Chapter 1
Introduction

1.1 What Is the Interstellar Medium?

The Interstellar Medium is the stuff between the stars. It is made up almost entirely of gas with a small smattering of tiny particles called dust grains. The ISM is readily apparent to the naked eye in the dark smudges in the Milky Way. With small telescopes or binoculars, fuzzy nebulae can be seen. First photographic plates and, nowadays, electronic imagers add up the light over long exposure times and reveal the colors of these features including the reddening of starlight, blue reflection nebulae, and a rainbow of emission lines. Vast clouds of atomic hydrogen were discovered with radio telescopes in the 1950s and then molecular clouds in the next two decades. The advent of space astronomy opened the Universe to exploration across the electromagnetic spectrum and the ISM showed its presence at every wavelength, including hot gas in X-rays, absorption lines in the ultraviolet, and warm dust around young stars in the infrared.

The different wavelengths reveal different components of the ISM. Figure 1.1 shows the Milky Way Galaxy at optical, infrared, and radio wavelengths to highlight the main components that we will discuss in this book. At top, in the optical ($\lambda \approx 0.5\ \mu m$) we mainly see starlight punctuated by dark clouds. By studying how the light is blocked, we learn about the interstellar dust in these clouds. In the next panel down, the near-infrared ($\lambda \approx 2\ \mu m$) images shows the stellar distribution more clearly, including the bulge near the Galactic Center. The fact that the dark clouds are now almost transparent tells us how big the dust grains are. Energy is conserved so if dust absorbs starlight, it must also radiate. The third panel down shows the emission from dust at far-infrared wavelengths ($\lambda \approx 350\ \mu m$). We discuss dust in Chapter 4. Now moving

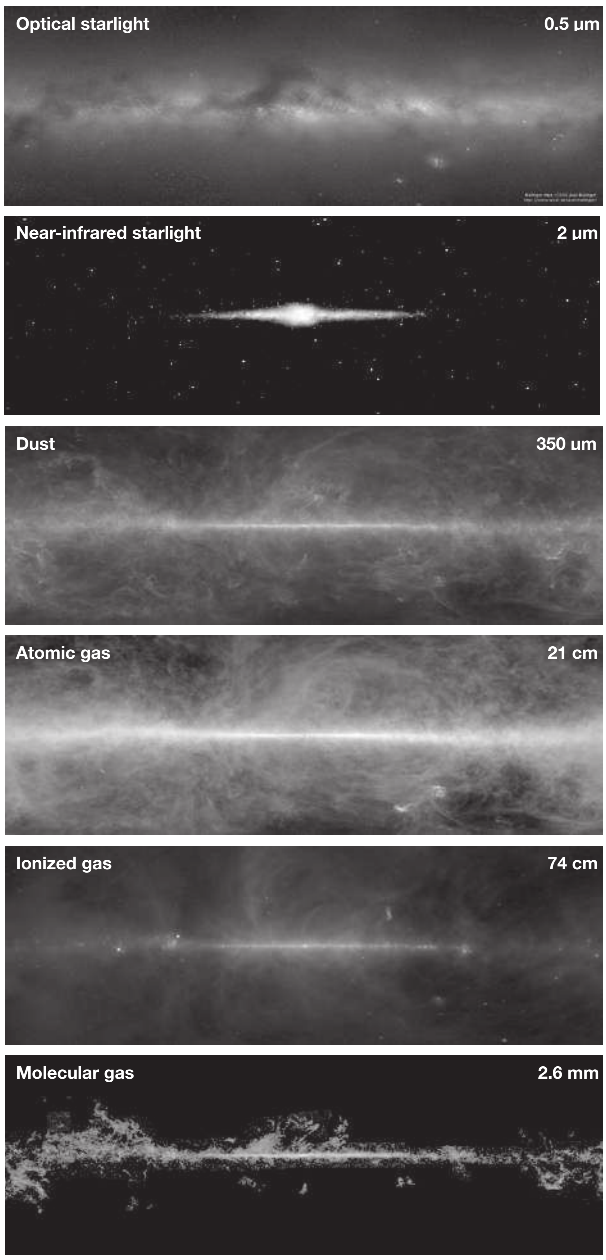

Fig. 1.1. The Galaxy at different wavelengths showing different components of the ISM. The horizontal axis is Galactic Longitude varying from -180° to $+180^\circ$ and the vertical axis is Galactic Latitude varying from -60° to $+60^\circ$.

