Editor's Note: Gareth Wynn-Williams is professor of astronomy at the University of Hawaii. He studies interstellar clouds and colliding galaxies with the infrared telescopes at the observatories high atop Mauna Kea, a dormant volcano on the Big Island of Hawaii. His new book, The Fullness of Space, explores the gas and dust that fill the space between stars, planets, and even galaxies. This highly readable, nontechnical book introduces the components of the interstellar medium — from neutral hydrogen gas to dust particles, from giant molecular clouds to elusive cosmic ray particles — and their interrelationships. The book also addresses the origin, evolution, and fate of interstellar matter. This excerpt explains what astronomers have discovered about the diffuse interstellar medium, and reveals the Sun’s position within an irregularly shaped bubble of very hot, extremely tenuous gas. © Copyright 1992, Cambridge University Press. Used with permission.

(Photo courtesy United Kingdom Schmidt Telescope)
To some astronomers, interstellar matter is a curse. It dims stars, distorts colors, conceals parts of our Galaxy, and limits how far we can see into space. It prevents us from detecting some kinds of radiation at all.

To other astronomers, interstellar matter is a cornerstone of their science. It is the stuff out of which new stars are made, and into which they eventually fade. Interstellar matter permits astronomers to trace the rotation of the Milky Way, to monitor the creation rate of new elements, and to determine the mass of distant spiral galaxies. The most distant objects known — certain quasars — shine by the light of the gases they contain, while the youngest stars in the Galaxy are discovered by means of the radiation from the dust particles that surround them. Interstellar space provides the scientist with a laboratory whose vastness and emptiness allow atoms to act in ways that cannot be duplicated on Earth.

The matter that fills the spaces between stars but is not part of a discrete nebula or a dense cloud of molecular gas is known as the diffuse interstellar medium, and is the focus of this article. The three forms of gas that make up the diffuse interstellar medium are:

**Cool clouds** — gas composed of neutral atoms or molecules, with temperatures around 80 K (-315°F) and particle densities of the order of 10-100 atoms/cm³. A single cool cloud may have portions that are mainly atoms and portions that are mainly molecules.

**Warm gas** — a tenuous mixture of neutral and ionized gas, with a temperature near 8000 K (14,000°F), and a density of around 0.1 atoms/cm³.

**Coronal gas** — very hot and extremely tenuous gas, with temperatures around one million degrees K and a density of less than 10⁻² atoms/cm³.
An Active Interstellar Medium

In the last few years there has been a radical change in the way astronomers perceive the interstellar medium. The picture of a peaceful ocean of gas quietly filling the voids between the stars is being abandoned. In the new picture, space is filled with fast moving shock waves that continuously stir up the gas. Interstellar clouds are transient phenomena that are both generated and destroyed in the aftermath of supernova explosions.

The expanding gases from a supernova explosion blast outwards into the surrounding interstellar medium with speeds of many thousands of kilometers a second. A large fraction of the energy of the supernova is transformed into kinetic energy of the gas as it roars outwards into space. When these expanding gases collide with stationary interstellar matter, they push it outwards, leaving behind a comparatively empty cavity surrounding the now-dead star. This cavity contains hot, low-density coronal gas. In the region of the collision, shock waves are generated, and the kinetic energy of the gas is converted to heat, raising the temperature to around a million degrees Kelvin. If the supernova is less than a million years old, the hot gases will appear roughly spherical, as they do in an x-ray image of Tycho’s supernova remnant (see photo above). Even after a supernova remnant loses its shape and identity, shock waves continue to move away from it at speeds of hundreds of kilometers a second. These shock waves continue to heat the interstellar medium and create more coronal gas. An interesting, and as yet unanswered, question is how much of the interstellar medium gets heated in this way?

Bubbles and Tunnels

An early assumption was that since supernovae are rare events, coronal gas should be confined to a few hot “bubbles” surrounded by denser warm (8000 K) gas. The interstellar medium would thus have a structure somewhat resembling Swiss cheese. Subsequent calculations, however, have suggested that these bubbles may continue to grow so large that they eventually touch each other. The separate supernova remnants will then overlap and merge. The bubbles of coronal gas will coalesce with each other to form connected “tunnels” that spread throughout the Galaxy. The interstellar medium would thus have a porous structure, with the coronal gas able to flow through the gaps in the warm gas, much as water flows through the holes in a sponge when it is squeezed.

