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-
Fig. 1. Comparison of the ‘classical’ (solid lines) and ‘Frenet-Serret’ tensor elements (symbols) according to Eq. (5) and Eq. (4), respectively, for the heliospheric Parker field. The results are shown at 10 AU for $\kappa_{11} = 0.05\kappa_0$ and $\kappa_{22} = 0.2\kappa_0$, i.e. $\kappa_{12}/\kappa_{11} = 4$. Such ratios are found for Jovian electrons (Ferreira et al. 2001).
vealed 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 is 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 atmospheric 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 atmosphere. Higher values are to be expected for more extreme states of the ISM around astrospheres of solar-type stars (Muller et al. 2006; Scherer et al. 2006). These astrospherically induced interstellar spectra will be modified by

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3. Astrospheric contributions to the interstellar proton spectrum

Contrary to earlier expectations recent measurements with the Voyager spacecraft have re-
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 & Paul1980; 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).

\[ \kappa_{OHS}(P) = \left( P/1 \text{ GV} \right) \kappa_{OHS}(1 \text{ GV}) \] (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 \( \kappa_{OHS}(1 \text{ GV}) = 10^{28} \text{ cm}^2/\text{s} \), a 20% effect can be seen for 100 MeV protons increasing to 50% for 10 GeV 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 occurring. 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 specific 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 scenario 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 two-fold: 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.

Acknowledgements. H.F. is grateful to A. Marcowith for the invitation to present the above results. The research was mainly carried out within a German-South African collaboration funded by the Bundesministerium für Bildung und Forschung (SUA 08/011) as well as the National Research Foundation and benefitted from support by the Deutsche Forschungsgemeinschaft for the projects ‘Galactocauses’ (FI 706/9-1), ‘Heliocauses’ (FI 706/6-3), and the FOR 1048 (FI 706/8-1).

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