# In Situ Observations of Interstellar Plasma with Voyager 1

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Launched over 35 years ago, Voyagers 1 and 2 are on an epic journey outward from the Sun to reach the boundary between the solar plasma and the much cooler interstellar medium. The boundary, called the heliopause, is expected to be marked by a large increase in plasma density, from about 0.002 per cubic centimeter ($cm^{-3}$) in the outer heliosphere, to about 0.1 $cm^{-3}$ in the interstellar medium. On 9 April 2013, the Voyager 1 plasma wave instrument began detecting locally generated electron plasma oscillations at a frequency of about 2.6 kilohertz. This oscillation frequency corresponds to an electron density of about 0.08 $cm^{-3}$, very close to the value expected in the interstellar medium. These and other observations provide strong evidence that Voyager 1 has crossed the heliopause into the nearby interstellar plasma.

As the Sun moves through the interstellar medium, the solar wind plasma flowing outward from the Sun is expected to form a bullet-shaped boundary, the heliopause (*1*, *2*), that separates the solar plasma from the much cooler interstellar plasma (fig. S1). Because the solar wind is supersonic, a shock wave, called the termination shock, must form to slow the solar wind to a subsonic speed so that it can be deflected downstream by the interstellar gas pressure. In 2004 and 2007, Voyagers 1 and 2 crossed the termination shock at 94.0 astronomical units [(AU) 1 AU = 1.49 × $10^8$ km] and 83.4 AU, respectively (*3*–*6*). Since then, they have been proceeding outward through the heliosheath, which is a region of shock-heated solar plasma between the termination shock and the heliopause.

The first indication of a possible encounter with the heliopause was on 28 July 2012, at 121 AU, when the Low Energy Charged Particle (LECP) and Cosmic Ray (CRS) instruments on Voyager 1 detected an abrupt decrease in the intensities of termination shock particles (TSPs) and anomalous cosmic rays (ACRs), and a coincident increase in the galactic cosmic ray (GCR) intensity (*7*–*9*). A total of five similar crossings of the boundary were observed, the last being on 25 August 2012, at which time the ACRs decreased to nearly undetectable levels. Because TSPs and ACRs are the dominant energetic charged particles in the heliosheath (*10*, *11*), the decrease in their intensities is consistent with a crossing of the heliopause, as is the increase in the GCR intensity. Although the Magnetometer (MAG) detected closely correlated changes in the magnetic field strength, no appreciable change was observed in the magnetic field direction (*12*). Because the magnetic field in the local interstellar plasma (*13*) is not expected to be in the same direction as in the heliosheath, the absence of a notable change in the magnetic field direction has led to doubts about whether this boundary was the heliopause.

This question could have been resolved had adequate plasma density measurements been available. To maintain pressure balance between the hot (~$10^6$ K) heliosheath plasma (*14*) and the cool (~$10^4$ K) interstellar plasma (*13*), a large plasma density increase is expected at the heliopause. Unfortunately, the Plasma (PLS) instrument on Voyager 1 failed in 1980, and the Plasma Wave (PWS) instrument (*15*), which may have measured the electron density from the frequency of electron plasma oscillations, detected no oscillations. Electron plasma oscillations occur at a characteristic frequency of the plasma called the electron plasma frequency, $f_p = 8980\sqrt{n_e}$ Hz, where $n_e$ is the electron number density in $cm^{-3}$ (*16*). These oscillations are usually excited by electron beams, such as those upstream of interplanetary shocks and after energetic solar electron events. (For a discussion of the mechanism by which electron plasma oscillations are produced, see supplementary text S1.) Electron plasma oscillations were last observed by Voyager 1 in December 2004, upstream of the solar wind termination shock (*5*).

This situation abruptly changed on 9 April 2013, when the PWS began to detect strong electric field emissions in the 3.11-kHz channel of the onboard spectrum analyzer (Fig. 1). The emissions had the spiky intensity variations characteristic of electron plasma oscillations and continued for almost a month and a half, finally disappearing on 22 May. During this period, we also obtained a series of short 48-s samples of the electric field waveform that were stored on the spacecraft's tape recorder. Using Fourier analysis techniques, we converted these waveforms into frequency-time spectrograms (Fig. 2A). The spectrograms show that the electric field oscillations have a very narrow bandwidth of only a few percent, with an average oscillation frequency of about 2.6 kHz. Using the previously given equation for $f_p$, this frequency corresponds to an electron density of $n_e$ = 0.08 $cm^{-3}$. Careful

