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REVIEW

Voyager observations of the interaction of the heliosphere with the interstellar medium

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Abstract This paper provides a brief review and update on the Voyager observations of the interaction of the heliosphere with the interstellar medium. Voyager has found many surprises: (1) a new energetic particle component which is accelerated at the termination shock (TS) and leaks into the outer heliosphere forming a foreshock region; (2) a termination shock which is modulated by energetic particles and which transfers most of the solar wind flow energy to the pickup ions (not the thermal ions); (3) the heliosphere is asymmetric; (4) the TS does not accelerate anomalous cosmic rays at the Voyager locations; and (5) the plasma flow in the Voyagers 1 (V1) and 2 (V2) directions are very different. At V1 the flow was small after the TS and has recently slowed to near zero, whereas at V2 the speed has remained constant while the flow direction has turned tailward. V1 may have entered an extended boundary region in front of the heliopause (HP) in 2010 in which the plasma flow speeds are near zero.

Introduction

The matter between stars, the interstellar medium, varies considerably from region to region in our galaxy. The Sun is inside a very large structure called the local bubble, a region of hot tenuous gas formed by supernova explosions tens of millions of years ago [1–3]. Adjacent to the local bubble is a similar but larger bubble, also formed from supernova explosions.

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Inside the local bubble are smaller, denser clouds which may have broken off from the bubble interaction region. The Sun is now in one of these denser, cooler clouds. The H density of the local cloud is about 0.2 cm^{-3}, the temperature is about 6000 K, and the cloud moves about 23 km/s with respect to the Sun [4,5]. The magnetic field strength cannot be directly measured, but based on models is 3–5 nT [6,7].

The Sun is the source of the variable solar wind, with speeds measured near Earth ranging from 250 to 2200 km/s, proton densities from 0.01 to > 100 cm^{-3}, and an average magnetic field strength of 5 nT. Since the solar wind and local interstellar medium (LISM) plasmas are both magnetized, they cannot mix, so the LISM flows around the heliosphere. The boundary between the LISM and solar wind is the heliopause (HP), analogous to Earth's magnetopause. Since the solar wind is supersonic, a shock (called the termination shock) forms upstream of the HP. At the TS, the solar wind becomes subsonic and be-

gins to turn toward the heliotail, the stretched-out downstream region analogous to Earth's magnetotail. If the LISM were supersonic, a bow shock would form in the LISM upstream of the HP, but recent data and analysis suggest that the LISM flow is subsonic and thus the heliosphere does not have a bow shock [5].

Voyagers 1 and 2 were launched in 1977 and are now exploring the interaction between the LISM and the solar wind. They both have crossed the TS and are in the region of shocked solar wind between the TS and the HP that is called the heliosheath. In late 2011 V1 was 119 AU from the Sun and V2 was 97 AU, moving outward at 3.5 and 3.1 AU/yr, respectively. This paper reviews the observations made by these spacecraft as they enter unexplored regions of space.

Pre-termination shock

The first observed influence of the LISM on the solar wind was from the LISM neutrals.

The neutrals are unaffected by the magnetic fields and flow into the heliosphere, where they are ionized in the solar wind and form hot, $\sim$1 keV, pickup ions. These pickup ions dominate the thermal pressure outside about 30 AU and play a major role in pressure balance structures outside this distance [8]. Accelerating the pickup ions to 1 keV slows the solar wind; this slowdown was first observed near 30 AU and by 80 AU the solar wind had slowed by about 20% [9]. Some of the energy from the pickup ions is transferred to the thermal protons, causing the temperature of the solar wind to increase with distance [10].

About 2.5 years before each TS crossing, the Voyagers detected a new energetic particle component with proton energies of tens of keV to tens of MeV flowing along the magnetic field lines [11,12]. This new particle component, called termination shock particles, signified that the Voyagers were entering a region analogous to Earth's foreshock, with particles accelerated at the TS streaming into the heliosphere along the magnetic field. For these particles to be observed, the TS distance had to be further at the flanks than at the nose so that magnetic field lines at the Voyagers would also pass through the TS. Thus the TS must be blunt, or flattened, in the nose direction [13]. The bluntness alone could not account for all the particle observations; an additional asymmetry in the heliospheric boundaries due to the interstellar magnetic field was also required [14].

