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Time-dependent 3-D modelling of the heliospheric propagation of few-MeV electrons

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Abstract. With a recently developed steady-state model of the propagation of Jovian and galactic electrons in the inner three-dimensional heliosphere we were able to demonstrate both the necessity and value of such modelling for (i) the determination of the diffusion tensor of energetic particles, (ii) an observational discrimination between Jovian and interstellar electrons as well as (iii) a bracketing of the range of the possible interstellar electron fluxes at low energies (see Ferreira et al., this volume). These studies revelead the need of a time-dependent modelling in order to fully explain measurements made with the Ulysses spacecraft. Therefore, by reducing the complexity of this approach with an averaging w.r.t. particle energy and by the use of mono-energetic transport parameters, we have derived an alternative formulation that allows us an explicit consideration of the time dependence of the electron fluxes. After a demonstration of the model's capability to reproduce (despite the energy-averaging) in a very good approximation the results of the energy-resolving steady-state model, we will present first results and exploit the new feature of an explicit time-dependence by comparisons with observations made with the Ulysses, the SOHO and the IMP-8 spacecraft.

1 Introduction

The potential of a thorough modeling of few-MeV electrons in the heliosphere to improve the understanding of the transport of energetic particles in turbulent electromagnetic fields has been increased significantly during recent years. This is because there has been obtained a continuous time series of the $\sim$7.5 MeV electron flux along the trajectory of the Ulysses spacecraft (see Ferrando (1997) and Heber et al., this conference) by now. These data span more than ten years and represent a substantial extension of previous *in-situ* electron observations beyond 1 AU that were recorded with instruments aboard the Voyager and Pioneer spacecraft (Moses, 1987; Lopate, 1991). On the other hand, a new significantly improved model for the heliospheric electron transport has been developed, recently (Fichtner et al., 2000; Ferreira et al., 2001a).

It is now possible to compare model results with observations in great detail, in particular also in the inner heliosphere probed by the Ulysses spacecraft where earlier models (Conlon, 1978; Moraal et al., 1991; Potgieter, 1996; Haasbroek et al., 1997) were not applicable. The main hurdle to take was the formulation and numerical implementation of a fully three-dimensional model of the electron transport in the inner heliosphere. The three-dimensional nature of the transport in that region is mainly due to the existence of a powerful inner-heliospheric local electron source, namely the Jovian magnetosphere.

As is known since the Pioneer 10 fly-by of Jupiter in 1974, the planet's magnetosphere is a source of electrons with energies up to $\sim$30 MeV (Simpson et al., 1974; Teegarden et al., 1974). While the measurements made with the Kiel Electron Telescope (KET) aboard Ulysses (see Ferrando (1997) and Heber et al., this conference) allow to explore the resulting inner heliospheric distribution of energetic electrons in detail, the outer heliospheric distribution can be probed with corresponding measurements with the Voyagers and Pioneers beyond the orbit of Jupiter. Comparing these observations with model results allowed to tackle three problems of interest, recently. First, one is able to constrain the transport parameters for electrons (Ferreira et al., 2001a, see also Ferreira et al., this volume). Second, one can distinguish the relative contributions of Jovian and galactic electrons to the total flux (Ferreira et al., 2001a, see also Ferreira et al., this volume). And, third, it is possible to bracket the range of the possible interstellar electron flux (Ferreira et al., 2001b).

Due to the complexity of the modelling in four phase space dimensions, these studies are carried out for steady states. A time-independent approach is well justified for various applications but naturally excludes the analysis of data on time scales of the solar rotation period ($\sim$ 26 days) and the solar

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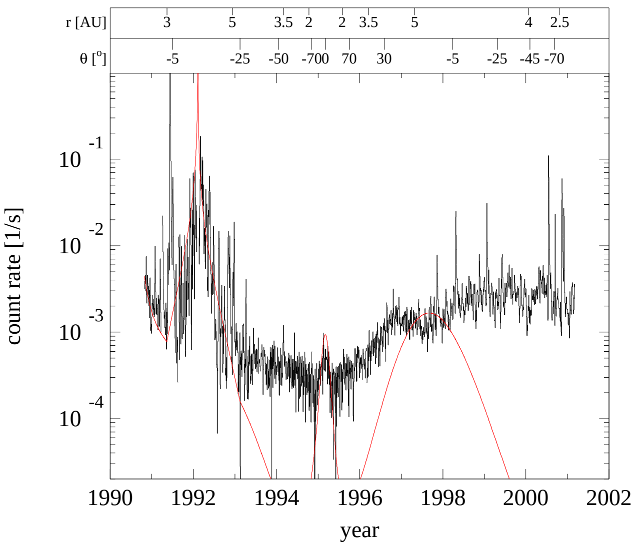

Fig. 1. The ~7.5 MeV electron flux measured with the Kiel Electron Telescope aboard the Ulysses spacecraft along its trajectory, see also Heber et al, this conference.

