20 Between the Stars: Gas and Dust in Space

Figure 20.1 NGC 3603 and Its Parent Cloud. This image, taken by the Hubble Space Telescope, shows the young star cluster NGC 3603 interacting with the cloud of gas from which it recently formed. The bright blue stars of the cluster have blown a bubble in the gas cloud. The remains of this cloud can be seen in the lower right part of the frame, glowing in response to the starlight illuminating it. In its darker parts, shielded from the harsh light of NGC 3603, new stars continue to form. Although the stars of NGC 3603 formed only recently, the most massive of them are already dying and ejecting their mass, producing the blue ring and streak features visible in the upper left part of the image. Thus, this image shows the full life cycle of stars, from formation out of interstellar gas, through life on the main sequence, to death and the return of stellar matter to interstellar space. (credit: modification of work by NASA, Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington), You-Hua Chu (University of Illinois Urbana-Champaign))

Chapter Outline

Thinking Ahead

Where do stars come from? We already know from earlier chapters that stars must die because ultimately they exhaust their nuclear fuel. We might hypothesize that new stars come into existence to replace the ones that die. In order to form new stars, however, we need the raw material to make them. It also turns out that stars eject mass throughout their lives (a kind of wind blows from their surface layers) and that material must go somewhere. What does this “raw material” of stars look like? How would you detect it, especially if it is not yet in the form of stars and cannot generate its own energy?

One of the most exciting discoveries of twentieth-century astronomy was that our Galaxy contains vast quantities of this “raw material”—atoms or molecules of gas and tiny solid dust particles found between the stars. Studying this diffuse matter between the stars helps us understand how new stars form and gives us important clues about our own origins billions of years ago.

20.1 The Interstellar Medium

Learning Objectives

By the end of this section, you will be able to:

- Explain how much interstellar matter there is in the Milky Way, and what its typical density is
- Describe how the interstellar medium is divided into gaseous and solid components

Astronomers refer to all the material between stars as *interstellar* matter; the entire collection of interstellar matter is called the **interstellar medium (ISM)**. Some interstellar material is concentrated into giant clouds, each of which is known as a **nebula** (plural "nebulae," Latin for "clouds"). The best-known nebulae are the ones that we can see glowing or reflecting visible light; there are many pictures of these in this chapter.

Interstellar clouds do not last for the lifetime of the universe. Instead, they are like clouds on Earth, constantly shifting, merging with each other, growing, or dispersing. Some become dense and massive enough to collapse under their own gravity, forming new stars. When stars die, they, in turn, eject some of their material into interstellar space. This material can then form new clouds and begin the cycle over again.

About 99% of the material between the stars is in the form of a *gas*—that is, it consists of individual atoms or molecules. The most abundant elements in this gas are hydrogen and helium (which we saw are also the most abundant elements in the stars), but the gas also includes other elements. Some of the gas is in the form of molecules—combinations of atoms. The remaining 1% of the interstellar material is solid—frozen particles consisting of many atoms and molecules that are called *interstellar grains* or **interstellar dust** (Figure 20.2). A typical dust grain consists of a core of rocklike material (silicates) or graphite surrounded by a mantle of ices; water, methane, and ammonia are probably the most abundant ices.

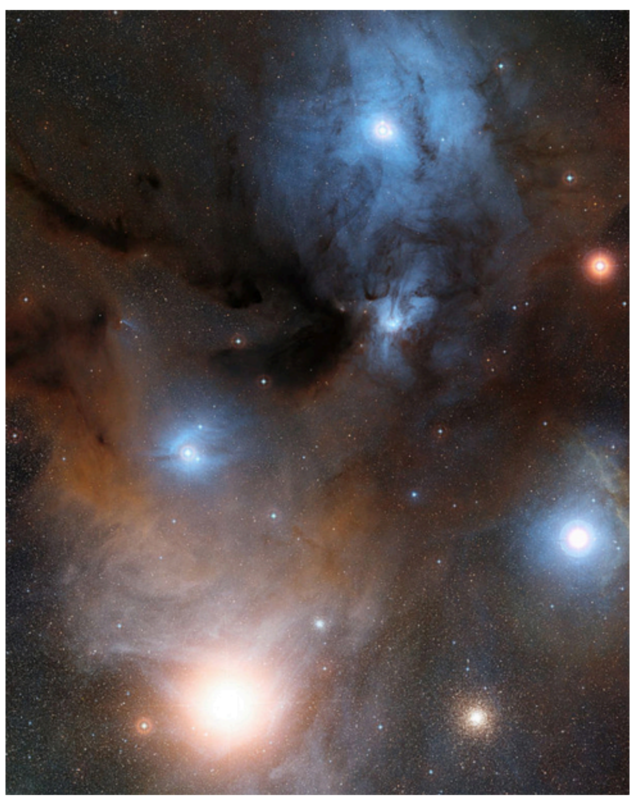

Figure 20.2 Various Types of Interstellar Matter. The reddish nebulae in this spectacular photograph glow with light emitted by hydrogen atoms. The darkest areas are clouds of dust that block the light from stars behind them. The upper part of the picture is filled with the bluish glow of light reflected from hot stars embedded in the outskirts of a huge, cool cloud of dust and gas. The cool supergiant star Antares can be seen as a big, reddish patch in the lower-left part of the picture. The star is shedding some of its outer atmosphere and is surrounded by a cloud of its own making that reflects the red light of the star. The red nebula in the middle right partially surrounds the star Sigma Scorpii. (To the right of Antares, you can see M4, a much more distant cluster of extremely old

stars.) (credit: modification of work by ESO/Digitized Sky Survey 2)

If all the interstellar gas within the Galaxy were spread out smoothly, there would be only about one atom of gas per cm^3 in interstellar space. (In contrast, the air in the room where you are reading this book has roughly 10^{19} atoms per cm^3.) The dust grains are even scarcer. A km^3 of space would contain only a few hundred to a few thousand tiny grains, each typically less than one ten-thousandth of a millimeter in diameter. These numbers are just averages, however, because the gas and dust are distributed in a patchy and irregular way, much as water vapor in Earth's atmosphere is often concentrated into clouds.

In some interstellar clouds, the density of gas and dust may exceed the average by as much as a thousand times or more, but even this density is more nearly a vacuum than any we can make on Earth. To show what we mean, let's imagine a vertical tube of air reaching from the ground to the top of Earth's atmosphere with a cross-section of 1 square meter. Now let us extend the same-size tube from the top of the atmosphere all the way to the edge of the observable universe—over 10 billion light-years away. Long though it is, the second tube would still contain fewer atoms than the one in our planet's atmosphere.

While the *density* of interstellar matter is very low, the volume of space in which such matter is found is huge, and so its *total mass* is substantial. To see why, we must bear in mind that stars occupy only a tiny fraction of the volume of the Milky Way Galaxy. For example, it takes light only about four seconds to travel a distance equal to the diameter of the Sun, but more than four *years* to travel from the Sun to the nearest star. Even though the spaces among the stars are sparsely populated, there's a lot of space out there!

Astronomers estimate that the total mass of gas and dust in the Milky Way Galaxy is equal to about 15% of the mass contained in stars. This means that the mass of the interstellar matter in our Galaxy amounts to about 10 billion times the mass of the Sun. There is plenty of raw material in the Galaxy to make generations of new stars and planets (and perhaps even astronomy students).

EXAMPLE 20.1

Estimating Interstellar Mass

You can make a rough estimate of how much interstellar mass our Galaxy contains and also how many new stars could be made from this interstellar matter. All you need to know is how big the Galaxy is and the average density using this formula:

$$\text{total mass} = \text{volume} \times \text{density of atoms} \times \text{mass per atom}$$

You have to remember to use consistent units—such as meters and kilograms. We will assume that our Galaxy is shaped like a cylinder; the volume of a cylinder equals the area of its base times its height

$$V = \pi R^2\, h$$

where *R* is the radius of the cylinder and *h* is its height.

Suppose that the average density of hydrogen gas in our Galaxy is one atom per cm^3. Each hydrogen atom has a mass of 1.7×10^{-27} kg. If the Galaxy is a cylinder with a diameter of 100,000 light-years and a height of 300 light-years, what is the mass of this gas? How many solar-mass stars (2.0×10^{30} kg) could be produced from this mass of gas if it were all turned into stars?

Solution

If the diameter of the Galaxy is 100,000 light-years, then the radius is 50,000 light-years. Recall that 1 light-year = 9.5×10^{12} km = 9.5×10^{17} cm, so the volume of the Galaxy is

$$V = \pi R^2\, h = \pi(50{,}000 \times 9.5 \times 10^{17}\ \text{cm})^2\ (300 \times 9.5 \times 10^{17}\ \text{cm}) = 2.0 \times 10^{66}\ \text{cm}^3$$

The total mass is therefore

$$M = V \times \text{density of atoms} \times \text{mass per atom}$$

$$2.0 \times 10^{66}\ \text{cm}^3 \times (1\ \text{atom/cm}^3) \times 1.7 \times 10^{-27}\ \text{kg} = 3.5 \times 10^{39}\ \text{kg}$$

This is sufficient to make

$$N = \frac{M}{(2.0 \times 10^{30}\ \text{kg})} = 1.75 \times 10^9$$

stars equal in mass to the Sun. That’s roughly 2 billion stars.

Check Your Learning

You can use the same method to estimate the mass of interstellar gas around the Sun. The distance from the Sun to the nearest other star, Proxima Centauri, is 4.2 light-years. We will see in Interstellar Matter around the Sun that the gas in the immediate vicinity of the Sun is less dense than average, about 0.1 atoms per cm^3. What is the total mass of interstellar hydrogen in a sphere centered on the Sun and extending out to Proxima Centauri? How does this compare to the mass of the Sun? It is helpful to remember that the volume of a sphere is related to its radius:

$$V = (4/3)\pi R^3$$

Answer:

The volume of a sphere stretching from the Sun to Proxima Centauri is:

$V = (4/3)\,\pi R^3 = (4/3)\,\pi\left(4.2 \times 9.5 \times 10^{17}\ \text{cm}\right)^3 = 2.7 \times 10^{56}\ \text{cm}^3$

Therefore, the mass of hydrogen in this sphere is:

$M = V \times \left(0.1\ \text{atom/cm}^3\right) \times 1.7 \times 10^{-27}\ \text{kg} = 4.5 \times 10^{28}\ \text{kg}$

This is only $(4.5 \times 10^{28}\ \text{kg})/(2.0 \times 10^{30}\ \text{kg}) = 2.2\%$ the mass of the Sun.

ASTRONOMY BASICS

Naming the Nebulae

As you look at the captions for some of the spectacular photographs in this chapter and The Birth of Stars and the Discovery of Planets outside the Solar System, you will notice the variety of names given to the nebulae. A few, which in small telescopes look like something recognizable, are sometimes named after the creatures or objects they resemble. Examples include the Crab, Tarantula, and Keyhole Nebulae. But most have only numbers that are entries in a catalog of astronomical objects.

Perhaps the best-known catalog of nebulae (as well as star clusters and galaxies) was compiled by the French astronomer Charles Messier (1730–1817). Messier’s passion was discovering comets, and his devotion to this cause earned him the nickname “The Comet Ferret” from King Louis XV. When comets are first seen coming toward the Sun, they look like little fuzzy patches of light; in small telescopes, they are easy to confuse with nebulae or with groupings of many stars so far away that their light is all blended together. Time and again, Messier’s heart leapt as he thought he had discovered one of his treasured comets, only to find that he had “merely” observed a nebula or cluster.

In frustration, Messier set out to catalog the position and appearance of over 100 objects that could be mistaken for comets. For him, this list was merely a tool in the far more important work of comet hunting. He would be very surprised if he returned today to discover that no one recalls his comets anymore, but his catalog of “fuzzy things that are not comets” is still widely used. When Figure 20.2 refers to M4, it denotes the fourth entry in Messier’s list. Visit https://www.nasa.gov/content/goddard/hubble-s-messier-catalog (https://www.nasa.gov/content/goddard/hubble-s-messier-catalog) for a gallery of M objects as photographed with the Hubble Space Telescope.

A far more extensive listing was compiled under the title of the *New General Catalog* (*NGC*) *of Nebulae and Star Clusters* in 1888 by John Dreyer, working at the observatory in Armagh, Ireland. He based his compilation on the work of William Herschel and his son John, plus many other observers who followed them. With the addition of two further listings (called the *Index Catalogs*), Dreyer's compilation eventually included 13,000 objects. Astronomers today still use his NGC numbers when referring to most nebulae and star groups.

20.2 Interstellar Gas

Learning Objectives

By the end of this section, you will be able to:

- Name the major types of interstellar gas
- Discuss how we can observe each type
- Describe the temperature and other major properties of each type

Interstellar gas, depending on where it is located, can be as cold as a few degrees above absolute zero or as hot as a million degrees or more. We will begin our voyage through the interstellar medium by exploring the different conditions under which we find gas.

Ionized Hydrogen (H II) Regions—Gas Near Hot Stars

Some of the most spectacular astronomical photographs show interstellar gas located near hot stars (Figure 20.3). The strongest line in the visible region of the hydrogen spectrum is the red line in the Balmer series[1] (as explained in the chapter on Radiation and Spectra); this emission line accounts for the characteristic red glow in images like Figure 20.3.

