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The interaction of solar wind structures with the termination shock and anomalous cosmic ray enhancements at low energies

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Voyager 1 anomalous cosmic ray measurements performed in close proximity to the termination shock during 2002–2004 show a new low-energy particle population in addition to the modulated spectrum. While the precise interpretation is still a subject of debate, several plausible explanations have been suggested, involving the excursion of the shock in response to changing conditions in the solar wind. Solar wind structures, such as shocks and merged interaction regions collide with the termination shock causing it to reform, become weaker or stronger and move inward or outward. We present an initial study of particle acceleration at a shock with incident perturbations in the form of simple waves (forward/reverse shock pairs or contact discontinuities) and discuss the effects of intermittent injection. It appears that motion of the TS alone cannot explain the observations. However, it is possible to reproduce essential features of the observed double spectrum by making several assumptions regarding the geometry of the system and the effectiveness of the injection process.

1. Introduction

The solar wind (SW) termination shock (TS) and the heliosheath are in a perpetually dynamic state owing to large scale structures in the solar wind such as global merged interaction regions (GMIRs), interacting with the heliospheric boundaries. The collision of such a structure with the TS can be represented as a series of elementary interactions between forward and reverse shocks and stream interfaces with a moderately strong stationary shock wave. The classical outcomes of such interactions are well known: the TS moves either toward or away from the Sun and a transmitted shock or rarefaction wave and a contact discontinuity (CD) appear in the heliosheath and propagate toward the HP [1, 10]. Typically, a large number of waves are injected into the heliosheath resulting in additional heating of the ambient plasma [11]. GMIRs also introduce propagating "barriers" in the heliosheath with magnetic field enhancement up to 4 times over the ambient field magnitude that could have a significant effect on galactic cosmic ray propagation [9].

Motion of the TS is undoubtedly an important factor affecting anomalous cosmic ray (ACR) acceleration. ACR spectra measured during the energetic particle increases in the second half of 2002 and in 2004 show two distinct populations of particles: a modulated spectrum at high energies ($\sim$ 100 MeV for protons) and a power law at low MeV energies with a rollover to a steeper spectrum at $\sim$ 3 MeV [2]. It has been suggested that the latter population originates at a local incursion of the TS [4] or at a location away from Voyager, but magnetically connected to the spacecraft [6], while the former arrives my means of cross-field diffusion and is therefore heavily modulated. The second possibility can be realized if the TS curvature near the Voyager 1 location is less than that of the Parker spiral and the field connects to a location on the shock surface downstream of the spacecraft [5]. The latter is required to explain the observed anisotropy, which was directed away from the Sun during the events [7]. 3D MHD simulations of the heliosphere that take into account plasma-neutral interactions show that this scenario is entirely plausible [8].

In this communication we discuss a series of simple 1D demonstrative solutions to the ACR transport equation for particles accelerated at a shock with incident perturbations in the form of simple waves. For simplicity we use planar geometry instead of spherical because shocks and contact discontinuities (CD) propagate unchanged in the former, but evolve in the the expanding SW. To ensure the appearance of the high-energy cutoff in the accelerated spectra we place a reflecting wall at the left boundary of the simulation box. This produces modulated spectra in front of the shock qualitatively similar to those in the spherical geometry with the cutoff produced by cooling at the wall rather than in the expanding flow as would be the case for the SW [3].

2. Termination shock evolution

The gas-dynamic part of the problem consists of a moderately strong stationary shock (compression ratio $s = 3$) in the initial conditions and a series of upstream perturbations. For the latter we use either a sequence of four CDs (the MCD model) produced by changing the plasma density at the left boundary by $\pm 40\%$, or a forward-reverse shock pair (FRS model) produced by a single increase in the plasma velocity by 50%. In the second model the propagating shocks have a compression ratio of 1.85.

