Astronomy 404
October 25, 2013

Chapter 12. The ISM and Star Formation

$$A_\lambda = 1.086\tau_\lambda$$

Mie Theory

$$Q_\lambda \equiv \frac{\sigma_\lambda}{\sigma_g}$$

$$\sigma_\lambda \propto \frac{a^3}{\lambda} \qquad (\lambda \gtrsim a)$$; $$\sigma_\lambda \propto a^2 \qquad (\lambda \ll a)$$

Jeans mass and Jeans length (zero external pressure):

$$M_J \simeq \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

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

Bonnor-Ebert mass: (with an external pressure P_0)

$$M_{\rm BE} = \frac{c_{\rm BE} v_T^4}{P_0^{1/2} G^{3/2}},$$

Free fall time scale:

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

Fragmentation of collapsing clouds - M_J goes down with increasing density, and goes up with increasing temperature.

Additional considerations of protostellar star formation:

- evaporation of dust grains
- dissociation of molecules
- ionization of atoms
- rotation of the cloud/star (angular momentum)
- magnetic fields
- ambipolar diffusion

For a cloud supported by magnetic pressure (instead of thermal pressure), the critical mass for star formation is

$$M_B = c_B \frac{\pi R^2 B}{G^{1/2}}$$, where $$c_B = 380\ \mathrm{N}^{1/2}\ \mathrm{m}^{-1}\ \mathrm{T}^{-1}$$

$$M_B \simeq 70\ \mathrm{M}_\odot \left(\frac{B}{1\ \mathrm{nT}}\right)\left(\frac{R}{1\ \mathrm{pc}}\right)^2$$

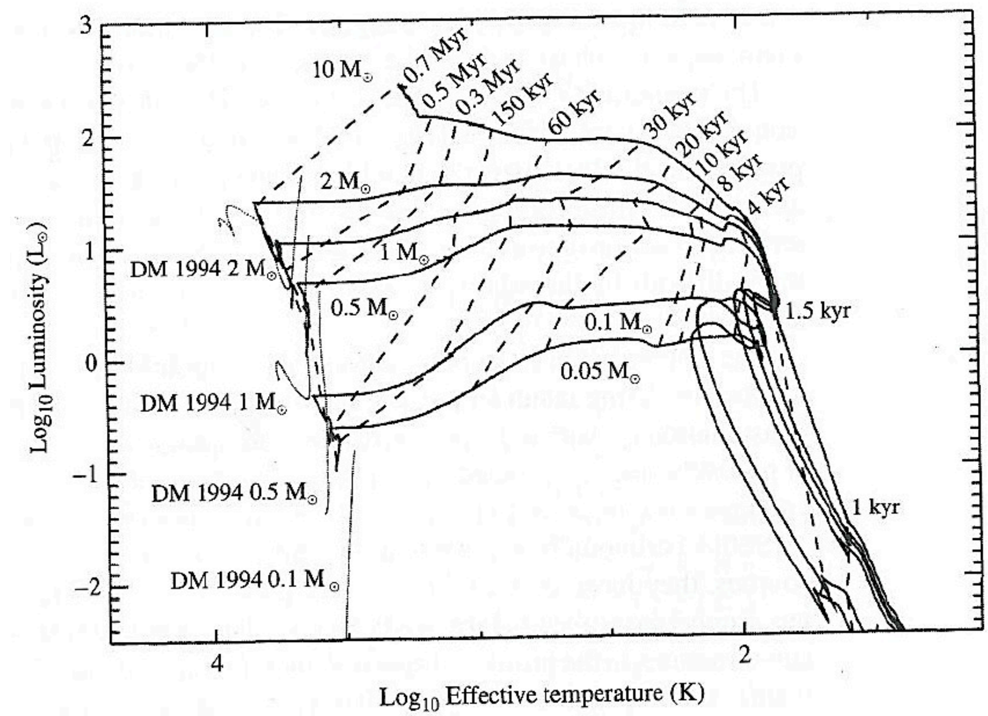
$M_c < M_B$ magnetically subcritical (stable)

$M_c > M_B$ magnetically supercritical (collapse)

