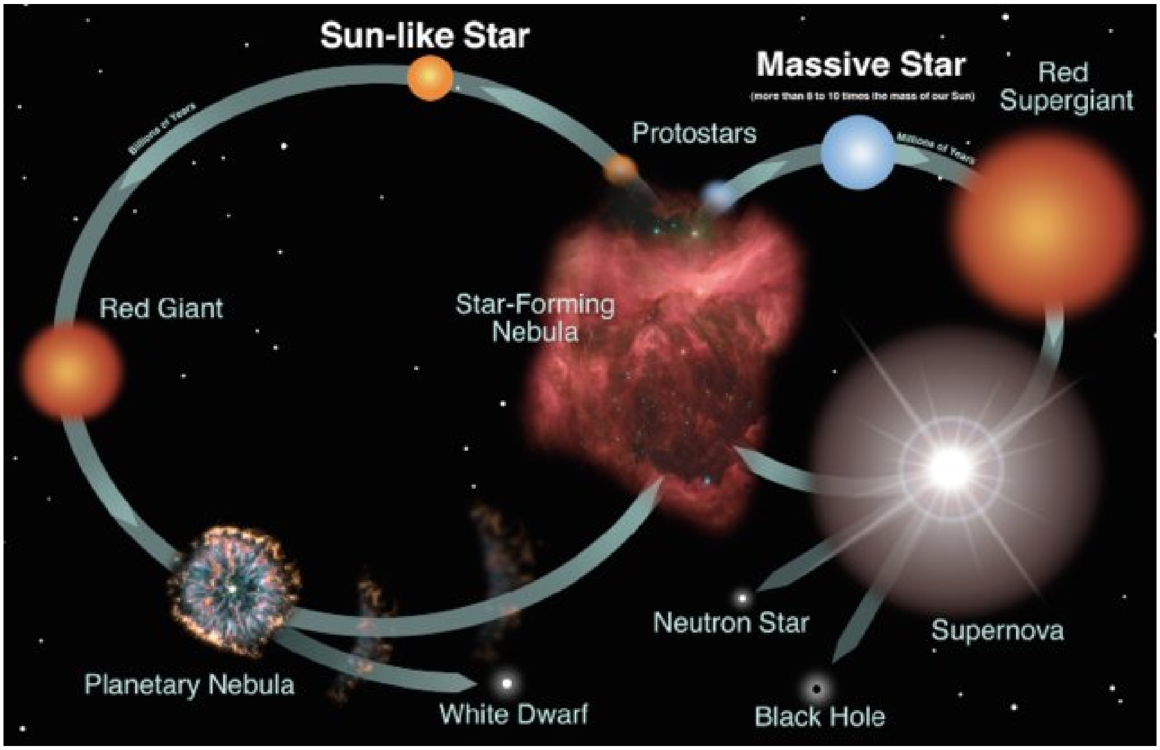

Figure 1: The life cycle of stars in the ISM.

ASTR368
ISM
C+O, Ch. 12

ISM

The interstellar medium (ISM), as the name suggests, is the material between stars. The ISM is a large recycling factory. Stars are born out of material in the ISM (mainly molecular gas). When they die, stars return the products of stellar evolution back to the ISM, from which the next generation of stars is born.

The physics of the ISM is complicated and varied, but the main components can be broken down into just two categories:
- gas
- dust

About 99% of the ISM by mass is gas. ISM gas is mostly diffuse material and is $\sim$90% hydrogen by number ($\sim$75% by mass). We'll talk more about ISM gas in a bit.

About 1% of the ISM by mass is "dust." By dust, I mean groupings of $\sim 50+$ atoms into "dust grains." These dust grains are solid in a sense, although their densities are low; they are similar in this way to the dust under your bed.

Dust (C+O, 12.1)

Despite its low abundance, dust in the ISM has a huge impact on what we see. Dust has a high optical depth at visible wavelengths, and it therefore absorbs and scatters light. Absorption+scattering is known

