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A new cosmic ray modulation model for the 11-year and 22-year cycles

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Abstract. A time-dependent cosmic ray modulation model based on the numerical solution of Parker's transport equation is presented. The model is developed to simulate time-dependent modulation for cosmic ray protons, electrons and helium for full 11-year and 22-year cosmic ray cycles using the concept of propagation diffusion barriers. The features of the model are discussed and the results of the simulation are compared to the observed 11-year and 22-year cycles for 1.2 GV electrons and 1.2 GV helium at Earth for the period 1975-1998. The model solutions are also compared to the observed charge-sign dependence along the Ulysses trajectory for the period 1990-1998. The compound approach to long-term modulation, as introduced here, is found to be remarkably successful.

1. Introduction

Cosmic ray (CR) modulation during increased solar activity is characterized by several large steps ("ups and downs") that are easily recognized from observations at Earth and beyond, and especially up to neutron monitor energies. Periods of maximum CR modulation are complex, they may last only three years (1969-1971), or up to six years (1979-1984), or may be dominated by a massive decrease as in 1991. Any underlying pattern, if existing, is obscured by an apparent randomness which makes modelling very difficult. Nevertheless, there exist several concepts (not yet well developed theories) on how long-term CR modulation occurs over 11 years, including the period of maximum modulation. These concepts have mainly attempted to explain the large step-like modulation. The first effort, using what can now be called propagating diffusion barriers (PDBs) was by Perko and Fisk (1983). Their work was extended to two spatial dimensions, including drifts, by le Roux and Potgieter (1995). Burlaga et al. (1985, 1993) established that merged interaction regions (MIRs), manifested by recognizable HMF enhancements/ rarefactions, are proper modulation barriers, and later extended it to global MIRs. When these features were combined with drifts in comprehensive numerical models, it was shown that the combination of drift, which dominate minimum modulation periods, with MIRs and global MIRs, which dominate maximum modulation periods, could produce the 11-yr and the 22-yr modulation cycles (e.g., le Roux and Potgieter, 1995). Several reviews discussed modelling using MIRs as modulation barriers in detail (Potgieter, 1995; Wibberenz et al., 1998; le Roux, 1999).

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The MIR-drift approach for long-term modulation still seems most reasonable although not without reservations. For example, Cane et al. (1999) raised the question of why modulation steps were seen at 1 AU well before any global merging could have taken place. They proposed that step-like and long-term modulation are primarily related to HMF enhancements (and rarefactions) which propagate from the Sun with the solar wind speed, superimposed on the long-term HMF trend associated with solar activity changes over a full modulation cycle, meaning that one does not have to wait for large merging to occur beyond 10-20 AU before increased modulation sets in.

For this paper we tested the basic concept as proposed by Cane et al. (1999) using a full time-dependent numerical model similar to that used by le Roux and Potgieter (1995). We found that this concept works well but only at neutron monitor energies so that an alternative model, called the compound approach, has been developed that combines the basic concept of MIRs and global increases in the HMF with drifts and the other basic modulation mechanisms. For an overview see, Potgieter and Ferreira (2001).

2. Modulation model and parameters

The model is based on the numerical solution of the Parker's (1965) time-dependent transport equation:

$$\frac{\partial f}{\partial t} = -(\boldsymbol{V} + \langle \boldsymbol{v}_{\mathbf{D}} \rangle)\cdot\nabla f + \nabla\cdot(\boldsymbol{K}_s\cdot\nabla f) + \frac{1}{3}(\nabla\cdot\boldsymbol{V})\frac{\partial f}{\partial \ln R} + Q, \quad (1)$$

