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Barbara Ryden , Richard W. Pogge
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Introduction

The Interstellar Medium is anything not in stars.
Professor Donald E. Osterbrock (1924–2007)
[from RWP's graduate ISM course notes,
January 13, 1984]

A seemingly disproportionate share of astronomy is devoted to the properties of baryonic matter and its interaction with photons. Baryonic matter, in practice, is matter that is made of protons and neutrons, with the addition of enough (non-baryonic) electrons to preserve charge neutrality on large scales. In the consensus model of cosmology, less than 5% of the density of the universe is provided by baryonic matter; the majority of the universe is made of dark energy ($\sim$69% of the total density) and dark matter ($\sim$26% of the total). This book rudely snubs the dark side of the universe; dark energy is ignored until we discuss cosmic evolution in Chapter 9, and dark matter is important only because it provides gravitational potential wells for baryonic matter to be trapped in. However, devoting an entire book to the baryonic five percent is easily justified by the rich variety of physical phenomena that arise from the interactions among baryons, electrons, and photons.

To begin, let's make an extremely rough census of the baryonic matter present in the universe today (Figure 1.1). About 7% of the baryonic matter is in the form of **stars** and other compact objects such as stellar remnants, brown dwarfs, and planets. Roughly 2% is in the diffuse gas of the **interstellar medium (ISM)** filling the volume between the stars within a galaxy. About 5% is in the gas of the **circumgalactic medium (CGM)**, bound within the dark matter halo of a galaxy but outside the main distribution of stars. Roughly 4% is in the hot gas of the **intracluster medium (ICM)** of clusters of galaxies, bound to the cluster as a whole but not to any individual galaxy. About 38% of the baryonic matter present today is in the **diffuse intergalactic medium (DIM)**, made of low-density, mostly photoionized gas, at temperatures $T < 10^5$ K. The final $\sim$44% of the baryonic component of the universe is in the **warm-hot intergalactic medium**

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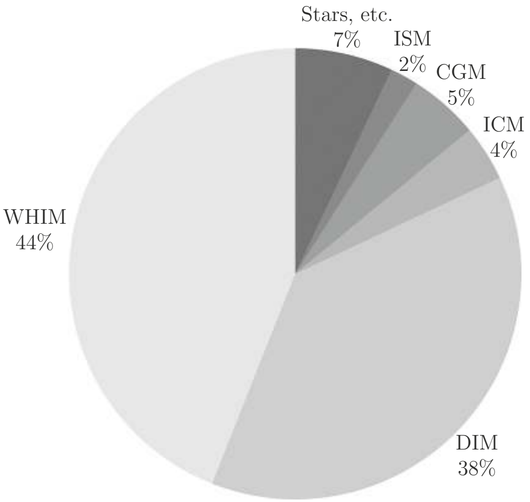

Figure 1.1 Approximate division of the baryonic mass density of the current universe. [Data from Nicastro et al. 2018, Martizzi et al. 2019, and references therein]

(WHIM), made of shock-heated gas at temperatures $10^5\,\mathrm{K} < T < 10^7\,\mathrm{K}$. (All percentages in this paragraph are approximate, especially for the imperfectly surveyed intergalactic medium.)

This book deals with the diffuse baryonic gas, typically at a density $\rho < 10^{-18}\,\mathrm{g\,cm^{-3}}$, that hasn't curdled into stars, brown dwarfs, planets, stellar remnants, or other dense massive lumps. However, we also discuss interstellar **dust**, consisting of tiny grains of solid material. "Tiny," in this context, means radii of less than one micron. Dust grains can consist of silicates, ices, carbonaceous materials, graphite, and even diamond. Why does a book dealing mainly with low-density gas condescend to consider solid material? This is partly for historical reasons. In the twentieth century, courses on the interstellar medium dealt with the grab-bag category of "non-stellar stuff"; thus, generations of astronomers were conditioned to lump gas and dust together. However, there are also sound physical reasons for considering interstellar gas in conjunction with interstellar dust. The dust and gas strongly influence each other. Dust reprocesses sunlight, altering the radiation field passing through the gas. Dust is made of elements with a high condensation temperature, so creating dust alters the chemical abundances of the surrounding gas. Dust grains are a leading source of free electrons in the interstellar gas. The surfaces of dust grains are the matrices where gas molecules form. Thus, in the denser, dustier regions of interstellar space, it makes little sense to study interstellar gas in isolation from interstellar dust. (The transparency of intergalactic space places fairly strong constraints on the amount of *intergalactic* dust.)

