Astron. Astrophys. 233, 598–604 (1990)

ASTRONOMY AND ASTROPHYSICS

The modulation of cosmic-ray electrons, positrons and helium nuclei as predicted by a drift model with a simulated wavy neutral sheet

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Received May 24, accepted November 3, 1989

Abstract. A recently developed axially-symmetrical drift model with a simulated wavy neutral sheet is applied to the modulation of cosmic-ray electrons (e^-), positrons (e^+) and helium (He) nuclei in the heliosphere, and its prediction as to the magnitude of charge-dependent modulation is established. We find that the ratio He/e^- at 800 MV shows a strong dependence on the waviness of the heliospheric neutral sheet for both positive and negative polarity configurations of the interplanetary magnetic field (IMF). We also find a significant change, a factor of ~ 50, in this ratio when the polarity of the magnetic field is reversed. With a 10% and 25% contribution of positrons to the total local interstellar spectrum, $(e^+ + e^-)$, this factor for $He/(e^+ + e^-)$ reduces to ~ 26 and ~ 14 respectively. This illustrates the important role positrons play in drift dominated modulation and implies that the positron intensity may even exceed that for electrons when the tilt angle of the neutral sheet, $\alpha \geq (40 \pm 10°)$ with the polarity configuration of the IMF as in 1969/71–80. A 25% contribution of positrons and a reduction of drift by a factor of 2 produces a factor of ~ 2 change in the $He/(e^+ + e^-)$ when α is changed from 10° to 70° and a factor of 7 ± 2 with a polarity reversal. The latter value is more reasonable than with full drift effects but still too large compared with observations which indicate an upper limit of a factor of 4 change in the $He/(e^+ + e^-)$ following the polarity reversal in 1980. The tilt dependence, on the other hand, seems more compatible with what has been observed. *These results are not significant enough evidence to rule out the effects of drift in modulation.* However, in conjunction with earlier conclusions, the results presented in this paper suggest that a theoretical reassessment of the magnitude and rigidity dependence of drift effects in the heliosphere seems to be required. Further, it is suggested that a next generation of drift models, probably time-dependent and incorporating effects such as magnetic helicity, needs to be considered in modulation studies.

Key words: cosmic rays: heliospheric modulation – charge dependence – Sun: activity of

1. Introduction

Charge dependent modulation is one of the important features of cosmic-ray drift models (e.g., Kóta and Jokipii, 1983; Potgieter and Moraal, 1983, 1985). The reason for this is that the drift velocity due to gradients and curvatures in the interplanetary magnetic field (IMF) has opposite directions for positive and negative particles. These particles should therefore experience different modulation conditions after they had entered the heliosphere as suggested by the drift pattern caused by the Parker spiral structure of the IMF.

A difference in the modulation of oppositely charged particles was already noted in the 1970's by, e.g., Caldwell et al. (1977) and Evenson et al. (1979) – see also references therein – when observed spectra for the period 1973–75 were added to those for 1968–72 and a simultaneous fit to the proton and electron spectra was unsuccessfully tried using a standard nondrift model (see also Webber et al., 1983; Evenson et al., 1983). Potgieter and Moraal (1985), on the other hand, showed that they could simultaneously fit proton and electron spectra for two consecutive solar minima (1965/1976) using one set of modulation parameters and the polarity reversal of the IMF in their drift model. Recently, strong evidence for charge dependent modulation was reported by Garcia-Munoz et al. (1986, 1987) who found a factor of 3 ± 1 change in the helium (70–95 MeV/nucleon) to electron (600–1000 MeV) ratio related to the two recent reversals of the IMF polarity. Since these particles have almost identical rigidities, conventional explanations such as typical hysteresis effects seem unlikely, but cannot be ruled out completely (Perko, 1987). Garcia-Munoz et al., however, pointed out that the shape of the electron intensity-time profile observed at Earth during 1970$\sim$80 is in apparent disagreement with drift models which predicted a peaked electron profile but almost flat proton profile for this period.

At the time of writing, the only published work on electron modulation using a drift model was that by Potgieter and Moraal (1985). It seems that the predicted peaked profile for electrons during the years mentioned had been deduced from the work by Kóta and Jokipii (1983) on the effect of the tilt of the wavy neutral sheet on proton modulation. In our experience some caution is necessary when conclusions about the modulation of electrons are based on results for protons (Moraal and Potgieter, 1982). In the present paper we therefore address electron modulation explicitly, using an axially-symmetric drift model with a simulated wavy neutral sheet, recently developed by Burger and Potgieter (1989). We shall also illustrate some general characteristics of drift dominated modulation, using realistic interstellar spectra and as realistic as possible values for the various other modulation parameters. Constraints on the possible choices for the latter will be discussed in the final section.

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Special attention is given to the predicted neutral sheet tilt effect on the intensity-time profiles for electrons, positrons and helium nuclei and the magnitude of the subsequent charge-dependent effect. In the final section we consider the implication of our results for current drift models, and also give an indication of how this and other recent developments could change the general features of these models. Preliminary results were reported by Potgieter et al. (1987a).

2. The model

The model is based on the numerical solution of the steady-state, axially-symmetric, cosmic-ray transport equation (e.g. Potgieter and Moraal, 1985). The important feature of the current model is its ability to emulate a wavy neutral sheet, which is essentially a three-dimensional property of the IMF, in a two-dimensional code (see also Webber et al., 1990). Burger and Potgieter (1989) developed this model by considering the effect of a wavy neutral sheet on the time scale of a solar rotation, and details can be found in that paper. The tilt angle α, which determines the maximum excursion of the neutral sheet with respect to the solar rotational equator, is a free parameter in this model. They also found from a detailed comparison of 27 day average proton intensities between the full three-dimensional model of Kóta and Jokipii (1983) and the present model that they typically agreed to within 10% for the parameters chosen by Kóta and Jokipii and at the energies considered here. We therefore regard the use of the two-dimensional model of Burger and Potgieter (1989) as a valid and efficient way of investigating neutral sheet tilt dependent modulation.