where $f(\boldsymbol{r},R,t)$ is the CR distribution function; R is rigidity, $\boldsymbol{r}$ is position, and t is time, with $\boldsymbol{V}$ the solar wind velocity. Terms on the right-hand side represent convection, gradient and curvature drifts, diffusion, adiabatic energy changes and a source, respectively. The latter represents any local heliospheric source, e.g., the Jovian electrons, but for this work all local sources were neglected. The symmetric part of the tensor $\boldsymbol{K_S}$ consists of a parallel diffusion coefficient ($K_{\|}$), and two perpendicular diffusion coefficients ($K_{\perp r}$ and $K_{\perp\theta}$). The anti-symmetric element (K_A) of the tensor describes gradient and curvature drifts in the large scale HMF, with $\boldsymbol{v_D}$ the averaged, charge-sign dependent drift velocity. The time-dependent transport equation was solved using the numerical procedure of le Roux and Potgieter (1995). The outer modulation boundary was assumed at 120 AU, where the different local interstellar spectra were specified . The termination shock was omitted, the effects of which are described by Ferreira et al. (2001) - see also Ferreira et al. (this volume). The solar wind speed V was assumed to change from 400 km. s^{-1} in the equatorial plane (θ = 90°) to a maximum of 800 km.s^{-1} when $\theta \leq 60°$ and $\theta \geq 120°$.

We assume $K_{\|} \propto f_1(r,R,t)$ as a basic form, similar to Ferreira et al. (this volume), with detail about the time-dependence given in the next section as the main issue. The other diffusion coefficients are specified respectively as:

$$K_{\perp r} = aK\,; \quad K_{\perp\theta} = f_2(\theta)K_{\|}; \quad K_A = (K_A)_0\frac{\beta R}{3B_m};$$

with a = 0.01 a constant which contributes to perpendicular diffusion in the radial direction, and $f_2(\theta)$ a function (Potgieter, 2000; Ferreira et al., this volume) that describes how perpendicular diffusion in the polar direction is enhanced (Kóta and Jokipii, 1995; Potgieter, 2000; Langner and Potgieter, this volume). B_m is the HMF magnitude, assumed to have a basic Parkerian geometry, but modified according to Jokipii and Kóta (1989). This modification inhibits drifts to some degree in the polar regions of the heliosphere. Equation (1) was solved in a spherical coordinate system, using observed current sheet "tilt angles" (Hoeksema, 1992). This was done for so-called A > 0 (e.g., ~1990 to present) and A < 0 (e.g., ~1980 to ~1990) magnetic field polarity epochs. The varying tilt angles were thus introduced as another time-dependent modulation parameter.

The basic concept as proposed by Cane et al. (1999) was tested by changing the diffusion coefficients time-dependently $\propto [B_0/B(t)]^n$, where n is a constant, B_0 is the average HMF magnitude at Earth during minimum modulation conditions, and $B(t)$ is the time-varying HMF magnitude at Earth as it changes from minimum to maximum activity. The increase in the total magnetic field with increasing solar activity was thus used as a slowly varying modulation parameter. These changes, as computed from the observed HMF values at 1 AU, were propagated outwards at the solar wind speed in a simulated heliosphere. The larger n (> 0) is made, the larger the temporal changes in the diffusion coefficients get, simulating essentially PDBs. At first, the power n was not changed with time.

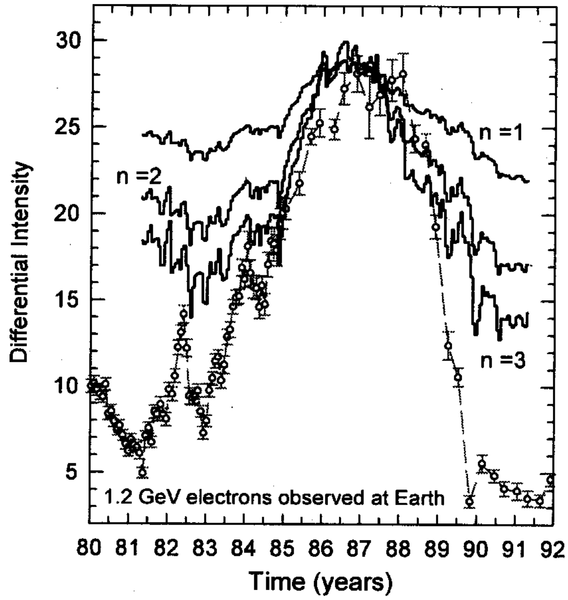

Fig. 1. Propagating diffusion barrier model computations for n =1; 2; 3 (see text) for 1.2 GeV electrons at Earth for the period 1981 to 1991, compared to 1.2 GeV electron observations-open circles (Clem et al., 1996; Evenson, 1998).

