Termination Shock Measured by Voyagers and IBEX

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Abstract

Our heliosphere’s innermost boundary—the termination shock—slows and heats the supersonic solar wind and energizes anomalous cosmic rays (ACRs). We show that in addition to their termination shock crossings, the Voyager 1 and 2 spacecraft measurements identify additional points on the termination shock when they magnetically disconnect from the ACR source. These four points define a spherical approximation of the termination shock with radius 117 au, offset ~32 au tailward, ~27 au north, and ~12 au to the port side of the Sun. Interstellar Boundary Explorer (IBEX) spacecraft observations independently confirm these general offsets, with the closest region of the termination shock ~ 20° south of the interstellar inflow direction and a minimum distance ~74 au. The maximum distance is ~161 au, consistent with required ACR acceleration times. Thus, Voyager and IBEX spacecraft observations have directly revealed the global size and location of our heliosphere’s termination shock for the first time.

Unifed Astronomy Thesaurus concepts: Interplanetary particle acceleration (826); Heliosphere (711); Cosmic rays (329); Solar wind termination (1535); Heliosheath (710); Termination shock (1690); Solar wind (1534)

1. Introduction

Our Sun and the entire solar system travel through interstellar space with the supersonically expanding solar wind carving out a bubble—our heliosphere—in the local interstellar medium. The heliosphere shields the inner solar system from the vast majority of galactic cosmic ray radiation (GCR). At the termination shock (TS), the solar wind is slowed, heated, and begins to deflect away from the inflowing interstellar medium. Beyond the TS, the deflected solar wind and inflowing interstellar flow meet at the heliopause.

Voyager 1 crossed the TS at 94.0 au in 2004.96 (Stone et al. 2005) and Voyager 2 crossed it at 83.7 au in 2007.66 (Richardson et al. 2008; Stone et al. 2008). Since then, Voyager 1 crossed the heliopause and entered interstellar space at 121.6 au in 2012 (Gurnett et al. 2013; Stone et al. 2013), and Voyager 2 just crossed the heliopause in late 2018 at ~119 au (Brown et al. 2018). Simultaneously, the Interstellar Boundary Explorer (IBEX) mission (McComas et al. 2009a) has been remotely imaging the heliosphere’s global interaction with the interstellar medium and showed that this interaction is highly asymmetric, with strong nose-to-tail asymmetry, and other asymmetries associated with the pressure induced by the interstellar magnetic field that is draped around the global heliosphere (e.g., McComas et al. 2009b, 2017; McComas & Schwadron 2014). Much has been learned about the heliosphere’s global interaction, but prior to this study, the size and shape of the global TS has not been observationally determined.

Anomalous cosmic rays (ACRs) are produced from interstellar pickup ions (Fisk et al. 1974) that are accelerated to energies of roughly a few hundred MeV over timescales of a year or less (Jokipii 1996; Mewaldt et al. 1996; Bargehouty et al. 2000; Gialalone et al. 2012). Early observational constraints led to the widely held belief that the TS was the source of their acceleration (Pesses et al. 1981; Jokipii 1992). However, when Voyager 1 crossed the TS it did not observe the expected peak in ACR intensities extending up to high energies (Stone et al. 2005). This dearth of ACRs was soon explained as arising naturally from a “blunt” TS geometry (McComas & Schwadron 2006), where the Sun’s magnetic connection starts at the closest point on the TS (near to the direction into the interstellar inflow) and moves progressively back along the flanks and tail of the TS as the solar wind continues to flow outward. ACRs are accelerated to increasingly higher energies until the magnetic flux tube disconnects from the shock. Subsequent simulations have further examined this effect and have shown that the acceleration is most efficient and extends to higher energies toward the flanks and tail (Kóta & Jokipii 2008; Schwadron et al. 2008; Guo et al. 2010; Kóta 2010; Senayake & Florinski 2013).

