Star formation

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BASIC PHYSICS OF STAR FORMATION
JEANS INSTABILITY
THE JEANS MASS, LENGTH, DENSITY
STEPS OF STAR FORMATION
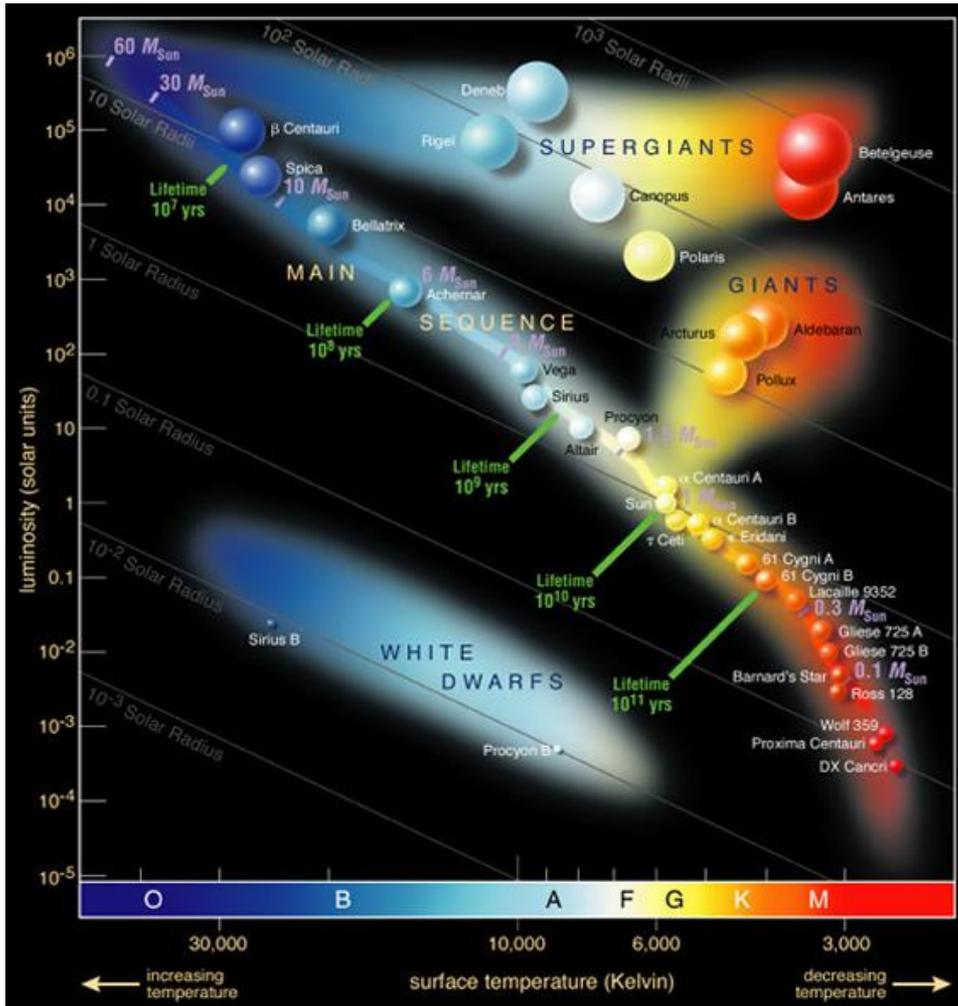
Introduction

- Today we will deal with early phases in the evolution of stars, as they evolve towards and during the main-sequence phase.

- We start with a very brief (and incomplete) overview of the formation of stars.

The Hertzsprung–Russell diagram

Stars are like people in that they are born, grow up, mature, and die. A star's mass determines what life path it will take.

The HR diagram shows the relationship between the stars' luminosities versus their effective temperatures.

