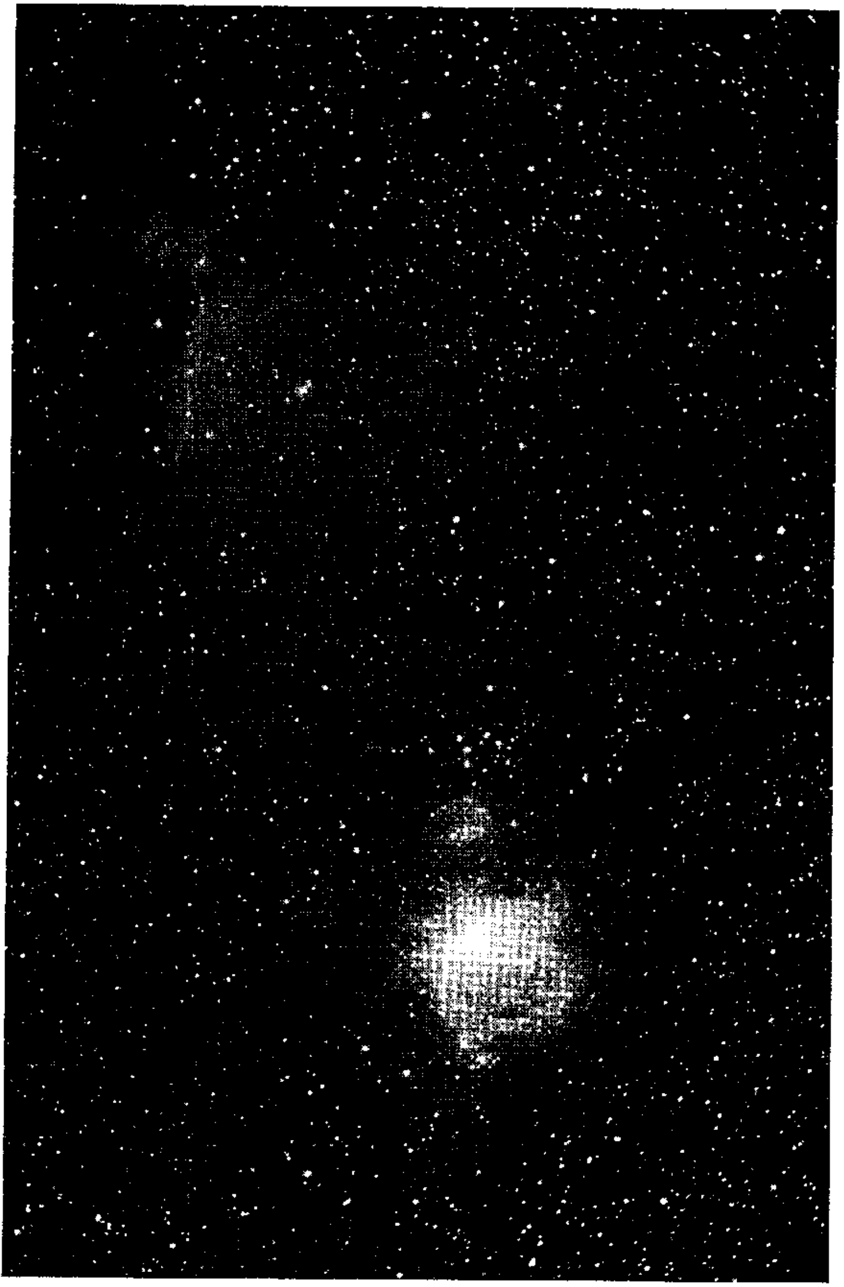
# 1. What Is the Diffuse Universe?

