Cosmic Rays and the Global Heliospheric Magnetic Field: Meridional Motion of Footpoints

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Abstract

We consider cosmic ray transport in magnetic field models where a meridional motion of the footpoints leads to organized meridional field components. We have developed a 3-D numerical code of cosmic-ray transport, incorporating a meridional HMF component. The fully time-dependent code includes the complete 3-D time-varying magnetic field. We use this code to study a Fisk-like field, as well as the effects of a dynamically changing current sheet. Preliminary results are discussed.

1. Introduction

In contrast to the standard Archimedean spiral, the heliospheric magnetic field (HMF) model proposed by Fisk [2] has an *organized* meridional B_θ component. An organized meridional B_θ will also arise at almost any temporal change of the global field, like a shift in the tilt of the heliospheric current sheet (HCS) [7]. The seemingly small difference in the HMF model may have significant effects on cosmic-ray transport. The organized meridional motion of the field lines may, over large distances, establish direct magnetic connection between high and low heliographic latitudes. Quantitative studies are not easy since the presence of B_θ poses serious challenge to numerical codes. Initial modeling efforts have been carried out by Burger and Hattingh [1] and Kóta and Jokipii [7].

We have developed a 3-D numerical code of cosmic-ray transport, incorporating a meridional HMF component. The code includes the complete 3-D time-varying magnetic field, but does not include corotating interaction regions. The code is used to simulate a Fisk-like field, as well as a dynamically changing HCS.

The presence of a small organized latitudinal field is important if cross-field diffusion ($\kappa_\perp$) is small. Our code has been designed for this task so that the scheme is optimized for small $\kappa_\perp$. We use heliomagnetic coordinates, which are attached to the field lines and which were successfully applied in earlier 3-D modeling [3-6]. What we call heliomagnetic coordinates are essentially identifying field lines by their footpoints [7].

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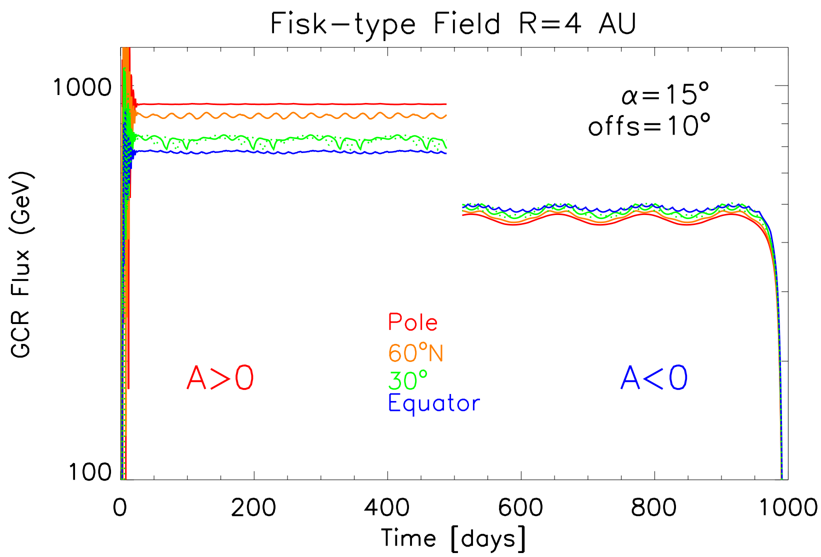

Fig. 1. Time-variation of GeV cosmic rays at 4 AU in a Fisk field for $A > 0$ (left) and $A, 0$ (right), for latitudes 0, 30^o, 60^o, and 90^o. 10^0 offset and 15^o tilt are used.

2. Modulation and Recurrent variations in a Fisk-Field

We adopt the simplest representation of the Fisk field [6] when the motion of the footpoints is the combination of two rotations: a rigid corotation around the rotational axis of the Sun and an additional rotation around and offset axis [9]. It should be borne in mind that this expression of the field was given for high latitudes, the extension to the streamer belt requires further considerations. Here we simply extend the high-latitude expression to lower latitudes, which will introduce a ∼100 day oscillation in the tilt of the HCS.

Fig. 1 illustrates a simulation obtained with a tilt angle of $\alpha = 15^o$, and an offset of 10^o. For the $A > 0$ cycle (left side), 26-day recurrent variations do indeed appear at latitudes as high as 60^o, supporting the original concept of the Fisk-field. The global picture of modulation, on the other hand, is litte effected. Simulations obtained with a standard spiral give very similar global results.

For $A < 0$ (right), the curves obtained for different latitudes are very close to each other, indicating a negligible latitudinal gradient (the prominent negative latitudinal gradient is restricted for smaller tilt of the HCS). The 100-day variation is due to the oscillation of the current sheet, introduced by the straightforward extension of the high-latitude field to the streamer belt.