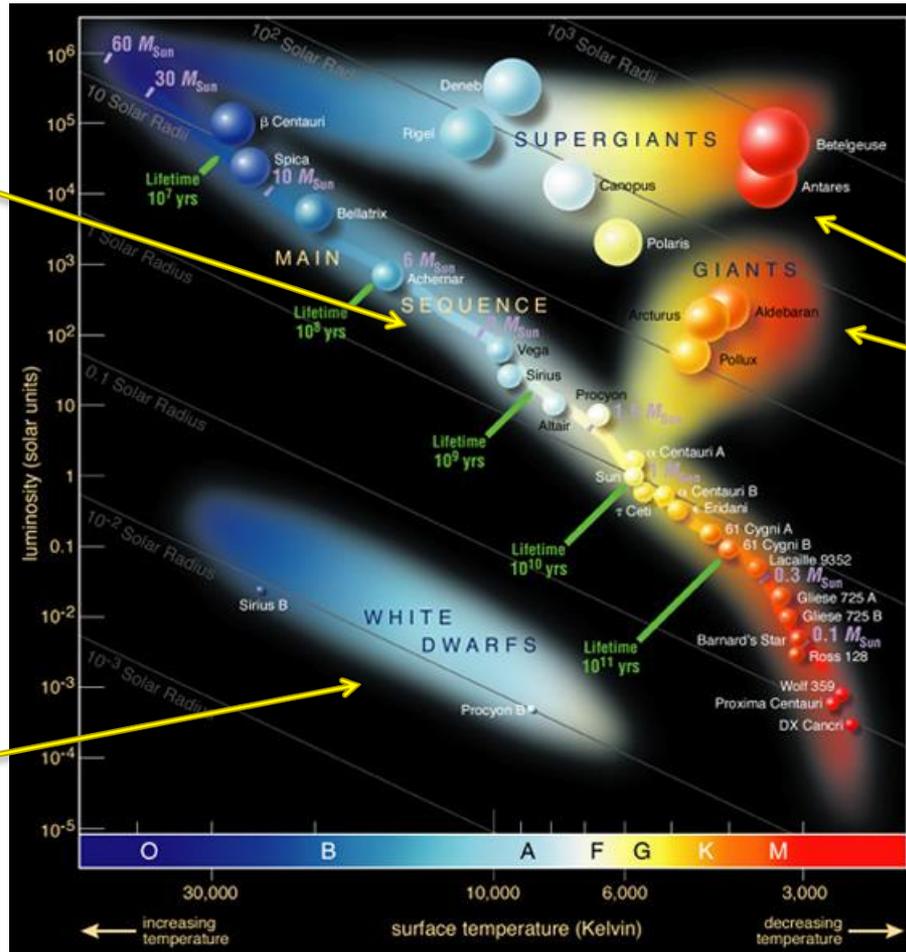Different evolutionary stages correspond to different positions at HR diagram.

90% of a lifetime a star spends at the Main Sequence, but before it, a star must be formed and have arrived there.

The HR diagram

Most of the stars lie on the Main Sequence, with increasing L as T increases

A relatively cool star can be quite luminous if it has a large enough radius (10-100 R$_\odot$): Red Giants and Supergiants

A relatively hot star can have very low luminosity, if its radius is very small (0.01 R$_\odot$): White Dwarfs

Star formation

- Observations indicate that stars are formed in giant molecular clouds with masses of order $10^2 - 10^5 \, M_{\odot}$. These clouds have typical dimensions of ~ 100 parsec, temperatures of $10-100$ K and densities of $10^2-10^4 \, \text{cm}^{-3}$ (where the lowest temperatures pertain to the densest parts of the cloud).

- A certain fraction, about 1%, of the cloud material is in the form of dust which makes the clouds very opaque to visual wavelengths.

- While the densities of molecular clouds are among the highest encountered in the Interstellar Medium (ISM), even this gas is extremely rarified compared to gas at an atmospheric density of $\sim 10^{19} \, \text{cm}^{-3}$. In fact, the densities of molecular clouds are many orders of magnitude lower than the density of the best vacuum achievable in the laboratory.

- As we have seen, the mean mass densities inside stars are $\sim 1 \, \text{g cm}^{-3}$, i.e., particle densities of $\sim 10^{24} \, \text{cm}^{-3}$. Thus, to form new stars, some regions of a molecular cloud must be compressed by many orders of magnitude.

The nearest giant molecular clouds are in the Orion star-forming region, at a distance of about 500 pc.

In spiral galaxies, star formation is concentrated along spiral arms.

Spiral arms are places where gas is compressed, probably the first step toward star formation.

What we know from observations?