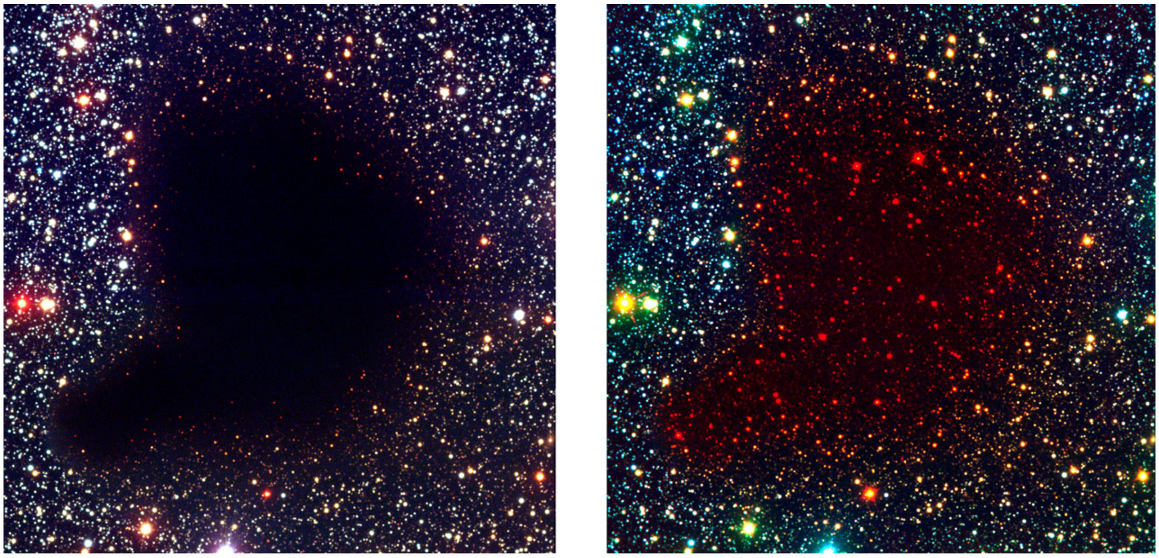

Figure 2: A Bok Globule (a small, dense, nearby molecular cloud) at different wavelenths. At longer wavelengths we see more stars and the stars in the direction of the globule are red. Both of these are effects of extinction, which is decreased at longer wavelengths.

as “extinction.” Extinction removes photons from the line of sight, and is strongly wavelength dependent (Figure 2).

We saw last lecture that:

$$m_\lambda - M_\lambda = 5\log d - 5 \tag{1}$$

Including extinction,

$$m_\lambda - M_\lambda = 5\log d - 5 + A_\lambda\,, \tag{2}$$

where A_λ is the extinction measured in magnitudes. Extinction of course increases the observed magnitude (makes it dimmer).

If we think of dust as having an optical depth at wavelength λ as τ_λ, we can write:

$$I_\lambda = I_{\lambda,0}e^{-\tau_\lambda} \tag{3}$$

Since the magnitude difference is a flux ratio,

$$I_\lambda / I_{\lambda,0} = 10^{0.4(m_{\lambda,0}-m_\lambda)} \tag{4}$$

or

$$m_\lambda - m_{\lambda,0} = -2.5\log(e^{-\tau_\lambda}) = 2.5\log e = 1.086\tau_\lambda \tag{5}$$

Since $m_\lambda - m_{\lambda,0} = A_\lambda$, we get the convenient result that

$$A_\lambda \simeq \tau_\lambda \tag{6}$$

This makes sense logically. At an optical depth of unity, the intensity has decreased by a factor of e ($\simeq 2.7$). We know also that one magnitude difference is a factor of 2.51.

From lectures last semester, the mean free path

$$mfp = 1/(\kappa\rho) = 1/(n\sigma) \tag{7}$$

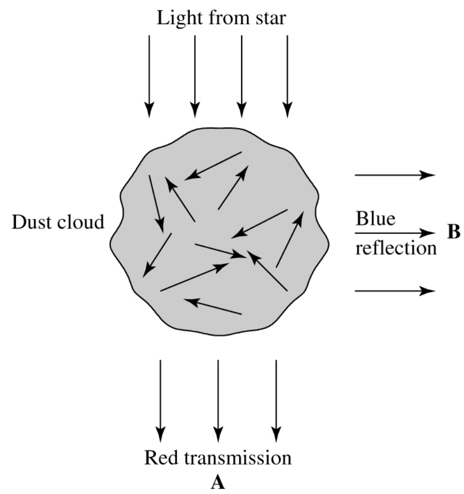

Figure 3: C+O Figure 12.2 showing the process of extinction.

So therefore

$$\tau = \int -\kappa \rho ds = \int \sigma_\lambda n ds = \sigma_\lambda N \tag{8}$$

Here, n is the volume density and N is the "column density," the amount of material in a $1\,\mathrm{m}^2$ cross section cylinder along the line of sight distance s. We will be using column density quite a bit - it is a fundamental quantity of astrophysics because it is directly related to what is observed.

