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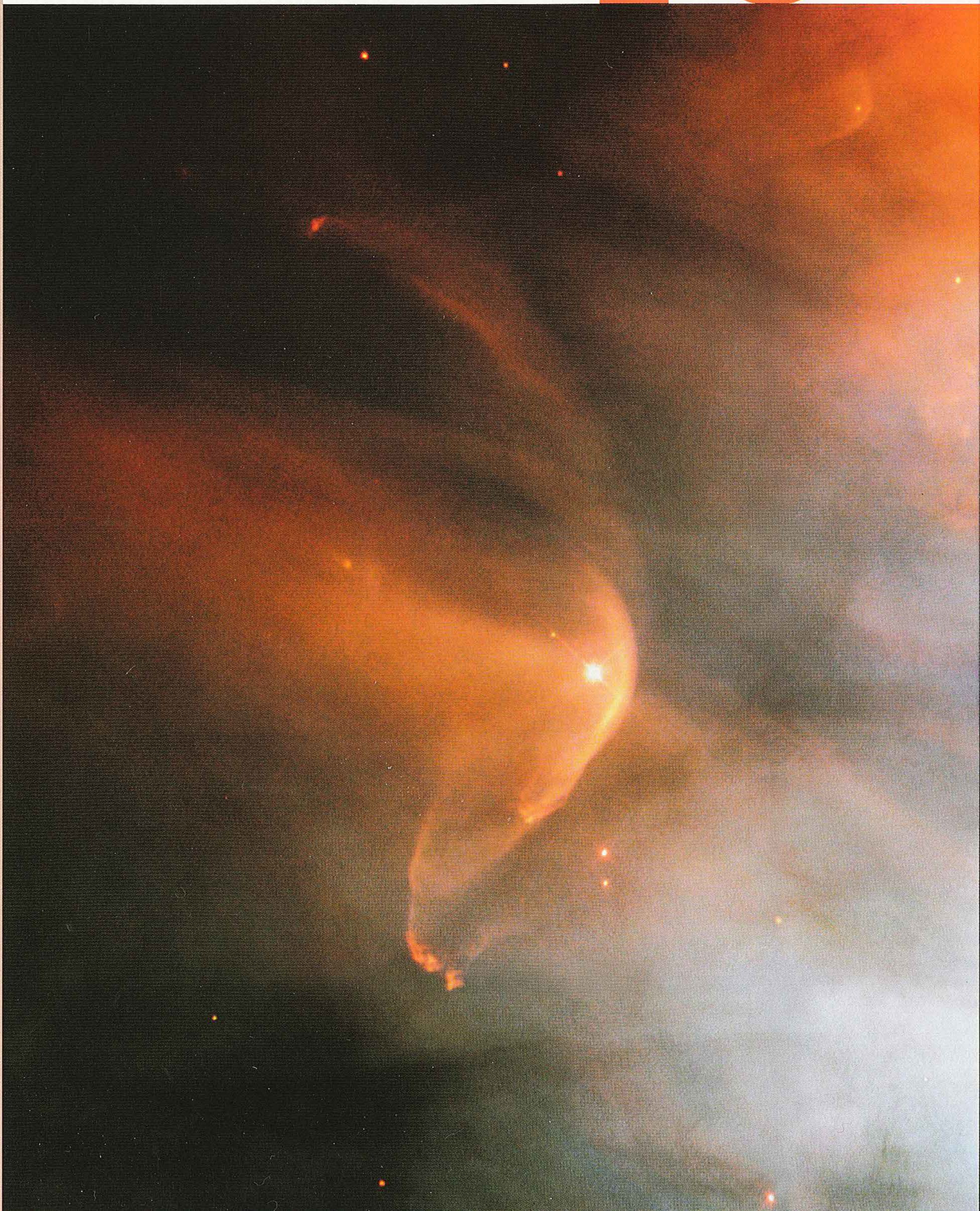
In this issue



