ACR Modulation Beyond the Heliospheric Shock

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Abstract

As the Voyager spacecraft are rapidly approaching the expected location of the heliospheric termination shock it is timely to extend the study of the modulation of cosmic rays to the region beyond the shock. The anticipated in-situ observations in the subsonic solar wind regime will supplement our knowledge about the global structure of the heliosphere and various energetic particle populations. Amongst the latter are galactic as well as anomalous cosmic rays (ACR), pick-up ions and energetic neutral atoms. In order to facilitate interpretation of forthcoming data, we have developed a model for the modulation of ACR in the heliosheath that is based on the cosmic ray transport equation and employing a realistic solar wind background flow computed with with a self-consistent large-scale model of the heliosphere. The results, i.e. the spatial distribution as well as the spectra of ACR in the boundary region of the heliosphere will be presented.

1 Introduction

Modulation of cosmic rays, both galactic and anomalous, was studied extensively in the inner (supersonic) solar wind region. The outer heliosphere, where the plasma flow speed is expected to be low, was so far left out of consideration, which is justified as long as one is interested in the cosmic ray distribution in the inner region, accessible to direct observations. However, it was pointed out (Hsieh et al, 1992) that the cosmic ray particles will be converted into energetic neutral atoms (ENA) via charge exchange with the background gas of the local interstellar medium (LISM) origin, with the resulting flux of ENA, for comparatively low particle energy (100 keV), high enough to be detected. In this way the low energy cosmic ray distribution in the outer heliosphere can be indirectly observed from the vicinity of the Earth. With this in view, models of the ACR spatial distribution in the outer heliosphere were developed (Czechowski et al., 1995, Czechowski and Grzedzielski, 1997, 1998). The main result was that the ACR ions concentrate in the region of the heliotail, causing anisotropy in the associated ENA flux, as seen in the data obtained by CELIAS/HSTOF on SOHO (the detailed discussion is given in the paper). Most of these calculations were based on very simplified models of the heliosphere. In this contribution we use instead the results of a gas dynamical calculation (Kausch, 1998), which treats the plasma, neutral gas and the cosmic ray pressure in a self-consistent way. We concentrate on the evolution of the ACR energy spectrum, which was not so far considered for the region beyond the termination shock. Because of the characteristics of the flow and the low energy of particles, the modulation of the ACR spectrum in the outer heliosphere is quite different from the one which applies in the supersonic solar wind region.

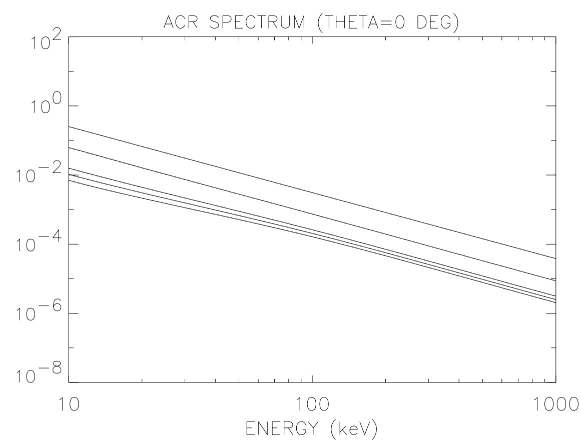

Figure 1: ACR energy spectrum evolution in Kausch model (apex direction). The spectra at distances (order from above) of 89 (shock), 101, 122, 147 and 177 AU are shown.

2 The Model

We use a test particle approximation, so that the back reaction of low energy ACR on the background flow is disregarded (the model of Kausch (1998) includes, however, the ACR and GCR pressure terms). The transport equation for the ACR distribution $U \equiv dN/d^3xdE$ is

$$\partial_t U = \nabla \cdot \kappa \cdot \nabla U - \mathbf{V} \cdot \nabla U + \frac{1}{3}\left(\frac{\partial U}{\partial lnp} - U\right) \nabla \cdot \mathbf{V} - \beta U \quad (1)$$

where $\mathbf{V}$ is the velocity of the plasma flow, κ the ACR diffusion tensor, p the ACR particle momentum, and β the loss rate, mostly due to charge-exchange. Although solar cycle effects will introduce a natural time dependence, we have so far restricted our calculations to the stationary case. For the diffusion tensor the scalar approximation was used: $\kappa_{ij} = \kappa\delta_{ij}$. Also, we assume that the diffusion coefficient in the LISM region (κ_2) is much larger than inside the heliosphere (κ_1): the value of the latter we estimate by $\kappa_1 = \kappa_{||}/3$ (with $\kappa_{||}$ given by the empirical formula of le Roux, Potgieter and Ptuskin, 1996) as for the case of isotropically disordered magnetic field. This assumption reflects the fact that in the outer heliosphere the effects of solar cycle magnetic field reversals (Nerney, Suess and Schmahl, 1995) must make the field structure complicated, so that the disordered field may be a reasonable approximation on the average. Although the three-dimensional model of the diffusion tensor would be preferable, we are restricted to the axially-symmetric approximation for numerical reasons (the third dimension we use for energy). The background flow models used here are all axially symmetric relative to the LISM flow direction.

