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Effects of the solar wind termination shock and heliosheath on the heliospheric modulation of galactic and anomalous Helium

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Abstract. The interest in the role of the solar wind termination shock and heliosheath in cosmic ray modulation studies has increased significantly as the Voyager 1 and 2 spacecraft approach the estimated position of the solar wind termination shock. The effect of the solar wind termination shock on charge-sign dependent modulation, as is experienced by galactic cosmic ray Helium (He^{++}) and anomalous Helium (He^{+}), is the main topic of this work, and is complementary to the previous work on protons, anti-protons, electrons, and positrons. The modulation of galactic and anomalous Helium is studied with a numerical model including a more fundamental and comprehensive set of diffusion coefficients, a solar wind termination shock with diffusive shock acceleration, a heliosheath and particle drifts. The model allows a comparison of modulation with and without a solar wind termination shock and is applicable to a number of cosmic ray species during both magnetic polarity cycles of the Sun. The modulation of Helium, including an anomalous component, is also done to establish charge-sign dependence at low energies. We found that the heliosheath is important for cosmic ray modulation and that its effect on modulation is very similar for protons and Helium. The local Helium interstellar spectrum may not be known at energies $<\sim$1 GeV until a spacecraft actually approaches the heliopause because of the strong modulation that occurs in the heliosheath, the effect of the solar wind termination shock and the presence of anomalous Helium.

Key words. Interplanetary physics (cosmic rays; heliopause and solar wind termination) – Space plasma physics (transport processes)

1 Introduction

A numerical model describing cosmic ray modulation in the heliosphere, including the solar wind termination shock (TS) and heliosheath, was applied to protons (p), anti-protons ($\overline{p}$), electrons (e^-), and positrons (e^+) in previous work (Langner et al., 2003; Langner and Potgieter, 2004; Potgieter and Langner, 2004b). This model has been extended to also include the modulation of galactic Helium (He^{++}) and Helium with anomalous Helium (He^{+}), in order to highlight the role and the importance of the TS and the heliosheath in heliospheric modulation.

The interest in the role and effects of these features has increased significantly as the Voyager 1 and 2 spacecraft gradually approach the estimated position of the TS (e.g. Webber et al., 2001). Observations closer to the predicted location of the TS (e.g. McDonald et al., 2000) enable us to study cosmic ray modulation in the outer heliosphere in more detail, especially the effects of the TS and what level of modulation may occur in the heliosheath. There is consensus that the TS should be in the vicinity of 90 AU (e.g. Stone and Cummings, 2001), although the TS may move significantly outwards and inwards over a solar cycle (e.g. Scherer and Fahr, 2003; Zank and Müller, 2003; Whang et al., 2004). This average value is supported by recent observations that Voyager 1 is indeed approaching the TS (McDonald et al., 2003; Stone and Cummings, 2003) or may have even crossed it (Krimigis et al., 2003). This study will therefore help to interpret the observations of the Voyager spacecraft. The position of the heliopause is less certain, probably at least 30–50 AU beyond the TS in the direction the heliosphere is moving (heliospheric nose). For our purposes, this region between the heliopause (modulation outer boundary) and the TS is called the heliosheath. For a review, see Fichtner (2001). By taking the interstellar helium ions into account in the multicomponent modeling of the solar wind interaction with the local interstellar cloud, Izmodenov et al. (2003) found that the heliopause and the TS are closer to the Sun than without the helium contribution. They estimated the location of the TS to be $\sim$93 AU, while the heliopause is at $\sim$160 AU.

Concerning modulation mechanisms, large-scale gradient, curvature and current sheet drifts that He experiences in the global heliospheric magnetic field (HMF) are most prominent. Drift models predict a clear charge-sign dependence for the modulation of, for example, cosmic ray e^- and He; e^- will drift inward primarily through the polar regions of the heliosphere during so-called $A<0$ polarity cycles, when

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the HMF is directed towards the Sun in the Northern Hemisphere. Helium, on the other hand, will then drift inward primarily through the equatorial regions of the heliosphere, encountering the wavy heliospheric current sheet in the process (Jokipii et al., 1977; Jokipii and Thomas 1981). During the $A>0$ polarity cycles the drift directions for the differently charged species reverse, so that a clear 22-year cycle is predicted (e.g. Kota and Jokipii, 1983; Ferreira et al., 2003a, 2004b) and observed (e.g. Heber et al., 2002). The numerical model, incorporating a TS with a heliosheath and drifts, used for this study, was described in detail by Langner et al. (2003) – see also Langner (2004). For recent reviews on cosmic ray modulation, see Heber (2001) and Ferreira and Potgieter (2004a).

Modelling the heliospheric modulation of galactic and anomalous He had been addressed by various authors (e.g. Steenberg and Moraal, 1996). However, with a new approach to diffusion coefficients and using a TS model including a heliosheath and drifts, revisiting He modulation has become appropriate. The same model was successful in explaining simultaneously the modulation of cosmic ray p, $\overline{p}$, e^-, and e^+ in the heliosphere. This study tests and illustrates the general applicability of the TS model and the set of diffusion parameters for various species, both polarity cycles, and as modulation changes from solar minimum to moderate solar maximum conditions, which in combination was not done before.

