Star Formation & the Milky Way

Pre-MS Stars and the Hayashi Track
The Shape of the Galaxy
Stellar Populations and Motions
Stars as a Gas
Stellar Relaxation Time
Differential Rotation of the Disk
Local Standard of Rest
Galactic Rotation Curves

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Star Formation & the Milky Way

- Synopsis of star formation
- The initial mass function
- Pre-MS stars and the Hayashi track
- The shape of the Galaxy
- Stellar populations and motions
- Stars as a gas: Scale height, velocities, the mass per unit area of the disk, stellar relaxation time, and equilibrium
- Differential rotation of the stars in the disk
- The local standard of rest
- Rotation curves and the distribution of mass
- Spiral structure in the Galaxy

NGC 3351, a spiral galaxy resembling the shape of the Milky Way. Image from Adam Block, Mt. Lemmon Sky Center, U. Az.

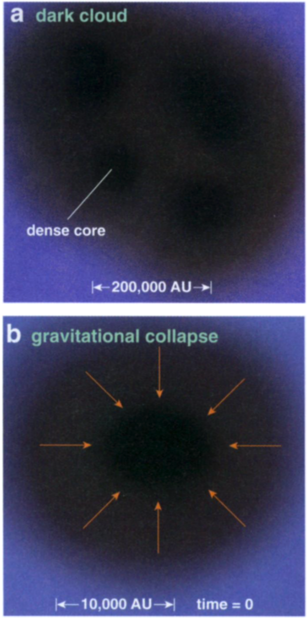
Reading: Kutner Sec. 16.2–16.3, Ryden Sec. 19.4–19.6, Shu Ch. 12

Star formation

1. A fragment of an interstellar molecular cloud (a) becomes unstable and begins collapsing (b), either because the material has cooled or because it has become compressed (**triggered**) from the outside.

2. The collapse proceeds from the **inside out** and **anisotropically**. The central denser region collapses faster:

$$t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G\rho_0}}$$



Star formation

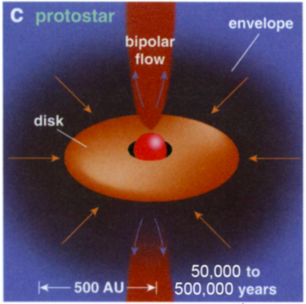
3. Because of conservation of angular momentum, and to a lesser degree from magnetic forces, collapse can always proceed much faster in one dimension than the other two.

   Soon a **disk configuration** is established with a well-defined and very dense central condensation: a **protostar** (c).

   - Protostars have larger luminosities than the stars that they will become, but their heat does not come from fusion.
   - Instead, it is largely **accretion power**: gas falling from large radii onto the protostar's surface.
   - The core of a protostar is about 10 times larger in radius than the star that it will become, and it accretes gas from the disk at a rate

     $$\frac{dm}{dt} = 10^{-5} - 10^{-7} M_{\odot}/\mathrm{yr}$$

     decreasing with core mass and as time goes on (Watson et al. 2016).



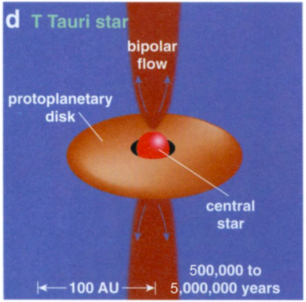
Star formation

4. The disk continues to **accrete** further material from the surrounding molecular cloud, and the protostar accretes material from the disk (d). Due to disk “viscosity,” mass moves inward and angular momentum outward.

   As the disk and central object accretes gas and dust, they drive a **bipolar outflow** into their surroundings, which is thought to carry off the last of the accreted material’s angular momentum.

   By the time that the clump outside the disk is used up or driven away by the outflow, the accretion rate is much less, and most of the luminosity is from **slow contraction of the core**.

   For low-mass stars, this core is called a **T Tauri star** when in this phase.