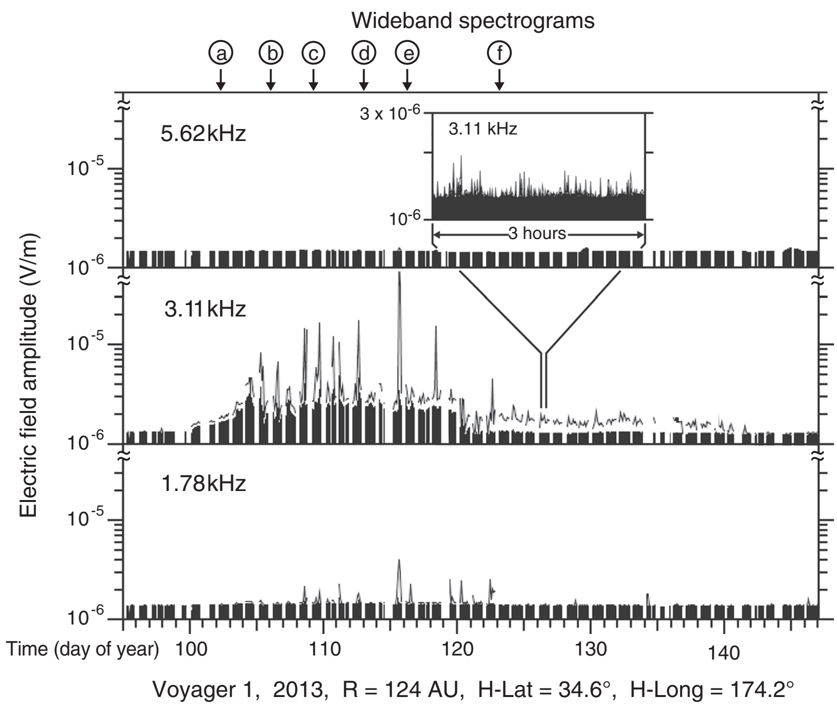


**Fig. 1. Electric field intensities in the 1.78-, 3.11-, and 5.62-kHz channels of the PWS 16-channel onboard spectrum analyzer.** The vertical black regions in each channel give the average field strengths, and the solid lines above give the peak field strengths.

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measurements of the frequency of the primary component, which can be followed from one spectrogram to the next, show that it increases slowly, at a rate of about 2.6 Hz/day. Sometimes, a second emission line can be seen at a frequency slightly above that of the primary component, as in spectrograms (b) and (f). Such sidebands are a common feature of electron plasma oscillations and can be produced by several processes, including, for example, three-wave parametric decay (*17*) and trapping of the primary beam-driven oscillations in small density cavities (*18*).

After examining waveform data recently played back from the spacecraft tape recorder, we found another interval with similar, but much weaker, electron plasma oscillations from 23 October to 27 November 2012 that could not be detected in the onboard spectrum analyzer data (Fig. 2B). The oscillation frequency for this event is about 2.2 kHz, which corresponds to an electron density of about 0.06 $cm^{-3}$, substantially less than for the April-May 2013 event. As indicated by the sloping dashed white line in Fig. 2B, the change in the oscillation frequency between the two events suggests a smoothly increasing plasma density—i.e., a density ramp—in the region between the two events. In support of this view, the rate of change of the plasma frequency for the dashed white line (2.6 Hz/day) is very close to the rate of change (2.7 Hz/day) given above for the April-May event, and close to that measured for the October-November event, which is slightly lower (~2.0 Hz/day). At Voyager 1's radial velocity of about 3.5 AU/year, these variations in the plasma frequency correspond to a density gradient of about 19% per AU. A somewhat similar density ramp has been inferred previously from the upward frequency drift of heliospheric 2- to 3-kHz radio emissions (*19*).