Ambipolar diffusion – during the collapse, the ionized particles are frozen-in with the magnetic field, but the neutral particles are not; however, as the neutrals drift across the magnetic field lines, they collide with the charged particles and slow down…

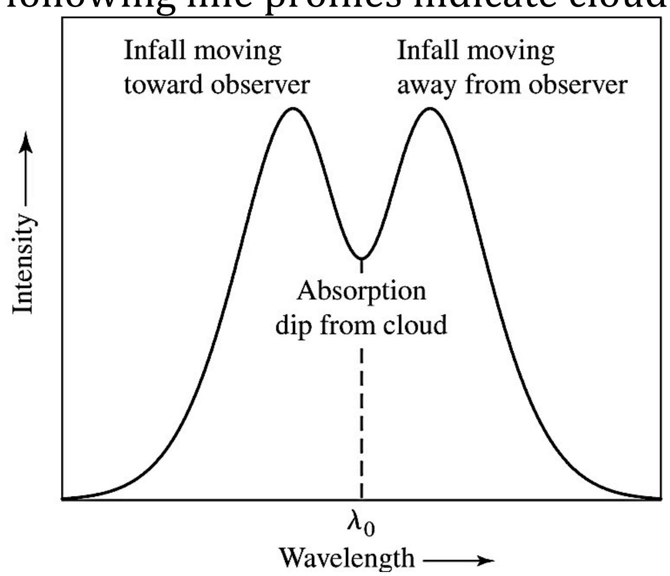
The timescale it takes for a neutral to drift across a cloud is:

$$t_{\mathrm{AD}} \simeq \frac{2R}{v_{\mathrm{drift}}} \simeq 10\ \mathrm{Gyr} \left(\frac{n_{\mathrm{H}_2}}{10^{10}\ \mathrm{m}^{-3}}\right)\left(\frac{B}{1\ \mathrm{nT}}\right)^{-2}\left(\frac{R}{1\ \mathrm{pc}}\right)^2$$



Theoretical evolutionary tracks of the gravitational collapse of clouds of various masses through the protostar phase. From D'Antona and Mazzitelli 1994, ApJS, 90, 457.

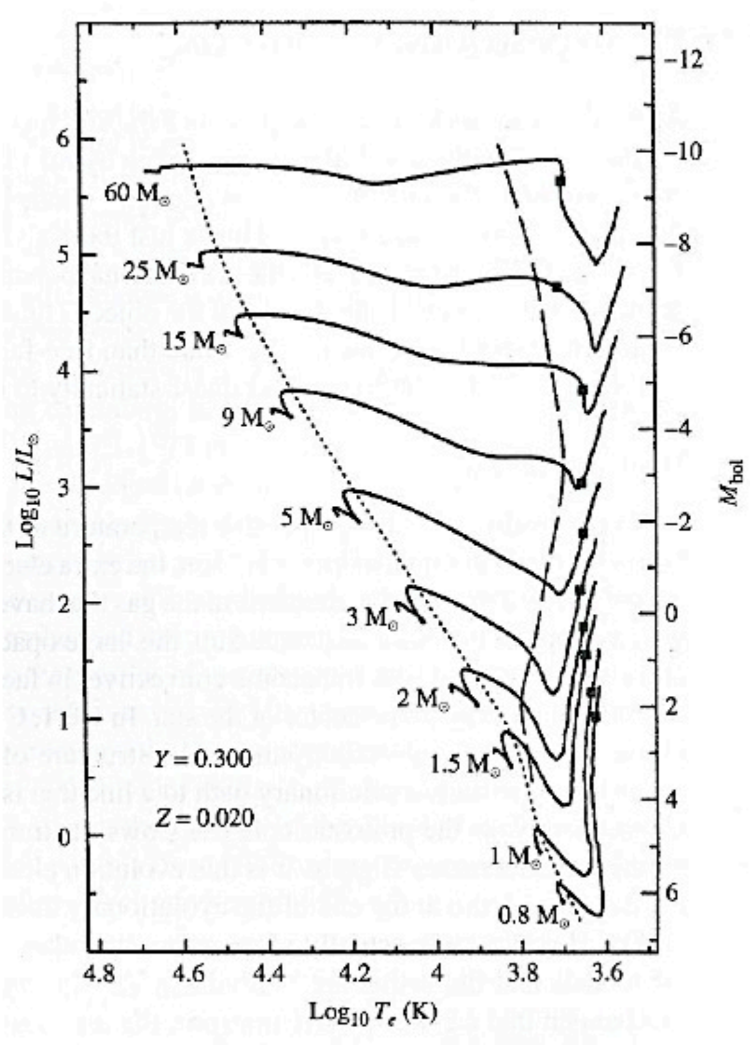
Observationally, it has been suggested that IR lines show the following line profiles indicate cloud collapse:



Pre-Main Sequence Evolution

The Kelvin-Helmholtz timescale of a solar-mass cloud is ~ 10^7 yr, while the free-fall timescale for a cloud density of 3×10^{-17} kg m^{-3} is ~ 4×10^5 yr. Therefore, cloud collapse is much slower than a free-fall. It takes 40 Myr for a cloud to contract to a 1 $M_\odot$ star.

The Hayashi track:



The opacity in the envelope/atmosphere of the a pre-main sequence star is dominated by H^-. As we only see into $\tau = 2/3$, the size of the emitting region decreases as collapse goes on, resulting in the decrease in luminosity.

The H^- opacity leads to convection. (Remember the Sun's convective envelope?)

^2H (deuterium) starts to burn, but due to the small abundance of ^2H, the energy generated has little effect on the collapse.

A turning point. When the core becomes hot enough and everything is ionized, it becomes radiative. A radiative core allows energy to escape into the convective envelope more rapidly, and causes the luminosity to increase.

Another turning point. As the core becomes hot enough to allow the first two steps of PP I chain (^1H to ^3He) and the first step of CNO cycle (turning ^{12}C to ^{14}N) reactions, the violent generation of energy causes convection and an expansion of the core. The core expansion reverses the gravitational energy release, causing the net luminosity to decrease.

When ^{12}C is exhausted and temperature is high enough to complete the entire PP I chain, a stable energy source is established, and the star has reached the main sequence.

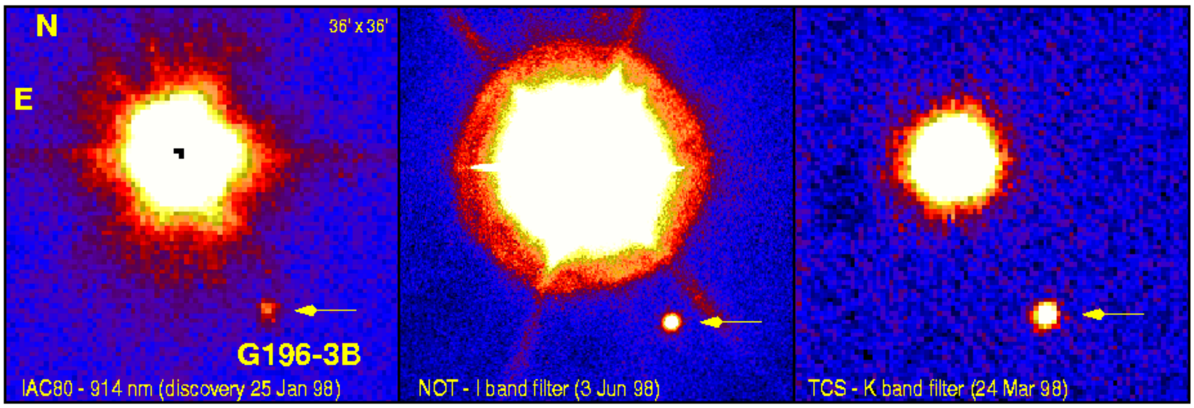
Pre-main sequence contraction times:

Initial Mass ($M_\odot$)	Contraction Time (Myr)
60	0.0282
25	0.0708
15	0.117
9	0.288
5	1.15
3	7.24
2	23.4
1.5	35.4
1	38.9
0.8	68.4

For low-mass stars, the pre-main sequence evolution is different. For $M < 0.5\ M_{\odot}$, the central temperature is not high enough for ^{12}C to turn into ^{14}N, so there is no expansion of the core.

