Are there Kronian electrons in the inner heliosphere?

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1 Introduction

The Jovian magnetosphere as the largest in our solar system is treated in the literature as the dominant source of a few-MeV electrons, which have been measured by various spacecraft. On the basis of a time-dependent three-dimensional modulation model the transport of MeV electrons in the heliosphere is simulated. For this purpose the cosmic rays, the Jovian and the Saturnian electron sources are, for the first time, considered together in the simulation of electron fluxes. The simulated electron intensities are discussed along the *Ulysses* and *Cassini* trajectories (see Fig. 1). Our results reveal that the electrons from the Kronian magnetosphere, as the second largest, can not be neglected in the very-low MeV energy range.

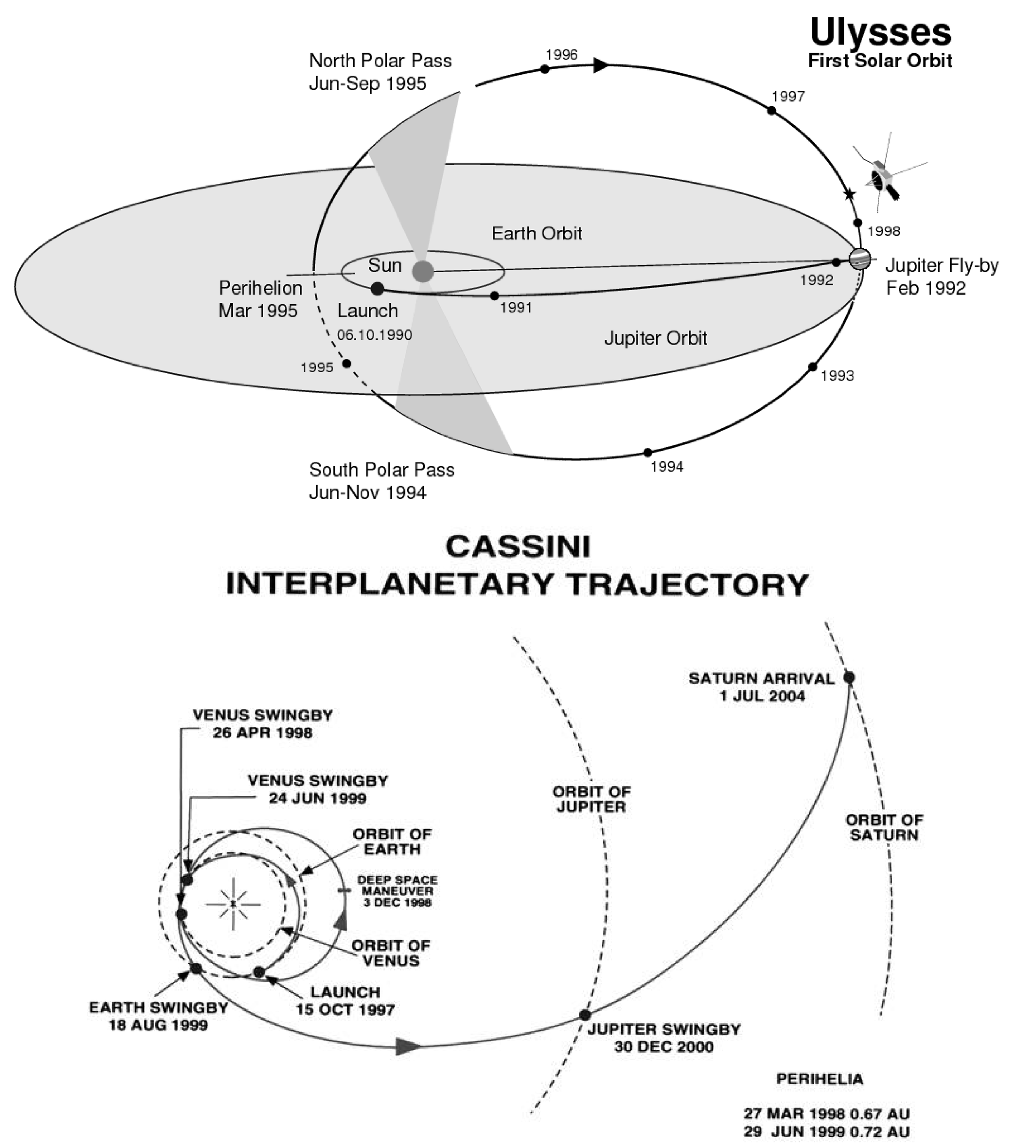

Fig. 1: The trajectories of the Ulysses and Cassini spacecraft. The Ulysses spacecraft passed by the planet Jupiter already at two times (1992, 2004) and Cassini passed by Jupiter in 2001 and reached Saturn in the year 2004. Shown is here Ulysses first orbit. Source: http://helio.estec.esa.nl/ulysses/ and http://saturn.jpl.nasa.gov/home/index.cfm

