Chapter 3

The Interstellar Medium

3.1 An Introduction to the Interstellar Medium

The interstellar medium (ISM) of a galaxy consists of the gas and dust distributed between the stars. The mass in the gas is much larger than that in dust, with the mass of dust in the disc of our Galaxy $\simeq 0.1$ of the mass of gas. Generally, the interstellar medium amounts to only a small fraction of a galaxy's luminous mass, but this fraction is strongly correlated with the galaxy's morphological type. This fraction is $\simeq 0\,\%$ for an elliptical galaxy, 1–25 % for a spiral (the figure varies smoothly from type Sa to Sd), and 15–50 % for an irregular galaxy.

The interstellar gas is very diffuse: in the plane of our Galaxy, where the Galactic gas is at its densest, the particle number density is $\simeq 10^3$ to 10^9 atomic nuclei m^{-3}. Some of this gas is in the form of single neutral atoms, some is in the form of simple molecules, some exists as ions. Whether gas is found as atoms, molecules or ions depends on its temperature, density and the presence of radiation fields, primarily the presence of ultraviolet radiation from nearby stars. Note that the density of the gas is usually expressed as the number of atoms, ions and molecules per unit volume; here they will be expressed in S.I. units of m^{-3}, but textbooks, reviews and research papers still often use cm^{-3} (with 1 cm^{-3} $\equiv 10^6$ m^{-3}, of course).

The interstellar medium in a galaxy is a mixture of gas remaining from the formation of the galaxy, gas ejected by stars, and gas accreted from outside (such as infalling diffuse gas or the interstellar medium of other galaxies that have been accreted). The ISM is very important to the evolution of a galaxy, primarily because it forms stars in denser regions. It is important observationally. It enables us, for example, to observe the dynamics of the gas, such as rotation curves, because spectroscopic emission lines from the gas are prominent.

The chemical composition is about 90 % hydrogen, 9% helium plus a trace of heavy elements (expressed by numbers of nuclei). The heavy elements in the gas can be depleted into dust grains. Dust consists preferentially of particles of heavy elements.

Individual clouds of gas and dust are given the generic term nebulae. However, the interstellar gas is found to have a diverse range of physical conditions, having very different temperatures, densities and ionisation states. There are several distinct types of nebula, as is described below.

The pressure, density and temperature of the gas in the interstellar medium are described accurately by the ideal gas law. This law, also known as the perfect gas law, can be expressed in a few different forms. Some of these will be very familiar to you,

but it is worth writing down the various forms at this stage to avoid confusion. For a volume V of gas of pressure P and absolute temperature T we have

$$PV = N_p\, k_B\, T = N_{mole}\, \mathcal{R}\, T$$

where N_p is the number of particles (atoms/molecules/ions) in the volume, N_{mole} is the number of moles in the volume, k_B is the Boltzmann constant ($k_B = 1.381 \times 10^{-23}\,\mathrm{J\,K^{-1}}$), $\mathcal{R}$ is the gas constant ($\mathcal{R} = 8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$). (Absolute temperature means temperature measured relative to absolute zero. So temperatures expressed in Kelvin, K, are on an absolute scale, while those expressed in degrees Celsius, °C, are not.) Working instead in terms of the number density n of particles at a point in a gas, and the density ρ, we have

$$P = n\, k_B\, T = \frac{k_B\, \rho\, T}{m_p} = \frac{k_B}{m_{AMU}}\frac{\rho\, T}{\mu} = \mathcal{R}\frac{\rho\, T}{\mu}$$

where m_p is the mean mass of the particles, μ is the mean molecular mass and m_{AMU} is the mass corresponding to one atomic mass unit (note that $\mathcal{R} \equiv k_B/m_{\mathrm{AMU}}$.) These equations are all forms of the ideal gas law, but $P = nk_B T$ is the form most often encountered when discussing the interstellar medium.

3.2 Background to the Spectroscopy of Interstellar Gas

The gas in the interstellar medium readily emits detectable radiation and can be studied relatively easily. The gas is of very low density compared to conditions on the Earth, even compared to many vacuums created in laboratories. Therefore spectral lines are observed from the interstellar gas that are not normally observed in the laboratory. These are referred to as *forbidden* lines, whereas those that are readily observed under laboratory conditions are called *permitted* lines. Under laboratory conditions, spectral lines with low transition probabilities are 'forbidden' because the excited states get collisionally de-excited before they can radiate. In the ISM, collisional times are typically much longer than the lifetimes of those excited states that only have forbidden transitions. So forbidden lines are observable from the ISM, and in fact they can dominate the spectrum.

Astronomy uses a particular notation to denote the atoms and ions that is seldom encountered in other sciences. Atoms and ions are written with symbols such as HI, HII, HeI and HeII. In this notation, I denotes a neutral atom, II denotes a singly ionised positively charged ion, III denotes a doubly ionised positive ion, etc. So, HI is H^0, HII is H^+, HeI is He^0, HeII is He^+, HeIII is He^{2+}, LiI is Li^0, etc. A negatively charged ion, such as H^-, is indicated only as H^-, although few of these are encountered in astrophysics. Square brackets around the species responsible for a spectral line indicates a forbidden line, for example [OII].