The following modulation parameters were used for the sample solutions in the next section. The solar wind speed was assumed constant at 400 km s^{-1}, and the outer and inner heliospheric boundary were taken as 50 AU and 0.005 AU respectively. The local interstellar electron spectrum (LIS) assumed was

$$j_T = 2.9 \exp\left[a(\ln E)^2 + b(\ln E) + c\right], \qquad (1a)$$

when the kinetic energy $E \geq 1$ GeV, and

$$j_T = 2.9\, dE^{-1.87}, \qquad (1b)$$

when $E < 1$ GeV. Here, j_T is the differential intensity and the values of the constants are: $a = -0.293$, $b = -1.870$, $c = -2.762$ and $d = 0.063$. This particular spectrum for electrons exceeds the LIS which had been used previously (Potgieter and Moraal, 1985) by a factor of 2.9 and is considered more realistic. The assumed interstellar helium spectrum is given by

$$j_T = 0.45\, E^{0.64}/(E + 0.25)^3. \qquad (2)$$

For the diffusion coefficient parallel to the background IMF we assumed the form

$$K_{\|} = K_0 \beta K_P(P)\left[1 + (r/r_e)^2\right], \qquad (3a)$$

where K_0 is a constant in units of $6\,10^{20}$ cm^2 s^{-1}, β is the ratio of particle speed to the speed of light, r_e is 1 AU, and $K_P(P)$ is the rigidity dependence of this parameter. For simplicity we assumed $K_P(P) = P/(1\text{ GV})$ when $P \geq 0.6$ GV, and $K_P(P) = 0.6$ when $P < 0.6$ GV. The diffusion coefficient perpendicular to the average background IMF was taken as

$$K_{\perp} = (K_{\perp})_0 \beta K_P(P)(B_e/B), \qquad (3b)$$

where B is the standard Parker spiral configuration of the IMF, $B_e = 5$ nT the magnitude of B at Earth and $K_P(P)$ as defined above. The constant $(K_{\perp})_0$ has the same units as K_0. For the asymmetric part of the diffusion tensor we adopted the expression

$$K_T = (K_T)_0 \beta P/(3B), \qquad (3c)$$

which describes curvature and gradient drift. The constant $(K_T)_0$ is dimensionless and equal to one for full drift effects and less than one for reduced drift effects.

3. The modulation of electrons and positrons according to a drift model with a simulated wavy neutral sheet

The main objective of this section is to illustrate the effect of the changing waviness of the heliospheric neutral sheet on the modulation of cosmic ray electrons and positrons. The waviness is represented by a tilt angle, α, which has the same physical meaning as that used by various other groups (e.g., Hoeksema et al., 1983; Kóta and Jokipii, 1983; Lockwood et al., 1988; Webber and Lockwood, 1988; Webber et al., 1990). For the purpose of illustration we included $\alpha \leq 5°$, although observations indicated that the 27 day averages of α did not fall below 8°–10°, at least not during the recent solar minimum period. We also limited α to a maximum value of 70° because it is unlikely that the global structure of the IMF remains well-ordered during the approach to solar maximum activity, i.e. for larger values of α, and the effectiveness of drift should then also be impaired. One example of disorder during these periods is the occurrence of multiple neutral sheets (Hoeksema et al., 1983).

In obtaining the results presented in this paper we used a set of diffusion coefficients that gave acceptable simultaneous fits to the helium and electron spectra observed at Earth in 1977. In order to reduce the range of parameters that could fit the 1977 spectra (Webber et al., 1990), we kept $(K_{\perp})_0 = 0.3$ in Eq. (3b). Then, with $(K_T)_0 = 1.0$ in Eq. (3c), and $\alpha = 10°$, the constant K_0 in Eq. (3a) had to have the value 0.8. Note that with the new interstellar spectra used for this work, it was no longer possible to simultaneously fit the electron and helium nuclei data at Earth for 1977 and to stay within the Palmer (1982) consensus values. The diffusion coefficient, $K_{\|}$, for instance, is significantly smaller (a factor of ~ 10) than what Palmer proposed for this parameter. The inference that can be drawn from this will be discussed in the final section.

In Fig. 1 are shown the assumed local interstellar spectrum (LIS) for electrons together with two sets of computed, modulated spectra at Earth as a function of the tilt angle, α, and the two polarity configurations of the IMF. The one set, where all the curves coincide, despite a 70° variation in α, is with $A < 0$, i.e., when the northern hemispheric IMF is directed inwards. The other set is with $A > 0$, when the northern field is directed outward. The basic modulation features shown in Fig. 1 are also applicable to positrons except that $A > 0$ is to be replaced by $A < 0$, and vice versa, and that the absolute intensities for positrons are much lower, of course. According to drift theory electrons (positrons) will enter the inner heliosphere primarily via the polar regions during an $A < 0$ ($A > 0$) period and primarily via the equatorial regions along the neutral sheet during an $A > 0$ ($A < 0$) period. As expected, electrons (positrons) respond strongly to an increasing tilt angle with $A > 0$ ($A < 0$) as shown by the dashed curves in Fig. 1. On the other hand, with $A < 0$ ($A > 0$), this