The following topics are addressed in detail: (1) the effects of the TS on the modulation of galactic He, and He with anomalous He, in a simulated heliosphere for both HMF polarity cycles as modulation changes from minimum to moderate maximum conditions; (2) the differences in modulation between a model with and without a TS; (3) the level and the importance of modulation in the simulated heliosheath for galactic He, and (4) to establish the consequent charge-sign dependence and the effects of the TS on the modulated ratios of e^-/He and e^-/He with anomalous He, with the electron modulation contaning a Jovian electron source (Ferreira et al., 2003b). Different isotopes for galactic He and anti-Helium were not considered for this study.

2 Modulation model

The details of the model were fully described by Langner et al. (2003), Langner and Potgieter (2004), and Potgieter and Langner (2004b), therefore only the most essential parts will be repeated here for the convenience of the reader. The Parker (1965) transport equation is solved time-dependently in a spherical coordinate system as a combined diffusive shock acceleration and drift modulation model with two spatial dimensions, neglecting any azimuthal dependence and is symmetric around the equatorial plane. Similar numerical models were described and used by, for example, Jokipii et al. (1993), Steenberg and Moraal (1996) and Potgieter and Ferreira (2002).

The outer modulation boundary was assumed at r_b=120 AU, where the local interstellar spectrum for He is specified. For He with an anomalous component a source was injected at the TS position over all latitudes at a energy of ∼86.0 keV as a delta function with a magnitude set to give reasonable fits to anomalous He observations at 60 AU and to He observations at Earth (Steenberg and Moraal, 1996; see also Steenberg, 1998). The solutions are independent of this injection energy as long as it is lower than the acceleration cutoff energy (see also Steenkamp, 1995). Since the mass-to-charge ratio, A/Z, is not the same for galactic He (A/Z=2 for He^{++}) and anomalous He (A/Z=4 for He^{+}), the model has to be run separately for these species. Solutions are therefore shown as a linear combination of solutions for galactic He and anomalous He.

The "tilt angles", as calculated by Hoeksema (for details, see Wilcox Solar Observatory with courtesy of J. T. Hoeksema: http://wso.stanford.edu) were assumed, to represent solar minimum and moderate maximum modulation conditions with α=10° and α=75°, respectively, during $A>0$ (e.g. ∼1990–2001) and $A<0$ (e.g. ∼1980–1990) magnetic polarity cycles. This TS model does not describe extreme solar maximum conditions; a different code has to be used for that purpose (e.g. Ferreira and Potgieter, 2003).

The TS was assumed at r_s= 90 AU with a compression ratio s=3.2, and a shock precursor scale length of L=1.2 AU. For the precursor scale length in front of the shock, V decreases in the equatorial plane, for example, from the upstream value of V_1 according to the relationship given in Langner et al. (2003) – see also le Roux et al. (1996). This means that up to the shock, $V(r)$ decreases by $0.5\,s$ starting at L, then abruptly as a step function to the downstream value, in total to V_1/s. Beyond the TS, V decreases further as $1/r^2$ to the outer boundary. This $1/r^2$ decrease is a reasonable first-order approximation in the nose region of the heliosphere but is an oversimplification elsewhere (e.g. Scherer and Fahr, 2003). For He with an anomalous component solutions with s=2.0 are obtained in order to find reasonable compatibility with the anomalous He observations at 60 AU. The HMF increases by a factor s at the TS and V changes from 400 km/s in the equatorial plane (θ=90°) to 800 km/s in the polar regions. This increase of V by a factor of 2 happens in the whole heliosphere for $120°\leq\theta\leq60°$ for solar minimum conditions, but it is reduced to a factor of 1.10 with $170°\leq\theta\leq10°$ for moderate maximum modulation conditions. (Model is symmetric with respect to the polar axis.)

The diffusion coefficients $\kappa_{||}$, $\kappa_{\perp}$, and κ_T are based on those given by Burger et al. (2000) for a steady-state model, except for some changes to their values caused by the introduction of the TS in this model. Perpendicular diffusion is assumed to enhance towards the poles in order to fit the observed latitudinal gradients (e.g. Burger et al., 2000; Ferreira et al., 2000). For a complete description of these diffusion coefficients, see Langner et al. (2003). They are optimal for a numerical TS model without an azimuthal dependence and without solar maximum transient effects, for example, global merged interaction regions. This set can also be used by changing only the rigidity dependences of $\kappa_{||}$ accordingly at low rigidities for electrons and positrons to give reasonable fits to a variety of data sets and is the same for both polarity cycles.

3 Modelling results

The results which will be shown in the following sections concentrate on four aspects of the heliospheric modulation of He: (1) The difference in the modulation of galactic He and galactic He with anomalous He. (2) How the inclusion of a TS in the model alters the modulation of He and the subsequent effects of charge-sign dependent modulation on the ratios: e^-/He, and e^-/He with anomalous He. (3) The nature of modulation effects to be expected near the TS and in the heliosheath. (4) The effects of increased solar activity and tilt angle dependence.