For $M < 0.072\ M_{\odot}$, the core is never hot enough to start nuclear reactions to burn H, so no stable H-burning main sequence is reached.

Brown dwarfs



Brown dwarfs have masses $\sim 0.013 - 0.072\ M_{\odot}$. They are found in IR surveys because of their low temperatures.
Brown dwarfs burn deuterium (^{2}H), but the most massive ones ($> 0.06\ M_{\odot}$) can burn Li.

Massive star formation

Massive stars have high central temperatures and quickly reach temperatures for ^{12}C burning into ^{14}N to start, so the luminosity stays almost flat in the evolutionary track.

Massive stars generate energy so quickly that the energy feedback may halt the accretion of material onto the forming massive star. Because they are formed faster than the low-mass stars, it may be problematic for low-mass stars to form in a cloud that is rapidly dissipated by the UV radiation and stellar winds of massive stars.

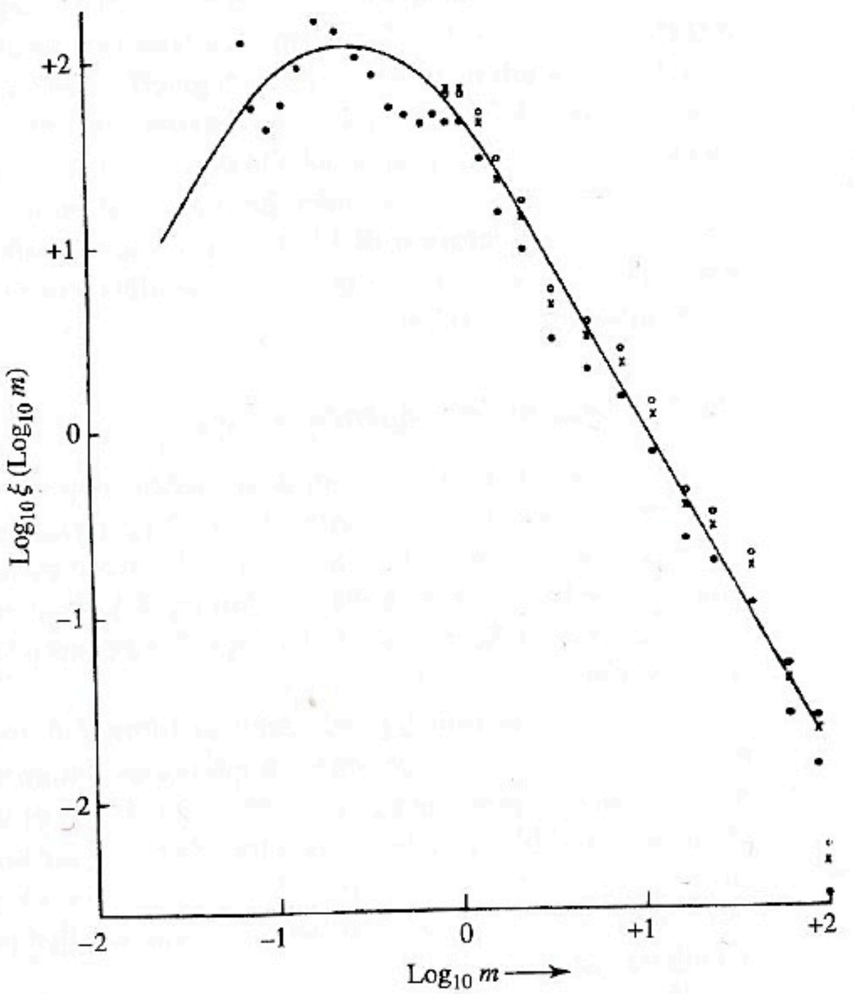
It is not clear whether massive stars and low-mass stars are formed in a similar fashion, i.e., via vaccretion disk and bipolar outflows. It has been proposed that massive stars are formed by merger of smaller stars.