3.3 Cold Gas: the 21 cm Line of Neutral Hydrogen

Cold gas emits only in the radio and the microwave region, because collisions between atoms and the radiation field (e.g. from stars) are too weak to excite the electrons to energy levels that can produce optical emission.
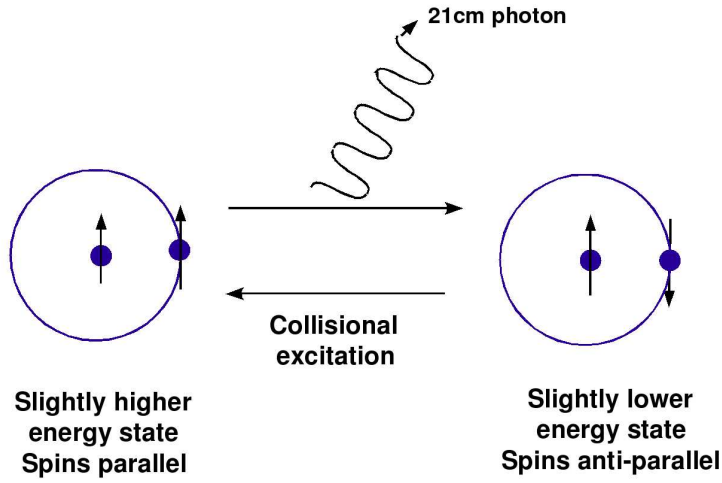
The most important ISM line from cold gas is the 21 cm line of atomic hydrogen (HI). It comes from the hyperfine splitting of the ground state of the hydrogen atom (split because of the coupling of the nuclear and electron spins). Note that this involves hydrogen *atoms*, not molecules and not ions. The energy difference between the two states is $\Delta E = 9.4 \times 10^{-25}\,\mathrm{J} = 5.9 \times 10^{-6}\,\mathrm{eV}$. This produces emission with a rest wavelength $\lambda_0 = hc/\Delta E = 21.1061$ cm and a rest frequency $\nu_0 = \Delta E/h = 1420.41$ MHz. This is an emission spectral line at radio wavelengths. In this process, hydrogen atoms are excited into the upper state through collisions (collisional excitation), but these collisions occur relatively infrequently in the low densities encountered in the cold interstellar medium. The transition probability is $A = 2.87 \times 10^{-15}\,\mathrm{s}^{-1}$. The lifetime of an excited state is $\simeq 1/A = 11$ million years. However, the time between collisions is actually much shorter than this, and collisional de-excitation occurs before most atoms can decay spontaneously. This is followed later by other collisions, and therefore collisional excitation. This means that a proportion of the hydrogen atoms will be in the excited state at any time. Although the transition probability is very low, there is so much atomic hydrogen in the interstellar medium that sufficient 21cm radio emission occurs for it to be detectable.

The 21cm spin flip transition itself cannot be observed in a laboratory because of the extremely low transition probabilities, but the split ground state shows up in the laboratory through of the hyperfine splitting of the Lyman lines in the ultraviolet. In the ISM, the 21cm line is observed primarily in emission, but can also be observed in absorption against a background radio continuum source.

HI observations have many uses. One critically important application is to measure the orbital motions of gas to determine rotation curves in our own Galaxy and in other galaxies. HI observations can map the distribution of gas in and around galaxies.

3.4   Cold Gas: Molecules

Molecular hydrogen (H_2) is very difficult to detect directly. It has no radio lines (including millimetre and submillimetre wavelength radiation), which is unfortunate, since it prevents the coldest and densest parts of the ISM being observed directly. There is H_2 band absorption in the far ultraviolet, but this can only be observed from above the Earth's atmosphere.

What saves the situation somewhat is that other molecules (molecules other than H_2) do emit in the radio/microwave region. Molecular energy transitions can be due to changes in the electron energy levels, and also to changes in vibrational and rotational energies of the molecules. All three types of energy are quantised. Transitions between the electron states are in general the most energetic, and can produce spectral lines in the optical, ultraviolet and infrared. Transitions between the vibrational states can produce lines in the infrared. Transitions between the rotational states are in general the least energetic and produce lines in the radio/microwave region.

CO has strong lines at 1.3 mm and 2.6 mm from transitions between rotational states. CO is particularly useful as a tracer of H_2 molecules on the assumption that the densities of the two are proportional. Mapping CO density is therefore used to determine the distribution of cold gas in the ISM.

Cold, dense molecular gas is concentrated into clouds. These are relatively small in size ($\simeq 2-40$ pc across). Temperatures are $T \sim 10$ K and densities $\sim 10^8$ to $10^{11}\,\mathrm{m}^{-3}$. Molecular clouds fill only a very small volume of the ISM but contain substantial mass. Regions of gas in molecular clouds can experience collapse under their own gravitation to form stars. The newly formed hot stars in turn irradiate the gas with ultraviolet light, ionising and heating the gas.

Giant molecular clouds are larger regions of cold, molecular gas. Their masses are large enough (up to $10^6\ M_\odot$) that they can have perturbing gravitational effects on stars in the disc of the Galaxy. Within our Galaxy they are mostly found in the spiral arms.

3.5   Hot Gas: HII Regions

Hot gas is readily observed in the optical region of the spectrum. Gas that is largely ionised produces emission lines from electronic transitions when ions and some atoms revert to lower energy states. The gas is therefore observed as nebulae.

An important kind of object is HII regions, which are regions of partially ionised hydrogen surrounding very hot young stars of O or B spectral types. Hot stars produce a large flux of ultraviolet photons, and any Lyman continuum photons (i.e. photons with wavelengths $\lambda < 912\,\text{\AA}$) will photoionise hydrogen producing a region of H^+, i.e. HII ions. These wavelengths correspond to energies > 13.6 eV, the ionisation energy from the ground state of hydrogen. The ionised hydrogen then recombines with electrons to form neutral atoms. But the hydrogen does not have to recombine into the ground state; it can recombine into an excited state and then radiatively decay after that. Electrons will cascade down energy levels, emitting photons as they do, in a process known as radiative decay.

This process produces a huge variety of observable emission lines and continua in the ultraviolet, optical, infrared and radio parts of the spectrum. Free-bound transitions (involving free electrons combining with ions to become bound in atoms) produce continuum radiation. Bound-bound transitions (involving electrons inside an atom moving to a different energy level in the same atom) produce spectral lines.