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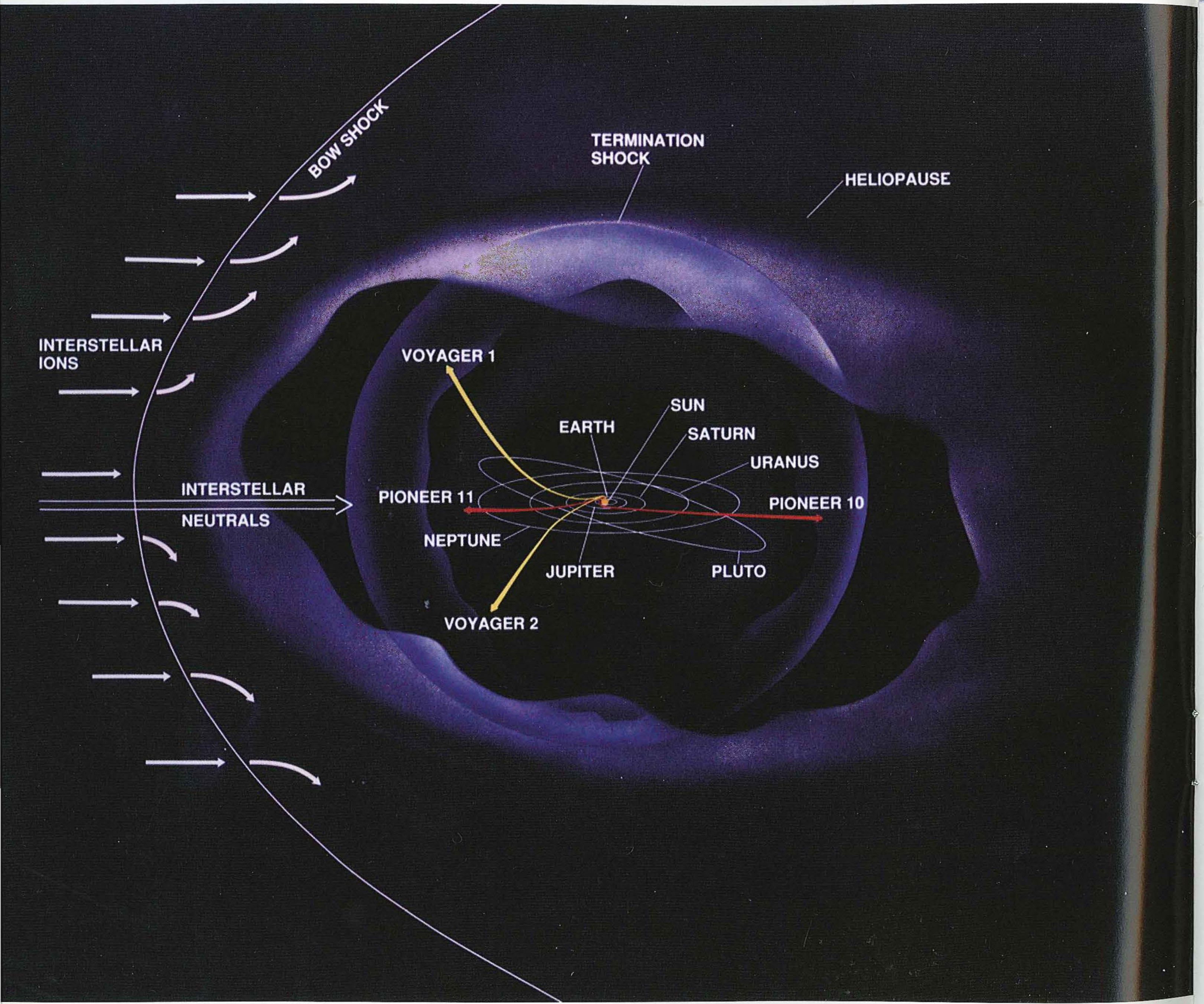


Voyager Journeys to Interstellar Space

by Edward C. Stone

Right: Both Voyager spacecraft were designed and built for NASA at the Jet Propulsion Laboratory and are also operated by the lab.

Left: Voyagers 1 and 2 will soon venture out of the heliosphere, the bubble created by the solar wind, and into interstellar space. Although the Pioneer spacecraft were launched earlier, the Voyagers are faster and will become our first interstellar probes. First they will cross the termination shock, where the solar wind slows from supersonic to subsonic speeds. Finding exactly where the termination shock is will allow researchers to estimate the current extent of the heliosphere and determine how much farther the spacecraft have to go to reach interstellar space.

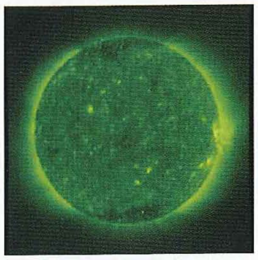
Twenty-five years ago we embarked on a journey of exploration that returned an unequaled wealth and diversity of discovery, a journey that continues as we search for the edge of interstellar space. We launched two Voyager spacecraft in August and September 1977, taking advantage of a special opportunity: once every 176 years Jupiter, Saturn, Uranus, and Neptune are in positions on the same side of the sun that allow a spacecraft to fly by all four. The 30-year journey to Neptune was shortened to only 12 by the slingshot boost from swinging by each of the planets along the way. We were fortunate that this opportunity occurred in the late 1970s. Ten years earlier, our technology would not have been ready, and a few years later, after the Space Shuttle era had begun, the launch vehicles we needed would have been retired.

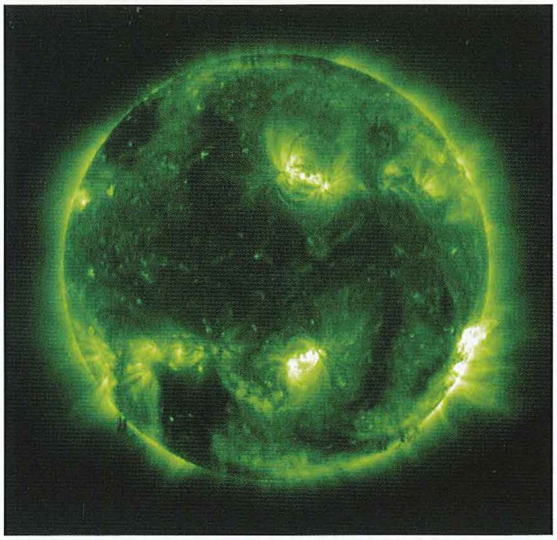
During this journey, the Voyagers revealed the remarkable ways in which common geophysical processes produce diverse worlds: dozens of immense hurricane-like storms on Jupiter, of which the Great Red Spot is the largest, at two-to-three Earths across; the lava lakes and 50-mile-high volcanic plumes on Jupiter's moon Io, heated by the tidal flexing of its crust; the icy crust of Io's neighbor, Europa, the smoothest surface in the solar system; spiral waves in the rings of Saturn caused by tiny satellites and other moons shepherding kinked, narrow rings; Saturn's largest moon, Titan, with organic molecules raining on a surface obscured by a 200-mile-high haze layer; Uranus, tipped on its side with its magnetic pole near the equator, and its nine narrow, black rings; its small moon, Miranda, with one of the most geologically complex surfaces in the solar system; and finally Neptune, with the fastest winds, even though it is six times farther from the sun than Jupiter, with sunlight only 1/900th of what it is on Earth; and its moon, Triton, the coldest object in the solar system, with geysers erupting from its frozen-nitrogen polar caps.

