An explanation of the Voyager paradox: Particle acceleration at a blunt termination shock

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[1] Voyager 1 recently crossed the termination shock at the edge of our heliosphere. In contrast to the expectations of essentially all prior models, however, Voyager 1 did not observe the source of Anomalous Cosmic Rays (ACRs) as had been widely anticipated. We show here that the dearth of higher energy particles near the nose of the heliosphere is a natural consequence of the magnetic geometry in the region ahead of a flattened shock. Particle energization happens primarily back along the flanks of the shock where the injection energy is lower and where the magnetic field has had progressively longer connection times to accelerate particles. In addition to explaining the most baffling aspects of the Voyager 1 observations, this paradigm makes explicit predictions about what should be observed when Voyager 2 reaches the termination shock, significantly further back from its nose. **Citation:** McComas, D. J., and N. A. Schwadron (2006), An explanation of the Voyager paradox: Particle acceleration at a blunt termination shock, *Geophys. Res. Lett.*, *33*, L04102, doi:10.1029/2005GL025437.

1. Introduction

[2] The 23 September issue of *Science* documented the Voyager 1 spacecraft's recent and remarkable crossing of the heliospheric Termination Shock (TS) [*Stone et al.*, 2005; *Decker et al.*, 2005; *Gurnett and Kurth*, 2005; *Burlaga et al.*, 2005], the innermost structure in our heliosphere's interaction with the local interstellar medium. The TS marks the boundary where the Sun's super-magnetosonically expanding solar wind abruptly slows to become sub-magnetosonic flow. Because the Sun and heliosphere move through the magnetized interstellar plasma (with a relative velocity of $\sim$25 km s^{-1}) the slowed solar wind must be diverted back and away from the upstream medium; this diversion occurs in the inner heliosheath, the region beyond the TS and inside the heliopause – the boundary that separates plasmas of solar and interstellar origins.

[3] The TS has been widely believed to be the accelerator of Anomalous Cosmic Rays (ACRs), produced from a seed population of interstellar neutral atoms, which freely drift into the heliosphere prior to being ionized and picked up in the solar wind flow [*Pesses et al.*, 1981]. In order to reach the observed energies of $\sim$100 MeV/nuc, ACRs are thought to be accelerated by a "diffusive" acceleration process where they successively gain energy by scattering back and forth across the TS many times. Theories of ACR generation prior to Voyager's passage through the TS almost universally predicted that just beyond the TS, the energy spectrum would extend smoothly as an unmodulated power-law spectrum, or "unfold," up to ACR energies. The characteristic ACR bump, caused by modulation, in the spectrum at high energies (10–100 MeV/nuc) that has become the ACR observational trademark inside the TS would finally subside, signifying Voyager's local passage through the ACR acceleration region.

[4] On 16 December 2004, the Voyager 1 spacecraft crossed the termination shock at a heliocentric distance of $\sim$94 AU, directly measuring the expected compression of magnetic field [*Burlaga et al.*, 2005] inferring strong slowing of the solar wind [*Decker et al.*, 2005], and observing the end of upstream plasma oscillations [*Gurnett and Kurth*, 2005]. The shock was also a steady source of lower energy energetic protons [*Stone et al.*, 2005] and the lowest energy electrons and ions exhibited roughly ten-fold increases across the shock, with smaller increases at higher energies [*Decker et al.*, 2005]. It was completely unexpected when the observed ACRs did not peak at the TS as had been so widely predicted. Instead, for example, the 20 MeV/nucleon helium was <10% of the predicted source intensity and 4 MeV/nucleon oxygen was only $\sim$5% of that expected for a weak termination shock source [*Stone et al.*, 2005]. Finally, energetic particle distributions have been highly isotropic since crossing the shock and their fluxes have continued to rise steadily as Voyager 1 has moved deeper into the heliosheath [*Stone et al.*, 2005; *Decker et al.*, 2005].