If the “tunnel” idea is correct, it would imply that at least 50% of interstellar space is filled by coronal gas. Can it really be true that this thin hot gas, which was only detected in 1973, and which still cannot be seen by telescopes on the Earth’s surface, fills over half the volume of our Galaxy? The question is controversial, but a number of astronomers think the answer is yes. We should note, however, that even if coronal gas were to fill 90% of the volume of the Galaxy, its density is so low that it would still comprise only a tiny fraction of the total mass of the interstellar medium.

Onions and Sheets

This new picture of a dynamic interstellar medium considerably alters our picture of where neutral, molecular, and ionized gas are found. Earlier ideas stressed that most regions of interstellar space are either predominantly molecular or predominantly atomic or predominantly ionized by ultraviolet radiation from hot stars. This idea is still valid, but it is now believed that the three types of gas can co-exist in the same cloud. Astronomers have calculated that a cloud of dense gas surrounded by coronal gas adopts a layered structure, something like an onion. The temperature is coldest and the density is highest in the middle. If the cloud...
The Diffuse Interstellar Medium

contains enough dust to exclude ultraviolet radiation, molecular hydrogen will be found in its dark core. Surrounding the H$_2$ is the cool (80 K) neutral atomic hydrogen that produces absorption lines in distant galaxies and quasars. The cool neutral hydrogen is in turn surrounded by a layer of 8000 K warm gas, which may be either neutral or ionized, depending on how bright the local starlight is. The outermost layer consists of gas which is in contact with the coronal gas which surrounds it. Heat is conducted inward through this layer from the surrounding hot coronal gas.

If these onion-like clouds are in contact with the million-degree coronal gas, why do they not all simply evaporate away? The answer is that there is a dynamic balance between the formation and destruction of interstellar clouds. Over a long enough period of time the numbers of clouds of different masses remain approximately constant. Individual clouds last typically for a few million years — a time that is long in the human scale, but very brief when compared to the 16-billion-year age of the Galaxy. New clouds are formed when shock waves from supernovae sweep up fresh gas and compress it into denser clouds. The resulting small clouds may either grow into large ones by joining to each other when they meet, or they may shrivel away by evaporation. The clouds that grow continue to do so until conditions become ripe for the formation of new stars in their interiors.

So far, we have said very little about the shapes of the clouds. There is a strong temptation to depict them as spheres, as in the diagram below left. The temptation arises because scientists are naturally inclined to attack simple problems before difficult ones. Because the sphere is the only perfectly symmetric three-dimensional shape, calculations of processes such as heat conduction are far simpler for spherical clouds than for odd-shaped ones. Astronomers therefore try to develop general ideas about cloud structure on the basis of hypothetical spherical clouds, then adapt these ideas, if necessary and if possible, to the more realistic shapes we believe real interstellar clouds to possess.

What are those shapes? Unfortunately they are very difficult to determine. Because our view of a particular cloud is always from the same angle it is almost impossible to know how thick a cloud is in the direction along our line of sight. This difficulty is acute in the case of clouds which appear to us to be long and thin (for example, the photo at right). Are we seeing a rope-like cloud from the side, or a sheet-like cloud from the edge? In most cases we cannot tell, but it is strongly suspected that much of the cool gas in the Galaxy lies in thin sheets that mark intersections of shock waves from different supernovae.

The shapes of clouds may also be affected by several other factors. Interstellar magnetic fields are certainly important in some cases. Elsewhere, the rotation of the cloud, and of the Galaxy itself, can produce forces that distort the cloud from its original shape. The gravitational pull of distant stars drags interstellar gas towards the plane of the Milky Way disk. Finally, if the cloud is large enough, its own internal gravitational forces will cause it to shrink under its own weight, setting the cloud on the road to its conversion into a new star.