For almost 30 years, the plasma wave instruments on Voyagers 1 and 2 have been detecting transient radio emissions from the outer heliosphere in the frequency range from about 2 to 3 kHz. Two particularly strong events have occurred, the first in 1983–1984 (*20*), and the second in 1992–1993 (*19*). It is now generally agreed that these radio emissions are produced near the electron plasma frequency when a strong interplanetary (IP) shock associated with a global merged interaction region reaches the heliopause and interacts with the nearby interstellar plasma. Two components are usually observed, both starting when the IP shock first contacts the heliopause. The first component usually starts at about 2 kHz and gradually increases in frequency with increasing time, eventually reaching about 3 to 3.5 kHz after about half a year. The second component also starts at about 2 kHz and stays at this frequency for a year or more. An example of the radio emission spectrum detected by Voyager 1 during the strong 1992–1993 event is shown in Fig. 3A. In this case, the upward-drifting component is indicated by the sloping white dashed line, increasing in frequency by 1.5 kHz over a period of 231 days. The upward frequency drift is a common feature of the heliospheric radio emissions and is believed to be caused by an increase in the plasma frequency as the shock propagates into a region of increasing plasma density beyond the heliopause, i.e., a density ramp, possibly caused by a "pileup" of plasma in the region upstream of the heliopause (*19*), or a plasma "transition region" caused by the interaction with neutral hydrogen, the so-called hydrogen wall (*21*). The very prominent constant-frequency component near and slightly above 2 kHz is thought to be either radiation trapped in the low-density heliospheric cavity, or generated beyond the flanks of the heliopause where there is little or no pileup of plasma.

In Fig. 2B, we suggested (as indicated by the sloping white dashed line) that the spacecraft is passing through a smoothly increasing plasma

