PERSPECTIVES: PLANETARY SCIENCE

News from the Edge of Interstellar Space

Edward C. Stone

Auroral activity and magnetic storms that occasionally disrupt electric power grids are caused by the supersonic solar wind that sweeps past Earth as it blows radially away from the Sun. This wind creates the heliosphere, a bubble of magnetized plasma that surrounds the Sun and includes the orbits of all known planets. Two spacecraft, Voyager 1 and 2, are approaching the edge of the heliosphere—the heliopause—where the radially decreasing pressure of the expanding solar wind balances the inward pressure of the local interstellar medium. En route, the spacecraft are sending back important information about the far reaches of the solar system.

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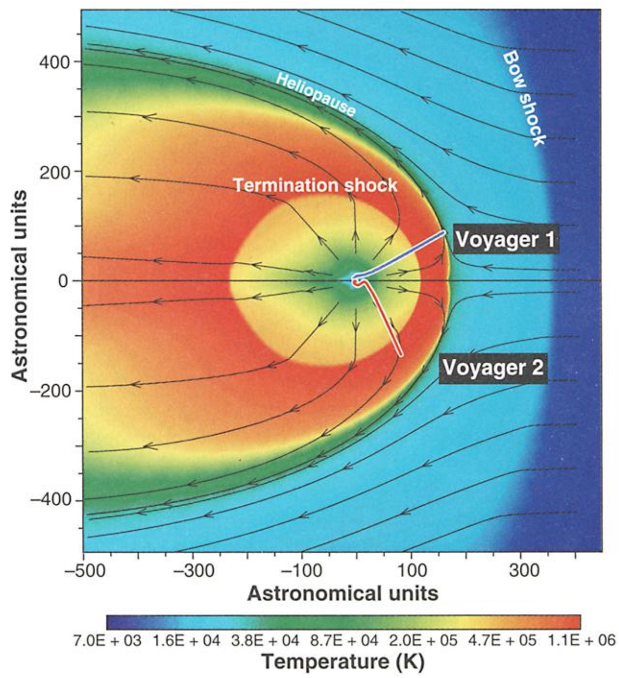
The size of the heliosphere varies as the solar wind pressure changes with the 11-year solar cycle, with maximum size at the time of minimum solar activity (*1*). Currently, the heliosphere is shrinking because solar activity is near its maximum. Furthermore, it is distorted into a cometlike shape by the motion of the interstellar medium relative to the Sun. A long tail extends in the downwind direction. The two Voyager spacecraft are headed in the opposite, upwind direction, where the heliopause is closest to the Sun (see the first figure).

The exact location of the heliopause remains uncertain because the strength and direction of the interstellar magnetic field and the densities of ionized H and He, which contribute to the interstellar pressure, are not precisely known. If we knew the size of the heliosphere, we would thus also have a measure of the properties of the local interstellar medium.

The Voyager spacecraft are still too far from the heliopause to provide direct information about its location. But they may soon encounter another feature of the outer solar system, the termination shock, which provides an important clue to the overall size of the heliosphere.

As the solar wind approaches within ~40 astronomical units (AU) (1 AU = Sun-Earth distance) of the heliopause, it slows abruptly to a hot, subsonic flow that gradually turns in the tailward direction. This results in a termination shock front, the location of which is a direct indication of the size of the heliosphere and the pressure of the local interstellar medium. The location of the termination shock has not yet been determined directly. But there have been recent estimates based on five distinct approaches (see the second figure).



The heliosphere in the interstellar medium. The interstellar wind flows around the heliosphere, which is formed by the supersonic solar wind as it expands radially from the Sun. At the termination shock, the solar wind abruptly slows and heats up (10^6 K) as it turns toward the tail of the heliosphere. In this model, the interstellar wind is supersonic (*7*) and a bow shock forms upstream of the nose of the heliosphere, where the interstellar wind slows and is warmed to a still relatively cool 20,000 K. The heliopause separates the cool interstellar ions deflected around the heliosphere from the hot solar ions inside the heliosphere.