Transitions in hydrogen atoms down to the first excited level ($n = 2$) produce Balmer lines, which lie in the optical. These are prominent in nebulae. Transitions down to the ground ($n = 1$) state produce Lyman lines in the ultraviolet. In each series, the individual lines are labelled $\alpha, \beta, \gamma, \delta, ...$, in order of decreasing wavelength. The transitions from n to $n-1$ levels are the strongest. Therefore the α line of any

series is the strongest.

Lyman series lines of hydrogen are:

Lyα $\lambda = 1216$ Å   (in ultraviolet)
Lyβ 1026 Å   (")
Lyγ 973 Å   (")

Balmer series lines of hydrogen are:

Hα $\lambda = 6563$ Å   (in optical)
Hβ 4861 Å   (")
Hγ 4340 Å   (")
Hδ 4102 Å   (")
Hϵ 3970 Å   (")

Atoms in H II regions can also be collisionally excited. Atomic hydrogen has no levels accessible at collision energies characteristic of H II regions ($T \sim 10^4$ K) but N II, O II, S II, O III, Ne III all do. The [O III] lines at 4959Å and 5007Å are particularly prominent. Some of the most prominent lines in the optical spectra of H II regions, other than the hydrogen lines listed above, are the following lines produced by oxygen, neon, helium and nitrogen:

[O II]   3727 Å   He I 5876 Å
[Ne III] 3869 Å   [N II] 6548 Å
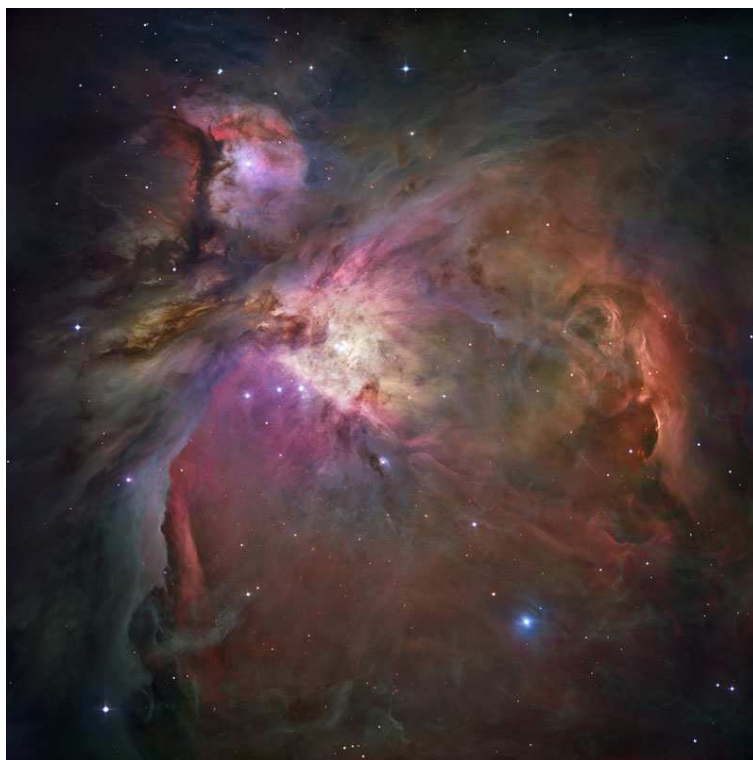[O III]   4959 Å   [N II] 6584 Å
[O III]   5007 Å

Figure 3.1: The Orion Nebula, M42. This is the most famous example of a H II region. The gas fluoresces because of the ultra-violet radiation from hot, young stars recently formed in a dense region of gas. [Hubble Space Telescope image produced by NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team.]
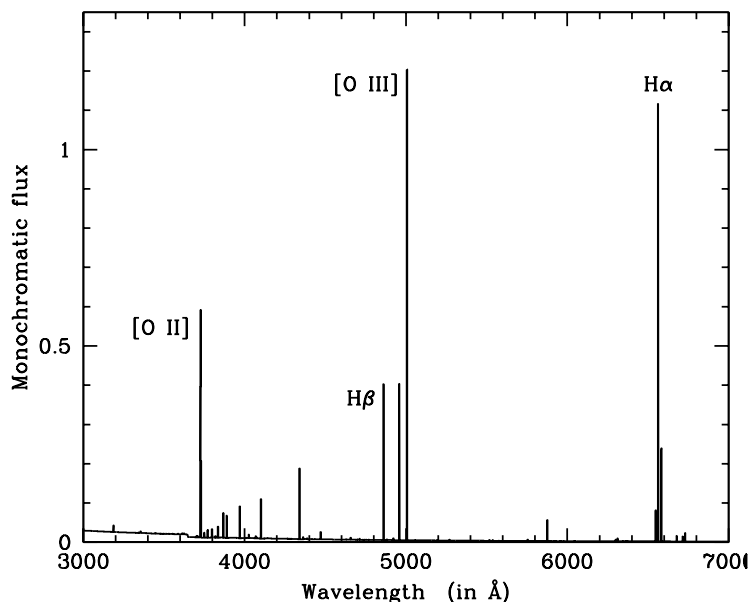
The optical spectrum of the Orion Nebula. The spectrum shows very strong emission lines from species such as H I, [O II] and [O III].

Colour optical images of H II regions of the kind used in popular astronomy books show strong red and green colours: the red is produced mainly by the Hα line, while the green is produced by [O III] and Hβ. H II regions are seen prominently in images of spiral and irregular galaxies. Their emission lines dominate the spectra of late-type galaxies and are valuable for use in measuring redshifts.

