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.

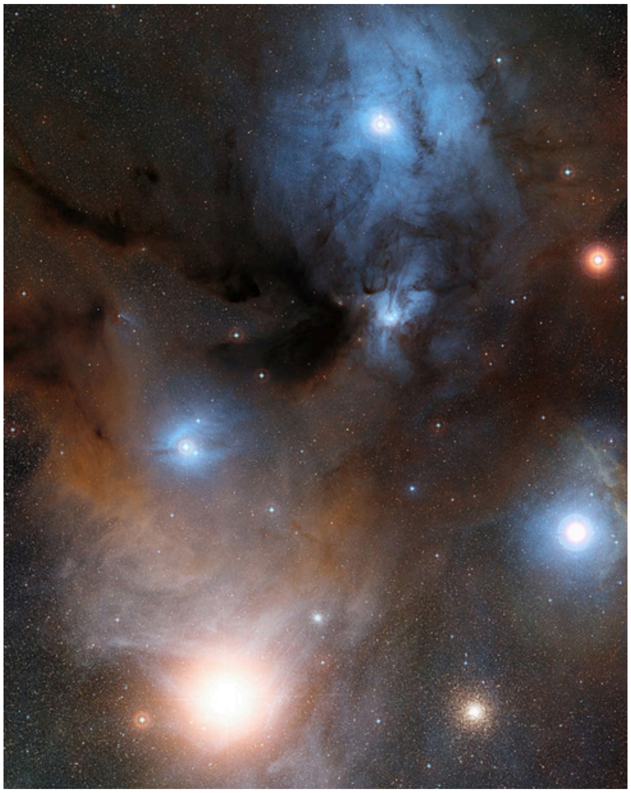

Figure 20.2 Various Types of Interstellar Matter. The reddish nebulae in this spectacular photograph glow with light emitted by hydrogen atoms. The darkest areas are clouds of dust that block the light from stars behind them. The upper part of the picture is filled with the bluish glow of light reflected 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

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[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.