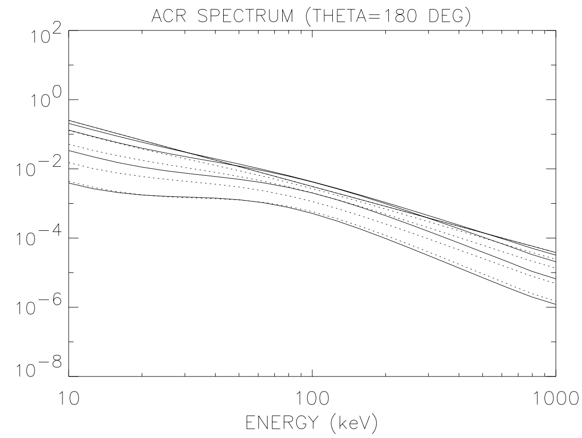

Figure 2: ACR energy spectrum evolution in Kausch model (anti-apex direction). The spectra at distances (order from above) of 187 (shock), 275, 380, 600 and 990 AU are shown. The dotted lines correspond to disregarding the divergence term.

While in the region inside the shock it is possible to consider the energy evolution as an initial value problem , downstream of the shock the flow divergence has no longer a definite sign and we must solve the boundary value problem. We must then prescribe the boundary conditions at the low and high limits in energy all over the space. In the calculations reported here we assume that the slope of the energy spectrum is constant in space at both energy limits (the consistency of this assumption is discussed in the next section).

Besides the gas dynamical model of Kausch, for comparison purposes we also use a much simpler analytic model of Parker (Parker, 1963).

3 Modulation

In the supersonic solar wind region the cosmic ray distribution is shaped by inward diffusion operating against convection by outflowing plasma, with adiabatic cooling due to the positive divergence of the flow. On the other hand, taking the solar wind termination shock to be the source of ACR, downstream of the shock the diffusion and convection are both directed outward. At low energy ($10^2 keV$) the charge exchange rate is high ($10^{-9}\ s^{-1}$) and affects the shape of the ACR spatial distribution: as this rate is strongly dependent on energy, the ACR energy spectrum downstream will become different from the spectrum at the shock (modulation). The energy dependence of the diffusion coefficient can be seen to be less important.

Another source of modulation is the adiabatic acceleration (deceleration) due to the divergence of the plasma flow. From Kausch's results, outside of the termination shock there are regions of both positive and negative divergence, which is of the order of 10^{-8} s^{-1} near the shock and 10^{-9} s^{-1} in the heliotail. These values are comparable with (or higher than) the maximum (low energy) value of the charge-exchange rate β. Nevertheless, the effect of the divergence term on modulation is small. Generally, we find that the divergence term tends to leave the pure power law spectrum unchanged. This is easy to see if the divergence term and convection are dominant in the transport equation (for a power law the divergence term is equivalent to the energy-independent loss term). The situation is similar in the low energy region, where the charge-exchange rate β_{cx} is approximately energy-independent (it has a maximum near 10 keV) and the diffusion term is small: this is why assuming the unmodulated power law should not cause large errors at low energy limit.

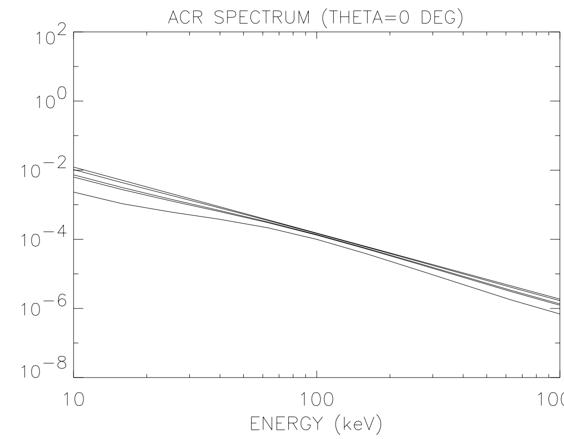

Figure 3: ACR energy spectrum evolution in Parker model (apex direction). The spectra at distances (order from above) of 89 (shock), 101, 122, 147 and 177 AU are shown.

4 Results

Figures 1 to 4 show, for the cases of Parker's and Kausch's models, the calculated energy spectra at different distances from the Sun, both in the apex and anti-apex (heliotail) direction. The strong modulation seen in the case of Parker's model is because the hydrogen density inside the heliopause was assumed to be much higher (0.1 cm^{-3}) than the value which follows from Kausch's simulation (about 0.02 cm^{-3} in the heliotail). The results obtained by disregarding the divergence term are shown by the dotted lines.

The modulation is predominantly due to the energy dependence of the loss rate β (or, charge-exchange cross section). Kausch's model assumption of low outside n_H makes the modulation relatively weak in this case.

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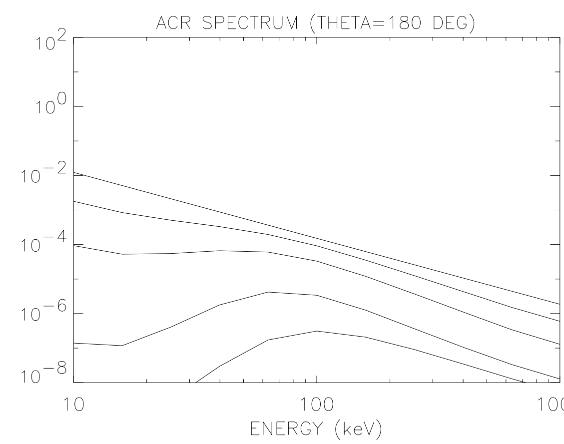

Figure 4: ACR energy spectrum evolution in Parker model (anti-apex direction). The spectra at distances (order from above) of 187 (shock), 275, 380, 600 and 990 AU are shown.

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