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Cosmic ray transport in the heliosphere and its connection to the interstellar proton spectrum

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Abstract. In recent years one could witness tremendous progress regarding the physics of the transport of cosmic rays (CRs) in the heliosphere. This progress derives from both theoretical advances and new measurements from the outer boundary region of the heliosphere. At the same time theory and observations give new constraints on the local interstellar CR spectra. The review describes the new data, ideas and corresponding developments that extend the previously merely conceptual link to an actual physical link between the heliospheric and interstellar transport of CRs.

Key words. Cosmic Rays – Heliosphere – Interstellar Spectrum

1. Introduction

For many years the study of the heliospheric transport of cosmic rays (CRs) has provided valuable insights into fundamental astrophysical processes. The concepts worked out at and tested for the heliosphere have been transferred very successfully to other, not directly accessible astrophysical systems like supernova and stellar wind termination shocks or the interstellar medium (ISM). In view of recent measurements of the boundary region of the heliosphere with the Voyager spacecraft and the Interstellar Boundary Explorer (IBEX), especially the conceptual link between the CR transport in the heliosphere and in the ISM is growing into a physical link. This is because it has become evident that both astrophysical systems should not be treated as completely separated media but rather as multifacetedly interconnected, particularly also with respect to the CR transport.

In this brief review we first summarize the state of the art in heliospheric CR transport and motivate a re-formulation of the tensor of spatial diffusion (section 2). After that we turn to the heliosphere-ISM link via CRs by discussing the heliospheric and astrospheric contribution to the interstellar proton spectrum (IS, section 3) and the modulation of the latter even in the region beyond the he-

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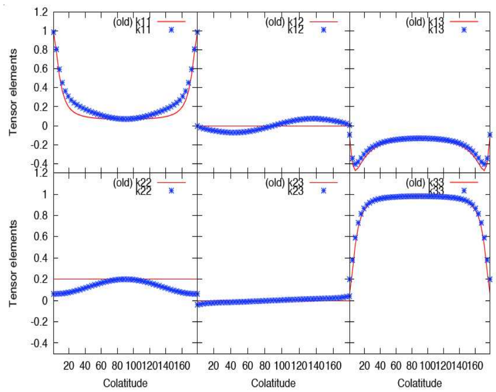

Fig. 1. Comparison of the 'classical' (solid lines) and 'Frenet-Serret' tensor elements (symbols) according to Eq. (3) and Eq. (4), respectively, for the heliospheric Parker field. The results are shown at 10 AU for $\kappa_{\perp 1} = 0.05\kappa_{\|}$ and $\kappa_{\perp 2} = 0.2\kappa_{\|}$, i.e. $\kappa_{\perp 2}/\kappa_{\perp 1} = 4$. Such ratios are found for Jovian electrons (Ferreira et al. 2001).

liosphere's outer boundary, i.e. beyond the heliopause (section 4). We summarize in the final section 5.

2. The state of the art in (diffusive) heliospheric CR transport

2.1. Basic theory: the present paradigm

As long as one can neglect anisotropies of the phase space distribution of CRs in momentum space, their transport can be described with the following equation (see, e.g., Berezinskii et al. 1990; Schlickeiser 2002; Shalchi 2009) for the omnidirectional distribution $f(\boldsymbol{r}, p, t)$ being a function of location $\boldsymbol{r}$, momentum p, and time t:

$$\begin{aligned}\frac{\partial f}{\partial t} &= \nabla\cdot\left[\overset{\leftrightarrow}{\kappa}_G \nabla f\right] + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D \frac{\partial f}{\partial p}\right] \\ &- \boldsymbol{u}\cdot\nabla f + \frac{p}{3}(\nabla\cdot\boldsymbol{u})\frac{\partial f}{\partial p} + S(\boldsymbol{r}, p, t)\end{aligned} \quad (1)$$

with the anisotropic spatial diffusion tensor $\overset{\leftrightarrow}{\kappa}_G$ $(\boldsymbol{r}, p, \boldsymbol{B}(t))$, the scalar momentum diffusion coefficient $D(\boldsymbol{r}, p, \boldsymbol{B}(t))$, a convection and drift velocity $\boldsymbol{u}(\boldsymbol{r}, t)$, adiabatic energy changes $\nabla\cdot\boldsymbol{u}$, and sources $S(\boldsymbol{r}, p, t)$.