*"Now entertain conjecture of a time*
*When creeping murmur and the pouring dark*
*Fills the wide vessel of the Universe"*
*— Shakespeare (Henry V, Act 4)*

Nowhere in the universe can we find a perfect vacuum. Around ordinary stars, a hot magnetized plasma seethes and bubbles outward in a thermally powered wind. Within the disks of spiral galaxies, dusty clouds of molecular gas continually coalesce and collapse under their self-gravity to form new stars. The light from these newborn stars heats and ionizes their placental cloud before finally dispersing it back into the galactic disk, ready to repeat the cycle (Fig. 1.1). Wherever there are stars, some will reach the end of their lives to explode as supernovae, hurling out the gas that has been transformed in their thermonuclear furnaces into heavy elements such as iron. The shocks of these events rumble their way through space, heating the interstellar gas anew. Some is thrown up and far away from the galactic plane, while other parts are crushed into dense sheets and filaments which shine briefly as their shock energy is radiated away. In clusters of galaxies, heated gas glows softly in X-rays, cooling over billions of years before finally falling back into the bright galaxy cores to help feed the massive monster black holes that lurk at their centers. In intergalactic space, jets of plasma shot from the cores of active galaxies emit radio waves as relativistic charged particles circle in the magnetic fields, shedding their energy. Even in the vast reaches of space between the clusters of galaxies, hot plasma can still be found. Here it is so tenuous that it can never cool again, and a hydrogen nucleus could travel a distance equal to the width of our galaxy before encountering another of its kind.

This then is the broad canvas of the diffuse universe, displaying a rich range of thermal plasma phenomena and covering a remarkable variety of conditions and chemical compositions. We work to understand the physics of such plasmas because, by gaining insight into their physics, we can hope to understand and interpret the observed phenomena, measure physical parameters and determine chemical compositions. Since all the stars in all the galaxies have been ultimately formed from this gas, our study provides insight into the structure and evolution of the universe we live in.



1.1. Turbulent ionized plasmas filling a nearby region of space around the
e star-forming region of the Orion Nebula.



What sets the physics of these cosmic gas clouds apart from the molecular gas found in the atmosphere of our planet or from the hot ionized plasmas found in the interiors of stars? The answer to this question lies in the densities that characterize the interstellar and intergalactic plasmas. We generally refer to the density of gas in units of atoms per cubic centimeter. For example, the mean density of the gas in the plane of our galaxy at the solar radius is about $0.3\,\mathrm{cm}^{-3}$. Inside a molecular cloud, the density is much higher, say, $10^6\,\mathrm{cm}^{-3}$. Nonetheless, this is completely negligible compared with the density encountered in the earth's atmosphere ($\sim 2 \times 10^{18}\,\mathrm{cm}^{-3}$). In our atmosphere, an atom collides with another on a timescale of a few nanoseconds. In the molecular cloud the collision timescale is extended to several days. However, the internal atomic or molecular timescales range from around a nanosecond to several millions of years for the neutral hydrogen 21 cm emission line. In the earth's atmosphere, each atom that suffers a collision will be involved in another encounter before it has a chance to adjust internally through atomic processes from the previous collision. By contrast, the atom in our molecular cloud is free to radiate any excess internal energy it has picked in the collision and will return to its ground state to await the next collision.

As a result, the atoms of our diffuse astrophysical plasmas are usually sitting in their ground state, while the atoms in the earth's atmosphere are in a dynamical balance with collisional processes, every possible atomic state is fed by collisions as fast as it is being depleted by other collisions. This condition is known as *local thermodynamic equilibrium* (LTE). In this case, at a temperature $T$, the number density of atoms or molecules in any excited state, $j$, compared with the number in the ground state ($j = 1$), is given by the *Boltzmann equilibrium:*

$$\frac{N_j}{N_1} = \frac{g_j}{g_1} \exp\left(\frac{-\Delta E_m}{kT}\right), \tag{1.1}$$

where $k$ is the Boltzmann constant ($k = 1.380622 \times 10^{-16}\,\mathrm{erg\,K^{-1}}$), $\Delta E_m$ is the energy difference between the ground and the excited state, and $g_j$ is the statistical weight of the excited state (if the excited level has a total angular momentum quantum number $J$, then $g_j = 2J + 1$). In addition, the electrons, and each species of atom or molecule in the gas will have their energy distributed according to the *Maxwell Distribution:*

$$n(E)dE = \frac{2N}{\pi^{1/2}(kT)^{3/2}} E^{1/2} \exp\left(\frac{-E}{kT}\right) dE. \tag{1.2}$$

The low densities in the diffuse plasmas ensure that Boltzmann equilibrium is rarely achieved, the populations of excited states are determined by the balance between collisions from low-lying levels and radiative decay. In most cases, collisions between like species are still sufficiently frequent to set up the Maxwell distribution. However, we will encounter a few examples of gas which has passed recently through a shock so that its ions have not had time to achieve the Maxwell distribution, and in some cases it is even difficult to define the energy distribution of the electrons.