Figure 20.3 Orion Nebula. The red glow that pervades the great Orion Nebula is produced by the first line in the Balmer series of hydrogen. Hydrogen emission indicates that there are hot young stars nearby that ionize these clouds of gas. When electrons then recombine with protons and move back down into lower energy orbits, emission lines are produced. The blue color seen at the edges of some of the clouds is produced by small particles of dust that scatter the light from the hot stars. Dust can also be seen

1 Scientists also call this red Balmer line the H-alpha line, with alpha meaning it is the first spectral line in the Balmer series.

silhouetted against the glowing gas. (credit: NASA,ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team)

Hot stars are able to heat nearby gas to temperatures close to 10,000 K. The ultraviolet radiation from the stars also ionizes the hydrogen (remember that during ionization, the electron is stripped completely away from the proton). Such a detached proton won't remain alone forever when attractive electrons are around; it will capture a free electron, becoming a neutral hydrogen once more. However, such a neutral atom can then absorb ultraviolet radiation again and start the cycle over. At a typical moment, most of the atoms near a hot star are in the ionized state.

Since hydrogen is the main constituent of interstellar gas, we often characterize a region of space according to whether its hydrogen is neutral or ionized. A cloud of ionized hydrogen is called an **H II region**. (Scientists who work with spectra use the Roman numeral I to indicate that an atom is neutral; successively higher Roman numerals are used for each higher stage of ionization. H II thus refers to hydrogen that has lost its one electron; Fe III is iron with two electrons missing.)

The electrons that are captured by the hydrogen nuclei cascade down through the various energy levels of the hydrogen atoms on their way to the lowest level, or ground state. During each transition downward, they give up energy in the form of light. The process of converting ultraviolet radiation into visible light is called *fluorescence*. Interstellar gas contains other elements besides hydrogen. Many of them are also ionized in the vicinity of hot stars; they then capture electrons and emit light, just as hydrogen does, allowing them to be observed by astronomers. But generally, the red hydrogen line is the strongest, and that is why H II regions look red.

A fluorescent light on Earth works using the same principles as a fluorescent H II region. When you turn on the current, electrons collide with atoms of mercury vapor in the tube. The mercury is excited to a high-energy state because of these collisions. When the electrons in the mercury atoms return to lower-energy levels, some of the energy they emit is in the form of ultraviolet photons. These, in turn, strike a phosphor-coated screen on the inner wall of the light tube. The atoms in the screen absorb the ultraviolet photons and emit visible light as they cascade downward among the energy levels. (The difference is that these atoms give off a wider range of light colors, which mix to give the characteristic white glow of fluorescent lights, whereas the hydrogen atoms in an H II region give off a more limited set of colors.)

Neutral Hydrogen Clouds

The very hot stars required to produce H II regions are rare, and only a small fraction of interstellar matter is close enough to such hot stars to be ionized by them. Most of the volume of the interstellar medium is filled with neutral (nonionized) hydrogen. How do we go about looking for it?

Unfortunately, neutral hydrogen atoms at temperatures typical of the gas in interstellar space neither emit nor absorb light in the visible part of the spectrum. Nor, for the most part, do the other trace elements that are mixed with the interstellar hydrogen. However, some of these other elements can *absorb* visible light even at typical interstellar temperatures. This means that when we observe a bright source such as a hot star or a galaxy, we can sometimes see additional lines in its spectrum produced when interstellar gas absorbs light at particular frequencies (see Figure 20.4). Some of the strongest interstellar absorption lines are produced by calcium and sodium, but many other elements can be detected as well in sufficiently sensitive observations (as discussed in Radiation and Spectra).

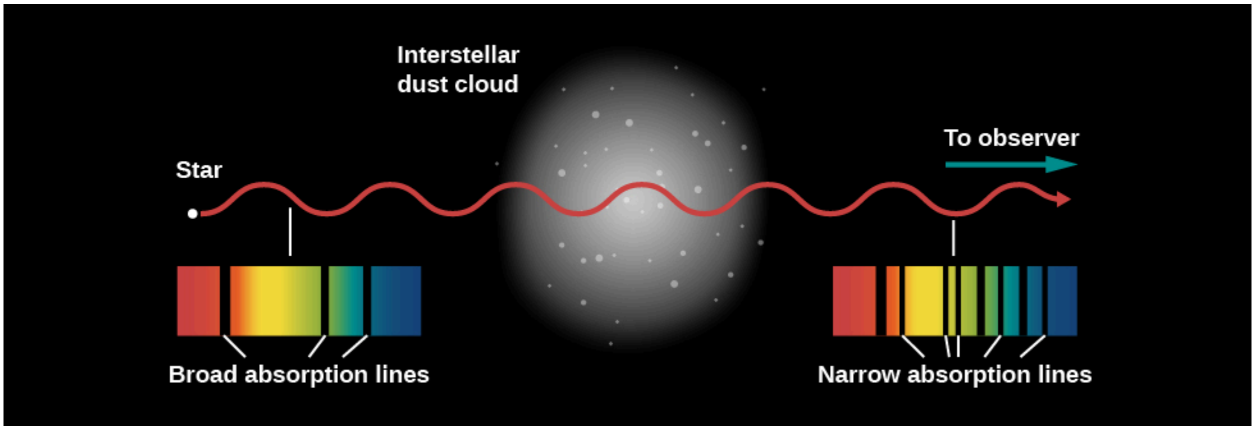

Figure 20.4 Absorption Lines though an Interstellar Dust Cloud. When there is a significant amount of cool interstellar matter (gas with some dust) between us and a star, we can see the absorption lines of the gas in the star's spectrum. We can distinguish the two kinds of lines because, whereas the star's lines are broad, the lines from the gas are narrower.

The first evidence for absorption by interstellar clouds came from the analysis of a spectroscopic binary star (see The Stars: A Celestial Census), published in 1904. While most of the lines in the spectrum of this binary shifted alternately from longer to shorter wavelengths and back again, as we would expect from the Doppler effect for stars in orbit around each other, a few lines in the spectrum remained fixed in wavelength. Since both stars are moving in a binary system, lines that showed no motion puzzled astronomers. The lines were also peculiar in that they were much, much narrower than the rest of the lines, indicating that the gas producing them was at a very low pressure. Subsequent work demonstrated that these lines were not formed in the star's atmosphere at all, but rather in a cold cloud of gas located between Earth and the binary star.

While these and similar observations proved there was interstellar gas, they could not yet detect hydrogen, the most common element, due to its lack of spectral features in the visible part of the spectrum. (The Balmer line of hydrogen is in the visible range, but only excited hydrogen atoms produce it. In the cold interstellar medium, the hydrogen atoms are all in the ground state and no electrons are in the higher-energy levels required to produce either emission or absorption lines in the Balmer series.) Direct detection of hydrogen had to await the development of telescopes capable of seeing very-low-energy changes in hydrogen atoms in other parts of the spectrum. The first such observations were made using radio telescopes, and radio emission and absorption by interstellar hydrogen remains one of our main tools for studying the vast amounts of cold hydrogen in the universe to this day.

In 1944, while he was still a student, the Dutch astronomer Hendrik van de Hulst predicted that hydrogen would produce a strong line at a wavelength of 21 centimeters. That's quite a long wavelength, implying that the wave has such a low frequency and low energy that it cannot come from electrons jumping between energy levels (as we discussed in Radiation and Spectra). Instead, energy is emitted when the electron does a flip, something like an acrobat in a circus flipping upright after standing on his head.

The flip works like this: a hydrogen atom consists of a proton and an electron bound together. Both the proton and the electron act is if they were spinning like tops, and spin axes of the two tops can either be pointed in the same direction (aligned) or in opposite directions (anti-aligned). If the proton and electron were spinning in opposite directions, the atom as a whole would have a very slightly lower energy than if the two spins were aligned (Figure 20.5). If an atom in the lower-energy state (spins opposed) acquired a small amount of energy, then the spins of the proton and electron could be aligned, leaving the atom in a slightly *excited state*. If the atom then lost that same amount of energy again, it would return to its ground state. The amount of energy involved corresponds to a wave with a wavelength of 21 centimeters; hence, it is known as the *21-centimeter line*.

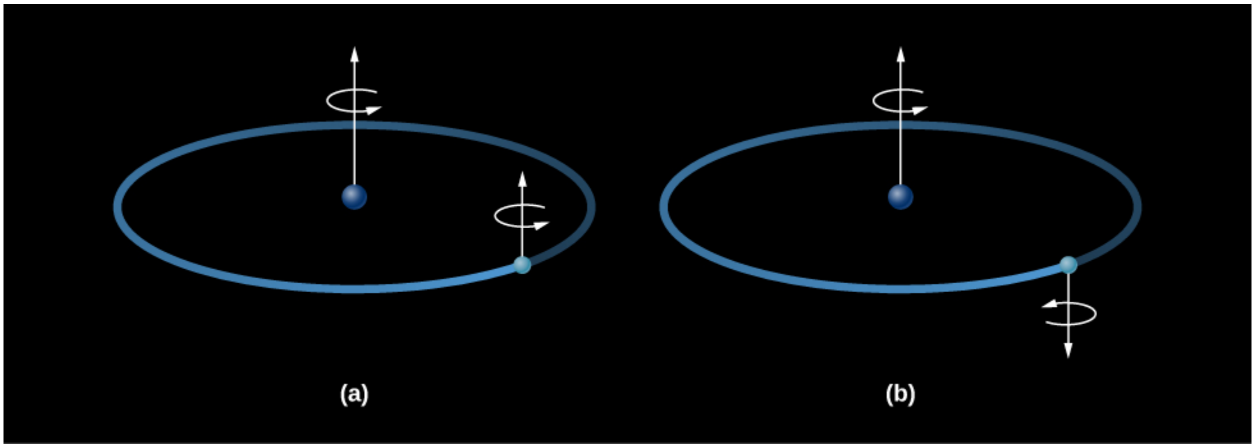

Figure 20.5 Formation of the 21-Centimeter Line. When the electron in a hydrogen atom is in the orbit closest to the nucleus, the proton and the electron may be spinning either (a) in the same direction or (b) in opposite directions. When the electron flips over, the atom gains or loses a tiny bit of energy by either absorbing or emitting electromagnetic energy with a wavelength of 21 centimeters.

Neutral hydrogen atoms can acquire small amounts of energy through collisions with other hydrogen atoms or with free electrons. Such collisions are extremely rare in the sparse gases of interstellar space. An individual atom may wait centuries before such an encounter aligns the spins of its proton and electron. Nevertheless, over many millions of years, a significant fraction of the hydrogen atoms are excited by a collision. (Out there in cold space, that’s about as much excitement as an atom typically experiences.)

An excited atom can later lose its excess energy either by colliding with another particle or by giving off a radio wave with a wavelength of 21 centimeters. If there are no collisions, an excited hydrogen atom will wait an average of about 10 million years before emitting a photon and returning to its state of lowest energy. Even though the probability that any single atom will emit a photon is low, there are so many hydrogen atoms in a typical gas cloud that collectively they will produce an observable line at 21 centimeters.

Equipment sensitive enough to detect the 21-cm line of neutral hydrogen became available in 1951. Dutch astronomers had built an instrument to detect the 21-cm waves that they had predicted, but a fire destroyed it. As a result, two Harvard physicists, Harold Ewen and Edward Purcell, made the first detection (Figure 20.6), soon followed by confirmations from the Dutch and a group in Australia. Since the detection of the 21-cm line, many other radio lines produced by both atoms and molecules have been discovered (as we will discuss in a moment), and these have allowed astronomers to map out the neutral gas throughout our home Galaxy. Astronomers have also detected neutral interstellar gas, including hydrogen, at many other wavelengths from the infrared to the ultraviolet.

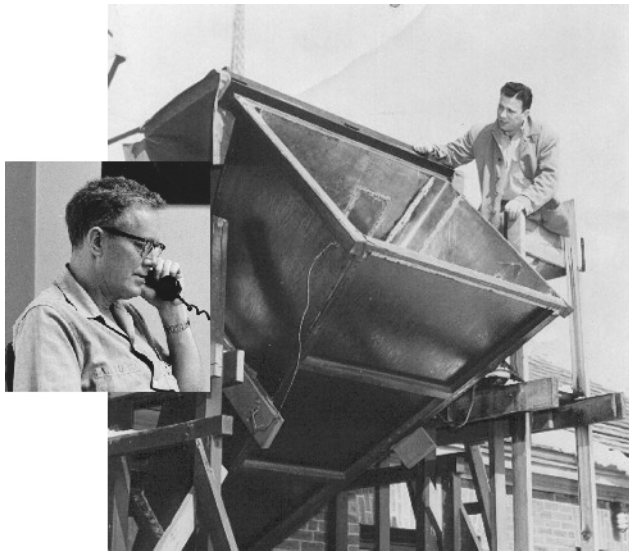

Figure 20.6 Harold Ewen (1922–2015) and Edward Purcell (1912–1997). We see Harold Ewen in 1952 working with the horn antenna (atop the physics laboratory at Harvard) that made the first detection of interstellar 21-cm radiation. The inset shows Edward Purcell, the winner of the 1952 Nobel Prize in physics, a few years later. (credit: modification of work by NRAO)

Modern radio observations show that most of the neutral hydrogen in our Galaxy is confined to an extremely flat layer, less than 300 light-years thick, that extends throughout the disk of the Milky Way Galaxy. This gas has densities ranging from about 0.1 to about 100 atoms per cm^3, and it exists at a wide range of temperatures, from as low as about 100 K (–173 °C) to as high as about 8000 K. These regions of warm and cold gas are interspersed with each other, and the density and temperature at any particular point in space are constantly changing.

