1

The galactic ecosystem

The Milky Way is largely empty. Stars are separated by some 2 pc in the solar neighborhood ($\rho_\star = 6 \times 10^{-2}\,\mathrm{pc}^{-3}$). If we take our Solar System as a measure, with a heliosphere radius of $\simeq$235 AU, stars and their associated planetary systems fill about 3×10^{-10} of the available space. This book deals with what is in between these stars: the interstellar medium (ISM). The ISM is filled with a tenuous hydrogen and helium gas and a sprinkling of heavier atoms. These elements can be neutral, ionized, or in molecular form and in the gas phase or in the solid state. This gas and dust is visibly present in a variety of distinct objects: HII regions, reflection nebulae, dark clouds, and supernova remnants. In a more general sense, the gas is organized in phases – cold molecular clouds, cool HI clouds, warm intercloud gas, and hot coronal gas – of which those objects are highly visible manifestations. This gas and dust is heated by stellar photons, originating from many stars (the so-called average interstellar radiation field), cosmic rays (energetic [$\sim$GeV] protons), and X-rays (emitted by local, galactic, and extragalactic hot gas). This gas and dust cools through a variety of line and continuum processes and the spectrum will depend on the local physical conditions. Surveys in different wavelength regions therefore probe different components of the ISM. This first chapter presents an inventory of the ISM with an emphasis on prominent objects in the ISM and the global structure of the ISM.

The interstellar medium plays a central role in the evolution of the Galaxy. It is the repository of the ashes of previous generations of stars enriched by the nucleosynthetic products of the fiery cauldrons in the stellar interiors. These are injected either with a bang, in a supernova explosion, or with a whimper, in the much slower moving winds of low-mass stars on the asymptotic giant branch. In this way, the abundances of heavy elements in the ISM slowly increase. This is part of the cycle of life for the stars of the Galaxy, because the ISM itself is the birthplace of future generations of stars. It is this constant recycling and its

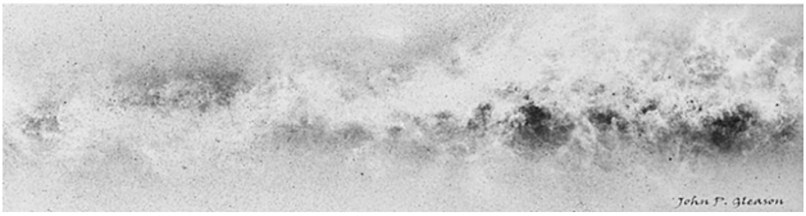

Figure 1.1 A panoramic image of a (southern) portion of the Milky Way's disk. The image has been inverted and dark corresponds to emission from ionized gas and reflection nebulae. The light band stretching irregularly across the whole image is due to absorption by dust clouds. Image courtesy of J. P. Gleason.

associated enrichment that drives the evolution of the Galaxy, both physically and in its emission characteristics.

1.1 Interstellar objects

1.1.1 HII regions

Ionized gas nebulae feature prominently in the Milky Way as bright visible nebulous objects. The Great Nebula in Orion (M42; Fig. 1.2) and the Lagoon Nebula (M8) are well-known examples. HII regions span a range in brightness, however, and fainter examples are the California Nebula and IC 434 (Fig. 1.3). The gas in these regions is ionized and has a temperature of about 10^4 K. Densities range from 10^3–10^4 cm^{-3} for compact ($\sim$0.5 pc) HII regions such as the Orion Nebula to $\sim$10 cm^{-3} for more diffuse and extended nebulae such as the North America Nebula ($\sim$10 pc). The optical spectra of these regions are dominated by H and He recombination lines and collisionally excited, optical (forbidden) line emission from trace ions such as [OII], [OIII], and [NII]. HII regions are also strong sources of thermal radio emission (free–free) from the ionized gas and of infrared emission due to warm dust. HII regions are formed by young massive stars with spectral type earlier than about B1 ($T_{\rm eff} > 25\,000$ K), which emit copious amounts of photons beyond the Lyman limit ($h\nu > 13.6$ eV) and ionize and heat their surrounding, nascent molecular clouds. They are, therefore, signposts of sites of massive star formation in the Galaxy.