Historically, diffuse astrophysical plasmas have been divided into broad environmental divisions or domains, of which the most familiar and the best studied is the medium between the stars in our galaxy. This medium, and the gas in between stars in other galaxies is generally referred to as the interstellar medium (ISM). It provides in its dense molecular phase the cradle and the birthplace of stars. In turn, it derives its complex phase structure and energy balance from the input of energy derived from nuclear burning occurring within these stars in the form of photons, stellar winds, and outflows or stellar explosions. Figure 1.2 shows the broad divisions of plasmas found in the universe on a density-temperature diagram. A number of astrophysical phenomena within the diffuse universe domain are shown in the diagram, along with their characteristic sizes.

Within the ISM itself, the details of these interactions have provided a potent testing ground for theory and have provided a good deal of insight into the evolution of stars and the chemical and structural evolution of galaxies. The dense molecular clouds have given us an understanding of molecular chemistry, interstellar dust physics, the diffusion of magnetic fields, and a detailed insight into the gravitational instabilities which lead to the formation of stars. Detailed study of star-formation regions embedded within them has led to an understanding of how newly forming stars shed the angular momentum of their parent cloud through the formation of collimated outflows and jets, and the interaction of these jets with the clouds provides a rich laboratory to study shock physics and chemistry. Radio observations of molecular lines enable us to study physical conditions in star-forming regions, and they also tell us about the isotope ratios of various elements, which are key data in understanding the sites of production of the heavier elements.

The photoionized regions around massive young stars provide a means of probing the chemical composition of the atomic gas both in our galaxy, and in distant galaxies. In particular, they provide us with estimates of the primordial helium abundance – a key parameter in cosmological models. We can also study the bubbles formed by the powerful radiation-pressure driven winds of their central stars.

The so-called planetary nebula shells which have been ejected and photoionized by dying solar-like stars provide insight into the chemical processing and dredge-up which has occurred in their atmospheres, and provide observational tests of theories of stellar evolution in low mass stars, while the nova shells ejected from the surfaces of white dwarf stars enable us to study explosive nuclear processing under electron-degenerate conditions.

Finally, the material ejected in supernova explosions gives us a sample of the end products of nucleosynthesis in stars. The properties of the shock waves driven into the surrounding medium measure the kinetic energy input into the ISM by these explosions, while the properties of the radio synchrotron