In many cases momentum diffusion can be neglected (but see section 3 below) and the remaining key transport quantity is the diffusion tensor, which reads in a local magnetic field-aligned coordinate system

$$\overset{\leftrightarrow}{\kappa}(\boldsymbol{r}, p, t) = \begin{pmatrix} \kappa_{\perp 1} & \kappa_{xy} & 0 \\ \kappa_{yx} & \kappa_{\perp 2} & 0 \\ 0 & 0 & \kappa_{\|} \end{pmatrix} \quad (2)$$

and whose off-diagonal elements vanish for axisymmetric turbulence and zero magnetic helicity (Stawicki 2005; Weinhorst et al. 2008). The coefficients parallel to the local magnetic field $\boldsymbol{B}$ can be determined using quasilinear theory, the derivation of the perpendicular ones requires nonlinear approaches (for a recent review see Shalchi 2009). While most often the perpendicular diffusion is considered to be isotropic ($\kappa_{\perp 1} = \kappa_{\perp 2}$), there is observational (e.g., Ferreira et al. 2001), modelling (Tautz et al. 2011), and theoretical evidence (Jokipii 1973; Weinhorst et al. 2008) that this is not true for cases where the magnetic field is not homogeneous.

Numerous successful applications investigating various aspects of heliospheric CR transport have confirmed the validity of the above transport equation as well as its completeness regarding the major physical processes (Fisk 1999). There are, however, still unanswered questions regarding the exact dependence of some processes on the underlying magnetic field turbulence, like the particle drifts (Burger & Visser 2010) or the spatial diffusion tensor (Shalchi 2009). We discuss one example for the latter in the following section.

2.2. The fully anisotropic diffusion tensor

As stated above, there is evidence that the diffusion tensor is fully anisotropic in an inhomogeneous magnetic field. If so, the choice of the orientation of the 'perpendicular' axes along which spatial diffusion is described by $\kappa_{\perp 1}$ and $\kappa_{\perp 2}$ is important and a corresponding formulation of the diffusion tensor must contain this information. In the, so far, most general representations of the diffusion tensor this is not the case (see, e.g. Kobylinski 2001; Burger et al.

2008). In this ‘classical’ approach the unit vector $\boldsymbol{e}_\vartheta$ (spherical polar coordinates) is chosen to determine one of the ‘perpendicular’ axes. This orientation is, however, not related to the field inhomogeneity. Thus, the question arises as to which coordinate system to choose?

The most natural directions are related to the curvature and torsion of a magnetic field and are provided by the Frenet-Serret trihedron defined by a tangential, normal and binormal unit vector given by $\boldsymbol{t} = \boldsymbol{B}/B$, $\boldsymbol{n} = (\boldsymbol{t}\cdot\nabla)\,\boldsymbol{t}/k$ and $\boldsymbol{b} = \boldsymbol{t}\times\boldsymbol{n}$, respectively, where k denotes the curvature. These vectors determine the transformation of the local tensor $\overleftrightarrow{\kappa}$ given in Eq. (2) to $\overleftrightarrow{\kappa}_G$ in the global frame required in Eq. (1). For the heliospheric magnetic field (archimedean spiral, Parker 1958) one obtains with the ‘classical’ choice the principal form

$$\overleftrightarrow{\kappa}_{G,cl} = \begin{pmatrix} \kappa_{\perp r} & 0 & \kappa_{r\phi} \\ 0 & \kappa_{\perp\theta} & 0 \\ \kappa_{r\phi} & 0 & \kappa_{\|} \end{pmatrix} \tag{3}$$