1.1.2 Reflection nebulae

Reflection nebulae are bluish nebulae that reflect the light of a nearby bright star. NGC 2023 in the Orion constellation (see Fig. 1.3) and the striated nebulosity associated with the Pleiades are familiar cases. In this case, the observed light

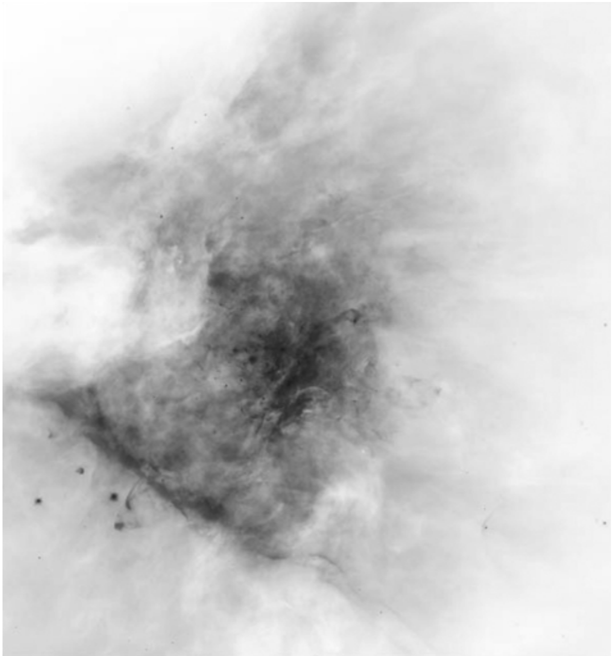

Figure 1.2 A black and white representation of the Orion Nebula as observed by the Hubble Space Telescope in [OIII], Hα, and [NII]. Light and dark have been inverted. The gas is ionized by the Trapezium cluster, in particular θ^1 C Ori, in the center of the image. The bright bar in the south-west is an ionization front eating its way into the surrounding neutral material in the photodissociation region known as the Orion Bar. The dark bay (light in this image), a cloud of foreground obscuring material, is also evident to the east. This image gives a clear view of the complex topography created by the interaction of a newly formed massive star with its surrounding natal cloud. Image courtesy of R. O'Dell.

is not due to hot gas but rather reflected starlight. There is no radio emission but there is infrared emission from warm dust, although this is less luminous than for HII regions. For the compact reflection nebulae, densities are typically a little smaller ($\simeq 10^3\,\text{cm}^{-3}$) than for compact HII regions. Reflection nebulae are illuminated by stars with spectral types later than about B1. Regions around hotter stars also show (faint) reflected light emission but the spectrum is then dominated by the emission from the ionized gas. For the earlier stellar types, the surrounding nebulosity may be the material from which the star was formed (e.g., NGC 2023; NGC 7023). Often, however, the nebulosity is due to a chance encounter between the star and a cloud (e.g., the Pleiades). Reflection nebulae can also be associated with the ejecta of a late-type star (e.g., IC 2220; the Red Rectangle).

Figure 1.3 Part of the Orion molecular cloud containing the Horse Head Nebula. The diffuse glow behind the horse head is IC 434 ionized by the bright star, σ Ori. The horse head is a protrusion of the molecular cloud obvious in the lower part of this image. The nebula to the south-east of the horse head is the reflection nebula, NGC 2023. Image courtesy of the Canadian-France-Hawaii telescope, J.-C. Cuillandre, Coelem.