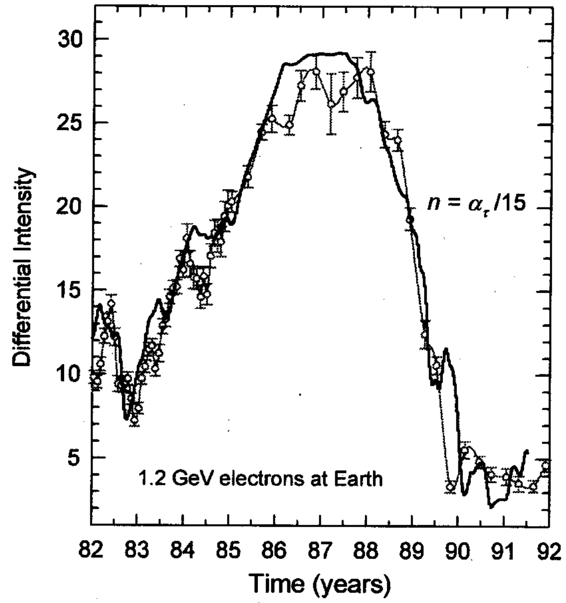

Fig. 2. Compound model with $\eta(t)$ = α_t/15 (see text) for 1.2 GeV electrons as Earth for the period 1982 to 1991, compared to observations (open circles) as in Fig. 1.

3. Results and discussion

When using such a model, the basic challenge is to reproduce the observed CR amplitudes of the 11-year cycle at energies of interest to modulation. It was quickly realized that with $n \approx 1.0$ it could only be done at neutron monitor energies because changing the diffusion coefficients with

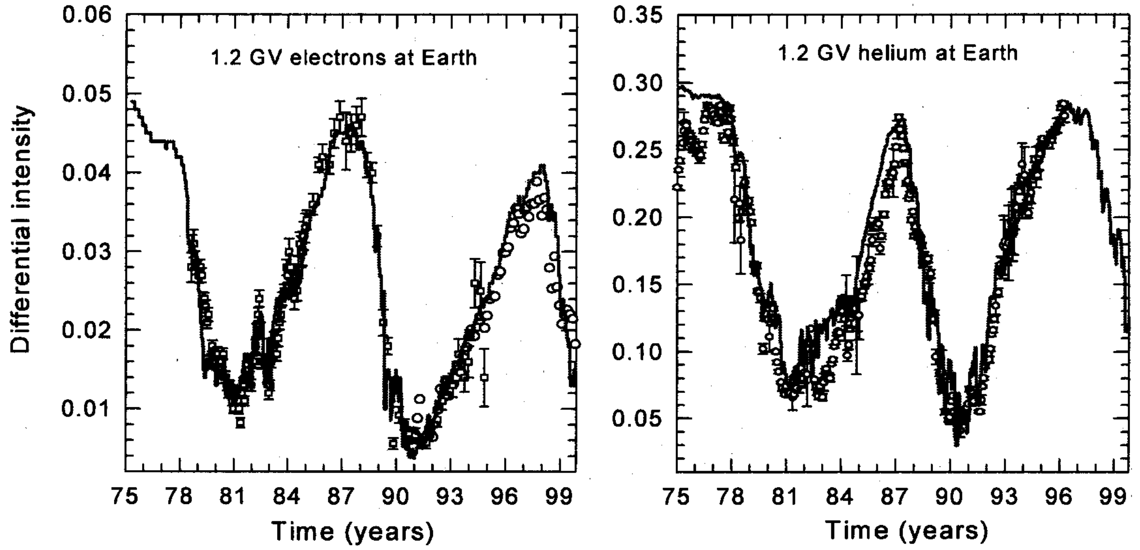

Fig. 3. Computed long-term modulation compared to 1.2 GV electron and helium observations (e.g., Clem et al., 1996; Evenson, 1998). Additional electron data (circles) are shown from 1990 onwards (Heber, private communication). For these simulations the compound model as described in the text was used. Differential intensity is in units of part. $m^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}$.