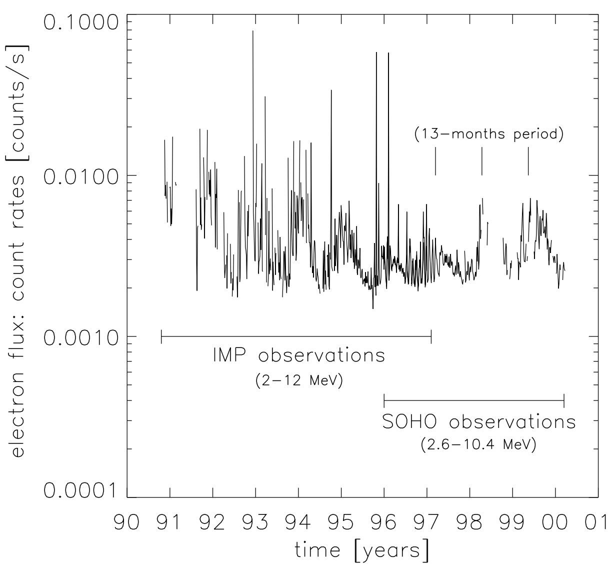

Fig. 2. Electron flux observations at the orbit of Earth on the IMP and the SOHO spacecraft, see Moses (1987) and Müller-Mellin et al. (1995).

cycle (~ 11 years). These limitations, therefore, still prevent studies of the modulation effect of, e.g., corotating interaction regions and solar activity even within the framework of the newly developed model.

However, the modelling performed so far confirmed the expectation that for energies lower than about 10 MeV the effects of drifts and adiabatic cooling are negligibly small (see, e.g., Ferreira et al., this volume). These findings point to an opportunity how to formulate a time-dependent model of the three-dimensional electron transport, namely by a momentum-averaged treatment. Although still simplifying the actual physical situation, this most recent approach to the electron transport in the heliosphere allows an analysis of Ulysses data (Fig. 1) on all time-scales of interest. Furthermore, the time-dependence of the 1 AU data (Fig. 2) recorded by the IMP-8 and the SOHO spacecraft (Moses, 1987; Müller-Mellin et al., 1995) can be investigated and, thus, used as additional information to constrain the transport parameters. In this contribution we report about the model and first results.

2 The model

2.1 The time-dependent transport equation

The basic idea of our approach to a time-dependent three-dimensional modelling of electron flux modulation in the heliosphere is a momentum averaging of Parker's transport equation. In view of negligible adiabatic cooling of electrons at energies below 10 MeV, this appears to be a reasonable approximation. So, with the definition of the electron pressure as (w and p denote particle speed and momentum, respectively):

$$P(\boldsymbol{r}, t) \;=\; \frac{4\pi}{3} \int\limits_0^\infty f(p, \boldsymbol{r}, t) p w p^2 dp \qquad (1)$$

and the neglect of drifts the transport equation takes the form:

$$\frac{\partial P}{\partial t} = \nabla \cdot \left(\overleftrightarrow{\kappa}\ \nabla P \right) - \boldsymbol{u}_{sw} \cdot \nabla P - \frac{4}{3}\left(\nabla \cdot \boldsymbol{u}_{sw} \right) P \qquad (2)$$

where $\overleftrightarrow{\kappa}$ has to be understood as the momentum-averaged diffusion tensor, i.e. $\overleftrightarrow{\kappa}\ (\boldsymbol{r}, t) \equiv <\overleftrightarrow{\kappa}\ (\boldsymbol{r}, p, t)> = \overleftrightarrow{\kappa}\ (\boldsymbol{r}, \hat{p}, t)$, with $\hat{p} = const.$

The resulting $P(\boldsymbol{r}, t)$ exhibits the same variations as the phase space distribution $f(\boldsymbol{r}, \hat{p}, t)$ evaluated for a prescribed momentum $\hat{p}$.

2.2 The parameters in the transport equation

The time-independent part of the two functions $\boldsymbol{u}_{sw}(\boldsymbol{r}, t)$ and $\overleftrightarrow{\kappa}\ (\boldsymbol{r}, \hat{p}, t)$ are defined as in Fichtner et al. (2000). So, for the solar wind velocity the representation introduced by *Hattingh* [1998] with a tilt angle for the heliospheric current sheet of $\theta' = 10\,\mathrm{deg}$ is employed. The spatial diffusion tensor is assumed to be diagonal ($\overleftrightarrow{\kappa} = \kappa_{ij}\,\delta_{ij}$) in a local coordinate system (with a z-axis along the magnetic field direction) with the elements: $\kappa_{xx} = \kappa_\perp(r, R) = a\,\kappa_\|$ and $\kappa_{yy} = \kappa_{\theta\theta}(r, R) = b\,\kappa_\|\,F(\theta)$, $\kappa_{zz} = \kappa_\|(r, R) = \kappa_0\,\frac{v}{c}\,\kappa_r(r)\,\kappa_R(R)$, where r and R denote heliocentric distance and rigidity, respectively. A parallel mean free path $\lambda_\| \approx 0.3$ AU at 1 AU below ~ 1 GV gives $\kappa_0 = 4.5 \cdot 10^{22}$ cm^2/s. The speed of light is denoted by c. Furthermore, there are the functions