Alternative mechanisms for ACR acceleration have been proposed, including by compressive turbulence in the heliosheath (Fisk & Gloeckler 2009), magnetic reconnection near the heliopause (Drake et al. 2010), second-order Fermi processes (Strauss et al. 2010), and the combination of shock and magnetic islands acceleration (e.g., Zank et al. 2015). However, there is overwhelming evidence for the blunt TS paradigm as a dominant process for ACR acceleration. Besides being a simple and natural extension of the previously accepted ACR acceleration mechanism, it is strongly supported by multiple observations. For example: (1) variations of ACRs in response to transient events enabled reasonable estimations of the TS location prior to Voyager 1’s crossing (e.g., McDonald et al. 2000); (2) inner heliosheath parameters applied to simple shock acceleration models yield consistent acceleration times approaching 1 yr (e.g., Jokipii 2012); (3) prior to each spacecraft’s TS crossing, low-energy ACRs were observed to stream preferentially from the nearer side of the TS (Krimigis et al. 2003; Jokipii et al. 2004; Decke et al. 2005, 2008; Stone et al. 2017). Finally, the blunt TS geometry allowed McComas & Schwadron (2006) to predict the progressive unfolding of the ACR spectrum as each of the Voyagers moved out further...
Beyond the TS into the surrounding heliosheath. The unfolding of the ACR spectrum did occur as predicted, as the Voyagers sampled ACRs on magnetic flux tubes connected progressively farther back along the flanks and tail of the TS. In this study, we show that the Voyagers remotely detect the eventual disconnection of the magnetic flux tubes from the TS. These disconnections provide measures of the distance from the Sun to two other distant locations on the TS flanks/tail. These additional points allow us to calculate a spherical approximation of the TS and the offset of its center from the Sun, greatly increasing our observational knowledge and understanding of the heliosphere’s geometry, asymmetries, and scale.

### 2. Magnetic Disconnections from the TS

Figure 1 shows the variation in ACR intensities observed by Voyager 1 in the heliosheath as a function of the GCR intensity. The date of observations is color-coded and strongly correlates with the GCR intensity in the heliosheath (Cummings et al. 2016) as Voyager 1 moved outward and closer to the external GCR source. Consistent with the unfolding of the ACR spectrum as Voyager 1 traveled beyond the TS (McComas & Schwadron 2006; Cummings & Stone 2007; Stone et al. 2017), ACR intensities also increase as the spacecraft’s outward motion caused it to be connected to points progressively farther back on the TS. However, Figure 1 shows that around 2010.3 (arrow), the ACR intensities plateau and then begin to decay while the GCR intensities continue to increase. The clear interpretation of this disparate behavior of ACR versus GCR variations is that the intensities begin to decrease when the flux tube sampled by the Voyager 1 is no longer closely magnetically connected to the acceleration source on the flanks/tail of the TS—that is, when it disconnects from the TS. Beyond this point, the ACRs either need to diffuse across the field—which is much slower than along it—or travel much further along the field, making multiple loops around the TS.

The situation for Voyager 2 is more complicated than for Voyager 1, owing to the expansion and compression of the plasma in the heliosheath. These effects are driven by larger and more numerous variations in solar wind output and dynamic pressure starting in 2012 and are associated with increasing solar cycle activity. Our analysis accounts for about a one year delay for solar wind propagation from the Sun to Voyager 2 within the heliosheath. The plasma and field pressure variations were observed directly at Voyager 2 (Richardson et al. 2017; Burlaga et al. 2018). Schwadron & Bzowski (2018) studied the cooling and heating of the plasma associated with these expansions and compressions of the heliosheath; these changes within the heliosheath account for time variations (Dialynas et al. 2017) seen in higher energy Energetic Neutral Atoms (ENAs).

