Particles acceleration at solar wind termination shock

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Abstract

A selfconsistent time dependent model is developed to study anomalous cosmic ray (ACR) acceleration at the heliospheric termination shock in the upwind direction and the shock modification under the influence of pickup protons and ACRs. Preliminary results demonstrate that ACR spectrum, termination shock structure and its position are very sensitive to the efficiency of ACR injection/acceleration. Relatively high injection rate of pickup protons is required in order to reproduce ACR proton spectrum consistent with the experiment.

1. Introduction

It is widely believed that the anomalous cosmic rays (ACRs) are the result of heliospheric acceleration of freshly ionized interstellar particles [1]. Interstellar neutral atoms streaming into the solar system are ionized by ultraviolet radiation or by charge exchange with the solar wind and are subsequently accelerated. Diffusive acceleration of some fraction of these pickup ions at the heliospheric termination shock is considered as a main source of ACRs [2]. The detailed model for ACR acceleration at the termination shock should take into account the backreaction of pickup ions and ACRs on the shock structure which is expected to be significant [3].

We develop here time-dependent model that takes into account the selfconsistent interaction of the thermal solar wind plasma, pickup ions and ACRs. It is very similar to the le Roux & Fichtner model [3], but nevertheless our results are essentially different compared with theirs. Opposite to le Roux & Fichtner [3] our results demonstrate that the ACR spectrum, shock structure and its position are very sensitive to the injection rate of pickup protons at the termination shock, where some their fraction is presumably involved into the acceleration process. According to our results to reproduce the observed ACR fluxes quite a high injection rate is required.

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2. Model

The description of ACR acceleration by a spherical termination shock is based on the diffusive transport equation for the ACR distribution function $f(r,p,t)$:

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r} r^2 \kappa \frac{\partial f}{\partial r} - w\frac{\partial f}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 w)\frac{p}{3}\frac{\partial f}{\partial p} + Q, \tag{1}$$

where $Q = Q_s \delta(r - R_s)$ is the source term due to injection of pickup ions; R_s is the shock radius; r, t and p denote the heliocentric radial distance, the time, and particle momentum, respectively; κ is the radial ACR diffusion coefficient; w is the radial mechanical velocity of the scattering medium (i.e. solar wind plasma). We assume, that the injection of some (small) fraction of pickup ions into the acceleration process takes place at the subshock, which is treated as a discontinuity in our model. For the sake of simplicity we restrict our consideration to protons, which are the dominant pickup ions in the solar wind. At present we only have some experimental and theoretical indications as to what value of the injection rate can be expected. We use here a simple injection model, in which a small fraction η of the incoming pickup protons is instantly injected at the gas subshock with a speed $\lambda > 1$ times the postshock gas sound speed c_{s2}:

$$Q_s = \frac{u_1 N_{inj}}{4\pi p_{inj}^3}\delta(p - p_{inj}),\ N_{inj} = \eta N_1^{pu},\ p_{inj} = \lambda m c_{s2}, \tag{2}$$

where $u = w - V_s$, $V_s = dR_s/dt$ is the shock speed, N^{pu} is the number density of pickup protons, and m is the proton mass. An appropriate value $\lambda = 4$ [4] is used here. The subscripts 1(2) refer to the point just ahead (behind) the subshock.

We use the ACR diffusion coefficient

$$\kappa(p) = 6 \times 10^{20}(p/mc)(v/c)(50\ \mu\mathrm{G}/B)\ \mathrm{cm}^2/\mathrm{s}, \tag{3}$$

where v is particle velocity, c is the speed of light, B is magnetic field strength. In the vicinity of the termination shock, that is at $|r - R_s| \ll R_s$, this coefficient coincides with that which was assumed by le Roux & Fichtner [3], whereas at smaller distances $r \ll R_s$ it is significantly smaller. Therefore the ACR spectra at the shock front are expected to be very similar in these two models, whereas at smaller distances $r \ll R_s$ ACR fluxes are expected to be progressively lower compared with their model. Note that opposite to le Roux & Fichtner [3] we do not take into account the influence of the galactic cosmic rays on the shock structure. This difference between two models is not very essential, because galactic cosmic ray influence is not significant [3].

The velocity profile $w(r,t)$ and pickup proton distribution $N^{pu}(r,t)$ are selfconsistently computed from a system of gas dynamic equations which include the ACR pressure P_c and the source and loss terms which describe the production

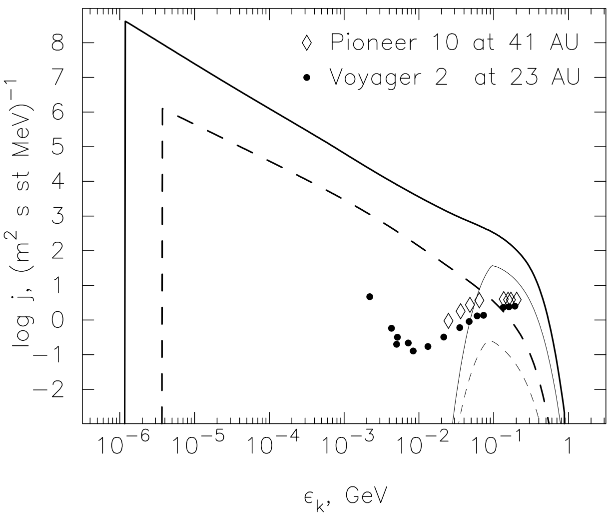

Fig. 1. Differential ACR intensity as a function of kinetic energy for high ($\eta = 3 \times 10^{-2}$, solid lines) and low ($\eta = 3 \times 10^{-4}$, dashed lines) injection rates. Thick and thin lines correspond to $r = R_s$ and $r = 30$ AU respectively. Experimental data measured at $r = 23$ AU and 41 AU are shown [5].