The details of the process of star formation are not understood yet. We can outline, however, some of the general criteria under which gravitational contraction of a gas cloud can proceed, and potentially lead to the conditions required for star formation. This is what we know from observations:

- Stars form out of molecular gas which is assembled into dense molecular clouds in spiral arms.

- Molecular clouds have a complex, often filamentary structure. Individual stars, or small groups, form from the smallest scale structures, cloud cores of size ~0.1 pc.

- Molecular clouds probably have lifetimes of 10^6 to 10^7 yr, which is only a few dynamical times. Star formation is a fairly rapid process once molecular clouds have formed.

- If massive stars form within a young cluster, their ionizing radiation / stellar winds / supernovae destroy the molecular cloud on a short time scale.

- Most stars (~80%) form in clusters at least as rich as Orion.

Basic physics of star formation

Consider the forces acting on a "star forming unit" within a molecular cloud - a molecular cloud core:

- **Gravity**   -   act to collapse the cloud
- **Pressure**
- **Magnetic fields**   sources of support against
- **"Bulk motions"**   collapse to form a star

If somehow we form a core in which gravity dominates over all other forces, collapse will occur on the dynamical or free-fall time:

$$t_{dyn} = \frac{\pi}{2\sqrt{2}} \left(\frac{R^3}{GM} \right)^{1/2} = \left(\frac{3\pi}{32} \right)^{1/2} \frac{1}{\sqrt{G\bar{\rho}}}$$

… for a cloud of mass M, radius R, and mean density $\bar{\rho}$.

The Jeans Mass

Ignore for now magnetic fields and bulk motions. The **Jeans mass** is the minimum mass a cloud must have if gravity is to overwhelm pressure and initiate collapse.

Borderline case is the one where the cloud is in hydrostatic equilibrium:

$$\frac{dP(r)}{dr} = -\frac{Gm}{r^2}\rho(r)$$

To derive an estimate of the Jeans mass, consider a cloud of mass M and radius R:

○ approximate derivative dP/dr by $-P/R$

○ assume pressure is that of an ideal gas: $P = \frac{\Re\rho T}{\mu}$

Substitute:

$$-\frac{\Re\rho T}{\mu\, R} = -\frac{GM}{R^2}\rho \quad \rightarrow \quad M = \frac{\Re}{\mu G}TR$$

Can eliminate R in favor of the density ρ using $M = \frac{4}{3}\pi R^3\rho$ and we get a final expression for **the Jeans mass**:

$$M_J = \left(\frac{\Re}{\mu G}\right)^{3/2}\left(\frac{3}{4\pi}\right)^{1/2}T^{3/2}\rho^{-1/2}$$

This is a basic formula for star formation. Numerical constants can vary depending on the details of the derivation.

Mass scale of star formation

$$M_J = \left(\frac{\Re}{\mu G}\right)^{3/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{3/2} \rho^{-1/2}$$

Observationally, stars form from cold dense **molecular** gas with typical density $\rho \sim 10^{-19}$ g cm^{-3} and temperature $T \sim 10$ K, take $\mu = 2$ for molecular hydrogen **What ?**

Put all these numbers in the Jeans mass formula and get

$$\Re = 8.314 \times 10^7 \text{ erg mol}^{-1}\text{K}^{-1}$$

$$M_J = 7.8 \times 10^{32}\text{ g} \approx 0.4\ M_\odot$$

...which matches the typical mass of stars in the Galaxy!

Level of agreement here is "too good to be true", however we can conclude that the Jeans mass in these conditions is about a Solar mass and sets the basic mass scale for star formation.

The Jeans length

We can likewise define a characteristic length scale — **the Jeans length** — by eliminating mass rather than radius from the previous expression:

$$M = \frac{\Re}{\mu G} T R \quad \rightarrow \quad \frac{4}{3}\pi R^3 \rho = \frac{\Re}{\mu G} T R$$

$$R_J = \left(\frac{\Re}{\mu G}\right)^{1/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{1/2} \rho^{-1/2}$$

For the same density / temperature as before, $R_J \sim 1.2 \times 10^{17}$ cm $= 10^4$ AU

Free-fall timescale for a cloud of this density is:

$$t_{dyn} \sim \frac{1}{\sqrt{G\bar{\rho}}} \sim 10^{13} \text{ s} \sim 10^5 \text{ yr}$$

Star formation in these conditions should create solar mass stars within a few hundred thousand years.