Figure 2 shows the comparable ACR versus GCR plot for Voyager 2 (top panel). The lower two panels demonstrate the effects of the expansions and compressions on these two particle populations. For both ACRs and GCRs, times of expansion (cooling) produce relatively flat time series. In contrast, during intervals of compression at Voyager 2, both the ACRs and GCRs rise more rapidly owing to heating in such structures (Schwadron & Bzowski 2018). It is worth noting that those authors used only the in situ measurements of the thermal plasma density, measured by a different instrument on Voyager 2, so determination of the compression and expansion regions was completely independent of the ACR and GCR variations studied here. The one large-scale exception to this rule is at 2012.1, when the ACR rates began to drop sharply as the GCR rates remain flat or increase while Voyager 2 was still well within a compression region. Disconnection of the flux tube from the ACR source back along the flanks and tail of the TS again naturally explains this abrupt change at Voyager 2. In addition, the additive effects of Voyager 2 being in a prolonged compression region while the connection point simultaneously moved back along the TS can explain the faster rise in ACR rates seen in 2010–2011 at Voyager 2 compared to 2008–2010 at Voyager 1.

### 3. Geometry of the TS

For Voyager 1, the disconnection occurred at 2010.3 at a distance of 113.2 au and for Voyager 2, at 2012.1 at a distance 97.6 au. These times are only approximate because of small scale variations in the count rates. To calculate the distance to the disconnection points on the backside of the TS, we use the ratio of the average solar wind speed (∼420 km s⁻¹) inside the TS to the typical radial speed observed in the heliosheath by Voyager 2 (∼120 km s⁻¹; see Appendix A). Since the solar wind inside the TS is ∼3.5 times as fast as in the heliosheath, it moves about three and a half times farther radially outward than the distance of the spacecraft beyond the TS at any time. Assuming no motion of the TS over time, the tailward disconnection point measured by Voyager 1 is at 94.0 + 3.5 × (113.2–94.0) = 161.2 au; the disconnection point measured by Voyager 2 is at 83.7 + 3.5 × (97.6–83.7) = 132.4 au.

With this information, we are able to calculate the approximate 3D size and location of the TS directly from observations, for the first time. We know the Voyager 1 and 2 TS crossing locations precisely and have just calculated the disconnection distances to points on the backside of the TS. Because the solar wind flow is nearly radial inside the TS, the disconnection points must be at essentially the same solar rotational latitudes as their respective TS crossings. Further, disconnection should occur at the longitude where the TS distance is greatest. For all latitudes, this is likely very close to the downwind interstellar flow longitude (McComas et al. 2015).
Because we have four known points on the TS, we fit the general shape for four unknowns—a sphere. Of course, the TS is almost certainly not exactly spherical, but this provides a good first approximation. This yields a sphere of radius 117 au, which is offset from the Sun by ∼32 au downwind (opposite the interstellar inflow direction), ∼27 au north (in the sense of the Sun’s rotational axis) and ∼12 au to the port side (see Appendix B for the details). We also assessed the uncertainty of the TS parameters derived from this calculation by assigning notional errors to the crossing distances. We use a 1 au error on the Voyager 1 and 2 TS crossings since those were directly measured, and assume a much larger, 10 au, error on the derived disconnection distances. Together, these produce changes in the derived radius of 1.5 au, and x, y, z offsets of (2.7, 8.8, 2.4) au, all but the y value of which are much smaller than the assumed disconnection distance errors.

A tailward offset (−x) of the TS of ∼32 au is not surprising owing to the dynamic pressure of the inflowing interstellar medium. The large northward offset (z) of ∼27 au is likely created by the magnetic forces pushing upward on the southern portion of the heliopause owing to the strong magnetic pressure imparted by the highly inclined local interstellar magnetic field (McComas et al. 2009b). In contrast, a port offset (y) is opposite to what one might naively expect from the port/starboard tilt of the external magnetic field. The center of the sphere with little transverse offset, or even a small (∼12 au) port offset, is consistent with the error derived above, but may also indicate the strong influence of the Sun and solar wind on the interaction. The main factor is likely the strong heliolatitude organization of solar wind structure, such as the North–South asymmetry observed in the recent solar cycles (Chowdhury et al. 2013).

