Chapter One

Introduction

The subject of this book is the most beautiful component of galaxies – the gas and dust between the stars, or **interstellar medium**. The interstellar medium, or **ISM**, is, arguably, also the most important component of galaxies, for it is the ISM that is responsible for forming the stars that are the dominant sources of energy. While it now appears that the mass of most galaxies is primarily in the form of dark matter particles that are collisionless, or nearly so, it is the baryons (accounting for perhaps $\sim$10% of the total mass) that determine the visible appearance of galaxies, and that are responsible for nearly all of the energy emitted by galaxies, derived from nuclear fusion in stars and the release of gravitational energy in accretion disks around black holes. At early times, the baryonic mass in galaxies was primarily in the gas of the interstellar medium. As galaxies evolve, the interstellar medium is gradually converted to stars, and some part of the interstellar gas may be ejected from the galaxy in the form of galactic winds, or in some cases stripped from the galaxy by the intergalactic medium. Infalling gas from the intergalactic medium may *add* to the mass of the ISM. At the present epoch, the galaxy in which we reside – the Milky Way – has most of its baryons incorporated into stars or stellar remnants. But even today, perhaps 10% of the baryons in the Milky Way are to be found in the ISM. The "mass flow" of the baryons in the Milky Way is illustrated schematically in Figure 1.1.

Our objective is to understand the workings of the ISM – how it is organized and distributed in the Milky Way and other galaxies, what are the conditions (temperature, density, ionization, ...) in different parts of it, and how it dynamically evolves. Eventually, we would like to understand star formation, the process responsible for the very existence of galaxies as luminous objects.

The subject of this book, then, is *everything* in the galaxy that is between the stars – this includes the following constituents:

- **Interstellar gas**: Ions, atoms, and molecules in the gas phase, with velocity distributions that are very nearly thermal.

- **Interstellar dust**: Small solid particles, mainly less than $\sim 1\,\mu\mathrm{m}$ in size, mixed with the interstellar gas.

- **Cosmic rays**: Ions and electrons with kinetic energies far greater than thermal, often extremely relativistic – energies as high as $10^{21}\,\mathrm{eV}$ have been detected.

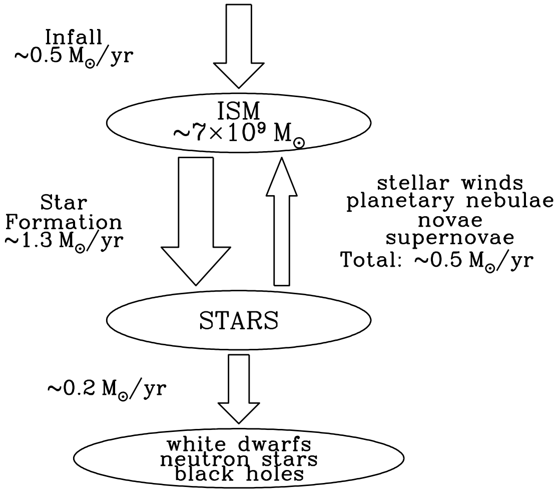

Figure 1.1 Flow of baryons in the Milky Way. See Table 1.2 for the ISM mass budget, and §42.4 for the value of the star formation rate in the Milky Way.

- **Electromagnetic radiation**: Photons from many sources, including the cosmic microwave background (CMB); stellar photospheres (i.e., starlight); radiation emitted by interstellar ions, atoms, and molecules; thermal emission from interstellar grains that have been heated by starlight; free–free emission ("bremsstrahlung") from interstellar plasma; synchrotron radiation from relativistic electrons; and gamma rays emitted in nuclear transitions and π^0 decays.

- **Interstellar magnetic field**: The magnetic field resulting from electric currents in the interstellar medium; it guides the cosmic rays, and in some parts of the ISM, the magnetic field is strong enough to be dynamically important.

- **The gravitational field**: This is due to all of the matter in the galaxy – ISM, stars, stellar remnants, and dark matter – but in some regions, the contribution of the ISM to the gravitational potential leads to self-gravitating clouds.

- **The dark matter particles**: To the (currently unknown) extent that these interact nongravitationally with baryons, electrons, or magnetic fields, or either decay or annihilate into particles that interact with baryons, electrons, or magnetic fields, these are properly studied as part of the interstellar medium. The interactions are sufficiently weak that thus far they remain speculative.

