Filled with colossal fountains of hot gas and vast bubbles blown by exploding stars, the interstellar medium is far more interesting than scientists once thought.
NASA GSFC ASTROPHYSICS DATA FACILITY (radio continuum [408 MHz], atomic hydrogen, far-infrared, x-ray and gamma ray); ROY DUNCAN Software Infrastructure Group (radio continuum [2.4–2.7 GHz]); THOMAS DAME Harvard-Smithsonian Center for Astrophysics (molecular hydrogen); STEPHAN D. PRICE Hanscom AFB (mid-infrared); AXEL MELLINGER University of Potsdam (visible light).
RADIO CONTINUUM (408 MHz)
Reveals fast-moving electrons, found especially at sites of past supernovae

ATOMIC HYDROGEN (1420 MHz)
Reveals neutral atomic hydrogen in interstellar clouds and diffuse gas

RADIO CONTINUUM (2.4–2.7 GHz)
Reveals warm, ionized gas and high-energy electrons

MOLECULAR HYDROGEN (115 GHz)
Reveals molecular hydrogen (as traced by carbon monoxide) in cold clouds

FAR-INFRARED (12–100 microns)
Reveals dust warmed by starlight, specially in star-forming regions

MID-INFRARED (6.8–10.8 microns)
Reveals complex molecules in interstellar clouds, as well as reddish stars

VISIBLE LIGHT (0.4–0.6 micron)
Reveals nearby stars and tenuous ionized gas; dark areas are cold and dense

X-RAY (0.25–1.5 kiloelectron-volt)
Reveals hot, shocked gas from supernovae

GAMMA RAY (greater than 300 megaelectron-volts)
Reveals high-energy phenomena such as pulsars and cosmic-ray collisions
A superbubble originates with a cluster of massive stars. One star goes supernova, forming a bubble of hot, low-density gas. Because massive stars have similar lifespans, another one soon blows.

The views above and on the preceding page are cross sections through the Milky Way.
The term “interstellar medium” once conjured up a picture like the one at right: frigid, inky clouds of gas and dust in repose near the galactic plane. Today astronomers recognize the medium as a protean atmosphere roiled by supernova explosions. Gas gushes through towering chimneys, then showers back down in mighty fountains.

Some of the interstellar medium takes the form of discrete clouds of atomic hydrogen (\( \text{H}^\text{I} \)) or molecular hydrogen (\( \text{H}_2 \)), most of the rest is in a pervasive ionized (\( \text{H}^\text{II} \)) or atomic gas. Intermixed is a trace amount of other elements. The total mass is about one fifth of the galaxy’s stars.

<table>
<thead>
<tr>
<th>Component</th>
<th>IN CLOUDS</th>
<th>BETWEEN CLOUDS</th>
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<tr>
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<tr>
<td>( \text{H}_2 )</td>
<td>15 K</td>
<td>8,000</td>
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<tr>
<td>( \text{H}^\text{I} )</td>
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<td></td>
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<td>35 20</td>
</tr>
<tr>
<td>Mass Fraction (%)</td>
<td>18 30</td>
<td>30 20</td>
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The two bubbles link up. Stellar winds help energize the bubbles. A third explodes. The interstellar medium starts to look like Swiss cheese. All three bubbles link up, forming a passage for hot gas and radiation.
We often think of the moon as a place, but in fact it is a hundred million places, an archipelago of solitude. You could go from
100 degrees below zero to 100 degrees above with a small step. You could yell in your friend’s ear and he would never hear you. Without an atmosphere to transmit heat or sound, each patch of the moon is an island in an un navigable sea.

The atmosphere of a planet is what binds its surface into a unified whole. It lets conditions such as temperature vary smoothly. More dramatically, events such as the impact of an asteroid, the eruption of a volcano and the emission of gas from a factory’s chimney can have effects that reach far beyond the spots where they took place. Local phenomena can have global consequences. This characteristic of atmospheres has begun to capture the interest of astronomers who study the Milky Way galaxy.

For many years, we have known that an extremely thin atmosphere called the interstellar medium envelops our galaxy and threads the space between its billions of stars. Until fairly recently, the medium seemed a cold, static reservoir of gas quietly waiting to condense into stars. You barely even notice it when looking up into the starry sky. Now we recognize the medium as a tempestuous mixture with an extreme diversity of density, temperature and ionization. Supernova explosions blow giant bubbles; fountains and chimneys may arch above the spiral disk; and clouds could be falling in from beyond the disk. These and other processes interconnect far-flung reaches of our galaxy much as atmospheric phenomena convey disturbances from one side of Earth to the other.