The photoionisation and recombination process in H II regions and planetary nebulae produces, by a convenient accident, one Balmer photon for each Lyman continuum photon from the hot star, so the ultraviolet flux from the star can be measured by observing an optical spectrum of the H II region surrounding the hot star. The reason is basically that the gas is opaque to Lyman photons and transparent to other photons, since *almost all the H atoms are in the ground state*. A Lymancontinuum photon initially from the star will get absorbed by a hydrogen atom, producing a free electron. This electron will then be captured into some bound state. If it gets captured to the ground state we are back where we started (with a ground state atom and a Lyman continuum photon), so consider the case where the electron is captured to some $n > 1$ state. Such a capture releases a free-bound continuum photon which then escapes, and leaves an excited state which wants to decay to $n = 1$. If it decays to $n = 1$ bypassing $n = 2$, it will just produce a Lyman photon which will almost certainly get absorbed again. Only if it decays to some $n > 1$ will a photon escape. In other words, if the decay bypasses $n = 2$ it almost always gets another chance to decay to $n = 2$ and produce a Balmer photon that escapes. The Lyα photons produced by the final decay from $n = 2$ to $n = 1$ random-walk through the gas as they get absorbed and re-emitted again and again. The total Balmer photon flux thus equals the Lyman continuum photon flux. One can then place the source star in an optical-ultraviolet colour–magnitude diagram, and determine a colour temperature which is called the Zanstra temperature in this context.

H II regions and planetary nebulae also produce thermal continuum radiation. The process that produces this is free-free emission: free electrons in the H II can interact with protons without recombination, and the acceleration of the electrons in this process produces radiation. (Electrons can interact with other electrons in similar fashion

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as well, but this produces no radiation because the net electric dipole moment does not change.) The resulting spectrum is not blackbody because the gas is transparent to free-free photons: there is no redistribution of the energy of the free-free photons. In fact the spectrum is quite flat at radio frequencies – this is the same thing as saying that the time scale for free-free encounters is $\ll 1/\nu$ for radio frequency ν.

Detailed analyses of the relative strengths of the emission lines from HII regions can provide measurements of the temperatures, densities and chemical composition of the interstellar gas. This is possible for nebulae in our Galaxy and for emission lines in other galaxies. Measuring the chemical compositions of gas in galaxies is important in understanding how the abundances of chemical elements vary from one place in the Universe to another.

3.6 Hot Gas: Planetary Nebulae

A planetary nebula is like a compact HII region, except that it surrounds the exposed core of a hot, highly evolved star rather than a hot young star. The gas is ejected from the star through mass loss over time. Ultraviolet photons from the star ionise the gas in manner similar to HII regions, and the gas emits photons like a HII region. Emission processes are similar to HII regions, but the density, temperature and ionisation state of the gas around a planetary nebula can be somewhat different to a HII region.

Planetary nebulae are relatively luminous and have prominent emission lines. As such they can be observed in other galaxies and can be detected at greater distances than many individual ordinary stars. They can be used to trace the distribution and kinematics of stars in other galaxies.
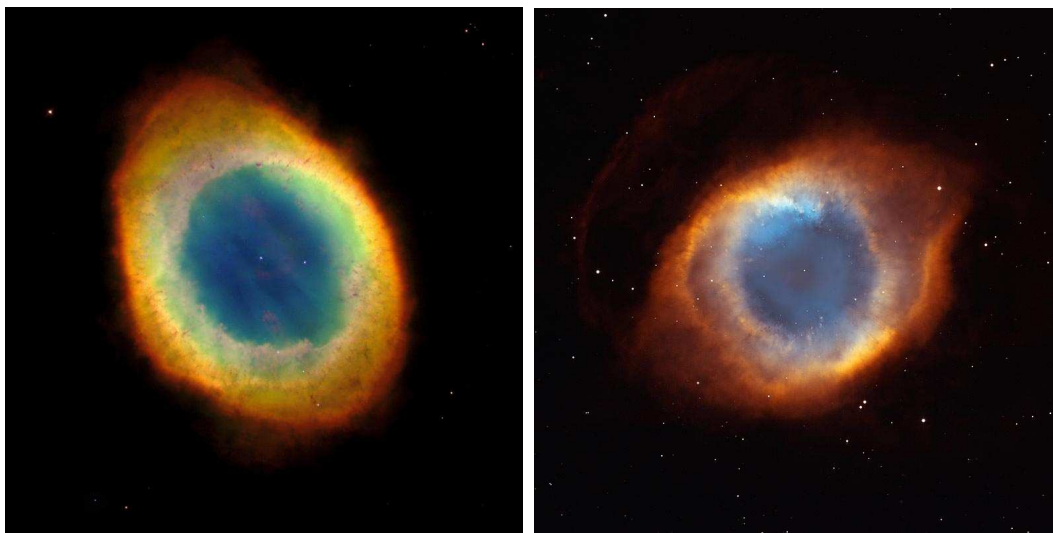

Figure 3.2: Examples of planetary nebulae: the Ring Nebula (M57), left, and the Helix Nebula, right. Gas has been ejected from a hot, evolved star and the ultraviolet radiation from the star ionises the gas. [Images from the Hubble Space Telescope. Ring Nebula: produced by the Hubble Heritage Team (AURA/STScI/NASA). Helix Nebula: produced by NASA, NOAO, ESA, the Hubble Helix Nebula Team, M. Meixner (STScI), and T.A. Rector (NRAO).]

