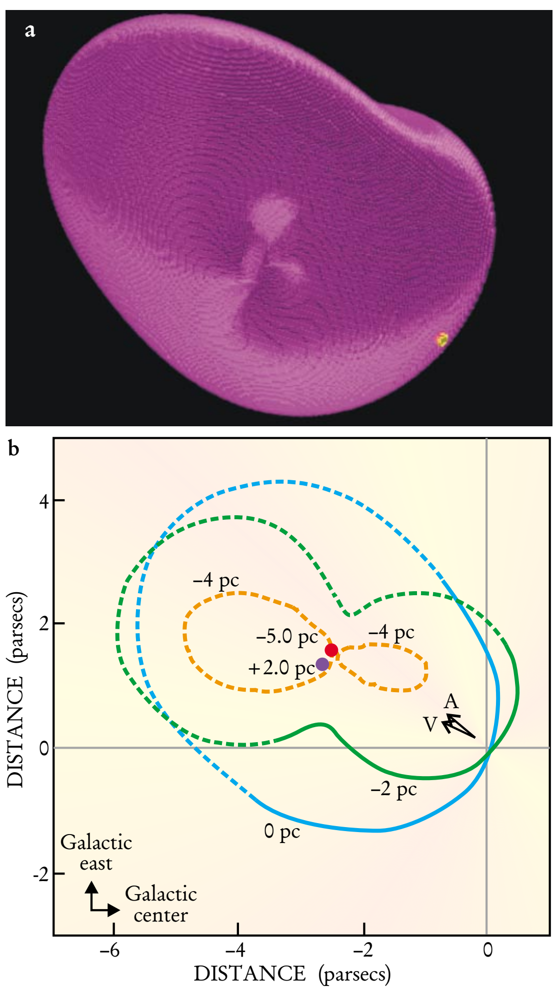
Mapping the Interstellar Cloud We Live in

> The Solar System will soon be abandoned by the warm cloud of atomic hydrogen that surrounds our heliosphere.

We often speak of the Hubble Space Telescope as a unique window on the most distant and ancient galaxies. But the HST can also tell us things we never knew about our most intimate interstellar surroundings. The 10 January *Astrophysical Journal* brings us the first of two articles,[1] by Jeffrey Linsky, Seth Redfield, and colleagues at the University of Colorado, that offer a three-dimensional map of the "local interstellar cloud," derived mostly from ultraviolet absorption spectra recorded by instruments aboard the HST. The LIC, they report, is a rather uniform, egg-shaped cloud of warm atomic hydrogen, only 20 light-years long, in which the Solar System and its surrounding heliosphere of solar wind and magnetic field sit like a tiny, off-center yolk. (See the figure below.)

The metaphor is not entirely apt. The misshapen egg will soon abandon its little yolk. The LIC is sweeping past the heliosphere at a speed of 26 km/s. In less than 3000 years, Linsky and company calculate, the cloud will have passed us by, leaving the heliosphere at the mercy of another passing cloud or of the much more rarefied and ionized hot interstellar matrix between the warm clouds.

The new environment might shrink or expand our heliosphere—which nowadays extends about a light-day from the Sun—with some effect on auroras and solar magnetic fields. But that's certainly not the principal reason for investigating the local interstellar medium. "We got into this business through our interest in the chemical evolution of the Galaxy," Linsky told us. "For example, one wants to know how much of the primordial deuterium left over from the Big Bang has been destroyed by astrophysical processes, and how thoroughly the surviving deuterium is mixed throughout the Galaxy." It is thought that stellar processes cannot make deuterium; they can only consume it. Quite apart from its interest for the theory of Big Bang nucleosynthesis (see PHYSICS TODAY, August 1996, page 17) deuterium turns out to be the observational key to the mapping of the LIC.



THE LOCAL Interstellar Cloud, as mapped by the Colorado group.[1] **(a)** In this 3-dimensional rendering, the Solar System and its heliosphere appears as a yellow dot very near the cloud's back end. **(b)** In this contour map of the cloud's boundary, now viewed from the North Galactic Pole with the Solar System at the origin, contours are parallel to the Galactic plane and labeled, in parsecs, by their distances from the plane. (1 pc = 3.3 light-years.) The dashed sections are less well determined than the solid curves. The colored dots indicate the top and bottom extremes of the cloud. Arrow **V** is the flow direction of the cloud past the Solar System, and **A** is the direction from the Sco–Cen association of hot young stars.

