Heliospheric Termination Shock Mediation by Anomalous Cosmic Rays: Insights from Recent Voyager Data.

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Abstract

The two Voyager spacecraft provide valuable information about the energetic particle population near the termination shock (TS), such as the anomalous cosmic ray (ACR) spectra, the intensity gradients, and the radial diffusion coefficients obtained from anisotropy measurements. While the spectra and gradients have been modeled successfully using the test-particle approach, the shock modification by the ACR pressure gradient has not yet been addressed in the full context of the available data. Here we present the results of a self-consistent axisymmetric model of the solar wind modified by both charge exchange and ACR pressure gradients. Our results indicate that during solar minima anomalous cosmic rays with energies above 100 keV are not likely to have a significant impact on the properties of the termination shock.

1. Introduction

The problem of TS mediation by the shock-accelerated particles is important in our understanding of the structure of the outer heliosphere. Theory [7] predicts that galactic cosmic rays move the shock inward because of the deceleration of the wind upstream and increased confining pressure, while the ACRs have the opposite effect owing to the appearance of the precursor and cooling of the downstream plasma. The subshock compression ratio is reduced in both cases. Qualitative studies have been performed in the hydrodynamic approximation [2] and using a kinetic (transport equation) approach [8, 3]. Here we present a realistic 2D axisymmetric model of the solar wind that includes the interaction between the three principal particle species: plasma, neutral atoms and ACRs. The current model is an extension of [4] in that it uses an adaptive mesh refinement (AMR) approach and includes pickup ions (PUI) and self-consistent particle acceleration at the TS.

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2. Model Description

In this model we solve the system of coupled conservation laws for the plasma, which includes charge-exchange, ACR pressure, and ACR injection source terms. The system may be written symbolically as

$$\frac{\partial U}{\partial t} + \nabla \cdot \mathbf{F} = Q_{\mathrm{ACR}} + Q_{\mathrm{CE}} + Q_{\mathrm{inj}}. \tag{1}$$

In this equation U is the state vector which has plasma density ρ, momentum $\rho\mathbf{u}$, energy ϵ, magnetic field $\mathbf{B}$, and PUI number density n_{PUI} as its components. Further, $\mathbf{F}$ is the flux matrix and the Qs refer to the above-mentioned source terms. Charge exchange is modeled according to [9]. The magnetic field is included in the kinematic approximation. This approach is justified since we do not include the region immediately adjacent to the heliopause, where the field is dynamically important [3].

Energetic particles are described by the usual kinetic transport equation for the phase space density f

$$\frac{\partial f}{\partial t} + (\mathbf{u} + \mathbf{v}_{\mathrm{d}}) \cdot \nabla f + \nabla \cdot (\kappa \cdot \nabla f) = \frac{\nabla \cdot \mathbf{u}}{3} \frac{\partial f}{\partial \ln p} + S, \tag{2}$$

where the injection term S is related to Q_{inj} in Eq. (1). Our choice of diffusion coefficients is based on the theoretical model [11], using the constant relative magnitude of the magnetic turbulence $\langle \delta B_{x,y}^2 \rangle / B^2$ and the outer scale l_{c}, according to [3]. Injection occurs at the shock at the lower momentum boundary at a rate that is a fraction of the PUI flux at each latitude. ACR acceleration models based on solving Eq. (2) are reviewed in [6].

Equations (1) and (2) are solved inside a spherical domain 150 AU in radius. The density and velocity of the solar wind at the inner boundary is varied with latitude, resulting in the TS attaining a non-spherical shape (see Figures 1 and 2). The numerical code used in [4] has been significantly enhanced by implementing an AMR algorithm to solve both the hydrodynamic wind equations and the ACR transport equation. This method uses multiple grids covering regions exhibiting large spacial gradients in density or velocity, such as the termination shock. Grid generation is completely automated and is suitable for solving time-dependent problems. A sample adaptive grid topology is shown in Figure 1.

3. ACR Influence on the Plasma Dynamics

The main results obtained here are shown in Figure 2. In the left panel we show ACR proton spectra at 30° latitude at the shock and at two heliocentric distances corresponding to the Voyagers' locations. The shock spectra calculated with the help of our model are in agreement with the results of [1] calculated

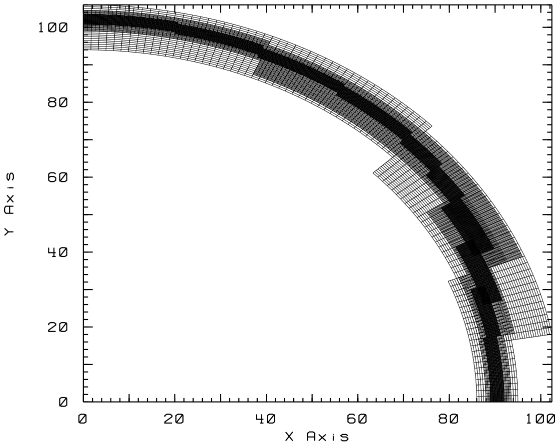

Fig. 1. AMR grid topology of the self-consistent simulation.