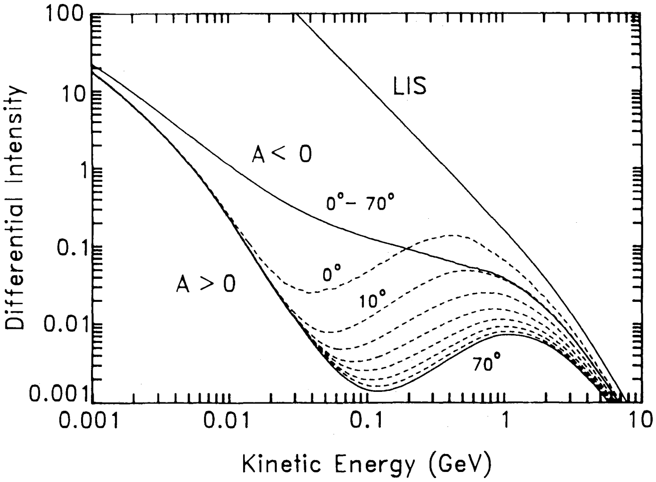

Fig. 1. The effect of an increasing tilt angle, α, of the heliospheric neutral sheet on computed electron spectra (dashed lines) at Earth for the ~1970–80 configuration of the IMF ($A>0$). The tilt angle is increased from 0° to 70° in steps of 10°. No effect is predicted for the period ~1960–70 ($A<0$) and the spectra coincide at the $\alpha=0°$ level. The curve indicated by LIS is the assumed local interstellar electron spectrum. The differential intensity is in units of particles $m^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}$

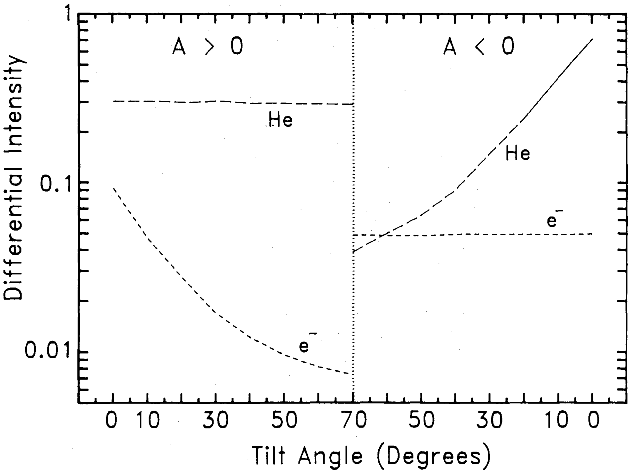

Fig. 2. The predicted differential intensity (particles $m^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}$) for electrons ($e^-$) and helium (He) for 800 MV at Earth as a function of neutral sheet tilt angle, α. The period $A>0$ is represented by $\alpha=0°-70°$, and $A<0$ by $\alpha=70°-0°$. The change in the polarity of the IMF (e.g., 1980) is depicted by the central, vertical dotted line

model predicts no response for electrons (positrons) to changing the waviness of the neutral sheet. Several interesting modulation features are evident from this figure:

(1) The calculated spectrum with $\alpha=10°$ and $A>0$ will give a reasonable good fit to the 1977 observed electron spectrum for $E>100$ MeV.

(2) The modulated spectra with $A>0$ do not respond linearly to the linear change in α. The largest decrease in intensity to a 10° change occurs with α decreasing from 0° and 10°.

(3) Below 10 MeV the effect of an increasing α on the $A>0$ spectra vanishes completely, while the effect of changing the IMF polarity on the intensities below 1 MeV becomes very small compared to the significant effect at 100 MeV. The energies where these features occur depend on the rigidity dependence assumed for the diffusion coefficients. Note that $K_P(P)$ in Eqs. (3a) and (3b) is constant below 0.6 GV and consequently also $K_{\|}/\beta$ and $K_{\perp}/\beta$, whereas K_T/β remains proportional to P. It can therefore be expected that drift effects will systematically diminish with decreasing energy while diffusion becomes relatively more important. The situation below ~100 MeV can thus be altered significantly by changing the relative contribution of diffusion and drift to modulation at these energies. (This will not happen for protons until down to very low energies and constitutes the major difference between proton and electron modulation apart from charge-dependence.) However, for the present study we consider electron modulation below ~100 MeV to be less important since electrons at these lower energies probably have a Jovian origin (e.g., Moses, 1987).

(4) Perhaps the most significant feature of the model is the extraordinary insensitivity of the electron (positron) spectra tc changes in the neutral sheet waviness when $A<0$ ($A>0$). Because of this feature the model predicts a flat intensity-time profile for electrons during this period, but a peaked profile for $A>0$. (This will be shown in more detail in the next section.) This prediction for electrons (positrons), together with the well-documented prediction for protons (e.g., Kóta and Jokipii, 1983; Potgieter and Moraal, 1985; Webber et al., 1990), indicates that a significant charge-dependent effect should occur. The question now arises: How large do *current* drift models actually predict this charge-dependent effect?

4. The magnitude of charge-dependent modulation

In this section we shall establish the actual magnitude of charge-dependent modulation as predicted by the present drift model. The observations of Garcia-Munoz et al. (1986, 1987) were for 600–1000 MeV electrons and 70–95 MeV/nucleon (739–866 MV) helium so that in order to compare the predictions of our model with these observations we chose a representative value of 800 MV for both species.