Clouds warm and cold

The standard theory of the interstellar medium anticipates that the all-pervading hydrogen gas separates into three distinct stable regimes: cold clouds, warm clouds, and the hot matrix that surrounds them. The cold clouds of molecular and atomic hydrogen, with temperatures ranging from about 10–100 K, have densities of a few thousand atoms or molecules per cm^3. That's where new stars are formed. The warm clouds are too hot ($7–10 \times 10^3$ K) for molecules to survive, but cool and diffuse enough so that most of the atomic hydrogen is in its neutral ground state. The hot interstellar matrix, with temperatures of order 10^6 K, is mostly ionized. Its extremely low density (10^{-3} protons per cm^3) greatly retards cooling.

The warm cloud that envelops us is the one most amenable to study, and therefore the one best suited for checking the assumptions and predictions of the theory. Furthermore, because astronomers have to view the wider cosmos through the LIC—at least for another few millennia—it pays to know as much as possible about this foreground veil.

From what was known about other warm interstellar clouds imaged in reflected starlight, it was widely assumed that the LIC is a rather wispy structure of thin filaments or fluffy layers. But the Colorado group's map shows us something quite different: a stocky ovoid figure of rather uniform density and temperature, with a relatively smooth, well-defined surface.

Mapping with deuterium

How did Linsky and company arrive at this three-dimensional map? It is based on hydrogen column densities in many different directions, measured by absorption of light from a sampling of 32 stars outside the LIC. (Column density is density integrated along a line of sight.) But in fact, the group determined the hydrogen column density *indirectly*, by using deuterium and singly ionized calcium as surrogates for ordinary hydrogen.

The trouble with ordinary hydrogen (^{1}H) is that there's just too much of it. The thickness of the LIC is a million times greater than the cloud's optical attenuation length at the ultraviolet Lyman α wavelength (1216 Å). The center of this principal hydrogen absorption line is utterly black, and therefore useless for measuring absorber thicknesses.

One can make some use of the Lyα line's gray wings. But there seems to be a better solution. The Lyα line of deuterium is isotope-shifted just 0.3 Å blueward of the ^{1}H line. Because the LIC has only about 1.5 deuterium atoms for every 10^5 hydrogens, the deuterium Lyα line is not saturated. Having convinced themselves that the D/H abundance ratio is adequately constant throughout the LIC, the Colorado group concluded that measuring deuterium column densities and then dividing by D/H would yield the best determinations of the hydrogen column densities and hence the distances to the outer LIC surface in the various directions.

The group recorded most of its ultraviolet absorption data by means of the Goddard High Resolution Spectrograph, which was one of the HST's original instruments. More recently, Linsky and coworkers have been availing themselves of the powerful second-generation Space Telescope Imaging Spectrometer, which replaced the GHRS aboard the HST in 1997.

Doppler selection

How does the Colorado group know that the recorded Lyα absorption is attributable entirely to atoms in the LIC, which is the structure they're trying to map? There are, after all, several warm interstellar clouds along the line of sight between us and a typical star in the group's database. The answer is: The group takes advantage of the fact that the atoms in any given cloud are moving at a rather uniform common velocity, superimposed on random thermal and turbulent motions.

In the case of the LIC, that common velocity, V_{LC}, relative to the solar system and its heliosphere, is 26 km/s in the direction indicated by the arrow marked **V** in the figure's lower panel. "We take this flow vector from other people's measurements of absorption by calcium in the LIC and the flow of interstellar helium through the Solar System,"[2] Linsky told us. Its direction—and the long axis of the LIC—are suspiciously close to the direction (arrow **A**) from the crowded Scorpius–Centaurus association of hot young stars, some 400 light-years away. This suggests that the LIC is being propelled by stellar winds and supernova shock waves from the Sco–Cen association. Our little heliosphere, at the origin of coordinates and very close to the "back" end of the LIC, does not participate in this general rush away from Sco–Cen and will thus soon be left behind.

Knowing all this, one can use Doppler shifts to distinguish absorption of the starlight in the LIC from extraneous absorption in other clouds along the line of sight: When the Colorado group looks at a star in some direction that makes an angle θ with the flow vector **V**, they require that the deuterium Lyα absorption line be redshifted by $(V_{LC}/c)\cos\theta$. That becomes a blueshift, of course, when one is looking back toward Sco–Cen.