3.7 Hot Gas: Supernova Remnants

Supernovae eject material at very high velocities into the interstellar medium. This gas shocks, heats and disrupts the ISM. Low density components of the ISM can be significantly affected, but dense molecular clouds are less strongly affected. Hot gas from supernovae can even be ejected out of the Galactic disc into the halo of the Galaxy. Supernova remnants have strong line emission. They expand into and mix with the ISM.
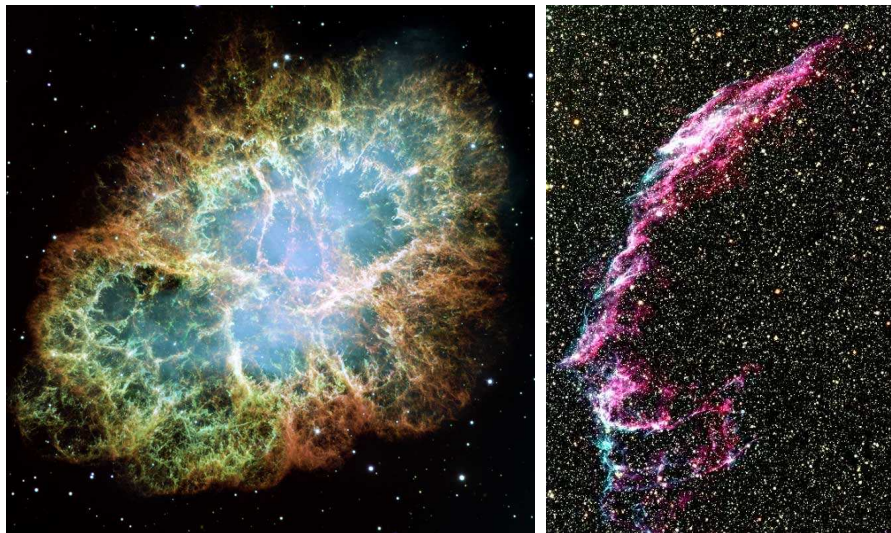

Figure 3.3: Examples of supernova remnants: the Crab Nebula (M1), left, and part of the Veil Nebula, right. The Crab Nebula is a very young supernova remnant, produced by a supernova observed in the year 1054. The Veil Nebula is an older example. [The Crab Nebula image is from the Hubble Space Telescope: it was produced by NASA, ESA, J. Hester and A. Loll (Arizona State University). The Veil Nebula image is from the 0.9m Burrell Schmidt Telescope at Kitt Peak National Observatory, Arizona: it was provided by NOAO/AURA/NSF.]

3.8 Hot Gas: Masers

In the highest density HII regions ($\sim 10^{14}$ m^{-3}), either very near a young star, or in a planetary-nebula-like system near an evolved star, population inversion between certain states becomes possible. The overpopulated excited state then decays by stimulated emission, i.e., it becomes a maser. An artificial maser or laser uses a cavity with reflecting walls to mimic an enormous system, but in an astrophysical maser the enormous system is available for free; so an astrophysical maser is not directed perpendicular to some mirrors but shines in all directions. But as in an artificial maser, the emission is coherent (hence polarised), with very narrow lines and high intensity. Masers from OH and H$_2$O are known. Their high intensity and relatively small size makes masers very useful as kinematic tracers.

3.9 Hot Gas: Synchrotron Radiation

Finally, we'll just briefly mention synchrotron radiation. It is a broad-band non-thermal radiation emitted by electrons gyrating relativistically in a magnetic field, and can be observed in both optical and radio. The photons are emitted in the instantaneous direction of electron motion and polarised perpendicular to the magnetic field. The really spectacular sources of synchrotron emission are systems with jets (young stellar objects with bipolar outflows, or active galactic nuclei). It is synchrotron emission that lights up the great lobes of radio galaxies.

3.10 Absorption-Line Spectra from the Interstellar Gas

If interstellar gas is seen in front of a continuum background light source, light from the source is found to be absorbed at particular wavelengths. A number of interstellar lines and molecular bands are seen in absorption. This process requires a relatively bright background source in practice.

The molecular absorption can be very complex. Electron transitions in the molecules do not produce single strong spectral lines, but a set of bands. This is because of the effect of the various vibrational and rotational energy states of the molecules in the gas, combined with the stronger electronic transitions.

Some of the interstellar absorption features are not well understood. One particular problem is the diffuse interstellar bands in the infrared. These are probably caused by carbon molecules, possibly by polycyclic aromatic hydrocarbons (PAHs).

An interesting example of the importance of interstellar absorption lines concerns measurements of the temperatures of cold interstellar CN molecules. Like most heteronuclear molecules, CN has rotational modes which produce radio lines. The radio lines can be observed directly, but more interesting are the optical lines that have been split because of these rotational modes. Observations of cold CN against background stars reveal, through the relative widths of the split optical lines, the relative populations of the rotational modes, and hence the temperature of the CN. The temperature turns out to be $2.7\,\mathrm{K}$, i.e., these cold clouds are in thermal equilibrium with the microwave background. The temperature of interstellar space was first estimated to be $\simeq 3\,\mathrm{K}$ in 1941, well before the Big Bang predictions of 1948 and later, but nobody made the connection at the time.

3.11 The Components of the Interstellar Medium

It is sometimes convenient to divide the diffuse gas in the interstellar medium into distinct components, also called phases:

- the cold neutral medium – consisting of neutral hydrogen (HI) and molecules at temperatures $T \sim 10 - 100\,\mathrm{K}$ and relatively high densities;
- the warm neutral medium – consisting of HI but at temperatures $T \sim 10^3 - 10^4\,\mathrm{K}$ of lower densities;
- the warm ionised medium – consisting of ionised gas (HII) at temperatures $T \sim 10^4\,\mathrm{K}$ of lower densities;

- the hot ionised medium – consisting of ionised gas (HII) at very high temperatures $T \sim 10^5 - 10^6$ K but very low densities.

(Note that sometimes only three phases are considered, with the warm neutral medium and the warm ionised medium lumped together as warm gas.)

These phases are pressure-confined and are stable in the long term. Ionisation by supernova remnants is an important mechanism in producing the hot ionised medium. The cold neutral medium makes up a significant fraction $\sim 50\%$ of the ISM's mass, but occupies only a very small fraction by volume. Some other individual structures in the ISM, such as supernova remnants, planetary nebulae, HII regions and giant molecular clouds, are not included in these phases because they are not in pressure equilibrium with these phases.