In fact, telescopes on the ground and in space are showing the galaxy’s atmosphere to be as complex as any planet’s. Held by the combined gravitational pull of the stars and other matter, permeated by starlight, energetic particles and a magnetic field, the interstellar medium is continuously stirred, heated, recycled and transformed. Like any atmosphere, it has its highest density and pressure at the “bottom,” in this case the plane that defines the middle of the galaxy, where the pressure must balance the weight of the medium from “above.” Dense concentrations of gas—clouds—form near the midplane, and from the densest subcondensations, stars precipitate.

When stars exhaust their nuclear fuel and die, those that are at least as massive as the sun expel much of their matter back into the interstellar medium. Thus, as the galaxy ages, each generation of stars pollutes the medium with heavy elements. As in the water cycle on Earth, precipitation is followed by “evaporation,” so that material can be recycled over and over again.

Up in the Air

THINKING OF THE INTERSTELLAR medium as a true atmosphere brings unity to some of the most pressing problems in astrophysics. First and foremost is star formation. Although astronomers have known the basic principles for decades, they still do not grasp exactly what determines when and at what rate stars precipitate from the interstellar medium. Theorists used to explain the creation of stars only in terms of the local conditions within an isolated gas cloud. Now they are considering conditions in the galaxy as a whole.

Not only do these conditions influence star formation, they are influenced by it. What one generation of stars does determines the environment in which subsequent generations are born, live and die. Understanding this feedback—the sway of stars, especially the hottest, rarest, most massive stars, over the large-scale properties of the interstellar medium—is another of the great challenges for researchers. Feedback can be both positive and negative. On the one hand, massive stars can heat and ionize the medium and cause it to bulge out from the midplane. This expansion increases the ambient pressure, compressing the clouds and perhaps triggering their collapse into a new generation of stars. On the other hand, the heating and ionization can also agitate clouds, inhibiting the birth of new stars. When the largest stars blow up, they can even destroy the clouds that gave them birth. In fact, negative feedback could explain why the gravitational collapse of clouds into stars is so inefficient. Typically only a few percent of a cloud’s mass becomes stars.

A third conundrum is that star formation often occurs in sporadic but intense bursts. In the Milky Way the competing feedback effects almost balance out, so that stars form at an unhurried pace—just 10 per year on average. In some galaxies, however, such as the “exploding galaxy” M82, positive feedback has gained the upper hand. Starting 20 million to 50 million years ago, star formation in the central parts of M82 began running out of control, proceeding 10 times faster than before. Our galaxy, too, may have had sporadic bursts. How these starbursts occur and what turns them off must be tied to the complex relation between stars and the tenuous atmosphere from which they precipitate.

Finally, astronomers debate how quickly the atmospheric activity is petering out. The majority of stars—those less massive than the sun, which live tens or even hundreds of billions of years—do not contribute to the feedback loops. More and more of the interstellar gas is being locked up into very long lived stars. Eventually all the spare gas in our Milky Way may be exhausted, leaving only stellar dregs behind. How soon this will happen depends on whether the Milky Way is a closed box. Recent observations suggest that the galaxy is still an open system, both gaining and losing mass to its cosmic surroundings. High-velocity clouds of relatively unpolluted hydrogen appear to be raining down from intergalactic space, rejuvenating our galaxy. Meanwhile the galaxy may be shedding gas in the form of a high-speed wind from its outer atmosphere, much as the sun slowly sheds mass in the solar wind.
Atoms, denoted by astronomers as HI. Beginning in the 1950s, megahertz (21-centimeter) line emitted by neutral hydrogen is the most famous spectral line of astronomy: the 1,420-nanometer wavelength blackbody emission from neutral hydrogen gas. The primary marker of interstellar matter is the hydrogen atom, which comprises about 75 percent of all matter in the galaxy. It resides in lumps and filaments with densities of 10 to 100 atoms per cubic centimeter and temperatures near 100 kelvins, embedded in a more diffuse, thinner (roughly 0.1 atom per cubic centimeter) and warmer (a few thousand kelvins) phase. Most of the HI is close to the galactic midplane, forming a gaseous disk about 300 parsecs (1,000 light-years) thick, roughly half the thickness of the main stellar disk you see when you notice the Milky Way in the night sky.