The left panels of Figs. 1 and 2 show the modulation as a function of kinetic energy obtained with the TS model with respect to the LIS for galactic He and for He with anomalous He added. This is done at 1, 60, 90 and 115 AU in the equatorial plane for the $A>0$ and $A<0$ polarity cycles with α=10° and α=75°, respectively. The right panels of Figs. 1 and 2 show the corresponding differential intensities at 0.016, 0.2 and 1.0 GeV as a function of radial distance in the equatorial plane. In Fig. 1 the solutions are shown respectively for a model with and without a TS. In Fig. 2 the solutions are shown with the compression ratio s=3.2 and s=2.0, respectively. The decrease in s was necessary to obtain reasonable compatibility with the anomalous He observations at 60 AU, as mentioned above. The solutions in the inner heliosphere ($r<\sim$40 AU) are largely insensitive to this change. Decreasing s causes the peak in the modulated anomalous He spectra to shift to lower energies, as the observations seem to require, and can be caused by a decreasing shock strength with increasing solar activity, similar to protons (Langner and Potgieter, 2004). These quantitative aspects of anomalous He modulation were discussed in detail by, for example, Steenberg et al. (1998) and were not pursued further in this work. Comparing the energy spectra and radial dependence of the intensities for the chosen energies in these two figures, one notes: (1) that modulation for He differs from solar minimum to moderate solar maximum; (2) the effect on the solutions of switching the HMF polarity from $A>0$ to $A<0$. (3); that the modulation of He is affected by incorporating a TS evident by comparing solutions with and without a TS present in the model; (4) the significant effect at energies below ∼100 MeV on the modulation of He when an anomalous component is added; (5) the "barrier" type modulation caused by the heliosheath and that it differs significantly for different energies, with the largest effect at low energies. These aspects are further discussed below.

In Fig. 3 the effects of the TS on the modulation of He are emphasized by depicting the ratio of intensities obtained with and without a TS as a function of kinetic energy at radial distances of 1, 60, 90 and 115 AU, and as a function of radial distance at energies of 0.016, 0.2 and 1.0 GeV, respectively, in the equatorial plane for both polarity cycles when α=10°. The modulation parameters of the two models were kept the same for these calculations in order to quantify the effects of the TS on the modulation of He. The ratios as a function of energy converge naturally at $E>\sim$10 GeV because the TS has progressively less modulation effects the higher the energy. The ratios as a function of radial distance approach the required unity at 120 AU where the LIS were specified.

In Fig. 4 the intensity ratios of electrons to He, e^-/He, and e^-/(He with an anomalous He source) are shown as a function of rigidity in the equatorial plane at 1 and 90 AU for both polarity cycles with α=10° and α=75°, respectively. The electron intensities used to compute the ratios also contain a jovian electron source at 5 AU. The e^- intensities are taken from Potgieter and Langner (2004b). As a reference, these ratios are compared to the corresponding LIS (unmodulated) ratios at 120 AU.

Next, the modulation computed to take place in the heliosheath, between r_b and r_s, is compared to what happens between r_b and 1 AU (LIS to Earth) and between r_s and 1 AU (TS to Earth). This comparison is emphasized by showing in Fig. 5 the intensity ratios j_{LIS}/j_1, j_{LIS}/j_{90} and j_{90}/j_1 for He and He with anomalous He as a function of kinetic energy in the equatorial plane for both polarity cycles with α=10°, where j_{LIS} is the intensity at 120 AU, j_{90} is the intesity at 90 AU and j_1 is the intensity at 1 AU. Note that for a few cases the ratios become less than unity which will be explained below.

4 Discussion

In this section the lesser known modulation features shown above will be discussed individually. From Fig. 1 follows that the modulated He spectra at large radial distances ($r\rightarrow r_s$) for the $A<0$ cycle exceed the corresponding LIS between ∼200 MeV and a few GeV, as has been noted for protons (Jokipii et al., 1993; Langner et al., 2003). The effect of the TS on the modulation of He with respect to the LIS is significant; it decreases the intensities at lower energies (e.g. at 100 MeV) but increases it at higher energies (e.g. at 1 GeV), because the lower energy particles are being accelerated to higher energies. Obviously, this cannot happen without a TS. This effect also seems absent for larger α's and clearly depends on the drift direction. The energy spectra in Fig. 1 also depict how the slopes of the modulated He spectra systematically obtain the characteristic spectral index (E^1-energy slope) at lower energies which is caused by adiabatic "cooling" with decreasing radial distance. Beyond the TS ($r>r_s$), the spectra obtain a much steeper energy slope at low energies caused by the assumed divergence free solar wind speed in the heliosheath ($V\propto 1/r^2$). These low energy particles experience increased modulation primarily caused by $\kappa_\perp\propto R^{1/3}$ at these radial distances. This happens, however, at much lower energies ($E<\sim$1.0 MeV) than for protons shown by Langner and Potgieter (2004). This implies that the LIS for