There is of course no well-defined boundary to a galaxy, and all of the preceding constituents are inevitably present between galaxies – in the **intergalactic medium** (IGM) – and subject there to the same physical processes that act within the interstellar medium. The purview of this book, therefore, naturally extends to include the intergalactic medium.

Table 1.1 Units

pc	$= 3.086 \times 10^{18}$ cm	parsec
$M_\odot$	$= 1.989 \times 10^{33}$ g	solar mass
$L_\odot$	$= 3.826 \times 10^{33}\,\mathrm{erg\,s^{-1}}$	solar luminosity
yr	$= 3.156 \times 10^{7}$ s	sidereal year
Myr	$\equiv 10^{6}$ yr	megayear
AU	$= 1.496 \times 10^{13}$ cm	astronomical unit
Å	$\equiv 10^{-8}$ cm	Ångstrom
nm	$\equiv 10$ Å $\equiv 10^{-7}$ cm	nanometer
μm	$\equiv 10^{-4}$ cm	micron
$\mathrm{km\,s^{-1}}$	$\equiv 10^{5}\,\mathrm{cm\,s^{-1}}$	km per sec
Jy	$\equiv 10^{-23}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$	jansky
R	$\equiv (10^{6}/4\pi)\mathrm{photons\ cm^{-2}\,s^{-1}\,sr^{-1}}$	rayleigh
D	$\equiv 10^{-18}\mathrm{esu\ cm}$	debye
eV	$= 1.602 \times 10^{-12}$ erg	electron-volt
G	$= 10^{-4}$ tesla $= 10^{-4}\,\mathrm{weber\,m^{-2}}$	gauss

The primary aim of this book is to provide the reader with an exposition of the physics that determines the conditions in, and evolution of, the interstellar medium and the intergalactic medium. We will also emphasize the ways that observational data (e.g., strengths of emission lines or absorption lines) can be used to determine the physical properties of the regions where the emission or absorption is occuring.

We will employ the units of measurement that are currently used routinely by researchers in this field – for the most part, we use cgs units (including for electromagnetism), supplemented by standard astronomical units such as the parsec (pc), solar mass ($M_\odot$), and solar luminosity ($L_\odot$); see Table 1.1.

Historically, astronomers have reported optical wavelengths in Ångstroms (Å). In recent years, much of the physics literature has shifted to nanometers (nm), and consideration was given to doing so here. After weighing pros and cons, I decided to stick with Ångstroms; in practical work, it is necessary to specify optical wavelengths to (at least) four digits to avoid confusion, and it seems easier to remember them without a decimal point. And, after all, conversion from Å to nm is simply division by 10, a rather minor concern in a field that measures distance in pc, brightnesses in magnitudes, and angles in degrees, arcminutes, and arcseconds. So this book will use Ångstroms for wavelengths shorter than 1 μm.

I am, however, departing from established tradition by using wavelengths in vacuo for all transitions. This means that the wavelengths of familiar optical lines are now all shifted by $\sim$1 Å – e.g., the famous [O III] doublet is now $4960, 5008$, rather than the wavelengths in air ($4959, 5007$) that have been entrenched in usage for the past century. This will cause some pain for those who have burned the air wavelengths into their memories, but it is time to abandon this anachronism from days when spectroscopy was done in air at (near) standard temperature and pressure.