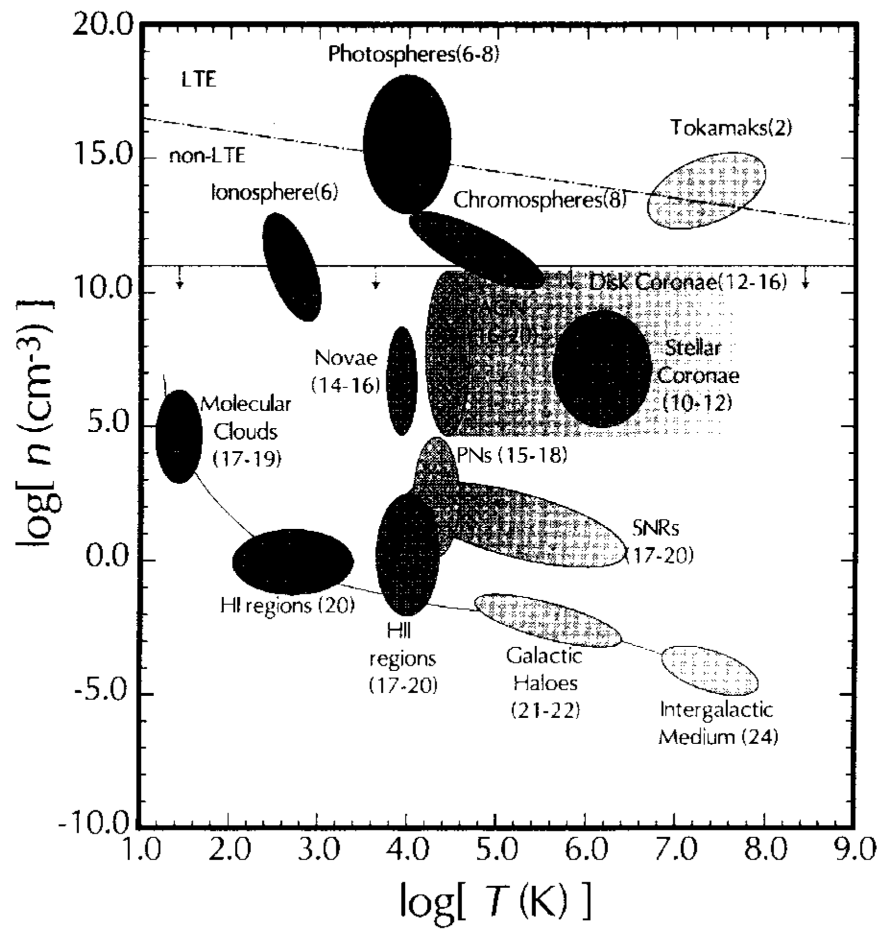



**Fig. 1.2.** Densities and characteristic sizes of diffuse astrophysical plasmas in the universe. For each class of objects, the characteristic size in log(cm) is given. The approximate boundary between plasmas in LTE and non-LTE plasmas is marked as a dash-dot line. The diffuse universe lies approximately below the horizontal line marked with arrows. The thin solid curve connects the dominant phases of galactic and intergalactic diffuse media.

spectrum generated in the shell provides insight into particle acceleration mechanisms and the origin of cosmic-rays.

With each generation of stars, some of the ISM is lost forever in the dying embers of stars – in the white dwarfs, in neutron stars formed during supernova explosions, or in black holes formed in the collapse of the cores of massive stars. In addition, some matter is effectively lost in low-mass stars which frugally burn their nuclear fuel over timescales much longer than the age of the universe, while yet another part is stored for long periods within normal stars like our own sun. In the solar neighborhood, the ISM now accounts for somewhat less than 15% of the total baryonic mass, and this figure is typical of the arms of spiral galaxies today.

However important the gas and dust in galaxies may be, we must not forget other parts of the cosmos where we find components that are not moulded and controlled by stars alone, and indeed may not even be located between stars as the word interstellar implies. In the cores of many galaxies lurk massive black holes which when fed by matter subject their environs to extremes of ionization or temperature. Here we find rings of gas which are irradiated by X-rays, massive outflows of material, or highly relativistic jets of gas shot out into intergalactic space. These plasmas could collectively be regarded as the *active galactic medium* (AGM). Developing an understanding of the properties of the AGM is a cornerstone of research in active galaxies.

Finally, on the largest of scales we have the *intergalactic medium* (IGM) or the hot gas found within whole clusters of galaxies, the intracluster medium (ICM). This material is detected by means of the X-rays it produces, by the effect it has upon the propagation of relativistic jets, by faraday rotation and depolarization of distant radio sources, by evidence of ram-pressure stripping of matter in galaxies, or through the absorption it can produce in the light of distant galaxies. Since the IGM is the most difficult to observe, it is also the least well studied of the diffuse astrophysical plasmas.

## 1.1 Phases

Diffuse matter in the universe is found over an extraordinary range of scales from structures smaller than the size of the solar system ($\sim 10^{15}$ cm) up to regions encompassing whole clusters of galaxies ($\sim 10^{24}$ cm). Fortunately, the characteristic densities decrease rapidly as the scale size increases since otherwise the mass of the diffuse medium would be infinite! A consequence of this enormous dynamic range in parameter space is that the range of possible phenomena is very rich. However, provided that characteristic timescales remain appreciably shorter than the characteristic timescale for the evolution of the universe ($\sim 10^{10}$ yr), it is remarkable how often phenomena occurring on small scales find physical analogues on much larger scales. As an example, we might cite the bipolar outflows from very young stars which have characteristic scales $10^5$ yr and $10^{17}$ cm, but which have physics very similar to the bipolar jets in active galactic nuclei (AGN), with ages of order $10^7$ yr and scales as large as $10^{23}$ cm.