3.12   Interstellar Dust

Interstellar dust consists of particles of silicates or carbon compounds. They are relatively small, but have a broad range in size. The largest are $\simeq 0.5\ \mu$m in size (i.e. $\simeq 5 \times 10^{-7}$ m) with $\sim 10^4$ atoms, but some appear to have $\lesssim 10^2$ atoms and thus are not significantly different from large molecules.

Dust has a profound observational effect – it absorbs and scatters light. Dust diminishes the light of background sources, a process known as interstellar *extinction*. Examples of this are dark nebulae, and the *zone of avoidance* for galaxies at low galactic latitudes.

Consider light of wavelength λ with a specific intensity I_λ passing through interstellar space. (Specific intensity of light here means the energy transmitted in a direction per unit time through unit area perpendicular to that direction into unit solid angle per unit interval in wavelength.) If the light passes through an element of length in the interstellar medium, it will experience a change $\mathrm{d}I_\lambda$ in the intensity I_λ due to absorption and scattering by dust. This is related to the change $\mathrm{d}\tau_\lambda$ in the optical depth τ_λ at the wavelength λ that the light experiences along its journey by

$$\frac{\mathrm{d}I_\lambda}{I_\lambda} \; = \; -\,\mathrm{d}\tau_\lambda \; . \tag{3.1}$$

(Note that $\mathrm{d}I_\lambda$ is negative because the intensity is reduced by the absorption.) Integrating over the line of sight from a light source to an observer, the observed intensity is

$$I_\lambda \; = \; I_{\lambda 0}\, \mathrm{e}^{-\tau_\lambda} \; , \tag{3.2}$$

where $I_{\lambda 0}$ is the light intensity at the source and τ_λ is the total optical depth along the line of sight.

This can be related to the loss of light in magnitudes. The magnitude m in some photometric band is related to the flux F in that band by $m \; = \; C \; - \; 2.5\,\log_{10}(F)$, where C is a calibration constant. So, the change in magnitude caused by an optical depth τ in the band is $A \; = \; -2.5\,\log_{10}(\mathrm{e}^{-\tau}) \; = \; +1.086\,\tau$. The observed magnitude m is related to the intrinsic magnitude m_0 by

$$m \; = \; m_0 \; + \; A, \tag{3.3}$$

where A is the extinction in magnitudes (the intrinsic magnitude m_0 is the magnitude that the star would have if there were no interstellar extinction). A depends on the
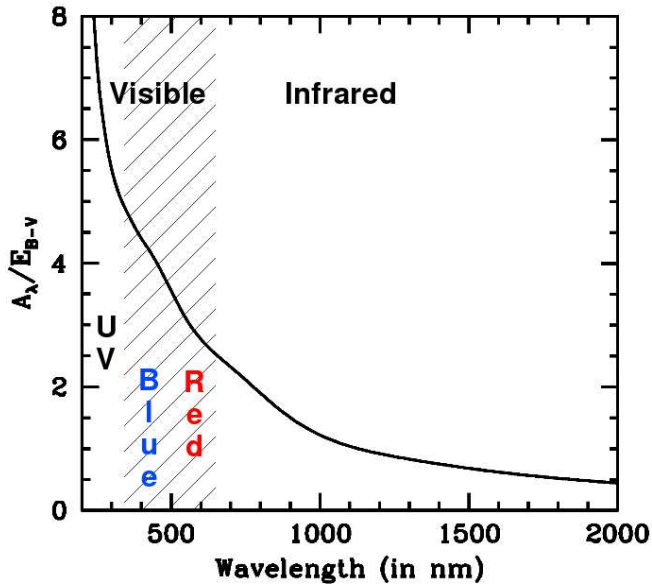
The interstellar extinction law. The extinction caused by dust is plotted against wavelength and extends from the ultraviolet through to the near-infrared.
[Based on data from Savage & Mathis, Ann. Rev. Astron. Astrophys., 1979.]

photometric band. For example, for the V (visual) band (corresponding to yellow-green colours and centred at 5500 Å), $V = V_0 + A_V$, while for the B (blue) band (centred at 4400 Å), $B = B_0 + A_B$. For sight lines through the Galaxy at the Galactic poles, $A_V \simeq 0.00$ to 0.05 mag, while at intermediate galactic latitudes, $A_V \simeq 0.05$ to 0.2 mag. However, in the Galactic plane, the extinction can be many magnitudes, and towards the Galactic Centre it is $A_V \gg 20$ mag.

A_λ is a strong function of wavelength and it scales as $A_\lambda \sim 1/\lambda$ (but not as strong as the $\sim 1/\lambda^4$ relation of the Rayleigh law). There is therefore much stronger absorption in the blue than in the red. This produces an interstellar reddening by dust: as light consisting of a range of wavelengths passes through the interstellar medium, it is reddened by the selective loss of short wavelength light compared to long wavelengths. Colour indices are reddened, e.g. $B - V$ is reddened so that the observed value is $(B - V) = (B - V)_0 + E_{B-V}$, where $(B - V)_0$ is the intrinsic values (what would be observed in the absence of reddening) and E_{B-V} is known the *colour excess*. The colour excess measures how reddened a source is. The colour excess is therefore the difference in the extinctions in the two magnitudes, e.g. $E_{B-V} = A_B - A_V$. If the intrinsic colour can be predicted, i.e. we can predict $(B - V)_0$ (e.g. from a spectrum), it is possible to calculate E_{B-V} from $E_{B-V} = (B - V) - (B - V)_0$. E_{B-V} data can then be used to map the dust distribution in space. It is found from observations that the extinction in the V band $A_V \simeq 3.1 E_{B-V}$. Extinction gets less severe for $\lambda \gtrsim 1\,\mu m$ as the wavelength gets much longer than the grains. Grains are transparent to X-rays.