Figure 3 shows the calculated distance from the Sun to the TS (top). The closest point is only ∼74 au (ecliptic 231°6, −30°6), and the farthest point is more than twice as far at ∼161 au (ecliptic 51°6, 30°6); this difference in distances is consistent with connection times of most of a year and thus the required diffusive shock acceleration timescale to reach maximum observed ACR energies (Mewaldt et al. 1996). IBEX observations already showed that the heliosheath pressure maximum, and thus closest regions of the TS, is likely centered ∼20° south of the inflow direction (McComas & Schwadron 2014; Schwadron et al. 2014). More recently, McComas et al. (2018b, 2019) examined the outer heliosphere’s response to a large (∼50%) multiyear enhancement in the solar wind dynamic pressure that passed 1 au over the second half of 2014. The closest region of the heliosheath “lit up” with strongly enhanced ENA emissions in the highest energy bands observed by IBEX in 2017 (bottom of Figure 3). In earlier years, the ENA signal in these energy bands was almost constant over the forward hemisphere (McComas et al. 2017). Therefore, the enhancement definitively shows the position where the pressure enhancement in the solar wind arrived first at, and thus the closest region of, the TS and...
Figure 3. Mollweide map of distance from the Sun to the TS from our spherical approximation of the TS passing through the four known points (top). Dashed lines show latitudes of the Voyagers (V1 and V2) crossings (and hence their disconnections from the TS) and the solid white line shows the $B - V$ plane (defined by the local interstellar magnetic field ($B$) and plasma inflow ($V$) vectors and orders the external forces on the heliosphere). The spatial distribution of $\sim$4.3 keV ENA fluxes observed by IBEX in 2017 (bottom) show that the nearest region of the TS (and heliosheath) is located close to that indicated by the spherical approximation, and not to the port (left in this image) as would be expected for the transverse tilt of the interstellar field (along the $B - V$ plane).

Figure 4. Schematic representation of the three-dimensional heliosphere. Inside the TS, the solar wind expands radially in all directions, wrapping up the interplanetary magnetic field into Archimedean spirals (black/white). As shown by McComas & Schwadron (2006), the blunt TS geometry produces a characteristically variable geometry with increasing perpendicular shock geometries and longer connection times for particle acceleration as the connection point moves back tailward along the TS (red). Beyond the TS, V1 and V2 were magnetically connected (yellow “Connection Region”) farther back along the flanks of the TS until the magnetic flux tube each was on disconnected from the farthest point back on the shock. The two TS crossing points and two disconnection points define a sphere that observationally determines the overall size and location of the TS for the first time. This spherical approximation for the TS has a radius of 117 au and is centered at $\{x, y, z\} = \{-32, 12, 27\}$ au in the coordinate system shown.
heliosheath. The good agreement of the closest regions of our offset sphere with these direct IBEX observations further validates our 3D approximation of the TS.

4. Discussion

The geometry of the heliosphere and offset TS structure are displayed schematically in Figure 4. The TS is offset significantly tailward and northward of the solar equatorial plane because of the combined effects of the interstellar dynamic and magnetic pressures exerted by the inflowing interstellar medium and magnetic field. This field is draped around the heliosphere and has an angle of \( \sim 60^\circ \) extending under the south side of the heliosphere.

We note that the spherical approximation of the TS derived here is just that, approximate, and the times of disconnections and latitudes and longitudes are not exact. More importantly, we assumed a time stationary TS even though variations in solar wind dynamic pressure affect the distance to the TS. For example, simulations indicate that a very large, \( \sim 50\% \), increase should expand the TS by \( \sim 7\text{ au} \) (McComas et al. 2018b; Zirnstein et al. 2018). Still, the TS will expand in all directions and this is \( <10\% \) effect in radius, so we do not expect the spherical approximation to be vastly different even for a time-varying shock distance.

In this study we used in situ observations from the two Voyager spacecraft at their TS crossings points and in the heliosheath, in concert with remote global observations from IBEX, to provide the first observational determination of the size and 3D location of the TS. Going forward, IBEX will continue to observe the next nearest portions of the the TS and heliosheath through the expansion of the solar wind’s recent dynamic pressure enhancement and returning ENAs (McComas et al. 2017, 2018b, 2019). Beyond that, the Interstellar Mapping and Acceleration Probe, currently under development for launch in 2024 (McComas et al. 2018a), will provide even much more subtle and detailed observations of the heliosphere’s global interstellar interaction and role of the TS in that interaction.