Confirming with calcium

Limited by the scarcity of Hubble telescope observing time, the Colorado group has, for the moment, HST deuterium absorption spectra from only 16 stars surrounding the LIC. That's barely adequate for producing a reliable map of the local cloud. So the group has augmented this primary data set with some shorter-wavelength hydrogen data from the Extreme Ultraviolet Explorer satellite and, more important, hydrogen column densities based on ionized-calcium absorption spectra in the directions of 13 additional stars.

Because the principal absorption line of singly ionized gaseous calcium is in the visible, one can use ground-based telescopes to collect these supplementary data. (Ultraviolet astronomy requires satellites because the atmosphere absorbs so much UV.) Furthermore, Doppler separation of the LIC absorption component is much easier for metals than for deuterium, because the slower thermal motion of the heavier metal atoms makes for narrower absorption lines. And one can plausibly assume that the LIC's overall Ca/H abundance ratio is the same as the Sun's.

But there's a problem. Unlike hydrogen and deuterium, metal atoms often adhere to dust grains in the interstellar clouds and thus become lost to spectroscopic observation. Not knowing, *a priori*, the fraction of calcium ions in the LIC that adhere to dust grains, the Colorado group treated that fraction as a free parameter in seeking a best fit between its deuterium and calcium data sets. The joint fit turned out to be quite good; both techniques seem to be finding the same outer limits for the warm interstellar cloud that surrounds us.

The hydrogen column densities in a total of 32 different LIC directions determined from the various absorption data sets indicated an outer surface smooth enough to be fitted with 9 spherical-harmonic terms. The resulting "Colorado model" of the LIC, shown in the figure's contour map as one would see it looking down from the North Galactic Pole, can be viewed from any angle on the group's Web site.[3] The Web site also lets observers determine the hydrogen column density through the LIC in any direction they might need.

Confronting theory

The standard theory assumes pressure equilibrium between the clouds and the hot matrix that surrounds them, so that temperature is roughly proportional to the inverse of density. Furthermore, it assumes that the ionization of hydrogen is in equilibrium with the ambient ultraviolet radiation field that does the photoionizing.

"But that's not what we see," Linsky told us. "We find that 45% of the LIC's hydrogen is ionized. That's much more than you'd expect at radiation equilibrium." Furthermore, for the observed density of the LIC, the theory predicts[4] a temperature of 9400 K. But the Colorado group measures a temperature of only 7000–8000 K.

A prescient 1996 paper by theorists Frederick Bruhweiler and Cheng-Hsuan Lyu at Catholic University in Washington DC offers a very plausible explanation.[5] They pointed out that the shock wave from a supernova explosion in the Sco–Cen association would completely ionize the hydrogen and helium in the LIC, 400 light-years away! Given the demographics of Sco–Cen, one would expect at least one such explosion some time between 2 and 4 million years ago. In that case, they argued, the ionic recombination in the LIC would still be quite far from recovering equilibrium—in good agreement with the observations. In fact, if one replaces the assumption of ionization equilibrium in the standard theory by the observed overionization levels, Linsky asserts, it predicts a temperature in much better agreement with the Colorado group's measurement.

"All the local interstellar clouds seem to be moving away from the Sco–Cen association," Bruhweiler told us. "The LIC appears to be part of an expanding complex of clouds on the boundary of a cavity about 700 light-years across, excavated by the stellar winds and supernova shock waves from the association of hot young stars at its center."

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References

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The Decreasing Arctic Ice Cover

New studies indicate that the Arctic Ocean's ice cover is about 40% thinner than it was 20 to 40 years ago, and the area of its perennial ice could be shrinking at a rate of about 7% per decade.

Ongoing monitoring of Earth's north polar region has been turning up numerous signs of change in its atmosphere, waters, and ice pack (see Physics Today, November 1998, page 17). Such studies have revealed that the Arctic ice mass is shrinking, but now, it seems, the rates of decline are much more rapid than previously thought.[1,2] Such changes are of concern because the polar region is expected to amplify any change in Earth's climate.

Ice thickness

The data on sea-ice thickness come primarily from submarine-borne instruments. In the 1990s the US Navy welcomed civilian scientists and their instruments aboard its Sturgeon-class submarines for five data-taking cruises in the Arctic. Sonar beams were directed upward from the subs to determine the ice draft—that is, the depth of sea ice below sea level. D. Andrew Rothrock, Yanling Yu, and Gary Maykut of the University of Washington have so far analyzed the data from the first three cruises (1993–97) and found that mean drafts in the central Arctic Ocean varied between 1 m and 3 m.