1.1.3 Dark nebulae

A striking aspect of the all-sky optical view of the Milky Way is the presence of many dark regions in which few stars are seen (cf. Fig. 1.1). The direction towards the center of the Galaxy is rampant with such dark clouds, which actually seem to divide the galactic plane in two. The Coalsack near the Southern Cross is a particularly nice example of a roundish dark cloud. Dark clouds are readily apparent when backlighted. The Horse Head Nebula (see Fig. 1.3) silhouetted against the reddish glow of the HII region, IC 434, and the dark bay in the Orion HII region (see Fig. 1.2) are two famous examples. Individual dark clouds come in a range of sizes from tens-of-parsecs large to the tiny ($\sim 10^{-2}$ pc) Bok globules associated with HII regions such as the Orion Nebula. Likewise, some dark clouds are completely black ($A_v > 10$ magnitudes) while others are hardly discernible. While dark clouds are outlined by the absence of stars, they do show faint optical reflected light. Also, they become bright at mid- and far-infrared wavelengths. Some really dense clouds are opaque even at mid-IR wavelengths and appear as infrared dark clouds (IRDC) in absorption against background galactic mid-IR emission.

1.1.4 Photodissociation regions

While HII regions and reflection nebulae dominate the Galaxy at visible wavelengths, in the infrared, photodissociation regions dominate the sky. Originally, the name photodissociation regions (PDRs; sometimes also called photodominated regions with fortunately the same abbreviation) was given to the atomic–molecular zones that separate ionized and molecular gas near bright luminous O and B stars (e.g., surrounding HII regions and reflection nebulae) and the Orion Bar (Fig. 1.2) and NGC 2023 (Fig. 1.3) are prime examples of classical PDRs. In these regions, penetrating far-ultraviolet (FUV) photons (with energies between 6 and 13.6 eV) dissociate and ionize molecular species. Most of the FUV photons are absorbed by the dust, but a small fraction heat the gas through the photoelectric effect to a few hundred degrees. Photodissociation regions are thus bright in IR dust continuum and atomic fine-structure cooling lines as well as molecular lines. In essence, of course, everywhere where FUV photons strike a cloud, a PDR will ensue. Indeed, the term PDRs has now expanded to include all regions of the ISM where FUV photons dominate the physical and chemical processes. As such, PDRs include the neutral atomic gas of the ISM as well as much of the gas in molecular clouds (except, e.g., for dense starless cores).

1.1.5 Supernova remnants

Supernova remnants (SNRs) are formed when the material ejected in the explosion that terminates the life of some stars shocks surrounding ISM material and an SNR's spectrum is that of a high velocity shock. About 100 supernova remnants are visible in our Galaxy; they are generally characterized by long, delicate filaments radiating in-line radiation (Fig. 1.4). Supernova remnants are prominent sources of radio emission due to relativistic electrons spiraling around a magnetic field (synchroton emission) and some 200 have been identified at radio wavelengths. Supernova remnants also stick out at X-ray wavelengths because of emission by hot ($\simeq 10^6$ K) gas. Not all SNRs are wispy. The Crab Nebula is an example of a compact SNR.

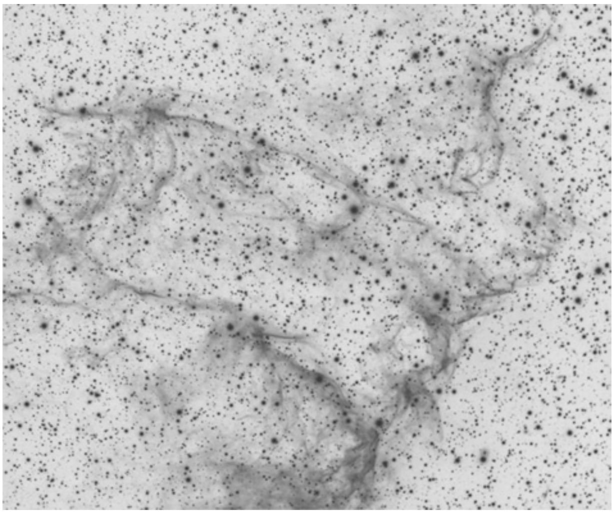

Figure 1.4 A small portion of the Cygnus Loop, the remnant of a supernova that exploded about 10 000 years ago. The image has been inverted to bring out the delicate structure of the nebulosity. The emission is due to a shock wave and is about 3 pc in size. Image courtesy of L. K. Tan, StarryScapes.

1.2 Components of the interstellar medium

The gas in the ISM is organized in a variety of phases. The physical properties of these phases are summarized in Table 1.1.

