Modulation of galactic cosmic rays near and beyond the termination shock

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Abstract

Measurements at the distant outer heliosphere by the Voyager spacecrafts show that galactic cosmic rays are still strongly modulated even close to the expected location of the termination shock. In this paper, we present a model calculation including the region of the heliosheath. By a simulation of particle trajectories using Markov stochastic processes, we investigate the physical reason for the modulation of the flux of cosmic rays detected at the termination shock. Although the particles do not lose much energy in the heliosheath, the cosmic rays detected at the Voyagers have spent a significant amount of time sunward of the spacecraft in a region where adiabatic energy loss by the expanding solar wind is still significant. The model predicts that galactic cosmic rays measured outside the termination shock will still be modulated. The spacecraft have to get much farther out in order to directly measure the true interstellar spectrum of galactic cosmic rays.

1. Introduction

In cosmic ray modulation problems, it is well known that the energy change that modulates the flux is primarily provided by the divergent solar wind in an adiabatic expansion effect. Outside the termination shock (TS) the solar wind loses this divergent character, and gradually is subsumed into the more linear flow of the interstellar medium. From this behavior it has long been assumed that the modulation of galactic cosmic rays in the heliosphere is a function of the amount of divergent solar wind between the observation point and the TS. In other words, there is assumed to be no modulation outside the shock. This is known as the force free approximation. However, with the advent of stochastic particle approaches to solving modulation problems, this idea can be shown to be incomplete.

Recent measurements by Voyager [1,2] have hinted that the modulation of GCR is still strong even when nearing the TS. Using a stochastic model developed by Zhang [4] we may demonstrate a simple reason why. Figure 1 shows a sample particle orbit in the heliosphere. The particle is initially located at R=120 AU,

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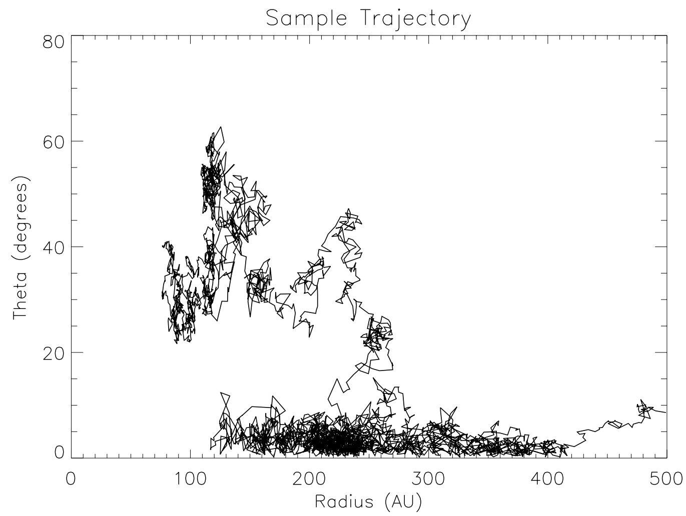

Fig. 1. Sample Particle Trajectory at R=120 AU

$\theta = 45°$, and $\phi = 0$. The TS is located at 110 AU here. When we trace the particle backward in time according to the proper stochastic equations of motion, we see that it spends a significant amount of time inside the TS. Many particle trajectories that pass through this end point will have spent time inside the TS, thus giving us a reasonable mechanism for this outer heliospheric modulation.

2. Model

The basic technique of stochastic modulation is outlined in detail in Zhang [4]. Here we detail the heliosphere model, along with the shock and outer heliosphere parameters. The heliosphere model used is the typical Parker spiral with no tilt or offset. Using average parameters from Zank *et al* [3] we can impose a termination shock at 110 AU. At the shock we decrease the velocity to 30% of the inner magnitude, from 400 km/s to 120 km/s in the slow wind region. There is a corresponding increase in the magnetic field magnitude of about a factor of 4. Outside the TS, we require that the solar wind velocity fall off as $1/r^2$ until we reach a cutoff point at 180 AU where we impose a constant radial field again. This dictates that $\nabla \cdot \vec{V} = 0$ everywhere outside the TS, allowing us to demonstrate that we do not need any actual modulation occuring outside the TS to see the effects of inner heliospheric modulation there.