In 1989 Voyager flew by Neptune, completing an unprecedented decade of discovery. But the mission is not over. What lies beyond the giant outer planets? Voyager is still in the bubble of plasma, called the heliosphere, that surrounds the sun. (It's called an astrosphere around other stars.) The two Voyagers are now headed to the outer edges of this bubble and then into interstellar space, where for the first time a spacecraft from Earth will be completely immersed in matter from stars other than the sun.

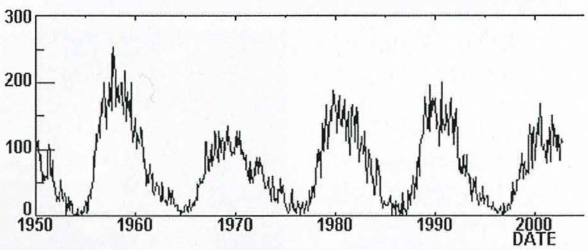
A supersonic wind from the sun creates the bubble. The sun's visible surface is about 5,800 degrees C and has sunspots that mark the eruption of magnetic flux from deep inside. The sunspots are the visible indications of the polarity reversal of the solar magnetic field that occurs every 11 years. They tend to come in pairs, with their number varying over the 11-year cycle, seesawing from a period of maximum sunspot activity to one of minimum activity. A solar maximum occurred in 1980, again in 1990, and most recently in 2001.

In the images of the corona shown in green on the next page, you can see the arches associated with magnetic fields looping from one region to

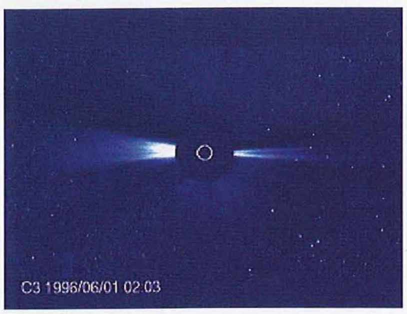




Over a cycle of 11 years, the sun goes from a period of minimum activity (December 1996, far left) through one of maximum activity (June 1999, left), characterized by a great increase in the number of sunspots, which are the surface expression of magnetic eruptions from deep inside the sun. These images in the extreme ultraviolet show the magnetic loops from sunspot to sunspot, mixing the magnetic fields and releasing the energy that heats the solar atmosphere and creates the hot plasma called the corona. There are darker regions, or "holes," in the corona (note particularly the polar holes at solar minimum), where the plasma is escaping.



The number of sunspots varies over an 11-year period.



Blocking the sun's light with a coronagraphic disk (the sun is the size of the small white circle in the center) reveals the brighter plasma trapped near the equator, while the solar wind escapes at 2 million mph through the darker coronal holes. At solar maximum (right) greater activity and magnetic complexity results in fewer magnetic holes in the corona; the solar wind, therefore, streams out more slowly at all latitudes.

another. Solar maximum, when there are many sunspots and magnetic loops, is on the right; if this were in motion, you would see it roiling and changing as the turbulent motions in the atmosphere mix the magnetic fields from nearby regions, causing them to merge and release energy. It is this magnetic energy that heats the extended solar atmosphere to create the corona, the bright plasma of over a million degrees surrounding the sun. There are darker "holes" in the corona where the plasma easily escapes along magnetic field lines that open out into interplanetary space. Because there is less material in coronal holes, there is less light from those regions.

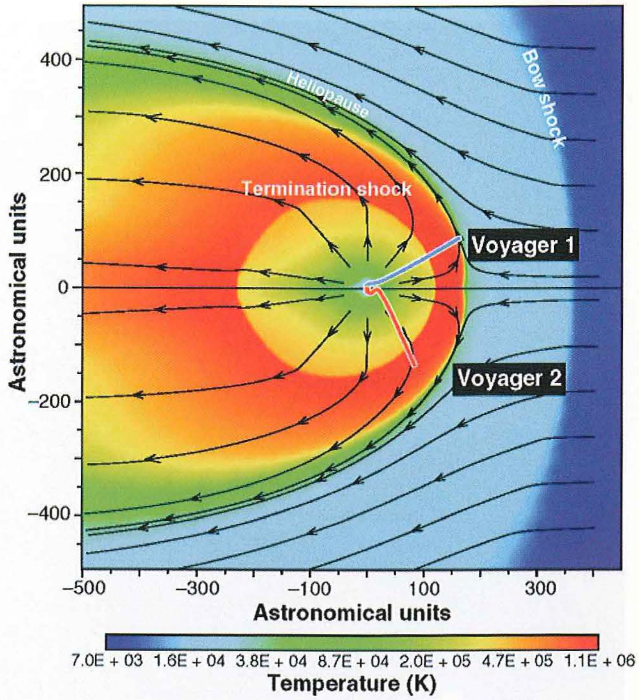
At solar minimum on the left, the corona is much simpler, with a large coronal hole in each polar region. Faint lines stream radially outward in the polar coronal holes where the plasma flows away from the sun at two million miles per hour. Wind speed is highest when the sun is quiet, while during active periods with many sunspots the corona is more turbulent and chaotic and the wind more variable, with speeds as low as only one million mph. That's a key factor that I'll come back to shortly.

Now let's look at the corona as it expands farther from the sun. In the blue images at left, the sun is the size of the small white circle and is blocked from view by a disk that creates an artificial solar eclipse. At the solar minimum in 1996 (on the left), there are bright regions near the solar equator where closed magnetic loops retain the coronal plasma, while at higher latitudes the wind streams away radially, filling up space at two million mph. But at solar maximum, on the right, the corona is quite different, with closed magnetic loops and bright regions at all latitudes. Because of the complex magnetic field associated with the increased solar activity, the darker regions corresponding to coronal holes are much more limited, and the wind streams outward more slowly.

