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On the determination of the γ-ray contribution in the 3-10 MeV KET electron channel along the Ulysses trajectory

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Abstract. Since the first Jovian fly-by of Pioneer 10 in 1973, it has been established that Jupiter's magnetosphere is a powerful accelerator of electrons up to several tens of MeV, which are released into interplanetary space. Measurements from Pioneer, Voyager and from spacecraft near Earth, e.g. IMP, indicate that the Jovian electron flux exceeds the galactic one close to the ecliptic plane in the inner heliosphere. Galactic cosmic ray electrons may become important at high heliographic latitudes. Since Jupiter can be regarded as a "point" source, measurements of Jovian electrons are ideally suited to study the transport of particles in three dimensions in the inner heliosphere. Different scenarii, varying the local interstellar spectrum as well as the propagation parameters show the need for a higher precision of Ulysses measurements. In this presentation we analyze data from the cosmic ray and solar particle investigation Kiel Electron Telescope (KET) on board of Ulysses with a special emphasis on the background caused by γ-rays generated by energetic cosmic rays interacting with the spacecraft matter. We are able to determine the background contribution more precisely than before by using 1 AU measurements from IMP 8 and the SOHO spacecraft, model calculations describing these observations, and Ulysses data during the ecliptic crossing in February 1995, when the spacecraft was oppositely located to Earth and close to 1 AU.

1 INTRODUCTION

The KET on board Ulysses measures proton, and α-particles in the energy range from $\sim$4 to $>$2000 MeV/n and electrons in the range from $\sim$3 to $>$200 MeV in different energy channels. Fig. 1 shows a sketch of the KET sensor. The telescope is described in Simpson et al. (1992) and consists of two parts: (1) the entrance telescope with the semiconductor detectors D1 and D2, the Cherenkov detector C1, and the anti-coincidence A, and (2) the calorimeter, a lead fluoride Cherenkov detector C2, in which an electromagnetic shower can develop, and a scintillation detector S2, which counts the number of charged particles leaving C2.

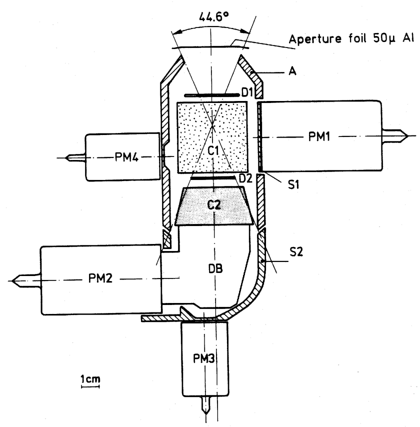

Fig. 1. Sketch of the KET sensor

The two electron channels of interest here are defined according to the detector responses, with the common requirement that a Cerenkov signal is seen in C1, and that no particles trigger the anti-coincidence. The lowest energy channel, E4, corresponds to electrons entering D1 and stopping either in D2 or the top of C2 (no signal in C2 and S2); they have energies in the 3-10 MeV range. The second channel, E12, corresponds to electrons developing a sizeable shower in C2 with no charged particle detected in S2; the energy range of this channel is about 7-170 MeV. For these electron channels lower and upper thresholds are set in D1 and D2 at $\sim$ 0.4 and 3 times respectively the signal of a singly charged minimum ionizing particle. From ground based calibration, it is known that some contribution to the E4 count-rate is due to γ-rays, generated by the Radioisotope Thermoelectric Generator (RTG). In Heber et al. (1999) we could show that a significant number of E12 events are due to γ-rays generated locally by hadronic interaction of galactic cosmic rays with the spacecraft material. These gamma rays may enter the telescope from behind and are either converted into an electron-positron pair or give rise to photoelectric or Comp-

