Chapter 4

The Interstellar Medium (ISM)

CO §12

The interstellar medium (ISM) is the *stuff* between the stars. It is a rich but complex physical system, with gas collecting in large molecular clouds (*Giant Molecular Clouds*, GMC's), which form stars that then destroy the clouds, polluting the gas with metals. Stellar winds and super nova explosions stir the gas, and may even expell some gas from the MW into the surrounding circumgalactic medium. Dust, magnetic fields and cosmic rays[1] play an important but poorly understood rôle. This chapter concentrates on the composition of the ISM, explains how the different components can be observed, discusses how stars and gas interact, and concludes with the important concept of Jeans mass, relevant for how stars form in clouds.

4.1 The baryon cycle

Figure 4.1 attempts to illustrate the complex flow of baryons inside the ISM. On the left, some of the ISM gas gets dense enough to form molecular clouds in which stars form. Stellar evolution makes some of these stars lose mass, and at the end of their lives, they may return most of their mass back into the

[1] COSMIC RAYS are energetic particles (photons, electrons, protons, nuclei of heavier elements), with kinetic energies up to orders of magnitude higher than what can presently be achieved in labs such as SLAC or Cern, that bombard Earth. With Profs Rochester and Wolfendale, Durham has a rich history in cosmic ray physics, and continues to do so with its involvement in the HESS telescope in Namibia.

ISM, for example through a planetary nebula phase (for intermediate mass stars), or through super nova (SN) explosions (for more massive stars). The gas lost by these stars is enriched by their nucleo-synthesis products and may also contain dust. In addition, the SNe inject tremendous amounts of energy into the ISM. How all of this fits together is not terribly well understood.

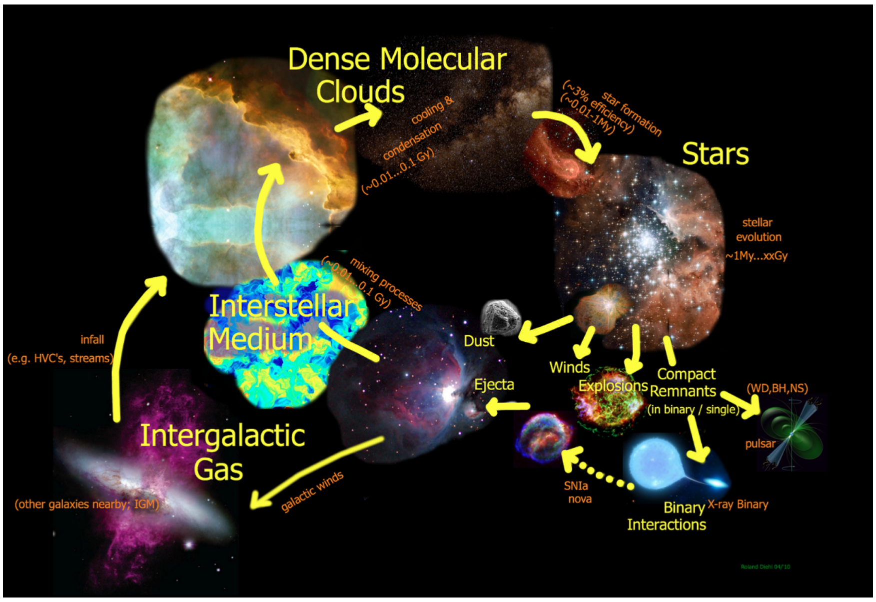

Figure 4.1: Baryon cycle in the ISM, from gas to clouds to stars and back to gas.

4.2 Interstellar dust (CO §12.1)

Interstellar dust consists of small (micron-sized) solid particles, made of C and/or Si, and various ices, as illustrated by Fig. 4.2. The main source of dust is thought to be super novae and AGB stars. The dust grains affect the chemistry of the ISM, its thermodynamics (relation between temperature and density), and also the propagation of light. Quite relevant to life, such tiny particles presumably enable planet formation. Dust particles may *absorb* or *scatter* light, with the scattered light polarized.