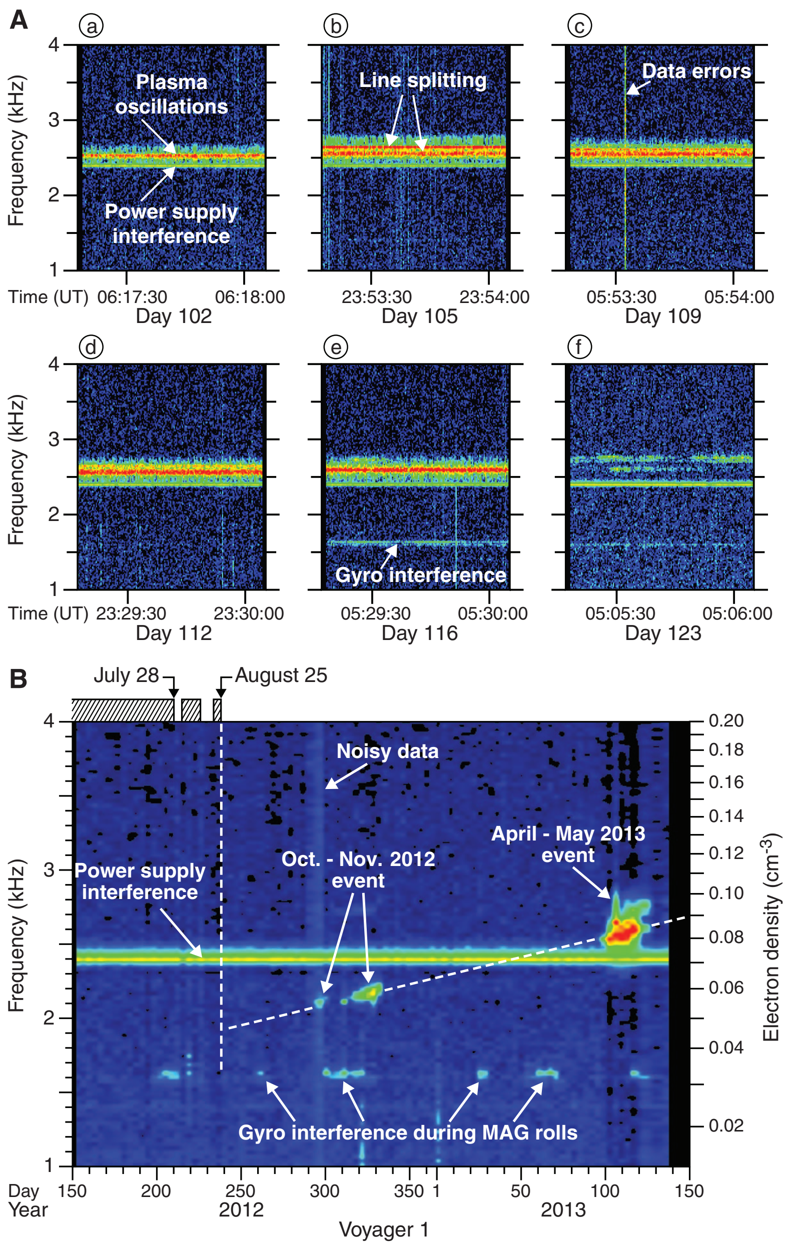


**Fig. 2. High-resolution spectrograms.** (**A**) Six selected 48-s frequency-time spectrograms computed from the electric field waveform for the times labeled "a" through "f" in Fig. 1. These data are recorded about twice per week on the spacecraft tape recorder. (**B**) A composite spectrogram, constructed from spectrograms similar to those in (A), extending over a period of 1 year, starting on day 150, 29 May 2012. In addition to the strong electron plasma oscillation event in the April-May 2013 time period, a much weaker event can be seen at a frequency of about 2.2 kHz in October-November 2012. An electron density scale is given on the right. The vertical dashed white line denotes the last increase in GCRs on 25 August 2012. The sloping dashed white line suggests a density ramp in the region between the two plasma oscillation events.

density—i.e., a density ramp—as it moves outward from the Sun. Radio direction-finding measurements (*22*) show that the 1992–1993 radio emission originated very close to the region where Voyager 1 is currently located, within about 10° to 15° as viewed from the Sun. Therefore, we investigated whether the density ramp reported here corresponds quantitatively to the density ramp inferred remotely from of the upward-drifting frequency component of the heliospheric radio emissions. To test this hypothesis, we have replotted Fig. 2B in Fig. 3B, with the time of the increase in the GCR intensity on 25 August lined up with the onset of the radio emission in Fig. 3A. In addition, we have adjusted the time scale such that the density ramps in the two plots have the same slope. When the density ramp in Fig. 3B is then extrapolated backward in time to the point where the increase in the GCR intensity occurs, the plasma frequency is 1.9 kHz, almost exactly the same frequency as the onset of the radio emission in Fig. 3A. Despite the obvious assumptions involved with this extrapolation, this coincidence provides strong support for the view that the GCR intensity increase on 25 August was at the heliopause.

A major unknown factor involved in the interpretation of the upward-drifting radio emission in Fig. 3A is the propagation speed of the IP shock. To estimate the shock speed, we extrapolate the density ramp in Fig. 3B into the future, to the point at which the plasma frequency has increased by 1.5 kHz, to about 3.4 kHz, the same frequency increase as in Fig. 3A. We see that it will take 542 days from the time of the increase in the GCR intensity to reach this point. At the current rate that Voyager 1 is moving outward from the Sun, 3.58 AU/year, this corresponds to a change in radial distance of 5.3 AU. For the density ramps to have the same radial gradient, one can see from Fig. 3A that it would take 231 days for the IP shock to propagate a comparable radial distance, namely 5.3 AU. The shock responsible for the radio emission would then have to propagate outward at a rate of 5.3 AU/231days, which corresponds to ~40 km/s. This is a very plausible shock propagation speed, comparable to those obtained from plasma simulations of IP disturbances propagating into the nearby interstellar medium by Zank and Müller (*21*) and Washimi *et al*. (*23*). These comparisons provide strong support for the view that the density ramp inferred from the plasma oscillation events reported here, and the density ramp inferred from the 1992–1993 heliospheric radio emission event, are caused by the same basic density structure on the upstream side of the heliopause, and that the GCR intensity increase on 25 August 2012 marked the crossing of Voyager 1 into the interstellar plasma.

Because electron plasma oscillations are known to be driven by electron beams, we have searched

