doi:10.1088/0004-637X/735/2/128

ON COSMIC RAY MODULATION BEYOND THE HELIOPAUSE: WHERE IS THE MODULATION BOUNDARY?

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Received 2011 April 8; accepted 2011 April 27; published 2011 June 24

ABSTRACT

Two of the paradigms in modeling the transport of galactic cosmic rays are that the modulation boundary is the heliopause and that the local interstellar spectra are identical to the galactic cosmic ray spectra. Here we demonstrate that the proton spectrum is already modulated due to an altered interstellar diffusion in the outer heliosheath as a consequence of the heliospheric "obstacle" in the interstellar flow. The main modulation effect however is adiabatic energy losses during a "confinement time" of cosmic rays inside the heliosphere.

Key words: acceleration of particles – astroparticle physics – plasmas – shock waves – Sun: heliosphere

Online-only material: color figures

1. INTRODUCTION

One of the paradigms of modeling cosmic ray transport in the heliosphere is that the local interstellar spectrum (LIS) is modulated only inside the heliopause, i.e., the contact discontinuity between the solar wind and the interstellar medium (ISM; for heliospheric models see, e.g., Zank 1999; Borrmann & Fichtner 2005; Ferreira et al. 2007; Müller et al. 2008; Florinski & Pogorelov 2009).

All corresponding transport models, those assuming a spherical heliosphere (e.g., Potgieter 2008; Hitge & Burger 2010; Strauss et al. 2010), an aspherical heliosphere (Langner & Potgieter 2005; Ngobeni & Potgieter 2011), and those taking into account two- or three-dimensional plasma flows (e.g. Scherer & Ferreira 2005; Langner et al. 2006a, 2006b; Ferreira et al. 2007; Florinski & Pogorelov 2009; Borovikov et al. 2011), consider the heliopause as the modulation boundary for cosmic rays.

There are several reasons, however, why the modulation boundary cannot be identical with the heliopause.

1. On the scale of the heliosphere (i.e., several hundred AU) the cosmic ray diffusion cannot be expected to be isotropic because of the ordered local interstellar magnetic field (see Figure 5 and the related discussion below).
2. This magnetic field is, however, not homogeneous but wrapped around and piling up in front of the "obstacle" heliosphere, resulting in an effective increase in the local field strength and turbulence.
3. If a bow shock exists, it should further enhance the turbulence in the outer heliosheath (OHS), i.e., the region of the disturbed interstellar flow beyond the heliopause. Note that a bow shock with a spatially varying compression ratio can only form in the upwind hemisphere.
4. The lower diffusion coefficients in the heliosphere imply an increased confinement time in the heliosphere, during which the cosmic ray particles are efficiently cooled, as will be discussed in detail below.

The second paradigm claims that the LIS is everywhere on the modulation boundary identical to the galactic spectrum for a given species. This, however, might not be the case because of a scale-dependently structured interstellar magnetic field, enhanced turbulence, and local cosmic ray sources.

Here we concentrate on the OHS modulation for a given LIS and only briefly discuss the potential spatial variation of the LIS.

2. THE OUTER HELIOSHEATH

2.1. *The Structure of the OHS*

The OHS is the region of the disturbed interstellar flow beyond the heliopause, regardless whether a bow shock exists or not. The best evidence for the existence of the OHS is the hydrogen wall observed in Lyα features (Müller et al. 2001; Wood et al. 2007; Quémerais et al. 2010). The hydrogen wall is the consequence of a disturbed charge exchange equilibrium caused by the deviation of the interstellar plasma flow around the obstacle heliosphere (e.g., Müller et al. 2008). Rather than considering a complex structure of the OHS, as discussed by various authors (Opher et al. 2006; Pogorelov et al. 2009; Izmodenov et al. 2005) particularly in connection with the recent *Interstellar Boundary EXplorer* (*IBEX*) observations (McComas et al. 2009b; Schwadron et al. 2009), we restrict ourselves to a simplified consideration concentrating on the principal effects. To do so, we employ a spherical model with an effective scalar diffusion coefficient in the OHS. We do, however, discuss the expected consequences of using more realistic models.