Ultra-Hot Interstellar Gas

While the temperatures of 10,000 K found in H II regions might seem warm, they are not the hottest phase of the interstellar medium. Some of the interstellar gas is at a temperature of a *million* degrees, even though there is no visible source of heat nearby. The discovery of this ultra-hot interstellar gas was a big surprise. Before the launch of astronomical observatories into space, which could see radiation in the ultraviolet and X-ray parts of the spectrum, astronomers assumed that most of the region between stars was filled with hydrogen at temperatures no warmer than those found in H II regions. But telescopes launched above Earth's atmosphere obtained ultraviolet spectra that contained interstellar lines produced by oxygen atoms that have been ionized five times. To strip five electrons from their orbits around an oxygen nucleus requires a lot of energy. Subsequent observations with orbiting X-ray telescopes revealed that the Galaxy is filled with numerous bubbles of X-ray-emitting gas. To emit X-rays, and to contain oxygen atoms that have been ionized five times, gas must be heated to temperatures of a million degrees or more.

Theorists have now shown that the source of energy producing these remarkable temperatures is the explosion of massive stars at the ends of their lives (Figure 20.7). Such explosions, called *supernovae*, will be discussed in detail in the chapter on The Death of Stars. For now, we'll just say that some stars, nearing the ends of their lives, become unstable and literally explode. These explosions launch gas into interstellar space at velocities of tens of thousands of kilometers per second (up to about 30% the speed of light). When this ejected gas collides with interstellar gas, it produces shocks that heat the gas to millions or tens of millions of degrees.

Figure 20.7 Vela Supernova Remnant. About 11,000 years ago, a dying star in the constellation of Vela exploded, becoming as bright as the full moon in Earth's skies. You can see the faint rounded filaments from that explosion in the center of this colorful image. The edges of the remnant are colliding with the interstellar medium, heating the gas they plow through to temperatures of millions of K. Telescopes in space also reveal a glowing sphere of X-ray radiation from the remnant. (credit: Digitized Sky Survey, ESA/ESO/NASA FITS Liberator, Davide De Martin)

Astronomers estimate that one supernova explodes roughly every 100 years somewhere in the Galaxy. On average, shocks launched by supernovae sweep through any given point in the Galaxy about once every few million years. These shocks keep some interstellar space filled with gas at temperatures of millions of degrees, and they continually disturb the colder gas, keeping it in constant, turbulent motion.

Molecular Clouds

A few simple molecules out in space, such as CN and CH, were discovered decades ago because they produce absorption lines in the visible-light spectra of stars behind them. When more sophisticated equipment for obtaining spectra in radio and infrared wavelengths became available, astronomers—to their surprise—found much more complex molecules in interstellar clouds as well.

Just as atoms leave their "fingerprints" in the spectrum of visible light, so the vibration and rotation of atoms within molecules can leave spectral fingerprints in radio and infrared waves. If we spread out the radiation at such longer wavelengths, we can detect emission or absorption lines in the spectra that are characteristic of specific molecules. Over the years, experiments in our laboratories have shown us the exact wavelengths associated with changes in the rotation and vibration of many common molecules, giving us a template of possible lines against which we can now compare our observations of interstellar matter.

The discovery of complex molecules in space came as a surprise because most of interstellar space is filled with ultraviolet light from stars, and this light is capable of *dissociating* molecules (breaking them apart into individual atoms). In retrospect, however, the presence of molecules is not surprising. As we will discuss further in the next section, and have already seen above, interstellar space also contains significant amounts of dust capable of blocking out starlight. When this dust accumulates in a single location, the result is a dark cloud where ultraviolet starlight is blocked and molecules can survive. The largest of these structures are created where gravity pulls interstellar gas together to form giant **molecular clouds**, structures as massive as a million times the mass of the Sun. Within these, most of the interstellar hydrogen has formed the molecule H_2 (molecular hydrogen). Other, more complex molecules are also present in much smaller quantities.

Giant molecular clouds have densities of hundreds to thousands of atoms per cm^3, much denser than interstellar space is on average. As a result, though they account for a very small fraction of the volume of interstellar space, they contain a significant fraction—20–30%—of the total mass of the Milky Way's gas.

Because of their high density, molecular clouds block ultraviolet starlight, the main agent for heating most interstellar gas. As a result, they tend to be extremely cold, with typical temperatures near 10 K (−263 °C). Giant molecular clouds are also the sites where new stars form, as we will discuss below.

It is in these dark regions of space, protected from starlight, that molecules can form. Chemical reactions occurring both in the gas and on the surface of dust grains lead to much more complex compounds, hundreds of which have been identified in interstellar space. Among the simplest of these are water (H_2O), carbon monoxide (CO), which is produced by fires on Earth, and ammonia (NH_3), whose smell you recognize in strong home cleaning products. Carbon monoxide is particularly abundant in interstellar space and is the primary tool that astronomers use to study giant molecular clouds. Unfortunately, the most abundant molecule, H_2, is particularly difficult to observe directly because in most giant molecular clouds, it is too cold to emit even at radio wavelengths. CO, which tends to be present wherever H_2 is found, is a much better emitter and is often used by astronomers to trace molecular hydrogen.

The more complex molecules astronomers have found are mostly combinations of hydrogen, oxygen, carbon, nitrogen, and sulfur atoms. Many of these molecules are *organic* (those that contain carbon and are associated with the carbon chemistry of life on Earth.) They include formaldehyde (used to preserve living tissues), alcohol (see the feature box on Cocktails in Space), and antifreeze.

In 1996, astronomers discovered acetic acid (the prime ingredient of vinegar) in a cloud lying in the direction of the constellation of Sagittarius. To balance the sour with the sweet, a simple sugar (glycolaldehyde) has also been found. The largest compounds yet discovered in interstellar space are *fullerenes*, molecules in which 60 or 70 carbon atoms are arranged in a cage-like configuration (see Figure 20.8). See Table 20.1 for a list of a few of the more interesting interstellar molecules that have been found so far.

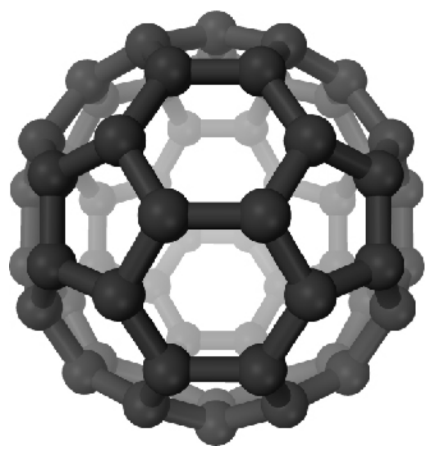

Figure 20.8 Fullerene C60. This three-dimensional perspective shows the characteristic cage-like arrangement of the 60 carbon atoms in a molecule of fullerene C60. Fullerene C60 is also known as a “buckyball,” or as its full name, buckminsterfullerene, because of its similarity to the multisided architectural domes designed by American inventor R. Buckminster Fuller.

Some Interesting Interstellar Molecules		
Name	**Chemical Formula**	**Use on Earth**
Ammonia	NH_3	Household cleansers
Formaldehyde	H_2CO	Embalming fluid
Acetylene	HC_2H	Fuel for a welding torch

Table 20.1

Some Interesting Interstellar Molecules		
Name	**Chemical Formula**	**Use on Earth**
Acetic acid	$C_2H_2O_4$	The essence of vinegar
Ethyl alcohol	CH_3CH_2OH	End-of-semester parties
Ethylene glycol	$HOCH_2CH_2OH$	Antifreeze ingredient
Benzene	C_6H_6	Carbon ring, ingredient in varnishes and dyes

Table 20.1

The cold interstellar clouds also contain cyanoacetylene (HC_3N) and acetaldehyde (CH_3CHO), generally regarded as starting points for *amino acid* formation. These are building blocks of proteins, which are among the fundamental chemicals from which living organisms on Earth are constructed. The presence of these organic molecules does not imply that life exists in space, but it does show that the chemical building blocks of life can form under a wide range of conditions in the universe. As we learn more about how complex molecules are produced in interstellar clouds, we gain an increased understanding of the kinds of processes that preceded the beginnings of life on Earth billions of years ago.

LINK TO LEARNING

Interested in learning more about fullerenes, buckyballs, or buckminsterfullerenes (as they're called)? Watch a brief video from NASA's Jet Propulsion Laboratory (https://openstax.org/l/30NASAjetprop) that explains what they are and illustrates how they were discovered in space.

MAKING CONNECTIONS

Cocktails in Space

Among the molecules astronomers have identified in interstellar clouds is alcohol, which comes in two varieties: methyl (or wood) alcohol and ethyl alcohol (the kind you find in cocktails). Ethyl alcohol is a pretty complex molecule, written by chemists as C_2H_5OH. It is quite plentiful in space (relatively speaking). In clouds where it has been identified, we detect up to one molecule for every m^3. The largest of the clouds (which can be several hundred light-years across) have enough ethyl alcohol to make 10^{28} fifths of liquor.

We need not fear, however, that future interstellar astronauts will become interstellar alcoholics. Even if a spaceship were equipped with a giant funnel 1 kilometer across and could scoop it through such a cloud at the speed of light, it would take about a thousand years to gather up enough alcohol for one standard martini.

Furthermore, the very same clouds also contain water (H_2O) molecules. Your scoop would gather them up as well, and there are a lot more of them because they are simpler and thus easier to form. For the fun of it, one astronomical paper actually calculated the proof of a typical cloud. *Proof* is the ratio of alcohol to water in a drink, where 0 proof means all water, 100 proof means half alcohol and half water, and 200 proof means all alcohol. The proof of the interstellar cloud was only 0.2, not enough to qualify as a stiff drink

20.3 Cosmic Dust

Learning Objectives

By the end of this section, you will be able to:

- Describe how we can detect interstellar dust
- Understand the role and importance of infrared observations in studying dust
- Explain the terms extinction and interstellar reddening

Figure 20.9 shows a striking example of what is actually a common sight through large telescopes: a dark region on the sky that appears to be nearly empty of stars. For a long time, astronomers debated whether these dark regions were empty “tunnels” through which we looked beyond the stars of the Milky Way Galaxy into intergalactic space, or clouds of some dark material that blocked the light of the stars beyond. The astronomer William Herschel (discoverer of the planet Uranus) thought it was the former, once remarking after seeing one, “Here truly is a hole in heaven!” However, American astronomer E. E. Barnard is generally credited with showing from his extensive series of nebula photographs that the latter interpretation is the correct one (see the feature box on Edward Emerson Barnard).

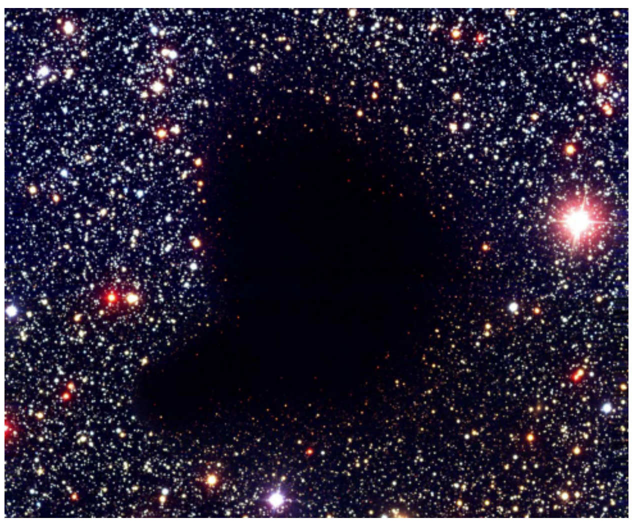

Figure 20.9 Barnard 68. This object, first catalogued by E. E. Barnard, is a dark interstellar cloud. Its striking appearance is due to the fact that, since it is relatively close to Earth, there are no bright stars between us and it, and its dust obscures the light from the stars behind it. (It looks a little bit like a sideways heart; one astronomers sent a photo of this object to his sweetheart as a valentine.) (credit: modification of work by ESO)

Dusty clouds in space betray their presence in several ways: by blocking the light from distant stars, by emitting energy in the infrared part of the spectrum, by reflecting the light from nearby stars, and by making distant stars look redder than they really are.

VOYAGERS IN ASTRONOMY

Edward Emerson Barnard

Born in 1857 in Nashville, Tennessee, two months after his father died, Edward Barnard (Figure 20.10) grew up in such poor circumstances that he had to drop out of school at age nine to help support his ailing mother. He soon became an assistant to a local photographer, where he learned to love both photography and astronomy, destined to become the dual passions of his life. He worked as a photographer's aide for 17 years, studying astronomy on his own. In 1883, he obtained a job as an assistant at the Vanderbilt University Observatory, which enabled him at last to take some astronomy courses.