Real interstellar clouds rarely have simple shapes. It is often difficult to determine whether clouds such as this are rope-like, or sheet-like. (Courtesy Lick Observatory)

The Local Neighborhood

Where do we, in the solar system, fit into this picture? Are we in a cloud or a bubble? Can we draw a map of the gas and dust within several hundred light years of the Sun? These questions are tough for astronomers to answer, because they require that we take a very broad view of the subject. The view is broad in the literal sense of encompassing 360° all around us, and broad in the technical sense of requiring a synthesis of many different kinds of data.
Living in a Molecular Cloud

The most massive objects in the Galaxy are the giant molecular clouds, vast accumulations of hydrogen molecules and other more complicated chemical compounds. Would life be any different if the Sun were inside a molecular cloud instead of its current position in the Galaxy? There is so much interstellar dust inside a molecular cloud that we would be able to see nothing beyond the edge of the solar system. Although the Sun, the planets and their moons would look much as they do now, there would be no background of stars, and no galaxies and nebulae to view through telescopes. The only compensation is that we might see more comets than we do now, but on some moonless nights there would be nothing to see in the sky at all. For those of us with an interest in astronomy the loss of information would be catastrophic. Everything we know about the universe that is based on visible, ultraviolet and x-ray observations would be lost, although if we had infrared and radio telescopes we would be able to use them to see out of the cloud.

It is not only astronomers and romantics whose lives would be affected by the loss of the starlit sky. The history of the last few centuries might have been very different. For one thing, the lack of fixed navigation points would have probably set back the exploration of the oceans by hundreds or even thousands of years. The patterns of international settlement, and of naval power, would have been totally different if mariners had not had the confidence to sail far from known coastlines.

The interstellar medium near the Sun. This highly schematic representation shows the Sun inside an irregularly shaped bubble of coronal gas. The bubble is surrounded by warm (8000 K) gas and by clouds. A few wispy clouds are found inside the bubble, which appears to about 200 parsecs, or 650 light years, across. (Courtesy G. Wynn-Williams)

The most likely origin for this bubble was a supernova explosion in our neighborhood some 100,000 years ago. Unfortunately there is little chance of our ever finding the neutron star or black hole remains of the star that exploded.

The local bubble is by no means free of neutral gas. Faint hydrogen absorption lines can be seen in the ultraviolet spectra of some of our closest neighbor stars. They imply that we are sitting at the edge of a small cloudbot of neutral gas, about five parsecs in diameter. The density of this cloudlet is only 0.1 particles/cm^2, and its temperature is around 8000 K. The cloudlet is therefore comprised of warm neutral gas, not the much denser gas seen in the "cool clouds," which typically have temperatures of 80 K. When we look at the stars in the constellation of Sagittarius, we are looking through the cloudblet, but it contains so little dust that we cannot see any perceptible reddening of these stars. Ultraviolet spectra of stars farther out in the bubble indicate that it contains a number of regions of cool neutral gas, but there are not enough data to determine the shapes of sizes of these clouds. For want of a better theory, we can guess that some of these cool regions resemble the "onion" clouds we discussed earlier. Some of the loops and arcs seen in a map of the sky as it appears at a wavelength of 21 centimeters (see photo at far right) are almost certainly part of the shell of material swept up by the supernova that created the local bubble.

The Galactic Halo

We have alluded several times to the fact that most of the interstellar matter in our Galaxy is found in the plane of the Milky Way. The gas is confined to a thin layer because it is pulled there by gravity. The gravitational force that the gas feels is the sum of the pulls of millions of stars. The net effect of all these stars is that the interstellar gas falls to where the concentration of stars is the highest — the plane of the Milky Way. Interstellar gas reacts to the twin forces of gravity and pressure in much the same way that the Earth's atmosphere does; its density and pressure fall off gradually with height. We can describe the thickness of an atmosphere in terms of its half-height, which is the distance
It is also extremely doubtful whether our current technological civilizations could have risen at all if the stars had not been there. A turning point in the history of science was the discovery of Johannes Kepler that the planets move in elliptical paths. This work led directly to Isaac Newton's formulation of the laws of gravitation and motion, and triggered a revolution in science that is still going on to this day. Kepler would almost certainly not have come up with the theory of elliptical orbits if the stars had been invisible. The unmoving distant stars provided him with fixed reference points against which the motions of the planets could be logged. Without them, he would have been faced with a much harder problem of disentangling the motions of the planets from those caused by the motion of the Earth as it spins in its orbit around the Sun.