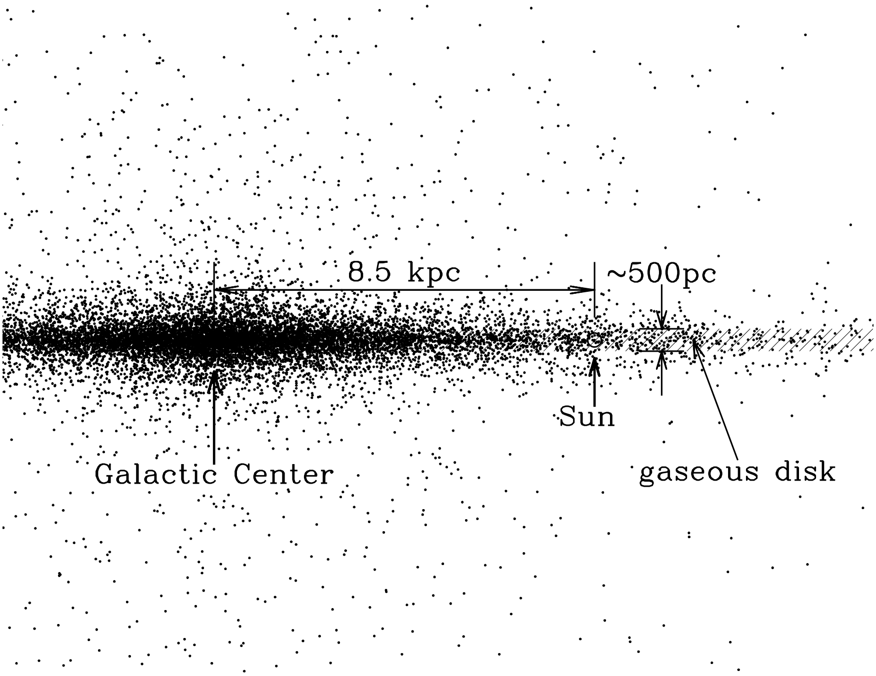

Figure 1.2 Structure of the Milky Way, viewed edge-on. The dots represent a sampling of stars; the volume containing most of the interstellar gas and dust is shaded. Compare with the infrared image of the stars in Plate 1, the dust in Plate 2, and various gas components in Plates 3–5.

1.1 Organization of the ISM: Characteristic Phases

In a spiral galaxy like the Milky Way, most of the dust and gas is to be found within a relatively thin gaseous disk, with a thickness of a few hundred pc (see the diagram in Fig. 1.2 and the images in Plates 1–5), and it is within this disk that nearly all of the star formation takes place. While the ISM extends above and below this disk, much of our attention will concern the behavior of the interstellar matter within a few hundred pc of the disk midplane.

The Sun is located about 8.5 kpc from the center of the Milky Way; as it happens, the Sun is at this time very close to the disk midplane. The total mass of the Milky Way within 15 kpc of the center is approximately $10^{11} M_\odot$; according to current estimates, this includes $\sim 5 \times 10^{10} M_\odot$ of stars, $\sim 5 \times 10^{10} M_\odot$ of dark matter, and $\sim 7 \times 10^9 M_\odot$ of interstellar gas, mostly hydrogen and helium (see Table 1.2). About 60% of the interstellar hydrogen is in the form of H atoms, ~20% is in the form of H_2 molecules, and ~20% is ionized.

The gaseous disk is approximately symmetric about the midplane, but does not have a sharp boundary – it is like an atmosphere. We can define the half-thickness

Table 1.2 Mass of H II, H I, and H_2 in the Milky Way ($R < 20\,\mathrm{kpc}$)

Phase	$M(10^9\,M_\odot)$	fraction	Note
Total H II (not including He)	1.12	23%	see Chapter 11
Total H I (not including He)	2.9	60%	see Chapter 29
Total H_2 (not including He)	0.84	17%	see Chapter 32
Total H II, H I and H_2 (not including He)	4.9		
Total gas (including He)	6.7		

$z_{1/2}$ of the disk to be the distance z above (or below) the plane where the density has dropped to 50% of the midplane value. Observations of radio emission from atomic hydrogen and from the CO molecule indicate that the half-thickness $z_{1/2} \approx 250\,\mathrm{pc}$ in the neighborhood of the Sun. The thickness $2z_{1/2} \approx 500\,\mathrm{pc}$ of the disk is only ~6% of the ~8.5 kpc distance from the Sun to the Galactic center – it is a *thin* disk. The thinness of the distribution of dust and gas is evident from the $100\,\mu\mathrm{m}$ image showing thermal emission from dust in Plate 2, and the H I 21-cm line image in Plate 3.