2 Modulation Model

The time-dependent three-dimensional modulation of the electron flux in the heliosphere is based in our model on a momentum integration of Parkers transport equation, in which we use the following definition of the electron pressure:

$$P_{\rm e}(\vec{r},t) = \frac{4\pi}{3}\int_0^\infty f\,(\vec{r},p,t)\,pwp^2\,dp \quad , \qquad (1)$$

where w is the particle speed. Parker's transport equation then takes the form:

$$\frac{\partial P_{\rm e}}{\partial t} = \nabla\cdot(\kappa\nabla P_{\rm e}) - \vec{u}_{\rm sw}\cdot\nabla P_{\rm e} - \frac{4}{3}(\nabla\cdot\vec{u}_{\rm sw})\,P_{\rm e} \quad , \qquad (2)$$

where $\vec{u}_{\rm sw}$ is the solar wind velocity and κ has to be understood as the momentum-averaged diffusion tensor. The four-dimensional integrated Parker transport equation (2) is the basis for our electron flux simulations in the heliosphere.

3 Measurements of the Jovian and Kronian magnetosphere

Fig.2 shows measurements of the differential electron intensity around 1 MeV from the 5 spacecraft Voyager (1 and 2), Pioneer (10 and 11) and Cassini. Our aim is now to determine the source function of Kronian electrons to use it simultaneously with that of Jovian electrons in the simulations. The main and obvious effect is, however, that electrons accelerated in the Kronian magnetosphere should not be expected to be negligible in comparison to Jovian electrons. Because of similar slopes of the magnetospheric energy spectra, we use the source function of Jupiter also for Saturn in the simulations, but multiplying by a factor $S_{\rm j}$. We set $S_{\rm j}$ to 1.5, 7.5 and 0.3 to study the general behaviour and distribution of Kronian electrons in the heliosphere.

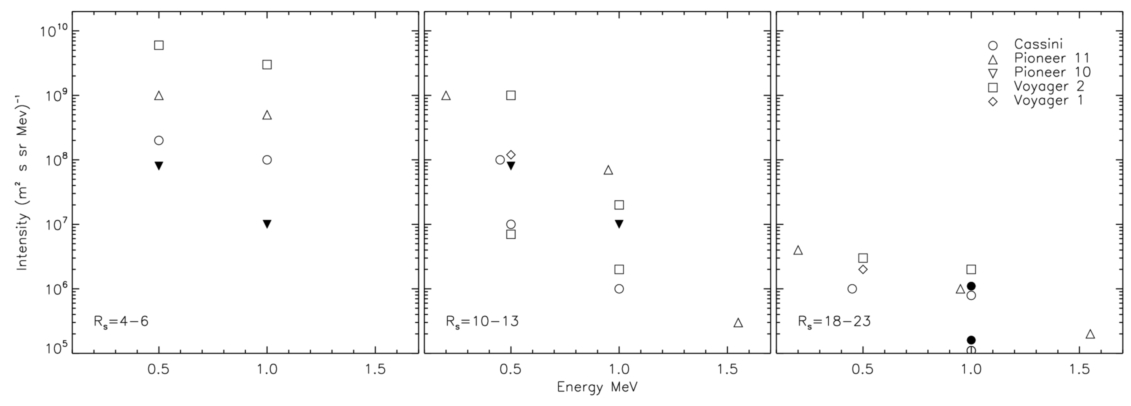

Fig. 2: Measurements of the differential electron intensity around 1 MeV from the 4 spacecraft Voyager (1 and 2), Pioneer 11 and Cassini. For comparison, measurements of Pioneer 10 and Cassini at Jupiter are shown. Open symbols stand for measurements at Saturn and filled symbols at Jupiter. The first two panels refer to inbound measurements of the Kronian magnetosphere at a distance of about 5 and 11 $R_{\rm s}$. The right panel is for a distance of approximately 20 $R_{\rm s}$, which for Voyager 2 and Pioneer 11 corresponds to their crossing distance of the Kronian magnetopause. The Voyager 1 and Cassini data points are measurements inside the Kronian magnetosphere. Pioneer 10 measurements refer to a distance of about 3 $R_{\rm j}$, which is inside the Jovian magnetosphere. The upper Cassini data point in the right panel determines the location, where Cassini entered the Jovian magnetosphere, which was at a distance of about 200 $R_{\rm j}$, whereas the lower data point is equivalent to the spacecraft's closest approach to Jupiter of about 140 $R_{\rm j}$. ($R_{\rm j} = 71400$ km, $R_{\rm s} = 60330$ km).