Extinction is greater at shorter wavelengths. This is why you can get cell phone signal from large distances that you can't even see with your naked eye and why eifi travels through walls. The wavelength dependence of extinction is known as interstellar reddening because the photons that are removed from the line of sight are preferentially blue, leading to things looking red (Figure 2).

Dust in the ISM has a characteristic temperature of $\sim 30\,\mathrm{K}$. It emits nearly as a "grey-body." Grey-bodies are optically thin blackbody; although their spectral energy distributions follow the same curve as a backbody, their intensities are less. Where does the emission of a 30 K blackbody peak? Around $100\,\mu$m!. Despite the very low abundance, emission from dust is a major component of the emission from galaxies, and this emission completely dominates the energy output from galaxies from $\sim 500\,\mu$m to $\sim 3\,\mu$m (Figure 4).

Gas (also C+O, 12.1)

Most of the Universe is hydrogen, 90% of the barionic material by number or 75% by mass. This hydrogen exists in:
- ionized (most abundant form in universe, not for galaxies like MW), extremely low density in galaxies like our own, 10^{-3} to 10^{-1} (excluding HII regions) per cc, higher densities in clusters, $T >\sim 5000\,\mathrm{K}$
- atomic ("neutral"), low density of maybe 0.1 to tens of atoms per cc T from 10s to $\sim 10000\,\mathrm{K}$
- molecular, density $10^2 - 10^6$ per cc, T $\sim 25\,\mathrm{K}$

Notice the inverse relationship between density and temperature!

Ionized gas gives off continuous radiation (not blackbody because it is not optically thick!). They also emit line radiation from electronic transitions. We won't discuss those emission processes at length here though.

Luckily, neutral hydrogen (also called "atomic") has a transition at 21cm (1400 MHz). Hydrogen of course has one electron whose spin can be aligned (higher energy config.) or anti-aligned (lower energy config) with the proton spin. It will change spins in a "spin-flip transition," and emit a photon corresponding to the energy difference. This is incredibly rare, but we detect it because of the massive abundance of hydrogen.

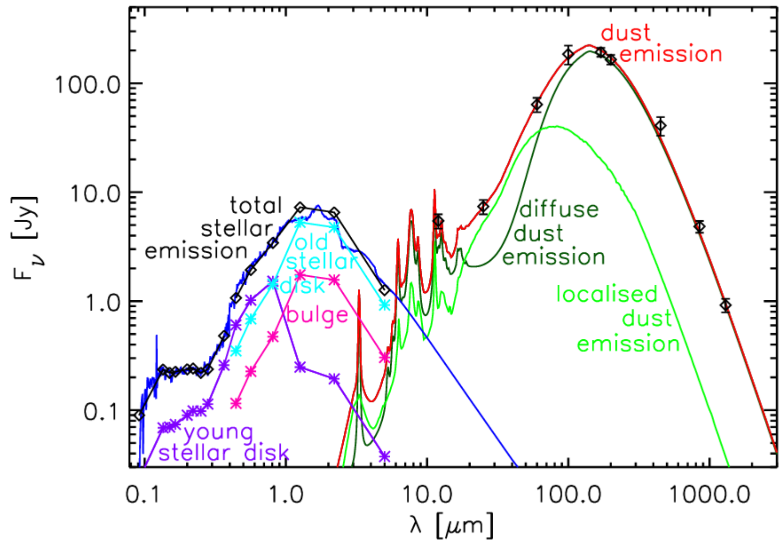

Figure 4: The integrated emission from a galaxy. The major components are stars and dust.

It is almost always optically thin.

21cm is "line" or "emission line" radiation. That means it has a width, a central frequency, and a peak intensity. As a review, the width is caused by:
- natural broadening
- temperature broadening
- pressure broadening (sometimes)
- turbulence/bulk motions

The central frequency is caused by:
- the quantum mechanics of the transitions
- any Doppler shift

The peak intensity is given by:
- the column density of material (if optically thin)

The optical depth will be greatest at the center of the line, and the optical depth decreases on either side of the center. For Hydrogen, at line center, our book gives:

$$\tau_H = 5.2 \times 10^{-23} N_H T^{-1} \Delta V \tag{9}$$

where N_H is the column density of HI in units of m^{-2}, T is the temperature in K, and ΔV is the FWHM line width in $\mathrm{km\,s^{-1}}$.

Molecular Hydrogen

Dense material in normal galaxies is molecular (as is the hydrogen in our atmosphere). Stars form from molecular gas. We would love to detect H_2, but it has no easily observed transitions at the low temperatures of the ISM where we find molecular gas. So instead we use other molecules as tracers of H_2. The most common of these is CO, but NH_3, HCN, HCO^+, HNC, H_2CO, CH, and OH are also common. Since the dust to gas ratio is "relatively" constant, we can use dust (detected in either emission or absorption) as as tracer of molecular hydrogen.