The diffuse medium has always represented an important component of the baryonic mass in the universe. Shortly after the recombination epoch in the early expansion of the universe, diffuse matter reigned supreme, accounting for all the baryonic mass, with the exception of a few primordial



black holes. However, gravity soon took over, and the gas clouds started coagulating and collapsing. It should always be remembered that gas is sticky stuff. When two gas clouds collide, their energy of motion is turned into heat through shocks, which is then radiated away into space. Thus cloud-cloud collisions can be considered as almost completely inelastic, conserving momentum, but losing all their kinetic energy. Shocks are also highly compressive and aid the development of a cold dense phase in the ISM which in turn favors star formation when the densities become high enough. Early in the evolution of the universe, these processes led first to the formation and then to the evolution of galaxies. Today the ISM in galaxies is kept in a dynamic, self-regulating equilibrium determined by the rate of star formation, balanced against the energy and/or momentum input these stars put back into the surrounding interstellar medium. In galaxies, the ISM forms a multiphase structure in response to this feedback, and develops a hierarchical and fractal spatial structure.

The multiphase structure, discussed in detail in Chap. 14, develops as a consequence of the fact that a stable balance of heating and cooling at a given pressure can often be achieved at more than one temperature. Various names have been given to the most common phases of the ISM in galaxies. The *molecular medium* (MM), the *cold neutral medium* (CNM) and the *warm neutral medium* (WNM) are three such phases of the atomic gas in the ISM. In similar fashion, we may also find components due to a *warm ionized medium* (WIM) and a *hot ionized medium* (HIM). None of these components should be regarded as static in time or space, and matter is constantly in flux between them.

Dying stars constantly feed matter back into the ISM, which has been transformed into heavier elements of one kind or another – often labelled, in cavalier fashion, "metals" by astronomers. [1] The processes of chemical evolution are described in detail by Pagel (1997). Much of the non-volatile fraction of heavy elements finds its way eventually into interstellar dust grains, which are important constituents of the ISM, absorbing and polarizing the light from distant stars, coupling gas and magnetic fields through photoelectric or collisional charging, playing an important role in the total energy balance of the ISM, and providing sites on their surfaces for chemical reactions which allow complex molecules to form.

If a plasma is hot, its lifetime in the hot phase depends on its heat content or internal energy and how fast it can radiate this heat away. The rate of radiation is a complex function of temperature and of density. Thus, we can arrange the plasmas we meet in the ISM according to their characteristic scale size, density and temperature. This has been done in Fig. 1.2. The realm

[1] The astronomical definition of metallicity comes from stellar astronomy. The material making up the stars is defined as consisting of three components, hydrogen, helium, and the heavier elements with mass-fractions $X$, $Y$, and $Z$ respectively. Material with the solar atmosphere mass fractions is defined as having solar metallicity.

of the molecular clouds and the H I regions is the realm of astrochemistry, while all of the other classes of objects are predominantly regions of ionized plasmas of one kind or another. Although an approximate division between LTE and NLTE plasmas is indicated, this transition is rather fuzzy, and depends on the particular ion or atom considered. Although, as we will see, fully NLTE plasmas are reasonably straightforward to understand, and so are fully LTE plasmas, the region close to the transition zone between the two cases is computationally awful, since all levels of all atoms have to be considered together along with their associated radiative transfer problems. This is certainly not a physical regime that can be left to the student, but requires the full capability of modern supercomputers and almost unlimited atomic data. In this book, we will consider only thermal processes in low-density plasmas, leaving these transitional plasmas, relativistic plasmas, and their emission processes to other texts.