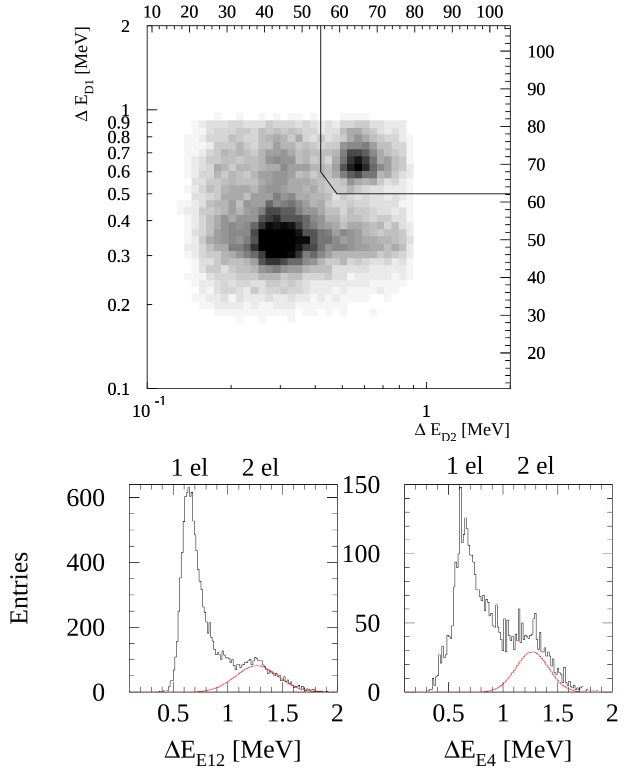

Fig. 2. Upper panel: Energy loss matrix of D1 and D2. The upper right area marks the expected range for two electrons simultaneously crossing D1 and D2. Lower panel: Distribution of the sum of the energy losses along the diagonal in E12 and E4 ($|PHN_{D2} - PHN_{D1}| < 10$).

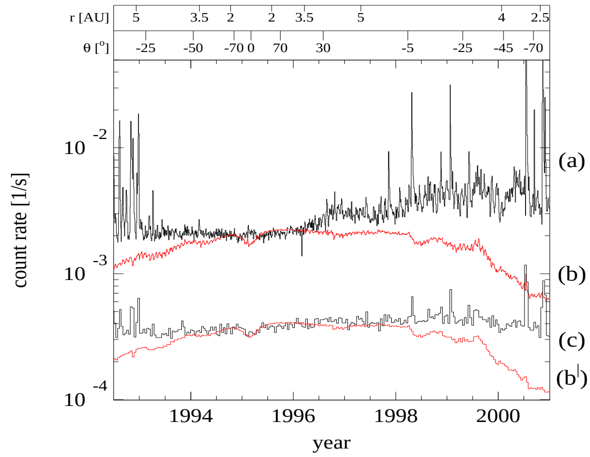

Fig. 3. Observed 2 day averaged "raw" count rate of 3-10 MeV electrons (a), and >250 MeV protons (b), as well as 13-day averaged 3-10 MeV background (c) and >250 MeV protons (b'). (b') differs from (b) due to the fact of a longer accumulation period, and its normalisation to the 3-10 MeV background.

ton electrons inside C2. These electrons either escape the instrument through the front aperture, or do not leave a signal sufficient to trigger the anti-coincidence. Since no information on the directionality of a particle is available, such particles would give a valid E4 or E12 event depending on the C2 signal.

In what follows we will discuss the influence of such a γ-ray background in the 3-10 MeV electron channel. The upper panel in Fig. 2 displays the in-flight energy loss distribution in D1 vs D2. As discussed by Ferrando et al. (1996) the entries in the upper right corner can be unambiguously attributed to a simultaneous ($\Delta t \leq 1\ \mu s$) crossing of two electrons in D1, C1 and D2. The lower panel of Fig. 2 show the energy loss distribution $\Delta E_{D1} + \Delta E_{D2}$ in E12 (left) and E4 (right) for all entries for which the Pulse Height Number (PHN) difference is smaller than 10 - parallel to the diagonal of the in-flight energy loss distribution in D1 vs D2. Obviously a part of the 2-electron-entries (>1 MeV) are caused by multiple scattering of electrons in the silicon detectors and their Landau-distribution. If we assume that the 1-electron loss distribution has an exponential tail, we can estimate the number of 1-electrons measured in the 2-electron regime. To determine the decay constant an exponential law in the energy loss from the peak energy of the 1-electron distribution to 0.95 MeV has been fitted to the data and subtracted from the 2-electron distribution. The residual distribution above 1 MeV has been approximated by a gaussian. The result of this procedure is shown in both lower panels of Fig. 2. The mean energy ΔE and the sigma σ of the gaussian distribution are: $\Delta E_{E4} = 1.26 \pm 0.4$ MeV and $\Delta E_{E12} = 1.26 \pm 0.1$ MeV, and $\sigma_{E4} = 0.15 \pm 0.02$ MeV and $\sigma_{E12} = 0.19 \pm 0.01$ MeV for E4 and E12, respectivily. Since these distributions are nearly identical, we conclude that this background is caused by the same mechanism. As in Heber et al. (1999) we interpret these entries as background electrons moving from the back to the front of the instrument. However, it is important to note that especially for E4 and during solar event periods a significant number in the 2-electron distribution is caused by single genuine cosmic ray electrons.