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Interstellar gas, though it contributes only $\sim$2% of the baryons in the universe, is particularly interesting and will be the subject of much of this book. Because it occupies the same region as the stellar portion of a galaxy, it interacts in a variety of ways with stars. Stars are made from interstellar gas, they emit stellar winds into the ISM over the course of their lives, and, when massive stars reach the end of their lifetimes, they inject chemically enriched gas at high speeds into the surrounding interstellar gas. Stars also emit photons; the higher-energy stellar photons are capable of exciting the interstellar gas. Ionized nebulae, such as the Orion Nebula, would be dim at visible wavelengths if they weren't excited by ultraviolet light from stars. As it is, the emission lines of nebulae have strong diagnostic power, enabling us to determine the densities, temperatures, and ionization states of interstellar gas.

The interstellar gas in our galaxy (the Milky Way Galaxy) has five different phases. At the moment, we simply list and describe them. Later, we will investigate *why* the interstellar gas has five phases, and what physical processes determine their observed properties. Table 1.1 summarizes the properties of the phases of the interstellar medium. The typical temperature T and number density $n_{\rm H}$ of hydrogen nuclei are given for locations in the midplane of our galaxy's disk, at the Sun's distance from the galactic center, $R = 8.2\,{\rm kpc}$. The mass fraction is the contribution from each phase to the total mass surface density of gas, $\Sigma_{\rm gas} \approx 10\,{\rm M}_\odot\,{\rm pc}^{-2}$, at a distance $R = 8.2\,{\rm kpc}$ from the galactic center. (For comparison, the mass surface density of stars at $R = 8.2\,{\rm kpc}$ is $\Sigma_\star \approx 50\,{\rm M}_\odot\,{\rm pc}^{-2} \sim 5\Sigma_{\rm gas}$.) An approximate scale height h_z is given for each phase in the direction perpendicular to the galaxy's disk; the cooler phases are seen to stay closer to the midplane.

Molecular clouds have H_2 as their dominant form of hydrogen. The densest portions of molecular clouds, where the number density can be as high as $n \sim 10^6\,{\rm cm}^{-3}$, are self-gravitating regions where stars can form. Although molecular clouds occupy a minuscule fraction of the ISM's volume, their relatively high density means they contribute about a fifth of the ISM's mass. A useful method

Table 1.1 Phases of the ISM in the Milky Way Galaxy[a]

Name	T [K]	$n_{\rm H}$ [cm^{-3}]	Mass fraction	h_z [pc]
Molecular Clouds	15	>100	20%	75
Cold Neutral Medium	80	40	30%	100
Warm Neutral Medium	6000	0.4	35%	300
Warm Ionized Medium	8000	0.2	12%	900
Hot Ionized Medium	10^6	0.004	3%	3000

[a] *Data from Ferrière 2001 and Tielens 2005*

of observing molecular clouds is by looking for millimeter-wavelength emission from small molecules such as carbon monoxide.

The **cold neutral medium (CNM)** has atomic hydrogen, or H I, as its dominant form of hydrogen. The cold neutral medium is distributed in sheets and filaments occupying only ∼1% of the volume of the ISM but containing roughly a third of the ISM's mass. A useful method of observing the CNM is by looking for the UV and visible absorption lines it produces in the spectra of background stars and quasars.