1.2.1 Neutral atomic gas

The 21 cm line of atomic hydrogen traces the neutral gas of the ISM. This neutral gas can also be observed in optical and UV absorption lines of various elements towards bright background stars. The neutral medium is organized in cold ($\simeq 100$ K) diffuse HI clouds (cold neutral medium, CNM) and warm (≈ 8000 K) intercloud gas (warm neutral medium, WNM). A standard HI cloud (often called a Spitzer-type cloud) has a typical density of $50\ \mathrm{cm}^{-3}$ and a size of 10 pc. The density of the WNM is much less ($\simeq 0.5\ \mathrm{cm}^{-3}$). Between 4 and 8 kpc from the galactic center, 80% of the HI mass in the plane of the Galaxy is in diffuse clouds in a layer with a (Gaussian) scale height of about 100 pc. At higher latitudes, however, much of the HI mass is in the intercloud medium with a larger scale height of 220 pc but with an exponential tail extending well into the lower halo. These two neutral phases have, on average, similar surface densities. Because the Sun is located in the local bubble, the local, total WNM column density towards the North Galactic Pole is about 2.5 times that of the CNM. In the outer Galaxy, the HI scale height rapidly increases.

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Table 1.1 *Characteristics of the phases of the interstellar medium*

Phase	n_0^a (cm^{-3})	T^b (K)	ϕ_v^c (%)	M^d (10^9 $M_\odot$)	$< n_0 >^e$ (cm^{-3})	H^f (pc)	Σ^g ($M_\odot$pc^{-2})
Hot intercloud	0.003	10^6	~50.0	—	0.0015	3000	0.3
Warm neutral medium	0.5	8000	30.0	2.8	0.1^h	220^h	1.5
					0.06^h	400^h	1.4
Warm ionized medium	0.1	8000	25.0	1.0	0.025^i	900^i	1.1
Cold neutral medium^j	50.0	80	1.0	2.2	0.4	94	2.3
Molecular clouds	>200.0	10	0.05	1.3	0.12	75	1.0
HII regions	1–10^5	10^4	—	0.05	0.015^k	70^k	0.05

[a] Typical gas density for each phase.
[b] Typical gas temperature for each phase.
[c] Volume filling factor (very uncertain and controversial!) of each phase.
[d] Total mass.
[e] Average mid-plane density.
[f] Gaussian scale height, $\sim \exp[-(z/H)^2/2]$, unless otherwise indicated.
[g] Surface density in the solar neighborhood.
[h] Best represented by a Gaussian and an exponential.
[i] WIM represented by an exponential.
[j] Diffuse clouds.
[k] HII regions represented by an exponential.

1.2.2 Ionized gas

Diffuse ionized gas in the ISM can be traced through dispersion of pulsar signals, through optical and UV ionic absorption lines against background sources, and through emission in the Hα recombination line (see Fig. 1.5). The first two can only be done in a limited number of selected sight-lines. The faintness and large extent of the galactic Hα hamper the last probe. While most of the Hα luminosity of the Milky Way is emitted by distinct HII regions, almost all of the mass of ionized gas (10^9 M$_\odot$) resides in a diffuse component. This warm ionized medium (WIM) has a low density ($\simeq$0.1 cm^{-3}), a temperature of $\approx$8000 K, a volume filling factor of $\simeq$0.25, and a scale height of $\simeq$1 kpc. The weakness of the [OI] λ6300 line (in a few selected directions) implies that the gas is nearly fully ionized. The source of ionization is not entirely clear. Energetically, ionizing photons from O stars are the most likely candidates but these photons have to "escape" from the associated HII regions and travel over large distances (hundreds of parsecs)