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The first approach is based on the dynamic pressure balance between the solar wind and the interstellar magnetic field. Using Voyager 2 measurements for the solar wind pressure and assuming an interstellar magnetic field of 0.5 nanotesla, Belcher *et al.* (*2*) calculated that for 1990 through 1993, the termination shock was on average located between 78 and 108 AU. Although based on a highly uncertain estimate of the interstellar magnetic field, this interstellar pressure is very similar to a more recent assessment that included uncertainties in the various contributions to the interstellar pressure and led to a distance of 88 ± 22 AU (*3*, *4*).

Ionized interstellar H and He are deflected around the heliosphere. In contrast, neutral interstellar atoms flow deep into the heliosphere, where they are ionized and picked up by the interplanetary magnetic field in the outward flowing solar wind. Using Ulysses observations of such interstellar pickup ions within 5 AU of the Sun, Gloeckler *et al.* (*5*) derived an upper limit of ~85 AU for the shock distance. Ulysses observations of increased solar wind dynamic pressure at high solar latitudes have also been incorporated into models of the interaction of the heliosphere and the interstellar medium, yielding shock locations of 88 AU (*6*), 95 AU (*7*), 80 ± 10 AU (*8*), and 88 to 103 AU (*9*).

Low-frequency radio emissions thought to be excited in the local interstellar medium by the arrival of a large interplanetary shock complex are exploited in the second approach. Gurnett and Kurth have combined the observed onset times of these radio emissions with a magnetohydrodynamic model for the propagation of such shocks outward from the Sun (*10*). They estimated a heliopause located at 110 to 160 AU, corresponding to a termination shock at 80 to 115 AU. In a recent shock propagation model that includes the presence of interstellar neutral atoms and pickup ions in the heliosphere, Zank *et al.* (*11*) estimated a termination shock distance of less than 85 to 90 AU.

The backscattering of solar H Lyman-α radiation by neutral interstellar H provides a third route to estimating the size of the heliosphere. Differences in the backscattered ultraviolet intensities observed by Voyager (upwind) and Pioneer 10 (downwind) in 1990 imply the existence of a termination shock between 70 and 105 AU (*12*).

The termination shock accelerates interstellar pickup ions to total energies of more than 250 MeV. These anomalous cosmic

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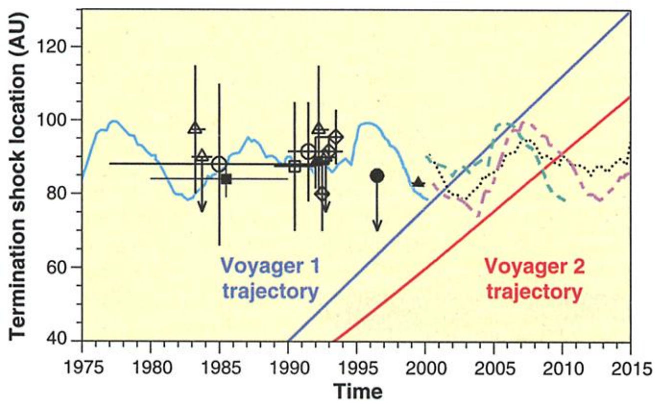

Where is the termination shock? Five methods have been used to estimate the distance to the termination shock. Each uses a different type of data: the solar wind dynamic pressure (open and filled circles, open diamonds), the timing of heliospheric radio emissions (open triangles), anomalous cosmic ray intensity gradients (filled squares), the duration of cosmic ray intensity decreases (filled triangles), and the intensity of solar ultraviolet backscattered from interstellar neutral H (open squares). Solid blue line, predicted variation in the shock location arising from observed changes in the solar wind pressure over the last three solar cycles (*1*). To illustrate the possible range of shock distances in the years ahead, the predicted location from the prior cycles (solid blue line) has been shifted 10 (blue dashes), 20 (black dots), and 30 (purple dashes) years.

rays diffuse and drift inward from the shock, establishing an intensity gradient that provides a fourth method for estimating the shock distance. Extrapolating the gradients observed inside 49 AU outward to the shock source gave a best fit shock location of 84 ± 5 AU for the 1980s (*13*).