The absence of starlight would have affected the history of life on Earth even before human intelligence developed. For one thing, many mammals are nocturnal; their ability to find food, and hence evolve, would have been impaired on moonless nights; they might have developed infrared-sensitive "eyes" like some snakes. For another, we know that migrating birds use the stars as one of their ways of navigating over long distances. Sees are spread round the world in the feathers and stomachs of birds, so if migration had evolved in a different way, the pattern of the world's flora would have been affected just as much as its fauna.

— From *The Fullness of Space* by Gareth Wynn-Williams.
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upwards one has to go in order for the density to decrease by a factor of two. Studies of the 21-centimeter hydrogen line have shown that the half-height for neutral hydrogen in the plane of the Galaxy is about 180 parsecs.

Since pressure increases with temperature, a hot gas can support itself against gravity better than a cold gas. Consequently, the half-height of a hot gas is greater than that of a cool gas. Since coronal gas is about 100 times hotter than the warmest neutral gas, the height of the coronal gas "atmosphere" of the Galaxy is likely to be very much greater than the 180-parsec height of the neutral gas. It is therefore not surprising that coronal gas has been found well outside the plane of the Milky Way Galaxy. This outlying gas is referred to as the halo of the Galaxy. Its full extent is not known, but it extends many kiloparsecs into the region in which few stars of any kind are found.

Not only coronal gas is found in the Galaxy's halo. Surveys of the sky at the 21-centimeter wavelength have led to the discovery of a number of large gas clouds in regions of the sky far away from the Milky Way. These clouds are referred to as high-velocity clouds because their Doppler shifts (the change in wavelength of a spectral line that is caused by the motion of an object towards us or away from us) are much larger than would be expected from nearby gas in the Galactic plane. Distances to high-velocity clouds are extremely hard to determine, but there is strong circumstantial evidence that some of them lie within a few kiloparsecs of the Galactic plane.

An intriguing feature of the high-velocity neutral clouds is that most of them have Doppler shifts which indicate that they are approaching the plane of the Galaxy. A possible explanation for some of the high-velocity clouds is that they are part of a galactic fountain, which works as follows. Coronal gas is generated in the plane of the Galaxy by supernovae; because of its large half-height it rises out of the plane into the halo. There it slowly cools and recombines to form neutral gas which, being cooler and denser than the coronal gas, sinks back to the plane of the Milky Way, becoming visible as the blueshifted high-velocity clouds. In this picture, the coronal and the high-velocity neutral gas are therefore all part of the same slow cycle of the interstellar medium.

The Galactic Halo. Because it is so hot, coronal gas can rise to great heights above the Galactic plane. As it cools, it recombines to form neutral clouds which fall back towards the plane of the Galaxy. Some of these so-called high-velocity clouds may be detected by their blueshifted 21-centimeter hydrogen absorption lines. (Courtesy G. Wynn-Williams)

The Fate of the Interstellar Medium

The interstellar medium is in a state of perpetual flux. It is continually diminished as stars are formed from it and replenished as they eject material back into it. Do these two processes balance, forming a kind of equilibrium, or is the total amount of

Neutral hydrogen gas away from the Galactic plane has a wispy appearance. This shows the gas above the plane; the blank area at lower left is the region of the sky that was not visible to the radio telescope that collected the data. (Courtesy C. Heiles)
Welcome To Our New Executive Director — Robert J. Havlen

The Board of Directors of the Astronomical Society of the Pacific is pleased to announce that Robert J. Havlen has been named the new Executive Director of the Society. Havlen comes to the ASP from the National Radio Astronomy Observatory (NRAO) in Socorro, New Mexico where he was Head of Observatory Services.

Havlen was drawn to astronomy as a young boy in his hometown of North Syracuse, New York. “Many professional astronomers are attracted to the field through their studies in physics, chemistry, geology or mathematics. My entry into the field was much more basic. As part of a Boy Scout project, I had to find north at night.” Soon he was grinding his own telescope mirror, learning astrophotography and attending meetings of the Syracuse Astronomical Society. A summer program in astronomy for high school students, organized by the National Science Foundation, and an internship at the NRAO in Green Bank, West Virginia while an undergraduate at the University of Rochester fueled his interest in astronomical research. The summer in Green Bank also awakened a lifelong love of spelunking.