The **warm neutral medium (WNM)** also has H I as its dominant form of hydrogen. In older papers, particularly those published before 1990, the WNM is sometimes referred to as the "warm intercloud medium." A useful method of observing the WNM is by looking for 21 cm radio emission from atomic hydrogen. The neutral phases of our galaxy's ISM, including molecular clouds, the CNM, and the WNM, provide most of the mass of the ISM despite occupying only ∼25% of its volume.

The **warm ionized medium (WIM)** has ionized hydrogen, or H II, as its dominant form of hydrogen. The WIM is sometimes referred to as "diffuse ionized gas." The warm ionized medium is primarily photoionized by hot stars. A useful method of observing the WIM is by looking for the Balmer emission lines of hydrogen. Although H II regions (around hot stars) and planetary nebulae (around newly unveiled white dwarfs) have temperatures similar to the warm ionized medium, they have much higher densities.

The **hot ionized medium (HIM)** also has H II as its dominant form of hydrogen. In older papers, the HIM is sometimes referred to as the "coronal gas," referring to the fact that its temperature is comparable to that of the Sun's corona, although its density is much lower. The hot ionized medium is primarily shock-heated by supernovae. A useful method of observing the HIM is by looking for far-ultraviolet absorption lines of ions such as O VI in the spectra of background stars; the hottest portions of the HIM also produce diffuse soft X-ray emission. The ionized phases of our galaxy's ISM, including both the WIM and the HIM, occupy most of the volume of the ISM despite providing only ∼15% of its mass. The Sun is located inside a bubble of hot ionized gas called the Local Bubble, roughly 100 parsecs across.

The total mass of the interstellar medium in our galaxy is not perfectly known. In part, this is due to the difficulty in doing a complete census of the different phases; in part, it is due to the necessity of drawing a somewhat arbitrary boundary between the interstellar medium and the circumgalactic medium. Most estimates yield $M_{\rm ism} \approx 7 \times 10^9\,{\rm M}_\odot$, with about 1% of that mass being in the form of interstellar dust. For comparison, the total mass of stars in our galaxy is $M_\star \approx 6 \times 10^{10}\,{\rm M}_\odot$, yielding an interstellar-to-stellar mass ratio $M_{\rm ism}/M_\star \approx 0.12$. This ratio varies greatly from one galaxy to another. For instance, the Small Magellanic Cloud, a gas-rich irregular galaxy, has $M_{\rm ism}/M_\star \approx 1.4$. By contrast,

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Table 1.2 Solar abundance of elements[a]

Element	ppm by number	percentage by mass	atomic number	1st ionization energy [eV]
hydrogen (H)	910 630	71.10%	1	13.60
helium (He)	88 250	27.36%	2	24.59
oxygen (O)	550	0.68%	8	13.62
carbon (C)	250	0.24%	6	11.26
neon (Ne)	120	0.18%	10	21.56
nitrogen (N)	75	0.08%	7	14.53
magnesium (Mg)	36	0.07%	12	7.65
silicon (Si)	35	0.08%	14	8.15
iron (Fe)	30	0.13%	26	7.90
sulfur (S)	15	0.04%	16	10.36

[a] *Data from Lodders 2010*

the giant elliptical galaxy M87 has $M_{\rm ism}/M_\star < 0.02$ in its central regions (within $r = 5\,$kpc of the galaxy's center).

The chemical composition of the ISM in our galaxy is not homogeneous; in addition, the mean chemical composition changes with time. However, we have a fairly good idea of the composition of one particular patch of the ISM at one particular time. By studying the composition of the Sun's atmosphere, supplemented by information from primitive meteorites, we can deduce the relative abundance of elements in the protosolar nebula from which the Sun formed 4.57 billion years ago. The resulting **solar abundance** for the 10 most abundant elements is shown in Table 1.2, along with their atomic numbers and first ionization energies. Of the atoms from which the Sun formed, about 91.1% were hydrogen and 8.8% were helium. This means that all the heavier elements in the periodic table together contributed only $\sim 0.1\%$ of the atoms. Astronomers frequently refer to elements heavier than helium as "metals," even though they are not all metallic by the standard chemist's definition; we will follow this convention. The **solar metallicity** $Z_\odot$ is the fraction of the Sun's initial mass made of "metals"; the numbers in Table 1.2 yield $Z_\odot = 0.015$. Although different regions in the ISM and IGM have different mixes of elements, we will use $Z_\odot$ as our benchmark metallicity and the relative abundances in Table 1.2 as our benchmark blend of metals.