[5] These observations indicate that ACRs are not accelerated ubiquitously at the TS as previously believed. Alternate suggestions invoke acceleration in special, localized regions on the TS including "favored acceleration locations at the termination shock (FALTS)" [*Schwadron and McComas*, 2003], or possibly near the poles of the TS or at lower latitudes, where increased turbulence could result in higher rates of diffusive shock acceleration [*Stone et al.*, 2005]. Another possibility is that ACRs might not really be accelerated anywhere on the TS, but instead, somewhere further out, beyond this shock, either through some sort of distributed energization in the inner heliosheath or even further out at the heliopause, where magnetic "reconnection" between solar and interstellar fields might provide a fundamentally different energization mechanism. In reality, however, each of these suggestions runs into significant problems in explaining Voyager 1's observations, either due to lack of sufficient acceleration rates, or

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by predicting characteristics such as high time variability, which are not observed.

2. Particle Acceleration at a Blunt Termination Shock

[6] We propose here an explanation for the Voyager 1 observations in which flattening of the nose of the TS produces a macroscale geometry that leads to a time dependant acceleration process. In this process higher energy particles are generated at locations where the magnetic field lines have pierced the TS for longer times, back along the flanks of the TS. Another aspect of the flattened TS shape is that the magnetic field angle with respect to the shock varies in a characteristic way such that significantly lower particle injection energies are allowed along the flanks of the TS. By including a realistic shock geometry, ACR energization can be produced through standard shock acceleration mechanisms, thus retaining the important ACR interstellar pick up ion composition signature.

[7] The configuration is schematically displayed in Figure 1. The thick black line shows an equatorial TS shape derived from a 2-D hydrodynamic simulation, which included a strong TS and an upstream bow shock [*Zank*, 1999]. Inside the TS is the standard Archimedean spiral magnetic field, while outside are heliosheath field lines that connect up to the spiral at the TS. For a spherical shock (circular cross-section) any given flux tube pierces the shock at only one point and outside the shock the field is simply wrapped in a concentric spiral. However, for a more realistic shock that is flattened on the nose or flared out on the flanks, a single magnetic field line traverses the shock many times [*Zank*, 1999] leading to a region ahead of the TS where field lines stay connected to the shock for increasingly longer times. *Jokipii et al.* [2004] recently invoked the flattening of the TS for a different purpose - to provide a possible explanation for particle anisotropies observed by Voyager 1 in precursor events inside the TS.

[8] When a flux tube initially pierces the TS near the nose, it is populated with relatively few energetic particles with energy spectra very similar to those measured just inside the TS. As the field line moves further out, it stays connected back along the flanks of the TS allowing more and more time to generate significant fluxes of higher energy particles. In those regions higher and higher energy particles can be produced and the energy spectra progressively unfold. The piercing points continue to move back along the flanks until they disconnect from the shock; at that point the particle fluxes should have reached their maxima and the ACR spectra should be fully unfolded. Thus, while energetic particles are accelerated everywhere on the TS, ACRs can only be accelerated to their final energies back along the flanks of the TS, where the oldest trapped flux tubes connect to it.

[9] We provide here a simple model for the magnetic geometry in the inner heliosheath for a symmetric flaring TS structure. We parameterize the shape of the shock as:

$$R_{TS} = R_{\rm Nose} + (R_{\rm Flank} - R_{\rm Nose})\left(\frac{|\varphi - \varphi_{Nose}|}{|\varphi_{Flank} - \varphi_{Nose}|}\right)^{\gamma}$$
$$\text{for } 0 \le |\varphi - \varphi_{Nose}| \le |\varphi_{Flank} - \varphi_{Nose}| \qquad (1)$$