$$\kappa_r(r) \;=\; (1 + r)/2 \qquad (3)$$

$$\kappa_R(R) = \begin{cases} 1 & ; R \le R_1 \\ (R/R_1)^{\frac{1}{3}} & ; R_1 < R \le R_2 \\ (R_2/R_1)^{\frac{1}{3}}\,(R/R_2) & ; R_2 < R \le R_3 \\ (R_2/R_1)^{\frac{1}{3}}\,(R_3/R_2)\,(R/R_3)^2 & ; R > R_3 \end{cases} \qquad (4)$$

$$F(\theta) = \quad C^{+} + C^{-}\tanh\left[(\tilde{\theta} - 90\deg - \theta_F)/\Delta\theta\right] \qquad (5)$$

with $\tilde{\theta} = \theta$ for $\theta \geq 90\deg$ and $\tilde{\theta} = 180\deg - \theta$ otherwise, $(R_1, R_2, R_3) = (0.4, 10, 12)\,GV$, and $C^{\pm} = (d \pm 1)/2$, $d = 20$, $\theta_F = 35\deg$, and $\Delta\theta = 45\deg/(2\pi)$. The constants $a = b = 0.005$ and $\lambda_{\|} \approx 0.3$ AU at 1 AU are chosen according to the constraints following from the analysis of data recorded by the KET instrument aboard Ulysses Ferrando (1997). The assumed R-dependence $\kappa_R(R)$ is an approximation to that of the damping model for dynamical turbulence (Bieber et al., 1994). In the momentum-averaged modelling, for the above representation of the diffusion tensor the choice of a constant momentum translates into a constant (prescribed) rigidity.
This choice of the diffusion coefficients is compatible with the Ulysses data up to 1998 (Ferreira et al., 2001c).

2.3 The boundary conditions

The spherical domain of integration is bounded by the surface of the Sun, where vanishing pressure is assumed, and an outer modulation boundary at 100 AU where the pressure of the interstellar electrons is prescribed. In addition, there is a moving local electron (pressure) source at the position of Jupiter which is orbiting the Sun at a heliocentric distance of about 5.1 AU.

2.4 The time-dependence

First, there is a time-dependence of the diffusion tensor which is modelled according to the typical variation in the sunspot number, an approach succesfully employed for a modulation study by le Roux and Fichtner (1999). Second, the effect of corotating interaction regions (CIRs) as propagating diffusion barriers is modelled by a narrow spiral region of decreased diffusion coefficients as depicted in Fig. 3. The latitudinal extent of the CIRs is limited to $\pm 30^0$ around zero heliographic latitude. Finally, the Jovian source as well as the observation points (i.e. the Ulysses, IMP and SOHO spacecraft) are moving. The activity-related time-dependence of the solar wind velocity field is not taken into account in the computations shown below.

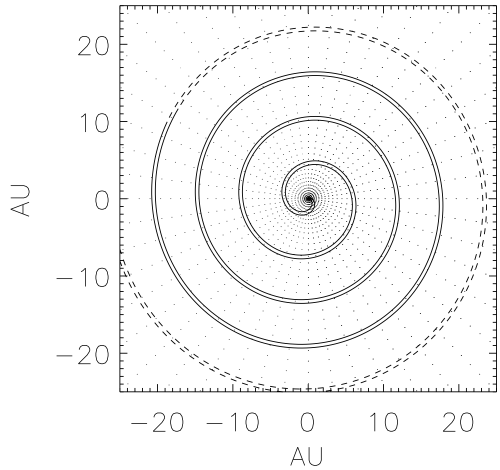

Fig. 3. The simulated corotating interaction region (CIR). The diffusion coefficient is reduced in the narrow region between the two solid lines which mark the boundaries of the CIR. The dashed continuation lines indicate the decay of the CIR as a isolated diffusion barrier due to merging processes (with other CIRs) in the outer heliosphere.