Hydrogen can also come in a molecular form (H₂), which is extremely difficult to detect directly. Much of the information about it has been inferred from high-frequency radio observations of the trace molecule carbon monoxide. Where carbon monoxide exists, so should molecular hydrogen. The molecules appear to be confined to the densest and coldest clouds—the places where starlight, which breaks molecules into their constituent atoms, cannot penetrate. These dense clouds, which are active sites of star formation, are found in a thin layer (100 parsecs thick) at the very bottom of the galactic atmosphere.

Until very recently, hydrogen molecules were seen directly only in places where they were being destroyed—that is, converted to atomic hydrogen—by a nearby star’s ultraviolet radiation or wind of outflowing particles. In these environments, H₂ glows at an infrared wavelength of about 2.2 microns. In the past few years, however, orbiting spectrographs, such as the shuttle-based platform called ORFEUS-SPAS and the new Far Ultraviolet Spectroscopic Explorer (FUSE) satellite, have sought molecular hydrogen at ultraviolet wavelengths near 0.1 micron. These instruments look for hydrogen that is backlit by distant stars and quasars: the H₂ leaves telltale absorption lines in the ultraviolet spectra of those objects. The advantage of this approach is that it can detect molecular hydrogen in quiescent regions of the galaxy, far from any star.

To general astonishment, two teams, led respectively by Philipp Richter of the University of Wisconsin and Wolfgang Gringel of the University of Tübingen in Germany, have discovered H₂ not just in the usual places—the high-density clouds located within the galactic disk—but also in low-density areas far outside the disk. This is a bit of a mystery, because high densities are needed to shield the molecules from the ravages of starlight. Perhaps a population of cool clouds extends much farther from the midplane than previously believed.

A third form of hydrogen is a plasma of hydrogen ions. Astronomers using this form of hydrogen as an unconventional source of energy to maintain the high temperatures. Supernova shocks and fast stellar winds appear to do

**Hot and Cold Running Hydrogen**

To tackle these problems, those of us who study the interstellar medium have first had to identify its diverse components. Astronomers carried out the initial step, an analysis of its elemental composition, in the 1950s and 1960s using the spectra of light emitted by bright nebulae, such as the Orion Nebula. In terms of the number of atomic nuclei, hydrogen constitutes 90 percent, helium about 10 percent, and everything else—from lithium to uranium—just a trace, about 0.1 percent.

Because hydrogen is so dominant, the structure of the galaxy’s atmosphere depends mainly on what forms the hydrogen takes. Early observations were sensitive primarily to cooler, neutral components. The primary marker of interstellar material is the most famous spectral line of astronomy: the 1,420-megahertz (21-centimeter) line emitted by neutral hydrogen atoms, denoted by astronomers as H i. Beginning in the 1950s, radio astronomers mapped out the distribution of HI within the galaxy. It resides in lumps and filaments with densities of 10 to 10 atom per cubic centimeter and temperatures near 100 kelvins, embedded in a more diffuse, thinner (roughly 0.1 atom per cubic centimeter) and warmer (a few thousand kelvins) phase. Most of the HI is close to the galactic midplane, forming a gaseous disk about 300 parsecs (1,000 light-years) thick, roughly half the thickness of the main stellar disk you see when you notice the Milky Way in the night sky.

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the trick. Coexisting with the hot plasma is the warm plasma, which is powered by extreme ultraviolet radiation. The weight of these extended layers increases the gas pressure at the midplane, with significant effects on star formation. Other galaxies appear to have coronas as well. The Chandra X-ray Observatory has recently seen one around the galaxy NGC 4631 [see middle illustration on next page].

**Blowing Bubbles**

Having identified these new, more energetic phases of the medium, astronomers have turned to the question of how the diverse components behave and interrelate. Not only does the interstellar medium cycle through stars, it changes from H\textsubscript{2} to H\textsubscript{i} to H\textsubscript{ii} and from cold to hot and back again. Massive stars are the only known source of energy powerful enough to account for all this activity. A study by Ralf-Jürgen Dettmar of the University of Bochum in Germany found that galaxies with a larger-than-average massive star population seem to have atmospheres that are more extended or puffed up. How the stars wield power over an entire galaxy is somewhat unclear, but astronomers generally pin the blame on the creation of hot ionized gas.