2.2. *Diffusion in the OHS*

As opposed to the ISM, the assumption of isotropic spatial diffusion cannot be defended for the OHS because, obviously (Figure 5), the interstellar magnetic field is ordered on scales of a few hundred AU. As can clearly be seen from the figure, the cosmic rays reach the heliopause mainly by perpendicular rather than parallel diffusion. Assuming a typical interstellar isotropic diffusion coefficient $\kappa_{\rm ISM} = 3 \times 10^{28}\,{\rm cm}^2\,{\rm s}^{-1}$ (e.g., Büsching & Potgieter 2008) and a typical ratio of perpendicular to parallel diffusion of $\kappa_\perp/\kappa = 0.02$ (Giacalone & Jokipii 1999; Shalchi et al. 2010) as well as an averaging over one parallel and two perpendicular directions, one obtains $\kappa_{\rm ISM} = \kappa/3 + 2\kappa_\perp/3$ from which follows $\kappa \approx 9 \times 10^{28}\,{\rm cm}^2\,{\rm s}^{-1}$ and $\kappa_\perp \approx 2 \times 10^{27}\,{\rm cm}^2\,{\rm s}^{-1}$. Moreover, the diffusion coefficient in the ISM, $\kappa_{\rm ISM}$, is also not well known: values—depending on energy—in the range between 10^{26} and $10^{30}\,{\rm cm}^2\,{\rm s}^{-1}$ (Aharonian et al. 2006; Ptuskin et al. 2006; Büsching & Potgieter 2008) are discussed.

Considering only the turbulence convected with the ISM across the bow shock—using the traditional conservation

