Differences in the temporal variations of galactic cosmic ray electrons and protons: Implications from Ulysses at solar minimum

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Abstract. According to standard drift dominated modulation models the intensity variations of galactic cosmic ray protons and electrons respond differently to the latitudinal extension of the heliospheric current sheet α. In an A>0 solar cycle intensities of protons should vary weakly with the latitudinal extension, whereas electrons should show a strong response. We investigate this charge dependent variation in the 1990s (A>0) using Ulysses Kiel Electron Telescope (KET) measurements. Proton measurements at 2.5 GV corrected for latitudinal variations show the same time profile as electrons from mid 1994 until the beginning of 1996, and later from September 1997 to the end of 1997. In 1996 and 1997, when α was below $\sim 25^\circ$, two long lasting time periods were found when electrons had a $\sim$5-10% higher level. These variations are in agreement with our computations indicating that drift effects play an important role in determining the temporal variation of electrons close to solar minimum.

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 average large-scale heliospheric magnetic field [*Parker*, 1965] leads to gradient and curvature drift of cosmic rays [*Jokipii et al.*, 1977]. When the solar magnetic field is directed outward from the Sun in the north polar region (denoted by A>0) models predict that positively charged particles drift in over the solar poles and are ejected along the heliospheric current sheet (HCS). In contrast, electrons drift into the inner heliosphere along the HCS and are ejected in polar regions. When the heliospheric 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], *Potgieter and Moraal* [1985] developed steady-state modulation models and *LeRoux 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. Such a charge dependent behaviour was observed close to solar minimum in the previous A<0 cycle [*Evenson*, 1998].

In this paper we investigate the time profiles of 2.5 GV protons and electrons close to the present solar minimum in 1996 and 1997 and compare our measurements with steady state model computations [*Burger and Hattingh*, 1995; *Potgieter et al.*, 1997]. For the values of α we use the maximum latitudinal extent of the HCS as calculated by Hoeksema (http://quake.stanford.edu/wso/Tilts.html). For small values, α can be taken as the tilt of the current sheet. Note, although α is directly connected to the magnetic configuration of the heliosphere, it is also correlated to solar activity [*Haasbroek et al.*, 1995].

2. Instrumentation

The observations were made with the KET aboard Ulysses. The KET measures protons and Helium 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 GCR intensity measured along the Ulysses orbit results from a combination of temporal and spatial variations. Ulysses was launched on October 6, 1990, in the declining phase of solar cycle 22. In January 1993 the spacecraft was at a solar distance of 5.1 AU and a heliographic latitude $\theta \approx 23^\circ$ S. It took 19 months to reach a maximum southern latitude of 80° S at a distance of 2.3 AU. From Septem-

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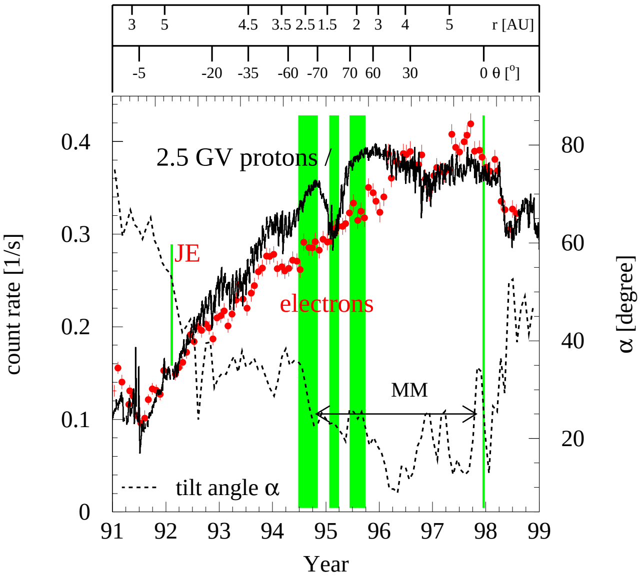

Figure 1. Daily averaged count rates of 2.5 GV protons and 26 day averaged count rates of 2.5 GV electrons from 1991 to mid 1998. The dashed line shows the variation of α as explained in the text. The horizontal arrow (MM) indicates the time period of minimum modulation conditions, when no major solar events were observed.

ber 1994 to August 1995 the spacecraft performed a whole latitude scan of 160° within 11 months. In April 1998 in the rising phase of solar cycle 23 Ulysses returned to the heliographic equator at a radial distance of 5.3 AU, thus completing its first out of the ecliptic orbit.

3. Observations

The time profile of 2.5 GV electrons (filled symbols) and protons (solid line) from 1991 to end 1998 is displayed in Figure 1. Both channels are normalised to each other in March 1995, when Ulysses crossed the heliographic equator at ~1.3 AU. Radial distances and latitudes are indicated on 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. In March/April 1998 the GCR intensity started to decrease again. 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]. In contrast, the electron profile is dominated by temporal variations [*Ferrando et al.*, 1996].

