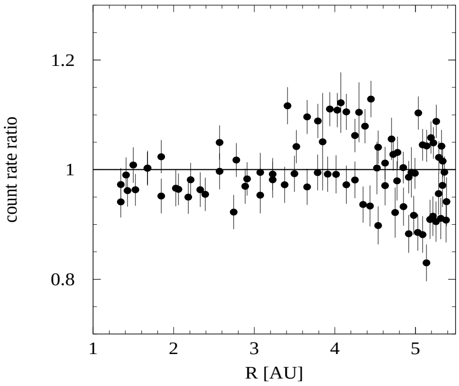

Figure 3: "Heliographic equator equivalent" electron to proton count rate ratio as function of radial distance.

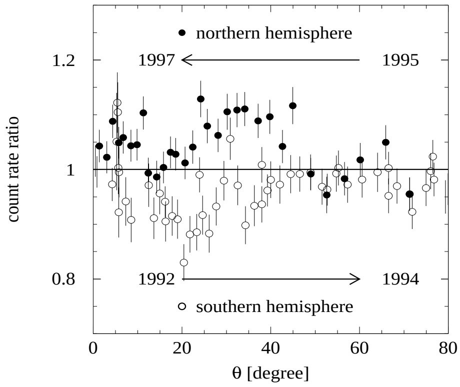

Figure 4: "Heliographic equator equivalent" electron to proton count rate ratio as function of latitude.

contrast to Fig. 1 a logarithmic scale was chosen to emphasise the similarities between 1 AU and Ulysses observations. The "heliographic equator equivalent" proton channel tracks the corresponding electron channel for most times during this period. We will show next that the influence of possible differences between the radial gradients of electrons and protons and of a possible small latitudinal gradient of the electrons is small.

Radial gradient differences for electrons and protons: Fuji and McDonald (1997) investigated the radial gradients of protons in two successive solar cycles and found larger radial gradients in an A$<$0 than in an A$>$0 magnetic cycle. Such differences might also be expected for different charge signs at the same position in space and time. However, as pointed out by Potgieter (1997) differences in the radial gradient for different charge sign should be much smaller in the inner than in the outer heliosphere. Fig. 3 displays the 2.5 GV electron to proton ratio as a function of Ulysses radial distance for the time period in Fig. 2. As we can see there is no systematic variation in this ratio as a function of distance as would be expected if the radial gradients of the two particle types were markedly different. The straight line superimposed indicates a constant ratio of unity. Using all data we can estimate a radial gradient difference between electrons and protons $\Delta G_r = G_r^e - G_r^p \sim 0.4 \pm 0.3$%/AU, consistent with no difference between the two radial gradients.

When going back to Fig. 2 we see that the two counting rates deviate from each other at certain time periods. One of these periods occurs from early 1991 to early 1992, i.e. at the time of the HMF polarity reversal, see the discussion and a possible interpretation in Heber *et al.* (1998a). When we restrict the discussion to the period from 1993 onwards we see that the two particle channels track each other exceedingly well apart from conditions near solar minimum which we will discuss later. Note that electrons and protons also respond in the same way to the small depression in early 1994.

Non zero latitudinal gradient for electrons: Fig. 4 displays the 2.5 GV electron to proton ratio as function of Ulysses heliographic latitude. The open and filled symbols indicate time periods when Ulysses was in the southern and northern hemisphere, respectively. This should not be taken as an indication for a North/South- asymmetry, but it represents data obtained during different time periods, as indicated in the figure. The straight line again indicates a constant ratio of 1. As for the radial variation the data sets allow to estimate an electron latitudinal gradient of -0.03 ± 0.03%/degree, which is consistent with zero.

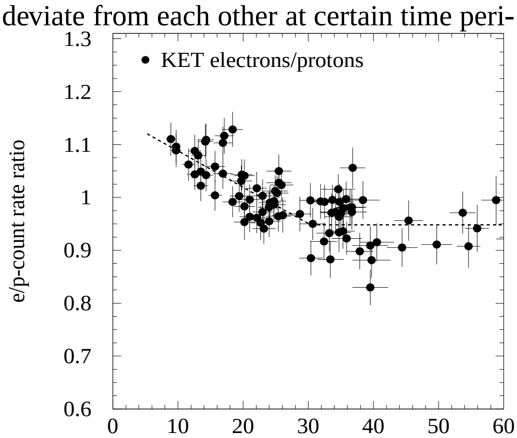

Figure 5: "Heliographic equator equivalent" electron to proton count rate ratio as function of α^*.

Variation with tilt angle: In Heber *et al.* (1999) we conclude that charge sign dependent modulation and therefore drift effects are important only if the maximum latitudinal extent of the heliospheric current sheet is below $\sim$25-30°. Fig. 1 also displays the evolution of α as indicated by the dashed line. Cosmic rays at a given position in the heliosphere, for example at Earth, do not respond immediately to changes in α near the sun, but with a certain delay Δt. Near 1 AU the best anti-correlation between α and relativistic cosmic ray protons is found for $\Delta t \approx$ 2–3 solar rotations (e.g., Cane *et al.*, 1999). We found a good anti-correlation for Δt = 3-5 solar rotations.

Fig. 3 displays the count rate ratio of "heliographic equator equivalent" electrons and protons as a function of $\alpha^* = \alpha(t - \Delta t)$. In comparison to Heber *et al.* (1999) we used a value of $\Delta t = 5$ solar rotation, to take into account the larger mean distance of Ulysses from the sun. Taking into account the uncertainties of our measurements it is obvious from this figure that the ratio is increasing with decreasing α^* for $\alpha_0^* <\sim 30°$. For larger α^* this ratio can be approximated by a constant. We can determine α_0^*, when fitting a linear decrease for $\alpha^* < \alpha_0^*$ and a constant for $\alpha^* > \alpha_0^*$. We obtain $\alpha_0^* = 30 \pm 1°$, and a rate of increase of -0.0065 ± 0.0006/degree.

4 Conclusion and Summary

We present in this paper the e/p-ratio along the Ulysses trajectory as an important tool for the study of modulation effects. The first step was the separation of temporal and spatial variations along the Ulysses orbit. We have shown that to first order the latitudinal gradient of electrons is consistent with zero, whereas the proton count rates can be corrected for latitudinal effects using the observed proton variation during the rapid pole-to-pole passage. In agreement with modulation models we found that the radial gradients for electrons and protons in the inner heliosphere and in an A>0-solar cycle are approximately the same. The resulting "heliographic equator equivalent" count rates of electrons and protons are dominated by the variation of α^*, in good agreement with our previous result in Heber *et al.* (1999), where we analysed time periods close to solar minimum only. We find that the e/p-ratio is increasing for decreasing α^* only for time periods when α^* is below 30°. We conclude therefore that drift effects are an important factor in controlling galactic cosmic ray transport only when $\alpha^* < 30°$. This is consistent with the modelling result of Le Roux and Potgieter (1990).

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