2 Observations

Fig. 3 displays the 2 day averaged count rates of 3-10 MeV electrons (a), >250 MeV galactic cosmic ray (GCR) protons (b), and the 13-day averaged count rates of the 3-10 MeV electron background (c) and >250 MeV GCR protons (b'). In both sets the electron and proton curves are normalised to each other during Ulysses' south polar passage. As discussed in e.g. Ferrando et al. (1993) the sharp increases in 1992/1993 of the electron intensity are due to special propagation conditions of electrons from Jupiter to Ulysses. The increase in the electron flux starting in 1996 has been discussed in Heber et al. (2001). While the GCR protons track the electron background from 1994 to beginning of 1996 reasonably well, the 3-10 MeV electron profile (a) is different from the GCR time profile at most times. Since the intensity of GCR protons exceeds the one of the 3-10 MeV background electrons, we conclude that there is large contribution of a GCR-proton induced background from 1994 to 1996. The influence of the background in E4 can be reduced by using only the 1-electron time profiles. However, we cannot exclude that a part of the γ-ray generated background is

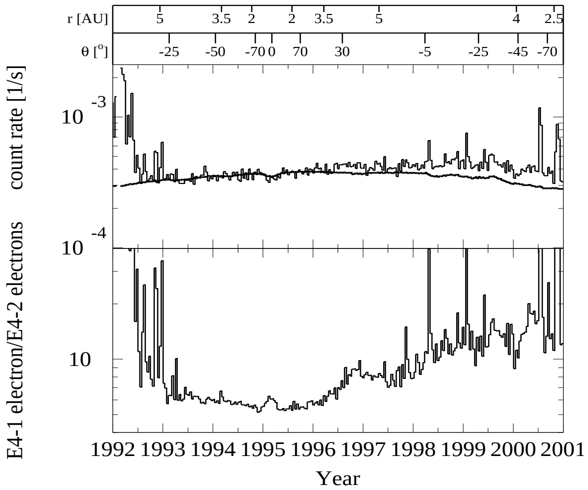

Fig. 4. Measured 13-day averaged 2-electron E4 count rate and approximation of the RTG and GCR γ-ray background by eq. 1 (upper panel) as well as 13-day averaged count rate ratio of 1-electron 3-10 MeV E4 count rate and the RTG and GCR γ-background (lower panel).

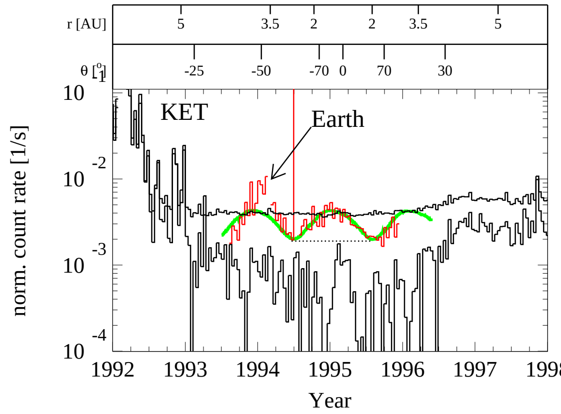

Fig. 5. The upper and lower curves are 13-day averaged normalised uncorrected and corrected 1-electron E4 count rates. The correction and normalisation applied are explained in the text. The dashed curve from mid 1993 to end 1995 displays the time profile of 13-day averaged 2-12 MeV electrons at IMP. The dotted vertical line reflects the minimum intensity observed by IMP from 1994 to 1996. The thick grey curve results from a modulation model calculation (Ferreira et al., 2001).

contributing to the 1-electron count rates.