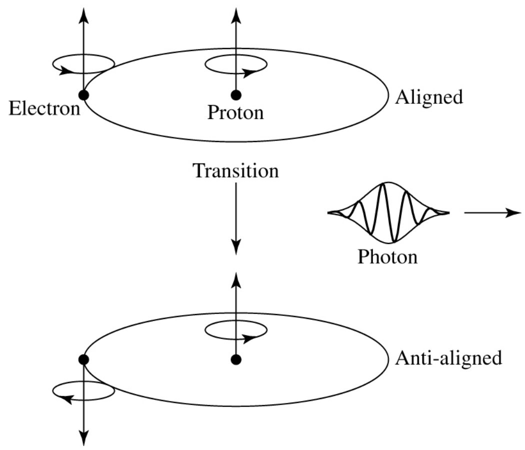

Figure 5: HI Emission

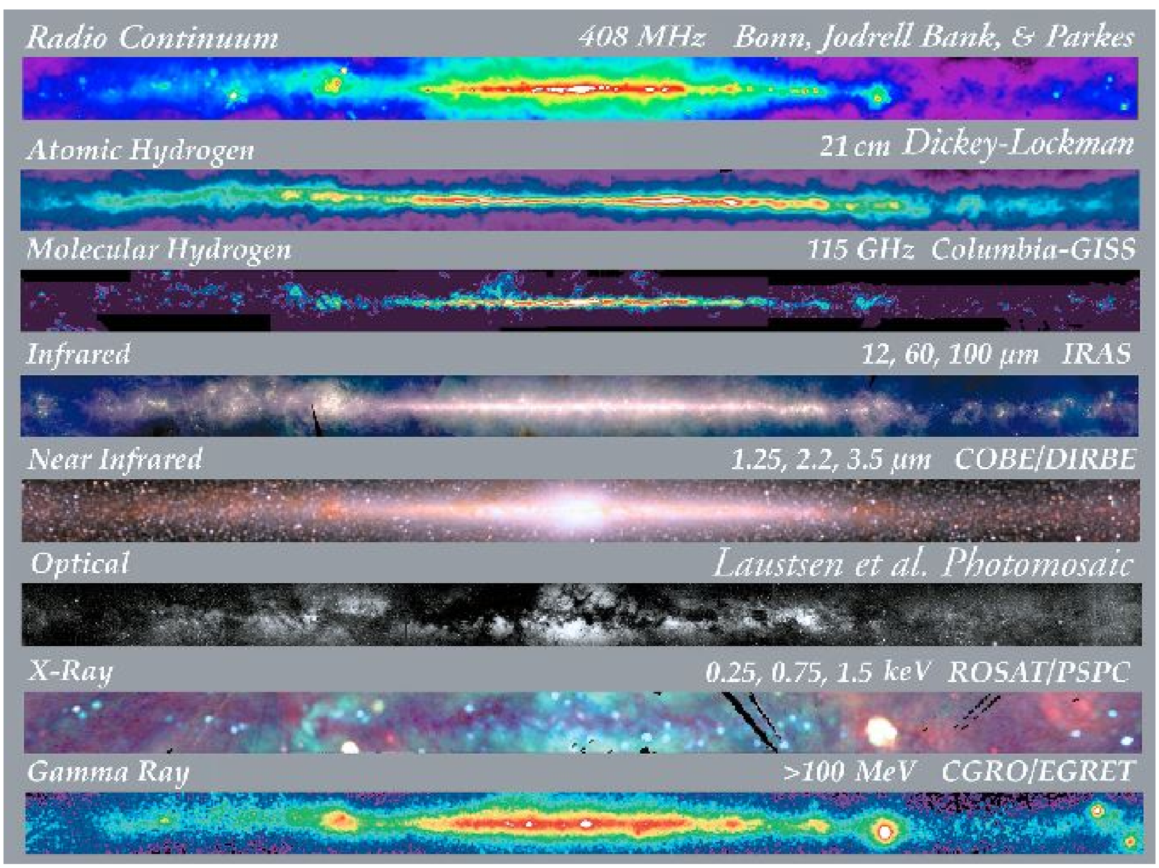

Figure 6: The MW observed at different wavelengths.

Figure 7: Orion Nebula as seen by Hubble.