4 Simulation of the heliosphere with Jupiter and Saturn electrons

First of all, we present a simulation with only two electron sources, namely the galactic and the Jovian electrons. The computed 1 MeV intensities (normalized to the galactic source) along the Ulysses and Cassini trajectories are shown in Fig.3 a). The diffusion tensor κ and the solar wind speed $\vec{u}_{\rm sw}$ are time-independent and are kept at the conditions valid for the solar minimum. In Fig.3 b) we have, in addition, implemented the Kronian electron source. We set $S_{\rm j} = 1.5$, so that the Saturn source is 1.5 times stronger than the source at Jupiter. In general, the intensities are higher in comparison to Fig.3 a).

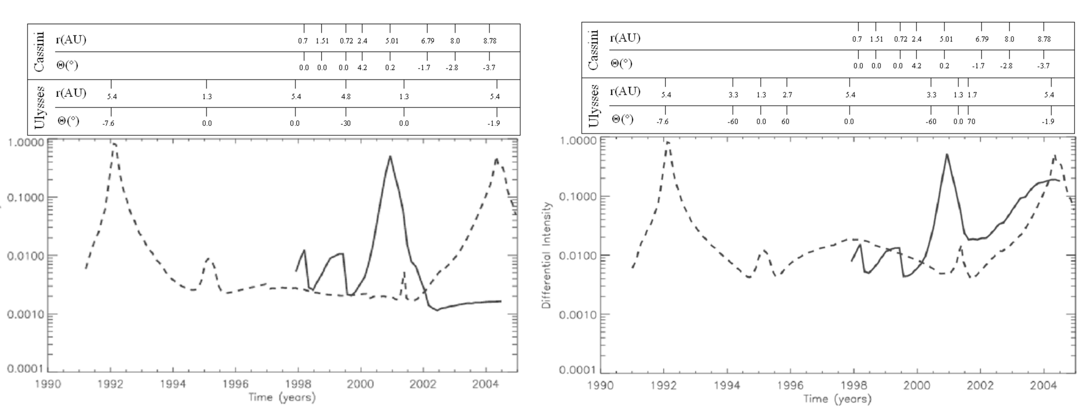

Fig. 3: The computed electron intensities (normalized to the galactic source) along the Cassini (solid line) and Ulysses (dashed line) trajectories at an energy of 1 MeV. a) This simulation was performed only with the galactic and the Jovian electron source. b) This simulation was performed with the galactic, the Jovian and the Kronian electron source. We set $S_{\rm j} = 1.5$, so that the Saturn source is 1.5 times stronger then the source at Jupiter. The heliocentric distance and heliographic latitude of the Ulysses and Cassini trajectories are shown at the top panel.

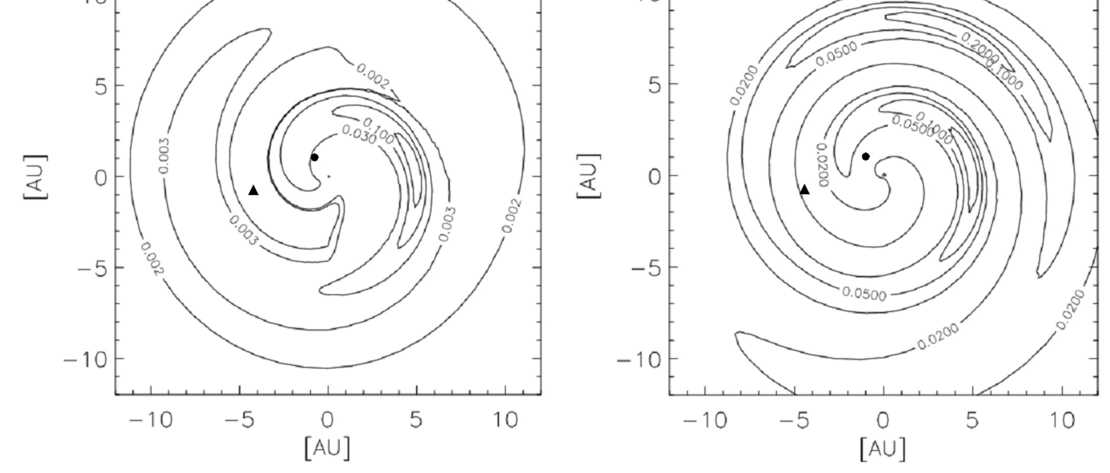

Fig. 4: Contour plot of the 1 MeV electron intensity in the ecliptic plane at 1998.0 inside 10 AU: the left panel is related to the situation in Fig.3 a) (no Saturn source) and the right panel to Fig.3 b) (with Saturn source, $S_{\rm j} = 1.5$). The position of Ulysses is marked as the filled triangle and Cassini as the filled circle. The Parker spiral and the extensions of the Jupiter and Saturn source are clearly visible at about 5 AU and 9 AU.