This gas appears to be produced by the high-velocity (100 to 200 kilometers per second) shock waves that expand into the interstellar medium following a supernova. Depending on the density of the gas and strength of the magnetic field in the ambient medium, the spherically expanding shock may clear out a cavity 50 to 100 parsecs in radius—a giant bubble.

In doing so, the shock accelerates a small fraction of the ions and electrons to near light speed. Known as cosmic rays, these fleet-footed particles are one way that stellar death feeds back (both positively and negatively) into stellar birth. Cosmic rays raise the pressure of the interstellar medium; higher pressures, in turn, compress the dense molecular clouds and increase the chance that they will collapse into stars. By ionizing some of the hydrogen, the cosmic rays also drive chemical reactions that synthesize complex molecules, some of which are the building blocks of life as we know it. And because the ions attach themselves to magnetic field lines, they trap the field within the clouds, which slows the rate of cloud collapse into stars.

If hot bubbles are created frequently enough, they could interconnect in a vast froth. This idea was first advanced in the 1970s by Barham Smith and Donald Cox of the University of Wisconsin–Madison. A couple of years later Christopher F. McKee of the University of California at Berkeley and Jeremiah P.
Ostriker of Princeton University argued that the hot phase should occupy 55 to 75 percent of interstellar space. Cooler neutral phases would be confined to isolated clouds within this ionized matrix—essentially the reverse of the traditional picture, in which the neutral gas dominates and the ionized gas is confined to small pockets.

Recent observations seem to support this upending of conventional wisdom. The nearby spiral galaxy M101, for example, has a circular disk of atomic hydrogen gas riddled with holes—presumably blown by massive stars. The interstellar medium of another galaxy, seven billion light-years distant, also looks like Swiss cheese. But the amount of hot gas and its influence on the structure of galactic atmospheres still occasion much debate.

Chimneys and Fountains

THE SUN ITSELF APPEARS to be located within a hot bubble, which has revealed itself in x-rays emitted by highly ionized trace ions such as oxygen. Called the Local Bubble, this region of hot gas was apparently created by a nearby supernova about one million years ago.

An even more spectacular example lies 450 parsecs from the sun in the direction of the constellations Orion and Eridanus. It was the subject of a recent study by Carl Heiles of the University of California at Berkeley and his colleagues. The Orion-Eridanus Bubble was formed by a star cluster in the constellation Orion. The cluster is of an elite type called an OB association—a bundle of the hottest and most massive stars, the O- and B-type stars, which are 20 to 60 times heavier than the sun (a G-type star) and 10³ to 10⁵ times brighter. The spectacular deaths of these short-lived stars in supernovae over the past 10 million years have swept the ambient gas into a shell-like skin around the outer boundary of the bubble. In visible light the shell appears as a faint lacework of ionized loops and filaments. The million-degree gas that fills its interior gives off a diffuse glow of x-rays.

The entire area is a veritable thunderstorm of star formation, with no sign of letting up. Stars continue to precipitate from the giant molecular cloud out of which the OB association emerged. One of the newest O stars, theta¹ C Orionis, is ionizing a small piece of the cloud—producing the Orion Nebula. In time, however, supernovae and ionizing radiation will completely disrupt the molecular cloud and dissociate its molecules. The molecular hydrogen will turn back into atomic and ionized hydrogen, and star formation will cease. Because the violent conversion process will increase the pressure in the interstellar medium, the demise of this molecular cloud may mean the birth of stars elsewhere in the galaxy.

Galactic bubbles should buoyantly lift off from the galactic midplane, like a thermal rising above the heated ground on Earth. Numerical calculations, such as those recently made by Mordecai-Mark MacLow of the American Museum of Natural History in New York City and his colleagues, suggest that bubbles can ascend all the way up into the halo of the galaxy. The result is a cosmic chimney through which hot gas spewed by supernovae near the midplane can vent to the galaxy’s upper atmosphere. There the gas will cool and rain back onto the
galactic disk. In this case, the superbubble and chimney become a galactic-scale fountain.