to the gas, the fourth panel shows the emission from atomic hydrogen in the $\lambda = 21$ cm spectral line. There is a striking similarity to the dust emission, which shows that the gas and dust are well mixed in the ISM and, as we show in Chapter 5, the ratio between them is constant. The gas is concentrated along the Galactic plane but it also extends well above, indicating the ISM is a very dynamic place. These fluid motions are the subject of Chapter 8. The longest wavelength image, $\lambda = 74$ cm, in the fifth panel shows radiation from ionized gas. The emission is from accelerating charged particles in low-density plasma. The motions may be either relatively slow, such as the thermal motions in bubbles of warm gas around hot stars, but energetic phenomena such as supernovae can shock particles to relativistic speeds, producing strong emission as they gyrate around magnetic field lines. The way in which the intensity varies with wavelength distinguishes each case. We discuss ionized regions in Chapter 6. The relativistic particles, known as cosmic rays, permeate the ISM and play an important role in its heating and chemistry. Finally, the bottom panel shows the distribution of molecular gas in the Galaxy, as detected through the $\lambda = 2.6$ mm spectral line of carbon monoxide. The physics and chemistry of molecular clouds are discussed in Chapter 7. These regions are the coldest, densest parts of the ISM and the places where stars are born, the subject of Chapter 9. Having focused on the different phases of the ISM in each chapter, we return to a Galactic perspective and consider the ecology of the ISM in Chapter 10. All these components are of course found in other galaxies and some in the space between galaxies. Indeed, the two features in the HI map that stand out just right of center and below the plane are the Large and Small Magellanic Clouds, and a keen eye can spot the Andromeda galaxy on the left. The book concludes with an extragalactic perspective in Chapter 11.

The dust and gas, hot and cold, ionized, atomic, or molecular, are the subjects of this book. Most of the Universe is actually dark matter and energy and, in a sense, these are part of the ISM too. However, these components do not interact with baryonic matter or radiation and they are so broadly distributed that they have no significant net gravitational force on the scale of the objects that we consider here. Thus, in all respects, dark matter and energy have no effect on the processes described in this book. Apart from a perhaps self-serving remark that any astrophysical search for them almost certainly requires a thorough understanding of the radiation from the ISM, they are not discussed further.

1.2 The Vacuum of Space

By terrestrial standards, the ISM is an almost perfect vacuum. The typical distance between stars is about $2\,\mathrm{pc} = 6 \times 10^{16}\,\mathrm{m}$, about 100 million times greater than the radius of our Sun and 4000 times greater than the size of its heliosphere. The ISM fills the vast space in between but its total mass in the entire Galaxy is only $M \approx 7 \times 10^9\,M_\odot$. Approximating the volume as a cylinder with radius $R \approx 10^4\,\mathrm{pc}$, scale height $H \approx 250\,\mathrm{pc}$, this implies an average density $\rho = M/2\pi RH \approx 3 \times 10^{-21}\,\mathrm{kg\,m^{-3}}$. Hydrogen accounts for about 74% of the mass, helium for about 25%, and other elements make up the remaining 1%. The corresponding hydrogen number density is, therefore, $n_\mathrm{H} \approx 10^6\,\mathrm{m^{-3}}$. This is easier to remember as about one particle per cubic centimeter.[1]

In comparison, we can calculate the density of air from the ideal gas law using the pressure at sea level, $P = 10^5\,\mathrm{N\,m^{-2}}$ (1 bar), and temperature, $T \approx 300\,\mathrm{K}$, to get $n = P/kT \approx 2 \times 10^{25}\,\mathrm{m^{-3}}$, a full 19 orders of magnitude higher than the average density in the ISM. To help visualize just how enormous a difference this is, consider a cylinder between you and a wall in the room you are in, about 10 m away. Now imagine that cylinder stretched lengthwise, extending from the edge of the Solar System to the center of the Galaxy, 8.2 kpc away. Each cylinder would have the same number of atoms!

There is a small overlap between the highest vacuums we can achieve in laboratories with the densest regions that we discuss in this book, $n \sim 10^{12}\,\mathrm{m^{-3}}$, but in general the extremely low densities in space mean that particle collisions are relatively rare, which allows us to observe some physical processes that we don't see on Earth.