The extinction becomes very strong for long sight lines through the disc of the Galaxy. The Galactic Centre is completely opaque to optical observations. There is some patchiness in the distribution of the dust. A few areas of lower dust extinction towards the bulge of our Galaxy, such as Baade's Window, enable the stars in the bulge to be studied.

We can model the extinction caused by dust in the Galaxy to predict how the extinction in magnitudes towards distant galaxies will depend on their galactic latitude

b. The optical depth caused by dust extinction when light of wavelength λ travels a short distance $\mathrm{d}s$ through the interstellar medium is given by $\mathrm{d}\tau_\lambda = \kappa_\lambda\,\rho_d\,\mathrm{d}s$, where ρ_d is the density of dust at that point in space and κ_λ is the mass extinction coefficient at that point for the wavelength λ. Observations of star numbers show that their number density declines exponentially with distance from the Galactic plane. We shall adopt a similar behaviour for the density of dust, and therefore assume that the density of dust varies with distance z above the Galactic plane as $\rho_d(z) = \rho_{d0}\,\mathrm{e}^{-|z|/h}$, where ρ_{d0} and h are constants.
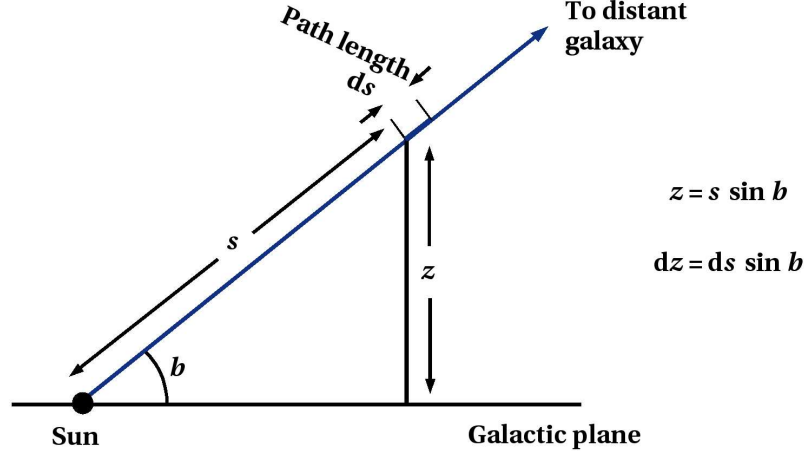
The optical depth when travelling a distance $\mathrm{d}s$ along the line of sight at galactic latitude b is $\mathrm{d}\tau_\lambda = \kappa_\lambda\,\rho_d(z)\,\mathrm{d}s = \kappa_\lambda\,\rho_d(z)\,\mathrm{d}z/\sin|b|$ where z is the distance north of the Galactic plane. Integrating along the line of sight,

$$\int_0^{\tau_\lambda} \mathrm{d}\tau_\lambda' = \int_0^\infty \frac{\kappa_\lambda\,\rho_d(z)\,\mathrm{d}z}{\sin|b|} = \int_0^\infty \frac{\kappa_\lambda\,\rho_{d0}\,\mathrm{e}^{-|z|/h}}{\sin|b|}\,\mathrm{d}z = \frac{\kappa_\lambda\,\rho_{d0}}{\sin|b|}\int_0^\infty \mathrm{e}^{-|z|/h}\,\mathrm{d}z$$

assuming that the opacity κ_λ does not vary with distance from the Galactic plane. Therefore,

$$\tau_\lambda = \frac{\kappa_\lambda\,\rho_{d0}\,h}{\sin|b|} = \kappa_\lambda\,\rho_{d0}\,h\,\mathrm{cosec}|b|\ . \tag{3.4}$$

Since the extinction in magnitudes is $A_\lambda = 1.086\tau_\lambda$, we get

$$A_\lambda = 1.086\,\kappa_\lambda\,\rho_{d0}\,h\,\mathrm{cosec}|b|\ . \tag{3.5}$$

Therefore the extinction in magnitudes towards an extragalactic object is predicted to vary with galactic latitude b as $A_\lambda \propto \mathrm{cosec}|b|$ in this particular model. By coincidence, the same $\mathrm{cosec}|b|$ dependence of A_λ on galactic latitude b is obtained using a simplistic model in which the dust is found in a slab of uniform density centred around the Galactic plane.

3.13   Interstellar Dust: Polarisation by Dust

However, extinction by dust does one very useful thing for optical astronomers. Dust grains are not spherical and tend to have some elongation. Spinning dust grains tend
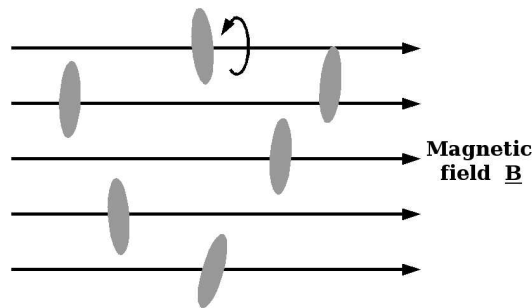
to align with their long axes perpendicular to the local magnetic field. They thus preferentially block light perpendicular to the magnetic field: extinction produces polarised light. The observed polarisation will tend to be parallel to the magnetic field. Hence polarisation measurements of starlight reveal the direction of the magnetic field (or at least the sky-projection of the direction).

Dust also reflects light, with some polarisation. This is observable as reflection nebulae, where faint diffuse starlight can be seen reflected by dust.