Star formation

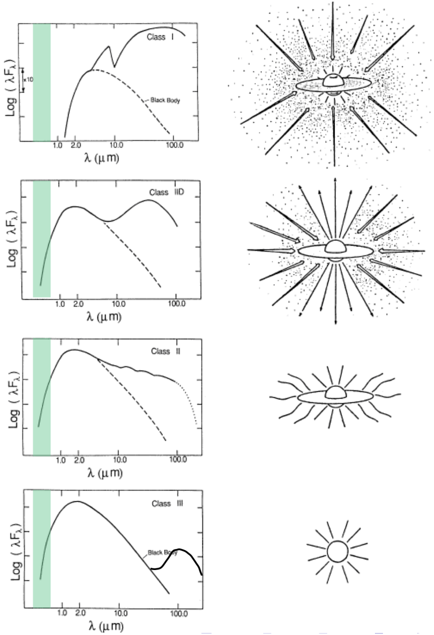
5. The central object becomes a star and its wind and radiation eventually stop the accretion and dissipate the gas in the disk.

   Class 0 or I protostar: class 0 seen at mm/radio; class I: far-IR

   Class II protostar: "T Tauri stars," opaque disk, envelope almost gone, accretion onto star from disk at rate that decreases with age, dropping below $10^{-10} M_{\odot}\ \mathrm{yr}^{-1}$ by 5 Myr.

   Class III protostar: very little dust and gas left in disk. Accretion has stopped.

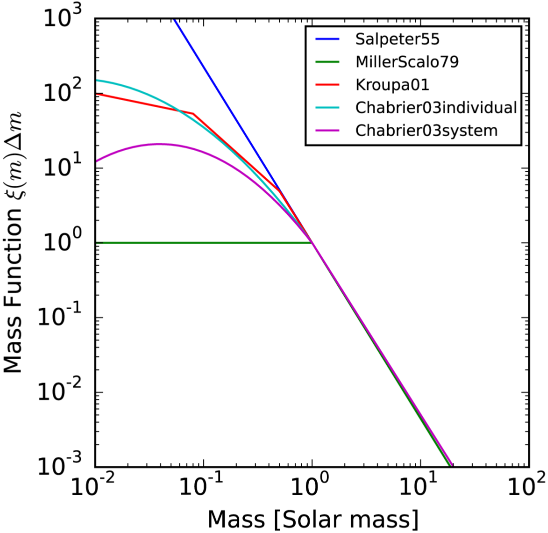
Left: spectral energy distributions of protostar classes (Wilking 1989). Green band shows visible light.



The initial mass function

The **initial mass distribution** is an empirical function describing the distribution of stellar masses that will form from a single molecular cloud.

Observations of numerous young stellar clusters reveal that their stellar mass distributions are nearly identical (the primary difference due to the cluster's age).



Pre-Main Sequence stars

- It takes young lower-mass stars millions of years to settle down to their final sizes and get fusion running.
- During this slow gravitational collapse, the conversion of gravitational potential energy dominates the luminosity of young stars. Recall that gravitationally-driven luminosity is

$$L = -\frac{3}{5}\frac{GM^2}{R^2}\frac{dR}{dt}$$

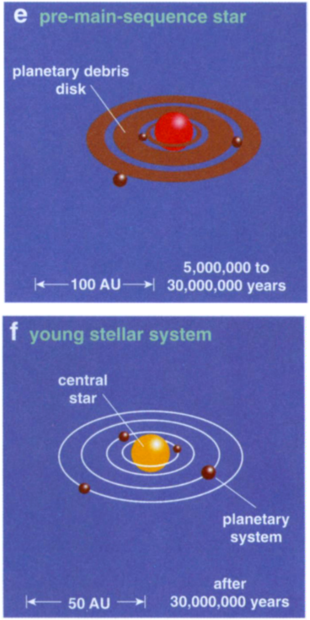
- The gravitational collapse luminosity decreases with time and the star's effective temperature changes little while this is going on. So the young star descends almost vertically at first through the H-R diagram. This path is called the Hayashi track.