The baryons in the interstellar medium of the Milky Way are found with a wide range of temperatures and densities; because the interstellar medium is dynamic, all densities and temperatures within these ranges can be found somewhere in the Milky Way. However, it is observed that most of the baryons have temperatures falling close to various characteristic states, or "phases." For purposes of discussion, it is convenient to name these phases. Here we identify seven distinct phases that, between them, account for most of the mass and most of the volume of the interstellar medium. These phases (summarized in Table 1.3) consist of the following:

- **Coronal gas**: Gas that has been shock-heated to temperatures $T \gtrsim 10^{5.5}\,\mathrm{K}$ by blastwaves racing outward from supernova explosions. The gas is collisionally ionized, with ions such as O VI ($\equiv O^{5+}$) present. Most of the coronal gas has low density, filling an appreciable fraction – approximately half – of the volume of the galactic disk. The coronal gas regions may have characteristic dimensions of $\sim 20\,\mathrm{pc}$, and may be connected to other coronal gas volumes. The coronal gas cools on ~Myr time scales. Much of the volume above and below the disk is thought to be pervaded by coronal gas.[1] It is often referred to as the "hot ionized medium," or **HIM**.

- **H II gas**: Gas where the hydrogen has been photoionized by ultraviolet photons from hot stars. Most of this photoionized gas is maintained by radiation from recently formed hot massive O-type stars – the photoionized gas may be dense material from a nearby cloud (in which case the ionized gas is called an **H II region**) or lower density "intercloud" medium (referred to as **diffuse H II**).

[1] This gas is termed "coronal" because its temperature and ionization state is similar to the corona of the Sun.

Table 1.3 Phases of Interstellar Gas

Phase	T(K)	$n_{\rm H}$(cm^{-3})	Comments
Coronal gas (HIM) $f_V \approx 0.5?$ $\langle n_{\rm H}\rangle f_V \approx 0.002\,{\rm cm}^{-3}$ ($f_V \equiv$ volume filling factor)	$\gtrsim 10^{5.5}$	~ 0.004	Shock-heated Collisionally ionized Either expanding or in pressure equilibrium Cooling by: ◇ Adiabatic expansion ◇ X ray emission Observed by: • UV and x ray emission • Radio synchrotron emission
H II gas $f_V \approx 0.1$ $\langle n_{\rm H}\rangle f_V \approx 0.02\,{\rm cm}^{-3}$	10^4	$0.3 - 10^4$	Heating by photoelectrons from H, He Photoionized Either expanding or in pressure equilibrium Cooling by: ◇ Optical line emission ◇ Free–free emission ◇ Fine-structure line emission Observed by: • Optical line emission • Thermal radio continuum
Warm H I (WNM) $f_V \approx 0.4$ $n_{\rm H} f_V \approx 0.2\,{\rm cm}^{-3}$	~5000	0.6	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Pressure equilibrium Cooling by: ◇ Optical line emission ◇ Fine structure line emission Observed by: • H I 21 cm emission, absorption • Optical, UV absorption lines
Cool H I (CNM) $f_V \approx 0.01$ $n_{\rm H} f_V \approx 0.3\,{\rm cm}^{-3}$	~ 100	30	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • Optical, UV absorption lines
Diffuse H_2 $f_V \approx 0.001$ $n_{\rm H} f_V \approx 0.1\,{\rm cm}^{-3}$	$\sim 50\,{\rm K}$	~ 100	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • CO 2.6-mm emission • optical, UV absorption lines
Dense H_2 $f_V \approx 10^{-4}$ $\langle n_{\rm H}\rangle f_V \approx 0.2\,{\rm cm}^{-3}$	$10 - 50$	$10^3 - 10^6$	Heating by photoelectrons from dust Ionization and heating by cosmic rays Self-gravitating: $p > p$(ambient ISM) Cooling by: ◇ CO line emission ◇ C I fine structure line emission Observed by: • CO 2.6-mm emission • dust FIR emission
Cool stellar outflows	$50 - 10^3$	$1 - 10^6$	Observed by: • Optical, UV absorption lines • Dust IR emission • H I, CO, OH radio emission

Bright H II regions, such as the Orion Nebula, have dimensions of a few pc; their lifetimes are essentially those of the ionizing stars, $\sim 3 - 10$ Myr. The extended low-density photoionized regions – often referred to as the **warm ionized medium**, or **WIM** – contain much more total mass than the more visually conspicuous high-density H II regions. According to current estimates, the Galaxy contains $\sim 1.1 \times 10^9\, M_\odot$ of ionized hydrogen; about 50% of this is within 500 pc of the disk midplane (the distribution of the H II is discussed in Chapter 11). In addition to the H II regions, photoionized gas is also found in distinctive structures called **planetary nebulae**[2] – these are created when rapid mass loss during the late stages of evolution of stars with initial mass $0.8M_\odot < M < 6M_\odot$ exposes the hot stellar core; the radiation from this core photoionizes the outflowing gas, creating a luminous (and often very beautiful) planetary nebula. Individual planetary nebulae fade away on $\sim 10^4$ yr time scales.

