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Near-relativistic electron events. Monte Carlo simulations of solar injection and interplanetary transport

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8 Conclusions and future perspectives

We have presented a Monte Carlo model to simulate the transport of solar NR electrons in the interplanetary medium, including adiabatic focusing, pitch-angle dependent scattering, and solar wind effects. By taking into account the angular response of the LEFS60 telescope of the EPAM instrument on board the *ACE* spacecraft, we have been able to transform the simulated pitch-angle distributions into the sectored intensities measured by the telescope. We have developed an algorithm to deconvolve the effects of interplanetary transport on observational sectored intensities in order to infer the best-fit transport conditions and the underlying solar injection profile of NR electrons. We have studied seven NR electron events observed by the LEFS60 telescope between 1998 and 2004 with the aim of estimating the roles that solar flares and CME-driven shocks play in the acceleration and injection of NR electrons, as well as the conditions of their transport along the IMF.

Specifically,

1. We have developed an algorithm to calculate the angular response of the sectors scanned by a particle detector on board a spin-stabilized spacecraft. The algorithm has allowed us to derive the angular response of the eight sectors of the LEFS60 telescope of the EPAM instrument on board the *ACE* spacecraft. We have emphasized the importance of the concept of pitch-angle cosine coverage (μ-co) of the telescope in order to understand the percentage of the pitch-angle cosine range scanned by the telescope as a function of the IMF orientation.

2. We have developed a Monte Carlo model to simulate the transport of solar energetic particles in the interplanetary medium, including adiabatic focusing, pitch-angle dependent scattering and solar wind effects. Several tests have been applied to verify the reliability of the code. The code is suitable for the study of different types of solar energetic particles; in this work it has been applied to solar NR electrons.

3. We have combined the particle transport model with the angular response model of the LEFS60 sectors to transform simulated differential intensities into modeled sectored intensities, which are directly comparable with observations. In particular, we have

used sectored Green's functions of particle transport, i.e. sectored intensities observed by the telescope resulting from a delta solar injection.

4. The determination of the sectored Green's functions has allowed us to develop a method to deconvolve observational sectored intensities. This method allows, for the first time, the derivation of the injection profile and the transport conditions of NR electrons in the interplanetary medium without any a priori constraint on the injection profile (onset, duration or parameterization).

5. We have made evident the relevant role that the pitch-angle cosine coverage has when studying sectored intensities. A low μ-coverage can lead to misleading conclusions about the characteristics of the particle propagation and of the injection profile of the source. We have found that two requirements must be fulfilled in order to discern the actual scattering conditions and injection profile from LEFS60 sectored measurements: (1) the event must be observed with μ-co $\geq$ 70%; and (2) the telescope must scan particles propagating antisunward along the field direction.

6. We have set constraints on the conditions under which the application of the deconvolution algorithm provides reliable results. We have found that the injection profile resulting from the deconvolution shows intermittency and the value of the radial mean free path is underestimated if the adopted scattering model is not accurate enough to describe the actual interactions between IMF fluctuations and propagating particles. Furthermore, we have found that measurement errors can result in small previous artificial precursor injection episodes of small intensity and fluctuations in the injection profile.

7. We have applied the deconvolution algorithm to the study of seven NR electron events observed by the LEFS60 telescope between 1998 and 2004 that verify five selection criteria. For two events, we have derived a λ_r = 0.9 AU, while for the other five $\lambda_r \leq 0.2$ AU. Events with short (< 15 min) rise times are associated with long radial mean free paths, whereas events with longer rise times (from one hour to one day, approximately) are related to small radial mean free paths. Five events could be best fit assuming μ-dependent scattering with $\epsilon = 0.01$; the other two events could be best fit if isotropic pitch-angle scattering was assumed.

8. In this set of seven NR electron events, we have identified two types of injection episodes in the derived injection profiles: short (< 20 min) and time-extended (> 1 h). The injection profile of three events shows both components; an initial injection episode of short duration, followed by a second much longer lasting episode; two events only

show a time-extended injection; while the others show an injection profile composed by several short episodes.

9. We have compared the derived injection profiles with the timing of the associated electromagnetic (radio, X-rays and optical) emissions. We have found that the timing of the prompt short injection episodes agrees with the timing of the hard X-rays and radio type III bursts. On the other hand, time-extended injection episodes seem to be related to intermittent radio emissions at the height of the CME leading edge or below, and to type II radio bursts. Thus, we conclude that short injection episodes are preferentially associated with the injection of flare-accelerated particles, while longer lasting episodes are provided by CME-driven shocks.

The overall conclusion from this study is that there is a continuous spectrum of scenarios that allow for either flare or CME-driven shock NR electron injection, or for both, and that this can occur both under strong scattering and under almost "scatter-free" propagation conditions.

There are some important open issues about the NR electron transport and acceleration/injection processes that we would like to pursue in the near future; five relevant ones are:

- To extend the study to a larger sample of events in order to gain definitive understanding of the processes involved in the solar injection and interplanetary transport of NR electrons.
- To apply the model to multi-spacecraft observations, for example, from *STEREO* (*Solar Terrestrial Relations Observatory*) and in particular to data from the Solar Electron Proton Telescope (SEPT; Müller-Mellin et al. 2007). SEPT measures electrons in the energy range 20–400 keV with a view cone of 60°. Directional information is provided through use of several fields of view. The algorithms we have developed can be easily adapted to the study of SEPT measurements.
- To study the interplanetary conditions that influence the characteristics of the pitch-angle scattering processes, in order to derive accurate pitch-angle scattering diffusion coefficients.
- To study other methods to optimize the fits if the mean free path is rigidity and time dependent.
- To take into account the effects of a moving source. This extension of the model would allow us to study the injection of particles at traveling interplanetary shocks, for example.

Some of these questions can be analyzed with the tools developed in this thesis and various aspects of the models can be easily improved with the experience gained. Other questions demand a deeper analysis and therefore are part of our mid-term objectives.