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# The Effect of Large Heliospheric Current Sheet Tilt Angles in Numerical Modulation Models: A Theoretical Assessment

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**Abstract**

Drift along the heliospheric current sheet provides a natural explanation for the relatively flat intensity-time proton profile observed near Earth during $A > 0$ solar polarity cycles, versus the peaked profile during $A < 0$ solar polarity cycles, in the years around solar minimum. A numerical modulation model based on Parker's transport equation for galactic cosmic rays is used to illustrate what happens when the current sheet tilt angle approaches a hypothetical 90°. For the assumed idealistic modulation conditions, we find that the intensities for the two cycles approach the common no-drift values. We also find that although drift effects vanish at large tilt angles, the ratio of negatively charged to positively charged cosmic rays shows a large increase going from $A > 0$ cycles to $A < 0$ cycles. Furthermore, as a function of tilt angle this ratio shows much larger variations during $A < 0$ cycles than during $A > 0$ cycles.

## 1 Introduction:

The effect of particle drifts, and in particular drift along the wavy current sheet, has long being thought to be responsible for the characteristic shape of the cosmic-ray intensity profile observed near Earth around times of minimum solar activity (e.g., Jokipii & Thomas 1981). Positively charged particles, during a positive solar polarity cycle (when the field in the northern hemisphere of the sun points outward; denoted by $A > 0$) exhibit a rather flat response to the changing tilt near solar minimum. During alternate cycles, denoted by $A < 0$, and for the same range of tilt angles, the intensity profile shows a peak around solar minimum. It is by now well-established that drift-dominated models can readily explain these different profiles (e.g., Jokipii & Thomas 1981). While the role of drifts during periods of minimum solar activity appear to be well understood, the same cannot be said for periods when the sun approaches maximum activity, and the tilt angle becomes large. Previous studies (Potgieter & Burger 1990; Webber, Potgieter & Burger 1990) with steady-state two-dimensional models that simulate the effect of a wavy current sheet, suggest that the flat response of positively charged particles during $A > 0$ cycles would persist for large values of the tilt angle. Using a newer version of such a two-dimensional simulated wavy current sheet model, Burger & Hattingh (1998) show that the intensity of cosmic-ray protons during an $A > 0$ cycle does respond markedly when the tilt becomes larger than about 40° degrees, approaching the intensity for an $A < 0$ cycle. In this study we extend the analysis of Burger & Hattingh to show what happens when the tilt angle approaches 90°.

## 2 Modulation Model and Solar Minimum Spectra:

The two-dimensional, steady-state numerical modulation model that is used in this study is described elsewhere (e.g., Burger & Hattingh 1995). A comparison of cosmic-ray electron spectra from this model and those from a three-dimensional model, is discussed at this conference by Fereirra, Potgieter & Burger (1999). Hattingh (1998) makes a similar comparison for protons. These authors find good agreement between the two models. From a modeling point of view, there is therefore no reason to doubt the validity of the results from the two-dimensional model presented in this study.