Married in 1881, Barnard built a house for his family that he could ill afford. But as it happened, a patent medicine manufacturer offered a $200 prize (a lot of money in those days) for the discovery of any new comet. With the determination that became characteristic of him, Barnard spent every clear night searching for comets. He discovered seven of them between 1881 and 1887, earning enough money to make the payments on his home; this "Comet House" later became a local attraction. (By the end of his life, Barnard had found 17 comets through diligent observation.)

In 1887, Barnard got a position at the newly founded Lick Observatory, where he soon locked horns with the director, Edward Holden, a blustering administrator who made Barnard's life miserable. (To be fair, Barnard soon tried to do the same for him.) Despite being denied the telescope time that he needed for his photographic work, in 1892, Barnard managed to discover the first new moon found around Jupiter since Galileo's day, a stunning observational feat that earned him world renown. Now in a position to demand more telescope time, he perfected his photographic techniques and soon began to publish the best images of the Milky Way taken up to that time. It was during the course of this work that he began to examine the dark regions among the crowded star lanes of the Galaxy and to realize that they must be vast clouds of obscuring material (rather than "holes" in the distribution of stars).

Astronomer-historian Donald Osterbrock has called Barnard an "observaholic:" his daily mood seemed to depend entirely on how clear the sky promised to be for his night of observing. He was a driven, neurotic man, concerned about his lack of formal training, fearful of being scorned, and afraid that he might somehow slip back into the poverty of his younger days. He had difficulty taking vacations and lived for his work: only serious illness could deter him from making astronomical observations.

In 1895, Barnard, having had enough of the political battles at Lick, accepted a job at the Yerkes Observatory near Chicago, where he remained until his death in 1923. He continued his photographic work, publishing compilations of his images that became classic photographic atlases, and investigating the varieties of nebulae revealed in his photographs. He also made measurements of the sizes and features of planets, participated in observations of solar eclipses, and carefully cataloged dark nebulae (see Figure 20.9). In 1916, he discovered the star with the largest proper motion, the second-closest star system to our own (see Analyzing Starlight). It is now called Barnard's Star in his honor.

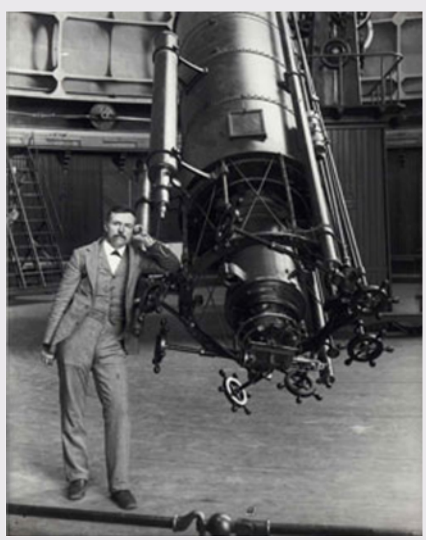

Figure 20.10 Edward Emerson Barnard (1857–1923). Barnard's observations provided information that furthered many astronomical explorations. (credit: The Lick Observatory)

Detecting Dust

The dark cloud seen in Figure 20.9 blocks the light of the many stars that lie behind it; note how the regions in other parts of the photograph are crowded with stars. Barnard 68 is an example of a relatively dense cloud or *dark nebula* containing tiny, solid dust grains. Such opaque clouds are conspicuous on any photograph of the Milky Way, the galaxy in which the Sun is located (see the figures in The Milky Way Galaxy). The "dark rift," which runs lengthwise down a long part of the Milky Way in our sky and appears to split it in two, is produced by a collection of such obscuring clouds.

While dust clouds are too cold to radiate a measurable amount of energy in the visible part of the spectrum, they glow brightly in the infrared (Figure 20.11). The reason is that small dust grains absorb visible light and ultraviolet radiation very efficiently. The grains are heated by the absorbed radiation, typically to temperatures from 10 to about 500 K, and re-radiate this heat at infrared wavelengths.

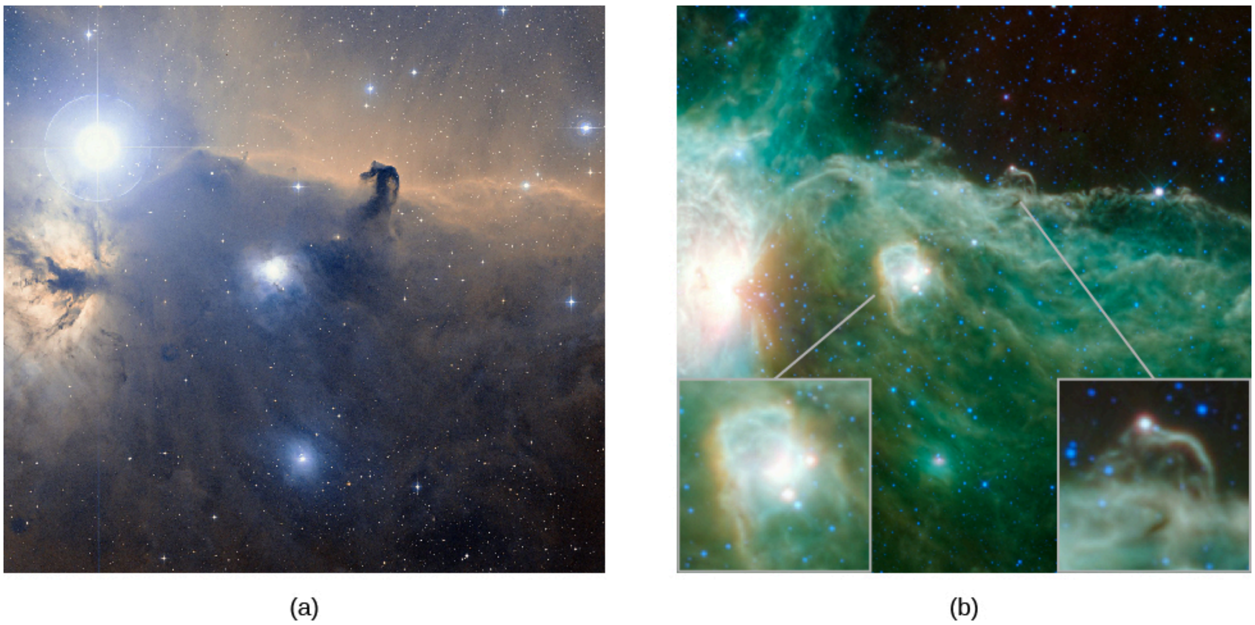

Figure 20.11 Visible and Infrared Images of the Horsehead Nebula in Orion. This dark cloud is one of the best-known images in astronomy, probably because it really does resemble a horse's head. The horse-head shape is an extension of a large cloud of dust that fills the lower part of the picture. (a) Seen in visible light, the dust clouds are especially easy to see against the bright background. (b) This infrared radiation image from the region of the horse head was recorded by NASA's Wide-Field Infrared Survey Explorer. Note how the regions that appear dark in visible light appear bright in the infrared. The dust is heated by nearby stars and re-radiates this heat in the infrared. Only the top of the horse's head is visible in the infrared image. Bright dots seen in the nebula below and to the left and at the top of the horse head are young, newly formed stars. The insets show the horse head and the bright nebula in more detail. (credit a: modification of work by ESO and Digitized Sky Survey; credit b: modification of work by NASA/JPL-Caltech)

Thanks to their small sizes and low temperatures, interstellar grains radiate most of their energy at infrared to microwave frequencies, with wavelengths of tens to hundreds of microns. Earth's atmosphere is opaque to radiation at these wavelengths, so emission by interstellar dust is best measured from space. Observations from above Earth's atmosphere show that dust clouds are present throughout the plane of the Milky Way (Figure 20.12).

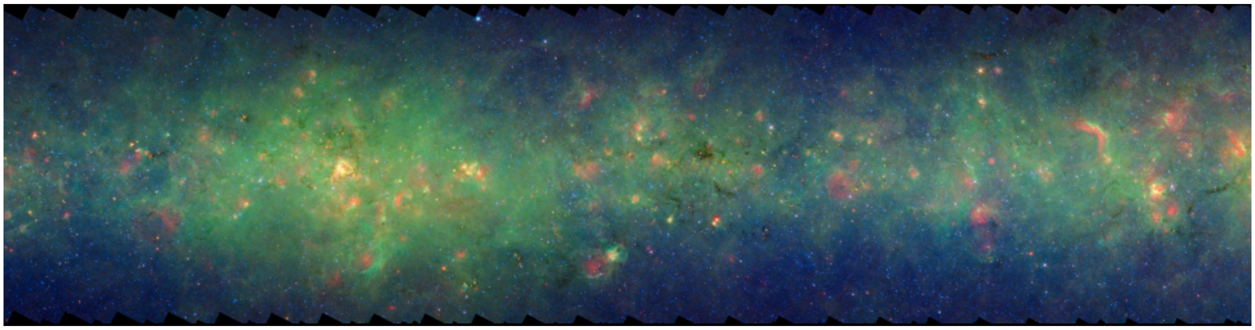

Figure 20.12 Infrared Emission from the Plane of the Milky Way. This infrared image taken by the Spitzer Space Telescope shows a field in the plane of the Milky Way Galaxy. (Our Galaxy is in the shape of a frisbee; the plane of the Milky Way is the flat disk of that frisbee. Since the Sun, Earth, and solar system are located in the plane of the Milky Way and at a large distance from its center, we view the Galaxy edge on, much as we might look at a glass plate from its edge.) This emission is produced by tiny dust grains, which emit at 3.6 microns (blue in this image), 8.0 microns (green), and 24 microns (red). The densest regions of dust are so cold and opaque that they appear as dark clouds even at these infrared wavelengths. The red bubbles visible throughout indicate regions where the dust has been warmed up by young stars. This heating increases the emission at 24 microns, leading to the redder color in this image. (credit: modification of work by NASA/JPL-Caltech/University of Wisconsin)

Some dense clouds of dust are close to luminous stars and scatter enough starlight to become visible. Such a cloud of dust, illuminated by starlight, is called a *reflection nebula*, since the light we see is starlight reflected off the grains of dust. One of the best-known examples is the nebulosity around each of the brightest stars in the Pleiades cluster (see Figure 20.1). The dust grains are small, and such small particles turn out to scatter light with blue wavelengths more efficiently than light at red wavelengths. A reflection nebula, therefore, usually appears bluer than its illuminating star (Figure 20.13).

Figure 20.13 Pleiades Star Cluster. The bluish light surrounding the stars in this image is an example of a reflection nebula. Like fog around a street lamp, a reflection nebula shines only because the dust within it scatters light from a nearby bright source. The Pleiades cluster is currently passing through an interstellar cloud that contains dust grains, which scatter the light from the hot blue stars in the cluster. The Pleiades cluster is about 400 light-years from the Sun. (credit: NASA, ESA and AURA/Caltech)

Gas and dust are generally intermixed in space, although the proportions are not exactly the same everywhere. The presence of dust is apparent in many photographs of *emission nebulae* in the constellation of Sagittarius, where we see an H II region surrounded by a blue reflection nebula. Which type of nebula appears brighter depends on the kinds of stars that cause the gas and dust to glow. Stars cooler than about 25,000 K have so little ultraviolet radiation of wavelengths shorter than 91.2 nanometers—which is the wavelength required to ionize hydrogen—that the reflection nebulae around such stars outshine the emission nebulae. Stars hotter than 25,000 K emit enough ultraviolet energy that the emission nebulae produced around them generally outshine the reflection nebulae.

Interstellar Reddening

The tiny interstellar dust grains absorb some of the starlight they intercept. But at least half of the starlight that interacts with a grain is merely scattered, that is, it is redirected rather than absorbed. Since neither the absorbed nor the scattered starlight reaches us directly, both absorption and scattering make stars look dimmer. The effects of both processes are called **interstellar extinction** (Figure 20.14).

Astronomers first came to understand interstellar extinction around the early 1930s, as the explanation of a puzzling observation. In the early part of the twentieth century, astronomers discovered that some stars look red even though their spectral lines indicate that they must be extremely hot (and thus should look blue). The solution to this seeming contradiction turned out to be that the light from these hot stars is not only dimmed but also reddened by interstellar dust, a phenomenon known as interstellar **reddening**.