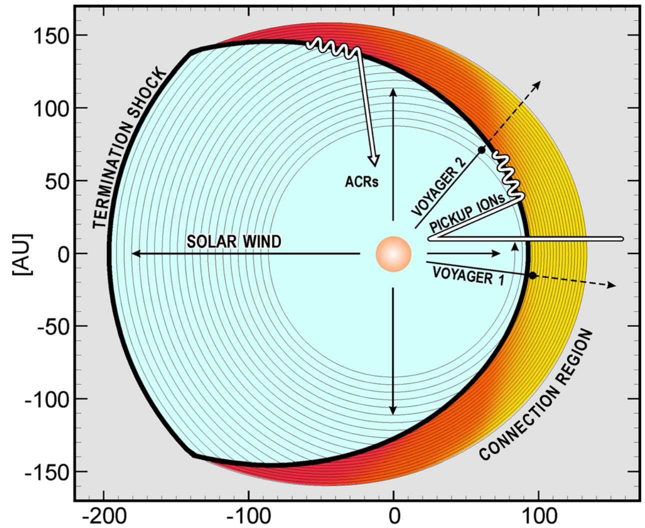

Figure 1. Schematic diagram of an equatorial cut through the Termination Shock. The magnetic field lines outside, in the connection region, must connect to the Archimedean spiral inside. The approximate positions of Voyager 1 and 2 are shown neglecting their different latitudes. Pickup ions are swept out to the shock in all directions, but those that cross the shock near the nose have the longest times to energize as their connection points move back along the flanks of the shock. The color coding represents the progressive energization of particles back along the shock and their difficulty in diffusing back noseward within the connection region.

where R_{TS} is heliocentric radius of the termination shock as a function of angle (longitude) from the nose, φ (at the nose, $\varphi_{Nose} = 0°$), the angle where the TS cuts off is φ_{Flank}, the heliocentric distance to the nose and flank cutoff of the termination shock are R_{Nose} and R_{Flank}, respectively, and γ is a power-law index that characterizes the shock flaring. For the shape taken from *Zank* [1999] and shown in Figure 1 the cutoff angle $\varphi_{Flank} = 135°$ and $\gamma = 2.7$; to first order we assume the cutoff angle and flaring rate to be independent of latitude. For $R_{Nose} = 93$ AU, consistent with Voyager 1 observations at 35° latitude, $R_{Flank} = 220$ AU. It is straightforward to invert equation (1) to solve for the angle (φ_{B-TS}) at which a field-line intersects the termination shock as a function of the radial distance (R_{B-TS}) of the field-line's intersection with the shock,

$$\varphi_{B-TS} = \varphi_{Nose} \pm |\varphi_{Flank} - \varphi_{Nose}|\left(\frac{R_{B-seg} - R_{\rm Nose}}{R_{Flank} - R_{Nose}}\right)^{1/\gamma} \qquad (2)$$

[10] Prior to crossing the shock, field lines move radially outward with upstream solar wind speed V_{SW} so that the crossing radius is $R_{B-TS}(t) \approx R_{Nose} + V_{SW} \cdot t_{CR}$ where t_{CR} is the time since a given flux tube pierced the nose and entered the connection region (this assumes that, on average, field-lines inside the TS are circular, which is approximately correct for the large spiral angles at large heliocentric distances). We use $R_{B-TS}(t)$ in equation (2) to solve for the azimuthal angle, $\varphi_{B-TS}(t)$, of the field line's intersection with the TS, as a function of time. We then