For particles with a cross-section σ, moving at speed v, simple geometric considerations illustrated in Figure 1.2 show that the timescale between collisions is $t_\mathrm{coll} = (n\sigma v)^{-1}$. The motions in the air are predominantly thermal with a characteristic speed $= (kT/m)^{1/2} = 300\,\mathrm{m\,s^{-1}}$ at room temperature. The most common particle is molecular nitrogen with $\sigma \simeq 4 \times 10^{-19}\,\mathrm{m^2}$, which gives $t_\mathrm{coll} \sim 4 \times 10^{-9}\,\mathrm{s}$. This is so short that if a collision excites an internal energy level of a particle, it will often de-excite through a second collision rather than through spontaneous emission of radiation. The distributions of kinetic and internal energies of the gas are therefore in collisional equilibrium. We will cover these concepts in more detail in the following chapter.

[1] Much of the astronomy literature still uses the cgs system though the recommended standard by the International Astronomical Union, and the approach I will take in this book, is to use SI units. The Appendix gives values for commonly used constants in both systems.

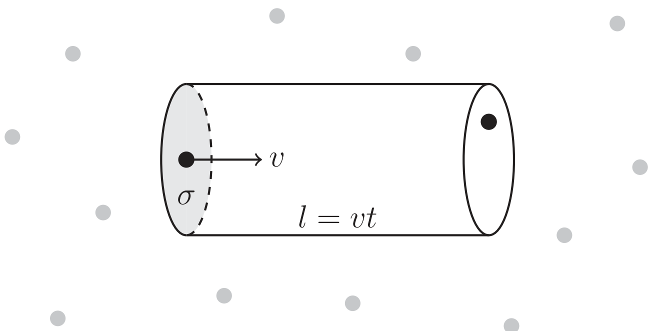

Fig. 1.2. A particle with cross-section σ moving at speed v sweeps out a volume σvt in time t. If it collides with one particle during this time, then the density of particles $n = 1/(\sigma vt)$. Therefore the collision timescale is $t_{\rm coll} = 1/(n\sigma v)$ and the mean free path $l = vt_{\rm coll} = 1/(n\sigma)$.

In the ISM, the typical particle is hydrogen with a smaller cross-section, $\sigma \simeq 6 \times 10^{-21}\,{\rm m}^{-2}$, slightly higher speed, $v \simeq 3000\,{\rm m\,s}^{-1}$, but much lower density, $n \simeq 10^6\,{\rm m}^{-3}$, implying $t_{\rm coll} \sim 2 \times 10^{10}\,{\rm s} \simeq 10^3$ years. This is so long that collisional excitation is often followed by radiative de-excitation. This affects the energy level distribution of gas particles and means that nebulae are lit with spectral lines that we don't see in terrestrial environments, and that temperatures are set not by conduction but by radiation.

Due to the low densities, the chemistry in molecular clouds is very different from the terrestrial setting. Simultaneous three-body collisions are almost non-existent and many important astrochemical reactions, including the formation of H_2, occur on dust grain surfaces.

The mean free path, $l = (n\sigma)^{-1}$, is of course much smaller in the relatively dense Earth's atmosphere, $\sim 0.1\,\mu{\rm m}$, compared to the ISM, $\sim 10^{14}$ m. However, the relevant comparison is to the size scales of the objects under consideration, for example a human, building, or mountain on Earth and an interstellar cloud in the ISM. In each case, gas particles will collide many times during their passage across an object of interest. We can therefore treat the ISM as an astrophysical fluid when studying how a gas cloud moves in response to, for example, external pressure forces or its own gravity.

1.3 Why Study the ISM?

The ISM is a unique physical and chemical laboratory on account of its ultra-low densities. It is also where stars are born and it is enriched by newly produced elements when stars die. It can outshine direct starlight in distant galaxies and it is where we can see the first atoms in the Universe.

However, the ISM is also messy, irregularly shaped, turbulent, magnetized, constantly shocked, and irradiated on scales from stellar to galactic. It is a complex subject and the details can sometimes overwhelm. Nevertheless, the ISM is also beautiful, both in the literal sense, as in images of colorful nebulae, and in the physics that helps us understand our origins and the way the Universe works.

The ISM, almost by definition, is everywhere and it affects all sorts of observations, sometimes as a nuisance through the absorption of starlight perhaps, but more often as an essential complement for understanding the Galaxy. In particular, it is the place where we can learn about the birth and death of stars, and the chemical enrichment and evolution of galaxies. Although we only provide a basic introduction to each of these subjects in this short book, the goal is for the reader to gain some physical insights into the big picture that underlies many areas of current research.