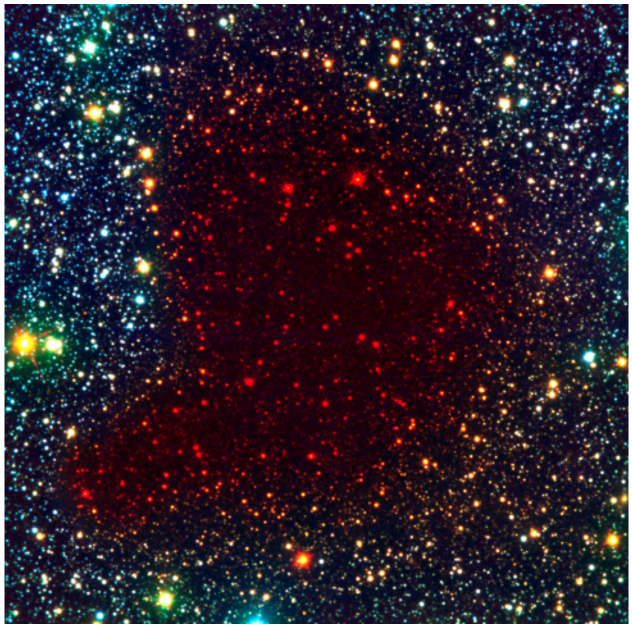

Figure 20.14 Barnard 68 in Infrared. In this image, we see Barnard 68, the same object shown in Figure 20.9. The difference is that, in the previous image, the blue, green, and red channels showed light in the visible (or very nearly visible) part of the spectrum. In this image, the red color shows radiation emitted in the infrared at a wavelength of 2.2 microns. Interstellar extinction is much smaller at infrared than at visible wavelengths, so the stars behind the cloud become visible in the infrared channel. (credit: ESO)

Dust does not interact with all the colors of light the same way. Much of the violet, blue, and green light from these stars has been scattered or absorbed by dust, so it does not reach Earth. Some of their orange and red light, with longer wavelengths, on the other hand, more easily penetrates the intervening dust and completes its long journey through space to enter Earth-based telescopes (Figure 20.15). Thus, the star looks redder from Earth than it would if you could see it from nearby. (Strictly speaking, *reddening* is not the most accurate term for this process, since no red color is added; instead, blues and related colors are subtracted, so it should more properly be called “deblueing.”) In the most extreme cases, stars can be so reddened that they are entirely undetectable at visible wavelengths and can be seen only at infrared or longer wavelengths (Figure 20.14).

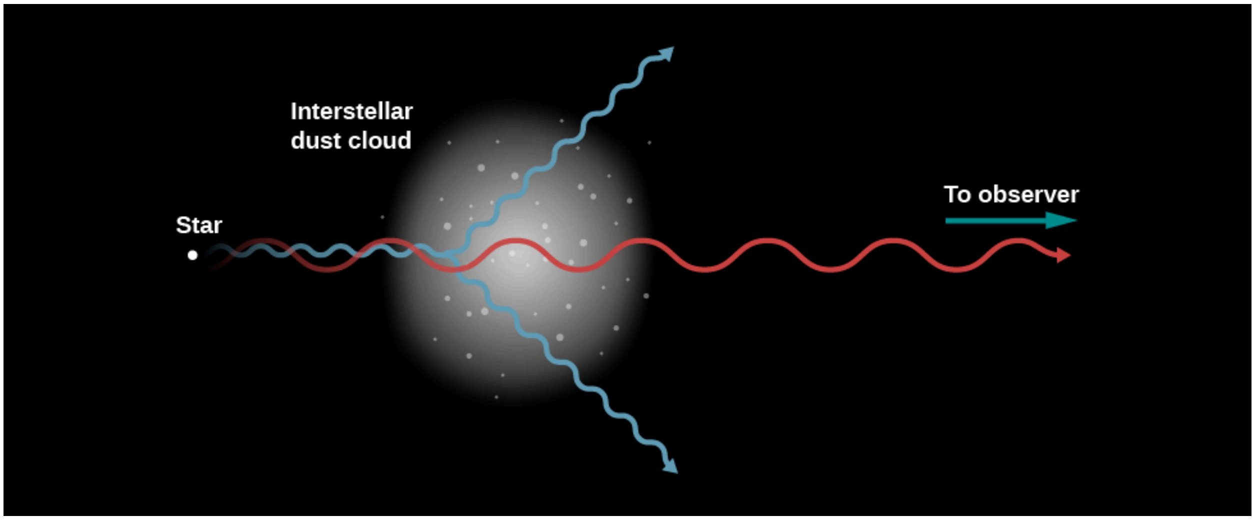

Figure 20.15 Scattering of Light by Dust. Interstellar dust scatters blue light more efficiently than red light, thereby making distant stars appear redder and giving clouds of dust near stars a bluish hue. Here, a red ray of light from a star comes straight through to the observer, whereas a blue ray is shown scattering. A similar scattering process makes Earth's sky look blue.

We have all seen an example of reddening on Earth. The Sun appears much redder at sunset than it does at noon. The lower the Sun is in the sky, the longer the path its light must travel through the atmosphere. Over this greater distance, there is a greater chance that sunlight will be scattered. Since red light is less likely to be scattered than blue light, the Sun appears more and more red as it approaches the horizon.

By the way, scattering of sunlight is also what causes our sky to look blue, even though the gases that make up Earth's atmosphere are transparent. As sunlight comes in, it scatters from the molecules of air. The small size of the molecules means that the blue colors scatter much more efficiently than the greens, yellows, and reds. Thus, the blue in sunlight is scattered out of the beam and all over the sky. The light from the Sun that comes to your eye, on the other hand, is missing some of its blue, so the Sun looks a bit yellower, even when it is high in the sky, than it would from space.

The fact that starlight is reddened by interstellar dust means that long-wavelength radiation is transmitted through the Galaxy more efficiently than short-wavelength radiation. Consequently, if we wish to see farther in a direction with considerable interstellar material, we should look at long wavelengths. This simple fact provides one of the motivations for the development of infrared astronomy. In the infrared region at 2 microns (2000 nanometers), for example, the obscuration is only one-sixth as great as in the visible region (500 nanometers), and we can therefore study stars that are more than twice as distant before their light is blocked by interstellar dust. This ability to see farther by observing in the infrared portion of the spectrum represents a major gain for astronomers trying to understand the structure of our Galaxy or probing its puzzling, but distant, center (see The Milky Way Galaxy).

Interstellar Grains

Before we get to the details about interstellar dust, we should perhaps get one concern out of the way. Why couldn't it be the interstellar *gas* that reddens distant stars and not the dust? We already know from everyday experience that atomic or molecular gas is almost transparent. Consider Earth's atmosphere. Despite its very high density compared with that of interstellar gas, it is so transparent as to be practically invisible. (Gas does have a few specific spectral lines, but they absorb only a tiny fraction of the light as it passes through.)The quantity of *gas* required to produce the observed absorption of light in interstellar space would have to be enormous. The gravitational attraction of so great a mass of gas would affect the motions of stars in ways that could easily be detected. Such motions are not observed, and thus, the interstellar absorption cannot be the result of gases.

Although gas does not absorb much light, we know from everyday experience that tiny solid or liquid particles can be very efficient absorbers. Water vapor in the air is quite invisible. When some of that vapor condenses into tiny water droplets, however, the resulting cloud is opaque. Dust storms, smoke, and smog offer familiar examples of the efficiency with which solid particles absorb light. On the basis of arguments like these, astronomers have concluded that widely scattered *solid* particles in interstellar space must be responsible for the observed dimming of starlight. What are these particles made of? And how did they form?

Observations like the pictures in this chapter show that a great deal of this dust exists; hence, it must be primarily composed of elements that are abundant in the universe (and in interstellar matter). After hydrogen and helium, the most abundant elements are oxygen, carbon, and nitrogen. These three elements, along with magnesium, silicon, iron—and perhaps hydrogen itself—turn out to be the most important components of interstellar dust.

Many of the dust particles can be characterized as sootlike (rich in carbon) or sandlike (containing silicon and oxygen). Grains of interstellar dust are found in meteorites and can be identified because the abundances of certain isotopes are different from what we see in other solar system material. Several different interstellar dust substances have been identified in this way in the laboratory, including graphite and diamonds. (Don’t get excited; these diamonds are only a billionth of a meter in size and would hardly make an impressive engagement ring!)

The most widely accepted model pictures the grains with rocky cores that are either like soot (rich in carbon) or like sand (rich in silicates). In the dark clouds where molecules can form, these cores are covered by icy mantles (Figure 20.16). The most common ices in the grains are water (H_2O), methane (CH_4), and ammonia (NH_3)—all built out of atoms that are especially abundant in the realm of the stars. The ice mantles, in turn, are sites for some of the chemical reactions that produce complex organic molecules.

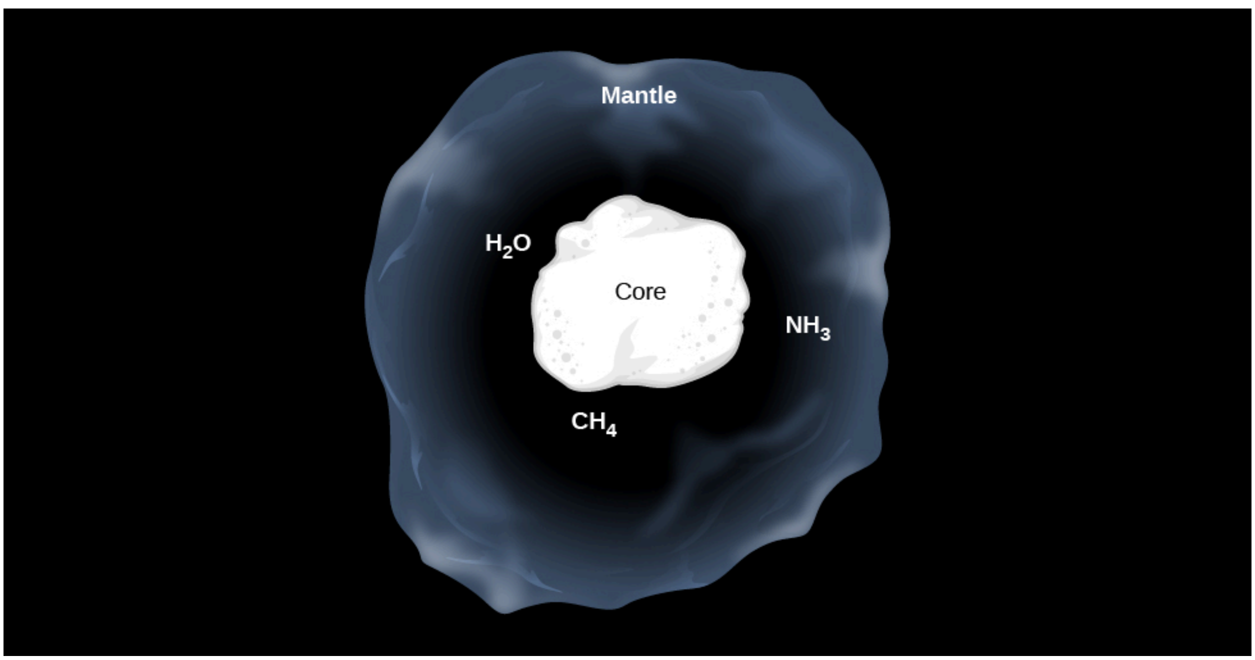

Figure 20.16 Model of an Interstellar Dust Grain. A typical interstellar grain is thought to consist of a core of rocky material (silicates) or graphite, surrounded by a mantle of ices. Typical grain sizes are 10^{-8} to 10^{-7} meters. (This is from 1/100 to 1/10 of a micron; by contrast, human hair is about 10–200 microns wide.)

Typical individual grains must be just slightly smaller than the wavelength of visible light. If the grains were a lot smaller, they would not block the light efficiently, as Figure 20.13 and other images in this chapter show that it does.

On the other hand, if the dust grains were much larger than the wavelength of light, then starlight would not be reddened. Things that are much larger than the wavelength of light would block both blue and red light with equal efficiency. In this way we can deduce that a characteristic interstellar dust grain contains 10^6 to 10^9

atoms and has a diameter of 10^{-8} to 10^{-7} meters (10 to 100 nanometers). This is actually more like the specks of solid matter in cigarette smoke than the larger grains of dust you might find under your desk when you are too busy studying astronomy to clean properly.

20.4 Cosmic Rays

Learning Objectives

By the end of this section, you will be able to:

- Define cosmic rays and describe their composition
- Explain why it is hard to study the origin of cosmic rays, and the current leading hypotheses about where they might come from

In addition to gas and dust, a third class of particles, noteworthy for the high speeds with which they travel, is found in interstellar space. **Cosmic rays** were discovered in 1911 by an Austrian physicist, Victor Hess, who flew simple instruments aboard balloons and showed that high-speed particles arrive at Earth from space (Figure 20.17). The term "cosmic ray" is misleading, implying it might be like a ray of light, but we are stuck with the name. They are definitely particles and have nearly the same composition as ordinary interstellar gas. Their behavior, however, is radically different from the gas we have discussed so far.

Figure 20.17 Victor Hess (1883–1964). Cosmic-ray pioneer Victor Hess returns from a 1912 balloon flight that reached an altitude of 5.3 kilometers. It was on such balloon flights that Hess discovered cosmic rays.

The Nature of Cosmic Rays

Cosmic rays are mostly high-speed atomic nuclei and electrons. Speeds equal to 90% of the speed of light are typical. Almost 90% of the cosmic rays are hydrogen nuclei (protons) stripped of their accompanying electron. Helium and heavier nuclei constitute about 9% more. About 1% of cosmic rays have masses equal to the mass of the electron, and 10–20% of these carry positive charge rather than the negative charge that characterizes electrons. A positively charged particle with the mass of an electron is called a *positron* and is a form of *antimatter* (we discussed antimatter in The Sun: A Nuclear Powerhouse).