Solar activity decreased from a moderate level in 1994/1995 to low levels at the end of 1996 and increased again at the end of 1997. This pattern of solar activity is also reflected in the evolution of α [*Hoeksema*, 1995] in Figure 1, indicated by the dashed line. In this paper we will focus on charge dependent modulation during minimum modulation conditions from mid 1994 to November 1997 as indicated by the arrow in Figure 1. The 38-125 MeV proton count rate (not shown here) shows no short term increases during this period.

4. Data Analysis

Determination of charge 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 1994 to end 1997) the variation of the cosmic ray intensity is separable in time and space. Spatial variations can be separated in a latitudinal and a radial component. We have shown in previous studies [*Heber et al.*, 1996, 1998] that we can determine both the latitudinal and radial gradients of protons thanks to Earth orbiting experiment measurements. In a first step we correct the proton data for their latitudinal variations by applying the results of the 2.5 GV proton time profile analysis during the fast latitude scan by *Heber et al.* [1996] to the whole period from mid 1993 to the end of 1997.

The correction of the electron data is less straightforward. It relies on Figure 2 which displays the 2.5 GV proton to electron ratio from mid 1994 to end of 1995, indicating charge dependent spatial modulation along the Ulysses trajectory at solar minimum [*Ferrando et al.*, 1996]. The solid curve in Figure 2 represents the variation of the temporally detrended 2.5 GV proton count rates only (from Figure 5 in *Heber et al.* [1996]). 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. A possible larger electron radial gradient in comparison to the proton has within the uncertainties no influence to this ratio as long as the difference is below a few %/AU, because the radial variation of Ulysses is only ~1 AU during this period. For 180–450 MeV/n, at a radial distance of 10 AU, *Fuji, and McDonald,* [1997] determined a radial gradient of ~3%/AU and ~1%/AU for selected A>0 and A<0 periods (see their figure 8).

Another possibility would be that there is indeed a significant latitudinal gradient of electrons, which would exactly compensate the temporal variations. We reject this possibil-

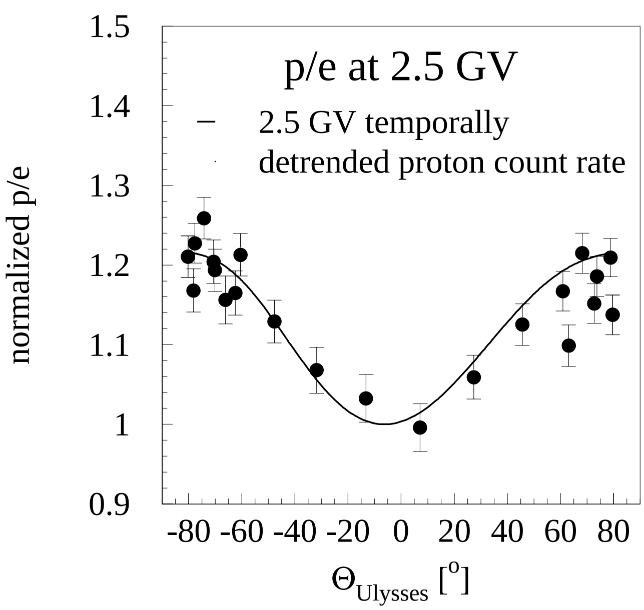

Figure 2. 2.5 GV p/e ratio as function of Ulysses heliographic latitude θ. The solid line is the latitudinal variation of 2.5 GV protons as determined by *Heber et al.* [1996].