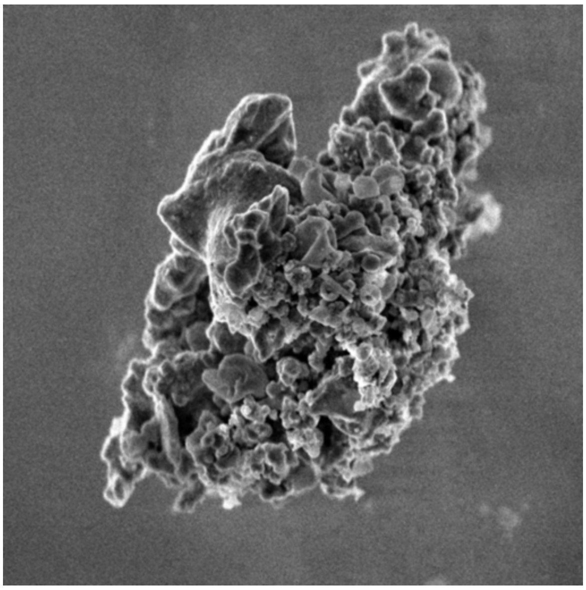

Figure 4.2: A dust grain.

Absorption: a photon may be absorbed by a dust grain, meaning its energy goes into heating the grain. When the dust grain cools down again, it does so by emitting radiation at longer wavelengths. It is thought that nearly 50% of all star light produced in the Universe is reprocessed by dust, converting (mostly) blue and UV light (emitted by stars) into IR light. Notice that the momentum of the photon is absorbed as well, meaning the dust grain gets a little kick when absorbing light. Dust clouds may therefore be accelerated by the radiation pressure exerted by nearby stars. A beautiful example is the 'light erosion' suffered by the so-called PILLARS OF CREATION (the Eagle nebula).

Scattering: a photon may reflect (scatter) off a dust grain, changing its direction but not its energy. The scattered light is polarized.

The amount of scattering and absorption depends on the wavelength of the light (in addition to the properties of the grains), a phenomenon we are familiar with in terms of how the Earth's atmosphere affects Sun light. Sun light gets scattered (mostly by atoms and molecules rather than by dust) with blue light getting scattered more than red light. This makes the sky blue and the Sun appear (slightly) redder, see Fig. 4.3. That scattering

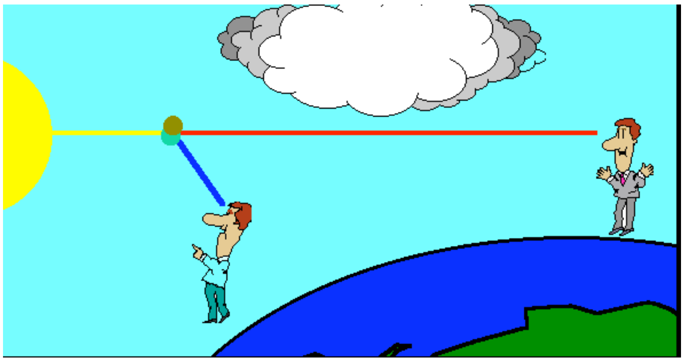

Figure 4.3: Scattering of Sunlight in the Earth's atmosphere, from The Physics and Relativity FAQ.

induces polarization is well known to anybody that has polarized sun glasses to reduce the glare from sunlight scattering off the ocean.

Applied to the ISM: dust will make more distant stars appear *fainter* (because light is absorbed) and *redder* (because blue light is absorbed more strongly). Think back to the dark bands we noticed in images of spiral galaxies: these are dust lanes where the amount of absorption is clearly very large; in the previous lecture we saw how these dust clouds glow in the IR. The large amount of dust in the MWs disc prevents us from seeing the MW's bulge in optical light - but we can detect it in the IR where absorption is much reduced.

Although the amount of scattering/absorption increases with decreasing wavelength λ, on average, some photons have *just* the right wavelength to be in resonance with quantum transitions of the atoms in the dust grain. Such absorption features allow us to determine the composition of grains.