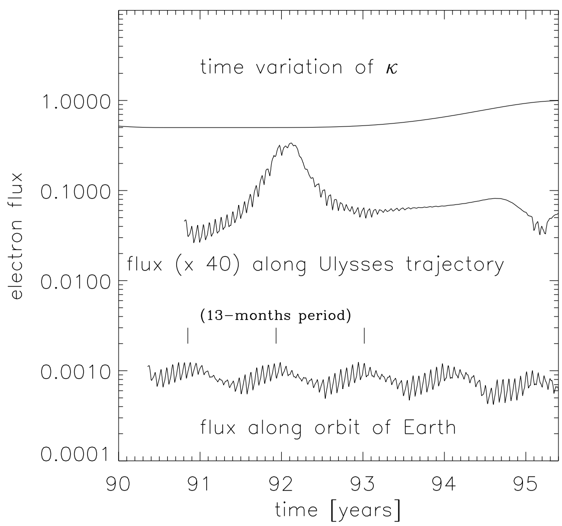

Fig. 4. The ~7.5 MeV electron flux along the trajectory of Ulysses and the orbit of Earth as computed with the time-dependent model.

3 Results

After a successful reproduction of the results discussed in Fichtner et al. (2000), which represents an *a posteriori* confirmation of the applicability of the averaged transport equation to the electron transport at energies below 10 MeV, the time variations of the diffusion tensor and the CIRs were activated.

The results are shown in Figs. 4 and 5. Figure 4 displays the assumed long-term variation of the diffusion tensor and the resulting time-profiles of the 7.5 MeV electron flux along the Ulysses and the SOHO trajectory. The Ulysses flux curve is shifted be a factor of 40 in order to facilitate visualisation of results.

For the present set of parameters, the effect of the CIRs is limited to lower latitudes. Therefore, the related 26-day variations are only significant for periods during which Ulysses was at low heliographic latitudes (which can be extracted from the top panels in Fig. 1). For an analysis of the quasi-steady state on time-scales between the periods of solar rotation and solar activity, see Ferreira et al., this volume. A further more detailed parameter study to investigate how to achieve quantitative agreement with the data on the basis of the present model will be presented elsewhere.

The flux at SOHO and IMP-8 is characterized by at least two time-periods: a 27-day variation due to CIRs (extended

26-day variation due to the orbital motion of the Earth) and a 13-months variation due to the relative position of the spacecraft (i.e. Earth) and Jupiter. A long-term effect of solar activity is not prominent in the observations. The reproduction of these expected periodicities in the data is rather a further successful test of the model than a new result. Only a closer comparison of the amplitudes of these computed intensity variations with those being observed reveals the potential of such modelling for an understanding of the diffusive transport.

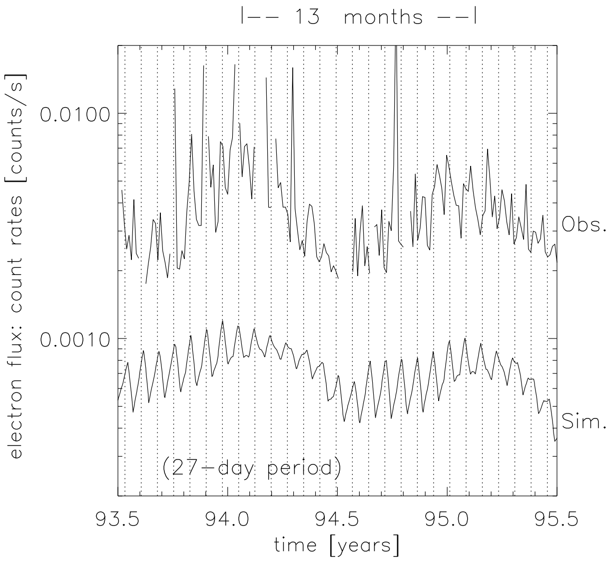

Fig. 5. The ∼7.5 MeV electron flux at the Earth as observed (top curve, data are the same as in Fig. 2) and as computed (bottom curve) with the time-dependent model. The dottet lines indicate the 27-day period. The vertical separation of the curves is arbitrary.

Figure 5 displays the actual observations from mid-1993 to mid-1995 (top curve) with the simulation (bottom curve). Obviously, not only the 27-day and 13-months periodicities are correctly reproduced but – more importantly – also the amplitudes of both variations. These results were obtained with a reduction factor of 10 for the diffusion coefficients inside the CIR. This rather high factor might be lower if the CIR would be broader than assumed here, pointing again to the need of a more detailed parameter study. However, it also points to an opportunity to indirectly study CIRs themselves.

4 Discussion

With a new time-dependent model we have studied the heliospheric transport of energetic electrons. The more-than-qualitative agreement of the amplitudes of the time variations of the near-Earth ∼7.5 MeV electron flux is of higher significance than the reproduction of their periods. It clearly demonstrates the capability of such modelling to extract information about the particle transport in both space and time. This will be done in the future by using the improved diffusion tensor obtained by Ferreira et al. (2001a). On the basis of such results, the new modelling approach also offers an opportunity for an indirect study of CIRs in their function as modulation barriers.

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