Termination shock

The realization that the supersonic solar wind must go through a termination shock to become subsonic was first reported by Parker [15]. The location of this shock is determined by the HP location and the upstream plasma parameters. The HP forms where the solar wind dynamic pressure is balanced by the total LISM pressure; the value of the LISM pressure is not well determined The distance to the TS, and thus the scale size of the heliosphere, were determined when V1 crossed the TS at 94 AU in 2004 [12,13,16].

Voyager 2 trails V1 by about 20 AU. It crossed the TS in 2007 at 84 AU [17–20], 10 AU closer than V1. Calculations of the TS motion based on changes in the solar wind dynamic pressure suggested that TS motion was responsible for only 2–3 AU of the distance change [17]. Thus the heliosphere is asymmetric, with the TS closer in the V2 than V1 directions. Models of the interaction of the heliosphere with the LISM show that an asymmetry occurs if the LISM magnetic field is tilted from the LISM flow direction and has a magnitude of > 3 nT [3,4]. If these conditions held, the magnetic field would drape around the heliosphere so that the magnetic field strength builds up outside the southern part of the heliosphere, and the increased magnetic pressure would push the boundaries of the southern heliosphere inward.

The TS crossing provided other surprises as well. The TS was a weak shock, with a compression ratio close to two. At Voyager 2, the speed decrease started about 80 days before the TS crossing as the speed went from 400 to 300 km/s in three discrete steps [17]. The last step coincided with a sharp gradient in the energetic particle pressure, with the inward pressure gradient force large enough to produce the observed slowdown [21]. At the V2 TS (V1 does not have a working plasma instrument), the speed decreased from 300 to 150 km/s, the density and magnetic field increased by a factor of 2, and the ion temperature increased by a factor of 30.

A major surprise (but see Zank et al. [22]) was that the heating of the thermal ions was much less than the decrease in the flow energy. Thus the flow energy had to go somewhere else. About 15% went to heating the energetic (tens of keV) ions, but the majority seems to have gone into heating the pickup ions [17], which are not directly observed.

The TS was the source of the low-energy particles observed in the foreshock; the intensities of these particles peaked at the TS [12,19]. However, the anomalous cosmic ray (ACR) intensities did not peak at the TS as expected, at least not where crossed by V1 and V2 [12,19]. ACRs are singly ionized particle with 10–100 MeV/nuc; they were observed first near Earth and their origin was thought to be pickup ions formed from LISM neutrals which were then accelerated at the TS. Thus a peak in the ACR intensity was expected at the TS. The ACR intensity did not increase at the TS; no evidence an ACR source at the TS was observed at either of the Voyager crossing locations.

Heliosheath

The heliosheath was thought to be, in analogy with planetary magnetosheaths, a highly turbulent region and this expectation has been correct [23–25]. Figs. 1 and 2 show the daily average plasma parameters obtained by fitting the observed spectra to convected, isotropic proton distributions. The broad envelope of the data and the 25-day running averages that are superposed show consistent trends. However, the individual sets of spectra very greatly on time scales of tens of minutes. The magnetic field also varies by factors of 2–3 over similar time scales [24], confirming the very dynamic and turbulent nature of this region. Although these fluctuations are large, they contain very little of the energy [25]. As V2 moves deeper into the heliosheath, these fluctuations decrease slowly in magnitude but remain significant.