4.3 Interstellar gas (CO §12.1)

Gas in the ISM can be in molecular, neutral, or ionised form. What determines which phase the gas is in? How are the different phases observed? The processes discussed below are illustrated in Fig. 4.4.

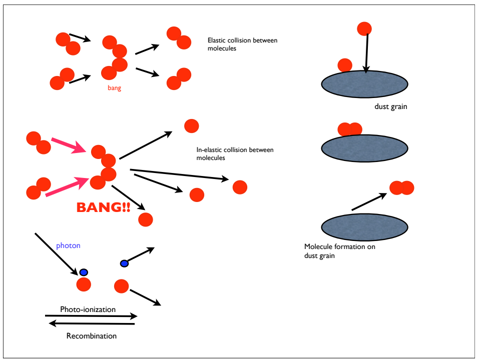

Figure 4.4: Common physical and chemical processes in the ISM.

Notation Astronomers use the (confusing) notation X III to denote the *doubly* ionised state of element X. For example, C III≡C^{2+}, H I is neutral Hydrogen, H II ionised Hydrogen, and O VI is five-times ionised O.

4.3.1 Collisional processes

Reminder L1 course, Kinetic theory of gases, Young & Freedman §18.3 The typical velocity v of particles (atoms, say) with mass m in a gas with temperature T is $v^2 \sim 3kT/m$. A collision between such particles will have typical kinetic energy $E \sim \frac{1}{2}mv^2 \sim 3kT/2$. The velocity distribution of such particles is a Maxwell-Boltzmann distribution, $\mathcal{P}(v) \propto \exp(-mv^2/(2kT))$.

To understand the physics of particle-particle collisions in a gas, let us start with cold molecular gas, which for simplicity consists of H_2 molecules only, and let's concentrate on collisions with electrons, e.

A diatomic molecule such as H_2 has 'internal degrees of freedom'(doF), meaning energy can be stored in rotation (2 doF) and vibration (1 doF, but with twice the amount of energy), in addition to the 3 doF associated with the velocity of the molecule. As with all energy levels in quantum mechanics, the energy of roto-vibrational doF are quantised, meaning you need to transfer sufficient energy to the molecule to make it spin, and even more to make it vibrate.

Consider an electron colliding with H_2 at low speed (hence low T). It cannot excite a rotation in the molecule because the collisions energy is too low to even excite the lowest rotational energy level. Hence the kinetic energy of the collision cannot change, and the collision is *elastic*. The diatomic molecule effectively acts as a mono-atomic molecule, with heat capacity at constant volume, $C_V = 3R/2$. Higher speed electrons (higher T) *can* excite rotations, the collision is no longer elastic, and $C_V = 5R/2$. At even higher T, also vibrations can be excited, and $C_V = 7R/2$. Here, R is the gas constant, see Y&F §18.4, and in particular Fig. 18.19. At even higher T, things get even more interesting.

If kT is sufficiently high, a collision may break the molecular bond,

$$e + \mathrm{H}_2 \to e + 2\,\mathrm{H}\,.$$

We can estimate the required temperature by comparing kT to the binding energy $E_{\mathrm{H}_2} \approx 4.5$ eV of H_2, $kT \approx 4.5\mathrm{eV} \to T \approx 5 \times 10^4\mathrm{K}$. This is nearly an order of magnitude higher than measured! The reason is that electrons have a Gaussian distribution of energies at a given T, and the higher energy electrons in the tail of the Gaussian *can* destroy the bond, even if the *average* energy electron can not.

At even higher $T \approx 10^4\mathrm{K}$, a collision may ionise the hydrogen atom,

$$e + \mathrm{H\,I} \to 2e + \mathrm{H\,II}\,.$$

In summary, we expect *cold gas to be molecular*, *warm gas to be atomic*, and *hot gas to be ionised*.