while it reads

$$\overleftrightarrow{\kappa}_{G,FS} = \begin{pmatrix} \kappa_{\perp r} & \kappa_{r\theta} & \kappa_{r\phi} \\ \kappa_{r\theta} & \kappa_{\perp\theta} & \kappa_{\theta\phi} \\ \kappa_{r\phi} & \kappa_{\theta\phi} & \kappa_{\|} \end{pmatrix} \tag{4}$$

when using the Frenet-Serret-trihedron. In Eq. (3) and Eq. (4) the tensor elements are functions of heliocentric distance and heliolatitude. A comparison of these elements at 10 AU vs. heliolatitude (Fig. 1) reveals that there are not only new non-zero elements but also that the new transformation results in significant differences between the ‘classical’ and the ‘Frenet-Serret’-elements.

The new diffusion tensor is presently implemented into a model of heliospheric modulation in order to explore whether the effects are significantly influencing conclusions regarding the strength and variation of perpendicular diffusion as obtained from comparisons of earlier numerical simulation results with observations.

3. Astrospheric contributions to the interstellar proton spectrum

Contrary to earlier expectations recent measurements with the Voyager spacecraft have revealed the inefficiency of diffusive acceleration at the solar wind termination shock (Stone et al. 2005) and, at the same time, the potential significance of momentum diffusion for the acceleration of CRs (Ferreira et al. 2007). Both spacecraft have crossed the solar wind termination shock and are now exploring the so-called (inner) heliosheath, i.e. the region between the shock and the heliopause. The latter is the contact discontinuity that separates the solar wind and the interstellar plasma.

The implication of these findings are not only that diffusive shock acceleration – while being important at energies up to a few MeV (le Roux & Webb 2009) – does not operate as expected at least for the only stellar wind termination shock that could ever be observed in-situ, but also that the source region of the so-called anomalous CRs (ACRs, Fichtner 2001; Panasyuk 2005) could be located closer to the heliopause (see, e.g., Fisk & Gloeckler 2009). This idea is nurtured by the observation of increasing ACR intensities beyond the shock towards the heliopause (Fig. 2, left panel) and the successful modelling of modulated spectra using both diffusive shock acceleration and momentum diffusion (Fig. 2, right panel).

Given that the observed intensity of ACRs in the heliosheath is easily a factor of ten higher than what had been expected if only diffusive shock acceleration were taking place, one has to re-consider the contribution of these particles to the IS at energies below about 1 GeV. This has been done by Scherer et al. (2008) who, first, estimated the heliospheric contribution and, second, the total astrospheric contribution of ACRs to the IS by all solar-type stars (Fig. 3). Obviously, the anomalous protons – which are accelerated out of a pool of suprathermal pick-up ions that originate from an ionisation of originally interstellar neutral hydrogen atoms convecting into the heliosphere – represent the dominant contribution to the IS below 25 MeV for the heliosphere and below about 100 MeV for the selected astrosphere. Higher values are to be expected for more extreme states of the ISM around astrospheres of solar-type stars (Müller et al. 2006; Scherer et al. 2006). These astrospherically induced interstellar spectra will be modified by