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Appendix A
Radial Flow Speed in the Heliosheath

To calculate the TS geometry in Section 3, we used the average radial speed in the heliosheath beyond the TS. We obtained this value by averaging Voyager 2 observations, shown in Figure 5.

Figure 5. Daily averages of plasma radial flow speed measured by Voyager 2’s Plasma Science experiment, shown for the interval between Voyager 2’s TS crossing and its disconnection point, which averages to be \( \sim 120\text{ km s}^{-1} \), as indicated by the solid red line.

Appendix B
Spherical Model of the TS Geometry

Because the heliosphere’s size and shape are determined by the interaction of the inflowing interstellar medium and outflowing solar wind, we choose a coordinate system based on these two organizing features. We define Cartesian coordinates \( (x, y, z) \) centered on the Sun as follows:

(1) The X-axis points toward 255°7′ in ecliptic longitude and 5°1′ in ecliptic latitude. This is antiparallel to the interstellar inflow direction. McComas et al. (2015) provide the current best consensus values for interstellar inflow well upstream (\( \sim 1000\text{ au} \)) from the heliosphere of \( \sim 25.4\text{ km s}^{-1} \) coming from \( \sim 75°7′ \) ecliptic longitude, \( \sim 5°1′ \) ecliptic latitude. Thus, the inflow velocity has a direction of \( (-1, 0, 0) \) in our coordinate system.

(2) The Z-axis is in the plane defined by the X-axis and the Sun’s rotation axis (ecliptic \( 345°7′, 82°7′ \)). The orientation is selected so that the North ecliptic pole has a positive \( z \) value. In this system, the North solar pole is in direction \( (0.088, 0, 0.996) \).

(3) The Y-axis completes the XYZ right-hand system. In this system positive and negative Y-axis show the port and starboard side of the heliosphere.

We find the TS shape approximated by a sphere based on the known positions of the TS crossings by Voyager 1 and Voyager 2, and by the distance and known heliographic latitude of the disconnection points. These points are shown in Table 1.

In this coordinate system we fit the four points on the TS with an arbitrary spherical shape \( (x-x_o) + (y-y_o) + (z-z_o) = a \). The parameters \( \{x_o, y_o, z_o\} \) indicate the offset of the center of the fit sphere from the center of the coordinate system (Sun) and the parameter \( a \) is the sphere’s radius. This produces \( \{x_o, y_o, z_o\} = (-32.24, 12.05, 27.02)\text{ au} \) and \( a = 117.45\text{ au} \). Due to the symmetry of the sphere, the farthest points from the Sun are at the HGI meridian that is defined by the vector \( \{x_o, y_o, z_o\} \) and the direction to the north solar pole, here it is along the HGI longitude \( 340°3′ \). Owing to the significant assumptions used in this calculation, we round all values to the nearest 1 au: \( \{x_o, y_o, z_o\} = (-32, 12, 27)\text{ au} \) and \( a = 117\text{ au} \).
**Table 1**
Points Defining the Spherical Approximation of the TS

| Distance From the Sun (au) | Heliographic Intertial Coordinates (HGI) | Ecliptic Coordinates | Cartesian Coordinates |
|----------------------------|------------------------------------------|----------------------|----------------------|
|                            | Long. (°) | Lat. (°) | Long. (°) | Lat. (°) | X (au) | Y (au) | Z (au) |
| Voyager 1 TS Crossing      | 94.0      | 172.3    | 253.0    | 34.1     | 81.7  | −9.5   | 45.7   |
| Voyager 2 TS Crossing      | 83.7      | 216.3    | 288.7    | −27.5    | 55.7  | 44.7   | −43.7  |
| Voyager 1 Disconnection    | 161.2     | 340.3    | 51.7     | 34.1     | −117.8| 43.5   | 101.1  |
| Voyager 2 Disconnection    | 132.4     | 340.3    | 39.8     | −27.5    | −116.0| 38.2   | −51.1  |

Note. Entries for the disconnection points in italics denote the values that were not known prior to fitting the sphere and finding the offsets of its center from the Sun.

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