Finally consider regions in the ISM with different temperatures, for example a warm, neutral gas cloud embedded in hot, ionised gas. The pressure in these gases should be comparable. Indeed, suppose the pressure in the cloud were lower, then the cloud will be compressed, increasing its pressure, until the cloud is in pressure balance. Our previous reasoning then further implies that warm clouds are neutral *and dense*, and hot gas is ionised and *tenuous* (of low density). This is indeed what we see in the ISM, were cold, dense molecular clouds are embedded in warmer, neutral gas, itself embedded in hot, ionised and tenuous gas. However there is one more mechanism that is important: photo-ionisation.

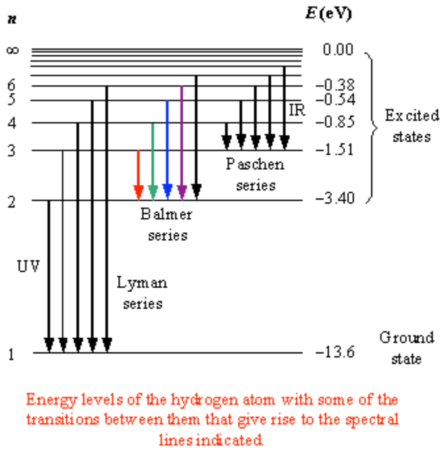

Figure 4.5: Electronic transitions in the Hydrogen atom, and nomenclature of the corresponding emission lines. Figure taken from the internet encyclopedia.

4.3.2 Photo-ionisation and HII regions (CO p.431)

A photon impinging on an atom may ionise the atom in a process called *photo-ionisation*, for example for H I:

$$\gamma + \text{H I} \rightarrow e + \text{H II}\,.$$

The photon energy has to be higher than $h\nu = 13.6$eV, where 13.6 eV is the binding energy of H I. The wave-length of such a photon is $\lambda = hc/(13.6 \text{ eV}) \leq 911$ Å. Such high-energy photons are only emitted in large numbers by hot stars, in particular by massive MS-stars.

In an ionised gas (a plasma), the reaction can also occur from right to left, when a proton catches an electron, leading to the emission of one or more photons: this is called *recombination*. Recombining hydrogen gas emits a set of characteristic lines, associated with the energy levels of H I, shown in Fig. 4.5. Recombinations in star forming regions cause the characteristic red glow of the H I $n = 3 \rightarrow 2$ Hα line of the Balmer series[2]

Recall that the massive stars that emit ionising radiation are short-lived. The detection of Hα emission from a galaxy is therefore a good handle of its

[2] The other transitions are also detected, but Hα is particularly strong.

star formation rate. Go back to the images of spiral galaxies from chapter I: you can see how many reddish star forming regions follow the spiral structure in disc galaxies, as beads on a string. It is the gas that surrounds the massive stars that produces this recombination radiation, with the image revealing the associated Hα radiation. We describe the ionisation structure of such gas clouds, called H II regions, next.

4.3.3 H II regions and Strömgren spheres

Suppose a hot star forms at time $t = 0$, emitting ionising radiation at a constant rate, $\dot{N}_\gamma$ (in ionising photons per second). Suppose further that the star is at the centre of a spherical cloud, initially atomic, with uniform hydrogen number density n (in hydrogen atoms per unit volume).

An *ionization* front will run into the cloud, with gas at distance $r \leq R$ being ionised. The radius of the front at time t, $R(t)$, follows from requiring each of the $(4\pi/3)R^3 n$ hydrogen atoms (the number of atoms in a sphere of radius R) has interacted with a photon. Since the number of photons emitted in time t is $\dot{N}_\gamma t$, this results in

$$\dot{N}_\gamma t = \frac{4\pi}{3}\, n\, R(t)^3\,.$$

The speed of the front follows from taking the derivative of this equation (taking into account that $\dot{N}_\gamma$ and n are both constant)

$$\dot{R}(t) = \frac{\dot{N}_\gamma}{4\pi R^2\, n}\,.$$

The speed of the front slows down as R increases. Notice also that $\dot{R} \to \infty$ for $R \to 0$: clearly this can't be right: the front can't move faster than c. The fact that is does is a limitation of our model.