The bubble that the solar wind creates around the sun changes size as the wind speed changes with solar activity. At solar minimum, the higher-speed wind creates a larger bubble than at solar maximum, when the winds are slower. Visual evidence of the solar wind can be seen with comet tails serving as wind socks. As a comet orbits the Sun, its tail always points away from the sun, blown outward by the solar wind.

The heliospheric bubble with the sun at its center is illustrated in the diagram on the opposite page, along with the Voyager trajectories. In the yellow area surrounding the sun, the temperature is about 250,000 degrees. The wind starts at a coronal temperature of more than a million degrees at the sun and cools as it flows outward. The density and pressure also decrease as the wind expands to fill an increasingly large volume. The outward expansion continues until the declining solar wind pressure is balanced by the inward

The bubble that the solar wind creates around the sun changes size as the wind speed changes with solar activity.



In the diagram above, the arrows indicate the flow of the solar wind (inside the bubble) and the interstellar wind outside. At the termination shock, the supersonic solar wind abruptly slows down, heats up to a million degrees, and then turns and flows down the tail of the heliosphere. Where the interstellar wind meets the heliopause, it's deflected around the heliosphere, which becomes a windsock indicating which direction the wind is blowing. A bow shock forms in front of the heliopause as the cold, supersonic interstellar wind slows down, warms up, and is deflected around the heliopause.

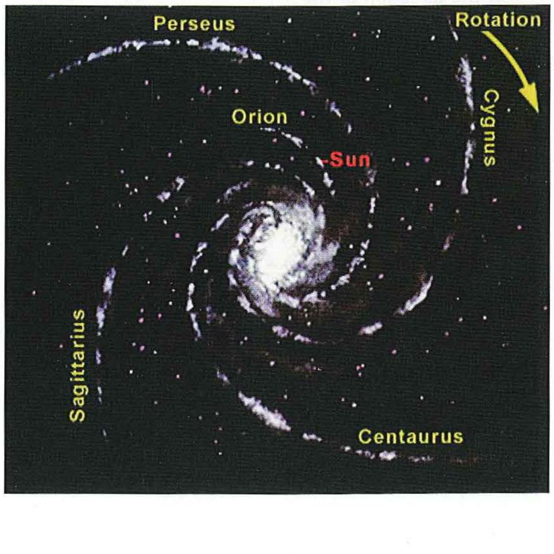
pressure of the interstellar wind of ions coming from the explosion of nearby stars. A boundary called the heliopause separates the two winds where they meet. The interstellar wind from the right in the figure flows around the heliosphere, deforming it into a wind-sock-like shape with a tail.

At over one million mph, the solar wind is supersonic, so it can't plunge directly into the boundary; just as a supersonic aircraft creates a shock (or sonic boom) in front of it, a shock forms where the solar wind abruptly slows to subsonic speeds as it approaches the heliopause. This is called the termination shock because it's the end of the supersonic flow of the solar wind. The wind slows from a million mph to 250,000 mph, and it becomes very hot (the red region) as the kinetic energy of the supersonic flow is converted into thermal energy in the subsonic wind. Beyond the termination shock, the subsonic wind slowly turns to flow down the heliospheric tail. As shown in the illustration, the interstellar wind is probably supersonic as well, so there is likely a shock out in front of the heliosphere called a bow shock.

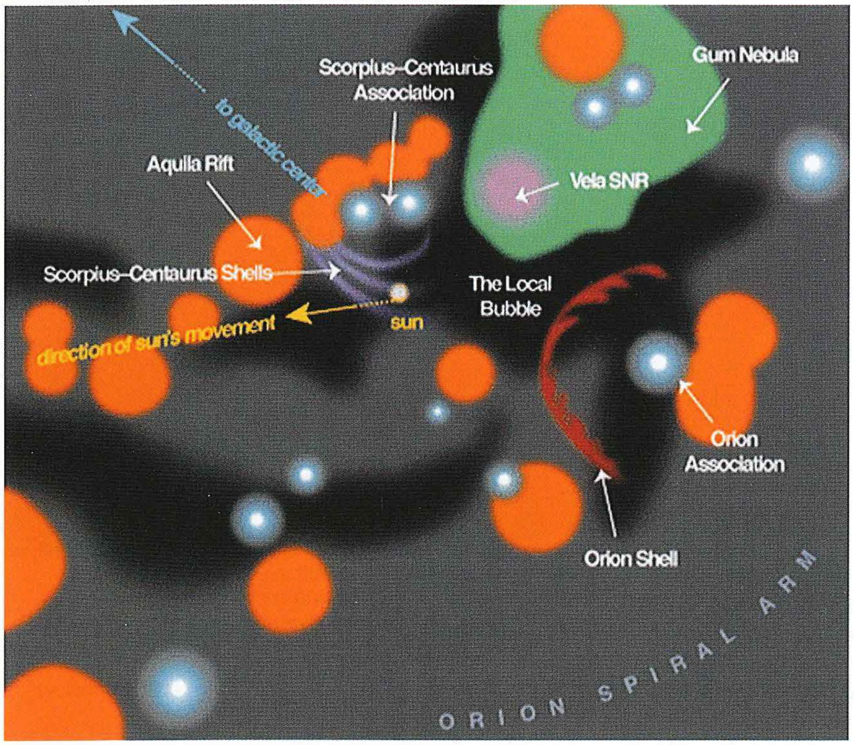
What evidence do we have for bow shocks in front of other stars? The cover shows a very young star in a nearby star-forming region in the Orion nebula about 1,500 light years away. Although we can't see the astrosphere around the star, we know it is there because we *can* see that a bow shock (the vertical arc in the middle) has formed in the interstellar wind that blows from the center of the Orion nebula. This is the shocked gas that forms as the interstellar wind abruptly slows and is deflected around the astrosphere. Another smaller bow shock is at the upper right.