Pre-Main Sequence stars

6. After 5 Myr or so, the core is no longer accreting mass, and the gas in the disk is either used up or driven away.

   It still lies well above its eventual resting place on the main sequence, in which condition we call it a pre-main sequence star (e).

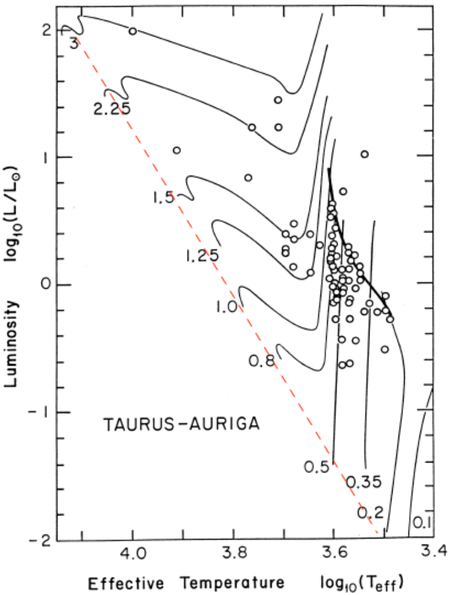
7. Finally, the core reaches pp-chain temperatures, fusion begins, and the star heats up, moving **horizontally** in the HR diagram, towards bluer colors and the main sequence.
   - This part of its HR path is called the Henyey track.



Pre-Main Sequence stars

- The Henyey and Hayashi tracks happen to be the reverse of the path each star takes at the end of its life as it becomes a subgiant and a red giant.
- For a given age, the redder (lower mass, later spectral type) stars lie further above the main sequence than the bluer ones.

Right: T Tauri tracks (Stahler 1988). The Main Sequence is shown by the diagonal line.



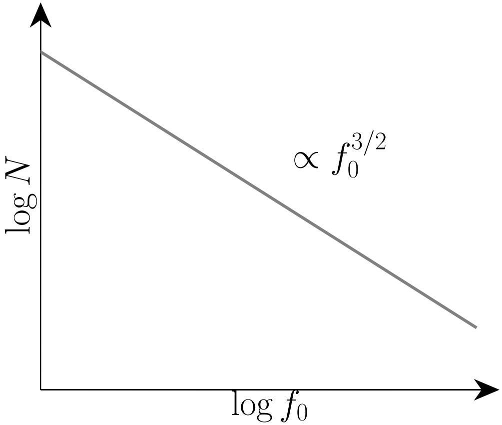
The number of stars brighter than f_0

Suppose stars are *uniformly distributed in space* with number density n and typical luminosity L. How many are brighter (i.e., have greater flux) than some value f_0?

Presuming there is no extinction, there is a distance r_0 corresponding to the flux f_0:

$$f_0 = \frac{L}{4\pi r_0^2} \quad \rightarrow \quad r_0 = \sqrt{\frac{L}{4\pi f_0}}$$

$$\begin{aligned} \implies N(f > f_0) &= \frac{4\pi}{3} r_0^3 n \\ &= \frac{4\pi n}{3} \left(\frac{L}{4\pi f_0} \right)^{3/2} \\ &\propto f_0^{-3/2} \end{aligned}$$



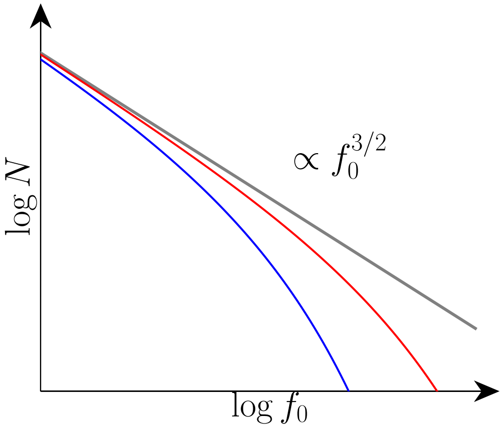
Shape of the Milky Way

Herschel (1785) and Kapteyn (1922) used this idea to characterize the shape of the Milky Way.