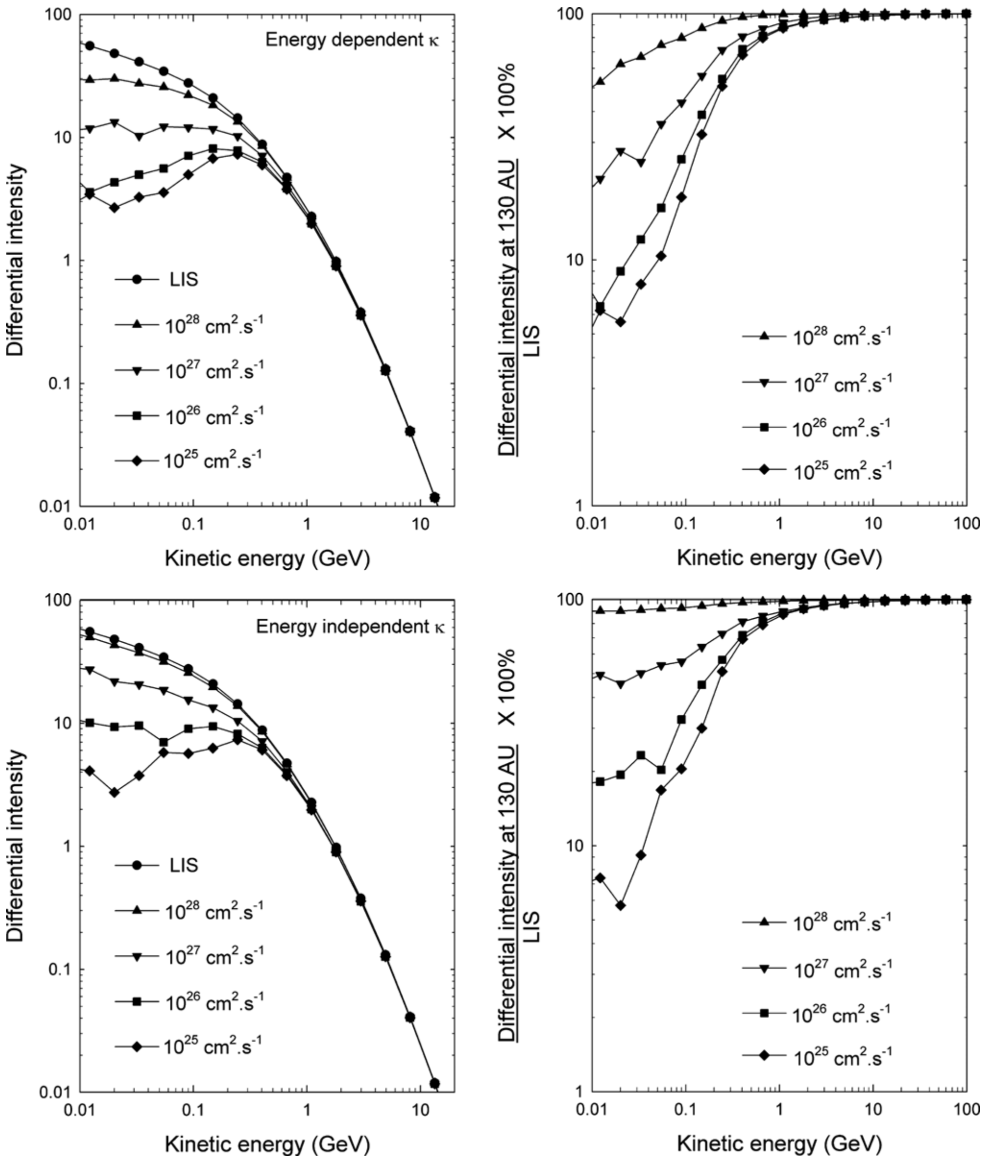

Figure 1. Local interstellar proton spectrum (LIS) upstream of the bow shock and the modulated heliopause spectra (upper left panel) for energy-dependent diffusion in the OHS with four different diffusion coefficients $\kappa_{\rm OHS}(1\,{\rm GV})$. The differential intensity is given in units of $1/({\rm m}^2\ {\rm s\ sr\ MeV})$. The upper right panel shows the spectra normalized to the LIS. The position of the termination shock is 100 AU, that of the heliopause is 130 AU, and that of the bow shock is 250 AU. The diffusion coefficient in the IHS is lowered by a factor of 10 compared to that inside the termination shock. The two lower panels show the same for an energy-independent diffusion coefficient in the OHS. It can be seen that an unrealistic energy-independent diffusion reduces the OHS modulation, but cannot prevent it.

laws—gives an increase of the downstream turbulence levels by factors of 2–3 (Chashei & Fahr 2005). In addition, the plasma passing over the bow shock converts into an anisotropic ion distribution which is unstable with respect to mirror modes or firehose instabilities. This anisotropic distribution function is isotropized to a marginally stable distribution, and during that process turbulent energy is produced, which in the case of a quasi-perpendicular shock amounts to 2/3 of the downstream thermal energy (Fahr & Siewert 2009), leading to a total increase of turbulence levels of a factor four. Thus, one can assume a further decrease of the perpendicular diffusion coefficient to $\kappa_\perp \approx 5\times10^{25}$ cm^2 s^{-1}.

3. MODEL RESULTS

The basis of the model is the Parker transport equation for the omnidirectional distribution function $\boldsymbol{f} = \boldsymbol{f}(r, P, t)$ with location r, the rigidity P, and time t:

$$\frac{\partial f}{\partial t} = -v\cdot\nabla\boldsymbol{f} + \nabla\cdot(\overleftrightarrow{\kappa}\,\nabla\boldsymbol{f}) + \frac{1}{3}(\nabla\cdot v)\frac{\partial f}{\partial \ln P}\,, \qquad (1)$$

where v is the solar wind velocity and $\overleftrightarrow{\kappa}$ is the diffusion tensor. The first term on the right-hand side describes convection, the second one diffusion, and the third one adiabatic energy changes.

Rather than investigating the cosmic ray transport in the actual complex magnetic field shown in Figure 5 or the even more complicated situation including a bow shock, in this first approach we study the significance of modulation in the OHS using a spherical model heliosphere with a scalar energy-dependent diffusion coefficient in the OHS:

$$\kappa_{\rm OHS}(P) = (P/1\,{\rm GV})\kappa_{\rm OHS}(1\,{\rm GV}) \qquad (2)$$

and for comparison, an energy-independent one.