- **Warm H I**: Predominantly atomic gas heated to temperatures $T \approx 10^{3.7}$ K; in the local interstellar medium, this gas is found at densities $n_{\rm H} \approx 0.6\,{\rm cm}^{-3}$. It fills a significant fraction of the volume of the disk – perhaps 40%. Often referred to as the **warm neutral medium**, or **WNM**.

- **Cool H I**: Predominantly atomic gas at temperatures $T \approx 10^2$ K, with densities $n_{\rm H} \approx 30\,{\rm cm}^{-3}$ filling ~1% of the volume of the local interstellar medium. Often referred to as the **cold neutral medium**, or **CNM**.

- **Diffuse molecular gas**: Similar to the cool H I clouds, but with sufficiently large densities and column densities so that H_2 self-shielding (discussed in Chapter 31) allows H_2 molecules to be abundant in the cloud interior.

- **Dense molecular gas**: Gravitationally bound clouds that have achieved $n_{\rm H} \gtrsim 10^3\,{\rm cm}^{-3}$. These clouds are often "dark" – with visual extinction $A_V \gtrsim 3$ mag through their central regions. In these dark clouds, the dust grains are often coated with "mantles" composed of H_2O and other molecular ices. It is within these regions that star formation takes place. It should be noted that the gas pressures in these "dense" clouds would qualify as ultrahigh vacuum in a terrestrial laboratory.

- **Stellar outflows**: Evolved cool stars can have mass loss rates as high as $10^{-4} M_\odot\,{\rm yr}^{-1}$ and low outflow velocities $\lesssim 30\,{\rm km\,s}^{-1}$, leading to relatively high density outflows. Hot stars can have winds that are much faster, although far less dense.

The ISM is dynamic, and the baryons undergo changes of phase for a number of reasons: ionizing photons from stars can convert cold molecular gas to hot H II; radiative cooling can allow hot gas to cool to low temperatures; ions and electrons can recombine to form atoms, and H atoms can recombine to form H_2 molecules.

[2]They are called "planetary" nebulae because of their visual resemblance to planets when viewed through a small telescope.

Table 1.4 Protosolar Abundances of the Elements with $Z \leq 32$ (based on Asplund et al. (2009); see text)