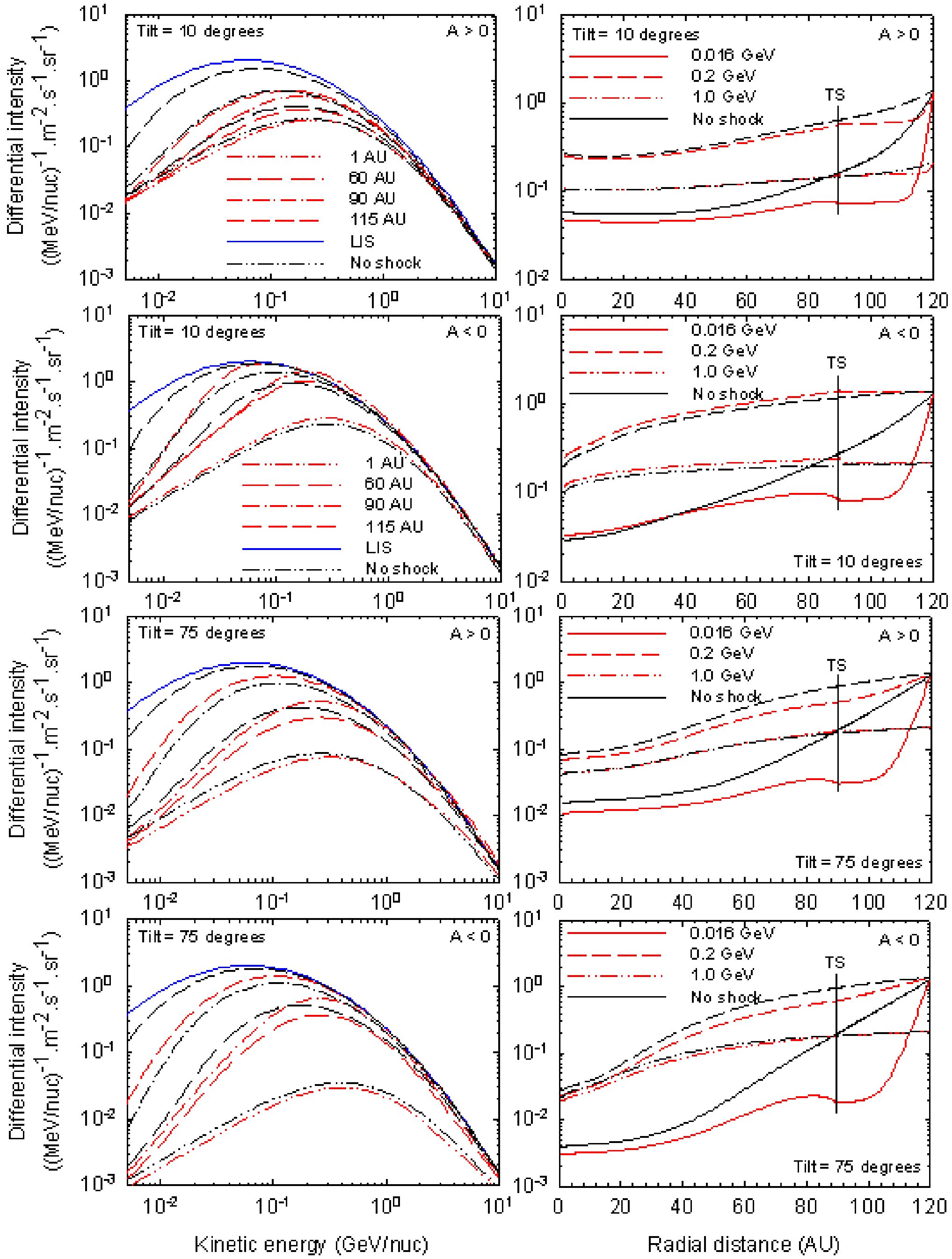

Fig. 1. Left panels: Computed differential intensities for galactic He as a function of kinetic energy for both polarity cycles, at radial distances of 1, 60, 90 and 115 AU (bottom to top) in the equatorial plane. Right panels: The corresponding differential intensities as function of radial distance for 0.016, 0.2 and 1.0 GeV, respectively. In all panels the TS is at 90 AU, as indicated, with the LIS specified at 120 AU, with "tilt angles" α=10° and 75°, respectively. Solutions without a TS are given as black lines and those with a TS as red lines at the same radial distances and energies. Note scale differences between the panels.

galactic He may not be known at these low energies until a spacecraft actually approaches the heliopause. This feature is not present in the solutions without a TS, as expected.

Hydrodynamic heliospheric models (e.g. Scherer and Fahr, 2003) indicate that the flow of the solar wind becomes parallel to the shock surface towards the polar regions, and thus the velocity does not necessarily decrease like $1/r^2$ in the region towards the heliospheric poles and into the tail. Furthermore, the modulation volume increases significantly in the tail region of the heliosphere. These aspects will, however, not have a qualitative influence on the results of this study other than to cause radial gradients that stay constant

