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Implications of the Two-Population Spectra Observed by Voyager-1 at the Termination Shock

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It seems conceivable that, in 2002-2004, Voyager-1 was still inside the termination shock, but its magnetic field line had intersected the shock between V-1 and the Sun. This may well occur if the field line intersect the shock multiple times, which can occur for a number of plausible reasons. We discuss this of multiple intersection in the light of new findings of V-1 since crossing the shock in December 2004. We address the effects of such multiple intersection on the energy spectra. and stress that the shock will not produce a uniform power-law everywhere. Instead, a two-population spectrum, similar to that observed by Voyager-1, can be expected if flirting field lines cross and recross the shock. The two-population spectra observed by V-1 is interpreted as a signature of acceleration at different sites.

1. Introduction

There is a consensus that Voyager-1 (V-1) did cross the termination shock (TS) at the end of 2004. Events associated with the proximity of the TS started in 2002, when V-1 observed unusual enhancements of particle fluxes. Krimigis et al. [1] interpreted their low-energy observations in terms of crossing the TS in 2002. On the other hand, anomalous cosmic rays (ACRs) remained modulated and below their solar minimum level, which led McDonald et al. [2] to conclude that V-1 was still inside the TS. The 2002 magnetic field measurements [3] did not show the predicted increase and the radio data [4] did not indicate shock crossing either.

The large field-aligned streamings detected from the sunward direction strongly suggested that particles were accelerated between V-1 and the Sun. This, however, need not necessarily imply that V-1 had to be beyond the shock. An alternative, and more likely interpretation [5] [6], [7] is that V-1 was still upstream, but on a field line that had already intersected the shock between V-1 and the Sun, which could account for the occurrence of low-energy field-aligned particle streaming from the sunward direction. Such multiple intersection of the TS can be resulted from a number of reasons, associated with either random or organized deviations from a spherical shock, or from the nominal spiral field.

Since the crossing in December 2004, V-1 found steady high particle fluxes, little variability, and small anisotropies. At the same time, ACRs still remain modulated. In the present work we discuss the model of multiple intersection in the light of these findings.

2. Model

We assume that (transient or organized) deviations either from a spherical shock or from the nominal spiral field lead to multiple intersections between the field line of Voyager-1 and the TS. This could arise from a number of conceivable causes, a plausible cause was discussed by Jokipii et al. [7]. Figure 1 shows a schematic illustration of one simple realization of our model. For the sake of simplicity, we let the magnetic field be convected at a uniform speed, but assume an excursion of the field line that results in three (or more) intersections with the termination shock. We emphasize that similar topology would result from an incursion of the TS suggested by Jokipii and Giacalone [8], or from FALTS due to velocity shears [9].

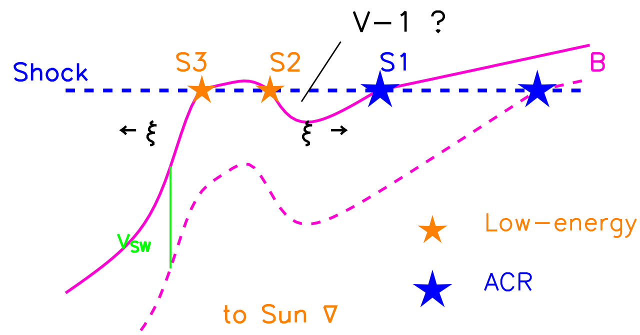

Figure 1. Schematic view of the model: an excursion of the field line (or incursion of the shock) results in multiple intersections (S1, S2, S3) with the shock.

Shock acceleration occurs at all three intersections S1, S2, and S3. ACR energies are reached, however, only at the rightmost intersection (S1), where enough time is available for acceleration. At the "new" sites (S2 and S3) acceleration starts only when the field line hits the shock. Low-energy particles from S2 and S3 could be seen by V-1 if it is close to one of these sites. Field-aligned streamings, pointing away from their respective sources, are expected upstream. To detect streaming from the sunward direction in 2002, V-1 had to be at a position near to and right from S2.

Large anisotropies are more likely to occur upstream of the shock. Left from the leftmost intersection (S3), particle streamings point toward the Sun, so this would be the "wrong" side to obtain the observed anisotropies. Downstream, between S2 and S3, a more or less isotropic distribution is expected, which does agree with the small anisotropies observed by V-1 in 2005.

Figure 1 illustrates the connection of V-1 to the TS at one instant. In time, always new field lines will be swept by V-1, so we expect the connection to the TS to have a considerable variability, due to random causes. This should lead to a variability in the fluxes reaching V-1 prior to crossing. Downstream, after crossing the TS, V-1 is always connected to the TS, hence lower variability is plausible.

3. Numerical Illustrations and Discussion

In the simulations presented here we consider a spherical shock and uniform radial solar wind, but impose a radial excursion on the nominal Parker spiral. We choose this case for its conceptual simplicity, and emphasize that other cases, like non-spherical shock, are topologically the same and give very similar results.

Large field-aligned anisotropies call for the use of the focused transport equation, which assumes gyrotropic distribution and retains the full pitch-angle information (for details see [5]).

We assume an underwound spiral by an artificial tenfold reduction of the rotational rate of the Sun. This way we avoid difficulties from omitting perpendicular diffusion while the underlying physics remains transparent, and qualitative features can best be seen. The TS of a shock-ratio 3 is placed at 90 AU, calculations are reduced to the 60-100 AU radial range. We note that 2-D numerical simulations including perpendicular diffusion (not discussed here) lead to conclusions similar to the ones presented here.