Z	X	$\langle m_X \rangle$/amu	$N_X/N_{\rm H}$	$M_X/M_{\rm H}$	Source
1	H	1.0080	1	1	
2	He	4.0026	$9.55 \times 10^{-2\pm0.01}$	3.82×10^{-1}	Photospheric
3	Li	6.941	$2.00 \times 10^{-9\pm0.05}$	1.38×10^{-8}	Meteoritic
4	Be	9.012	$2.19 \times 10^{-11\pm0.03}$	1.97×10^{-10}	Meteoritic
5	B	10.811	$6.76 \times 10^{-10\pm0.04}$	7.31×10^{-9}	Meteoritic
6	C	12.011	$2.95 \times 10^{-4\pm0.05}$	3.54×10^{-3}	Photospheric
7	N	14.007	$7.41 \times 10^{-5\pm0.05}$	1.04×10^{-3}	Photospheric
8	O	15.999	$5.37 \times 10^{-4\pm0.05}$	8.59×10^{-3}	Photospheric
9	F	18.998	$2.88 \times 10^{-8\pm0.06}$	5.48×10^{-7}	Meteoritic
10	Ne	20.180	$9.33 \times 10^{-5\pm0.10}$	1.88×10^{-3}	Photospheric
11	Na	22.990	$2.04 \times 10^{-6\pm0.02}$	4.69×10^{-5}	Meteoritic
12	Mg	24.305	$4.37 \times 10^{-5\pm0.04}$	1.06×10^{-3}	Photospheric
13	Al	26.982	$2.95 \times 10^{-6\pm0.01}$	8.85×10^{-5}	Meteoritic
14	Si	28.086	$3.55 \times 10^{-5\pm0.04}$	9.07×10^{-4}	Photospheric
15	P	30.974	$3.23 \times 10^{-7\pm0.03}$	1.00×10^{-5}	Photospheric
16	S	32.065	$1.45 \times 10^{-5\pm0.03}$	4.63×10^{-4}	Photospheric
17	Cl	35.453	$1.86 \times 10^{-7\pm0.06}$	6.60×10^{-6}	Meteoritic
18	Ar	39.948	$2.75 \times 10^{-6\pm0.13}$	1.10×10^{-4}	Photospheric
19	K	39.098	$1.32 \times 10^{-7\pm0.02}$	5.15×10^{-6}	Meteoritic
20	Ca	40.078	$2.14 \times 10^{-6\pm0.02}$	8.57×10^{-5}	Meteoritic
21	Sc	44.956	$1.23 \times 10^{-9\pm0.02}$	5.53×10^{-8}	Meteoritic
22	Ti	47.867	$8.91 \times 10^{-8\pm0.03}$	4.27×10^{-6}	Meteoritic
23	V	50.942	$1.00 \times 10^{-8\pm0.02}$	5.09×10^{-7}	Meteoritic
24	Cr	51.996	$4.79 \times 10^{-7\pm0.01}$	2.49×10^{-5}	Meteoritic
25	Mn	54.938	$3.31 \times 10^{-7\pm0.01}$	1.82×10^{-5}	Meteoritic
26	Fe	55.845	$3.47 \times 10^{-5\pm0.04}$	1.94×10^{-3}	Photospheric
27	Co	58.933	$8.13 \times 10^{-8\pm0.01}$	4.79×10^{-6}	Meteoritic
28	Ni	58.693	$1.74 \times 10^{-6\pm0.01}$	1.02×10^{-4}	Meteoritic
29	Cu	63.546	$1.95 \times 10^{-8\pm0.04}$	1.24×10^{-6}	Meteoritic
30	Zn	65.38	$4.68 \times 10^{-8\pm0.04}$	3.06×10^{-6}	Meteoritic
31	Ga	69.723	$1.32 \times 10^{-9\pm0.02}$	9.19×10^{-8}	Meteoritic
32	Ge	72.64	$4.17 \times 10^{-9\pm0.04}$	3.03×10^{-7}	Meteoritic

Asplund et al. (2009) have corrected the measured photospheric abundances of He, C, N, O, Ne, Mg, Si, S, Ar, and Fe to allow for diffusion in the Sun.

As recommended by Asplund et al. (2009), the photospheric abundance of Si, and meteoritic abundances (tied to Si), have been increased by a factor $10^{0.04}$ to allow for diffusion in the Sun. Similarly, the measured photospheric abundance of P has been multiplied by $10^{0.04}$ to allow for diffusion in the Sun.

$M(Z > 2)/M_{\rm H} = 0.0199$; $M({\rm total})/M_{\rm H} = 1.402$.

Table 1.5 Energy Densities in the Local ISM

Component		$u(\mathrm{eV\,cm^{-3}})$	Note
Cosmic microwave background	($T_{\rm CMB} = 2.725\,\mathrm{K}$)	0.265	a
Far-infrared radiation from dust		0.31	b
Starlight ($h\nu < 13.6\,\mathrm{eV}$)		0.54	c
Thermal kinetic energy $(3/2)nkT$		0.49	d
Turbulent kinetic energy $(1/2)\rho v^2$		0.22	e
Magnetic energy $B^2/8\pi$		0.89	f
Cosmic rays		1.39	g

a Fixsen & Mather (2002).
b Chapter 12.
c Chapter 12.
d For $nT = 3800\,\mathrm{cm^{-3}\,K}$ (see §17.7).
e For $n_{\rm H} = 30\,\mathrm{cm^{-3}}$, $v = 1\,\mathrm{km\,s^{-1}}$, or $\langle n_{\rm H}\rangle = 1\,\mathrm{cm^{-3}}$, $\langle v^2\rangle^{1/2} = 5.5\,\mathrm{km\,s^{-1}}$.
f For median $B_{\rm tot} \approx 6.0\,\mu\mathrm{G}$ (Heiles & Crutcher 2005).
g For cosmic ray spectrum X3 in Fig. 13.5.