time by maximum a factor of 2, corresponding to the maximum global change in the HMF magnitude from solar minimum to maximum, is not nearly enough to reproduce the observed amplitudes at lower rigidities (< 5 GV) over 11 years. Even values of $n \approx 3.0$ could not reproduce the required amplitude. This aspect is shown in Fig. 1 for 1.2 GeV electrons at Earth for the period 1981 to 1992. Although this concept could not reproduce the 11-year modulation amplitude, the positive side was that the method could produce step-like modulation changes quite realistically at Earth. It was also realized that n could not be a constant - it has to change with time - and that this time-dependence must be related to solar activity. From a drift point of view, the obvious choice was the time-varying heliospheric current sheet 'tilt angle' α.

We consequently introduced the compound concept for long-term modulation stating that the diffusion coefficients are proportional to $[B_0/B(t)]^{n(t)}$, with $n(t) = \alpha_t/\alpha_0$, where α_t is the observed time-varying tilt angle and α_0 is a 'constant' (read: maybe a constant, because it probably must be rigidity dependent as well) for a given energy. It is known from previous simulations that α_t plays a dominant role through drifts around solar minimum modulation, and that this role gradually subsides to be replaced by PDBs as the dominating modulation process around solar maximum modulation (see review by Potgieter, 1995). As mentioned above, using a time-varying tilt angle as the *only* time-dependent parameter in the model could also not give the required amplitudes. Using $n(t) = \alpha_t/\alpha_0$ means that n is small ($n \to 0$) for minimum modulation, but increases with increasing solar activity ($n = 2 \to 5$, depending on the energy). Note that in addition to $n(t)$, the extent of the heliospheric current sheet was changed with time, as done previously, meaning that its waviness changes with α_t and that every one of these change (averaged over 26 days), increasing from ~5° to 75° over a period of ~6 years, was also propagated outwards from the Sun with the solar wind speed.

In Fig. 2 the results of this compound modelling approach are compared to the 1.2 GeV electron observations using $n(t) = \alpha_t/15°$. This took care of the correct amplitude requirement, and even some of the steps, although some of the simulated steps do not have the correct magnitude and phase. The latter means that a further refinement of $n(t)$ is needed, but it was decided to test the concept further only in general terms, meaning that we concentrated on the amplitude and phase of the 11-year and 22 -year CR cycles.

We established that with α_0 = 7°-15°, the amplitude of the 11-year cycle for 1.2-2.5 GV protons, helium and electrons could be reproduced. The modelling results are given in Fig. 3 in comparison with 1.2 GV electron and helium observations, showing remarkably good agreement between the model and the observations.

It is evident that for these simulations the diffusion coefficients had to change with time, and in addition it was found that the enhancement of $K_{\perp\theta}$ had to be somewhat different for A > 0 cycles than for A < 0 cycles, confirming the work done with steady-state models (Potgieter, 2000). The gratifying aspect of these results is that solar maximum modulation could indeed be reproduced for different species using a relatively simple concept, while maintaining the major modulation features during solar minimum, like the flatter modulation profile for electrons in 1987, but a sharper profile for 1997.