By the end of 2011, V2 was 14 AU past the TS crossing distance of 84 AU. Models suggest that the TS has moved inward 8 AU since the TS crossing due the very low solar wind dynamic pressure during the recent solar minimum [26]. Thus V2 is about 22 AU deep into the heliosheath. The expectation was that the plasma speed would decrease across the heliosphere and the flow direction would turn tailward. Fig. 1
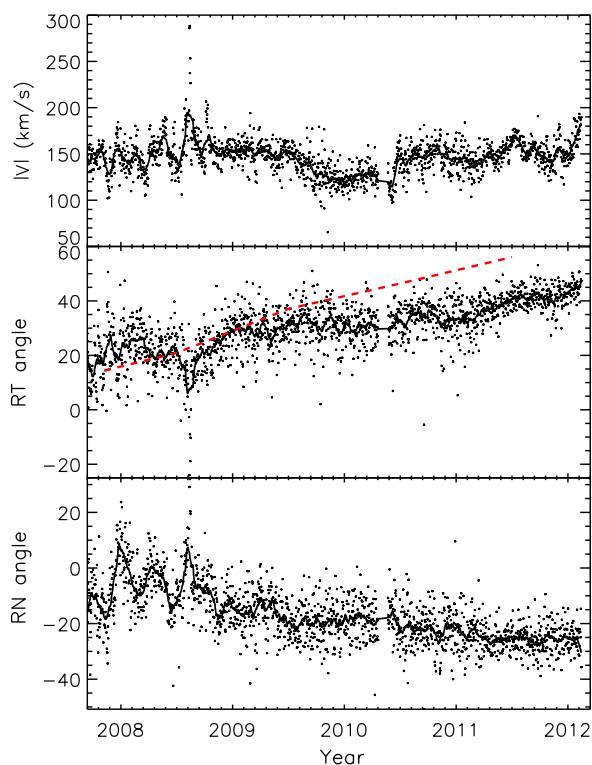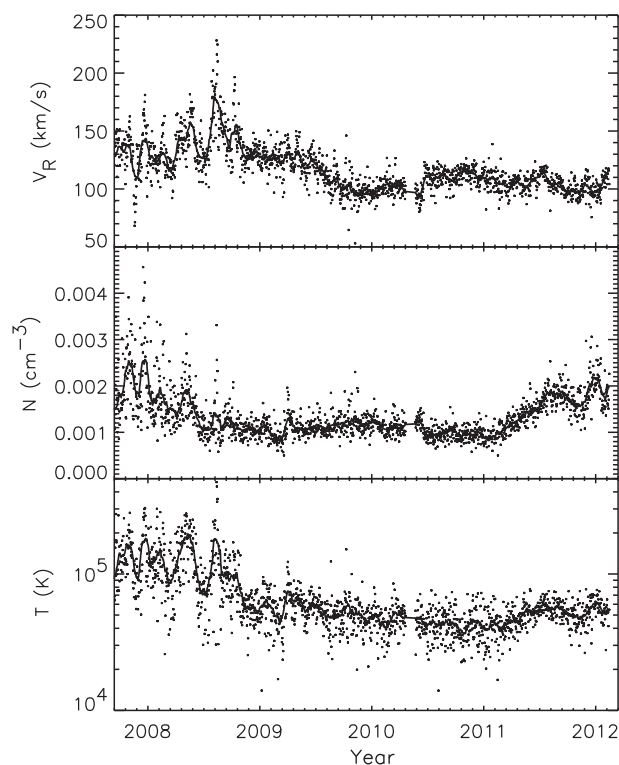
Fig. 1 Daily averages of the radial speed and flow angles RT and RN for the solar wind in the heliosheath. The solid lines show 25-day running averages and the dashed line in the middle panel shows the corrected RT flow angle.

Fig. 2 Daily averages of the radial speed, density and temperature in the heliosheath. The points are daily averages and the lines show 25-day running averages.

shows that, contrary to these expectations, the average speed at V2 has remained roughly constant at 150 km/s for over 4 years, with a brief dip in speed at 2009.7 followed by a recovery in 2010.5. These observations of steady speeds are not predicted by models [27,28] and are not understood.

Although the speed is not slowing, the direction of the flow at V2 is turning as expected.

Fig. 1 shows that the flow in the RT plane (the RTN coordinate system has R radially outward, T parallel to the solar equatorial plane and positive in the direction of solar rotation, and N completes a right-handed system) is about 20° after the TS crossing and increases to about 45° at the end of 2011. The flow in the RN plane was toward the south as expected, starting at about 10° after the TS, then oscillating for about a year before it started a monotonic increase to 25° at the end of 2011. The initial deflections at the TS must be due to the TS being at an angle to the radial flow. As discussed above, the TS is blunt near the nose, less curved than a circle, so the flow at the TS is deflected away from the nose of the heliosphere. As the plasma moves across the heliosheath it continues to turn away from the nose, as expected.

The RT angle plot shows a cutoff at about 50°. This cutoff is an instrumental effect; when the flow direction is at too large an angle to the instrument look direction the plasma is not detected. In this case the large amount of fluctuations in the heliosheath works to our advantage. The distributions of the plasma properties in the heliosheath are well represented by Gaussian distributions. The observed distributions of the plasma parameters are fit to Gaussians to find the average properties and standard deviations [23]. For the RT angle,

which is cut off at about 50°, we can fit the distribution below 50° with a Gaussian and determine the average flow angle. The flow angles determined from these fits are shown by the dashed line in Fig. 1, which shows the flow is 56° from radial in the T direction in 2011. Note that the RT angles (and thus speed) are greater than the RN angles throughout the heliosheath. Thus the TS must be more blunt in the RT than RN plane. More of the plasma goes around the sides than over the top of the heliosphere, at least in the southern hemisphere where V2 is located, which suggests that the heliosheath is compressed at the southern pole [29].

