Cosmic Ray Transport Beyond the Termination Shock: Modulation in the Heliosheath

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Abstract

We consider cosmic-ray modulation in the heliosheath in a simple model, assuming incompressible subsonic wind. A simple and quick approximate method is suggested to estimate the net modulation beyond the shock. The effects of temporal variations of the shock are addressed.

1. Introduction

There is a growing evidence that a significant, or even dominant part of the modulation of galactic cosmic rays (GCR) may occur in the heliosheath beyond the termination shock (TS) [5],[9]. Similar conclusion was reached from our 2-D and 3-D models, which include a crude model of the heliosheath [4]. Acceleration of anomalous cosmic rays (ACR) and reacceleration of GCR at the TS was discussed by Webb et al [9] in a spherical model. A more realistic model of the heliosphere including deflection and the formation of the heliotail has recently been modeled by Florinski et al. [1]

The present work addresses some aspects in a simple model. We discuss a simple approximate method to estimate the net modulation of GCR beyond the TS. A more sophisticated models of the heliosphere will be discussed later.

2. Simple Approximations

In a diffusive transport model, we assume an unmodulated interstellar spectrum, $f^{\star}(p)$ of GCR at the heliopause (HP) dividing the solar and interstellar material. A weak bow shock outside the HP is expected to have little effect. Some of the physical features can be illustrated in the simplest spherical model, assuming steady state, and incompressible wind beyond the TS. An analytical discussion of this case was given by Webb et al. [8]. In the absence of adiabatic energy change ($divV = 0$), the modulation equation of Parker [7] can be solved beyond the TS ($r > R_s$):

$$f(r,p) = \frac{\Psi(r)}{\Psi_0}\, f^{\star}(p) + \Big(1 - \frac{\Psi(r)}{\Psi_0}\Big)\, F(p) \qquad (1)$$

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where $F(p) = f(R_s, p)$ is the spectrum at the shock, and q accounts for source for anomalous cosmic rays (ACR). We assume $f^\star = 0$ for ACR, and $q = 0$ for GCR. The dimensionless quantity, Ψ is

$$\Psi(r,p) = exp\Big(\int_{R_s}^{r} V/\kappa.dr'\Big) - 1 \tag{2}$$

with $\Psi_0 = \Psi(R_{out})$ corresponding to the total integral from the TS to the outer boundary, R_{out}. The boundary condition at TS is

$$\kappa\frac{\partial f}{\partial r} + \frac{(V_1 - V_2)}{3}\frac{\partial f}{\partial ln\, p} = \frac{V_2}{\Psi_0}\,(f^\star - f) + q \tag{3}$$

which implies that, in this simplest case, the whole modulation in the heliosheath can be expressed by the single quantity, Ψ_0, and can be absorbed into a boundary condition.

Eq. (3) offers a simple and quick approximation to estimate the net modulation of GCR in the heliosheath at energies above ∼100 GV, by invoking the force-field approximation [2]. The force-field approximation (no net streaming, i.e. $S_r = 0$) can be applied within the TS if the diffusion coefficient, κ, is sufficiently large ($\kappa > V\,r$). Then, (2) reduces to

$$-\frac{\partial F}{\partial ln\, p} = \frac{3}{\Psi_0}\,(f^\star - F) \tag{4}$$

which can be readily integrated to obtain the shock-spectrum, $F(p)$. We propose this simple approximation, which is equivalent with placing a reflecting wall at the TS, as a counter-part of force-field solution beyond the TS.

It may be interesting to point out one implication of (1). An observer beyond the TS sees a mixture of two populations. The first term in (1) accounts for pristine interstellar particles that have not been subject to energy loss. The second term, on the other hand, describes particles that have crossed the TS (once or multiple times) prior to observation and hence experienced energy loss in the supersonic expanding wind (and reacceleration at the TS). The region immediately beyond the TS is still dominated by the second population.

The approximation (4) implies that particles that cross the TS lose more energy inside the TS than they gain at crossing. The other extreme case is valid for small κ ($\kappa \ll V\,r$), when cooling is negligible, and the convection-diffusion model is applicable [6]. This leads to the same as a planar shock:

$$V_1\,F + \frac{(V_1 - V_2)}{3}\frac{\partial F}{\partial ln\, p} = \frac{V_2}{\Psi_0}\,(f^\star - F) + q \tag{5}$$

which gives the maximum re-acceleration.

Shown in Fig. 1 is a comparison of the two approximations outlined above with numerical solution, assuming a power-law unmodulated spectrum, $f^\star(p)$. The reflecting condition (4) gives reasonable approximation. We note that the method can readily be extended to 2- and 3-dimensional cases.