Encouraged by these results, the compound concept was applied to simulating the electron to proton ratio along the Ulysses trajectory. It also turned out to be successful as the comparison with data shows in Fig. 4. However, by looking into greater detail on this shorter time scale, and in order to accommodate the observed latitudinal dependence by Ulysses in the modelling, it followed that absolute identical modulation parameters could not be used for electrons and

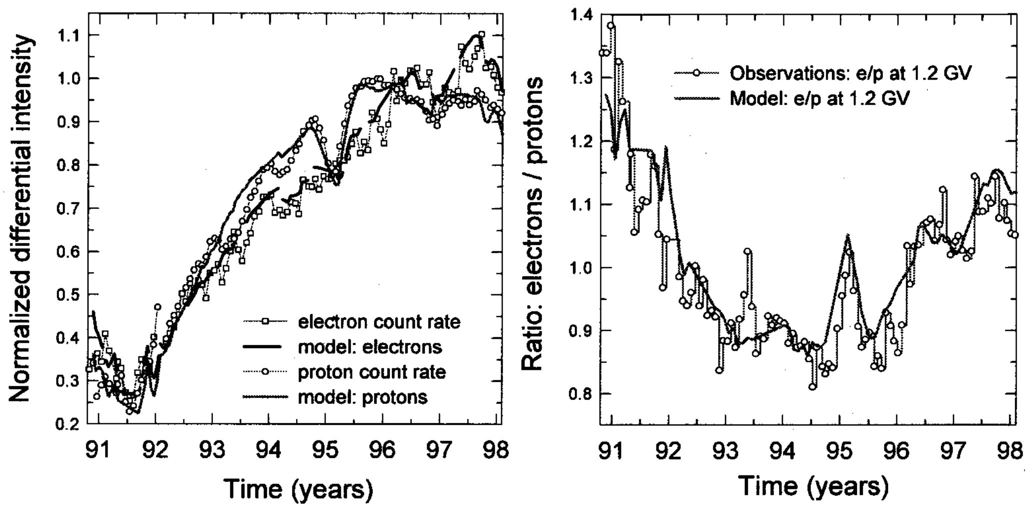

Fig. 4. Compound model approach to long-term modulation applied to 1.2 GV protons and electrons. Left panel: Observations (Heber *et al.*, 1999; Heber, private communication) compared with computed proton (solid line) and electron (dashed line) intensities along the Ulysses trajectory. Right panel: Corresponding computed electron to proton ratio (solid line) compared with observations.

protons when solar maximum conditions (1990-1992) were simulated. It is known that the enhancement of $K_{\perp\theta}$ in the polar direction (by a factor of ~ 10) is an absolute requirement in drift models to get the observed latitude dependence correctly simulated as shown in Fig. 4. Still using this approach, we found that for electrons a larger $K_{\perp\theta}$ (2% instead of 1% of $K_{||}$) had to be used in the equatorial plane, but keeping the same polar enhancement factor as for protons. This can be interpreted to mean one (or perhaps all) of the following: (1) That $K_{\perp\theta}$ is different for electrons than for protons. (2) That the diffusion coefficients may be different for the two species (because it was assumed that $K_{\perp\theta} \propto K_{||}$), but not necessarily at all energies. (3) That drifts are not yet handled correctly with increasing solar activity and/or (4) that an additional charge-sign dependent mechanism may be contributing to modulation, e.g., magnetic helicity (e.g., Burger et al., 1997).

4. Conclusions

Comprehensive modelling of time-dependent modulation indicates that the diffusion coefficients must be time-dependent, and that no unique set of modulation parameters exists - they seem to differ from solar minimum to solar minimum. Long-term modulation is a complicated interplay of the four major modulation processes, but we also realize, as shown in this paper, that long-term CR modulation modelling needs propagating diffusion barriers (PDBs) during increased solar activity to simulate realistic 11-year cycles. The major 'ingredients' of this approach are:
(1) The increase in the total magnetic field with solar activity with respect to the averaged field at solar minimum. (2) The time-dependence of the solar magnetic field magnitude combined with the time-dependence of the HMF tilt angles, the latter to control drifts over a complete 11-yr cycle. (3) The development of time varying PDB's that will increase in numbers and size with increasing solar activity as contained and compounded in the two above mentioned properties.

The combination of the major mechanisms, in particular drifts, with PDBs in such a compound approach is found to be successful in explaining complete 11-year and 22-year cycles, and charge-sign dependent modulation.

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