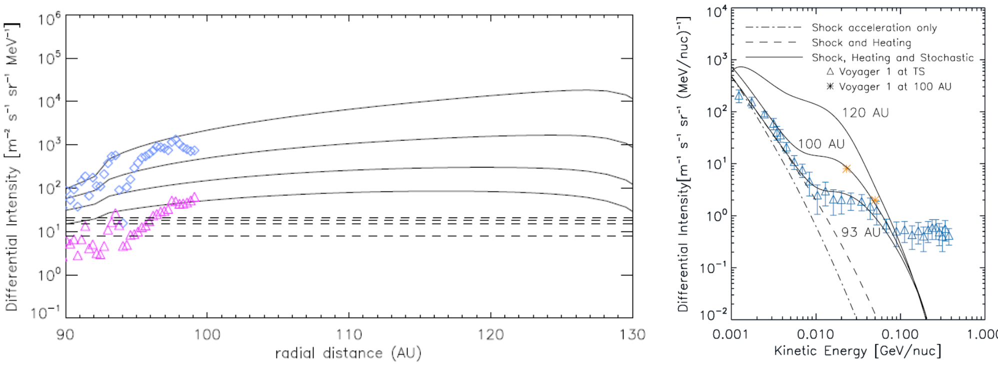

Fig. 2. Left panel: Model spectra and Voyager 1 data in the heliosheath with a heliopause at 130 AU: The dashed lines describe (bottom to top) the IS values at 5, 10, 15, and 20 MeV and the solid lines are the corresponding ACR fluxes. The triangles and diamonds are the 18-27 MeV and 4-6 MeV proton data (taken from Scherer et al. 2008). Right panel: Computed spectra for singly ionized anomalous helium at the termination shock (93 AU) for three acceleration scenarios, namely diffusive shock acceleration (DSA) only (dashed-dotted line), DSA and adiabatic heating (dashed line), and DSA, heating in the inner heliosheath and stochastic acceleration (solid lines). The latter case is shown at the shock (bottom solid line), at 100 AU and at 120 AU (top solid line). The Voyager 1 spectra from 16 to 23 January 2005 at the termination shock are shown as the triangles (taken from Ferreira et al. 2007).

interstellar propagation effects. In particular, the low-energy particles can undergo stochastic acceleration and, therefore, can easily contribute to the flux up to 1 GeV.

Given (i) that there are about 10^{11} F, G, and K (solar-type) stars – representing about one quarter of all stars in the Galaxy –, (ii) that the energization of ACRs can easily be more than twenty times as efficient as in the present day heliosphere, and (iii) that the resulting total energy density below 300 MeV is at least in the range $0.3 - 7.6 \cdot 10^{-2}$eV/cm^3, it can be concluded that up to 50% of the energy density of the IS below 300 MeV could be provided by solar-type (low mass) stars. This stellar contribution to the IS would complement that of non-solar type (high mass) O and B stars that had been discussed previously in the literature (e.g., Casse & Paul 1980; Binns et al. 2005).

4. Cosmic ray modulation beyond the heliopause

Another link between the heliospheric and interstellar transport of CRs results from the actual interaction of the solar wind with the ISM. The latter appears in the solar rest frame as a head wind blowing over the heliosphere, which resembles an 'obstacle' in the interstellar flow. This obstacle leads to a disturbed ISM in the vicinity of the heliosphere, as depicted in the left panel of Fig. 4. As first pointed out by Jokipii (2001) the spatial diffusion of CRs in the vicinity of the heliosphere must be expected to be different from that in the general ISM, for which it is most often assumed to be isotropic (see, however, Effenberger et al. 2011). The reason for such modification is threefold: (a) On the scale of the heliosphere (i.e., several hundred AU) the diffusion cannot be expected to be isotropic as a consequence of a regular local interstellar magnetic field; (b) the magnetic field is 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; and (c) if a bow shock exists, it should further enhance the turbulence in the outer heliosheath (OHS) between the heliopause and the bow shock. Taking these modifications into account Scherer et al. (2011) have solved Eq.(1) for a simplified spherical heliosphere assuming an essentially perpendicular diffusion of CRs in the OHS with