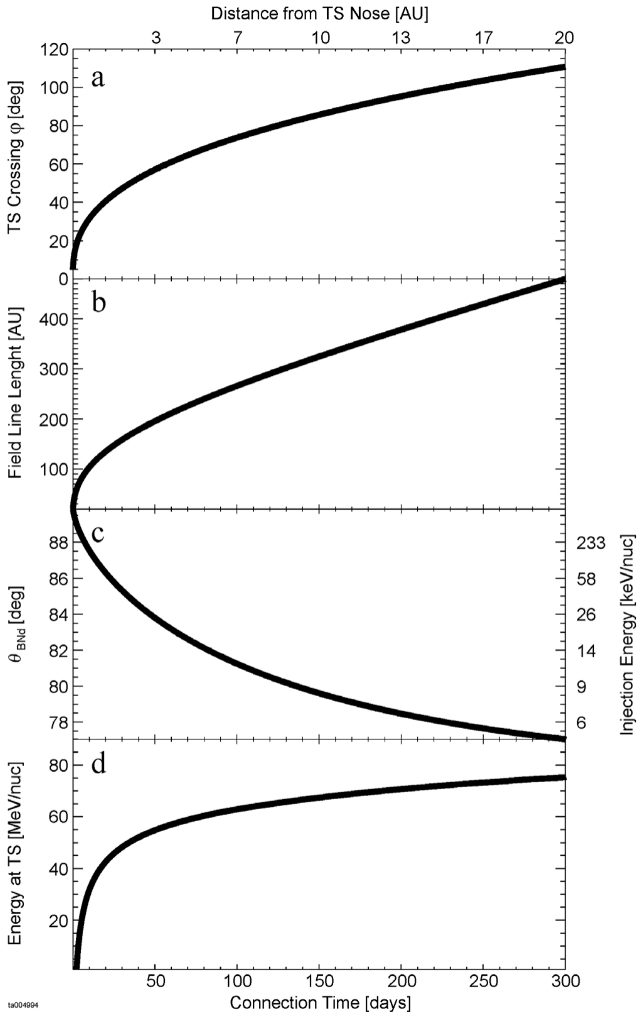

Figure 2. (a) Field line crossing angle, (b) length, (c) the downstream angle between the shock normal and magnetic field (θ_{BNd}) and injection energy, and (d) maximum characteristic energy as a function of connection time to the TS (bottom axis) and equivalently distance of field line upstream of the nose (top axis). All quantities are calculated from a simple model for the geometry shown in Figure 1, but at 35° latitude (Voyager 1). As the field line moves out in the connection region its ends move rapidly back down the flanks of the TS, both reducing the required injection energy and allowing more time for the particles to energize.

solve for the radial position, $R_{B-IH}(t,\varphi) = R_{Nose} + V_{HSh} \cdot t_{CR} + [R_{TS}(\varphi) - R_{Nose}](1 - V_{HSh}/V_{SW})$, of a point on the field-line in the connection region by propagating the field-line out with the radial speed in the heliosheath, V_{HSh}, after it crosses the TS at angle φ. We use a value of $\sim$100 km s^{-1} for V_{HSh} for this calculation, which is consistent with the observed shock jump of $\sim$3. The length of the connected field line segment in the equatorial plane is $\Delta s(t) = 2\sin\theta \int_0^{\varphi_{B-TS}(t)-\varphi_{Nose}} d\varphi R_{B-IH}(t,\varphi)$, where θ is the co-latitude. For all of the calculations shown below we use $\theta = 35°$ for consistency with Voyager 1.

[11] Figure 2a shows the φ angle (longitude) where a field line crosses the TS as a function of its connection time (how long since it first pierced the TS - bottom axis), and equivalently as a function of the distance of field line upstream from the nose of the TS (top axis). For the TS shape used here and a V_{HSh} of $\sim$100 km s^{-1}, the field lines pass beyond the flanks of the TS at $\sim$300 days and are no longer directly connected (after that they connect only after spiraling one or more times completely around the TS). Figure 2b shows the length of the field line in the connection region. As a field line is carried even a small distance out in front of the nose, its ends move rapidly back down the flanks of the TS. After the first several tens of days, the growth rate has turned over and the rates of angle spreading and length growth increasingly tend toward linear at longer times.

[12] Figure 2c shows θ_{BNd}, the angle between the shock-normal and the field-line downstream of the TS (in the inner heliosheath). The average field is nearly perpendicular right at the nose, but becomes progressively less perpendicular as the field lines move back along the flanks of the TS. The injection energy, $\sim m V_{HSh}^2/\cos^2(\theta_{BNd})$, (on the right axis) is the minimum energy that particles need to move upstream at the shock along the field and become injected into the acceleration process. As the injection energy rapidly drops below MeV energies away from the nose of the TS, it becomes increasingly easy to inject particles and begin the acceleration process.