In view of the above discussion, the four cases $\kappa_{\rm OHS}(1\,{\rm GV}) \in \{10^{25}, 10^{26}, 10^{27}, 10^{28}\}$ cm^2 s^{-1} will be considered. The latter case is analogous to the assumption that the diffusion coefficient

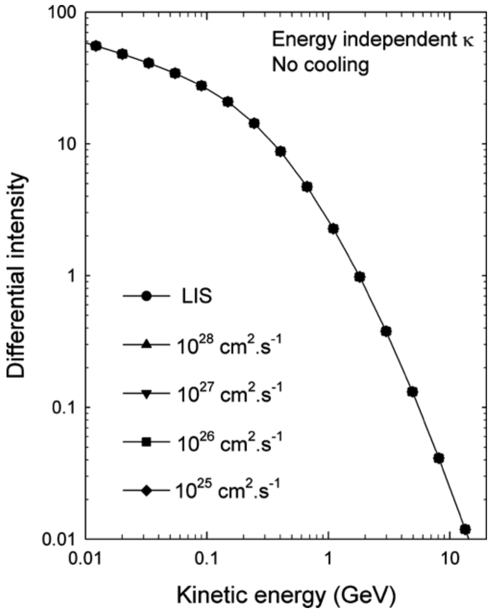

Figure 2. Same as in Figure 1 (with the differential intensity in units of $1/(\mathrm{m}^2, \mathrm{s\ sr\ MeV}))$, but here the adiabatic term in the inner heliosphere is set to zero. It is seen that the interstellar spectrum in the OHS is not modulated (all spectra lie on top of each other). Thus the confinement time of the particles inside the heliosphere is essential for the modulation in the outer heliosheath.

in the OHS is not modified, i.e., is equal to the interstellar scalar diffusion coefficient. We include the first case as an extreme. Our spherical model heliosphere has a bow shock radius of 250 AU, a heliopause at 130 AU, and a termination shock at 100 AU. Inside the OHS we study only diffusion/convection effects, while inside the termination shock we allow additionally for adiabatic losses, i.e., cooling effects. Between the termination and bow shock, the plasma flow is to a good approximation incompressible and, therefore, divergence-free, implying vanishing adiabatic energy changes. Furthermore, the diffusion coefficient in the inner heliosheath (IHS), the region between the termination shock and the heliopause, can be reduced by a factor of 2–10 (McDonald et al. 2002; Scherer & Ferreira 2005; Florinski & Pogorelov 2009). We consider the extreme case, i.e., a reduction by a factor of 10 for our reference model, but also study a different one below.

To model the transport we employ the backward stochastic differential equation (SDE) model described by Strauss et al. (2011). Note that the SDE description of cosmic ray transport is analogous to the well-known models solving the transport equation (Pei et al. 2010) and the kinks in the curve presented in Figure 1–2 are caused by the statistic nature of the SDEs. At the outer boundary a proton LIS must be specified, which in our case is that given by Webber & Higbie (2003).

The model results are presented in the upper panels of Figure 1.

3.1. Modulation in the OHS

Figure 1 (upper panels) reveals a significant modulation of the LIS in the OHS below about 1 GeV for all considered κ_{OHS}. Even for the interstellar value $\kappa_{\mathrm{OHS}}(1\,\mathrm{GV}) = 10^{28}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$, a 20% effect can be seen for 100 MeV protons increasing to 50% for 10 MeV protons. For the other three cases the modulation is stronger.

All four curves in the upper right panel manifest the modulation in the OHS. Surprisingly, even without any change of the diffusion coefficient from the undisturbed ISM to the OHS, a modulation of the LIS is evident. This indicates that the modulation is the consequence of a confinement effect: the particles entering the heliosphere (see below) are kept there for an extended period during which they are cooled, before they return to the OHS, i.e., particles leave the heliosphere with lower energy than when they entered it. This confinement/cooling effect is the dominant OHS modulation effect. In the following two subsections we test this hypothesis by studying the effectiveness of diffusion and cooling in different regions, including the IHS.

After the particles have returned to the OHS they have lower energies and hence also experience lower diffusion according to Equation (2). A lower diffusion coefficient allows for a more effective scattering, which means the probability for the particles to re-enter the heliosphere is increased. (Actually, using the backward SDEs, the (pseudo-)particles start at a given observation point and leave the system backward in time.) Therefore, a lower OHS diffusion coefficient forces the spectrum at the heliopause to lower values. Nevertheless, using the same diffusion coefficient in the OHS than in the ISM, still some particles enter the heliosphere and are modulated, lowering the spectrum at the heliopause.