We don't know how these ice thicknesses compare to those in the 1980s because much of the submarine data remains classified. However, Rothrock, Yu, and Maykut found two publicly available data sets taken during naval cruises between 1958 and 1976. They looked for data taken at roughly the same locations and time of year as in the 1990 cruises; they found 29 such sites in roughly six geographical regions covering most of the deep-water portion of the Arctic Ocean. In each of those regions, the ice drafts had dropped, by amounts ranging from 0.9 to 1.8 m. The mean ice draft decreased 1.3 m, from 3.1 m to 1.8 m. (See the figure at right.) As noted in the report,[1] "The changes are striking both in the uniformity of their sign and in their magnitudes."

The 1990s data were all collected in the months of September and October while the 1958–76 data were taken during cruises ranging from July to October. One expects seasonal variation in the ice draft as summer heat melts some ice and winter freezing replenishes it. Rothrock, Yu, and Maykut used a model of this seasonal variation to adjust all the data to 15 September. In the accompanying figure, the circles represent the actual measurements and the colored symbols are the adjusted values.

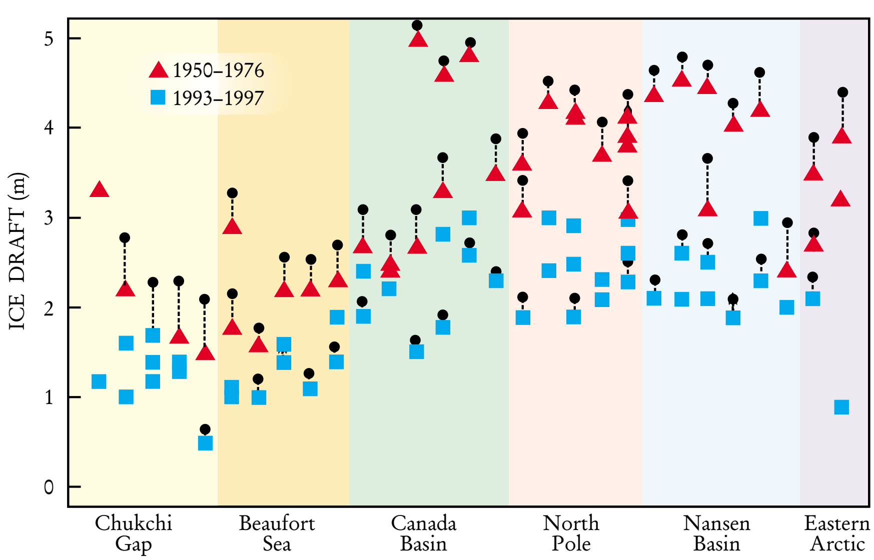
Other researchers have also studied trends in ice thickness, but their studies were more restricted in spatial extent.

Sea-ice coverage

The polar sea ice has been monitored since 1978 by satellite-borne sensors that detect low-frequency microwave radiation. Previous analyses of these microwave data found a drop of 3% per decade in the areal extent of the sea ice. Those results applied to the total ice, including both the perennial, or multiyear, ice—which doesn't melt in summer—and the more seasonal first-year ice. The area of multiyear ice alone was recently teased out of the same data by Ola Johannessen and his colleagues from the twin Nansen Environmental and Remote Sensing Centers, one in Bergen, Norway, and the other in Saint Petersburg, Russia.[2]

In theory, one can distinguish among multiyear ice, first-year ice, and open water based on the wavelengths of microwaves that each tends to emit. In practice, it's not so easy, largely because melting ice on the surface of multiyear ice, especially in summer, can confuse the readings. So Johannessen and his colleagues determined the extent of multiyear ice by looking only at the data from five winter months. From 1978 to 1998, the multiyear ice cover shrunk by 0.031 $\times$ 10^6 km^2/y, corresponding to a drop of 7% per decade, or more than twice the percentage decrease in total ice extent.

The Nansen group compared its data to ice thickness values deduced



Arctic ice thickness declined between 1958–76 (red triangles) and 1993–97 (blue squares). The ice drafts (thickness below the sea surface) were measured by sonar soundings from US Navy submarines. The triangles and squares represent data adjusted for season; circles are raw data points. (Adapted from ref. 1.)