HII regions

H II regions are the ionized zones around high mass stars. As stars get more massive, their temperatures increase. As the temperatures increase, they emit more UV radiation. This UV radiation ionizes the surrounding gas, creating an ionized sphere surrounding the star. We call these ionized spheres H II regions. Roman numerals for astronomers indicate ionization state. I - neutral. II - singly ionized, III - doubly ionized, etc.

H II regions are extremely bright. At optical wavelengths, we see Hα ($n = 3 \rightarrow 2$) emission from these, as electrons recombine with photons and transition down to the ground state. We'll see examples of these when we talk about galaxies in a bit. The book does the classic Stromgren sphere derivation. This gives a typical H II region size of a few pc. Keep this number in mind.

Review of Formation of Stars (briefly; C+O, Ch. 12.2)

Stars form via gravitational collapse. They are therefore governed by the Virial Theorem. Let's go through this derivation quickly, because we will see something similar for galaxies. The Virial Theorem says:

$$2K + U = 0\,, \tag{10}$$

where K is the kinetic energy of the system and U the potential energy of the system. The Virial Theorem gives the stability point. If $U > 2K$, the cloud has more gravitational (potential) energy than kinetic and will collapse. If $2K > U$, the cloud will not collapse.

What is K? We can use: $K = 3/2NkT$ where N is the number of particles, $N = M_c/(\mu m_H)$. where M_c is the cloud mass.

What is U? If we assume a spherical cloud of constant density, the gravitational potential energy is approximately $U \simeq -3/5GM_c^2/R_c$. Remember this term! It will come up again! After some algebra, we find that

$$M_c \simeq (5kT/G\mu m_H)^{3/2}(3/4\pi\rho_0)^1/2 \tag{11}$$

where ρ_0 is the initial density. This is known as the "Jeans Mass," $M_J = M_c$ above. There is also a Jeans radius:

$$R_J \simeq (15kT/(4\pi G\mu m_H\rho_0)^{1/2} \tag{12}$$

If there is a Jean's mass of material within a Jean's radius, we can form a star. Notice that these quantities only depend on the temperature and initial density. If the temperature is higher, we need more mass to overcome gravity. This is why clouds form preferentially in cold, dense material.

Homologous Collapse (free fall time)

Our book goes through a nice derivation of the timescale it takes for gravitational collapse. Let's take a look at this result and what it means, but skip the derivation.

If we assume that a cloud has no external pressure, and the gas temperature stays constant throughout collapse, and there is a Jeans mass in a Jeans radius, the cloud will just free fall collapse. When the star is formed, $K = U$, so half the potential energy must be radiated away. If this radiated energy does not travel freely (the cloud is optically thick, or marginally so), this will provide an additional pressure, restricting the collapse and increasing the collapse time.

This so-called "free-fall" time is

$$t_{ff} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2} \tag{13}$$

You'll have to derive a version of this for your homework. Notice that as ρ goes up, the free fall time goes down.

The Initial Mass Function

We know that small stars are common and large stars are rare. This in part is because small stars live a long time, but also in part because more small stars are created in general. The "creation" function is called the initial mass function, or IMF. The IMF appears to be nearly universal, and doesn't depend strongly on environment, metallicity, galaxy size, etc. The IMF peaks at about $0.5\,M_\odot$.

The total population of stars in a galaxy is of course the IMF times the stellar lifetimes. This is why high mass stars are rare - they are short-lived and rarely formed. The IMF is important because it tells us the average color of a population of stars (a galaxy) if star formation is ongoing. If star formation stops, the color will become redder as the blue stars will die first.

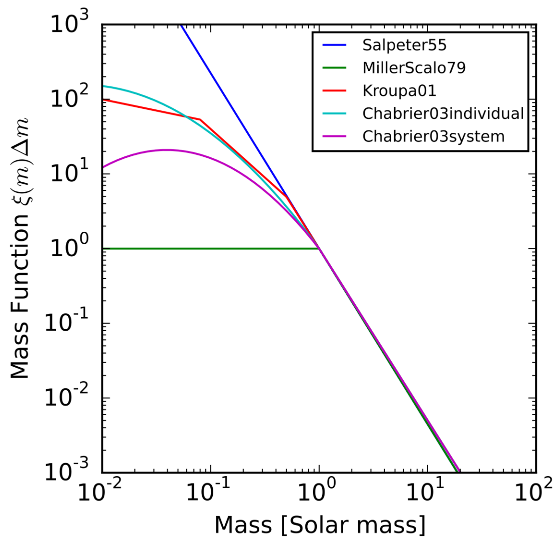

Figure 8: Representations of the initial mass function.