Our preliminary results suggest that a Fisk field would introduce local, recurrent 26-day cosmic-ray variations, but would not significantly alter the global pattern of modulation.

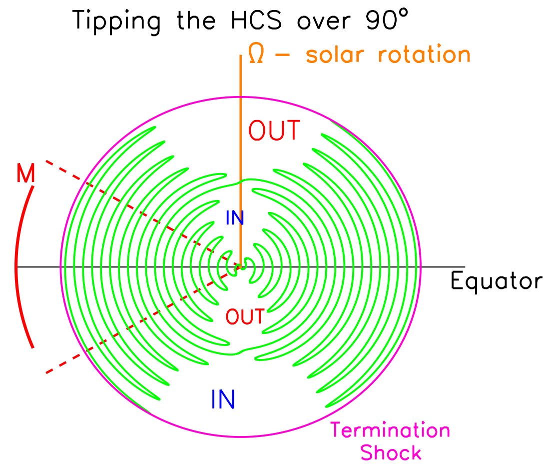

Fig. 2. Meridional cut of the HCS following a tip over the pole. the dipole is tipped between the signs >< around day 200.

3. Effects of a Dynamically Changing Current Sheet

Next we applied our code to simulate some features of the 22-year solar magnetic cycle. Recent observations of Ulysses showed that the HCS remained a well structured single, organized sheet during polarity reversal. One can consider a simple model in which the tilt of the HCS changes continuously through a full 360 degrees. This could be a crude simulation of the solar magnetic cycle, where the magnetic field polarity change at sunspot maximum simply corresponds to the tilt passing through 90 degrees [8].

We use our code to simulate such a combination of rotations. Apart from subtle differences, results were quite similar those obtained from a series of snapshots with steady tilt angles. This is expected as long as the tilt varies slowly.

Beside the slow turn of the magnetic dipole, the HCS may undergo faster, more abrupt changes with the re-organization of the field. These changes will inescapably give rise to meridional field components. A polarity reversal is not possible without generating meridional components either. We simulate a scenario illustrated in Fig. 2. A highly inclined dipole field with outward polarity at the northern pole ($A > 0$) tips abruptly (in tens of days) passing over the pole and becoming a highly tilted dipole with $A < 0$ polarity. Fig. 2 illustrates the complex structure of the resulting HCS.

The cosmic-ray intensity variations simulated for such a scenario are shown in Fig. 3. Radial gradients increase as the polarity changes from $A > 0$ to $A < 0$. The change is modest in the inner heliosphere, and is quite dramatic in the outer heliosphere. The delay corresponds to the transit time of the solar wind.

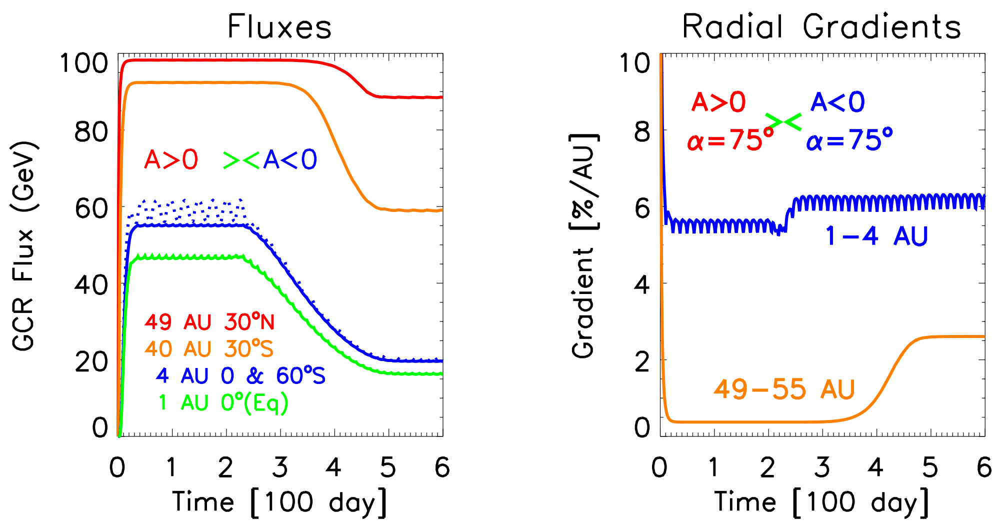

Fig. 3. Simulated cosmic-ray fluxes and radial gradients for the model shown in Fig. 2, at various radii and latitudes.

4. Conclusions

We have presented preliminary results of a new numerical code developed for the study cosmic-ray modulation in a Fisk field, or in other HMF that has organized B_θ component. The computational scheme employs heliomagnetic co-ordinates, and can handle a combination of rigid rotations around axes varying in time. The method has advantages if $\kappa_\perp$ is small, and the magnetic field is well organized. Future, more detailed, works will give more quantitative results.

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5. References

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