[13] While no one really knows precisely how particles are energized at shocks, we provide here a simple calculation that demonstrates how the growing connection times at the TS can readily accelerate particles up to ACR energies ($\sim$100 MeV/nuc). The characteristic acceleration rate from diffusive acceleration of particles with momentum p may be written for a shock with compression ratio, $r = V_{SW}/V_{HSh}$, as *Drury* [1983] and *Jokipii* [1987]

$$\frac{1}{p}\frac{dp}{dt} = \frac{V_u^2}{3r\kappa_{||}} \frac{r-1}{(\cos^2\theta_{\rm BNu} + \cos^2\theta_{\rm BNd})} \tag{3}$$

where $\kappa_{parallel}$ is the parallel diffusion coefficient, which is taken to be the same in the upstream and downstream medium near the shock. The θ_{BN} angles between the field line and shock normal upstream and downstream from the shock are $\theta_{\rm BNu}$ and $\theta_{\rm BNd}$, respectively. Based on the formalism for the shock and field structure described above, $\cos(\theta_{\rm BNu}) \approx (R_{TS}\sin\theta)^{-1}\, dR_{TS}/d\varphi$ and $\cos(\theta_{\rm BNd}) \approx (V_{HSh}/V_{SW})(R_{TS}\sin\theta)^{-1}\, dR_{TS}/d\varphi$, with the result that the characteristic acceleration rate is

$$\frac{1}{p}\frac{dp}{dt} = \frac{V_{SW}{}^2}{3\kappa_{||}} \left(\frac{V_{SW} - V_{HSh}}{V_{SW} + V_{HSh}}\right) \left[\frac{R_{TS}(\varphi)\sin\theta}{dR_{TS}/d\varphi}\right]^2 \tag{4}$$

[14] We use equation (4) to solve for the characteristic momentum (and therefore energy) as a function of time in the heliosheath. We have used several assumptions for parallel mean free path, $\lambda_{parallel}$ which is related to the parallel diffusion coefficient, $\kappa_{parallel} = \lambda_{parallel} v/3$, where v is the particle speed. Note that the characteristic injection energy (for *parallel* diffusive acceleration) is

$$E_{inj} \approx \frac{2mV_{SW}{}^2}{\cos^2\theta_u} = 2mV_{SW}{}^2 \left[\frac{R_{TS}(\varphi)\sin\theta}{dR_{TS}/d\varphi}\right]^2 \tag{5}$$

[15] Figure 2d shows the solution of (4) for the characteristic energy of a particle that is injected at 0.5 MeV/nuc

and assumes a mean free path ten times the particle gyroradius (10 times the Bohm diffusion limit). In this solution, we integrate for energization along the shock only where the injection energy equation (5) is smaller than the particle energy. Once it moves back down the flanks of the TS, the particle can be readily accelerated to typical ACR energies.

[16] Away from the TS, it takes particles time to diffuse along (through parallel diffusion) and across (through perpendicular diffusion) the field lines. The characteristic diffusion time to a point on a field line a distance L_S from the TS is $\sim L_S^2/\kappa_{parallel}$ (we have neglected perpendicular diffusion, which is much less efficient). To make an estimate of characteristic maximum energies observable at various locations within the connection region, we add to the connection time at the shock this characteristic parallel diffusion time and solve for the characteristic energy. Beyond the TS, we take a parallel mean free path $\lambda_{parallel} \sim 2\ (p/p_1)^{1/3}$ AU (p_1 is the momentum associated with an energy of 1 GeV/nuc), which is comparable to that given by *Cummings and Stone* [2001]. Although the particles rapidly energize at the shock, the large diffusion time prevents these particles from reaching an observer near the nose for a considerable time after they are accelerated. The solid lines in Figure 3 show characteristic maximum particle energies for the nose and various angles back from it, again all for a latitude of $\sim 35°$. At lower latitudes the connection time becomes even longer and maximum energies should be somewhat higher. The dashed line indicates that near the nose, particles from closer regions on the TS are likely to fill in somewhat at lower energies.