The calculated intensities at Earth for both electrons and helium nuclei as a function of tilt angle, α, are shown in Fig. 2. The tilt angle is varied from 0° to 70° representing an $A>0$ period, and then from 70° to 0° representing an $A<0$ period. The calculated intensities with $\alpha\simeq10°$ and $A>0$ in Fig. 2 are compatible with the 1977 data for both species of particles at this rigidity. The vertical dotted line in this figure (and the ones to follow) depicts the period of time during which the IMF reverses its polarity. This period may be several months (as in 1980) or a few years (as from 1969 to 1971). The change in intensity from just before the reversal starts to just thereafter must therefore not be interpreted as instantaneous as the single dotted line may suggest. The predicted behavior of the helium and electron intensities as a function of α and the configuration of the IMF shown in Fig. 2 clearly illustrates:

(1) The insensitivity of helium (also positrons and other positive particles) to a changing α during an $A>0$ period, whereas the electron intensities respond significantly.

(2) How the helium nuclei and electrons respectively respond to the reversal of the IMF polarity. According to this model the electron intensity should increase during this reversal period

whereas intensities for positive particles should decrease. The opposite should happen when the polarity changes from $A<0$ to $A>0$.

(3) What happens after the polarity reversal when the drift velocity directions reverse for the two species particles. The electron intensity now shows no response to a changing α whereas the helium intensity responds significantly, exactly the opposite from what happened before the polarity reversal.

Evidently, this model predicts vastly different intensity-tilt profiles for helium nuclei and electrons with the same rigidity. How large this predicted charge-dependent effect is, is depicted by the solid line in Fig. 3 where the ratio of the helium to electron intensities from Fig. 1 is plotted as a function of α for the epochs before and after the particular polarity reversal. This ratio shows a strong tilt dependence for both magnetic field configurations (a factor of ~ 12 for α changing from 0 ° to 70°) and a significant change in the ratio when the polarity reverses (a factor of ~ 50). However, at this point it is important to note that the measurements of Garcia-Munoz et al. (1986, 1987), although not explicitly mentioned by them, were done for the so-called total spectrum i.e. the sum of positrons and electrons, $(e^+ + e^-)$. Before a comparison between what the models predict and actual measurements can be made, it is essential that the contribution of positrons to the total spectrum should be taken into account, because as illustrated in Fig. 2, the modulation of positively and negatively charged particles differ significantly during the same IMF polarity epoch. The modulation of $(e^+ + e^-)$ as a function of α may therefore differ significantly from that for pure electrons. The crucial question when it comes to the relative modulation of electrons and positrons in the heliosphere is what fraction of the total very local interstellar spectrum is in fact positrons. The general perception seems that $e^+/(e^+ + e^-) \leq 0.10$ (e.g. Protheroe, 1982). However, recently Webber (1987) argued that this fraction may be as high as 0.20 ± 0.05. If this is indeed true, positrons may play a very important role in charge dependent modulation in the heliosphere.

To calculate the modulation of $(e^+ + e^-)$ as a function of α, we assumed, first, a 10% positron contribution to the total LIS, which, for the purpose of this paper, is given by Eq. (1), and further that the LIS for positrons has the same rigidity dependence as that for electrons. Although this may not be the actual situation, the assumptions are considered reasonable. The modulation of e^-, e^+, $(e^+ + e^-)$ and He as a function of α and the reversal of the IMF polarity are shown in Fig. 4. The parameters given above were also used in this case. Comparing the tilt dependence of $(e^+ + e^-)$ with that of pure electrons, one finds that the tilt dependence of the sum is less, by a factor of 2, during the $A>0$ period, whereas for $A<0$ there is practically no difference because of the much higher electron intensities compared to positron intensities for most of this period. Using the intensities shown in Fig. 4 to calculate the change in the ratios $e^+/(e^+ + e^-)$ and He$/(e^+ + e^-)$ with a polarity reversal, we found for both a factor of ~ 26, which is almost a factor of 2 less than for He$/e^-$ (Fig. 3).

Next, we used a 25% positron contribution, as an upper limit, to the total LIS and repeated the calculation done for Fig. 4. The corresponding intensities for e^-, e^+, $(e^+ + e^-)$ and He are shown in Fig. 5. Apart from the significant smaller α dependence of $(e^+ + e^-)$ compared to e^- with $A>0$, another interesting and probably important modulation feature occurs, and this is that under this assumption the positron intensities at Earth may

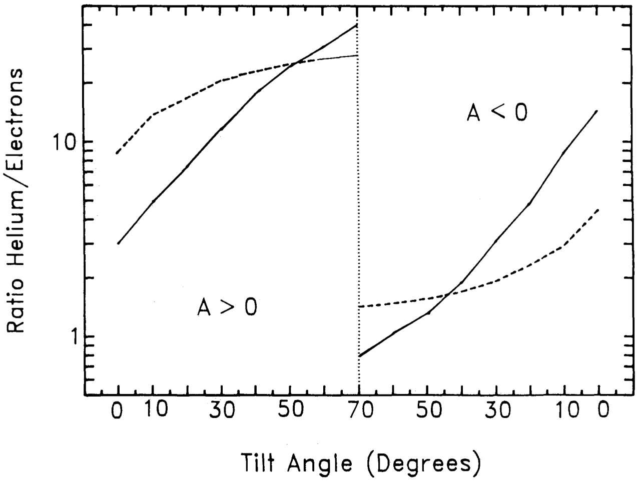

Fig. 3. The predicted ratio of the helium to the electron intensities for 800 MV as a function of α and the configuration of the IMF with full drift effects (solid line) and with drift effects reduced by a factor of 2 (dashed line)