The final approach is based on the observation that outward propagating shock complexes cause transient decreases in the intensities of anomalous and galactic cosmic rays. Model calculations indicate that the duration of such a decrease reflects the transit time of the interplanetary shock complex to the termination shock (*14*). Local temporal variations often perturb the observed recovery, but analysis of one such transient decrease in 1999 indicated that the termination shock was only 10 AU beyond Voyager 1 at 83 ± 1 AU (*15*). A related study used the duration of a transient inward flow of anomalous cosmic rays, leading to a shock distance of 88.5 ± 7 AU (*16*).

The assumptions and simplifications in each of the five methods introduce further uncertainties that are more difficult to quantify. Nevertheless, the models and observations are sufficiently different that the systematic uncertainties are unlikely to be correlated among the methods. The clustering of the estimates between 80 and 100 AU thus lends additional weight to the individual estimates.

The location of the termination shock is not fixed in time. Whang and Burlaga have incorporated the temporal variations observed by Voyager 2 into a two-dimensional magnetohydrodynamic model (*1*). They find that the location of the termination shock varies by about 20 AU over the solar cycle. The distance is smallest following times of maximum solar activity.

The shock is presently moving inward (see the second figure). Within the next few years, wind speed and pressure will increase, and with the arrival of the increased pressure, the termination shock will begin moving outward. This will affect when the Voyager spacecraft encounters the termination shock.

Voyager 1 is currently at ~82 AU and moves outward at 3.6 AU per year, followed by Voyager 2, now at ~66 AU and moving outward at 3.3 AU per year. Comparison with the Voyager 1 trajectory suggests the possibility of one or more encounters with the termination shock by 2005. If there has been no encounter by then, the shock will likely be moving outward again. It may then be 2 to 5 more years before it moves back into range for Voyager 1 to take a direct measure of the size of the heliosphere (*17*).

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PERSPECTIVES: MARINE BIOLOGY

Expansion of the Marine Archaea

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A remarkable consequence of the recent upheaval in the way we classify organisms has been the elevation of the Archaea (non-bacterial prokaryotes) to the rank of domain, making them equivalent to the Eukarya (eukaryotes) and Bacteria (*1*). The domain Archaea is subdivided into two kingdoms—Euryarchaeota and Crenarchaeota—and possibly a third, Korarchaeota. Karner *et al.* (*2*) calculate that the Archaea constitute about 20% of the total marine picoplankton biomass worldwide. Whereas Euryarchaeota thrive in a diverse array of environments, most Crenarchaeota seem to prefer hyperthermal habitats (>80°C). Indeed, the current record holder for growth at high temperatures (113°C) is a member of the Crenarchaeota isolated from a hydrothermal vent (*3*). However, molecular analyses of environmental samples indicate that some Crenarchaeota inhabit more mundane environments, such as terrestrial soils, lakes, and marine and freshwater sediments.

Although the Crenarchaeota have their roots in a hyperthermal environment, they have obviously expanded their range to occupy a variety of nonthermophilic habitats. But what prompted this expansion and when exactly did it take place? Possible answers are provided by Kuypers *et al.* (*4*) on page 92 of this issue. These investigators analyzed sediment samples "cored" from the ocean floor of the North Atlantic by the Ocean Drilling Program. They conclude that the Crenarchaeota expanded their habitat range dramatically by exploiting changing conditions during the mid-Cretaceous (124 to 83 million years ago). They pinpoint the precise time of the expansion by identifying unique membrane lipids characteristic of the Crenarchaeota in a ~45-cm-thick band of dark sediment deposited ~112 million years ago (see the figure). Their estimate of the archaeal expansion extends previous estimates (*5*) by about 60 million years.

What happened during the mid-Cretaceous that enabled the Crenarchaeota to branch out from the confines of their high-

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