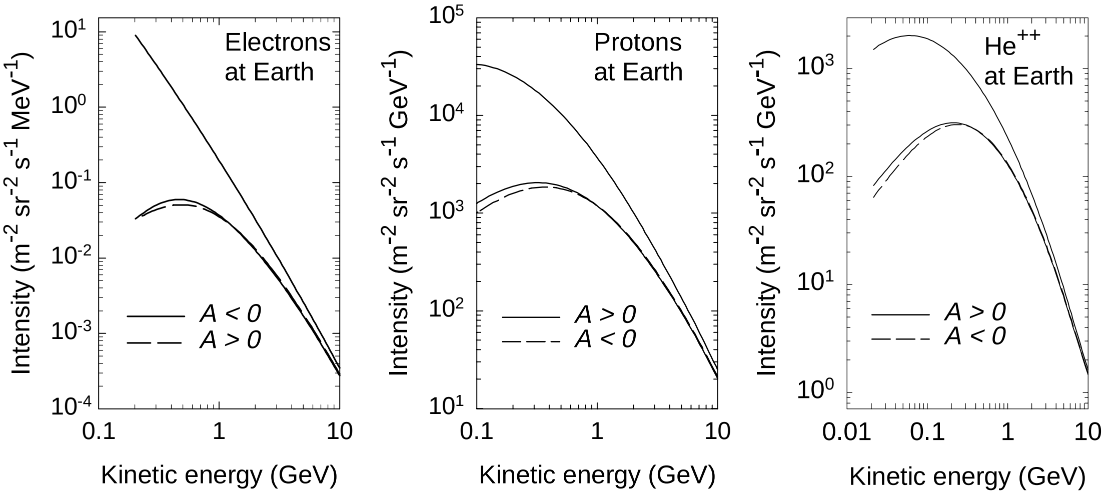


**Figure 1:** Solar minimum spectra for cosmic-ray electrons, protons and helium at Earth for the two polarity cycles of the solar magnetic field; $A > 0$ (e.g. 1996) and $A < 0$ (e.g.1987). The tilt angle is 15°.

As the title of this paper suggests, we are primarily interested in the role of the tilt angle from a theoretical point of view. In what follows, only the sign of the magnetic field is switched going from one solar polarity cycle to the other, and the tilt angle is increased linearly without changing any other parameter. The diffusion tensor and all the other parameters used for this study, are discussed at this conference by Burger, Potgieter & Heber (1999). The resulting solar minimum spectra for the three species we consider are shown in Figure 1.

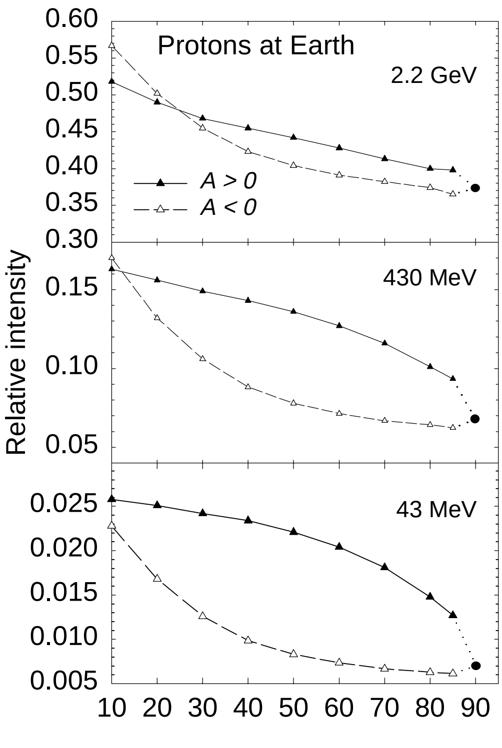


**Figure 2:** Intensity-tilt profiles for protons at Earth. The filled circles denote no-drift values, and the dotted lines are straight-line interpolations.

## 3 Tilt Angle Dependence of Protons at Earth:

Figure 2 shows how the intensity of cosmic-ray protons, relative to the corresponding interstellar value, varies as function of tilt angle. At all three energies the classic drift behavior, with the intensity-tilt (IT) profiles for an $A > 0$ cycle flatter than for an $A < 0$ cycle, is evident only for tilt angles up to about 45°. From 45° to about 60°, the IT profiles for both cycles have similar slopes. Beyond about 60°, the $A > 0$ IT profile drops, while the $A < 0$ IT profile flattens, both approaching the no-drift value, indicated with a filled circle. The fact that this approach to the no-drift value becomes more evident as the energy decreases, is due to numerical boundary effects, which in this cases diminishes as the particle's gyroradius decreases. Note that Webber, Potgieter & Burger (1990) used such IT profiles to deduce that drift effects need to be reduced in a rigidity-dependent manner, as is done in the present study (see Burger & Potgieter 1999 Eq. 4).

A comparison between the two-dimensional model and a three-dimensional model is shown in Figure 3 (Hattingh 1998). A different diffusion tensor is used, and the boundary is set at 40 AU. The convergence of the IT profiles in the three-dimensional model to a common value,