Interestingly, the cosmic ray spectrum at the heliopause shows the expected turnover to lower energies (Strong et al. 2000; Langner et al. 2003; Ptuskin et al. 2006), while that at the bow shock increases toward lower energies.

3.2. The Significance of Adiabatic Cooling in the Heliosphere

To determine the actual modulation process in the OHS we used an energy-independent diffusion coefficient κ_{OHS}, leading to the results shown in the lower panels of Figure 1. It can clearly be seen that the effect of the OHS modulation remains, but is less pronounced, because particles, which entered the heliosphere and lost some energy, experience the same diffusion in the OHS as before the energy loss. Therefore, their scattering behavior is unchanged in the OHS, reducing the modulation effect. As before, even if κ_{OHS} equals the interstellar diffusion coefficient, a moderate modulation is still observed.

Additionally, we switched off the adiabatic energy losses in the heliosphere. The result of this is shown in Figure 2. It can clearly be seen that no modulation takes place at all. That means all particles are only scattered inside the heliosphere, but are not losing any energy, and therefore the spectrum between the heliopause and the bow shock is not changed.

This latter test case clearly demonstrates that the modulation in the OHS is caused by the cooling or adiabatic energy losses inside the heliosphere. Moreover, even for the unrealistic case of energy-independent diffusion coefficients κ_{OHS}, the adiabatic energy losses inside the heliosphere result in the dominant modulation effect in the OHS. Next, we study possible effects of the IHS on the OHS modulation.

3.3. Effects of the Inner Heliosheath

As stated above, the divergence in the IHS is negligible or at least small. Nevertheless, the production of pick-up ions leads to a varying proton density in the IHS (e.g., Fahr et al. 2000). To take this effect or the not yet well-understood plasma features (e.g., very low proton temperatures behind the shock; Richardson et al. 2008) into account, we now allow for adiabatic energy losses in the IHS, i.e., for flow with non-zero divergence. The result is shown in Figure 3, where the ratios of the different κ_{OHS} to those of our main results (upper panel of Figure 1) are presented. The effect increases

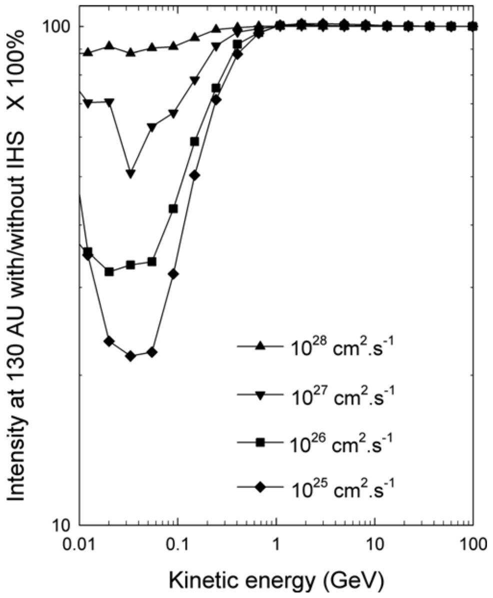

Figure 3. Ratio of the spectra of the reference model to one with an adiabatic cooling in the IHS. As expected, a larger region, where energy losses can appear, increases the OHS modulation.

the OHS modulation by 10%–50%, i.e., ratios are smaller than 1, as one would expect by increasing the region where adiabatic losses take place, and decreasing the region of divergence-free flows to the OHS only. Because it is not well known how large the adiabatic heating in the IHS is, this scenario gives an upper limit for the effectivity of the OHS modulation for our models.

Finally, we increased the diffusion coefficient in the IHS to the value upstream of the termination shock (not shown). This variation leads to a reduction of the modulation effect of a few percent because now the scattering in the IHS is reduced.

For an illustration, Figure 4 shows two examples of particle trajectories. Thus, we can conclude that the OHS modulation is effective, and none of our tests, except that one with no cooling everywhere, could prevent or reduce the OHS modulation significantly.