- If the MW has edges, N must decrease faster than $f_0^{-3/2}$ past the edges.
- Actual star counts at large fluxes are less than predicted by the $N \propto f_0^{-3/2}$ relationship.
- Implication: the MW has a finite size with identifiable edges.

Red: star count in direction of Galactic disk
Blue: star count $\perp$ to Galactic disk

Observed counts:

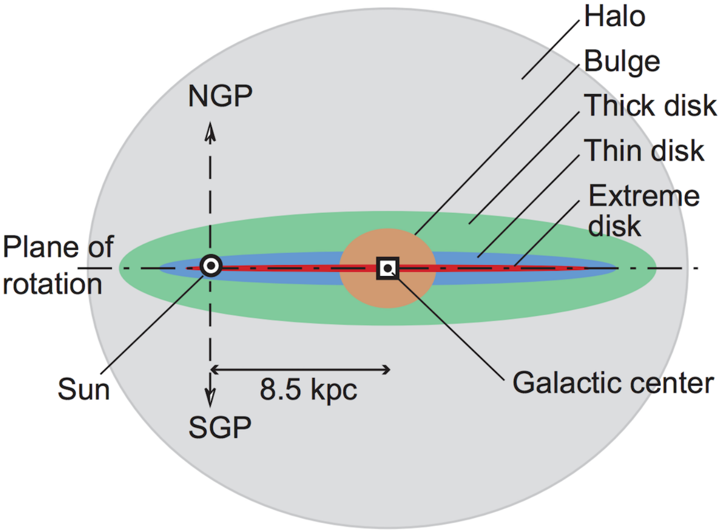


Halo, bulge, and disk

- **Bulge**: thick and bright concentration of stars surrounding the Galactic Center.
- **Disk**: a belt of stars and extinction passing through the center (this is the "Milky Way" proper).
- Since the belt seems not to have ends, we are also immersed in it.
- The distribution of stars is thicker than that of dust everywhere along the belt: there is a **thick disk** and a **thin disk** (much like other galaxies).

IR image of the Milky Way from the 2MASS All-Sky Survey.

Schematic structure of the Milky Way



The different components of the Galaxy (Buser 2000).

Mass of the halo, bulge, and disk

The different components of the Milky Way owe their distributions to differences in motion.

- The **disk** is dominated by rotation. Objects which belong to the disk have both random and rotational components to their motion, but the rotational component dominates.
- The **bulge** and **halo** are dominated by random motion with little or no evidence of rotation.

The dynamics and composition of stars are correlated:

Population I
: Small dispersion of velocities — i.e., small random velocities — with absorption lines of heavy metals. Confined to a very thin plane. Relatively young. Example: the Sun.

Population II
: Large dispersion of velocities, lying further from the Galactic Plane, and low metal content. Examples: globular clusters and halo stars.

- Population I lies predominantly in the disk, less in the bulge, and not in the halo. Population II are found in all three components.

Composition of the halo, bulge, and disk

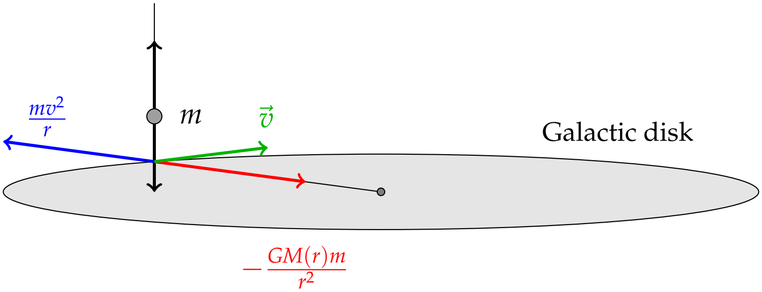
What is the Galaxy's mass? Stars move in response to the gravitational potential of the rest of the galaxy, so we can use their motion to trace out the mass distribution.