Fig.4 displays a contour plot of the ecliptic plane at 1998.0 inside 10 AU, where the left panel is related to the situation in Fig.3 a) (no Saturn source) and the right panel to Fig.3 b) (with Saturn source). The position of Ulysses is marked as the filled triangle and Cassini as the filled circle. Ulysses was in the beginning of 1998 in the ecliptic plane at about 5 AU, whereas Cassini was just launched at 1 AU. The Parker spiral and the extensions of the Jupiter and Saturn source are clearly visible at about 5 AU and 9 AU. The Saturn source is more spread in longitude there, as a result of the 1.5 times stronger source and the increased diffusion at larger distances. It is observable in the right panel, that the Jupiter and Saturn sources are connected by intensity contour lines there. This explains the Ulysses maximum in 1998.0 in Fig.3 b), because on these lines Saturn injects electrons into the inner heliosphere.

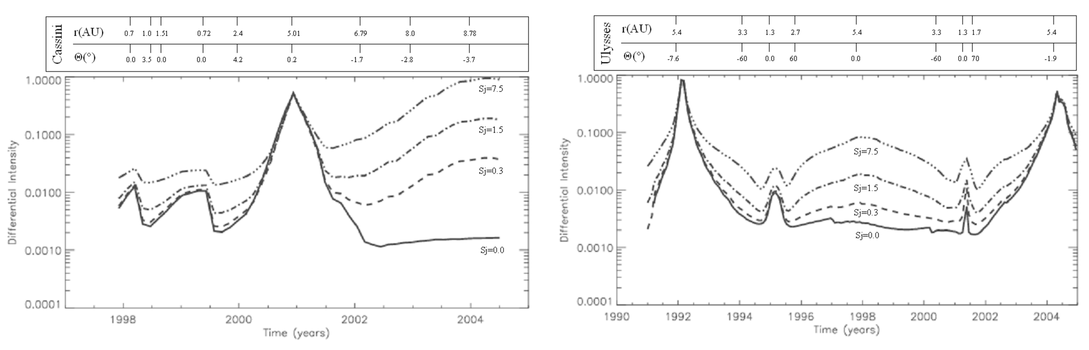

Fig. 5: The computed electron intensities along the Cassini trajectory a) and Ulysses trajectory b) at an energy of 1 MeV. Displayed are simulations with three factors of $S_{\rm j}$, 0.3,1.5 and 7.5 (dashed lines), together with the simulation without the Saturn source ($S_{\rm j}$=0, solid line). The heliocentric distance and heliographic latitude of the Cassini trajectory are shown at the top panel.

Figure 5 a) and b) display the simulations with the three factors of $S_{\rm j}$, 0.3,1.5 and 7.5 (dashed lines), together with the simulations without the Saturn source ($S_{\rm j}$=0, solid line) for the Ulysses and the Cassini trajectories, respectively. In Fig.5 a) is clearly visible that the Kronian electrons produce a maximum in 1998.0 along the Ulysses trajectory, even when the Saturn source strength is relative weak with $S_{\rm j} = 0.3$. Along the Cassini trajectory (Fig.5) b) the Kronian electrons have hardly an effect until the Jupiter flyby 2001, except when $S_{\rm j} = 7.5$. The very inner heliosphere is then filled even at low latitudes with Kronian electrons.

5 Summary and outlook

The simulated electron intensities were shown along the Ulysses and Cassini trajectories and it clearly turns out that the electrons from the Kronian magnetosphere can not be neglected. Even for the extreme case that the source strength is relatively small with $S_{\rm j} = 0.3$, the effect of Kronian electrons is visible along both the Ulysses and Cassini trajectories. The increased diffusion at greater heliocentric distance fostered the distribution of Kronian electrons in the inner heliosphere in comparison to the Jovian electrons. Obviously, while the existence of a non-negligible Kronian electron source complicates the fluxes at low energies, at the same time it adds a valuable constraint to diffusion models of energetic particles. The real distribution of electrons in the inner heliosphere and the actual source strength of Saturn in comparison to Jupiter, $S_{\rm j}$, can only be answered with data calibration. To date, no LEMMS data along the Cassini trajectory are available.