For his Ph.D. thesis at the University of Arizona, Havlen observed Cepheid variable stars in OB associations, loose groupings of hot, young, massive stars. He studied their dynamics and interactions with the interstellar medium. He then followed his thesis advisor, Bengt Westerlund, to Chile, where Westerlund had been named Director in Chile of the European Southern Observatory (ESO).

Havlen planned to spend just one year in Chile, but stayed seven. He continued his photometric and spectroscopic research on OB associations and the structure of the Galaxy, and began new studies of clusters of galaxies.

In 1977, he left ESO to begin a Visiting Lectureship at the University of Virginia. Two years later, he was named Assistant to the Director at NRAO, a position that later became the Head of Observatory Services. At the NRAO, he was responsible for organizing schedules for telescope users, coordinating referees’ reports for observing projects, and other telescope and observatory support functions. In Socorro, Havlen also worked with the Visitors’ Center at the Very Large Array (VLA) to enhance the public’s knowledge of and interest in astronomy. Despite his administrative responsibilities, Havlen has remained active in astronomical research. An upcoming observing run at the Cerro-Tololo Inter-American Observatory in Chile will focus on purported OB associations in the constellation of Puppis, an understudied region of the Milky Way Galaxy.

Havlen arrived at the ASP’s San Francisco headquarters and began work as its fourth Executive Director the last week of January. “I have been extremely encouraged by the comments that I have received from friends and colleagues when they hear that I have become ASP’s new Executive Director.” As he looks to the Society’s future, the Board of Directors and the Society’s staff would like to take this moment to wish him a hearty “Welcome Bob!”

interstellar matter subject to long-term change? Unfortunately there is no single observation that will tell us if and how fast the interstellar medium is being used up. An inventory has to be taken of the stars and the gas in the Galactic disk, together with estimates of the rate of formation of new stars and the total rate of mass loss from old stars. Ideally this inventory would cover the whole Galaxy, but in practice it has only been possible to survey the solar neighborhood within about three thousand light years of the Sun.

When we perform this inventory, we find that the interstellar matter contributes about 15-30% of the total mass (27-50 solar masses/parsec²) in the solar neighborhood. The rate of return of gas into interstellar space by red giants, supernovae, and the like is only about one fifth of the star formation rate, implying a net loss to the interstellar medium of about 4 x 10⁷ solar masses/parsec²/year. If this loss rate were to continue indefinitely, all the interstellar gas in the solar neighborhood would be used up during the next 3 billion years. After this, no further star formation would be possible.

To understand why the interstellar medium is disappearing at this rate, we need to mention a few important points about the lives of stars. Stars with masses more than ten times that of the Sun have short lifetimes of only a few million years, where “lifetime” refers to the time during which hydrogen “burning” takes place in nuclear fusion reactions at the core of the star. The Sun has a total lifetime of about 10 billion years, somewhat more than half the present age of the universe (although the Sun did not begin burning hydrogen until only about 4.5 billion years ago). Stars smaller than about half the mass of the Sun are able to burn hydrogen for times that are longer than the current age of the universe. Since substantial mass loss from stars generally does not start until after stars have stopped burning hydrogen, we can conclude that any interstellar matter that goes into making low-mass stars is essentially locked up for good. Matter is recycled back into the interstellar medium only from high-mass stars, which are greatly in the minority; only 10% of the total mass of stars in the solar neighborhood is made up of stars with masses larger than the Sun.

The conclusion that our Galaxy will run out of interstellar matter in a few billion years must be treated with caution for several reasons. First, the statistics apply only to our local neighborhood; other parts of the Galaxy may behave differently. Second, the estimate of star formation rate depends critically on the statistics (how many and how big) of faint stars, which are intrinsically difficult to study. Third, it is possible that new interstellar matter is entering the Galaxy from outside. Although the best explanation for most of the high-velocity clouds of hydrogen atoms mentioned earlier is that they contain gas which was earlier ejected from the plane of the Galaxy, it is possible that some of the gas in the high-velocity clouds is reaching the Milky Way for the first time. If so, the rate of infall might be enough to balance the loss of interstellar matter to star formation, and the interstellar medium could have a future longer than three billion years.