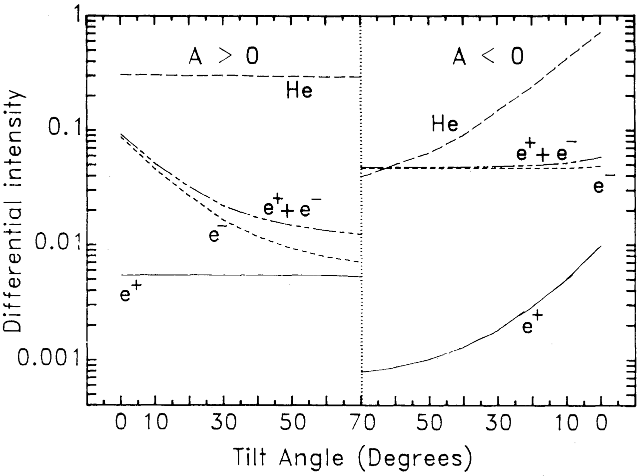

Fig. 4. The predicted differential intensity (particles $m^{-2} s^{-1} sr^{-1} MeV^{-1}$) for helium (He), electrons (e^-), positrons (e^+) and the sum of positrons and electrons $(e^+ + e^-)$ for 800 MV at Earth as a function of α. The positron contribution to the sum, $(e^+ + e^-)$, at the heliospheric boundary (50 AU) is 10%

exceed that for electrons when $\alpha \geq (40 \pm 10°)$ *and* $A>0$. Taking this into account the corresponding $e^+/(e^+ + e^-)$ and He$/(e^+ + e^-)$ ratios as a function of α are shown in Figs. 6 and 7 respectively. Comparing the tilt dependence, taken between 10° and 70°, of He$/e^-$ in Fig. 3 with that for He$/(e^+ + e^-)$ in Fig. 7 shows that it changed from a factor of ~ 12 to a factor of ~ 4 with $A>0$, while the change with the polarity reversal reduced from a factor of ~ 50 to ~ 14. This clearly illustrates what an important role positrons may play if modulation is indeed dominated by drift effects.

With the effect of positrons taken into account in our calculations, a more realistic comparison between the model's predictions and observations can now be made. The current model with full drift effects predicts a change of a factor of ~ 14 with a

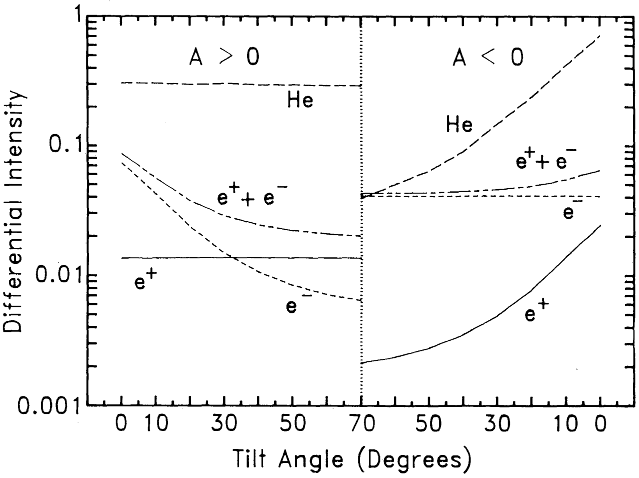

Fig. 5. Same as Fig. 4, for a 25% positron contribution to the sum, $(e^+ + e^-)$

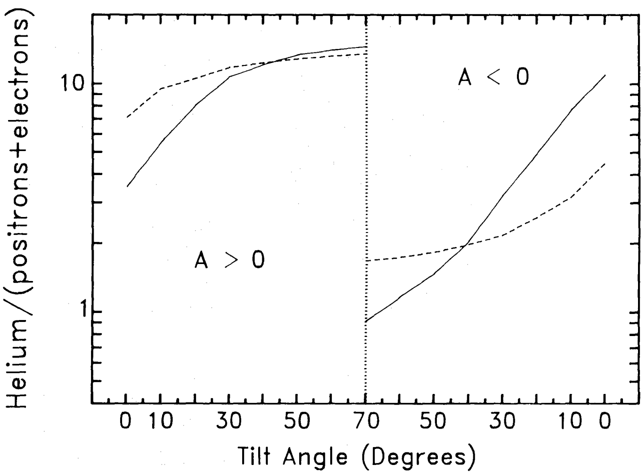

Fig. 7. Same as Fig. 6, for $He/(e^+ + e^-)$

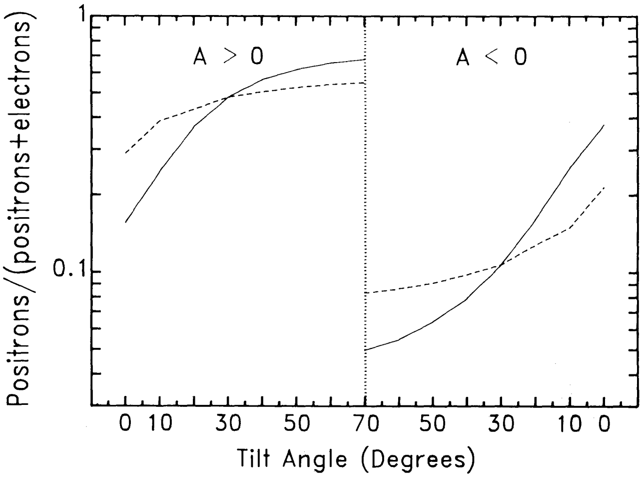

Fig. 6. The predicted ratio of $e^+/(e^+ + e^-)$ for 800 MV at Earth with full drift effects (solid lines) and with drift effects reduced by a factor of 2 (dashed lines). Both cases are with $e^+/(e^+ + e^-) = 0.25$ at the heliospheric boundary

polarity reversal and a tilt dependence which varies from 10° to 70° by a factor of 4 for $He/(e^+ + e^-)$ when $A > 0$. From observations, these factors are 3 ± 1 and ~ 2 respectively. It is not yet clear from observations what the tilt dependence for the $A < 0$ period is, except that it seems significantly larger than when $A > 0$ (Garcia-Munoz et al., 1987). This comparison of the model's predictions with observations shows that the present drift model, with as realistic as possible modulation parameters, and a 25% positron contribution to the total LIS, predicts too large charge-dependent modulation.