of pickup protons resulting from photoionization of, and charge exchange with, interstellar hydrogen exactly in the same form as in the le Roux & Fichtner model [3]. The above equations are solved numerically with the boundary conditions at $r_0 = 1$ AU (medium speed $w_0 = 400$ km/s, number density $N_0 = 5$ cm^{-3} and temperature $T_0 = 10^5$ K) and at $r = \infty$ (medium speed $w = 0$ and pressure $P = P_{ISM} = 1$ eV/cm^3).

3. Results and Conclusions

We analyze here the stationary state of the system which is established during the time interval of a few years after the beginning of pickup proton injection/acceleration. Since the actual injection rate of pickup protons is not known we present the calculations which correspond to the low ($\eta = 3 \times 10^{-4}$) and high ($\eta = 3 \times 10^{-2}$) injection rates. Fig.1 shows the differential ACR intensity $j = p^2 f$ as function of kinetic energy ϵ_k at $r = R_s$ and $r = 30$ AU. One can see that the shape of ACR spectra are essentially different for different η. At energies $\epsilon_k \sim 100$ MeV, which is the typical ACR energy, the flux value at low injection is more than two orders of magnitude smaller than at high injection. It is also clear from Fig.1 that relatively high injection rate $\eta \sim 10^{-2}$ is required to reproduce the observed ACR fluxes at $r = 23 \div 41$ AU. Note that the solutions obtained by le Roux & Fichtner [3] due to unknown reasons are dramatically different: their ACR spectra are almost insensitive to the injection rate except very low energy range.

The solar wind velocity profile $w(r)$, shown in Fig.2, consists of a pure gas subshock and extended smooth precursor originated in the upstream region $r < R_s$ due to the influence of pickup ions and ACRs. The solution without ACRs, that formally means $\eta = 0$, corresponds to the shock radius $R_s = 69$ AU, shock compression ratio $\sigma = w_0/w_2 = 4.2$ and subshock compression ratio $\sigma_s =$

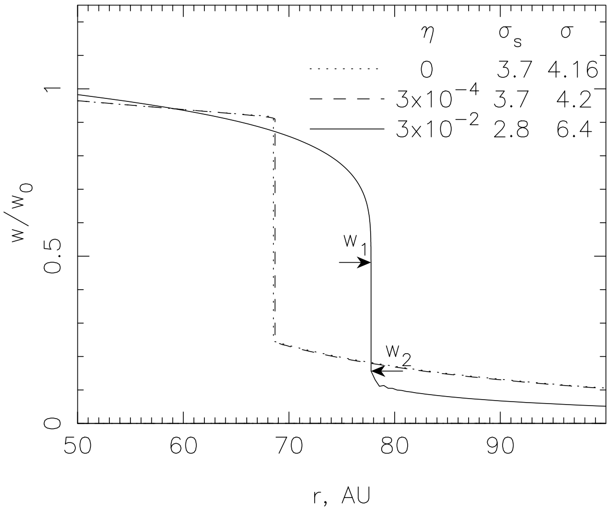

Fig. 2. The solar wind speed w as a function of heliospheric distance for high (solid line) and low (dashed) injection rate compared with with the solution without ACR ($\eta = 0$, dotted line).

$w_1/w_2 = 3.7$. At low injection rate $\eta = 3\times10^{-4}$ these shock parameters are almost the same (see Fig.2). In these case our values of the shock parameters are close to thous obtained by le Roux & Fichtner [3], which are $R_s = 74.3$ AU, $\sigma_s = 3.4$ and $\sigma = 4.25$. The increase of the injection rate leads to higher shock modification due to ACR backreaction, that is larger shock compression ratio and weaker subshock. The increase of the shock compression provides the increase of the postshock pressure that in turn shifts the shock position towards larger distance r. In the case of $\eta = 3 \times 10^{-2}$ shown in Fig.2 we have $R_s = 78$ AU, $\sigma = 6.4$ and $\sigma_s = 2.8$. Surprisingly that the solution obtained by le Roux & Fichtner at high injection rate is essentially different. Opposite to what is expected from general point of view at higher η they have smaller shock radius and lower shock compression ratio.

Thus our preliminary calculations demonstrate that opposite to the previous study [3] the ACR spectrum, produced as a result of the diffusive acceleration of some part of pickup protons, the termination shock structure and its position are very sensitive to the pickup proton injection rate. Quite a high injection rate $\eta \sim 10^{-2}$ is required to reproduce observed ACR fluxes.

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4. References

1. Fichtner H. 2001, Space. Sci. Rev. 95, 639
2. Pesses M.E., Jokipii J.R., Eichler D. 1981, ApJ Lett. 246, L85
3. le Roux J.A., Fichtner H. 1997, ApJ 477, L115
4. Berezhko E.G., Ellison D.C. 1999, ApJ 526, 385
5. McDonald F.B., Lukasiak, A., Webber W.R. 1995, ApJ 446, L101