At the termination shock, we must also account for shock acceleration and any mathematical effects due to the velocity discontinuity. We treat these effects with skew Brownian motion as detailed by Zhang [5]. The diffusion tensor inside

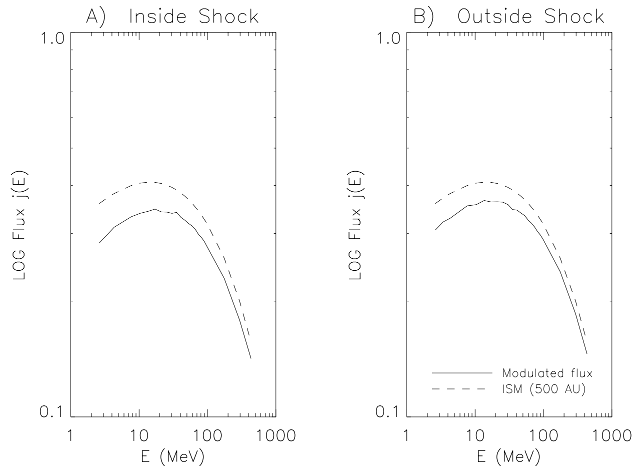

Fig. 2. Modulated Flux Inside and Outside the Shock Bound

the shock is defined as:

$$\kappa_{\parallel,\perp} = (\kappa_{\parallel,\perp})_o \beta (p/p_o)^{b_{\parallel,\perp}} (B_e/B)^{a_{\parallel,\perp}} \tag{1}$$

where these parameters are as defined by Zhang [4]. Outside the shock, we require the magnitude of the local magnetic field, B, to be a constant in r and equal to the value just outside the TS. Here we only allow latitudinal changes, which changes the form of some of the diffusion terms slightly. We impose an outer boundary at 500 AU, where we stop tracing. These parameters are for modeling solar minimum conditions, though it is clear that accurate values for all parameters are necessary for fitting the observations.

3. Results

Figure 2A shows the modulated flux spectrum at R=100 AU and $\theta = 45°$. This spectrum ranges from approximately 1-400 MeV for protons. The dotted line is the boundary value flux, and the solid line is the local modulated flux. We can see from this plot that there is still significant modulation, on the order of up to 20% at the lowest energies, where the modulation is strongest.

Figure 2B shows the same distribution for R=120 AU. Although there is clearly less modulation here, it is still significant, with the lowest energies exhibiting 15% modulation. Again we note the the lower energy fluxes are the ones that are most affected here, in good agreement with the observations.

Finally, Figure 3 shows a radial profile of modulation of 100 MeV proton flux at 45° longitude. We can see from this plot that the modulation will continue far outside the TS, with modulations of 8% or so even as far out as 150 AU.

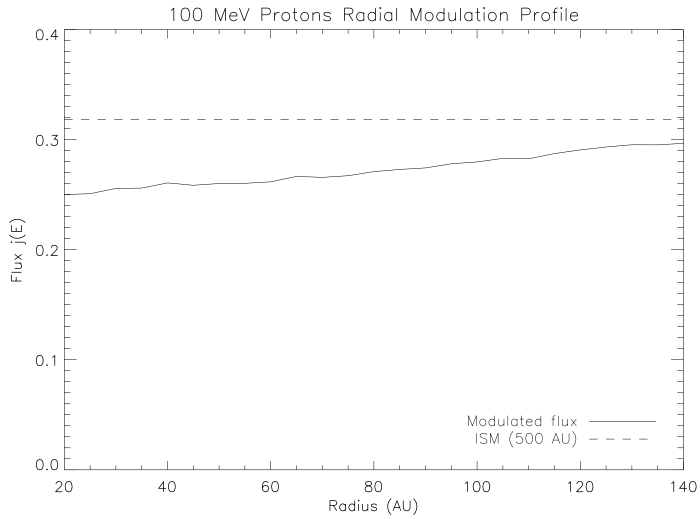

Fig. 3. Radial Profile of 100 MeV Proton Modulation

4. Conclusion

It is clear that from a stochastic particle approach, the modulation of GCR must continue even outside the TS. Figures 2 and 3 are clear in their implications. If we extrapolate outward in Figure 3 we can reasonably expect to see modulation effects for 40 AU or more outside the TS, and possibly farther. The lower energy particles ($< 100 MeV$) tend to show the greatest modulation, which is in good agreement with the observations in [1,2]. We expect that when appropriate parameters for solar maximum are chosen, the modulation level will be increased at the TS.

5. List of Symbols/Nomenclature

GCR=galactic cosmic ray	TS=termination shock
$f(p)$=distribution in momenta	Flux= $j(E) = f(p) * p^2$
V=solar wind velocity	κ= diffusion tensor element

6. References

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