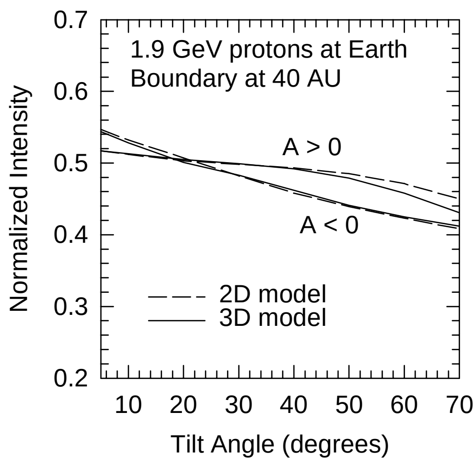


**Figure 3:** A Comparison of IT profiles from a two-dimensional and a three-dimensional model (Hattingh 1998)

is somewhat faster than in the two-dimensional model. Note, however, that the difference between the *A > 0* intensities at a tilt angle of 70° is less than 5%. Clearly the two models show the same qualitative behavior, and to a large extent the same quantitative behavior, as the tilt angle increases. (See also Ferreira, Potgieter, & Burger 1999)

## 4 Tilt Angle Dependence of Cosmic-Ray Intensity Ratios at Earth:

The tilt angle and solar polarity-sign dependence of the ratios $e^-/He^{++}$ and $e^-/p$ are shown in Figure 4, normalized with respect to the minimum value for each ratio. Although there are some quantitative differences between the two ratios, their qualitative behavior is the same. During an *A > 0* cycle, the ratio has a "w" shape, and shows smaller changes when the tilt angle changes than during an *A < 0* cycle, when the ratio has an "m" shape. Changes in the ratio becomes larger as the rigidity becomes smaller.

In earlier studies (e.g., Potgieter & Burger 1990; Webber, Potgieter, & Burger 1990) the smooth

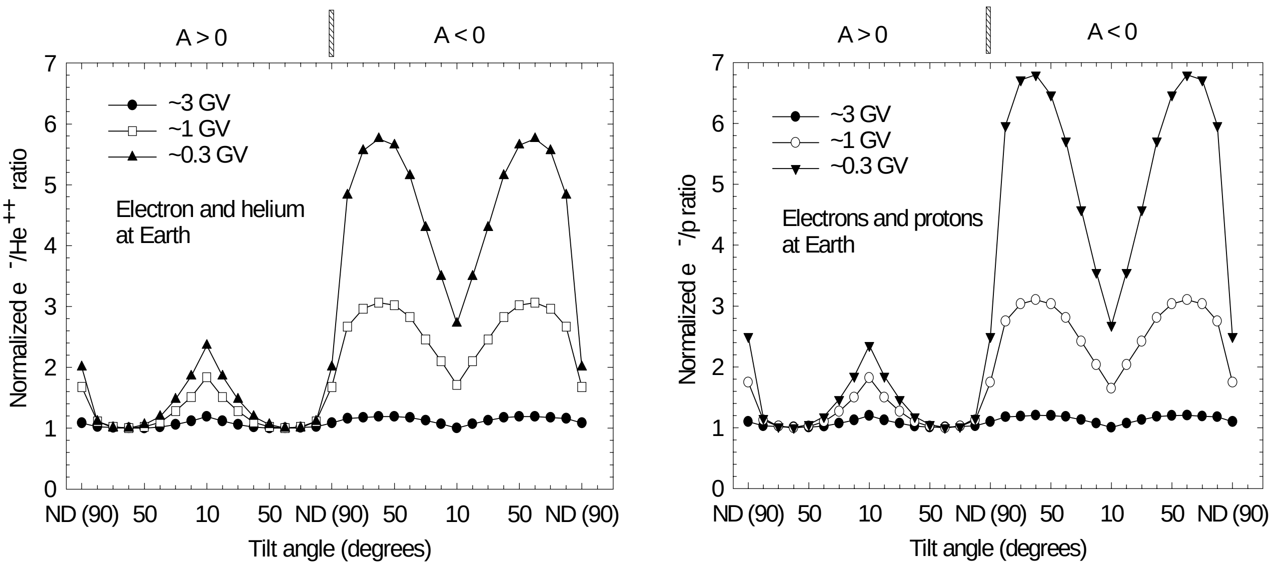


**Figure 4:** See text for description. "ND (90)" denotes a no-drift value at a hypothetical tilt angle of 90°.

transition from one polarity cycle to the next does not occur. The reason for this is that at large tilt angles, predecessors of the current two-dimensional model predicted a much flatter IT response of positively charged particles during an *A > 0* cycle, and therefore of negatively charged particles during an *A < 0* cycle.