3 Data Analysis and Discussion

To estimate the background contribution in the 2-electron electron channel we make the following assumptions: 1) The count rate is determined by a RTG rate assumed to be constant, a proton induced and an electron contribution. 2) From 1994 to 1996 the count rate is dominated by the RTG and the γ-ray's produced by GCR interactions in the spacecraft. 3) The GCR background is proportional to the GCR >250 MeV proton count rate. Under these assumptions we can approximate curve (c) in Fig. 3 from 1993 to 1996 by

$$C_{2-el} = C_{RTG} + \alpha \cdot C_{GCR} \tag{1}$$

A least square fit of equation (1) to the data leads to $C_{RTG} = (2.5\pm0.2)10^{-4}$ c/s and $\alpha = (3.5\pm0.4)10^{-4}$, the corresponding time profile is displayed by the lower curve in the upper panel of Fig. 4. From that figure our assumption of a γ-ray dominated 2-electron count rate during the time period from 1993 to 1996 is well justified.

In order to determine the time profile of 3-10 MeV electrons along the Ulysses trajectory we estimate the corresponding background contribution C^{bg}_{1-el} to be proportional to the 2-electron background C^{bg}_{2-el}; $C^{bg}_{1-el} = \beta C^{bg}_{2-el}$. The 3-10 MeV background corrected electron count rate is then given by $C_{1-el} = C^{m}_{1-el} - \beta C^{bg}_{2-el}$.

In the lower panel of Fig. 4 the ratio of the 1-electron count rate and the 2-electron background, as determined in the previous paragraph, is shown. This ratio has a minimum when Ulysses was at southern polar latitudes, and give the maximum for β when we assume that all 1-electron entries during this time are generated by the RTG and GCR γ-ray background. From Fig. 4 we get $\beta = 5.18 \pm 0.24$. The corrected (lower curve) and uncorrected (upper curve) 1-electron count rates C_{1-el} are displayed in Fig. 5, showing the strong influence of the correction. During Ulysses' ecliptic crossing in 1995 the corrected 1-electron count rate is approximately a factor five lower than the uncorrected one. We can regard the corrected and uncorrected count rate as lower and upper limits for the real time profile. Ferreira et al. (2001) showed by using a three dimensional cosmic ray modulation model, including diffusion, convection, adiabatic deceleration, and drifts that several scenarii for the model parameter lead to an equally good approximation of the given data set. However, to describe the transport of low energy electrons in the inner heliosphere, Ulysses measurements would be more constraining if we could determine the time profile with a much higher accuracy.

To determine the correction factor β more realistically, one should notice that in contrast to the E12 channel the E4 channel has a larger contribution of the 1-electron distribution in the 2-electron range (see lower panel of Fig. 2). In contrast to the 7-170 MeV electron channel we can make use of the 2-12 MeV electron time profile by the IMP satelite close to the Earth, which is displayed in Fig. 5. Fig. 6 displays Ulysses' trajectory from 1993 to end of 1995 and Earth' trajectory in 1995 in a reference frame where Sun and Jupiter are fixed and projected into the Jovian orbital plane. The crosses in Fig. 6 give the position of Ulysses and Earth, when the spacecraft crossed the heliographic equator on day 63 of 1995 at a radial distance of 1.3 AU. At that time Ulysses and Earth were on opposite sides of the Sun. A standard Parker magnetic field line, for a solar wind speed of 475 km/s, "passing through" Jupiter is also drawn in Figure 6. From Fig. 6 it is evident that neither Ulysses nor Earth were magnetically well connected to Jupiter. To determine the relative count rate at Ulysses with respect to that at Earth, we used a propagation model, as described in Ferreira et al. (2001). The superimposed thick

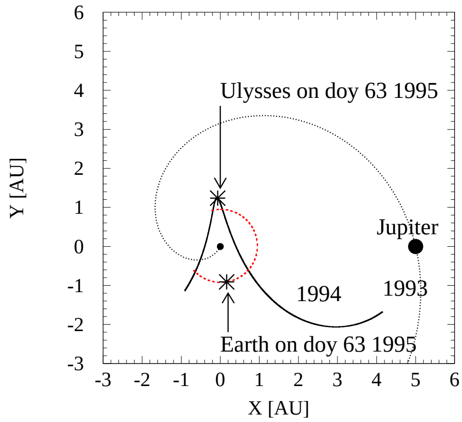

Fig. 6. Ulysses (solid curve) and Earth (dashed curve) trajectory in a projection onto the Jovian orbital plane in a system where the positions of Jupiter and Sun are fixed. A Parker magnetic field line (dotted curve) is shown for a solar wind speed of 475 km/s.