Chapter 2
Observations

Astronomy is an observationally driven science in the sense that theories generally try to explain what we see rather than the other way around. The HI 21 cm line is a notable exception, but most of the phenomena that we discuss in this book were first discovered at a telescope and only then understood through physical calculations.

The temperatures in the ISM range from less than ten to over a million kelvin. These, and other non-thermal processes, produce a range of radiation processes that affect light from radio to X-rays. As Figure 1.1 shows, different wavelengths show a different aspect of the ISM. Here we give a brief primer on observational nomenclature and techniques across the electromagnetic spectrum.

2.1 Radiation Diagnostics

Light can be detected over a broad range of wavelengths or frequencies, or in a narrow spectral feature, termed **continuum** and **line** respectively (Figure 2.1). In general, the former results from macroscopic dust particles or plasma where there is a broad range of energy states, whereas the latter is due to quantized jumps between the internal energy levels of atoms, ions, or molecules in diffuse gas.

The variation of continuum radiation over a wide (orders of magnitude) range of frequency is termed the **spectral energy distribution** and abbreviated to SED. Many of the emission or absorption lines in the ISM are Gaussian in shape and can be characterized by a central frequency, peak intensity, and width. However, line profiles can be more complex with, for example, multiple peaks or extended emission in the wings away from the line center.

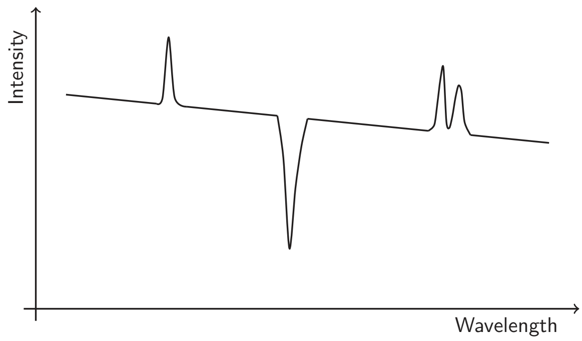

Fig. 2.1. A schematic plot of intensity versus wavelength showing continuum emission as a large-scale, slowly varying term and spectral line features, single peaked emission and absorption, and a double-peaked line profile at the right.

Light may also be polarized, and this is an important diagnostic in the ISM. Examples include scattering and emission by dust and effects induced by magnetic fields. We will discuss the relevant details as we encounter them in later chapters.

All images have a finite resolution, or intrinsic limit to distinguish two nearby objects. For a telescope with a (circular) aperture of diameter D, the **angular resolution** is

$$\theta = \frac{\lambda}{D} \text{ radians.} \tag{2.1}$$

Often this limit is quoted as 1.22θ, which is actually the scale at which the intensity is one-half its peak value. In practice, the scale at which two objects can be distinguished depends on their brightness profile and the quality (or signal-to-noise ratio) of the data. In almost all cases, the angle is small and the corresponding linear scale is $L = \theta d$ where d is the distance to the object.

Spectrometers are similarly limited in their ability to distinguish two peaks in line profiles, expressed in terms of wavelength as $\Delta\lambda$. The **spectral resolution** is defined to be

$$R = \frac{\lambda}{\Delta\lambda}, \tag{2.2}$$

and its value depends on the instrument design. For sources that are moving at speed v projected along our line of sight, the **Doppler effect** shifts the wavelength by a fractional amount $\Delta\lambda/\lambda = v/c$ where c is the speed of light. The spectral resolution therefore converts to a velocity resolution, c/R.

2.2 Telescopes across the Electromagnetic Spectrum

The Universe emits at all wavelengths but the Earth's atmosphere only lets a small range of these pass through to the ground. The ionized upper skin of the atmosphere reflects decameter and longer wavelength

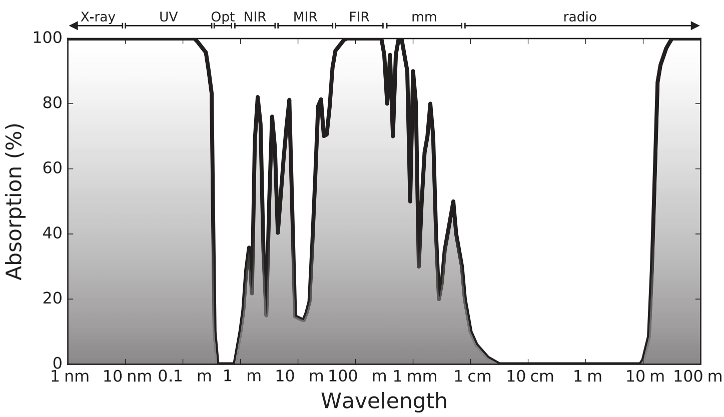

Fig. 2.2. Absorption of the atmosphere over 11 orders of magnitude in wavelength, from X-rays to the radio.