In a gas of neutral atoms, the total number density of gas particles at solar abundance is

$$n = n_{\rm H} + n_{\rm He} + n_{\rm O} + \cdots \approx 1.10 n_{\rm H} \qquad \text{[atomic]}. \tag{1.1}$$

However, in the limit that the hot gas in the solar abundance is completely ionized, the total number density is

$$n = 2n_{\rm H} + 3n_{\rm He} + 9n_{\rm O} + \cdots \approx 2.30 n_{\rm H} \qquad \text{[ionized]}, \tag{1.2}$$

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with free electrons providing $n_e \approx 1.20 n_{\rm H}$ and naked atomic nuclei providing $n_{\rm nuc} \approx 1.10 n_{\rm H}$. In cold molecular gas, we can make the lowest-order approximation that all atoms other than the noble gases are in diatomic molecules such as H_2, OH, CH, CO, and so forth. With this approximation, the total number density is

$$n = \frac{1}{2} n_{\rm H} + n_{\rm He} + \frac{1}{2} n_{\rm O} \cdots \approx 0.60 n_{\rm H} \qquad \text{[molecular]}. \tag{1.3}$$

In approximate calculations, the total number density n and the number density of hydrogen nuclei $n_{\rm H}$ are sometimes used interchangeably. A more careful translation between $n_{\rm H}$ and n requires knowing the ionization state of hot gas or the degree of molecular formation in cold gas.

The values of T and $n_{\rm H}$ in Table 1.1 imply that each phase has a pressure $P \sim 4 \times 10^{-13}\,\text{dyn}\,\text{cm}^{-2} \sim 4 \times 10^{-19}\,\text{atm}$, to within a factor of three. This is an extremely low pressure compared with the pressure of the air around us. Thus, your intuition about how gases behave, largely derived from your experience with air, might not be applicable to the tenuous gas of the interstellar medium. Even in laboratory settings, it is difficult to attain densities comparable to those of interstellar gas. Extremely high vacuum (XHV), defined as a pressure $P \leq 10^{-9}\,\text{dyn}\,\text{cm}^{-2}$, is challenging to produce in the lab; at room temperature ($T \approx 300\,\text{K}$), an XHV pressure $P = 10^{-9}\,\text{dyn}\,\text{cm}^{-2}$ corresponds to a number density $n \sim 20\,000\,\text{cm}^{-3}$. In the interstellar medium of the Milky Way, this XHV density is exceeded only in the dense cores of molecular clouds.

Although the pressure of the interstellar gas, $P_{\rm ism} \sim 4 \times 10^{-13}\,\text{dyn}\,\text{cm}^{-2}$, is low compared with a laboratory vacuum, it is higher than the pressure of the intergalactic gas. The intergalactic medium embraces a range of pressures, all of them quite low. For example, the warm-hot intergalactic medium has a typical pressure $P_{\rm whim} \sim 4 \times 10^{-16}\,\text{dyn}\,\text{cm}^{-2}$ at $T = 10^6\,\text{K}$. The diffuse intergalactic medium has a still lower pressure, $P_{\rm dim} \sim 4 \times 10^{-19}\,\text{dyn}\,\text{cm}^{-2}$ at $T = 7000\,\text{K}$.

The typical pressure of interstellar gas, $P = nkT \sim 4 \times 10^{-13}\,\text{dyn}\,\text{cm}^{-2}$, can be converted to a thermal energy density, $\varepsilon = (3/2)nkT \sim 0.4\,\text{eV}\,\text{cm}^{-3}$. In the context of interstellar space, is this a small or large energy density? Fortunately, the other energy densities in the local ISM are fairly well known. Table 1.3 gives the approximate values for energy densities in the interstellar medium near the Sun's location. All seven of these energy densities are within an order of magnitude of each other. Even if the rest of this book fades from memory, it will be useful to remember the general rule: "All energy densities in the local ISM are half an electron-volt per cubic centimeter."