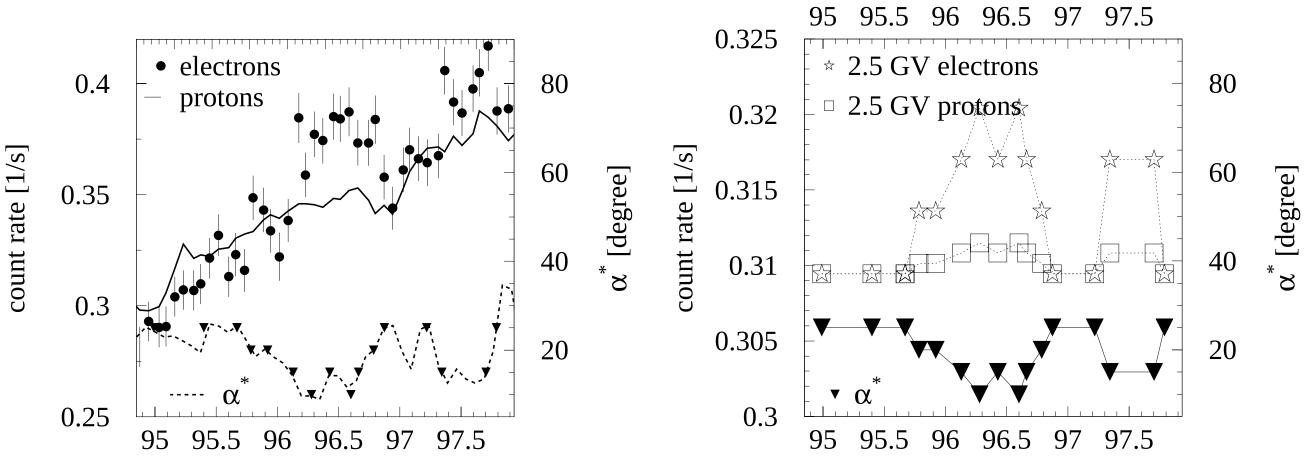

Figure 3. (a): 2.5 GV electron and proton count rates corrected for latitudinal variations, and $\alpha^*(t)$ (dashed curve). (b): Model predictions of proton and electron intensities as a function of α^* for selected time periods (triangles in (a)). Results are normalised in 1995. Note the different scales in the two panels.

ity because in this case the temporal variations would have to be symmetric relative to the time when Ulysses crossed the heliographic equator, which is very difficult to imagine. We conclude therefore that the electrons in agreement with the model computations show no significant latitudinal gradient. After applying these corrections for the latitudinal variation of Ulysses we can derive the "heliographic equator equivalent" proton and electron intensities as displayed in Figure 3 (a).

5. Discussion and Conclusion

Besides the heliographic equator equivalent 2.5 GV electron and proton intensity (arbitrarily normalised in spring 1997, when Ulysses was at a radial distance of 5 AU), Fig. 3 also displays the evolution of α^* as indicated by the dashed line and the filled triangles. α^* has been obtained from α shifted forward in time, $\alpha^*(t) = \alpha(t + \Delta t)$. Cosmic rays do not respond immediately to a change in α, 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 $\Delta t = 3$ solar rotations.

We can see in Figure 3 (a) that both time profiles show a monotonous increase due to the radial variation of Ulysses. When taking into account a radial gradient of 3%/AU (not shown here) for both species the proton time profile remains relatively flat, consistent with predictions from drift models for A>0 epochs. In contrast, the electrons vary to a larger degree. Their count rates are about 10% higher than those of the protons for several solar rotations in 1996 and about 5% higher for several solar rotations in 1997. The difference between the electron and proton response to the variations in α^* is restricted to tilt angles below $\sim$25°. For larger α^* the two particle species of opposite charge show more or less the same response to the variations in α^*. *Cane et al.* [1999] find a corresponding result when studying the same particle type during different polarities. The response of relativistic protons to variations in α^* at intermediate values is the same during A>0 and A<0 epochs.

In Figure 3 (b) we compare our measurements with model predictions. Modulation conditions near solar minimum can be approximated by a series of steady state solutions. The model and its parameters are described in *Burger and Hattingh* [1995] and *Potgieter et al.* [1997]. The parameters are chosen such that the model reproduces the observed latitudinal variation of 2.5 GV protons and electrons as well as the rigidity dependence of the latitudinal gradient in the inner heliosphere [*Potgieter et al.*, 1997]. To emphasise changes in the proton and electron intensities an expanded scale was chosen. The intensities are calculated for several different values of α^*, indicated by the triangles. The count rate of electrons exceeds that of protons only when α^* is below $\sim$25°, whereas the two curves remain close to each other for larger α^*.

Comparison with results obtained during an $A < 0$ epoch (e.g., [*Evenson*, 1998]) allows us to conclude that for periods around solar minimum (α^* <25°) the response of cosmic rays varies with the product qA (q = particle charge), with a stronger (weaker) response for $qA < 0$ ($qA > 0$), in qualitative agreement with the prediction from drift models.

It should be noted, by comparing Figure 3 (a) and (b) that the observed dependence on α^* is stronger (factor of $\sim$2) than the predicted one and the overall increase in the GCR intensities is underestimated by the model. However, the model parameters are chosen to "fit" the spatial modulation in 1994/1995 during Ulysses rapid pole to pole passage and not the temporal recovery of GCRs as in *Haasbroek et al.* [1995]. From the observational point of view a slightly larger radial gradient for electrons could in principle lower these differences. Taking into account these uncertainties the prediction for the temporal variation with the tilt angle agrees with our observations: the electron count rate exceeds the one of protons only when α^* is below $\sim$25° indicating charge sign dependent modulation. We conclude that drift effects play an important role in determining the temporal variation for $A > 0$ conditions around solar minimum.

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