What about our own galactic neighborhood? What's outside the heliosphere? If we could look down on our galaxy (which of course we can't because we're in it), we would see the sun in one of the spiral arms called the Orion arm. We're about 26,000 light years from the center of the Milky

Looking down on the Milky Way, we can locate our sun in the Orion arm spiraling out from the center of the galaxy, 26,000 light years away.



Both figures on this page from P. Frisch, *American Scientist*, 88(1):52-59, Jan.-Feb. 2000. Reprinted by permission of *American Scientist*, magazine of Sigma Xi, the Scientific Research Society. Art by Linda Huff/*American Scientist*.



About 5 million years ago, a massive explosion in the Scorpius-Centaurus Association (about 400 light years away) sent waves of cooler, denser "shells," or "clouds," through the Local Bubble, in which our sun lives. The denser medium in the cloud compresses the heliosphere, making the heliopause closer and quicker for Voyager to reach. The orange blobs here are star-forming regions.

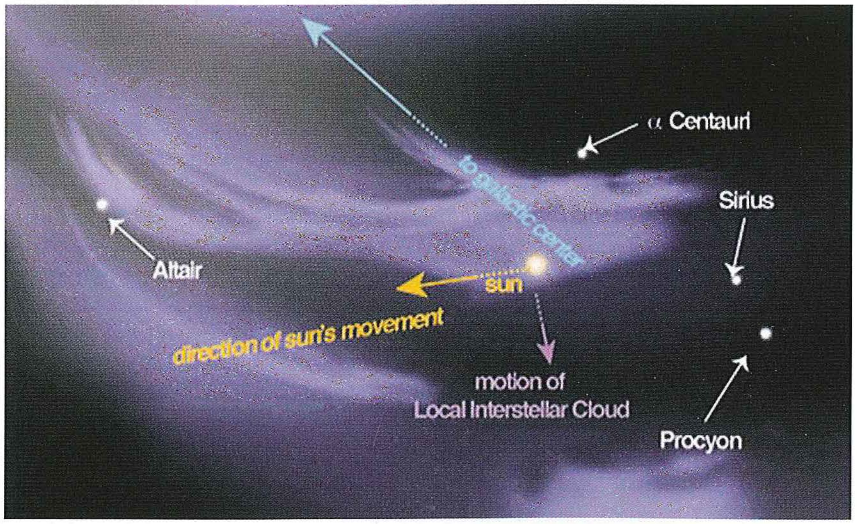
Way, about halfway out in the disk of the galaxy. In the drawing above, we zoom in closer to the Orion arm, to a scale of 1,500 light years across. The orange globs are stellar nurseries, dense molecular clouds that collapse to form stars. Near us, about 400 light years away, is a star-forming region called the Scorpius-Centaurus Association, where there was a great episode of star formation about five million years ago. At that time a massive star exploded, sending a shock wave through the molecular cloud, causing many new stars to form. The winds associated with that episode generated the "shells," or "clouds," that you can see here as blue arcs emanating from the Scorpius-Centaurus Association.

The black region in the drawing, called the Local Bubble, is very low density and very hot—about a million degrees. The shells, or clouds, are about 7,000 degrees, much cooler than the bubble that they're moving through. They're also denser than the bubble, but only relatively. "Denser" means that a cubic inch of cloud might contain 150 atoms, compared with the best laboratory vacuum, which would contain 10,000 times more. The Local Bubble is even more rarified, with less than one atom per cubic inch. Even though the interstellar medium is remarkably dilute, on a larger scale it behaves much like denser gases and fluids with which we are familiar.

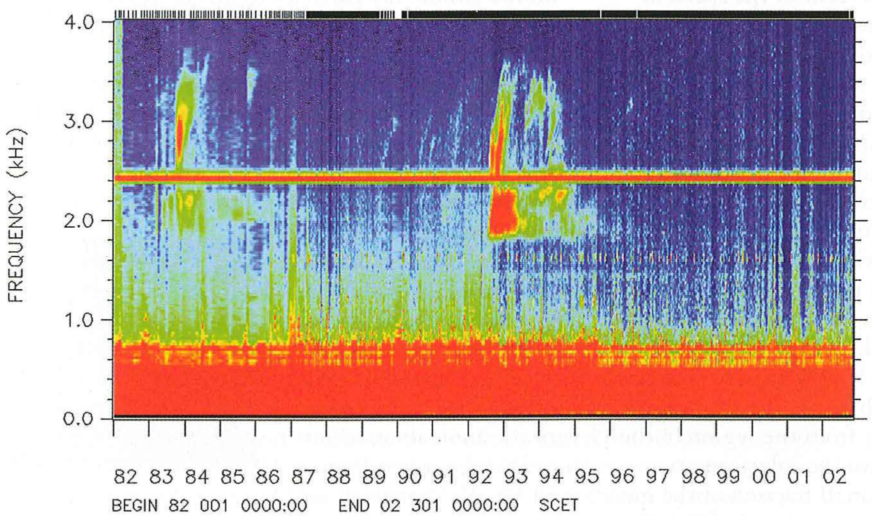
Now, the sun is moving relative to its surroundings. Actually, everything is orbiting the center of the galaxy, but if we neglect that and consider just the motion of the sun relative to everything around it, it's moving in the direction of the yellow arrow. If we zoom in even closer (below) and look at the local cloud, we can see that the sun is moving to the left in the image and the cloud is moving downward. It appears that the cloud enveloped the sun only in the last 1,000 to 100,000 years —in other words, very recently on a galactic time scale.