4. ON THE ISOTROPY OF THE LIS

So far we have shown that a cosmic ray modulation in the OHS takes place. Nevertheless, inspecting Figure 5 (taken from Chalov et al. 2010) shows that the interstellar magnetic field is ordered on scales of hundreds of AU to possibly several parsec (Amenomori et al. 2011). This is the currently favored principal configuration supported by energetic neutral atom measurements with the *IBEX* spacecraft (McComas et al. 2009a). In such a field configuration, the diffusion can no longer be assumed to be scalar, but is dependent on the direction of the magnetic field, i.e., the parallel diffusion along the field lines is larger than that perpendicular to it by a factor of 30–50 (Giacalone & Jokipii 1999; Potgieter 2008; Shalchi et al. 2010) as discussed above. Thus, again from Figure 5 it is evident that at some regions of the heliopause the particles from the interstellar space diffuse along the field lines to it, while in other place they have to diffuse perpendicular to it. Thus, the LIS can vary along the heliopause. Additionally, because the field lines are draped around the obstacle "heliosphere," at some positions an enhancement and at others a decrease of the magnetic field strength takes place. This can also alter the turbulence, and hence at those locations the LIS can be affected. What this discussion shows is that a more realistic heliosphere must be included in our model to treat the spatial inhomogeneities of the LIS.

Taking into account a bow shock, as discussed in Sections 1 and 2, will complicate the situation even further, because all models including a bow shock show that the compression ratio approaches unity toward the heliospheric poles, where the bow shock vanishes. Thus, the turbulence generated by the passing of the local ISM (LISM) plasma flow over the bow shock is latitude dependent, and any LIS will be modulated differently in latitude.

One can even drop our assumption that the LIS is not modulated beyond the bow shock, because the same arguments apply, i.e., particles can diffuse beyond the bow shock, but still experience adiabatic energy losses inside the heliosphere. These complications will be the subject of future work.

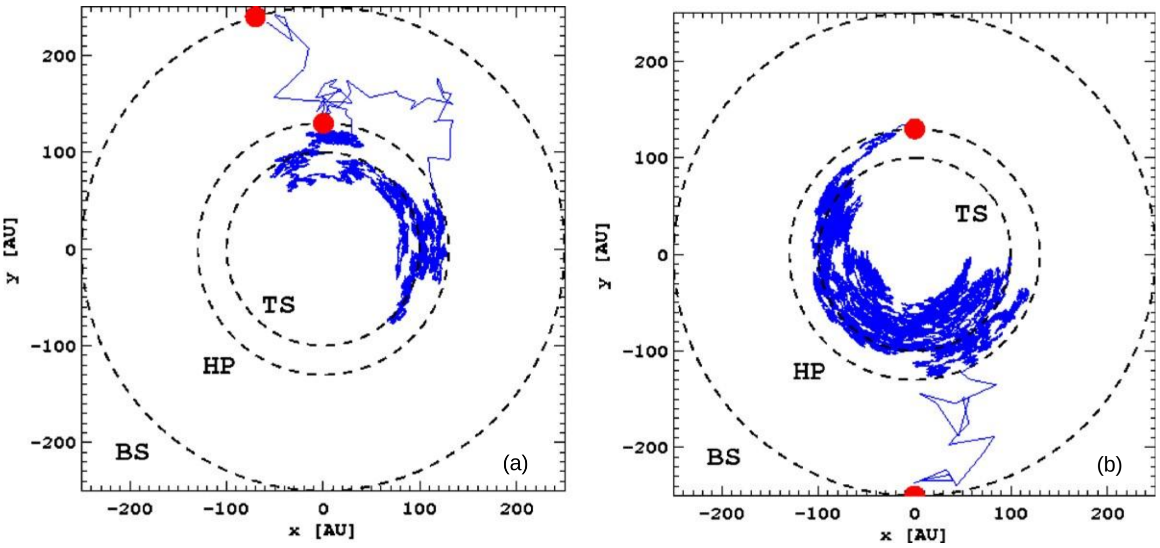

Figure 4. Trajectories of 100 MeV particles for $\kappa_{\rm OHS}(1\,{\rm GV}) = 10^{26}\ {\rm cm}^2\ {\rm s}^{-1}$. It is easily seen that these particles are confined for an extended period inside the heliosphere. The dotted circles are the assumed bow shock (BS at 250 AU), heliopause (HP at 130 AU), and termination shock (TS at 100 AU) distances. Some of the particles are re-entering the OHS multiple times (panel (a)) before they are "observed" at 130 AU, while others penetrate deep into the heliosphere (panel (b)).