When the gas is ionised, it will also recombine as discussed in the previous section. The *recombination rate* - the rate at which the gas recombines per unit volume producing H I, is of the form

$$\frac{\mathrm{d}n_{\rm H\ I}}{\mathrm{d}t} = \alpha\, n_{\rm H\ II}\, n_e \approx \alpha n^2\,.$$

The recombination coefficient, α, is an atomic constant; the last part of the equation assumes that inside the H II region, the gas is very high ionised, so that[3] $n_{\mathrm{H\ II}} \approx n$. The larger the ionised volume, the higher the total recombination rate in the gas. Eventually this causes the ionisation front to stall (stop increasing), because each recombination consumes a photon, leaving no ionising photons to ionise H I for the first time. This limiting radius is called the *Strömgren* radius, R_S, and its value can be found by equating the total recombination rate within R_S, to the rate $\dot{N}_\gamma$ at which the star emits ionising radiation:

$$\frac{4\pi}{3}\,\alpha\, n^2\, R_s^3 = \dot{N}_\gamma\,.$$

Using typical values of $n = 5\times 10^3\mathrm{cm}^{-3}$ for the density of a cloud, $\dot{N}_\gamma = 10^{49}\mathrm{s}^{-1}$ for the ionisation rate of a massive star, and using $\alpha \approx 3.1\times 10^{-13}$ $\mathrm{cm}^3\ \mathrm{s}^{-1}$ (valid for temperatures $\sim 10^4$ K in HII regions) gives a Strömgren radius $R_S \approx 0.21\mathrm{pc}$.

4.3.4 21-cm radiation (CO p. 405)

The electronic transitions of, for example, the Lyman and Balmer series, discussed earlier, correspond to transitions of the electron between different *orbital* energy levels. Recall that the energy level in a hydrogen atom only depends on the value of n, the *principle quantum number*, and not on l or m (which characterise the total angular momentum L, and L_z the angular momentum along the z-axis, respectively.)

However, both proton and electron have another purely quantum mechanical (QM) property called *spin*. The spin[4] of an elementary particle has some properties in common with a magnetic moment, and the energy of an electron in a hydrogen atom will be higher (less bound) if the electron and proton spins are parallel, and lower (more strongly bound) if they are anti-parallel[5] The curious rules of QM mean that these spins in fact can only be either parallel or anti-parallel.

Therefore, a hydrogen atom in which electron and proton spins are parallel, is very slightly less less bound than if the spins were anti-parallel. When

[3]Note that the electron and proton densities are the same, since the cloud was initially fully atomic.

[4]Spin does not feature in Schrödinger's model of the hydrogen atom, but it does appear in Dirac's version.

[5]Just as with bar magnets, who prefer to be anti-parallel rather than parallel.

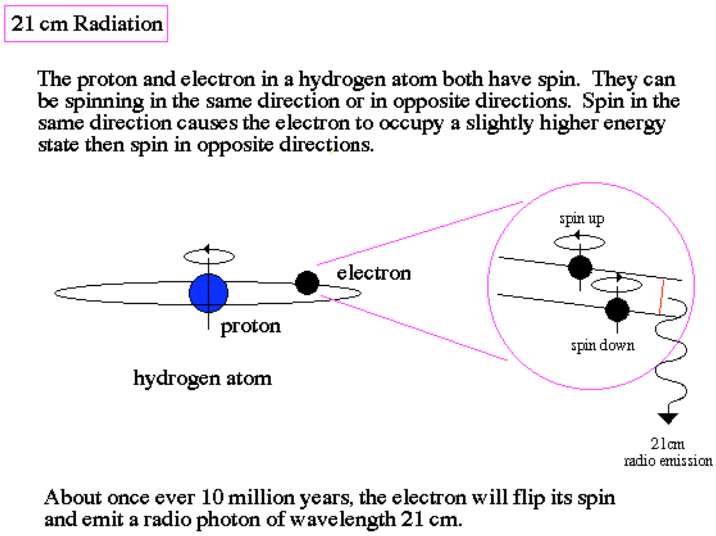

Figure 4.6: Emission of 21-cm radiation in Hydrogen due to a hyperfine transition, taken from Schombert.

a hydrogen atom flips from parallel to anti-parallel states, the energy difference is carried away by a photon with wavelength $\lambda \approx 21$ cm - this is the 'hydrogen 21-cm line', or *hyperfine* line, illustrated in Fig. 4.6. The warm H I gas in the MW, and other galaxies, can be observed in this transition. This line is a great probe of gas in the ISM. Notice that, given its long wavelength, it's propagation is not affected by dust[6].