The abundances of various atomic nuclei in cosmic rays mirror the abundances in stars and interstellar gas, with one important exception. The light elements lithium, beryllium, and boron are far more abundant in cosmic rays than in the Sun and stars. These light elements are formed when high-speed, cosmic-ray nuclei of carbon, nitrogen, and oxygen collide with protons in interstellar space and break apart. (By the way, if you, like most readers, have not memorized all the elements and want to see how any of those we mention fit into the sequence of elements, you will find them all listed in Appendix K in order of the number of protons they contain.)

Cosmic rays reach Earth in substantial numbers, and we can determine their properties either by capturing them directly or by observing the reactions that occur when they collide with atoms in our atmosphere. The total energy deposited by cosmic rays in Earth's atmosphere is only about one-billionth the energy received from the Sun, but it is comparable to the energy received in the form of starlight. Some of the cosmic rays come to Earth from the surface of the Sun, but most come from outside the solar system.

Where Do They Come From?

There is a serious problem in identifying the source of cosmic rays. Since light travels in straight lines, we can tell where it comes from simply by looking. Cosmic rays are charged particles, and their direction of motion can be changed by magnetic fields. The paths of cosmic rays are curved both by magnetic fields in interstellar space and by Earth's own field. Calculations show that low-energy cosmic rays may spiral many times around Earth before entering the atmosphere where we can detect them. If an airplane circles an airport many times before landing, it is difficult for an observer to determine the direction from which it originated. So, too, after a cosmic ray circles Earth several times, it is impossible to know where its journey began.

There are a few clues, however, about where cosmic rays might be generated. We know, for example, that magnetic fields in interstellar space are strong enough to keep all but the most energetic cosmic rays from escaping the Galaxy. It therefore seems likely that they are produced somewhere inside the Galaxy. The only likely exceptions are those with the very highest energy. Such cosmic rays move so rapidly that they are not significantly influenced by interstellar magnetic fields, and thus, they could escape our Galaxy. By analogy, they could escape other galaxies as well, so some of the highest-energy cosmic rays that we detect may have been created in some distant galaxy. Still, most cosmic rays must have their source inside the Milky Way Galaxy.

We can also estimate how far typical cosmic rays travel before striking Earth. The light elements lithium, beryllium, and boron hold the key. Since these elements are formed when carbon, nitrogen, and oxygen strike interstellar protons, we can calculate how long, on average, cosmic rays must travel through space in order to experience enough collisions to account for the amount of lithium and the other light elements that they contain. It turns out that the required distance is about 30 times around the Galaxy. At speeds near the speed of light, it takes perhaps 3–10 million years for the average cosmic ray to travel this distance. This is only a small fraction of the age of the Galaxy or the universe, so cosmic rays must have been created fairly recently on a cosmic timescale.

The best candidates for a source of cosmic rays are the supernova explosions, which mark the violent deaths of some stars (and which we will discuss in The Death of Stars). The material ejected by the explosion produces a shock wave, which travels through the interstellar medium. Charged particles can become trapped, bouncing back and forth across the front of the shock wave many times. With each pass through the shock, the magnetic fields inside it accelerate the particles more and more. Eventually, they are traveling at close to the speed of light and can escape from the shock to become cosmic rays. Some collapsed stars (including star remnants left over from supernova explosions) may, under the right circumstances, also serve as accelerators of particles. In any case, we again find that the raw material of the Galaxy is enriched by the life cycle of stars. In the next section, we will look at this enrichment process in more detail.

LINK TO LEARNING

You can watch a brief video about the Calorimetric Electron Telescope (CALET) (https://openstax.org/l/30CALETvid) mission, a cosmic ray detector at the International Space Station. The link takes you to NASA Johnson's "Space Station Live: Cosmic Ray Detector for ISS."

20.5 The Life Cycle of Cosmic Material

Learning Objectives

By the end of this section, you will be able to:

- Explain how interstellar matter flows into and out of our Galaxy and transforms from one phase to another, and understand how star formation and evolution affects the properties of the interstellar medium
- Explain how the heavy elements and dust grains found in interstellar space got there and describe how dust grains help produce molecules that eventually find their way into planetary systems

Flows of Interstellar Gas

The most important thing to understand about the interstellar medium is that it is not static. Interstellar gas orbits through the Galaxy, and as it does so, it can become more or less dense, hotter and colder, and change its state of ionization. A particular parcel of gas may be neutral hydrogen at some point, then find itself near a young, hot star and become part of an H II region. The star may then explode as a supernova, heating the nearby gas up to temperatures of millions of degrees. Over millions of years, the gas may cool back down and become neutral again, before it collects into a dense region that gravity gathers into a giant molecular cloud (Figure 20.18)

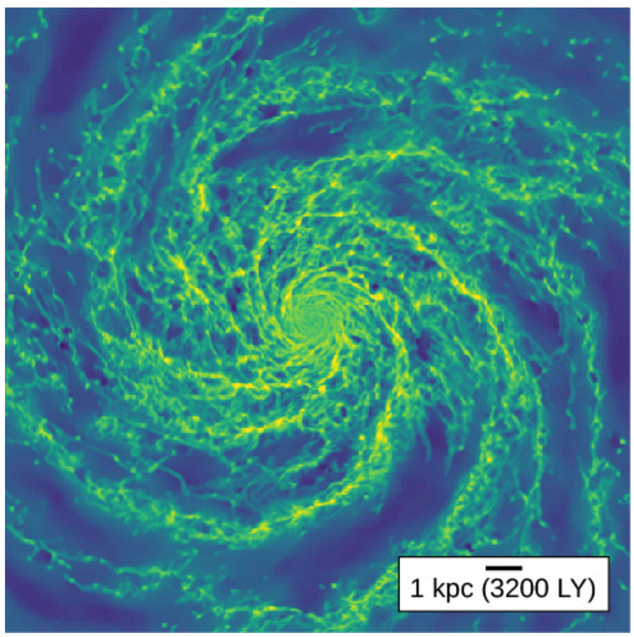

Figure 20.18 Large-Scale Distribution of Interstellar Matter. This image is from a computer simulation of the Milky Way Galaxy's interstellar medium as a whole. The majority of gas, visible in greenish colors, is neutral hydrogen. In the densest regions in the spiral arms, shown in yellow, the gas is collected into giant molecular clouds. Low-density holes in the spiral arms, shown in blue, are the result of supernova explosions. (credit: modification of work by Mark Krumholz)

At any given time in the Milky Way, the majority of the interstellar gas by mass and volume is in the form of atomic hydrogen. The much-denser molecular clouds occupy a tiny fraction of the volume of interstellar space but add roughly 30% to the total mass of gas between the stars. Conversely, the hot gas produced by supernova explosions contributes a negligible mass but occupies a significant fraction of the volume of interstellar space. H II regions, though they are visually spectacular, constitute only a very small fraction of either the mass or volume of interstellar material.

However, the interstellar medium is not a closed system. Gas from intergalactic space constantly falls onto the Milky Way due to its gravity, adding new gas to the interstellar medium. Conversely, in giant molecular clouds where gas collects together due to gravity, the gas can collapse to form new stars, as discussed in The Birth of Stars and the Discovery of Planets outside the Solar System. This process locks interstellar matter into stars. As the stars age, evolve, and eventually die, massive stars lose a large fraction of their mass, and low-mass stars lose very little. On average, roughly one-third of the matter incorporated into stars goes back into interstellar space. Supernova explosions have so much energy that they can drive interstellar mass out of the Galaxy and back into intergalactic space. Thus, the total amount of mass of the interstellar medium is set by a competition between the gain of mass from intergalactic space, the conversion of interstellar mass into stars, and the loss of interstellar mass back into intergalactic space due to supernovae. This entire process is known as the **baryon cycle**—baryon is from the Greek word for “heavy,” and the cycle has this name because it is the repeating process that the heavier components of the universe—the atoms—undergo.

The Cycle of Dust and Heavy Elements

While much of the mass of the interstellar medium is material accreted during the last few billion years from intergalactic space, this is not true of the elements heavier than hydrogen and helium, or of the dust. Instead, these components of the interstellar medium were made inside stars in the Milky Way, which returned them to the interstellar medium at the end of their lives. We will talk more about this process in later chapters, but for now just bear in mind what we learned in The Sun: A Nuclear Powerhouse. What stars “do for a living” is fuse heavier elements from lighter ones, producing energy in the process. As stars mature, they begin to lose some of the newly made elements to the reservoir of interstellar matter.

The same is true of dust grains. Dust forms when grains can condense in regions where gas is dense and cool. One place where the right conditions are found is the winds from luminous cool stars (the red giants and supergiants we discussed in The Stars: A Celestial Census). Grains can also condense in the matter thrown off by a supernova explosion as the ejected gases begin to cool.

The dust grains produced by stars may grow even further when they spend time in the dense parts of the interstellar medium, inside molecular clouds. In these environments, grains can stick together or gather additional atoms from the gas around them, growing larger. They also facilitate the production of other compounds, including some of the more complex molecules we discussed earlier.

The surfaces of the dust grains (see Cosmic Dust)—which would seem very large if you were an atom—provide “nooks and crannies” where these atoms can stick long enough to find partners and form molecules. (Think of the dust grains as “interstellar social clubs” where lonely atoms can meet and form meaningful relationships.) Eventually, the dust grains become coated with ices. The presence of the dust shields the molecules inside the clouds from ultraviolet radiation and cosmic rays that would break them up.

When stars finally begin to form within the cloud, they heat the grains and evaporate the ices. The gravitational attraction of the newly forming stars also increases the density of the surrounding cloud material. Many more chemical reactions take place on the surfaces of grains in the gas surrounding the newly forming stars, and these areas are where organic molecules are formed. These molecules can be incorporated into newly formed planetary systems, and the early Earth may have been seeded in just such a way.

Indeed, scientists speculate that some of the water on Earth may have come from interstellar grains. Recent observations from space have shown that water is abundant in dense interstellar clouds. Since stars are formed from this material, water must be present when solar systems, including our own, come into existence. The water in our oceans and lakes may have come initially from water locked into the rocky material that accreted to form Earth. Alternatively, the water may have been brought to Earth when asteroids and comets (formed from the same cloud that made the planets) later impacted it. Scientists estimate that one comet impact every thousand years during Earth’s first billion years would have been enough to account for the water we see today. Of course, both sources may have contributed to the water we now enjoy drinking and swimming in.

Any interstellar grains that are incorporated into newly forming stars (instead of the colder planets and smaller bodies around them) will be destroyed by their high temperatures. But eventually, each new generation of stars will evolve to become red giants, with stellar winds of their own. Some of these stars will also become supernovae and explode. Thus, the process of recycling cosmic material can start all over again.

20.6 Interstellar Matter around the Sun

Learning Objectives

By the end of this section, you will be able to:

- Describe how interstellar matter is arranged around our solar system
- Explain why scientists think that the Sun is located in a hot bubble

We want to conclude our discussion of interstellar matter by asking how this material is organized in our immediate neighborhood. As we discussed above, orbiting X-ray observatories have shown that the Galaxy is full of bubbles of hot, X-ray-emitting gas. They also revealed a diffuse background of X-rays that appears to fill the entire sky from our perspective (Figure 20.19). While some of this emission comes from the interaction of the solar wind with the interstellar medium, a majority of it comes from beyond the solar system. The natural explanation for why there is X-ray-emitting gas all around us is that the Sun is itself inside one of the bubbles. We therefore call our "neighborhood" the Local Hot Bubble, or **Local Bubble** for short. The Local Bubble is much less dense—an average of approximately 0.01 atoms per cm^3—than the average interstellar density of about 1 atom per cm^3. This local gas has a temperature of about a million degrees, just like the gas in the other superbubbles that spread throughout our Galaxy, but because there is so little hot material, this high temperature does not affect the stars or planets in the area in any way.

What caused the Local Bubble to form? Scientists are not entirely sure, but the leading candidate is winds from stars and supernova explosions. In a nearby region in the direction of the constellations Scorpius and Centaurus, a lot of star formation took place about 15 million years ago. The most massive of these stars evolved very quickly until they produced strong winds, and some ended their lives by exploding. These processes filled the region around the Sun with hot gas, driving away cooler, denser gas. The rim of this expanding superbubble reached the Sun about 7.6 million years ago and now lies more than 200 light-years past the Sun in the general direction of the constellations of Orion, Perseus, and Auriga.