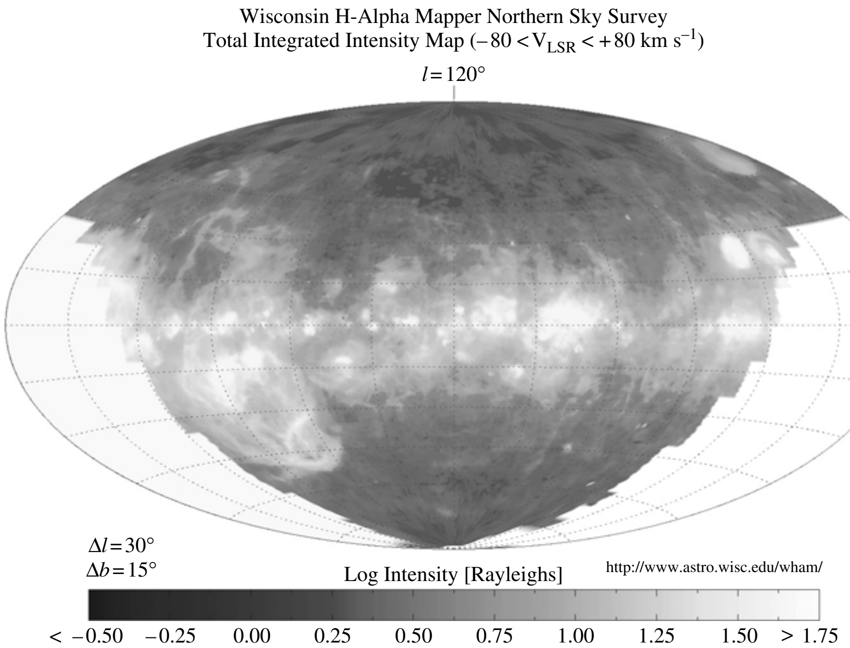

Figure 1.5 The integrated galactic (ℓ versus b) Hα emission obtained by the WHAM survey. This emission from ionized gas, about a million times fainter than the Orion Nebula, traces the warm ionized medium. Note the large filament (40°) sticking up out of the galactic plane. Image courtesy of R. Reynolds.

without being absorbed by omnipresent neutral hydrogen. Finally, the WIM shows a complex spatial structure including thin filaments sticking ~ 1 kpc out of the plane of the Galaxy, further compounding the ionization problem.

1.2.3 Molecular gas

The CO J $= 1 - 0$ transition at 2.6 mm is commonly used as a tracer of molecular gas in the Galaxy (Fig. 1.6). Surveys in this line have shown that much of the molecular gas in the Milky Way is localized in discrete giant molecular clouds with typical sizes of 40 pc, masses of 4×10^5 M$_\odot$, densities of $\simeq 200$ cm^{-3}, and temperatures of 10 K. However, it should be understood that molecular clouds show a large range in each of these properties. Molecular clouds are characterized by high turbulent pressures as indicated by the large linewidths of emission lines. Molecular clouds are self-gravitating rather than in pressure equilibrium with other phases in the ISM. While they are stable over time scales of $\simeq 3 \times 10^7$ years, presumably because of a balance of magnetic and turbulent pressure and gravity, molecular clouds are the sites of active star formation. Observations of molecular

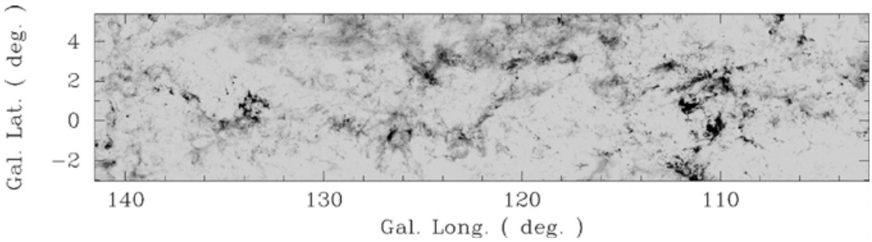

Figure 1.6 The emission of CO in the outer Galaxy obtained by the FCRAO survey. Much of the emission is local, stemming from molecular clouds between 0.5 and 1 kpc. In addition, giant molecular clouds associated with the NGC 7538-Sharpless 156-Sharpless 152 region ($\ell = 110°$) and the W3-W4-W5 region ($\ell = 135°$) are also present. The image has been inverted and dark corresponds to emission. Image courtesy of Chris Brunt (FCRAO).