Before that, the sun was in the Local Bubble, where the interstellar pressure is much lower than in the cloud. As a result, the solar wind would have expanded much farther outward and the heliosphere would have been much larger than it is now. We're fortunate that we're in a dense

Because the sun is moving in the direction of the yellow arrow and the dense cloud that it's in is drifting toward the bottom of the image, the interstellar wind appears to be coming from the direction of the center of the galaxy. Fortunately, that's the direction the Voyager spacecraft are headed, which means they are on the shortest route out of the heliosphere.



We were fortunate that in 1977 the planetary alignment was on the side of the solar system toward that direction [toward the galactic center], because that means we are heading in the general direction of the nose of the heliosphere—the shortest way out.



These low-frequency radio signals from the heliopause were detected when huge blast waves from the corona at solar maximum excited the interstellar plasma in 1983 and 1992. By observing when the eruption blasted off from the sun, we can calculate how far it is to the heliopause. Cosmic rays are providing the essential clues.

cloud where the inward pressure makes the heliosphere smaller and the journey to the edge of interstellar space shorter.

The shortest distance to the heliopause is toward the nose of the heliosphere, that is, toward the incident interstellar wind rather than down the tail of the heliosphere. The combined motions of the sun and the dense interstellar cloud are such that the interstellar wind appears to be coming from the direction of the center of the Milky Way. We know the direction of the interstellar wind because, unlike interstellar ions that are deflected around the heliosphere, neutral atoms in the wind, such as hydrogen and helium, drift deep into the heliosphere where their arrival direction can be observed. We were fortunate that in 1977 the planetary alignment was on the side of the solar system toward that direction, because that means we are heading in the general direction of the nose of the heliosphere—the shortest way out.

Although we know the direction to the nose of the heliosphere, we don't know precisely how far away it is. John Richardson from MIT continuously measures the outward pressure of the solar wind very accurately, but the uncertainty in our knowledge of the inward interstellar pressure leads to an uncertainty in our estimate of the distance to the heliopause where the two pressures are in balance. Our current knowledge of the pressure in the local interstellar cloud suggests that the distance to the nose of the heliosphere is between 125 to 140 astronomical units (AU; one AU is the distance from the sun to Earth). Neptune is at 30 AU, so the heliopause is four to five times farther from the sun than Neptune. At the end of 2003, Voyager 1 will be 90 AU from the sun, and Voyager 2 will be 72 AU.

We can also estimate the distance to the heliopause by observing the speed of a blast wave from a coronal mass ejection and determining how long it takes the blast wave to reach the heliopause. When a large blast wave reaches the heliopause, it excites the interstellar plasma to radiate radio waves, which we can detect. Since we can observe when the blast wave starts at the sun, and we can determine when the radio waves begin, we can estimate the distance if we know the speed of the blast wave.

Don Gurnett and Bill Kurth at the University of Iowa observed such radio emissions in 1983, the first time radio emissions from the heliopause were detected. The frequency is so low (around 2,000 cycles per second) that the radio waves are undetectable inside of about 10 AU because they are excluded by the denser solar wind plasma closer to the sun.

It had been suggested by Ralph McNutt, then at MIT, that a major blast wave was responsible and that, since such large blast waves occur at solar maximum, such episodes should occur every 11 years during periods of maximum solar activity. When the investigators observed another episode in 1992, they looked for ways to determine the time it took the blast wave to reach the heliopause. When an eruption from the sun blasts out through the solar system, it sweeps out the cosmic rays that have come in from the galaxy. So there's a temporary decrease in cosmic radiation at Earth when the blast sweeps past; that tells us the start time. At Earth, we observed a major decrease in galactic ray intensity in 1982, and 412 days later the radio emission appeared in 1983.

In 1991, another major blast wave swept up the cosmic rays at Earth, and 419 days later another episode of radio emissions began. So that gives us the time. All we need to know is the speed of the blast wave. Although we can measure the speed of the blast wave out to Voyager's distance, we've never been to the very outer edges of the heliosphere, so we don't know how much the blast wave slows as it encounters the termination shock and continues through the hot, slow wind beyond the shock to the heliopause. That means there is uncertainty about the speed and therefore in the estimated distance to the heliopause. But the best estimates suggest that the average time of 415 days corresponds to a distance of 110 to 160 AU, which is similar to the estimate mentioned earlier—four to five times as far out as Neptune.

Another way to estimate the size of the heliospheric bubble is one that Alan Cummings (PhD '73), a member of the professional staff, and I have been pursuing. We're looking at cosmic ray particles coming from the termination shock. These are called anomalous cosmic rays and originate as neutral atoms (hydrogen, helium, oxygen, neon, argon) from interstellar space flowing leisurely into the solar system. As they approach the sun, they become ionized and are carried back out to the termination shock by the solar wind at a million mph. Some of them will bounce back and forth across the shock for several years as their speed—initially only 0.1 percent of the speed of light—slowly increases with each bounce to as much as 10 percent of the speed of light. These anomalous cosmic ray particles then diffuse back inward toward the sun, some making it all the way to Earth.