- The **systematic motions** (rotation) can be used with Newton's Laws to measure masses within the Galaxy.
- Note: This works even better with interstellar gas than with stars.
- The *visible* mass of the Galactic halo is small compared to that of the disk and bulge, but we have strong evidence that the true mass of the halo is similar to the other components and is dominated by **dark matter**.

Stars are too massive to be influenced by the pressure of the ISM but they collide inelastically very rarely, so their **random motions** can be used with **thermodynamics** to measure masses within the Galaxy. In this sense, stars can be thought of as particles in a gas or fluid.

M/A of the Disk in the Solar neighborhood

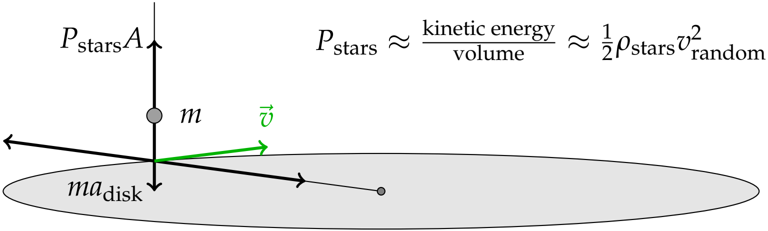
- The radial structure of the disk is determined in the usual manner from centrifugal support: balancing the force on a test particle at radius r from the mass $M(r)$ contained in interior orbits with centripetal acceleration.
- **Note**: This is just like a protoplanetary disk, or any other astro-disk.



M/A of the Disk in the Solar neighborhood

The vertical structure is determined by hydrostatic equilibrium, but there are two main differences from protoplanetary disks:

1. Much of a galactic disk is self-gravitating; the weight is from the disk itself, not from a "star" in the center.
2. The "pressure" is produced by the stars' motions.

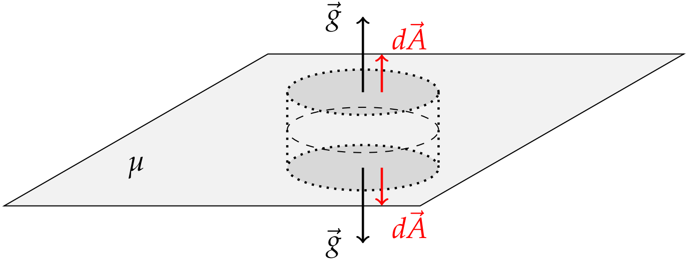


$$P_{\text{stars}} \approx \frac{\text{kinetic energy}}{\text{volume}} \approx \frac{1}{2}\rho_{\text{stars}} v^2_{\text{random}}$$

M/A of the Disk in the Solar neighborhood

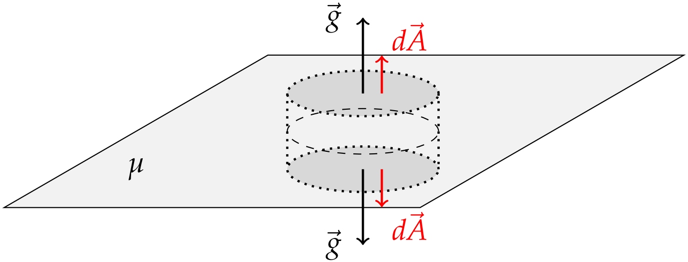
To study the radial structure, we can exploit the symmetry to use **Gauss' Law**, which tells us that the flux of field lines through a surface is equal to the stuff inside:

$$\oint \vec{E} \cdot d\vec{A} = 4\pi Q_{\text{in}} \qquad \oint \vec{g} \cdot d\vec{A} = -4\pi G M_{\text{in}}$$



For the infinite plane mass sheet, the "Gaussian surface" is a cylinder.

M/A of the Disk in the Solar neighborhood



Suppose the end caps have area A, so that $M_{\text{in}} = \mu A$. Then

$$\oint \vec{g} \cdot d\vec{A} = -4\pi G M_{\text{in}}$$
$$g 2A = -4\pi G \mu A$$
$$g = -2\pi G \mu$$
$$F = mg = -2\pi G \mu m$$