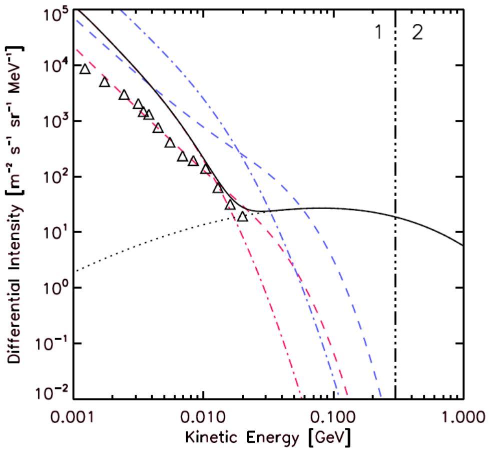

Fig. 3. The ACR spectrum at the heliopause (lower dash-dotted line) and an astropause of a solar-type star immersed in a denser (factor 6) and cooler (factor 2) ISM that moves with a comparatively low speed (factor 2) compared to the ISM surrounding the heliosphere (upper dash-dotted line). The dotted line is the IS given by Langner & Potgieter (2005), while the solid line is the spectrum at the heliopause including the ACRs. The lower/upper dashed line is the termination shock spectrum for the heliosphere/astrosphere. The triangles are the Voyager data at the termination shock (Stone et al. 2005) (taken from Scherer et al. 2008).

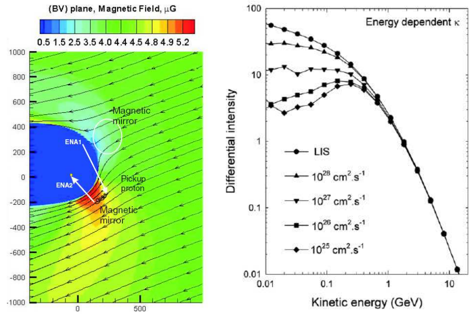

Fig. 4. Left panel: The interstellar magnetic field in the vicinity of the heliosphere, which can possibly probed using energetic neutral atoms (ENAs, measured with IBEX, see e.g., McComas et al. 2009) resulting from interstellar pick-up ions (taken from Chalov et al. 2010). Right panel: The IS upstream of the bow shock and the heliopause spectra for four different diffusion coefficients $\kappa_{OHS}(1\ GV)$ in the OHS. The differential intensity is given in units of $\mathrm{m^{-2}\ s^{-1}\ sr^{-1} MeV^{-1}}$ (taken from Scherer et al. 2011).

$\kappa_{OHS}(P) = (P/1\ GV)\,\kappa_{OHS}(1\ GV)$ (where P is rigidity) and the reference values given in the right panel of Fig. 4.

The figure reveals a significant modulation of the IS in the OHS below about 1 GeV for all considered diffusion coefficients. Even for the interstellar value of $\kappa_{OHS}(1GV) = 10^{28}\mathrm{cm^2/s}$, a 20% effect can be seen for 100 MeV protons increasing to 50% for 10 MeV protons. Further analysis revealed that, surprisingly, even without any change of the diffusion coefficient from the undisturbed ISM to the OHS, a modulation of the IS is occuring. This indicates that the main contribution to modulation is caused by a confinement effect: the particles entering the heliosphere are kept there for an extended period during which they are cooled, before they return into the OHS, i.e., particles leave the heliosphere with lower energy than they entered it. These results imply that one must distinguish between the IS and the heliopause spectrum of CRs.

So far, the turnover of the CR spectrum towards lower energies below 3-4 GeV has been attributed exclusively to a specfic rigidity dependence of the (scalar) interstellar diffusion coefficient (Moskalenko et al. 2002; Ptuskin et al. 2006). If the new additional modulation effect – which, in principle, should also exist for heavier CRs – will be confirmed this will have consequences for this senario as well as for the models of interstellar turbulence that have recently been used to explain this flattening (Shalchi & Büsching 2010).

5. Summary

We have reviewed the state of the art of the heliospheric transport of CRs and described how the earlier, merely conceptual link to the interstellar transport has recently grown into an actual physical link. The latter is at least twofold: On the one hand there is a likely contribution of solar-type stars to the IS in the energy range below about 1 GeV and on the other hand there exists a modulation of the IS even beyond the heliopause. Both effects signify that not only the transport of CRs in the heliosphere or, more general, in astrospheres is influenced by the interstellar transport determining the IS but also that the latter might depend to some extent on astrospheric transport. The next and final decade of in-situ measurements with the two Voyager spacecraft, complemented with remote observations by, e.g., IBEX, will probably shed more light on these interesting interrelations.

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