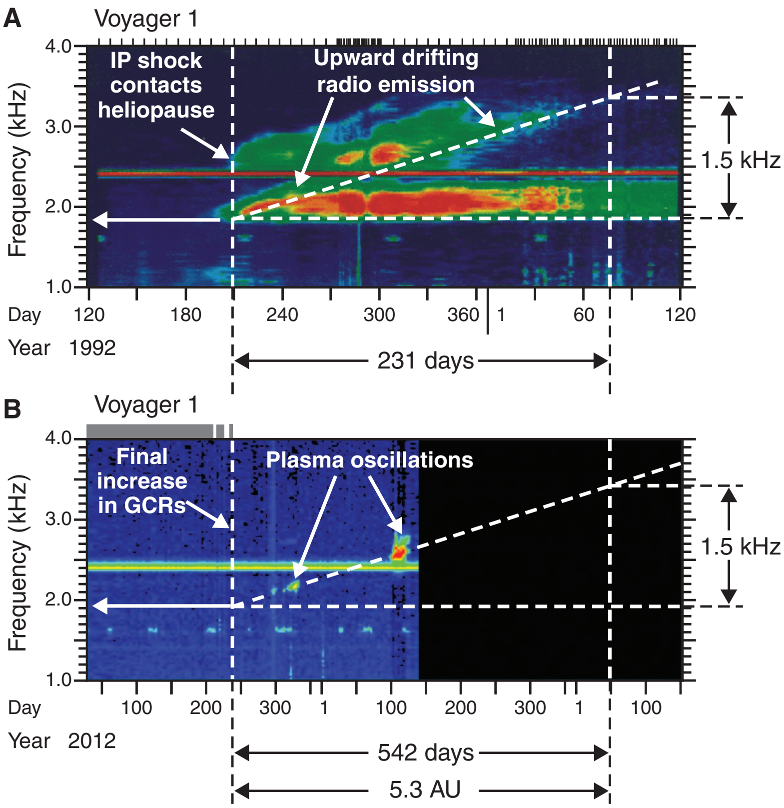


**Fig. 3. Comparison of heliospheric 2- to 3-kHz radio emissions to local plasma oscillations. (A)** A frequency-time spectrogram of the 1992–1993 heliospheric radio emission event detected remotely by Voyager 1 (*19*), and (**B**) a rescaled spectrogram of the plasma oscillation frequencies given in Fig. 2B. To facilitate a comparison, the time scales in the two spectrograms have been adjusted so that the white dashed lines have the same slope.

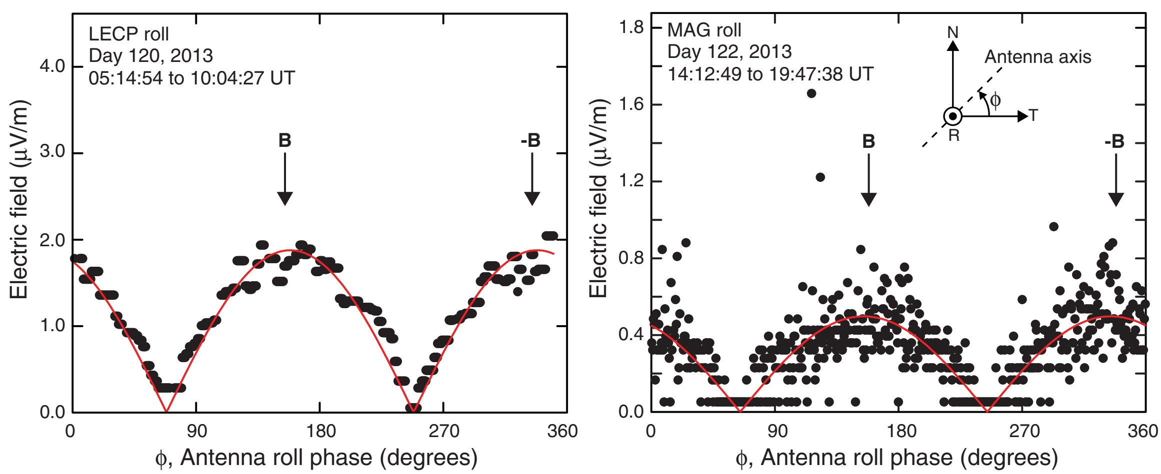


**Fig. 4. Electric field polarization.** Plots showing the electric field strength as a function of the roll angle, ϕ, for two spacecraft roll maneuvers. The rolls were around the spacecraft *Z* axis, which is aligned along the Earth-spacecraft line (i.e., very close to the Sun-spacecraft line) and perpendicular to the electric antenna axis (fig. S2). In both cases, a very pronounced modulation was observed, with two nulls per rotation. Magnetic field measurements during both roll maneuvers, indicated by **B** and **–B**, show that the component of **B** in the roll-plane is within 3° of the electric field direction projected onto the roll-plane. For further details, see supplementary text S2.