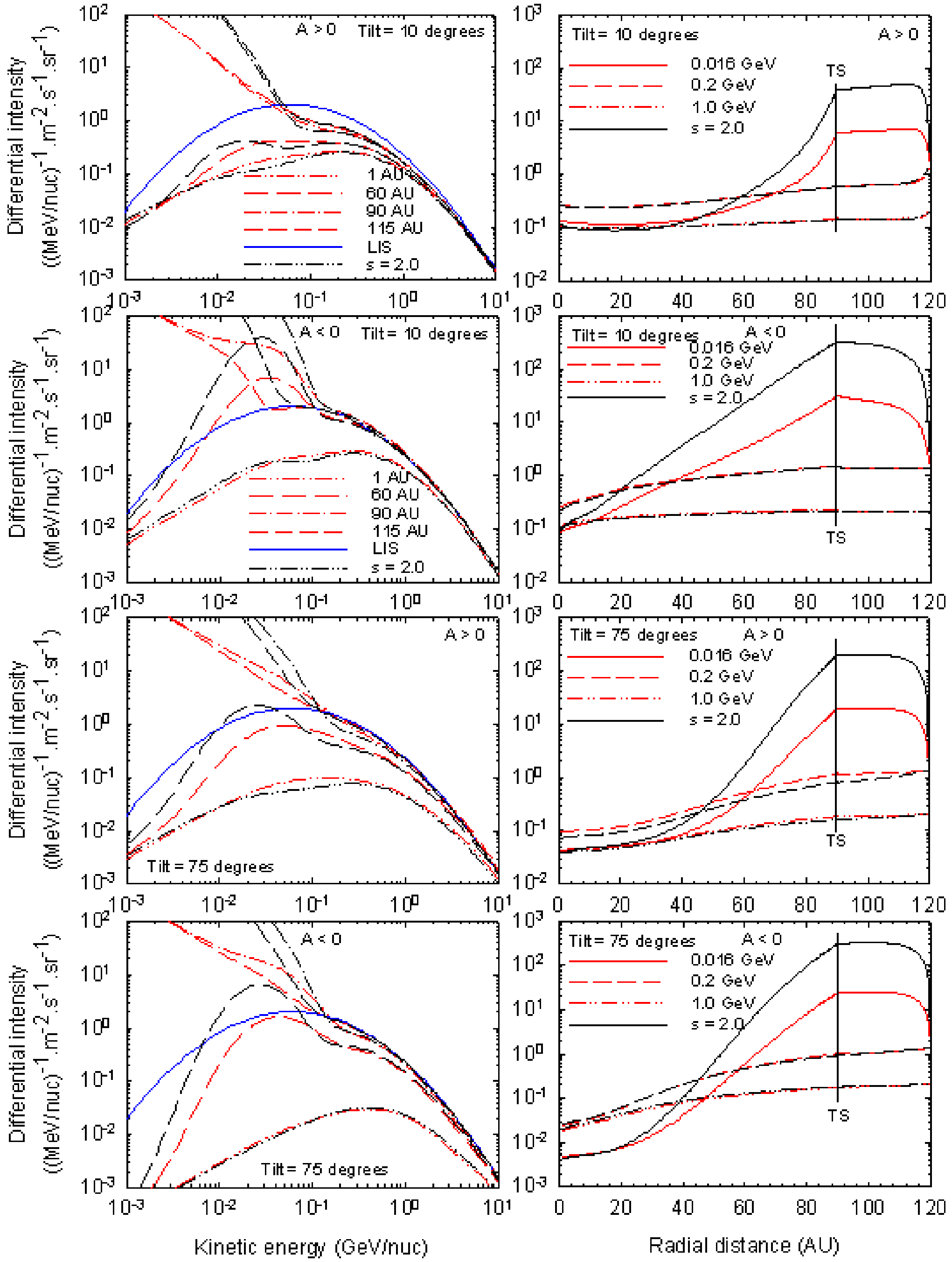

Fig. 2. Similar to Fig. 1 but for He with an anomalous component. Here the black lines represent solutions at the same energies and radial distances with s=2.0 instead of s=3.2 (red lines) to illustrate the effect of lowering the compression ratio of the TS.

farther out into the heliosheath, while the “barrier effect” is spread over larger radial distances (e.g. Ferreira et al., 2001). However, these aspects, which are beyond the scope of this axi-symmetric modulation model, need further investigation.

For He with an anomalous He source added, as is shown in Fig. 2, the intensities at the TS where the anomalous He source is injected follow the characteristic $E^{-1.2}$ spectrum with s=3.2 and $E^{-2.0}$ with s=2.0, which is dictated by the acceleration of anomalous He at the TS with $E<\sim$100 MeV. The inclusion of an anomalous He component has a profound effect on the He intensities at larger radial distances ($r>\sim$60 AU) at $E<\sim$100 MeV, but a relatively small effect on the intensities at Earth. This larger effect is because of the higher rigidity of He than that of protons for a given energy and should even be larger for heavier species (i.e. Oxygen, Boron, Carbon, see e.g. Mewaldt et al., 1996). Near the TS the spectrum is, of course, substantially different because of the injected anomalous He source. Note that the modulation