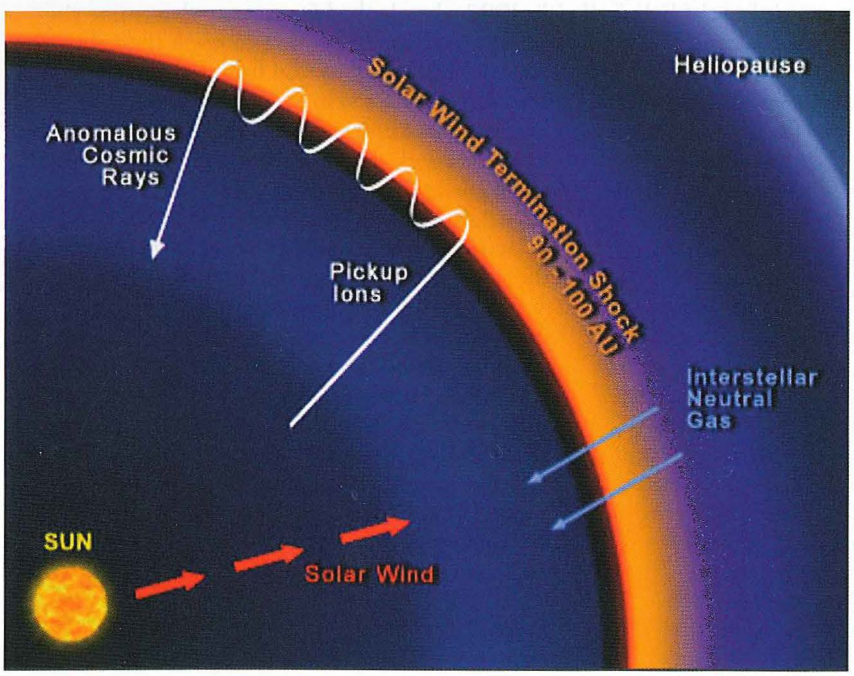
How does the acceleration of particles at the termination shock happen? It's essentially cosmic ping-pong. The solar wind, with imbedded magnetic irregularities, flows into the shock at a million mph, where it abruptly slows to 250,000 mph, causing the irregularities to slow as well. A cosmic ray particle, which is ionized, scatters off of the magnetic irregularities, bouncing back and forth like a ping-pong ball. As the ion bounces off the moving irregularities, it slowly gains speed. It may bounce back and forth across the shock for a year or two until it escapes from the region of the shock and diffuses back into the solar system.

Shock acceleration of a small fraction of the ions up to velocities approaching the speed of light is a fairly commonplace occurrence in the galaxy. In this case, we're using the ions accelerated at the termination shock to estimate how far it is to the shock. Because the anomalous cosmic rays originate at the shock, Voyager's cosmic ray detectors will observe an increasing intensity as it approaches the shock. By measuring the rate at which the intensity increases with increasing distance from the sun, we can extrapolate outward to determine how much farther away the shock is. We do that when solar activity is both at its minimum and its maximum.

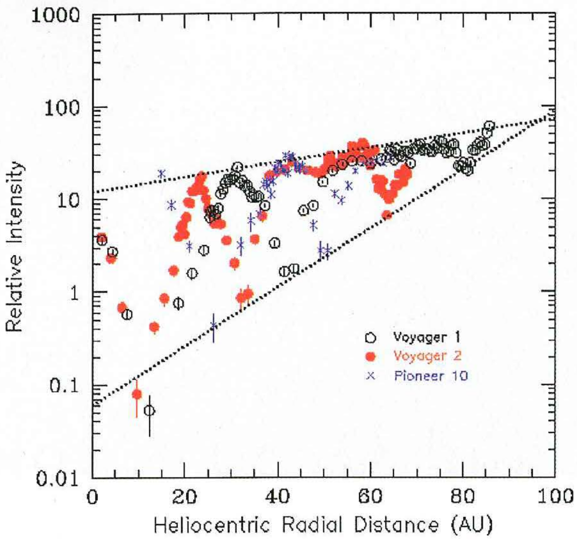
Cosmic rays are most effectively swept out when the sun is most active during its 11-year cycle. Even though the wind is slower at that time, it is more turbulent and more efficient at scattering cosmic ray particles and sweeping them outward. But when the sun is quiet, the wind is fast but much less turbulent, and the reduced scattering allows cosmic ray particles to diffuse inward more easily. So you would expect that during minimum solar activity, the cosmic ray flux intensity would not be much different closer to the sun than it is at their source. However, at maximum solar activity the intensity inside would be much lower than at the termination shock because cosmic rays are swept out more efficiently. That variation should happen with an 11-year cycle.

Voyager was launched in 1977, just at the end of a period of minimum solar activity, when there is a minimum of sweeping and the intensity is high. But by 1980, Voyager 1 and 2 were around 10 AU, and the intensity had decreased by a factor of 50 as the more turbulent solar wind swept most of the anomalous cosmic rays outward. A few years later, when Pioneer 10 (which was launched in 1972), Voyager 1, and Voyager 2 were at 43, 30, and 23 AU respectively, the sun was again quiet and the intensity was again high. At the next solar maximum in 1990, when the spacecraft were at 50, 43, and 33 AU, the intensity was again reduced, but higher than it was in 1980, when the spacecraft were farther from the shock. So, as expected, the intensity is higher closer to the shock.

We have a 30-year sequence of observations beginning with the launch of Pioneer 10. From the Voyager launches in 1977 until 1996, when Pioneer 10 no longer had enough power to measure the anomalous cosmic rays, we had spacecraft at three different locations to help us in extrapolating out to the shock. We can combine all these samples of space and time together in the plot at the top of the opposite page. If, instead of only three, we had a constellation of spacecraft spaced every AU between Earth and the shock at solar minimum, those spacecraft would have measured an intensity increase with radial distance as depicted by the top line, with the source of particles somewhere along the outward extension of the line. When the sun is very active, the set of spacecraft would have traced the much steeper



When anomalous cosmic rays—neutral atoms from interstellar space flowing into the solar system—get close to the sun, they become ionized and the solar wind carries them back to the termination shock. There they bounce back and forth across the shock, picking up enough speed for them to diffuse back in toward the sun. Measuring how their intensity changes with distance from the sun will help determine the distance to the termination shock.