We live in a galaxy where the ISM has five different phases, and has many possible energy sources, all of them comparable in density. It looks as though we have an interesting variety of physics in store. But why are there five different phases? Why should the interstellar gas have different phases at all? How did

Table 1.3 Energy densities in the local ISM[a]

Type	Energy density ($\mathrm{eV\,cm^{-3}}$)
Cosmic microwave background	0.2606
Thermal energy	0.4
Turbulent kinetic energy	0.2
Far-infrared from dust	0.3
Starlight	0.6
Magnetic energy	0.9
Cosmic rays	1.4

[a] *Data from Draine 2011, Table 1.5 and Table 12.1*

astronomers figure out the **multi-phase** nature of the ISM? That's a long enough story to require a separate section.

1.1 History of Interstellar Studies

In the sixteenth century, Thomas Digges, an early follower of Copernicus, discarded the concept of a celestial sphere to which the stars are attached. This led to the question of what lies between the stars that are scattered throughout space. In the year 1669, the natural philosopher Robert Boyle recorded an ongoing "Controversie betwixt some of the Modern Atomists and the Cartesians." The atomists believed, in Boyle's words, "that betwixt the Earth and the Stars, and betwixt these themselves, there are vast Tracts of Space that are empty." The Cartesians, by contrast, thought that there could not be a perfect vacuum. Instead, they believed "that the Intervals betwixt the Stars . . . are perfectly fill'd, but by a Matter far subtiler than our Air, which some call Celestial, and others Aether." Unfortunately, the subtle aether proposed by the Cartesians was too subtle to be detected.

The idea of visible interstellar material arose in the eighteenth century, with the study of nebulae. The word **nebula** (Latin for "cloud" or "fog") was applied to any extended luminous object in the night sky. William Herschel, with his large telescopes, was able to resolve some nebulae into stars. For decades, a debate continued over whether all nebulae could be resolved with high enough angular resolution. The situation became clearer in the 1860s, when William Huggins demonstrated that some nebulae have emission line spectra, characteristic of diffuse gas, rather than the absorption line spectra produced by populations of stars.

Figure 1.2 shows Huggins' spectrum of the Cat's Eye Nebula, a relatively bright planetary nebula at a distance $d \sim 1$ kpc from the Sun. Huggins saw three bright lines; the leftmost line (4861 Å) he correctly identified as the Balmer β line

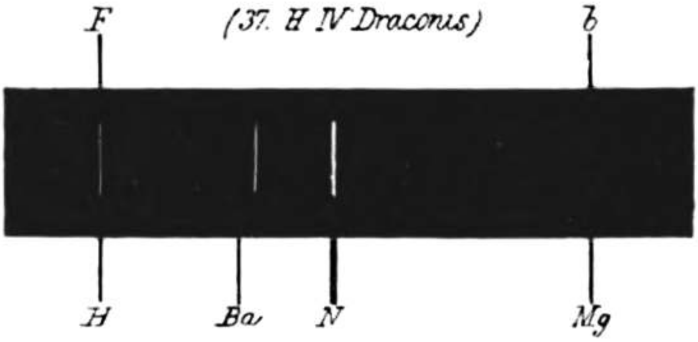

Figure 1.2 Emission line spectrum of the Cat's Eye Nebula, seen by William Huggins on August 29, 1864. This spectrum covers the blue-green portion of the visible range, from the Fraunhofer F line (H β, at 4861 Å) to Fraunhofer b (a blend of Mg and Fe lines at 5173 Å). [Huggins 1864]

of hydrogen, the rightmost line (5007 Å) he incorrectly identified as being due to nitrogen,[1] and the central line (4959 Å) he couldn't identify at all. Eventually, higher-resolution spectra revealed that the 5007 Å line wasn't due to nitrogen, and Huggins hypothesized that the 4959 Å and 5007 Å lines were emitted by a previously unknown element. Although Huggins proposed the name "nebulum" for this element, the variant "nebulium," put forward by the astronomy writer Agnes Clerke, proved to be more popular. It wasn't until 1927 that Ira Bowen discovered that the "nebulium" lines were actually forbidden lines from the ion O III.