Potgieter et al. (1985, 1987a, b, 1989) have argued that most observations do not seem to confirm the large drift effects predicted by contemporary steady-state drift models. One such example is the large difference between the radial gradients of cosmic-ray protons in the heliosphere before and after the polarity reversal in 1980 (for reviews see McKibben, 1987; Fillius, 1989). They consequently proposed the reduction of drift over the entire heliosphere to obtain better agreement between model predictions and observations (see also Forman, 1987). Ths reduction is not unfounded because Smith et al. (1987) showed that the magnitude of the IMF had changed at Earth from ~ 5 nT in 1976 to ~ 9 nT in 1982. Since $K_T \propto 1/B$, drift effects could well be reduced by a factor of 2, at least with increasing solar activity. Following the same line of reasoning we scaled drift down by a factor of 2, i.e., taking $(K_T)_0 = 0.5$ in Eq. (3c), and reducing neutral sheet drift accordingly. To illustrate the effect of this reduction we recalculated the intensities as a function of α and the corresponding ratios for the various cases and species of particles considered here. The ratios, He/e^-, $e^+/(e^+ + e^-)$ and $He/(e^+ + e^-)$, are shown by the dashed curves in Figs. 3, 6 and 7 respectively. In all three cases the tilt angle dependence is significantly reduced during both $A > 0$ and $A < 0$ epochs, and so is the change in the ratio with the reversal of the IMF polarity. The results in Fig. 7, for instance, show that reducing drift effects by a factor of 2 reduces the α dependence of $He/(e^+ + e^-)$ when $A > 0$, from a factor of ~ 4 to a factor of ~ 2, which is more compatible with the corresponding observation. The change in this ratio with a polarity change is reduced from a factor of ~ 14 to a factor of ~ 7, which is, however, compared with the measured value still by a factor of 2–3 too large.

Seen on its own, this result could be interpreted as to suggest a further global reduction of drift. This premise, however, is not supported by the intensity-time-tilt variations at Earth found for several proton energies by Webber et al. (1990). They have found good compatibility between the α dependence of proton data and the model's predictions, especially for the $A < 0$ epoch when drift effects were varied between full and half drift. In view of the current state of affairs with drift model predictions, we believe that some re-appraisal of drift effects seems to be needed. Such studies have already started, and in the last section we will discuss some results and also present an outline of how we foresee possible changes in drift effects.

5. Discussion and conclusion

Up to the present the emphasis in drift studies has been on positively charged particles, with the exception of positrons. In contrast to earlier studies (e.g., the references in the previous section), which showed that drift could explain some prominent features of the modulation of cosmic ray protons, the results presented in this paper showed that it seemed to fail to do the same for charge dependent modulation, in general, unless drift effects were reduced by a factor of 2 or more. It is therefore obvious that the magnitude of drift effects need to be re-examined and that other possibilities must also be considered to try and solve this problem.

Before we discuss possible ways of solving what appears to be a challenge to current drift models, it should be pointed out that the helium measurements (70–95 MeV/nucleon) could be contaminated to some extent by anomalous helium, as was pointed out by Garcia-Munoz et al. (1987). They estimated this contribution at a few percent. But, even a contribution of just 10% could influence the α dependence of He at Earth, especially if the contribution occurs during solar minimum activity and less, or even no contribution, during solar maximum activity. An effect like this would make the α dependence during the $A>0$ periods less strong, as had been observed. This aspect will, however, have to be investigated with a model which in a solar wind termination shock is incorporated for the acceleration of the anomalous helium.

Another aspect to mention, although we do not consider it as very serious, is the fact that we work with a two-dimensional model with a simulated wavy neutral sheet as were explained in detail by Burger and Potgieter (1989). A full three-dimensional model (Kóta and Jokipii, 1983) might give somewhat different results. Whether it can reduce the difference between predictions and observations concerning charge-dependent modulations, without using new concepts in the model, remains to be seen.

All of our previous work (see references in the previous section) suggested that, in order to explain certain observations, drift should be made less effective. In the present paper, an additional argument in this regard is the parallel mean free path that we were forced to accept in order to fit the 1977 helium and electron spectra simultaneously, and which is much smaller than the consensus values proposed by Palmer (1982). A wide variety of diffusion coefficients were tried as well as changes in other modulation parameters such as the outer heliospheric boundary, but none could rectify this problem. It is interesting to note that this problem did not appear in earlier work on electron modulation (Potgieter and Moraal, 1985) when a different LIS for electrons was assumed. The question now is how drift effects can be reduced, and to answer this, we consider some theoretical arguments.

Lee and Fisk (1981) proposed the presence of helical magnetic flux tubes in interplanetary space, and argued that drift effects would be eliminated for particles trapped within the flux tubes if their gyroradii were less than the flux-tube radius. Taking the separation of tangential discontinuities to be representative of flux-tube diameters ($\sim 10^9$ m), they conclude that drift suppression could occur for particles with energies less than about 1 GeV/nucleon. Work in progress on the effects of large scale fluctuations on average drift velocities, also provides theoretical support for the idea of reduced drifts. Our preliminary results suggest that a reduction of as much as a factor of three is possible for fluctuations with amplitudes comparable to the background magnetic field.