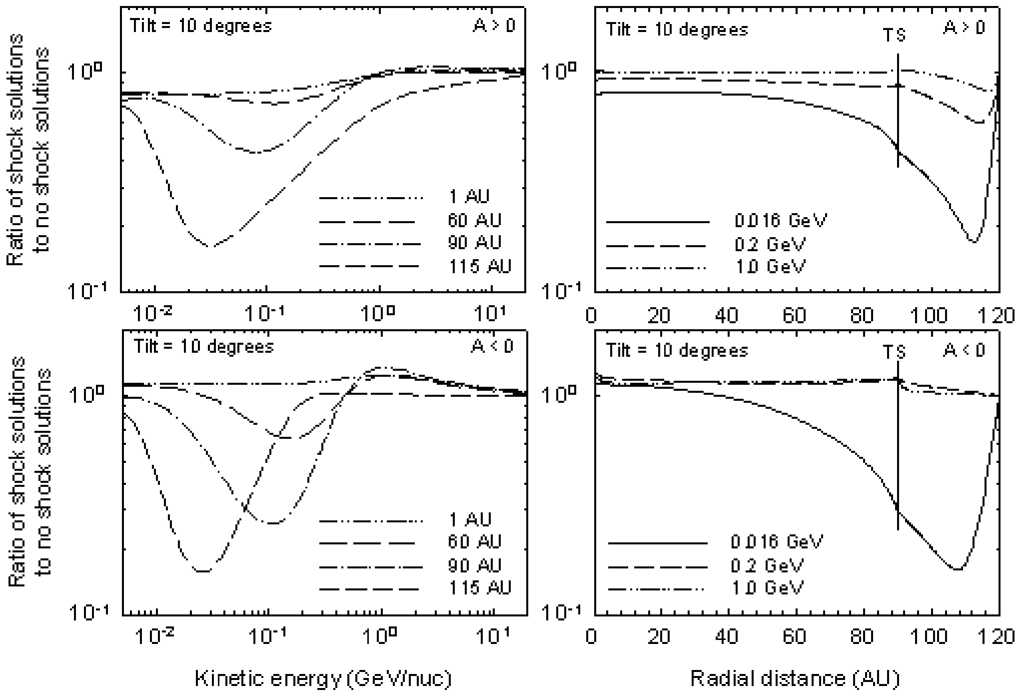

Fig. 3. Intensity ratios of solutions for He with a TS at 90 AU in the model compared to those without a TS as a function of kinetic energy at radial distances of 1, 60, 90 and 115 AU (left panels), and as a function of radial distance at energies of 0.016, 0.2 and 1.0 GeV (right panels) for both polarity cycles in the equatorial plane with α=10°.

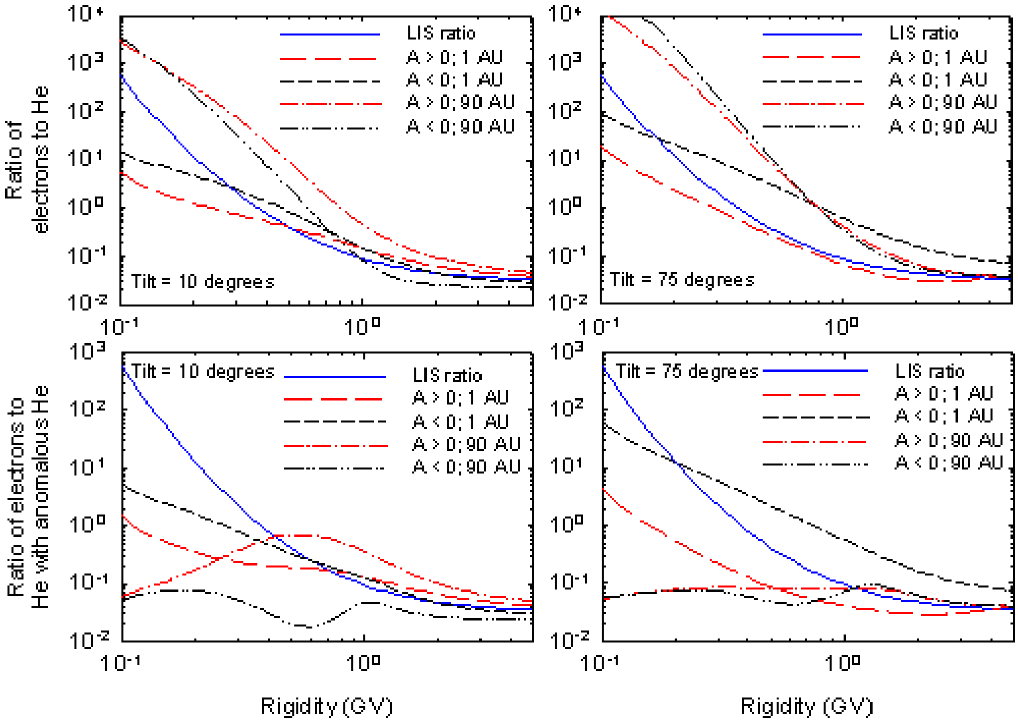

Fig. 4. Ratios e$^-$/He in the top two panels, and e$^-$/He (with an anomalous He component) in the bottom two panels as a function of rigidity in the equatorial plane at 1 AU and at 90 AU for both polarity cycles with α=10°(left panels) and α=75° (right panels), respectively. All ratios were computed with a TS at 90 AU and are compared with the LIS e$^-$/He ratio at 120 AU as a reference. The electron intensities used for the computations also contain a Jovian electron source at 5 AU.