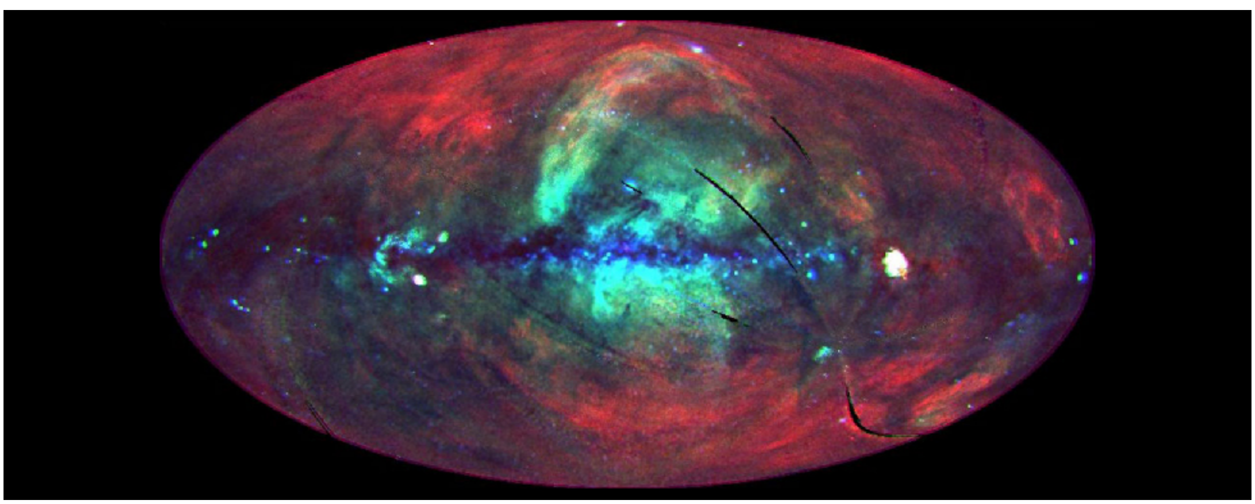

Figure 20.19 Sky in X-Rays. This image, made by the ROSAT satellite, shows the whole sky in X-rays as seen from Earth. Different colors indicate different X-ray energies: red is 0.25 kiloelectron volts, green is 0.75 kiloelectron volts, and blue is 1.5 kiloelectron volts. The image is oriented so the plane of the Galaxy runs across the middle of the image. The ubiquitous red color, which does not disappear completely even in the galactic plane, is evidence for a source of X-rays all around the Sun. (credit: modification of work by NASA)

A few clouds of interstellar matter do exist within the Local Bubble. The Sun itself seems to have entered a cloud about 10,000 years ago. This cloud is warm (with a temperature of about 7000 K) and has a density of 0.3 hydrogen atom per cm^3—higher than most of the Local Bubble but still so tenuous that it is also referred to as **Local Fluff** (Figure 20.20). (Aren't these astronomical names fun sometimes?)

While this is a pretty thin cloud, we estimate that it contributes 50 to 100 times more particles than the solar wind to the diffuse material between the planets in our solar system. These interstellar particles have been detected and their numbers counted by the spacecraft traveling between the planets. Perhaps someday, scientists will devise a way to collect them without destroying them and to return them to Earth, so that we can touch—or at least study in our laboratories—these messengers from distant stars.

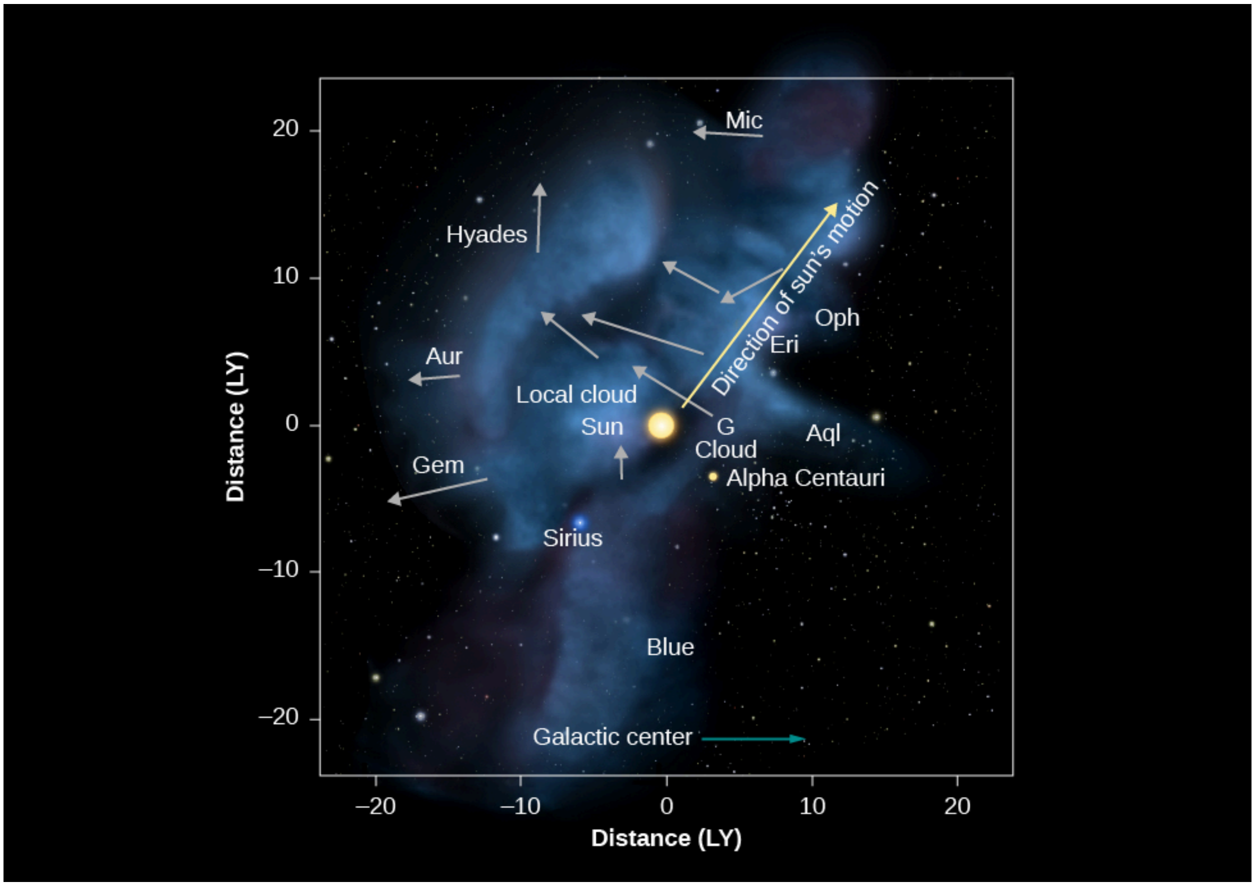

Figure 20.20 Local Fluff. The Sun and planets are currently moving through the Local Interstellar Cloud, which is also called the Local Fluff. Fluff is an appropriate description because the density of this cloud is only about 0.3 atom per cm^3. In comparison, Earth’s atmosphere at the edge of space has around 1.2×10^{13} molecules per cm^3. This image shows the patches of interstellar matter (mostly hydrogen gas) within about 20 light-years of the Sun. The temperature of the Local Interstellar Cloud is about 7000 K. The arrows point toward the directions that different parts of the cloud are moving. The names associated with each arrow indicate the constellations located on the sky toward which the parts of the cloud are headed. The solar system is thought to have entered the Local Interstellar Cloud, which is a small cloud located within a much larger superbubble that is expanding outward from the Scorpius-Centaurus region of the sky, at some point between 44,000 and 150,000 years ago and is expected to remain within it for another 10,000 to 20,000 years. (credit: modification of work by NASA/Goddard/Adler/University Chicago/Wesleyan)

Key Terms

baryon cycle the cycling of mass in and out of the interstellar medium, including accretion of gas from intergalactic space, loss of gas back into intergalactic space, and conversion of interstellar gas into stars

cosmic rays atomic nuclei (mostly protons) and electrons that are observed to strike Earth's atmosphere with exceedingly high energies.

H II region the region of ionized hydrogen in interstellar space

interstellar dust tiny solid grains in interstellar space thought to consist of a core of rocklike material (silicates) or graphite surrounded by a mantle of ices; water, methane, and ammonia are probably the most abundant ices

interstellar extinction the attenuation or absorption of light by dust in the interstellar medium

interstellar medium (ISM) (or interstellar matter) the gas and dust between the stars in a galaxy

Local Bubble (or Local Hot Bubble) a region of low-density, million degree gas in which the Sun and solar system are currently located

Local Fluff a slightly denser cloud inside the Local Bubble, inside which the Sun also lies

molecular cloud a large, dense, cold interstellar cloud; because of its size and density, this type of cloud can keep ultraviolet radiation from reaching its interior, where molecules are able to form

nebula a cloud of interstellar gas or dust; the term is most often used for clouds that are seen to glow with visible light or infrared

reddening (interstellar) the reddening of starlight passing through interstellar dust because dust scatters blue light more effectively than red

Summary

20.1 The Interstellar Medium

About 15% of the visible matter in the Galaxy is in the form of gas and dust, serving as the raw material for new stars. About 99% of this interstellar matter is in the form of gas—individual atoms or molecules. The most abundant elements in the interstellar gas are hydrogen and helium. About 1% of the interstellar matter is in the form of solid interstellar dust grains.

20.2 Interstellar Gas

Interstellar gas may be hot or cold. Gas found near hot stars emits light by fluorescence, that is, light is emitted when an electron is captured by an ion and cascades down to lower-energy levels. Glowing clouds (nebulae) of ionized hydrogen are called H II regions and have temperatures of about 10,000 K. Most hydrogen in interstellar space is not ionized and can best be studied by radio measurements of the 21-centimeter line. Some of the gas in interstellar space is at a temperature of a million degrees, even though it is far away in hot stars; this ultra-hot gas is probably heated when rapidly moving gas ejected in supernova explosions sweeps through space. In some places, gravity gathers interstellar gas into giant clouds, within which the gas is protected from starlight and can form molecules; more than 200 different molecules have been found in space, including the basic building blocks of proteins, which are fundamental to life as we know it here on Earth.

20.3 Cosmic Dust

Interstellar dust can be detected: (1) when it blocks the light of stars behind it, (2) when it scatters the light from nearby stars, and (3) because it makes distant stars look both redder and fainter. These effects are called interstellar extinction and reddening. Dust can also be detected in the infrared because it emits heat radiation. Dust is found throughout the plane of the Milky Way. The dust particles are about the same size as the wavelength of light and consist of rocky cores that are either sootlike (carbon-rich) or sandlike (silicates) with mantles made of ices such as water, ammonia, and methane.

20.4 Cosmic Rays

Cosmic rays are particles that travel through interstellar space at a typical speed of 90% of the speed of light. The most abundant elements in cosmic rays are the nuclei of hydrogen and helium, but electrons and positrons are also found. It is likely that many cosmic rays are produced in supernova shocks.

20.5 The Life Cycle of Cosmic Material

Interstellar matter is constantly flowing through the Galaxy and changing from one phase to another. At the same time, gas is constantly being added to the Galaxy by accretion from extragalactic space, while mass is removed from the interstellar medium by being locked in stars. Some of the mass in stars is, in turn, returned to the interstellar medium when those stars evolve and die. In particular, the heavy elements in interstellar space were all produced inside stars, while the dust grains are made in the outer regions of stars that have swelled to be giants. These elements and grains, in turn, can then be incorporated into new stars and planetary systems that form out of the interstellar medium.

20.6 Interstellar Matter around the Sun

The Sun is located at the edge of a low-density cloud called the Local Fluff. The Sun and this cloud are located within the Local Bubble, a region extending to at least 300 light-years from the Sun, within which the density of interstellar material is extremely low. Astronomers think this bubble was blown by some nearby stars that experienced a strong wind and some supernova explosions.

For Further Exploration

Articles

Goodman, A. “Recycling the Universe.” *Sky & Telescope* November (2000): 44. Review of how stellar evolution, the interstellar medium, and supernovae all work together to recycle cosmic material.

Greenberg, J. “The Secrets of Stardust.” *Scientific American* December (2000): 70. The makeup and evolutionary role of solid particles between the stars.

Knapp, G. “The Stuff between the Stars.” *Sky & Telescope* May (1995): 20. An introduction to the interstellar medium.

Nadis, S. “Searching for the Molecules of Life in Space.” *Sky & Telescope* January (2002): 32. Recent observations of water in the interstellar medium by satellite telescopes.

Olinto, A. “Solving the Mystery of Cosmic Rays.” *Astronomy* April (2014): 30. What accelerates them to such high energies.

Reynolds, R. “The Gas between the Stars.” *Scientific American* January (2002): 34. On the interstellar medium.

Websites and Apps

Barnard, E. E., Biographical Memoir: http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/barnard-edward.pdf (http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/barnard-edward.pdf).

Cosmicopia: https://cosmicopia.gsfc.nasa.gov/ (https://cosmicopia.gsfc.nasa.gov/). NASA’s learning site explains about the history and modern understanding of cosmic rays.

DECO: https://wipac.wisc.edu/deco (https://wipac.wisc.edu/deco). A smart-phone app for turning your phone into a cosmic-ray detector.

Hubble Space Telescope Images of Nebulae: https://esahubble.org/images/archive/category/nebulae (https://esahubble.org/images/archive/category/nebulae). Click on any of the beautiful images in this collection, and you are taken to a page with more information; while looking at these images, you may also want to browse through the slide sequence on the meaning of colors in the Hubble pictures (https://hubblesite.org/contents/articles/the-meaning-of-light-and-color (https://hubblesite.org/contents/articles/the-meaning-of-light-and-color)).