The recent work of Jokipii and Kóta (1989) concerns another possible mechanism for reducing drift effects. They suggest that the polar heliospheric magnetic field may deviate considerably from the generally accepted Parker spiral at large heliospheric distances, leading to smaller drift velocities and diffusion coefficients in those regions, if the latter are assumed inversely proportional to the magnetic field strength. We did several test runs with this effect incorporated in our model and found that if the IMF was changed by an average factor of 3 at ~ 30 AU in the polar regions of the heliosphere, the $He/(e^+ + e^-)$ changed by a factor of 1.3. With full drifts in the rest of the heliosphere this would not have much influence, but with reduced drifts, as shown in Fig. 7, and in conjunction with other effects suggested in this section it could be become significant.

Furthermore, the effects of scattering on drift need further investigation. Work in progress on diffusion coefficients similar to those employed by Kadokura and Nishida (1986) shows that it might be possible to change the rigidity dependence of K_T from the generally accepted form given in Eq. (3c), and consequently also its magnitude. The possibility of drift effects having a rigidity dependence different from $P^{1.0}$ is suggested by the recent work of Webber et al. (1990). These authors also used the drift model employed in the present work, and when fitting intensity-tilt data at various energies, they found that at lower energies (100–200 MeV) the need for reduced drift effects appeared to be stronger than at higher energies.

We therefore come to the conclusion that there seems to be ample theoretical arguments to support the premise of reduced drift effects, and none to the contrary. Depending on the outcome of the mentioned investigations in progress, and considering the arguments for an overall reduction of drift effects, it could well be that future drift studies will not be restricted to using K_T in its present form.

Another feature of current drift models that needs attention is the predicted insensitivity of electrons (and anti-protons – see Webber and Potgieter, 1989) as a function of tilt angle when $A<0$, and similarly for protons and positrons when $A>0$. For the latter species observational evidence shows peaked behaviour for $A<0$, and to a lesser extent but still clearly evident for $A>0$ (Smith and Thomas, 1986; Webber et al., 1990). If, however, we assume that within the region swept out by the neutral sheet the magnetic field is not as well ordered as that outside of this region, the following feature emerges: Since the thickness of this region increases as the tilt angle increases, this would also lead to a more peaked intensity-tilt profile for electrons when $A<0$, but still less pronounced than for $A>0$. We note that such a behaviour can be produced with our model if we decrease gradient and curvature drift in the region swept out by the neutral sheet region according to the "effective" magnetic polarity averaged over a solar rotation. Just outside of the neutral sheet region this value is of course one, decreasing to zero at the solar rotational equator while neutral sheet drift is adjusted to keep the effective drift velocity field divergence free. [The model by Potgieter and Moraal (1985) does give a more realistic tilt dependence when $A>0$ (see Reinecke et al., 1990).] Test runs with this model showed that compensation for this lack of response of the electron intensity as a function of α has a moderate effect, a factor of 1.2, on the $He/(e^+ + e^-)$.

Apart from drift, magnetic helicity is currently the only other known process that can cause charge-dependent modulation. Bieber et al. (1987) have confirmed their theoretical predictions by showing that the observed magnetic helicity is systematically larger south of the neutral sheet than north of it. These authors emphasize, however, that their measurements and calculations pertain to scales larger than a correlation length, and that the question whether there remains on the average a dominant sign of helicity at smaller scales (relevant for cosmic ray scattering) is left open. While it is clear that our knowledge of the detailed effects of magnetic helicity is still far from complete, the recent work by Bieber and Burger (1990) shows that helicity can produce a difference of more than 30% between the diffusion coefficients of oppositely charged particles parallel to the mean magnetic field. Moreover, if magnetic helicity acts to suppress drifts (see Lee and Fisk, 1981), and if drift on its own produces peaked intensity-tilt profiles, it might well be that helicity and drift work in concert to produce the observed intensity-time profiles. It is therefore imperative that the work of Bieber and Burger (1990) be extended to include the effect of helicity on propagation perpendicular to the mean magnetic field, and of course that helicity be included in a modulation model.

A last question is how dynamic effects as described by a time-dependent drift model (e.g. Le Roux and Potgieter, 1989) will change the results obtained by steady state models. As an illustration of how dynamic effects might influence intensities at Earth, consider the following. As the Sun approaches its period of minimum activity, the tilt angle at Earth will reach a minimum value some time before the same value is reached in the outer heliosphere. During epochs when $A<0$ this kind of "phase lag" could cause, for instance, intensity-tilt profiles at Earth to be asymmetric with respect to the minimum tilt value. (For preliminary results, see Le Roux and Potgieter, 1990). The effects of transients and features like merged interactive regions (MIR's) at large radial distances (e.g., Burlaga et al., 1985; Perko and Burlaga, 1987) can also not be ignored any longer when it comes to the numerical modelling of modulation. Features like MIR's in the outer heliosphere could lead to large barrier effects which might also play an important role in the modulation process (Lockwood and Quenby, 1987; Potgieter and Le Roux, 1989).

In conclusion, the results of this paper in conjunction with previous results suggest that a fundamental reassessment of the magnitude and rigidity dependence of drift effects is required, and that a next generation of drift models, probably time-dependent and incorporating effects such as magnetic helicity, needs to be considered for modulation studies. It seems clear that the puzzle of charge dependent modulation probably has more pieces than was previously thought. To identify them all and to fit them all together, will no doubt be a major undertaking.

Acknowledgements. We are grateful to H. Moraal for his useful suggestions about this work. Especially for demonstrating with model calculations the relative importance of positrons to drift modulation. We are also grateful to W.R. Webber for valuable discussions and for pointing out that the positron contribution could be as high as 25 percent. We thank J.A. Le Roux for interesting discussions and Miss M.L. van Staden for her valuable assistance.