## 5 Discussion and Conclusions:

Apart from magnetic polarity, only the tilt angle is changed to obtain the present results. Since the tilt angle is a proxy for solar activity, we therefore employ drifts to construct a simplified solar-activity cycle.

In our model, intensity-tilt profiles (Fig. 2) show three distinct regimes. During periods when the tilt is small, the well-known peaked profile for protons occurs when $A < 0$, and the "flat" profile (actually only flatter than the peaked profile) when $A < 0$. For larger tilt angles, a second regime occurs when the two profiles more-or-less track each other. Cane *et al.* (1999) find observational evidence for both regimes at neutron-monitor energies, but conclude that the second is not due to drift effects, in contrast to the results presented here. The third regime is when the $A > 0$ profile drops while the $A < 0$ profile flattens to converge to the no-drift intensity. Clearly, drifts are phased out as the tilt angle increases for *both* polarities.

The ratio of differently charged particle intensities throughout our hypothetical solar activity cycle, where only the tilt angle changes, shows that during $A > 0$ cycles, the largest changes occur around solar minimum modulation, and the local maximum occurs at solar minimum. At other times, little change in the ratio occurs, but there is an sharp increase in the ratio going from an $A > 0$ to an $A < 0$ cycle, which decreases as the rigidity of the particles decreases. During an $A < 0$ cycle, changes in the ratio is typically larger than during the alternate cycle, especially at lower rigidities. At solar minimum modulation the ratio is at a local minimum. Although our aim is not to fit data, we note that the qualitative features of the ratio-tilt angle profiles for the electron/helium ratio agrees remarkably well with observations (Bieber *et al.* 1999a, b).

Before attempting a detailed comparison of the current results with observations, one should bear in mind the following: (i) In a dynamical model, the symmetry with respect to solar minimum modulation is broken (le Roux & Potgieter 1990). (ii) Modulation caused by “barriers” cannot be neglected during non solar minimum modulation periods (e.g., Potgieter & le Roux 1992) (iii) The electron measurement may contain a sizable fraction of positrons (e.g., Evenson 1998). (iv) The state of the heliosphere during the approach to solar maximum, is certainly different from that in our present model (e.g., review by Jokipii & Wibberenz 1998). (iv) The sign of the solar magnetic field does not change abruptly through solar maximum, and as a rule, this does not occur at a tilt angle of 90°. This list is not meant to be complete; it should however serve as a caveat.

## References


Bieber, J.W., Burger, R.A., Engel, R., Gaisser, T.K., Roesler, S., & Stanev, T. 1999a, Phys. Rev. Lett., submitted

Bieber, J.W., Burger, R.A., Engel, R., Gaisser, T.K., & Stanev, T. 1999b, Proc. 26$^{th}$ ICRC (Salt Lake City), SH3.1.5

Burger, R.A., & Hattingh, M. 1995, Astrophys. Space Sci., 230, 375

Burger, R.A., & Hattingh, M. 1998, Ap. J., 505, 244

Burger, R.A., & Potgieter, M.S. 1999, Proc. 26$^{th}$ ICRC (Salt Lake City) , SH3.3.02

Cane, H.V., Wibberenz, G., Richardson, I.G., & Von Rosenvinge, T.T. 1999, Geophys. Res. Lett., 26, 565

Evenson, P.A. 1998, Space Sci. Rev., 83, 63

Ferreira, S.E.S., Potgieter, M.S., & Burger, R.A. 1999, Proc. 26$^{th}$ ICRC (Salt Lake City) , SH3.1.14

Hattingh, M. 1998, Ph.D.-thesis, Potchefstroom University for Christian Higher Education, Potchefstroom, South Africa

Hattingh, M., & Burger, R.A. 1995, Adv. Space Res., 13, 9213

Jokipii, J.R., & Thomas, B. 1981, Ap. J., 243, 1115.

Jokipii, J.R., & Wibberenz, G. 1998, , Space Sci. Rev., 83, 365

Le Roux, J.A., & Potgieter, M.S. 1990, A. J., 361, 275

Potgieter, M.S., & Burger, R.A. 1990, A&A, 233, 598

Webber, W.R., Potgieter, M.S., & Burger, R.A. 1990, Ap. J., 349, 634