4.3.5 Other radio-wavelengths

The 21-cm line cannot be used to study gas in dense clouds, because the gas will tend to be molecular instead of atomic. But radio-telescopes can be used to detect roto-vibrational transitions of these molecules, enabling the study of molecular clouds.

[6]The radio-dish on top of the physics department can detect 21-cm radiation from neutral gas in the MW

The MW contains molecular clouds with a wide range in masses, up to *Giant Molecular Clouds*, (GMCs) with masses up to $10^7 M_\odot$. These enormous complexes of gas and dust are almost exclusively found in spiral arms, and are the sites of star formation in the MW: most, if not all, stars are thought to form in GMCs.

4.3.6 The Jeans mass (CO p. 412)

The masses of GMCs are $\sim 10^6 M_\odot$, hence very much higher than those of the stars that form in them. Why is that?

The **Jeans** mass, M_J, in a gas with uniform density, ρ, and temperature, T, is the characteristic mass for which the thermal energy, K, and gravitational energy, U, in a sphere are in virial equilibrium, $2K = U$. When $M > M_J$, gravity dominates, and the sphere will tend to collapse; when $M < M_J$, pressure dominates, and the sphere is stable to collapse.

The thermal energy K in a sphere with mass M is

$$\begin{aligned} K &= M u \\ u &= \frac{3kT}{2\,\mu \mathrm{m_H}}\,, \end{aligned} \tag{4.1}$$

where k is Boltzmann's constant, and $\mu \mathrm{m_H}$ the mean molecular weight per particle. The binding energy U of the sphere is

$$\begin{aligned} U &= \frac{3}{5}\frac{GM^2}{R} \\ M &= \frac{4\pi}{3}\rho\, R^3\,. \end{aligned} \tag{4.2}$$

In virial equilibrium, $2K = U$, and the mass of the sphere is the Jeans mass[7]:

$$M_J = \left(\frac{5\mathrm{k_B}T}{\mu \mathrm{m_H} G}\right)^{3/2} \left(\frac{3}{4\pi\rho}\right)^{1/2}\,. \tag{4.3}$$

[7]You may find expressions which differ by factors of order unity in other texts

In clouds more massive than the Jeans mass, gravity overpowers pressure, and such clouds will collapse. In clouds less massive than M_J, pressure overpower gravity, and such clouds are not susceptible to collapse.

Fragmentation Consider the fate of a cloud with mass $M = M_J$ that starts to collapse. In general, both T and ρ will change, and hence M_J will change as well. If the gas behaves *adiabatically*, $\rho \propto T^{3/2}$, then $M_J \propto \rho^{1/2}$, and the Jeans mass will increase as the cloud collapses. Therefore, if $M = M_J$ initially, then as the cloud collapses, the mass will becomes smaller than the Jeans mass, and the cloud will expand again (basically the restoring pressure increases faster than gravity).

However, consider now a cloud that behaves isothermally, because the gas cools as it collapses so that its temperature remains the same rather than increasing as it gets compressed. Then, as the cloud collapses and ρ increases, M_J *decreases*: smaller clouds, that were initially stable because they had $M < M_J$, now can becomes unstable (because M_J decreased): the cloud may *fragment*.

4.4 Summary

After having studied this lecture, you should be able to

- Describe how we know the properties of interstellar dust from scattering and absorption of star light.
- Explain why we find different ionisation states of interstellar gas, depending on density, temperature, and ionising background.
- Compute the speed of an ionisation front.
- Derive the Strömgren radius for an HII region, and explain the concept.
- Explain the origin of the hydrogen 21-cm line, and explain its importance in understanding the structure of the MW.
- Explain the concept of Jeans mass, and its relation to fragmentation of clouds.