with the LECP team for evidence of an electron beam around the times of these observations. No electron beam was found, which is not surprising given that the lowest electron energy that can be detected by the LECP is quite high, ~28 keV. Often, beams responsible for electron plasma oscillations are at much lower energies. However, a possible causative event was identified in the GCR proton intensities starting on days 80 to 95, 2013 (*9*), close to the start of the electron plasma oscillations. This event likely originated from a period of extraordinary solar activity beginning early on 5 March 2012, the so-called St. Patrick's day solar storms (*24*). This timing agrees well with the interplanetary shock model proposed to explain the generation of heliospheric 2- to 3-kHz radio emissions via mode conversion from electron plasma oscillations (*19*). In the present case, no radio emission could be identified, probably because the plasma oscillations, although strong, are not at the very high field strengths (10 to 100 mV/m) typically associated with the generation of IP radio emissions (*25*). However, a test can be performed to show consistency with a beam source. For an electrostatic wave, such as an electron plasma oscillation, the electric field **E** must be parallel to the wave vector **k,** which, if driven by a field-aligned electron beam, should be aligned along the magnetic field. We have performed this test using two spacecraft roll maneuvers (Fig. 4). Both showed a very clear modulation in the electric field amplitude with two nulls per rotation, consistent with a linearly polarized electrostatic wave. Magnetic field measurements during both roll maneuvers showed that the component of the magnetic field in the roll plane is within 3° of the electric field direction, as expected.

Here, we have shown that the densities obtained from the recently observed electron plasma oscillations range from 0.06 to 0.08 $cm^{-3}$, gradually increasing with increasing radial distance at a rate of about 19% per AU. These densities are in close agreement with remote-sensing measurements of plasma densities in the interstellar medium (0.05 to 0.22 $cm^{-3}$) (*13*) and much greater than those in the heliosheath (~0.001 to 0.003 $cm^{-3}$), based on Voyager 2 PLS measurements out to its current position at 101 AU (*26*, *27*). Numerous computer simulations also show that the plasma densities remain at about this level throughout the heliosheath (*28*–*30*). The reason for the extremely low densities in the heliosheath is that as the solar wind expands outward from the Sun, the density decreases greatly, to ~0.001 $cm^{-3}$, ahead of the termination shock (*5*, *6*, *31*). Although the plasma is compressed by about a factor of 2 at the termination shock (*31*), once the flow is subsonic, there is no known way to compress the plasma to such high densities. An interplanetary shock can only produce a factor of 4 compression, whereas the heliosheath plasma would have to be compressed by a factor of ≥30 to reach the much higher densities reported here. These results, and comparison with previous heliospheric radio measurements, strongly support the view that Voyager 1 crossed the heliopause into the interstellar plasma on or about 25 August 2012.

The above conclusions assume that there is a single well-defined boundary, the heliopause, that separates the solar plasma from the interstellar plasma, with no linkage between their magnetic fields. The apparent conflict between our conclusion, and the absence of a change in the magnetic field direction (*12*), puts the above simplified picture into doubt. For example, the interstellar magnetic field may be linked to the solar magnetic field through an as-yet incompletely understood mechanism, such as magnetic flux tube interchange (*9*), magnetic reconnection (*32*), or the Kelvin-Helmholtz instability (*33*). Under such conditions, the very definition of the heliopause comes into question.


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Supplementary Text
Figs. S1 and S2
References (*34*–*36*)


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# Distances, Luminosities, and Temperatures of the Coldest Known Substellar Objects

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The coolest known brown dwarfs are our best analogs to extrasolar gas-giant planets. The prolific detections of such cold substellar objects in the past 2 years have spurred intensive follow-up, but the lack of accurate distances is a key gap in our understanding. We present a large sample of precise distances based on homogeneous mid-infrared astrometry that robustly establishes absolute fluxes, luminosities, and temperatures. The coolest brown dwarfs have temperatures of 400 to 450 kelvin and masses almost equal to 5 to 20 times that of Jupiter, showing they bridge the gap between hotter brown dwarfs and gas-giant planets. At these extremes, spectral energy distributions no longer follow a simple correspondence with temperature, suggesting an increasing role of other physical parameters, such as surface gravity, vertical mixing, clouds, and metallicity.

One major goal in astrophysics is to extend previous successes in the characterization and modeling of stellar atmospheres to the much cooler atmospheres of extrasolar planets. A key pathway is the identification of free-floating objects that share not only common

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**Finally Out**
Last summer, it was not clear if the Voyager 1 spacecraft had finally crossed the heliopause––the boundary between the heliosphere and interstellar space. **Gurnett *et al.*** (p. 1489, published online 12 September) present results from the Plasma Wave instrument on Voyager 1 that provide evidence that the spacecraft was in the interstellar plasma during two periods, October to November 2012 and April to May 2013, and very likely in the interstellar plasma continuously since the series of boundary crossings that occurred in July to August 2012.