clouds in the rotational transitions of a variety of species allow a detailed study of their physical and chemical properties. These studies show that molecular clouds have spatial structure on all scales. In particular, molecular clouds contain cores with sizes of $\simeq 1$ pc, densities in excess of 10^4 cm^{-3}, and masses in the range 10–10^3 $M_\odot$ in which star formation is localized. While CO is commonly used to trace interstellar molecular gas, H_2 is thought to be the dominant molecular species, with a H_2/CO ratio of 10^4–10^5. In addition, some 200 different molecular species have been detected – mainly through their rotational transitions in the submillimeter wavelength regions – in the shielded environments of molecular clouds. In general, these species are relatively simple, often unsaturated, radicals, or ions. Acetylenic carbon chains and their derivatives figure prominently on the list of detected molecules. However, this may merely reflect observational bias, since such species possess large dipole moments and relatively small partition functions, both of which make them readily detectable at microwave wavelengths.

1.2.4 Coronal gas

Hot ($\sim 10^5$–10^6 K) gas can be traced through UV absorption lines of highly ionized species (e.g., CIV, SVI, NV, OVI) seen against bright background sources. Such hot plasmas also emit continuum (bremsstrahlung, radiative recombination, two photon) and line (collisionally excited and recombination) radiation in the extreme ultraviolet and X-ray wavelength regions. These observations have revealed the existence of a pervasive hot (3–10×10^5 K) and tenuous ($\simeq 10^{-3}$ cm^{-3}) phase (the hot intercloud medium, HIM) of the ISM. The observations indicate a range of temperatures where the higher ionization stages probe hotter gas. The hot gas fills most of the volume of the halo (scale height $\simeq 3$ kpc) but the volume filling factor in the disk is more controversial. This gas is heated and ionized through shocks driven by stellar winds from early type stars and by supernova explosions. Much of the hot, high-latitude gas may have been vented by superbubbles created by the concerted efforts of whole OB associations into the halo in the form of a galactic fountain. This hot gas cools down, "condenses" into clouds, and rains down again on the disk. In the disk, the distribution of the hot gas is quite irregular. The Sun itself is located in a hot bubble with a size of approximately 100 pc.

1.2.5 Interstellar dust

The presence of dust in the interstellar medium manifests itself in various ways. Through their absorption and scattering, small dust grains give rise to a general reddening and extinction of the light from distant stars (Fig. 1.1). Moreover, polarization of starlight is caused by elongated large dust grains aligned in the galactic magnetic field (dichroic absorption). Furthermore, near bright stars, scattering of starlight by dust produces a reflection nebula. Finally, the interstellar medium is bright in the infrared because of continuum emission by cold dust grains. Analysis of the wavelength dependence of interstellar reddening implies a size distribution, $n(a) \sim a^{-3.5}$, which ranges from $\simeq$3000 Å all the way to the molecular domain ($\sim$5 Å). The number density of grains with sizes $\sim$1000 Å is $\simeq 10^{-13}$ per H atom. Most of the mass of interstellar dust is thus in the larger grains but the surface area is in the smallest grains. Abundance studies in the ISM show that many of the refractory elements (e.g., C, Si, Mg, Fe, Al, Ti, Ca) are locked up in dust; i.e., dust contains about 1% by mass of the gas.

Large ($\gtrsim$100 Å) interstellar dust grains are in radiative equilibrium with the interstellar radiation field at temperatures of $\simeq$15 K and the absorbed stellar photons are reradiated as infrared and submillimeter continuum emission. Near bright stars, the dust temperature is higher; typically some 75 K for a compact HII region. Emission by interstellar dust dominates these wavelength regions. Rotating interstellar dust grains also give rise to emission at radio wavelengths. Very small ($\lesssim$100 Å) dust grains undergo fluctuations in their temperature upon the absorption of a single UV photon and emit at mid-IR (25–60 μm) wavelengths.

1.2.6 Large interstellar molecules

Besides dust grains, the interstellar medium also contains a population of large molecules. These molecules are particularly "visible" at mid-IR wavelengths. The IR spectrum of most objects – HII regions, reflection nebulae, surfaces of dark clouds, diffuse interstellar clouds and cirrus clouds, galactic nuclei, the interstellar