## 1.2 Observability

It might seem rather trivial to remark that, in order for a given phase of the ISM to be detectable in its own emission lines or continuum, it must emit enough photons in any wavelength band to which our earthbound or spaceborne telescopes are sensitive. In practice, as we will see below, these emission processes are mainly governed by binary collisions between either atoms, ions, molecules or electrons. As a consequence, the local emissivity (measured in $\mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}}$) varies as the square of the local density. On the other hand, the surface brightness of an object is governed by whether this local emissivity, integrated along the line of sight, is sufficient to be detectable against the background (zodiacal emission, airglow, telescope emissivity, instrumental noise, or whatever). Therefore, a very useful parameter characterizing ISM sources is the so-called *emission measure* defined as

$$\mathrm{EM} = \int n_e^2 dl. \tag{1.3}$$

In many cases, since we do not really know the run of density along the line of sight, this integral is approximated by the mean density and path length through the region of interest, $\mathrm{EM} = \langle n_e \rangle^2 l$. Because astronomers like to define their densities in units of number densities ($\mathrm{cm^{-3}}$), but their distances in units of parsecs ($1\,\mathrm{pc} = 3.0856 \times 10^{18}\,\mathrm{cm} = 3.2615$ light years), the emission measure is generally given in the somewhat obscure units of $\mathrm{pc\,cm^{-6}}$.

As illustrative examples, consider these cases of ionized hydrogen plasmas. First, the case of a nova shell which has been ejected from the surface of a white dwarf at a typical velocity of $1{,}000\,\mathrm{km\,s^{-1}}$. After typically 100 days, the shell has reached the nebular phase, that is to say, it has become optically thin to the passage of radiation, and at that time it has a typical density of $10^7\,\mathrm{cm^{-3}}$. In this case the EM $\sim 10^9\,\mathrm{pc\,cm^{-6}}$. As a second example, take a typical planetary nebula. This is the ionized envelope of a dying star as it transits from a red giant to a white dwarf star. Typically, the envelope will have been expanding at $10–30\,\mathrm{km\,s^{-1}}$ for a few thousand years, so that it is about 0.1 pc across. At this time, it has a density of $10^4\,\mathrm{cm^{-3}}$, and the EM $\sim 10^7\,\mathrm{pc\,cm^{-6}}$. Still fainter are H II regions, which are typically 10–100 pc across and are ionized by the UV light of massive, hot, young stars a few million years old. In this case the density is as low as $10\,\mathrm{cm^{-3}}$, and so the EM is only $10^{3-4}\,\mathrm{pc\,cm^{-6}}$. Such nebulae are still easy to detect with modern telescopes, although some faint lines which are important in establishing the density, temperature, or abundances may be difficult to observe. Finally, consider the case of the diffuse ionized galactic ISM which pervades the disks of spiral galaxies. Here the densities are as low as $0.1\,\mathrm{cm^{-3}}$, while the medium is limited by its scale height above the galactic plane, typically 1,000 pc. In this case the EM is only $\sim 10\,\mathrm{pc\,cm^{-6}}$, and specialist instruments are needed simply to detect it, let alone measure it accurately enough for analysis.

Even when the plasma is too faint to be seen by its own emission, it may still be detected by the absorption it produces in a background source of continuum emission. This is because resonance transitions to higher states are excited by the continuum light in the beam, but the atom reradiates this light in all directions when it returns to the ground state. Thus, effectively, the light has been scattered out of the line of sight. The absorptions are proportional to the column density $\int n_e dl$, and the cross sections for absorption can be large, comparable with the Bohr radius squared. Thus, species which have column densities as low as $10^{12-13}\,\mathrm{cm^{-2}}$ along the line of sight may be detected with high dispersion spectrographs on large telescopes. Such absorption techniques are the only means whereby the hot, highly ionized, and very tenuous gas in our galactic halo can be detected. This gas has typical densities of $0.001\,\mathrm{cm^{-3}}$, and columns of $\sim 3\,\mathrm{kpc}$ ($10^{22}\,\mathrm{cm}$), so its emission measure would only be of order $10^{-2}\,\mathrm{pc\,cm^{-6}}$, and therefore totally undetectable in its own emission.