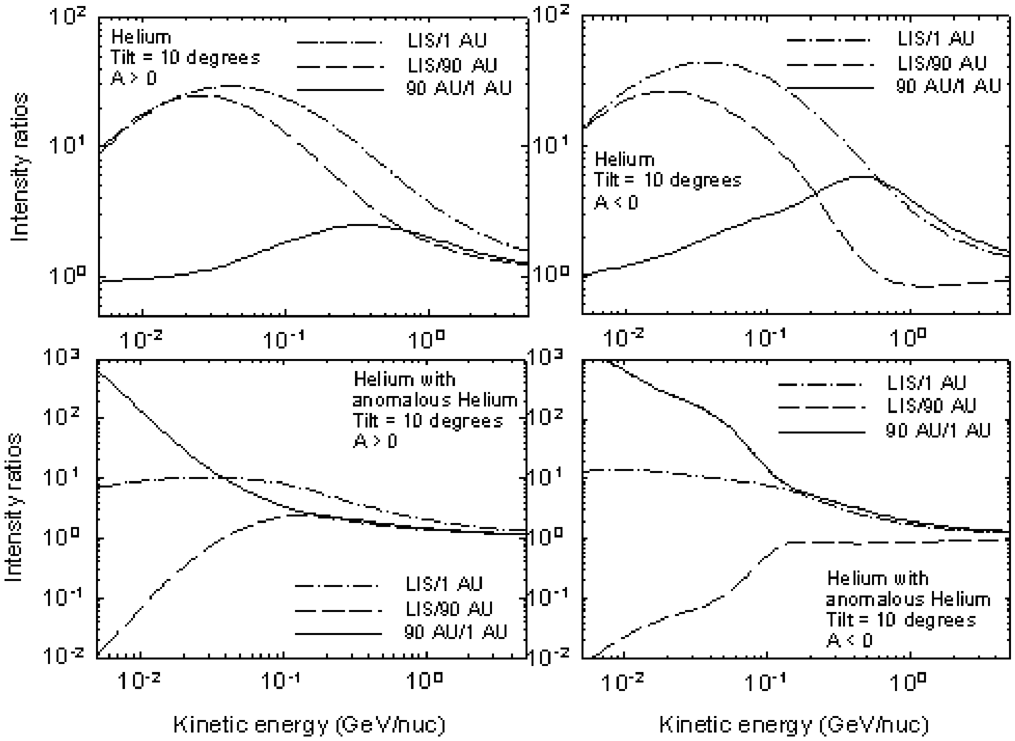

Fig. 5. Intensity ratios j_{LIS}/j_1, j_{LIS}/j_{90} and j_{90}/j_1 (120 to 1 AU, 120 to 90 AU and 90 to 1 AU) for galactic He and for He with an anomalous component as a function of kinetic energy in the equatorial plane with α=10°; shown in the left panels for $A>0$ and in the right panels for $A<0$. The LIS is specified at 120 AU and the TS is at 90 AU in the model.

for $r>\sim$50 AU is much larger in the $A<0$ cycle than for the $A>0$ cycle if α=10°. This is also true for α=75°, although the modulation then is also larger for the $A>0$ cycle than if α=10°. This effect is even more enhanced as the compression ratio decreases from s=3.2 to s=2.0. At $E\approx$60 MeV the cut-off energy of the anomalous He spectrum is quite evident for both values of α. The radial dependence of the 16 MeV intensity, that is shown in the right-hand panels, is consequently significantly different, but at higher energies the effect diminishes as the acceleration cut-off energy is approached. The "barrier" type modulation for this component at 16 MeV occurs inside the TS, and is not associated with the heliosheath, but occurring at smaller radial distances than have been predicted for protons, for example, for the $A>0$ cycle if α=10° this is evident from $\sim$40 AU already, while for the $A<0$ cycle the "barrier" effect disappears. This implicates that at these low energies a spacecraft should begin to observe a significant increase relatively far away from the TS for the $A>0$ cycle. These aspects will be shown more quantitatively in Fig. 5. Our results indicate that a compression ratio between 3.2 and 2.0 is preferred when anomalous He is also considered, and is consistent with the results that have been found for anomalous protons (Potgieter and Langner, 2003; 2004a). Clearly, a strong shock with s=4 is most unlikely.

The modulation in the heliosheath is clearly an important part of the total modulation for He, as shown in the right panels of Figs. 1 and 2. The TS plays in this respect a prominent role. For both species its effect becomes more pronounced the lower the energy. At higher energies, the "barrier" effect progressively diminishes; the radial dependence beyond the shock may vanish or even become negative, to create a conspicuous shock effect on the radial intensity profiles. This effect is strongly dependent on the HMF polarity cycles, and also on the level of drifts allowed beyond the TS. For an elaborate discussion on these effects for protons, see also Langner et al. (2003).

The differences between the solutions with and without a TS are evident when comparing the spectra in Fig. 1; these differences are emphasized in Fig. 3. Evidently, the effect of the TS on the modulation of galactic He with respect to the relevant LIS is significant. As mentioned above it decreases the intensities at lower energies but increases it at higher energies, as have been emphasized by the ratios in Fig. 3 which become larger than 1 for high energies. The differences between the two models can be significant, especially with $E<$100–300 MeV and $r>\sim$60 AU for both α=10° and 75°, similar to protons. For α=10° the ratios have the lowest values at 115 AU for $A>0$ at all energies, which indicates that the effect of the TS model is prominent at these larger distances. This is partly because of the assumed divergence free solar wind speed in the heliosheath region, causing the characteristic spectral slope which has been caused by adiabatic "cooling" to be steeper for the TS model if $r>\sim r_s$. The ratios at the different radial distances also have a minimum at a certain energy which becomes smaller as the radial distance increases, also related to the adiabatic "cooling" that these particles experience which tends to have the ratios converge to a steady value at low energies. Combined, these effects cause shifts in the minima of these ratios to lower energies, for increasing α and when the HMF polarity reverses.