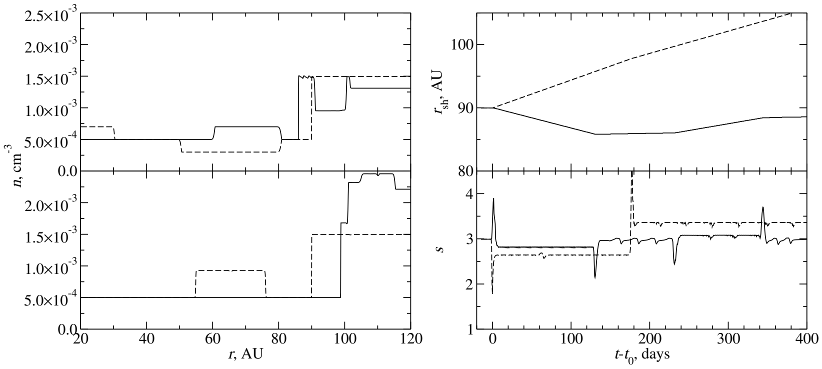

Figure 1. Left panels: plasma density 50 days before the collision of the front stream interface with the TS (dashed) and 200 days after the collision (solid lines) for the MCD (top) and FRS (bottom) initial conditions. Right panels: shock position (top) and compression ratio (bottom) for the MCD (solid) and FRS (dashed). Peaks are due to numerical errors in calculating s at the moments of collisions between simple waves. A much more detailed discussion of the interaction process may be found in [10].

Figure 1 shows the plasma density before and after the collision of the front structure with the stationary shock. The MCDs cause the shock front to move first in- and then outward by about 5 AU over a time scale of about 1 year without changing its compression ratio appreciably. The FRS pair moves the TS steadily outward with its compression ratio decreasing at first to 2.6 and then increasing to 3.35 (Fig.1, right). The heliosheath regions becomes filled with waves and discontinuities that are easy to identify. For example, the sequence of waves in the MCD model from left to right is TS, CD, rarefaction, CD, shock. In our simulation the TS only attains moderate speeds relative to the solar frame — 55 km/s for the MCD and 75 km/s for the FRS perturbations.

3. ACR acceleration at a moving shock

In solving the ACR transport equation we only inject particles at the TS. For ACR acceleration we consider first a scenario where the entire population of particles is produced by a single source at the shock. Particle spectra that would be observed by a spacecraft located at $r_{\mathrm{sh0}} - 4.5$ AU, where $r_{\mathrm{sh0}} = 90$ AU is the shock distance before the interaction, are shown in Fig. 2 (left panel) for the MCD case. Before the onset of interaction the

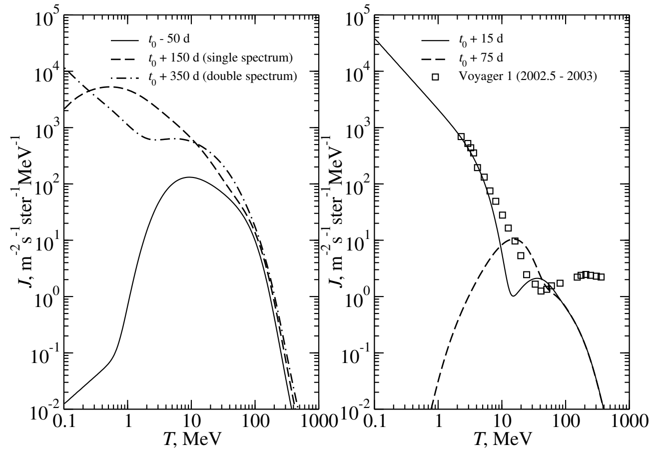

Figure 2. Left: accelerated particle spectra at $r_{\rm sh0} - 4.5$ AU for the time before the first CD hit the shock (solid), 5 months after the initiation of the collision for the single source scenario (dashed) and 1 year after the first collision for the dual source scenario (dot-dashed). Right: Shock spectra with intermittent injection during the injection phase (solid) and the acceleration phase (dashed).