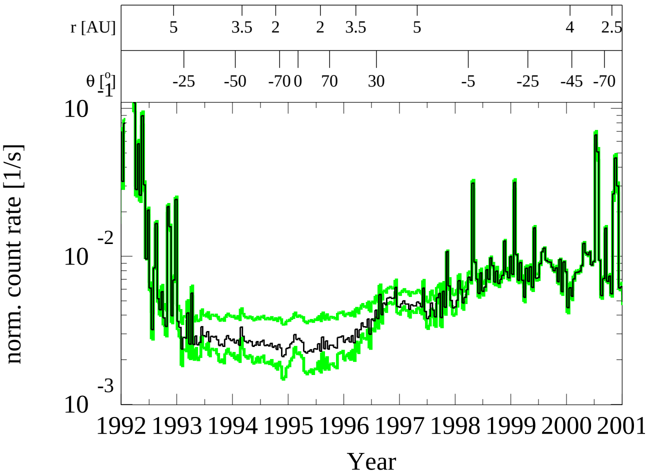

Fig. 7. Corrected 13-day averaged 1-electron E4 count rates. The lowest and highest grey curves display corrected time profiles by using the observed minimum and maximum of the IMP 2-12 MeV electron channel during the heliographic equator crossing, while the black curve uses the value predicted by the modulation model.

grey curve in Fig. 5 displays the result of the model, which indeed reproduces the Earth observation from 1993 to 1996. For details of this model see Ferreira et al. (2001).

In Fig. 5 KET and the 1 AU measurements are normalized to each other in November 1990, when the spacecraft was close to Earth. The horizontal line drawn in 1994 to end 1995 indicates the minimum count rate measured by IMP during this time period. Obviously, the corrected normalized KET count rate is below this minimum. Although the energy ranges of both instruments are not exactly the same, we assume that differences in the time profile due to slightly different mean energies are negligible. This assumption is confirmed by a comparison of 1.3 - 20 MeV electrons from the EPHIN-instrument (Müller-Mellin et al., 1995) onboard SOHO with the 2-12 MeV IMP electrons (not shown here).

The correction factor is determined by the fact that the normalized KET count rate close to the heliographic equator should match the model calculation. The result of this procedure is shown by the dark curve in Fig. 7. The minimum and the maximum of the Earth measurements have been used to estimate the uncertainty of our method, leading to the thick grey curves in Fig. 7. In contrast to Fig. 5 the maximum uncertainty is only a factor of two compared to the factor of five in 1995. The upper limit corresponds to the uncorrected 1-electron channel with a negligible correction, while the lower limit still needs a significant correction. In this context it is important to note that (1) the 1- to 2-electron ratio is $\sim$2 when Ulysses is at high southern latitudes, and (2) the RTG-background can be estimated to be $9 \cdot 10^{-4}$ c/s. The first is in good agreement with corresponding results for E12 by Heber et al. (1999), and the second is in good agreement with a value of $1 \cdot 10^{-3}$ c/s determined by Rastoin (1995), giving us confidence in our correction method.

4 Summary

In this paper we showed that a significant contribution to the 3-10 MeV electron channel of the KET is caused by γ-rays generated by Ulysses' RTG and by energetic cosmic rays in the spacecraft material. We developed a procedure in order to determine these background contribution. The unique Ulysses trajectory allows us to use 1 AU measurements from IMP 8 and the SOHO spacecraft, and model calculations describing the latter observations, to determine the count rates in November 1990 and February 1995, when the spacecraft was close to 1 AU close to heliographic equator. The result displayed in Fig. 7 will be used in future to determine MeV electron propagation parameters in the inner three-dimensional heliosphere.

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