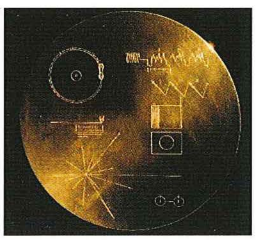


Pioneer 10 and Voyagers 1 and 2 have been measuring the intensity flux of cosmic rays across 80 AU and 30 years, including three cycles of solar maximum and minimum activity. If, instead of three spacecraft, there were a whole fleet (one every AU), they would have traced the top line at solar minimum and the steeper bottom line at solar maximum, when the cosmic rays are more cleanly swept out. The lines meet at the source of the particles—the termination shock.

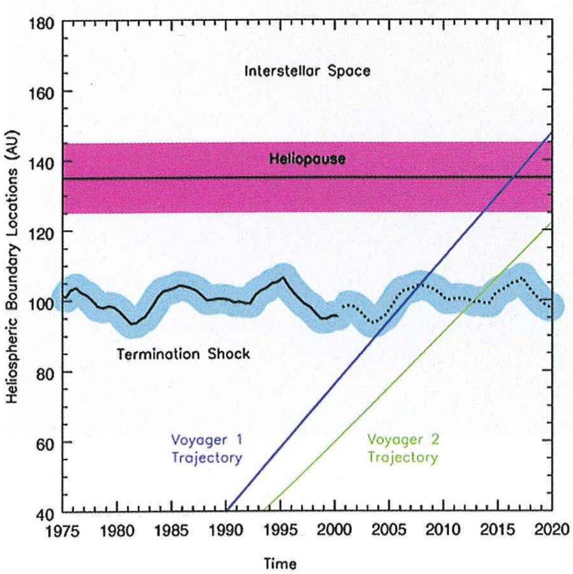
increase with distance as shown by the bottom line. And where these two lines meet is the source. This suggests that the source of the particles, the termination shock, is between 90 and 100 AU. And Voyager 1 is already beyond 88 AU and travels 10 AU every three years. So it might not be long before we get there.

But nature doesn't make it quite so easy. Remember that the heliosphere breathes over its 11-year cycle and is smallest when the sun is most active, because that's when the wind is slowest. Right now the termination shock is as close as it gets. The question is: how soon will it start moving farther away?

Theoretical models based on the observed solar wind pressure data provide estimates of the movement of the shock as shown by the wavy black line in the figure below. The blue band around the line indicates the uncertainty in the estimate. As the heliosphere breathes in and out, the termination shock moves with it, ranging between 95 and 105 AU over the solar cycle. Because of the obvious differences among the solar cycles, it is not possible to predict exactly when the shock will start moving outward. As an illustration of what might happen, the dotted line shows the shock location if it were to mimic what happened 22 years earlier. This suggests that the shock is likely to be moving outward by sometime in 2005. If the shock is located near the lower edge of the blue band, Voyager 1 would encounter it before then, but if the shock is nearer the upper edge, it would take four more years to reach it, with Voyager 2 following five years later. So, we are in a race to reach the termination shock in the next two years before it starts moving outward, possibly faster than Voyager 1.



Voyager carries a disk of images and sounds of Earth into interstellar space.



Because the heliosphere "breathes" in and out, the termination shock is a moving target. If Voyager 1 reaches the expanding termination shock (the bottom of the blue band in this model) by 2005, it could reach the heliopause (at the bottom of the magenta band) in another 10 years, with enough power left to radio back what it finds.

In the longer term, we're in another race—a race to reach the heliopause and enter interstellar space while Voyager still has enough electrical power to transmit data back to Earth. The heliopause is about 35 AU beyond the termination shock and is likely in the range shown by the magenta band in the figure, so it will be at least 10 years before Voyager 1 reaches the edge of interstellar space. Voyager is powered by plutonium 238, which has an 89-year half-life, so there should be enough electrical power to last until about 2020. The spacecraft is already 25 years old, so something else on the spacecraft may fail before that. But if nothing critical fails, it's possible that Voyager 1 could win the race and return the first observations from interstellar space.

That's where we are today in our continuing journey of discovery. Voyager 1 may encounter the termination shock in the next several years, followed five years later by Voyager 2. We will then have our first direct measure of the size of the heliosphere and how much farther it is to interstellar space. In 10 to 15 years, Voyager 1 will become our first interstellar probe, with Voyager 2 close behind. Both will begin an endless journey through interstellar space, carrying a message signifying that we have taken our first small step into our local neighborhood in the Milky Way. □

As project scientist for Voyager, Ed Stone oversaw all its scientific experiments, including one of his own: the cosmic ray experiment, which is now approaching the moment Stone has been waiting three decades for—when Voyager finally reaches the termination shock and sends back the first glimpse of the source of anomalous cosmic rays. Since his first NASA cosmic ray experiment in 1961, Stone has been principal investigator on nine NASA missions and co-investigator on five more. And he was also director of JPL from 1991 to 2001. Stone came to Caltech as a research fellow in 1964, after earning his PhD in physics from the University of Chicago. He has been professor since 1976 and the Morrisroe Professor of Physics since 1994, and was chairman of the Division of Physics, Mathematics and Astronomy from 1983 to 1988 and vice president for astronomical facilities from 1988 to 1990. This article was adapted from a November Watson Lecture, which can be viewed at http://atcaltech.caltech.edu/theater/.