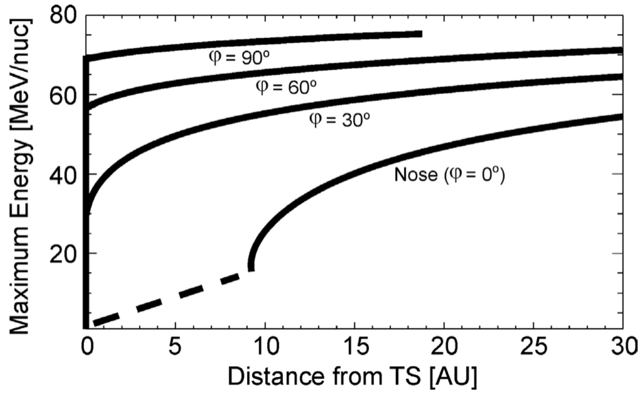

Figure 3. Maximum characteristic energy from the same calculation used for Figure 2 (solid lines), but showing the different spectra for distances radially out from the nose and at longitudes back from the nose of 30°, 60°, and 90°. The dashed line on the bottom curve indicates that lower energy particles are likely to fill in from closer location on the TS. Note that for even small angles back from the nose, like that expected for Voyager 2, significantly higher energy particles should be observed immediately beyond the TS.

3. Discussion

[17] It is important to note that while we have used a specific model for the TS shape, made assumptions about the heliosheath conditions, ignored perpendicular diffusion, and have not explicitly modeled particle flux, the qualitative results are not highly dependent on these details. For the (on average) Archimedean spiral interplanetary magnetic field (inside the TS), a significant connection region will occur for any realistic (flattened) TS shape. In addition, for a different shape TS that extends further back on the tailward side, the connection region would continue past the flanks and into the tail, with increasing energization back to the point where the magnetic field disconnects from the shock. While a complete model is likely to complicate the simple picture, the geometrical considerations of the TS geometry and magnetic structure in the connection region lead to the inescapable conclusion that acceleration of particles to ACR energies occurs where field lines have been connected for long periods of time, far from the nose of the TS.

[18] The process described here is consistent with the Voyager 1 results, and simply and naturally explains the most baffling aspects of those observations. Because Voyager 1 crossed the TS near the nose, it initially saw distributions of particles, which have only been recently connected. The roughly ten-fold increase at the lowest energies suggests that it did not cross exactly at the nose, but a short distance away, where the lowest energy particles had had time to start to intensify. More recently, as Voyager 1 has continued to travel further out, it has observed steadily rising fluxes of higher energy particles and the unfolding of the ACR spectrum, as expected for flux tubes sampled progressively further out in the connection region.

[19] An important result of the acceleration at the TS being driven by the global shape of the shock is that the ACR source should be relatively steady, as is observed. Even though local variations will impact the localized particle acceleration, the global acceleration is determined by the macro-scale geometry. Because a particle's connection time is simply related to its position back along the flanks of the TS, and energization occurs through many different interactions under locally varying shock conditions, the resultant distribution will be smoothed out and integrated over the various local interaction geometries experienced by the particles.

[20] The explanation given here provides some explicit predictions for what Voyager 1 should see as it continues further out in the heliosheath and what Voyager 2 should observe as it reaches the termination shock. At Voyager 1, the energetic particle fluxes should continue to rise and the ACR spectrum should continue to unfold relatively smoothly as it gets further out into the heliosheath, but will probably never see the fully unfolded ACR spectrum. Because Voyager 2 will cross the TS further back from the nose than Voyager 1 did, it should immediately sample older flux tubes and hence observe a larger jump in energetic particle fluxes and a more unfolded ACR spectrum where it crosses the shock. In addition any leakage of energetic particles through the TS (possibly as precursor events) could show higher energy particles and more unfolded spectra than observed ahead of the Voyager 1 crossing. Finally, beyond the connection region, field line lengths back to the TS become discontinuously longer and

ACR fluxes should drop as perpendicular diffusion becomes the essential transport mechanism.

[21] In conclusion, the seemingly paradoxical Voyager 1 observations of non-local ACR acceleration are likely a natural result of sampling particles that have just started to energize near the heliospheric nose. Because particles are magnetically connected in the region ahead of the TS, they continue to energize as they spend more time and propagate further back along the flanks of the TS. Diffusion of the particles out in this connection region determines their distributions beyond the TS with increasingly high energy ACRs observed both further back and further out in the confinement region.

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