The effect of the TS at Earth is not pronounced, as has been expected, although the inclusion of the TS in the model can evidently influence the modulation of He even at Earth at low energies. The galactic He intensities are lower at Earth at low energies with the TS than without it (this effect will, of course, not be observable because of the presence of anomalous He).

For the intensity ratios, e^-/He, and the e^-/He with anomalous He in Fig. 4, one can expect to see effects similar to those of e^-/p and e^-/p with anomalous protons (Potgieter and Langner, 2004b). At low energies He experiences large adiabatic energy losses while electrons do not, and in addition, electron modulation becomes progressively independent of drifts so that the e^-/He is a factor of $\sim$3000 for 100 MV at 90 AU. However, when the anomalous He component is added the e^-/He at 90 AU becomes significantly lower at low energies, for example, only 0.06 at 100 MV since the anomalous He dominates the galactic He intensities at these energies. The slight difference between the two cases at 1 AU indicates that anomalous He may reach the Earth. The crossover between the curves for the $A>0$ and $A<0$ polarity cycles for e^-/He evidently moves to lower rigidities with increasing radial distance, although this effect shifts to higher rigidities with increasing solar activity.

According to Fig. 5 a significant level of modulation occurs in the heliosheath for galactic He when $A>0$ with $E<\sim200$ MeV for solar minimum (α=10°) and for moderate solar maximum conditions (α=75°). This is also true for $A<0$ but at a somewhat lower energy. For α=75° the level of modulation in the heliosheath decreases significantly for $E>200$ MeV in contrast with that of j_{90}/j_1. This is also true for α=10° in the $A<0$ cycle and also to a lesser extent for the $A>0$ cycle. Obviously, all these ratios must converge at a high enough energy where no modulation is present.

The addition of the anomalous He component changes these ratios significantly for energies up to 1–2 GeV. The concept of "barrier" or heliosheath modulation, applicable to galactic cosmic ray (CR) species, changed when anomalous He (and protons) are considered. The heliosheath effects are still present at higher energies (rigidities), as the modelling indicates. Unfortunately, from an observational point of view clear indications of heliosheath modulation of galactic He (and protons) will be overwhelmed at low energies by the presence of the anomalous species. On the other hand, the presence of the anomalous particles should make the detection of the TS with particle detectors easier.

5 Conclusions

In this paper four aspects of heliospheric modulation for He were highlighted: (1) the differences in the modulation of galactic He and galactic He with anomalous He; (2) that the inclusion of a TS in the model altered this modulation and the consequent charge-sign dependence; (3) the kind of modulation effects to be expected near the TS and in the heliosheath; and (4) the effects of increased solar activity. Qualitatively, the results for He are similar to those of protons but there are quantitatively marked differences. These results confirm that this numerical model with a TS can reasonably reproduce the He modulation between the outer boundary and Earth; and for a variety of species as it has been illustrated in previous work (Langner et al., 2003; Langner and Potgieter, 2004; Potgieter and Langner, 2004b). Qualitatively, our results are consistent to those of Jokipii et al. (1993), but there are quantitatively marked differences; see also Fichtner (2001) and Stawicki et al. (2000). Although these results are most reasonable, it seems unavoidable that the diffusion coefficients should change time-dependently, together with the "tilt angle" and parameters like the compression ratio. These results indicate that a TS compression ratio between 3.2 and 2.0 is preferred when anomalous He is also considered. When these time-dependent parameters are better understood the detailed fitting of He observations will be undertaken.

The modulation for galactic He that has been produced with and without a TS differs significantly, depending on the HMF polarity. These differences increase towards lower energies and larger radial distances. The slight differences between the e^-/He and the e^-/He with anomalous He at 1 AU indicate that anomalous He may reach the Earth.

The heliosheath can be considered a distinguishable modulation "barrier" for galactic He with the overall effect clearly energy, polarity cycle and solar activity dependent, for example, most of the modulation may occur in the heliosheath for $E<\sim200$ MeV at solar minimum during $A<0$ cycles. This is, however, not true when the anomalous component is taken into account. From the TS model it is clear that the increases in galactic and anomalous CRs that a spacecraft like Voyager 1 may observed up to the TS could be followed by a period of almost no modulation (very little or even negative radial gradients) towards the heliopause because of the dominance of the anomalous He source, so that the bulk of modulation then takes place between the TS and 1 AU. These results indicate that the LIS for galactic He may not be known at $E<\sim$ 200 MeV until a spacecraft actually approaches the heliopause because of the TS and the subsequent presence of anomalous He, unless a clever analysis of anisotropy measurements could be used to distinguish between an inner and outer He source.

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