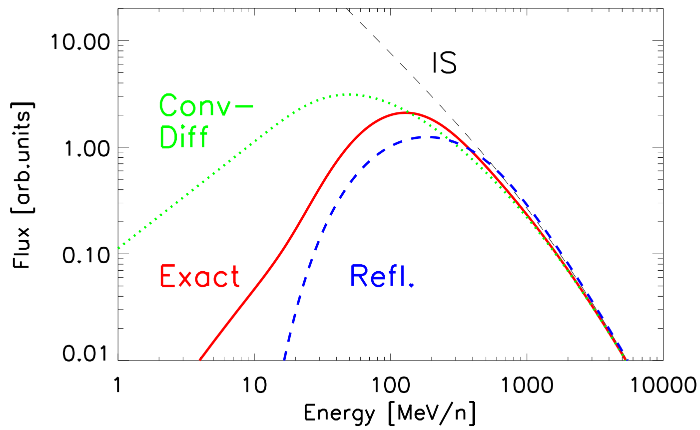

Fig. 1. Comparison of the force field, Eq. (4), and convection-diffusion, Eq. (5), approximations with numerical solution.

3. Temporal Variations

Temporal variations of the solar wind emanating from the Sun induce corresponding variations in the location and strength of the TS. In Fig. 2 we present a model simulation, where the solar wind speed decreases from a steady 500 km/s to values fluctuating between 500 and 400 km/s (keeping the mass flux constant), then returns to its original constant value (dotted curve).

Shown in Fig. 2 are the solar wind speed, density, and magnetic field at 90 AU (upper panel). The jumps indicate shock-crossing as the shock moves inward then outward in response to the changes in the solar wind ram pressure. The lower panel shows the simulated fluxes of He^+ accelerated at the TS. The low-energy fluxes increase as the shock moves inward. The largest increase is at the crossing, but significant increase can be observed even without crossing the shock. Similar, though somewhat smaller flux increases are obtained at 86 AU, without shock crossing. We note that there are qualitative similarities to the recent detection of unusual enhanced particle fluxes by Voyager-1 at 86 AU. We made no effort to fit these observations (duration, magnitude, spectrum, etc), and clearly there are significant quantitative differences.

4. Conclusions

We discussed quick approximative methods to evaluate the net modulation and obtain the shock-spectrum for GCR. Also we discussed some implications of temporal changes in the location of the TS. Future work is needed to attempt direct comparison with observations.

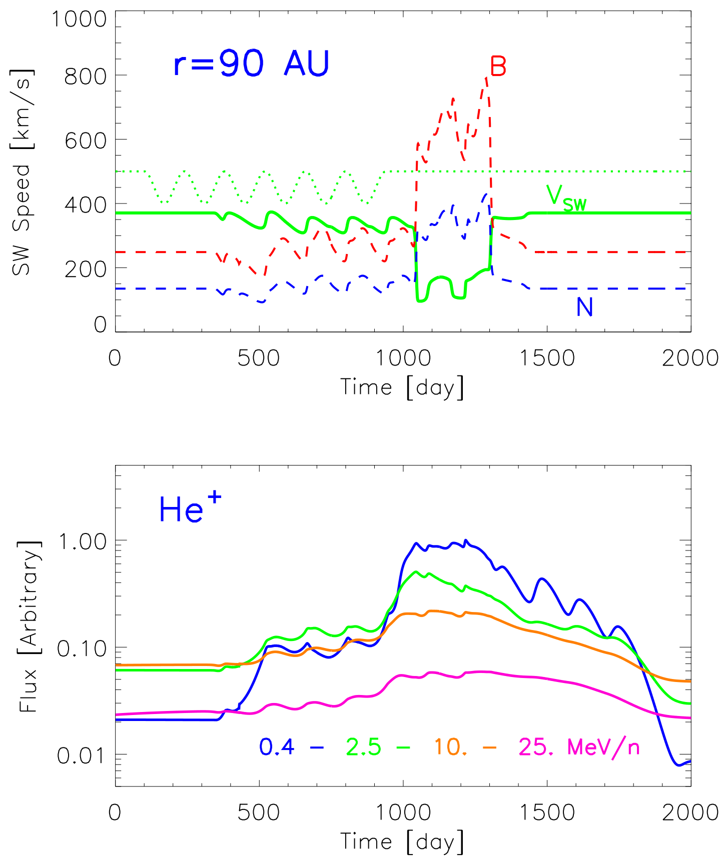

Fig. 2. Simulated temporal variation of the solar wind (upper panel) and corresponding ACR He^+ fluxes (lower panel) at 90 AU.

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5. References

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