Zero age main sequence

When stars first arrive the main sequence…

Initial mass function (IMF)

Below is the IMF derived for the Milky Way disk:



Salpeter's IMF

$$\xi(m)\Delta m = \xi_0 \left(\frac{m}{M_{\rm sun}}\right)^{-2.35} \left(\frac{\Delta m}{M_{\rm sun}}\right).$$

Kroupa's IMF (2001)

$$\xi(m) = m^{-\alpha},$$
$$\alpha = 0.3 \text{ for } m < 0.08,$$
$$\alpha = 1.3 \text{ for } 0.08 < m < 0.5,$$
$$\alpha = 2.3 \text{ for } 0.5 < m$$

Chabrier (2003) has different IMFs for individual stars and for stellar systems.

Charlie Conroy fits spectral features of elliptical galaxies at high redshift and has shown that the IMF is flatter in the low mass end, $M < 0.2\ M_\odot$.

Massive Stars

Their UV radiation can photo-ionize the ambient gas into HII regions. The Strömgren sphere (a spherical ionized gas cloud) has a radius of :

$$r_S \simeq \left(\frac{3N}{4\pi\alpha}\right)^{1/3} n_H^{-2/3}.$$

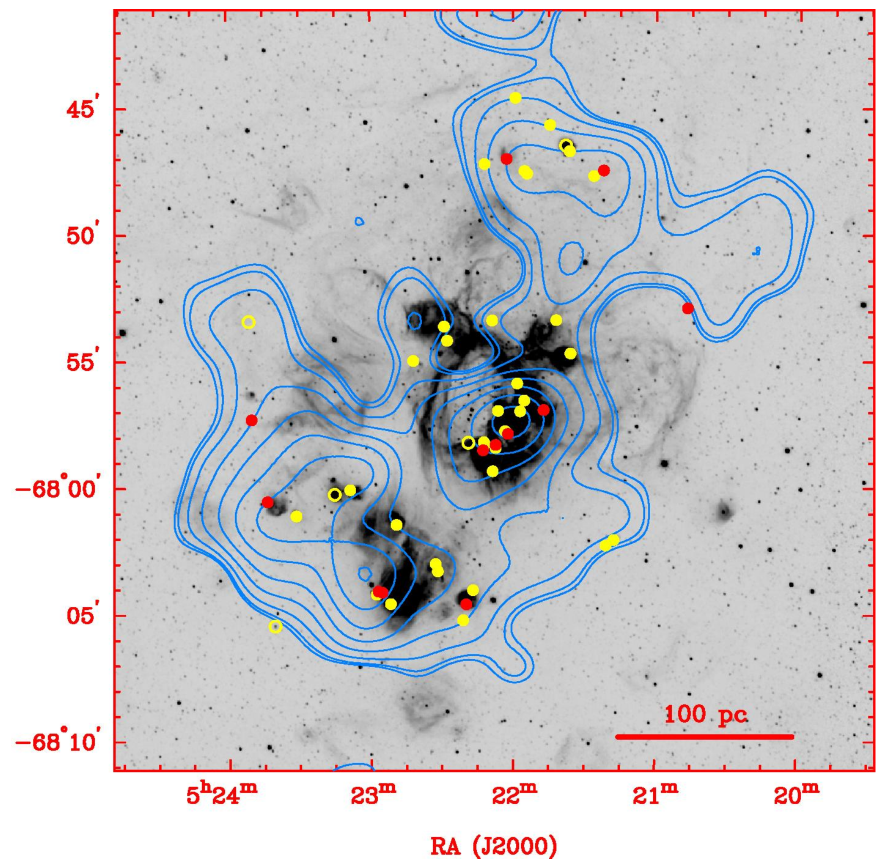
Note that this equation works only when the HII region is optically thick to the ionizing UV radiation.

$\alpha_B = 3.1 \times 10^{-19}\ m^3\ s^{-1}$ at 8000 K

$\alpha_B = 2.6 \times 10^{-19}\ m^3\ s^{-1}$ at 10,000 K

α_B is the recombination coefficient for recombinations to excited state, i.e., n= 2 or higher.

Massive stars are rarely formed in isolation. They are born in clusters or OB associations. They photoionize the ambient medium into HII regions.



In the above image, you see HII regions (black), young stellar objects (red dots for massive stars, and yellow dots for intermediate mass stars), and molecular clouds (cyan contours).

Low-mass pre-main sequence stars

T Tauri stars
FU Orionis Stars
Herbig-Haro objects
Herbig Ae/Be stars