There's one acknowledged complication in measuring the spectra of nebulae (and other celestial objects) from the Earth's surface. At visible wavelengths, air has a refractive index $n_r \approx 1.00028$ that is slightly greater than one. Thus, wavelengths measured by Huggins (and other earthly observers) are the "air wavelength" $\lambda_{\rm air}$ rather than the vacuum wavelength λ_{vac} measured in the absence of a refracting medium. The two wavelengths are related by $\lambda_{\rm air} = \lambda_{vac}/n_r$; at visible wavelengths, this means that $\lambda_{\rm air}$ is shorter than λ_{vac} by about one part in 3600. In this book, we adopt the common convention of using $\lambda_{\rm air}$ rather than λ_{vac} in the wavelength range from $\lambda_{\rm air} = 3000$ Å to $\lambda_{\rm air} = 1.1$ μm; this corresponds to the "optical window" at which the Earth's atmosphere is nearly transparent.[2]

Although many nebulae proved to consist of diffuse gas, which produces emission line spectra, there were a few surprises in store. For instance, in

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[1] In his laboratory, Huggins had noted a strong emission line in the spark spectrum of nitrogen, at a wavelength $\lambda \approx 5005$ Å. He initially thought this could be identical with the nebula's 5007 Å emission line.

[2] Because of this convention, when someone says, "The 5007 Å line of O III has wavelength $\lambda = 5008.24$ Å," it doesn't mean they are inept at rounding; it means they are adept at switching between air wavelength and vacuum wavelength.

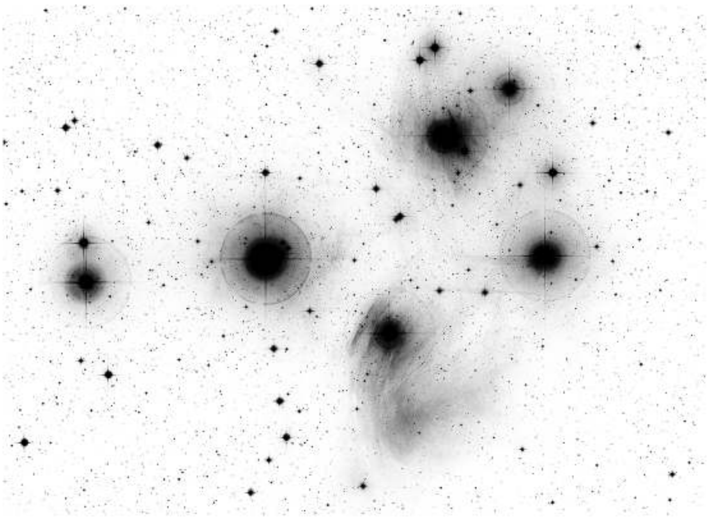

Figure 1.3 Negative image of the Pleiades star cluster ($d \approx 136$ pc) and its associated reflection nebula, seen at visible wavelengths. The image size is 90×65 arcmin, corresponding to 3.6×2.6 pc at the distance of the Pleiades. [POSS-II]

1912, when Vesto Slipher took the spectrum of the nebulosity surrounding the Pleiades (Figure 1.3), he expected to find an emission line spectrum. Instead, he found a continuous spectrum with absorption lines superposed. Slipher correctly conjectured that he was seeing light from the stars of the Pleiades reflected from “fragmentary and disintegrated matter,” or dust. The nebulosity surrounding the Pleiades is thus a **reflection nebula**.