spectrum is modulated at low energies. As the shock moves closer, the spectrum gradually unfolds, approaching an unmodulated power law. Indeed, for plausible values of the diffusion mean free path, ACR acceleration proceeds significantly faster than the dynamical scale associated with the motion of the shock ($\sim$ 1 AU per month), and the spectrum has time to adjust to the shock motion. Deviations from the steady-state distribution are only provided by modest changes in the strength of the TS. The situation is similar in the FRS case, although, of course, the amount of modulation only increases in time in this model as the shock moves farther away. It seems that motion of the TS by itself is not a valid explanation for the Voyager 1 measurements.

Next, we consider the case where some of the particles observed upstream of the shock come from a limited portion of the TS magnetically connected to the spacecraft, while the rest of the particles arrive from a broad range of longitudes by, e.g., cross-field diffusion. The spectrum shown at $r_{\rm sh0} - 4.5$ AU is essentially a sum of the modulated spectrum at this location and a portion (10% here) of the spectrum at a location 3 AU further downstream. Figure 2 (dot-dashed line) shows that it is possible to obtain a double population spectrum that qualitatively resembles Voyager 1 observations. However, the latter exhibit a change in the slope to a softer power law (which can also be interpreted as a cutoff) at about $\sim$3 MeV. As mentioned earlier, acceleration at the TS is sufficiently fast compared to the timescale of the shock motion, certainly enough to establish the power law to energies in excess of 10 MeV . The limited size of the acceleration region may be an important factor here; however, it is not possible to include it in the 1D model.

4. Intermittent injection

Disturbances in the solar wind also affect the direction of the interplanetary magnetic field. Even slight changes in the direction of $\mathbf{B}$ relative to the shock normal could have a dramatic effect on the rate of injection of low energy particles into the diffusive shock acceleration process. Figure 3 shows the effective injection energy at the TS, defined as the energy where the particle anisotropy upstream of the shock is ~ 1. More details about this calculation may be found in [12]. Injection is inefficient at quasi-perpendicular shocks. However, because

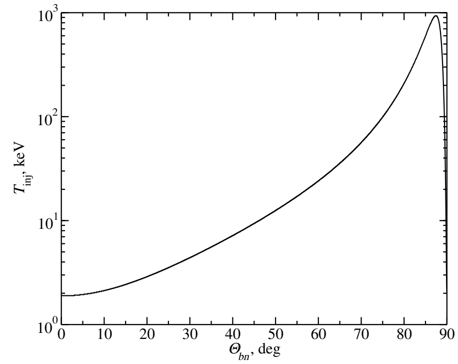

Figure 3. Injection threshold as a function of the shock-normal angle θ_{bn}.

$\kappa_\perp \ll \kappa_\parallel$ at all energies of interest, the injection threshold decreases sharply when the angle between $\mathbf{B}$ and the shock normal, θ_{bn} approaches 90° because there is not field-aligned anisotropy in this case.

For the final scenario we assume that the entire population of particles originates at a location magnetically connected to the spacecraft, i.e., the spectra observed are essentially spectra at $r_{\rm sh}$. In addition we assume a 130-day cyclical injection pattern where injection operates for 15 days when the shock is either quasi-parallel or strictly perpendicular, followed by 115 days of acceleration without injection. Because the TS is expected to be quasi-perpendicular most of the time, our assumptions regarding the injection cycle are not unreasonable.

Figure 2 (right panel) shows the resulting particle distributions at two different moments in time. During the injection part of the cycle a power law is quickly established at low energies. Once the injection ceases, particles continue to be accelerated to higher energies by the shock. At those times the distribution resembles a modulated spectrum, although it is more of a consequence of limited acceleration time rather than particle escape from the shock region upstream. Comparing the model spectra with the Voyager 1 observations shows a good qualitative agreement. It appears that intermittent injection might be the mechanism that could explain the properties of the double spectrum.

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