References

Bieber, J.W., Burger, R.A.: 1989, *Astrophys. J.* **348**, 597
Bieber, J.W., Evenson, P.A., Matthaeus, W.H.: 1987, *Geophys. Res. Letters* **14**, 864
Burger, R.A., Potgieter, M.S.: 1989, *Astrophys. J.* **339**, 501
Burlaga, L.F., McDonald, F.B., Goldstein, M.L., Lazarus, A.J.: 1985, *J. Geophys. Res.* **90**, 12 072
Caldwell, J.H., Evenson, P., Jordan, S., Meyer, P.: 1977, Proc. 15th Intern. Cosmic Ray Conf., Plovdiv, vol. 11, p. 203
Evenson, P. Caldwell, J.H., Jordan, S., Meyer, P.: 1979, *J. Geophys. Res.* **84**, 5361
Evenson, P., Garcia-Munoz, M., Meyer, P., Pyle, K.R., Simpson, J.A.: 1983, Proc. 18th Intern. Cosmic Ray Conf., Bangalore, vol. 3, p. 27
Fillius, W.: 1989, *Advances Space Res.* **9**, 209
Forman, M.A.: 1987, Proc. 20th Intern. Cosmic Ray Conf., Moscow, vol. 8, p. 165
Garcia-Munoz, M., Meyer, P., Pyle, K.R., Simpson, J.A.: 1986, *J. Geophys. Res.* **91**, 2858
Garcia-Munoz, M., Meyer, P., Pyle, K.R., Simpson, J.A.: 1987, Proc. 20th Intern. Cosmic Ray Conf., Moscow, vol. 3, p. 303
Hoeksema, J.T., Wilcox, J.M., Scherrer, P.H.: 1983, *J. Geophys. Res.* **88**, 9910
Jokipii, J.R., Kóta, J.: 1989, *Geophys. Res. Letters* **16**, 1
Kadokura, A., Nishida, A.: 1986, *J. Geophys. Res.* **91**, 1
Kóta, J., Jokipii, J.R.: 1983, *Astrophys. J.* **265**, 573
Lee, M.A., Fisk, L.A.: 1981, *Astrophys. J.* **248**, 836
Le Roux, J.A., Potgieter, M.S.: 1989, *Advances Space Res.* **9**, 225
Le Roux, J.A., Potgieter, M.S.: 1990, Proc. 21st Intern. Cosmic Ray Conf., Adelaide, vol. 6, p. 87
Lockwood, J.A., Quenby, J.J.: 1987, Proc. 20th Intern. Cosmic Ray Conf., Moscow, vol. 3, p. 406
Lockwood, J.A., Webber, W.R., Hoeksema, J.T.: 1988, *J. Geophys. Res.* **93**, 7521
McKibben, R.B.: 1987, *Rev. Geophys. Space Phys.* **25**, 711
Moraal, H., Potgieter, M.S.: 1982, *Astrophys. Space Sci.* **84**, 519
Moses, D.: 1987, *Astrophys. J.* **313**, 471
Palmer, I.D.: 1982, *Rev. Geophys. Space Phys.* **20**, 335
Perko, J.S.: 1987, J. Geophys. Res. **92**, 8502
Perko, J.S., Burlaga, L.F.: 1987, *J. Geophys. Res.* **92**, 6127
Potgieter, M.S., Burger, R.A., Le Roux, J.A.: 1987a, Proc. 20th Intern. Cosmic Ray Conf., Moscow, vol. 3, p. 295
Potgieter, M.S., Fisk, L.A., Lee, M.A.: 1985, Proc. 19th Intern. Cosmic Ray Conf., La Jolla, vol. 5, p. 180
Potgieter, M.S., Le Roux, R.A.: 1989, *Astron. Astrophys.* **209**, 406
Potgieter, M.S., Le Roux, J.A., Burger, R.A.: 1987b, Proc. 20th Intern. Cosmic Ray Conf., Moscow, vol. 3, p. 287
Potgieter, M.S., Le Roux, R.A., Burger, R.A.: 1989, *J. Geophys. Res.* **94**, 2323
Potgieter, M.S., Moraal, H.: 1983, Proc. 18th Intern. Cosmic Ray Conf., Bangalore, vol. 3, p. 17
Potgieter, M.S., Moraal, H.: 1985, *Astrophys. J.* **294**, 425
Protheroe, R.J.: 1982, *Astrophys. J.* **254**, 391
Reinecke, J.P.L., Potgieter, M.S., Van Staden, M.L.: 1990, Proc. 21th Intern. Cosmic Ray Conf., Adelaide, vol. 6, p. 95
Smith, E.J., Thomas, B.T.: 1986, *J. Geophys. Res.* **91**, 2933
Smith, E.J., Winterhalter, D., Slavin, J.A.: Proc. 6th Intern. Solar Wind Conf., vol. 2, p. 581
Webber, W.R.: 1987, Proc. 20th Intern. Cosmic Ray Conf., Moscow, vol. 8, p. 65
Webber, W.R., Kish, J.C., Schrier, D.A.: 1983, Proc. 18th Intern. Cosmic Ray Conf., Bangalore, vol. 3, p. 35
Webber, W.R., Lockwood, J.A.: 1988, *J. Geophys. Res.* **93**, 8735
Webber, W.R., Potgieter, M.S.: 1989, *Astrophys. J.* **344**, 779
Webber, W.R., Potgieter, M.S., Burger, R.A.: 1989, *Astrophys. J.* **349**, 634