The existence of dust had already been hinted at by the existence of **dark nebulae**, opaque objects such as Barnard 68 (Figure 1.4) that block the light of background stars. Dark nebulae were originally thought to be holes in the distribution of stars (“ein Loch im Himmel,” to use William Herschel’s words), but they were later recognized as being clouds of obscuring material. Dark nebulae are prominent in the brightest regions of the Milky Way.

At the beginning of the twentieth century, bright nebulae such as the Cat’s Eye Nebula were thought of as isolated clouds in otherwise empty, or nearly empty, space. An additional population of interstellar gas, invisible to the eye, was revealed by the work of Johannes Hartmann. In the year 1901, Hartmann began a study of Delta Orionis, a spectroscopic binary star at a distance $d \approx 380$ pc from the Sun. The two stars in the binary had relatively broad absorption lines that showed the expected time-varying Doppler shifts for orbiting stars. However, Hartmann also saw a narrow calcium absorption line that did not shift back and forth in wavelength. As Hartmann wrote in 1904 (the excited italics are in his original paper): *“The calcium line at λ3934 does not share in the period displacements of the lines caused by the orbital motion of the star.”*

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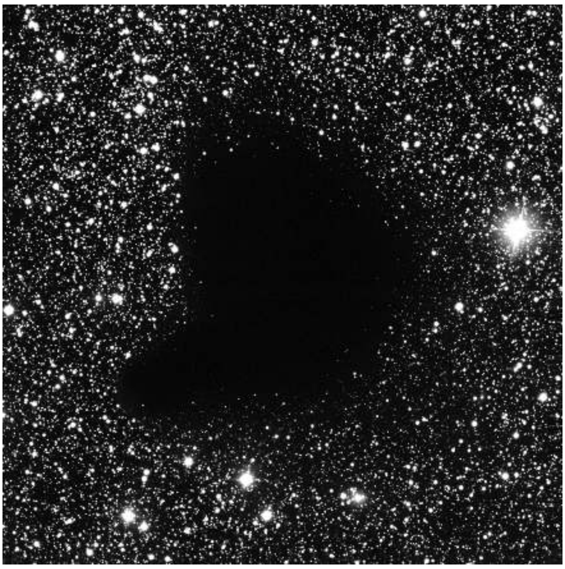

Figure 1.4 The dark nebula Barnard 68 ($d \sim 150\,\mathrm{pc}$) seen at visible and near-infrared wavelengths. The image size is 4.9×4.9 arcmin, corresponding to $\sim 0.21 \times 0.21\,\mathrm{pc}$ at the distance of Barnard 68. [FORS Team, VLT, ESO]

Hartmann concluded that the calcium absorption line was caused by a cloud of gas somewhere along the line of sight to Delta Orionis. Later, other astronomers found similar "stationary lines" along the line of sight to other bright stars. The lines were all narrow, and had strengths correlated with the distance to the background star: more distant stars showed stronger stationary lines because there is more interstellar gas along the line of sight. As higher-resolution spectrographs were used on the stationary lines, it was revealed that they had complex structures, consisting of many narrower lines with different radial velocities. This led to the realization that the ISM has a complex structure. It consists neither of smooth uniform gas nor of isolated ellipsoidal blobs drifting about in a near-vacuum.

In 1939, the astronomer Bengt Strömgren developed the idea that bright nebulae with strong emission line spectra are regions of photoionized gas, surrounding a hot star or other source of ionizing photons. The idealized **Strömgren sphere** will be discussed in Section 4.2, when we deal with the physics of ionized hydrogen. At least three types of bright ionized nebulae are recognized in the interstellar medium. First, **H II regions** are regions of interstellar gas heated and photoionized by embedded hot stars with effective surface temperature $T_{\mathrm{eff}} > 25\,000\,\mathrm{K}$.[3] The Orion Nebula (Figure 1.5) is an example of a nearby H II region.

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[3] In the usual OBAFGKM classification scheme for stars, running from hot O stars to cool M stars, stars with $T_{\mathrm{eff}} > 25\,000\,\mathrm{K}$ are of spectral type O or B.