1.2 Elemental Composition

The interstellar gas is primarily H and He persisting from the Big Bang, with a small reduction in the H fraction, a small increase in the He fraction, and addition of a small amount of heavy elements – from C to U – as the result of the return to the ISM of gas that has been processed in stars and stellar explosions. The abundance of heavy elements in the ISM – e.g., C, O, Mg, Si, and Fe – is a declining function of distance from the Galactic Center, with the abundance near the Sun (galactocentric radius $R \approx 8.5\,\mathrm{kpc}$) being about half the abundance in the Galactic Center region.

The composition of the ISM in the solar neighborhood is not precisely known, but is thought to be similar to the composition of the Sun. The current best estimates of solar abundances for elements with atomic number ≤ 32 (as determined from both observations of the stellar photosphere and studies of primitive carbonaceous chondrite meteorites) are given in Table 1.4. These abundances are intended to be the abundances in the protosun, which differ from photospheric abundances due to diffusion. H and He together account for most of the mass – the elements with $Z \geq 3$ contribute only $\sim 1\%$ of the total mass. Nevertheless, these heavy element "impurities" in many cases determine the chemistry, ionization state, and temperature of the gas, in addition to which they provide valuable observable diagnostics.

1.3 Energy Densities

Energy is present in the ISM in a number of forms: thermal energy $u = (3/2)nkT$, bulk kinetic energy $(1/2)\rho v^2$, cosmic ray energy $u_{\rm CR}$, magnetic energy $B^2/8\pi$, and energy in photons, which can be subdivided into cosmic microwave back-

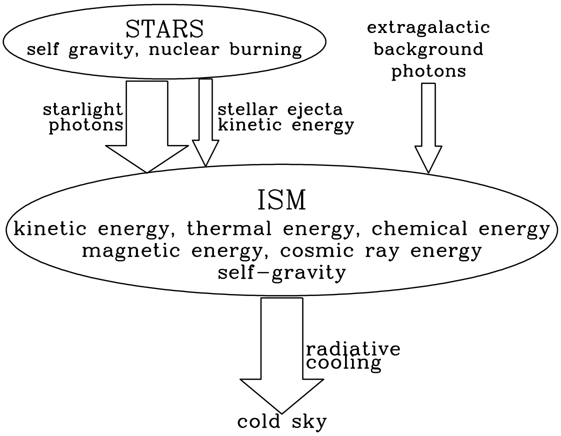

Figure 1.3 Flow of energy in the Milky Way.

ground, far-infrared (FIR) emission from dust, and starlight. It is a remarkable fact that in the local ISM, today, these energy densities all fall within the range $0.2 - 2\,\mathrm{eV\,cm^{-3}}$ – see Table 1.5. This near-equipartition is partly coincidental – the fact that the energy density in the CMB is similar to the other energy densities is surely accidental – but the other six energy densities are in fact coupled: the magnetic energy has been built up by fluid motions, so it is probably not a coincidence that the magnetic energy density $B^2/8\pi$ and the turbulent energy density $(1/2)\rho v^2$ are comparable in magnitude. Similarly, if the cosmic ray energy density were much larger, it would not be possible for the magnetized ISM to confine the cosmic rays, and they would be able to escape freely from the Galaxy – this negative feedback limits the cosmic ray energy density to approximate equipartition with the sum of the turbulent energy density and thermal pressure in the ISM. The fact that the starlight energy density is comparable to the gas pressure may be coincidental. However, if the starlight energy density were much larger (by a factor $\sim 10^2$), radiation pressure acting on dust grains would be able to "levitate" the ISM above and below the Galactic midplane, presumably suppressing star formation; this feedback loop may play a role in regulating the starlight energy density in star-forming galaxies.

The ISM is far from thermodynamic equilibrium, and it is only able to maintain this nonequilibrium state because of the input of "free energy," primarily in the form of ultraviolet radiation emitted by stars, but with a significant and important contribution of kinetic energy from high-velocity gaseous ejecta from supernovae. The overall flow of energy in the ISM is sketched in Figure 1.3. Ultimately, nearly all of the energy injected into the ISM in the form of starlight and kinetic energy of stellar ejecta is lost from the galaxy in the form of emitted photons, departing to the cold extragalactic sky.