for the weak shock case. Note that the shock is necessarily weak in the self-consistent model owing to a deceleration and heating of the solar wind by charge exchange. Note also that ACR spectra at the shock shown in Figure 2 exhibit a characteristic "bump" near the energy where $ur_{\rm s}/\kappa_{rr} \simeq 1$. This effect has been discussed in detail in [5] and is caused by the reflective property of the system's geometry and by drift motion of the accelerating particles along the shock face. The intensity gradients away from the shock predicted by the model are larger than observed, which is due mostly to a lack of variation in $\langle \delta B_{x,y}^2 \rangle / B^2$. Future models will include the turbulence evolution equation [11], generalized to allow multidimensional transport and small Alfvén numbers of the flow downstream of the TS. Further, the model should be able to agree with the diffusion coefficients calculated from the ACR anisotropy measurements by the Voyager experiment.

The right panel in Figure 2 shows the effect of the ACRs on the shock location and structure for the ACR spectra shown in the left panel. The visible gradual deceleration upstream of the TS is produced by charge exchange and is of the order of 90 km/s between 1 AU and the shock in the ecliptic. ACR pressure is considerably higher ($p_c \simeq 0.12\,{\rm eV\,cm^{-3}}$) in the ecliptic region than over the poles because more PUIs are available for injection and the cutoff is located at higher energy, owing to a smaller diffusion coefficient. Nevertheless, ACRs comprise less than 10% of the sum of the plasma dynamic and thermal pressures near the shock. As a result, TS modification is not significant as seen from the right plot of Figure 2. The compression ratio of the subshock decreases by about 10% to 3.0 in the ecliptic and the shock has moved outward (in agreement with the theory) by $0.3 - 1.0$ AU. Because the spectra at the TS calculated with our model agrees with that of [1], and our model overpredicts the radial gradients away from the shock, we expect that the actual effect will be even less than reported here.

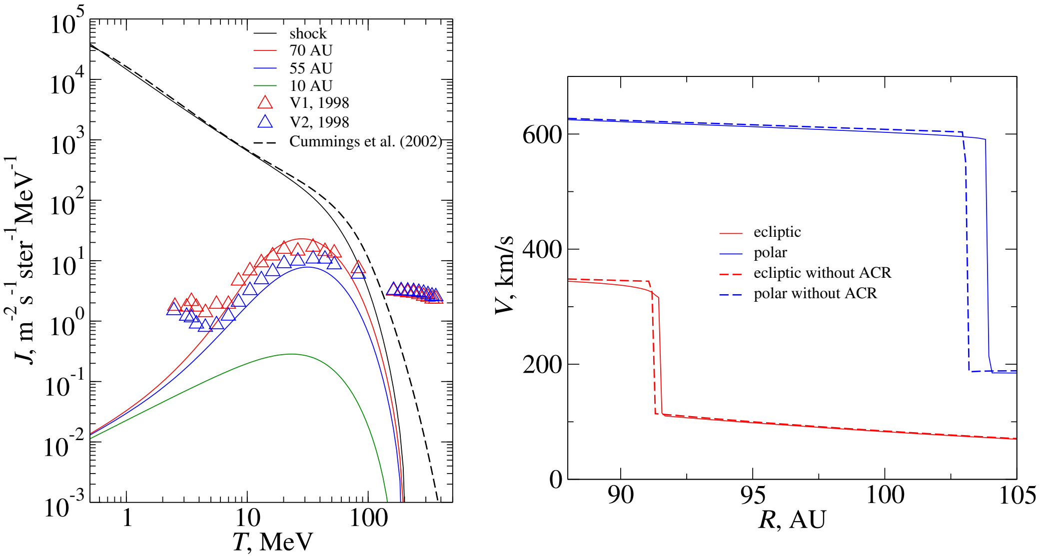

Fig. 2. Left: ACR proton spectra compared to the Voyager data taken during the 1998 solar minimum. Right: solar wind velocity in the vicinity of the TS with and without the ACR effects.

4. Conclusion

With the help of our new adaptive mesh MHD-kinetic model we found that ACR protons with the energies above 100 keV do not change the properties of the TS appreciably. Nevertheless, it remains to study the possibility of additional turbulence present in the immediate vicinity of the shock owing to hydrodynamic instabilities caused by the cosmic-ray gradients [10]. This effect may further suppress diffusion in this region leading to larger p_c gradients.

5. References

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