Cosmic ray Drifts at Solar Maximum

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Abstract

A fully time-dependent cosmic ray modulation model, based on the numerical solution of Parker's transport equation, is used to study the amount of particle drifts needed to explain the observed 2.5 GV electron to proton ratio (e/p) by the KET instrument on the Ulysses spacecraft. It is shown that the model successfully simulates the modulation of electrons and Helium ions for 11-year and 22-year cycles. It is based on the compound approach that incorporates the concept of propagation diffusion barriers combined with global increases in the heliospheric magnetic field when propagated from the Sun throughout the heliosphere, as well as drifts and the other basic modulation mechanisms. It is found that less than 10% drifts is needed at solar maximum, when the solar magnetic field reverses, to explain the observed e/p along the Ulysses trajectory.

1. Introduction

To describe the heliospheric modulation of cosmic rays successfully over long time periods a new approach was proposed, called the compound approach [7]. This approach combines the effects of the global changes in the heliospheric magnetic field (HMF) magnitude with drifts, therefore also time dependent current sheet 'tilt angles' $\alpha(t)$, to establish realistic time-dependent diffusion coefficients. The diffusion and 'drift' coefficients are scaled time dependently using a function:

$$f_2(t) = \left(\frac{B_0}{B(t)}\right)^n \tag{1}$$

with $B_0 = 5$ nT and $B(t)$ the measured HMF at Earth. Here $n = \alpha(t)/\alpha_0$, with $\alpha_0 = 11$, and is probably also rigidity dependent; n is small ($n \to 0$) for minimum modulation but increases with increasing solar activity ($n = 2 \to 5$). The larger n is made, the larger the temporal changes in the diffusion coefficients get, simulating essentially a series of propagating diffusion barriers (PDBs). These time dependent changes are propagated outwards into the heliosphere at the solar wind speed causing the PDBs to move to 1 AU and beyond.

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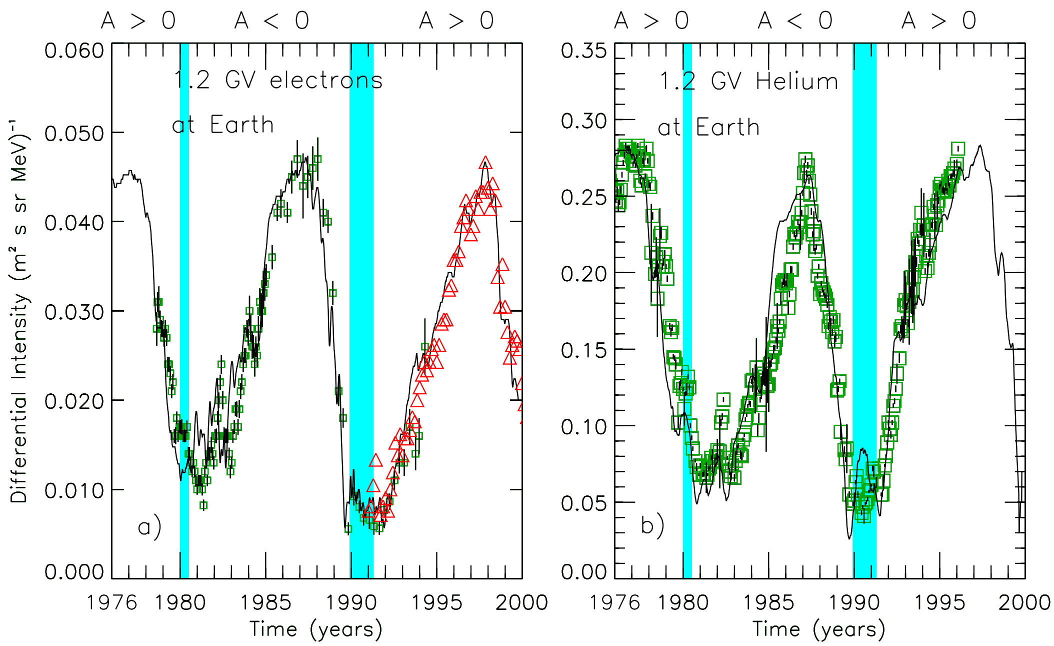

Fig. 1. Computed intensities compared to 1.2 GeV electron observations and 1.2 GV Helium observations at Earth [1, 2, 4, 6].

2. Results and discussion

Figure 1 shows the results of the compound modelling approach where the computed intensities are compared respectively to the 1.2 GeV electron and Helium observations at Earth. As illustrated, this approach produces the correct modulation amplitude and most of the modulation steps in the observations. Some of these simulated steps do not have the correct magnitude and phase indicating that some refinement of this approach is still needed, allowing, for example, for some global merging of the PDBs. However, the gratifying aspect of these results is that solar maximum modulation could indeed be largely reproduced for different cosmic ray species using a relatively simple concept, while maintaining the major modulation features during solar minimum, like the flatter modulation profile for electrons (Helium) in 1987 (1997), but a sharper profile for 1997 (1987).