3.14   Interstellar Dust: Radiation by Dust

Light absorbed by dust will be reradiated as a black-body spectrum (or close to a black-body spectrum). The Wien displacement law states that the maximum of the Planck function B_λ over wavelength of a black-body at a temperature T is found at a wavelength

$$\lambda_{\mathrm{max}} = \frac{2.898 \times 10^{-3}}{T} \ \ \mathrm{K\,m} \ . \tag{3.6}$$

This predicts that the peak of the black-body spectrum from dust at a temperature of $T = 10\,\mathrm{K}$ will be at a wavelength $\lambda_{max} = 290\,\mu\mathrm{m}$, from dust at $T = 100\,\mathrm{K}$ will be at a wavelength $\lambda_{max} = 29\,\mu\mathrm{m}$, and for $T = 1000\,\mathrm{K}$ will be at $\lambda_{max} = 2.9\,\mu\mathrm{m}$.

The radiation emitted by dust will be found in the infrared, mostly in the mid-infrared, given the expected temperatures of dust. This can be observed, for example using observations from space (such as those made by the IRAS and Spitzer satellites), as diffuse emission superimposed on a reflected starlight spectrum. However, the associated temperature of the black-body is surprisingly high – $T \sim 10^3\,\mathrm{K}$ – which is much hotter than most of the dust. The interpretation of this is that some dust grains are so small (< 100 atoms) that a single ultraviolet photon packs enough energy to heat them to $\sim 10^3\,\mathrm{K}$, after which these 'stochastically heated' grains cool again by radiating, mostly in the infrared. This process may be part of the explanation for the correlation between infrared and radio continuum luminosities of galaxies (e.g., at $0.1\,\mathrm{mm}$ and $6\,\mathrm{cm}$), which seems to be independent of galaxy type. The idea is that ultraviolet photons from the formation of massive stars cause stochastic heating of dust grains, which then reradiate them to give the infrared luminosity. The supernovae resulting from the same stellar populations produce relativistic electrons which produce the radio continuum as synchrotron emission.
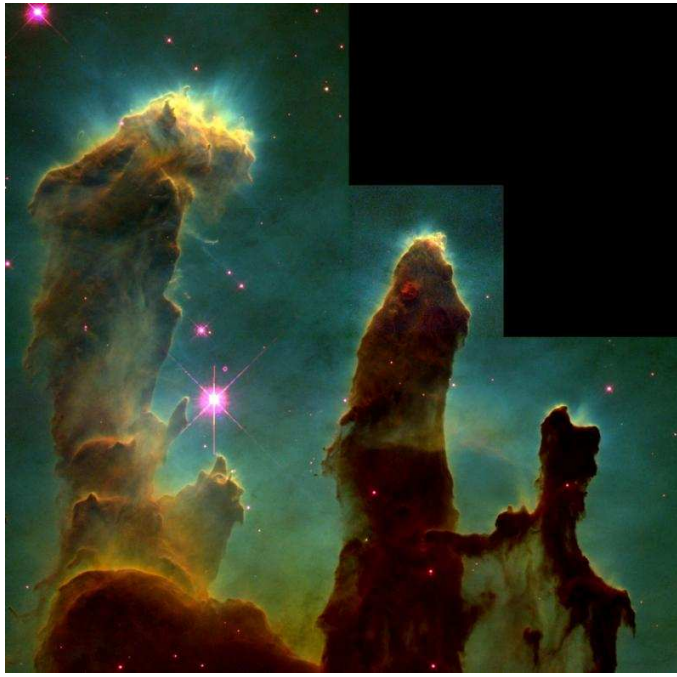
Figure 3.4: A region within M16, The Eagle Nebula. This famous Hubble Space Telescope image shows detail within a HII region. The blue-green colour from the mostly ionised gas is caused by the light of [OIII] and $H\beta$ emission lines from neutral hydrogen atoms. The gas is being ionised by ultraviolet radiation from hot, young stars off the top of the picture. The dark pillars, in contrast, are regions of cold, dense molecular hydrogen gas in which star formation is occurring. They are dark because the cold molecules emit virtually no light and because of the absorption of light by dust mixed with the gas. The ultraviolet radiation is 'burning' away the surface of the cold gas by photoionisation. [Hubble Space Telescope image produced by NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University).]

3.15   Star formation

Stars form by the collapse of dense regions of the interstellar medium under their own gravity. This occurs in the cores of molecular clouds, where the gas is cold (~ 10 K) and densities can exceed 10^{10} molecules m^{-3}.

A region of cold gas will collapse when its gravitational self-attraction is greater than the hydrostatic pressure support. This gravitational instability is often described by the *Jeans length* and *Jeans mass*. For gas of uniform density ρ, the Jeans length λ_J is the diameter of a region of the gas that is just large enough for the gravitational force to exceed the pressure support. It is given by

$$\lambda_J = c_s \sqrt{\frac{\pi}{G\rho}} \ , \tag{3.7}$$

where c_s is the speed of sound in the gas and G is the constant of gravitation. The Jeans mass is the mass of a region that has a diameter equal to the Jeans length and is therefore

$$M_J = \left(\frac{4}{3}\pi(\lambda_J/2)^3\right)\rho = \frac{\pi}{6}\rho\lambda_J^3 \ . \tag{3.8}$$

The time taken for a region of cold gas to collapse to form a star will depend on the extent that gas pressure slows the collapse. A limit on the time taken can be found from the *free-fall collapse time* T_{ff}, which is the time taken for a static cloud to collapse under its own gravity in the absence of gas pressure. The free-fall collapse time for a spherically symmetric distribution of mass with a total mass M and initial radius R to collapse from rest is

$$T_{ff} = \pi \sqrt{\frac{R^3}{8GM}} = \sqrt{\frac{3\pi}{32} \frac{1}{G\overline{\rho}}} , \qquad (3.9)$$

where $\overline{\rho}$ is the mean density before the collapse starts.

Star formation can be self-propagating. Stars will form, heat up and ionise the cold molecular gas, with the resulting outwards flow of gas compressing gas ahead of it. This compression causes instabilities that result in local collapse to form new stars. The enhanced density in the spiral arms of our Galaxy and of other spiral galaxies means that star formation occurs preferentially in the arms.