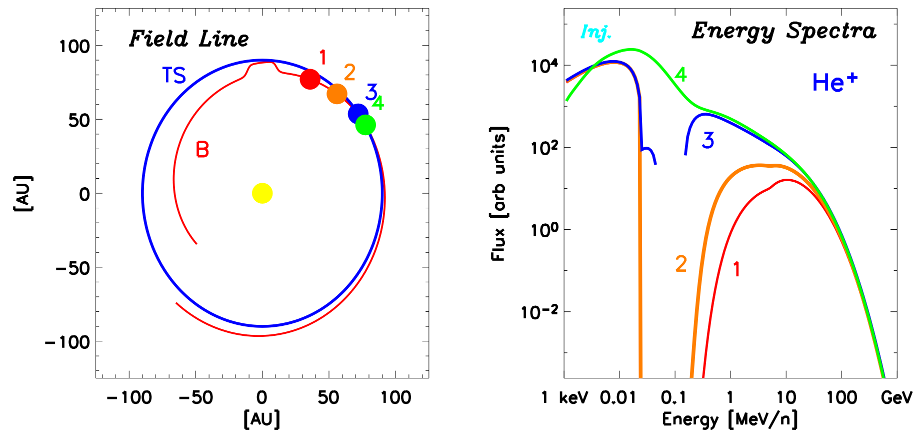

Figure 2. The excursion on the magnetic field line (left) has not yet reached to the shock. ACRs are modulated and low energy particles are absent at locations 1 and 2, inside the TS (right).

Figure 2 shows an example when the 10 AU excursion does not yet connect the TS, so it has no noticeable effect. Low-energy particles are not seen and ACR fluxes are increasingly modulated inward from the TS.

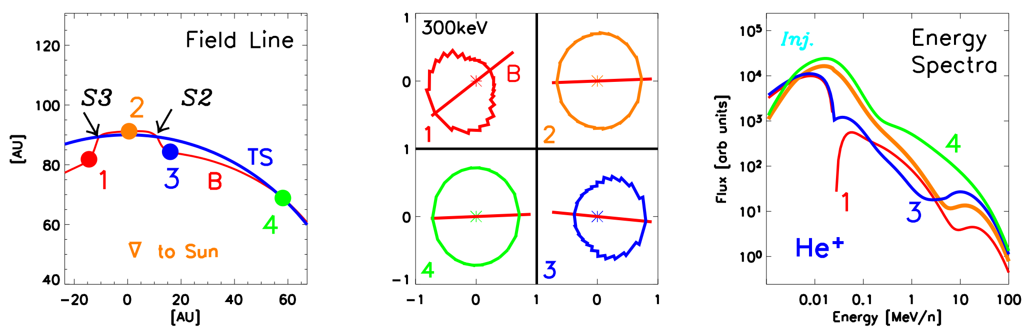

Figure 3. Energy spectra (right) and pitch-angle distributions (center) at four locations on a field line (left). Low-energy particles appear near the sites where the excursion reaches the shock. Large field-aligned streamings point away from their respective sources upstream (1 and 3), while near isotropy prevails downstream (2 and 4). Location 4 is downstream, at site S1. Note the difference between the two downstream spectra.

Figure 3 shows an instance when the excursion of the field line reaches the TS, so that two new additional sites of acceleration (S2, S3) emerge. As a result, low energy particles appear upstream on both sides, near S2 and S3. However, owing to the short time available, these sites cannot accelerate to higher ACR energies. The resulting energy spectra consist of two populations: a power-law at low energies, which is accelerated at the nearby fresh intersection, and a modulated ACR spectrum at higher energies, which is accelerated farther away at S1. Also shown in Fig. 3 are the predicted pitch-angle distributions measured in the solar wind frame. Field-aligned streamings, pointing away from their respective sites of acceleration, occur upstream near S2 and S3. At location 1, i.e. upstream left from S3, the field-aligned streaming points sunward, while at location 3, right from S2, low-energy particles stream from the sunward direction, and ACRs are still modulated similarly as observed by V-1 in 2002-2004. The downstream distribution turns out quite isotropic, in contrast to the highly anisotropic upstream ones. In the downstream segment (2) between S3 and S2, low-energy flux is expected to be steady, high, and more or less isotropic, similarly as observed by V-1 in 2005.

The unmodulated ACR spectrum is seen at at location 4, close to S1. We stress that two-population spectrum is predicted not only upstream but also in the downstream segment between sites S3 and S2. This is so, because ACRs are accelerated only at site S1, farther away. The shock will not produce a uniform power-law spectrum everywhere, the results obtained for a plane shock cannot be directly applied. The underlying reason is that the time available for acceleration is short if flirting field lines cross re-cross the shock only briefly. This is clearly seen in Fig. 3, where the downstream spectra are quite different at the two respective regions of the TS.

4. Conclusions

We considered a scenario where V-1's field line intersects the TS multiple times, and find that this model may account for V-1 observations both prior to and after the TS crossing in late 2004. A situation similar to Fig. 1 may occur for a number of reasons. Small deviations from either the nominal spiral field, or from a spherical shock, are likely to lead to multiple intersections. Then, low-energy particles appear from the nearby intersection, leading to large field aligned anisotropies. Acceleration, however, cannot start before the field line reaches the shock. Hence, the new nearby intersection has insufficient time to accelerate to ACR energies. ACRs, which are accelerated at and arrive from a more distant part of the TS (site S1), are still modulated.

We stress that a shock may not produce a uniform power-law spectrum everywhere, as long as cross-field transport is small. The two-population energy spectrum, consisting of a low-energy power-law and a still modulated ACR component as observed by V-1, may continue into the downstream regions if field lines cross and re-cross the TS. The spectrum may not unfold to a full power-law due to the insufficient time for acceleration. The strongest particle signature of the shock crossing is the disappearance of the large upstream anisotropies.

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