In Figure 2 solar maximum is shown in more detail with the computed e/p along the Ulysses trajectory for 1999–2002, in comparison with the observed 2.5 GV e/p from KET. Four scenarios are shown corresponding to different values of $(K_A)_0$ namely 1.0, 0.6, 0.1 and 0. Here $(K_A)_0$ is a constant through which the amount of drifts is changed explicitly in the model. For the compound approach drifts are also implicitly scaled time-dependently using the function $f_2(t)$ given by Eq. (1). Therefore, the total fraction of time-dependent drifts is given by $|(K_A)_0 f_2(t)|$ shown in the bottom panel. For 1999.0–1999.8, the scenarios

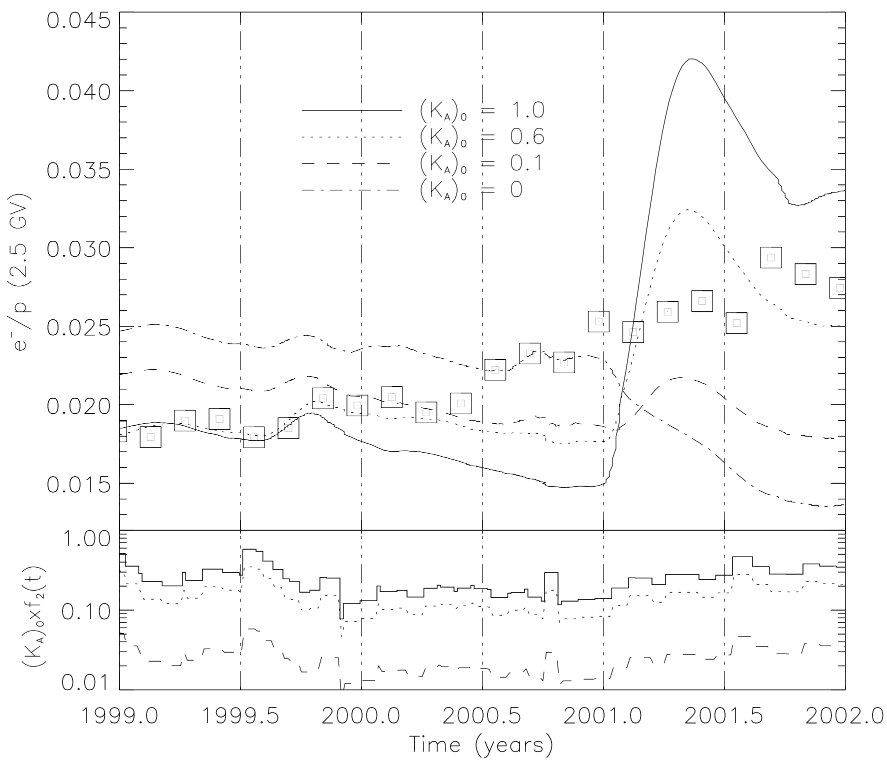

Fig. 2. Four different computed e/p as described in text along the Ulysses trajectory for 1999–2002, in comparison with the observed 2.5 GV e/p from KET [4].

$(K_A)_0 = 0.6 \rightarrow 1.0$ represent the data well along the Ulysses trajectory, with the total drifts varying between 50% → 15% → 60% → 15% over this period. For 1999.8–2000.3, the scenario $(K_A)_0 = 0.1$ is clearly better indicating that the total drifts had dropped below 10% with values as low as 1–3%. For the period 2000.3–2000.8, the $(K_A)_0 = 0$ scenario is better indicating that global drifts had vanished for the duration of the HMF polarity reversal. After the end of 2000, the non drift case becomes poorly compatible with the data indicating that drifts recovered very quickly after the polarity reversal so that for 2001.3–2002.0 the scenario $(K_A)_0 = 0.6$ is already good although the $(K_A)_0 = 1.0$ scenario gives a totally unrealistic increase in intensities owing to the reversal in polarity. The sharp increase in the computed intensities for the scenarios $(K_A)_0 = 0.6 \rightarrow 1.0$ is clearly not evident in the data. The steady increase in the observed e/p indicates that drifts, although little, must have been present close to the period of polarity reversal. The compound approach without modification of drifts through $(K_A)_0$ evidently results in too large charge-sign dependent modulation around solar maximum so that K_A needs to be decreased additionally to reach no drifts for at least six months, as illustrated. To produce realistic charge-sign dependent modulation during extreme solar maximum conditions, the heliosphere must become ‘diffusion dominated’ rather than ‘drift dominated’ [e.g., 3]. Additional mechanisms that may naturally reduce global drifts toward solar maximum activity but not considered here are e.g. decreases in the perpendicular diffusion coefficient in the heliospheric polar direction, multiple current sheets [5] and/or a different type of HMF geometry.

3. Conclusions

The compound approach to simulate cosmic ray modulation in the heliosphere is remarkably successful in describing the 11 and 22 year modulation cycles. However, during periods of very large solar activity the approach needs modification in the sense that drifts must be reduced to describe the e/p as measured by Ulysses more realistically during the year in which the HMF polarity reverses. We found that drifts reduced from a 50% level at the beginning of 1999 to a 10% level by the end of 1999, vanished during 2000 but quickly recovered after the polarity reversal during 2001 to levels above 10%. After 2001 our model predicts a steady increase in drifts from 10% up to 20% at the end of 2002.

4. References

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