radio waves back into space. Lower down in the denser, molecular part of the atmosphere, ultraviolet radiation is scattered and absorbed predominantly by nitrogen and ozone respectively. Still lower, infrared radiation is absorbed mainly by water and carbon dioxide. Nevertheless, there are small regions where the atmosphere is transparent, the optical window from $\lambda \approx 0.4$ to $0.7\,\mu$m, where our eyes (not coincidentally) work, and the radio window from $\lambda \approx 1$ cm to 10 m, which was very important for early studies of the ISM and remains so today. In between these two windows, there are narrow regions where the atmosphere partially transmits light. Because the transmission is greater at high and dry sites where the water vapor is low, most observatories are built on mountaintops.

The absorption of the atmosphere across the electromagnetic spectrum from a good astronomical site is shown in Figure 2.2. To observe wavelengths where the absorption is high requires either high-altitude balloon-borne telescopes or space observatories. The detection techniques also vary greatly across such a wide wavelength range. These considerations affect our observational view of the ISM and are discussed for each wavelength regime below.

Radio

Radio observations are at the long-wavelength end of the electromagnetic spectrum, $\lambda > 300\,\mu$m ($\nu < 1$ THz). The upper end has a practical limit of about 10 m set by the ionosphere. As the energy of a photon at these long wavelengths is very small, $E = h\nu = hc/\lambda \simeq 10^{-26}$–$10^{-21}$ J where h is the Planck constant, the light behaves more as a wave than a particle. Detection is therefore made via antennas and amplification of the current induced by the wave. Radio waves can be collected and focused through parabolic dishes as with optical telescopes.

Despite the low energy of radio waves, the detected continuum radiation comes from energetic phenomena, generally ionized gas that has been heated either by hot stars or contains rapidly moving charged particles in a strong magnetic field (Chapter 6). The most important spectral line is from atomic hydrogen at 21 cm (Chapter 5).

Because the wavelengths are long, radio telescopes have low angular resolution. The largest steerable radio dish is the Green Bank Telescope and has a diameter of 100 m. At its shortest operating wavelength of 1 cm, the angular resolution $\theta \simeq 10^{-4}$ radians $\simeq 20''$. This is fine for looking at many regions of extended, low surface brightness features in the ISM but limits our ability to study smaller objects such as star-forming cores in the Galaxy or clouds in external galaxies. Pairs of telescopes can be linked together to measure the interference pattern of the sky, similarly to Young's double-slit experiment, with an effective resolution $\theta = \lambda/B$ where B is the distance, termed baseline, between the two telescopes. The baselines can be much greater than any single-dish telescope with correspondingly higher resolution (lower θ). Multiple telescopes can be linked together to form an **interferometric array**. Because the phase information of the astronomical signal is preserved in radio wave detection, this is easier to perform than in the infrared or optical where only the energy of the photons is measured. The Very Large Array consists of 27 antennas, each 25 m in diameter, that can be moved into configurations ranging up to a maximum baseline of 36 km, corresponding to arcsecond resolution at 21 cm. Very long baseline interferometry (VLBI) links telescopes across the Earth with baselines of several thousands of kilometers and a resolution less than a milli-arcsecond. VLBI observations of quasars, which are fixed point sources, sets the coordinate reference system for the sky and is so accurate that continental drift can be measured to a precision of millimeters per year.

At shorter wavelengths, $\lambda < 1$ cm, atmospheric absorption by water attenuates the astronomical signal but observations can be carried out at very dry sites. Millimeter-wavelength astronomy reveals the thermal emission from cool dust grains (Chapter 4) and rotational transitions of molecules (Chapter 7). To amplify these high-frequency ($\nu > 30$ GHz) waves, the incoming astronomical source is mixed with a synthesized source and down-converted to a few GHz where longer wavelength radio signal processing techniques can be used, a technique known as **heterodyne detection**. The Atacama Large Millimeter Array, located on a high plateau in Chile at an altitude of 5000 m, consists of 50 dishes of 12 m diameter that can be arranged in compact configurations with baselines $B < 160$ m, to very extended configurations with a maximum baseline of 16 km. At $\lambda = 1$ mm, the range of achievable resolution is