(A color version of this figure is available in the online journal.)

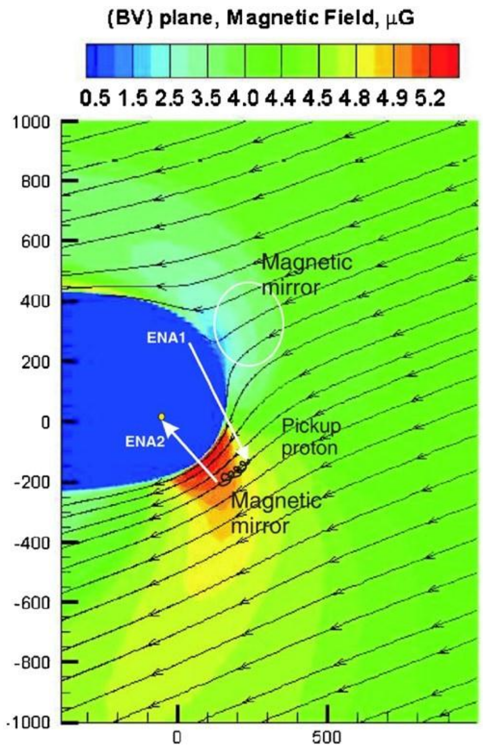

Figure 5. Spatial distribution and direction of the interstellar magnetic field in the LISM and OHS (taken from Chalov et al. 2010). The distances on the *x*- and *y*-axes are given in AU. Indicated are the energetic neutral atoms (ENAs, observed by the *IBEX* mission; McComas et al. 2009a) from which information about the magnetic field is deduced.

(A color version of this figure is available in the online journal.)

5. CONCLUSION AND DISCUSSION

We have proven that the LIS is already modulated in the OHS, i.e., the region of disturbed ISM flow (if present inside the bow shock). This modulation has two main causes, namely, (1) a modified diffusion in the OHS and (2) a confinement/cooling of particles in the heliosphere. To the best of our knowledge, these modulation effects have not been discussed before, especially not the effect of particle confinement in the heliosphere. Note that this confinement has to be distinguished from the extended so-called residence times of energetic particles in the IHS (Florinski & Pogorelov 2009) and also from the re-entering of particles from the OHS as has been studied by Bobik et al. (2008).

Our reference model shows the bending of the cosmic ray spectrum at the heliopause, discussed in the literature (e.g., Strong et al. 2000; Langner et al. 2003; Ptuskin et al. 2006; Herbst et al. 2010) as the heliopause LIS. According to our model, the spectrum at the heliopause unbends outward until it reaches our “true” LIS at the bow shock. According to our model, one would expect a galactic cosmic ray proton spectrum to increase toward small energies while other authors (e.g., Webber & Higbie 2009) propose such a spectrum at the heliopause.

Even though we have used simplified descriptions of the heliosphere, OHS, and corresponding transport, we have demonstrated that the new modulation effects are significant. Therefore, they deserve a more detailed modeling that incorporates the complex magnetic field (Figure 5) and the even more complicated situation including a bow shock as well as an extended heliotail.

Beyond the heliospheric application, these considerations are also relevant for cosmic ray transport on galactic scales, when taking into account inhomogeneities of the turbulent galactic magnetic field. The latter is likely to contain regions of locally altered diffusion coefficients acting as traps (e.g., Kryvdyk 2003) similar to the heliosphere as discussed above.

H.F. and K.S. are grateful to the Deutsche Forschungsgemeinschaft for funding the Heliocauses project and to the Bundesministerium für Forschung und Bildung for supporting the South Africa-German Collaboration (SUA 08/011). R.D.S., S.E.S.F, and M.S.P acknowledge the partial financial support of the SA National Research Foundation under the SA-German Research Cooperation Programme.

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