Interstellar Medium Online Tutorial: http://www-ssg.sr.unh.edu/ism/ (http://www-ssg.sr.unh.edu/ism/). Nontechnical introduction to the interstellar medium (ISM) and how we study it; by the University of New Hampshire astronomy department.

Messier Catalog of Nebulae, Clusters, and Galaxies: http://astropixels.com/messier/messiercat.html (http://astropixels.com/messier/messiercat.html). Astronomer Fred Espenak provides the full catalog, with information and images. (The Wikipedia list does something similar: https://en.wikipedia.org/wiki/List_of_Messier_objects (https://en.wikipedia.org/wiki/List_of_Messier_objects).

Nebulae: What Are They?: http://www.universetoday.com/61103/what-is-a-nebula/ (http://www.universetoday.com/61103/what-is-a-nebula/). Concise introduction by Matt Williams.

Videos

Barnard 68: The Hole in the Sky: https://www.youtube.com/watch?v=Faz5rgdQSo4 (https://www.youtube.com/watch?v=Faz5rgdQSo4). About this dark cloud and dark clouds in interstellar space in general (02:08).

Horsehead Nebula in New Light: http://www.esa.int/spaceinvideos/Videos/2013/04/The_Horsehead_Nebula_in_new_light (http://www.esa.int/spaceinvideos/Videos/2013/04/The_Horsehead_Nebula_in_new_light). Tour of the dark nebula in different wavelengths; no audio narration, just music, but explanatory material appears on the screen (03:03).

Hubblecast 65: A Whole New View of the Horsehead Nebula: http://www.spacetelescope.org/videos/heic1307a/ (http://www.spacetelescope.org/videos/heic1307a/). Report on nebulae in general and about the Horsehead specifically, with ESO astronomer Joe Liske (06:03).

Interstellar Reddening: https://www.youtube.com/watch?v=H2M80RAQB6k (https://www.youtube.com/watch?v=H2M80RAQB6k). Video demonstrating how reddening works, with Scott Miller of Penn State; a bit nerdy but useful (03:45).

Hubble Field Guide to the Nebulae: https://www.youtube.com/watch?v=PYRDiR7peLw (https://www.youtube.com/watch?v=PYRDiR7peLw). Video briefly explaining the difference between types of nebulae (04:24).

Collaborative Group Activities

A. The Sun is located in a region where the density of interstellar matter is low. Suppose that instead it were located in a dense cloud 20 light-years in diameter that dimmed the visible light from stars lying outside it by a factor of 100. Have your group discuss how this would have affected the development of civilization on Earth. For example, would it have presented a problem for early navigators?

B. Your group members should look through the pictures in this chapter. How big are the nebulae you see in the images? Are there any clues either in the images or in the captions? Are the clouds they are part of significantly bigger than the nebulae we can see? Why? Suggest some ways that we can determine the sizes of nebulae.

C. How do the members of your group think astronomers are able to estimate the distances of such nebulae in our own Galaxy? (Hint: Look at the images. Can you see anything between us and the nebula in some cases. Review Celestial Distances, if you need to remind yourself about methods of measuring distances.)

D. The text suggests that a tube of air extending from the surface of Earth to the top of the atmosphere contains more atoms than a tube of the same diameter extending from the top of the atmosphere to the edge of the observable universe. Scientists often do what they call “back of the envelope calculations,” in which they make very rough approximations just to see whether statements or ideas are true. Try doing such a “quick and dirty” estimate for this statement with your group. What are the steps in comparing the numbers of atoms contained in the two different tubes? What information do you need to make the approximations? Can you find it in this text? And is the statement true?

E. If your astronomy course has involved learning about the solar system before you got to this chapter, have your group discuss where else besides interstellar clouds astronomers have been discovering organic molecules (the chemical building blocks of life). How might the discoveries of such molecules in our own solar system be related to the molecules in the clouds discussed in this chapter?

F. Two stars both have a reddish appearance in telescopes. One star is actually red; the other’s light has been reddened by interstellar dust on its way to us. Have your group make a list of the observations you could perform to determine which star is which.

G. You have been asked to give a talk to your little brother’s middle school class on astronomy, and you decide to talk about how nature recycles gas and dust. Have your group discuss what images from this book you would use in your talk. In what order? What is the one big idea you would like the students to remember when the class is over?

H. This chapter and the next (on The Birth of Stars) include some of the most beautiful images of nebulae that glow with the light produced when starlight interacts with gas and dust. Have your group select one to four of your favorite such nebulae and prepare a report on them to share with the rest of the class. (Include such things as their location, distance, size, way they are glowing, and what is happening within them.)

Exercises

Review Questions

1. Identify several dark nebulae in photographs in this chapter. Give the figure numbers of the photographs, and specify where the dark nebulae are to be found on them.

2. Why do nebulae near hot stars look red? Why do dust clouds near stars usually look blue?

3. Describe the characteristics of the various kinds of interstellar gas (HII regions, neutral hydrogen clouds, ultra-hot gas clouds, and molecular clouds).

4. Prepare a table listing the different ways in which dust and gas can be detected in interstellar space.

5. Describe how the 21-cm line of hydrogen is formed. Why is this line such an important tool for understanding the interstellar medium?

6. Describe the properties of the dust grains found in the space between stars.

7. Why is it difficult to determine where cosmic rays come from?

8. What causes reddening of starlight? Explain how the reddish color of the Sun’s disk at sunset is caused by the same process.

9. Why do molecules, including H_2 and more complex organic molecules, only form inside dark clouds? Why don’t they fill all interstellar space?

10. Why can’t we use visible light telescopes to study molecular clouds where stars and planets form? Why do infrared or radio telescopes work better?

11. The mass of the interstellar medium is determined by a balance between sources (which add mass) and sinks (which remove it). Make a table listing the major sources and sinks, and briefly explain each one.

12. Where does interstellar dust come from? How does it form?

Thought Questions

13. Figure 20.2 shows a reddish glow around the star Antares, and yet the caption says that is a dust cloud. What observations would you make to determine whether the red glow is actually produced by dust or whether it is produced by an H II region?

14. If the red glow around Antares is indeed produced by reflection of the light from Antares by dust, what does its red appearance tell you about the likely temperature of Antares? Look up the spectral type of Antares in Appendix J. Was your estimate of the temperature about right? In most of the images in this chapter, a red glow is associated with ionized hydrogen. Would you expect to find an H II region around Antares? Explain your answer.

15. Even though neutral hydrogen is the most abundant element in interstellar matter, it was detected first with a radio telescope, not a visible light telescope. Explain why. (The explanation given in Analyzing Starlight for the fact that hydrogen lines are not strong in stars of all temperatures may be helpful.)

16. The terms H II and H_2 are both pronounced "H two." What is the difference in meaning of those two terms? Can there be such a thing as H III?

17. Suppose someone told you that she had discovered H II around the star Aldebaran. Would you believe her? Why or why not?

18. Describe the spectrum of each of the following:
A. starlight reflected by dust,
B. a star behind invisible interstellar gas, and
C. an emission nebula.

19. According to the text, a star must be hotter than about 25,000 K to produce an H II region. Both the hottest white dwarfs and main-sequence O stars have temperatures hotter than 25,000 K. Which type of star can ionize more hydrogen? Why?

20. From the comments in the text about which kinds of stars produce emission nebulae and which kinds are associated with reflection nebulae, what can you say about the temperatures of the stars that produce NGC 1999 (Figure 20.13)?

21. One way to calculate the size and shape of the Galaxy is to estimate the distances to faint stars just from their observed apparent brightnesses and to note the distance at which stars are no longer observable. The first astronomers to try this experiment did not know that starlight is dimmed by interstellar dust. Their estimates of the size of the Galaxy were much too small. Explain why.

22. New stars form in regions where the density of gas and dust is relatively high. Suppose you wanted to search for some recently formed stars. Would you more likely be successful if you observed at visible wavelengths or at infrared wavelengths? Why?

23. Thinking about the topics in this chapter, here is an Earth analogy. In big cities, you can see much farther on days without smog. Why?

24. Stars form in the Milky Way at a rate of about 1 solar mass per year. At this rate, how long would it take for all the interstellar gas in the Milky Way to be turned into stars if there were no fresh gas coming in from outside? How does this compare to the estimated age of the universe, 14 billion years? What do you conclude from this?

25. The 21-cm line can be used not just to find out where hydrogen is located in the sky, but also to determine how fast it is moving toward or away from us. Describe how this might work.

26. Astronomers recently detected light emitted by a supernova that was originally observed in 1572, just reaching Earth now. This light was reflected off a dust cloud; astronomers call such a reflected light a "light echo" (just like reflected sound is called an echo). How would you expect the spectrum of the light echo to compare to that of the original supernova?

27. We can detect 21-cm emission from other galaxies as well as from our own Galaxy. However, 21-cm emission from our own Galaxy fills most of the sky, so we usually see both at once. How can we distinguish the extragalactic 21-cm emission from that arising in our own Galaxy? (Hint: Other galaxies are generally moving relative to the Milky Way.)

28. We have said repeatedly that blue light undergoes more extinction than red light, which is true for visible and shorter wavelengths. Is the same true for X-rays? Look at Figure 20.19. The most dust is in the galactic plane in the middle of the image, and the red color in the image corresponds to the reddest (lowest-energy) light. Based on what you see in the galactic plane, are X-rays experiencing more extinction at redder or bluer colors? You might consider comparing Figure 20.19 to Figure 20.14.

29. Suppose that, instead of being inside the Local Bubble, the Sun were deep inside a giant molecular cloud. What would the night sky look like as seen from Earth at various wavelengths?

30. Suppose that, instead of being inside the Local Bubble, the Sun were inside an H II region. What would the night sky look like at various wavelengths?

Figuring for Yourself

31. A molecular cloud is about 1000 times denser than the average of the interstellar medium. Let's compare this difference in densities to something more familiar. Air has a density of about 1 kg/m^3, so something 1000 times denser than air would have a density of about 1000 kg/m^3. How does this compare to the typical density of water? Of granite? (You can find figures for these densities on the internet.) Is the density difference between a molecular cloud and the interstellar medium larger or smaller than the density difference between air and water or granite?

32. Would you expect to be able to detect an H II region in X-ray emission? Why or why not? (Hint: You might apply Wien's law)

33. Suppose that you gathered a ball of interstellar gas that was equal to the size of Earth (a radius of about 6000 km). If this gas has a density of 1 hydrogen atom per cm^3, typical of the interstellar medium, how would its mass compare to the mass of a bowling ball (5 or 6 kg)? How about if it had the typical density of the Local Bubble, about 0.01 atoms per cm^3? The volume of a sphere is $V = (4/3)\pi R^3$.

34. At the average density of the interstellar medium, 1 atom per cm^3, how big a volume of material must be used to make a star with the mass of the Sun? What is the radius of a sphere this size? Express your answer in light-years.

35. Consider a grain of sand that contains 1 mg of oxygen (a typical amount for a medium-sized sand grain, since sand is mostly SiO_2). How many oxygen atoms does the grain contain? What is the radius of the sphere you would have to spread them out over if you wanted them to have the same density as the interstellar medium, about 1 atom per cm^3? You can look up the mass of an oxygen atom.

36. H II regions can exist only if there is a nearby star hot enough to ionize hydrogen. Hydrogen is ionized only by radiation with wavelengths shorter than 91.2 nm. What is the temperature of a star that emits its maximum energy at 91.2 nm? (Use Wien's law from Radiation and Spectra.) Based on this result, what are the spectral types of those stars likely to provide enough energy to produce H II regions?

37. In the text, we said that the five-times ionized oxygen (OVI) seen in hot gas must have been produced by supernova shocks that heated the gas to millions of degrees, and not by starlight, the way H II is produced. Producing OVI by light requires wavelengths shorter than 10.9 nm. The hottest observed stars have surface temperatures of about 50,000 K. Could they produce OVI?

38. Dust was originally discovered because the stars in certain clusters seemed to be fainter than expected. Suppose a star is behind a cloud of dust that dims its brightness by a factor of 100. Suppose you do not realize the dust is there. How much in error will your distance estimate be? Can you think of any measurement you might make to detect the dust?

39. How would the density inside a cold cloud (T = 10 K) compare with the density of the ultra-hot interstellar gas ($T = 10^6$ K) if they were in pressure equilibrium? (It takes a large cloud to be able to shield its interior from heating so that it can be at such a low temperature.) (Hint: In pressure equilibrium, the two regions must have nT equal, where n is the number of particles per unit volume and T is the temperature.) Which region do you think is more suitable for the creation of new stars? Why?

40. The text says that the Local Fluff, which surrounds the Sun, has a temperature of 7500 K and a density 0.1 atom per cm^3. The Local Fluff is embedded in hot gas with a temperature of 10^6 K and a density of about 0.01 atom per cm^3. Are they in equilibrium? (Hint: In pressure equilibrium, the two regions must have nT equal, where n is the number of particles per unit volume and T is the temperature.) What is likely to happen to the Local Fluff?