Such fountains could perhaps be the source of the hot galactic corona and even the galaxy’s magnetic field. According to calculations by Katia M. Ferrière of the Midi-Pyrénées Observatory in France, the combination of the updraft and the rotation of the galactic disk would act as a dynamo, much as motions deep inside the sun and Earth generate magnetic fields.

To be sure, observers have yet to prove the pervasive nature of the hot phase or the presence of fountains. The Orion-Eridanus bubble extends 400 parsecs from the midplane, and a similar superbubble in Cassiopeia rises 230 parsecs, but both have another 1,000 to 2,000 parsecs to go to reach the galactic corona. Magnetic fields and cooler, denser ionized gas could make it difficult or impossible for superbubbles to break out into the halo. But then, where did the hot corona come from? No plausible alternative is known.

**Getting Warm**

The warm (10^4 kelvins) plasma is as mysterious as its hot relative. Indeed, in the traditional picture of the interstellar medium, the widespread presence of warm ionized gas is simply impossible. Such gas should be limited to very small regions of space—the emission nebulae, such as the Orion Nebula, that immediately surround ultramassive stars. These stars account for only one star in five million, and most of the interstellar gas (the atomic and molecular hydrogen) is opaque to their photons. So the bulk of the galaxy should be unaffected.

Yet warm ionized gas is spread throughout interstellar space. One recent survey, known as WHAM, finds it even in the galactic halo, very far from the nearest O stars. Ionized gas is similarly widespread in other galaxies. This is a huge mystery. How did the ionizing photons manage to stray so far from their stars?

Bubbles may be the answer. If supernovae have hollowed out significant parts of the interstellar medium, ionizing photons may be able to travel large distances before being absorbed by neutral hydrogen. The Orion OB association provides an excellent example of how this could work. The O stars sit in an immense cavity carved out by earlier supernovae. Their photons now travel freely across the cavity, striking the distant bubble wall and making it glow. If galactic fountains or chimneys do indeed stretch up into the galactic halo, they could explain not only the hot corona but also the pervasiveness of warm ionized gas.

A new WHAM image of the Cassiopeia superbubble reveals a possible clue: a loop of warm gas arching far above the bubble, some 1,200 parsecs from the midplane. The outline of this loop bears a loose resemblance to a chimney, except that it has not (yet) broken out into the Milky Way’s outer halo. The amount of energy required to produce this gigantic structure is enormous—more than that available from the stars in the cluster that formed the bubble. Moreover, the time required to create it is 10 times the age of the cluster. So the loop may be a multigenerational project, created by a series of distinct bursts of star formation predating the cluster we see today. Each burst reenergized and expanded the bubble created by the preceding burst.

**Round and Round**

That large regions of the galaxy can be influenced by the formation of massive stars in a few localized regions seems to require that star formation somehow be coordinated over long periods of time. It may all begin with a single O-type star or a cluster of such stars in a giant molecular cloud. The stellar radiation, winds and explosions carve a modest cavity out of the surrounding interstellar medium. In the process the parent cloud is probably destroyed. Perchance this disturbance triggers star formation in a nearby cloud, and so on, until the interstellar medium in this corner of the galaxy begins to resemble Swiss cheese. The bubbles then begin to overlap, coalescing into a superbubble. The energy from more and more O-type stars feeds this expanding superbubble until its natural buoyancy stretches it from the midplane up toward the halo, forming a chimney.

The superbubble is now a pathway for hot interior gas to spread into the upper reaches of the galactic atmosphere, producing a widespread corona. Now, far from its source of energy, the coronal gas slowly begins to cool and condense into clouds. These clouds fall back to the galaxy’s midplane, completing the fountainlike cycle and replenishing the galactic disk with cool clouds from which star formation may begin anew.

Even though the principal components and processes of our galaxy’s atmosphere seem to have been identified, the details remain uncertain. Progress will be made as astronomers continue to study how the medium is cycled through stars, through the different phases of the medium, and between the disk and the halo. Observations of other galaxies give astronomers a bird’s-eye view of the interstellar goings-on.

Some crucial pieces could well be missing. For example, are stars really the main source of power for the interstellar medium? The loop above the Cassiopeia superbubble looks uncomfortably similar to the prominences that arch above the surface of the sun. Those prominences owe much to the magnetic field in the solar atmosphere. Could it be that magnetic activity dominates our galaxy’s atmosphere, too? If so, the analogy between galactic atmospheres and their stellar and planetary counterparts may be even more apt than we think.