Fig. 2 shows the radial speed V_R, the density N and the temperature T in the heliosheath. Although the speed has remained roughly constant as shown above, V_R decreased from 130 to 100 km/s as the flow turned tailward. After the TS, the density initially averaged about twice the 0.001 cm^{-3} value in the solar wind but had large, factor of 3–4, fluctuations. By the end of 2008 the density had decreased by a factor of two and the fluctuations were smaller. The cause of the density decrease is likely partially the reduced solar wind flux coming from the Sun in the recent solar minimum [26] and partially a heliolatitude effect. At solar minimum the solar wind flux decreases with heliolatitude, so V2 at 30° S should observe less flux than observed near Earth at low-latitudes. However, a problem with this hypothesis is that these lower fluxes are associated with higher flow speeds, which are not observed in the heliosheath. The decrease in fluctuations may result from the very quiet solar wind conditions in this solar minimum combined with V2 moving further from the TS. The density increased by a factor of two during a 6 month period in 2011, perhaps because of a diminishment of the

heliolatitudinal flux gradient as solar minimum ends. The average density at the end of 2011 is similar to that observed just after the TS crossing, but the fluctuations in daily averages are much smaller. The temperature decreased from 150,000 K after the TS to about 40,000 K in 2011. This decrease is much larger than that expected from adiabatic cooling. Perhaps it reflects cooler solar wind encountering the TS or less heating at the TS due to differences in the upstream flow parameters. The temperature increased slightly in 2011 in concert with the increase in density, but the reason is unclear.

Although the plasma instrument on V1 does not work, the speeds in the R and T direction can be calculated from the low energy charged particle (LECP) instrument observations of tens of keV ion intensities using the Compton-Getting effect [30]. The speed profile observed by V1 is very different than that at V2. The speed after the TS was below 100 km/s and monotonically decreased from 70 km/s in mid-2007 to 0 km/s in early 2011 [31] and has since become negative. The T component of the speed averaged 40 km/s until mid-2010, when it started to decrease. Krimigis et al. [31] suggest that the decrease of the speed to near zero signifies that V1 has entered a boundary region in front of the HP in which flow is parallel to the HP. The V1 spacecraft was recently reprogrammed to do roll maneuvers so that VN could also be determined, and VN is also small < 20 km/s [32]. Thus the V1 has entered a region with nearly stagnant flow which was not predicted. V1 has now traveled more than 8 AU through this low-speed region. Models show that such a region could be part of the global spatial character of the heliosphere [33] or a time dependent feature near the boundary of the fast and slow solar wind regimes near solar minimum [34].

Since the observed speeds are very low, comparable to the 23 km/s expected in the LISM, one might wonder if V1 has already crossed the HP. The magnetic field increased by about a factor of 2 in the stagnation region but that the direction has not changed [32]. The field is still consistent with the Parker spiral direction; this direction is expected to change in the LISM, so V1 likely has not crossed the HP. The increase in magnetic field magnitude is consistent with predictions that the field will be compressed as it pushes up against the HP boundary [35]. The most probably explanation for these data is that V1 has entered a boundary layer near the HP but has not yet crossed the HP.

The ACR intensity has increased slowly as the Voyager spacecraft move deeper into the heliosheath [36]. At V1, the spectra are almost power laws, indicating that V1 is near the source region. Several suggestions have been published for the source of the ACRs. One is that they are accelerated on the flanks of the heliosphere where the particles can interact with the TS longer, then move along the magnetic field lines to the Voyager spacecraft [37]. Another hypothesis is that ACRs are accelerated by second order Fermi acceleration by magnetic islands or ridges near the HP [38]. A third is that reconnection occurs as the current sheets are compressed near the HP, leading to particle acceleration [39,40]. The Voyagers may be able to differentiate between these possibilities as they approach and cross the HP.

Summary

The Voyager spacecraft celebrate their 35th year in space in August 2012 and continue exploring new regions of space. They should continue to return data until 2025, when we expect they will be well into the interstellar medium. This paper describes some of the new discoveries and new mysteries resulting from recent observations. Some of the more intriguing puzzles are the source of the ACRs, the very different speed profiles observed in the V1 and V2 directions, and the formation of a boundary layer in front of the HP. Future observations and modeling efforts should shed light of these issues.

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