The Jeans density

The above condition can also be stated as a condition on the density, which must be larger than **the Jeans density**:

$$M_J = \left(\frac{\Re}{\mu G}\right)^{3/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{3/2} \rho^{-1/2} \quad \rightarrow \quad \boxed{\rho_J = \left(\frac{\Re}{\mu G}\right)^3 \frac{3T^3}{4\pi M^2}}$$

For a typical cloud mass of $1000\ M_\odot$ and temperature $50\ K$,

$$\rho_J \sim 1.8 \times 10^{-24}\ \text{g cm}^{-3}$$

corresponding to a number density of

$$n_J = \frac{\rho_J}{\mu m_p} = \frac{1.8 \times 10^{-24}}{2 \times 1.67 \times 10^{-24}} \approx 0.5\ \text{cm}^{-3}$$

Thus, the typical observed density of molecular clouds, 10^2–10^4 cm^{-3}, is several orders of magnitude higher than the Jeans density and, according to the criterion we have just formulated, the clouds should be unstable to gravitational collapse.

Since the clouds exist and appear to be long lived, another source of pressure, other than thermal pressure, must be present. It is currently believed that the dominant pressure is provided by turbulence, magnetic fields, or both.

Interstellar cloud collapse and fragmentation

What happens during the collapse?

Jeans mass formula:

$$M_J \propto T^{3/2} \rho^{-1/2}$$

Initially: gas is optically thin, the cloud is transparent to far-infrared radiation and thus cools efficiently, so that the early stages of the collapse are isothermal (T constant).

If T stays constant, the density of the collapsing cloud increases, its Jeans mass decreases.

- Gravity becomes even more dominant over pressure
- The stability criterion within the cloud may now also be violated:
  M_J drops - allows for possibility that the cloud might break up into smaller fragments, so that the cloud starts to fragment into smaller pieces, each of which continues to collapse.
- The fragmentation process probably continues until the mass of the smallest fragments (dictated by the decreasing Jeans mass) is less than $0.1\,M_\odot$.

Formation of a proto-stellar core

The increasing density of the collapsing cloud fragment eventually makes the gas opaque to infrared photons. As a result, radiation is trapped within the central part of the cloud, leading to heating the cloud and an increase in gas pressure. It changes the nature of the collapse from an "isothermal" phase to an "adiabatic" phase. By the definition of an adiabat,

$$P \propto \rho^\gamma \;\rightarrow\; T \propto \rho^{\gamma-1}$$

Substituting this into the Jeans equation we obtain

$$M_J \propto T^{3/2}\rho^{-1/2} = \rho^{\frac{3}{2}(\gamma-1)}\rho^{-1/2} = \rho^{\frac{(3\gamma-4)}{2}}$$

For γ=5/3, $M_J \propto \rho^{1/2}$.

In other words, the Jeans mass no longer decreases with increasing density!
Thus, the cloud is no longer unstable to fragmentation. As a result, the cloud core comes into hydrostatic equilibrium and the dynamical collapse is slowed to a quasistatic contraction. At this stage we may start to speak of a protostar.

The contraction will now proceed slowly, at a pace determined by the rate at which thermal energy is radiated away. The gravitational energy is converted to dissociation of H_2, which uses up 4.5 eV per molecule, and ionization of hydrogen, which takes 13.6 eV per atom (see below).

Accretion

The surrounding gas keeps falling onto the protostellar core, so that the next phase is dominated by accretion. Since the contracting clouds contain a substantial amount of angular momentum, the infalling gas forms an accretion disc around the protostar. These accretion discs are a ubiquitous feature of the star formation process and are observed around most very young stars, mostly at infrared and sub-millimeter wavelengths.

The accretion of gas generates gravitational energy. As with other accretion, half the energy goes into further heating of the core, and half is radiated away, providing the luminosity of the protostar:

$$L_{acc} = \frac{GM\dot{M}}{2R}$$

where M and R are the mass and radius of the core and $\dot{M}$ is the mass accretion rate. Meanwhile, the core heats up almost adiabatically since the accretion timescale $\tau_{\text{acc}} = M/\dot{M}$ is much smaller than the thermal timescale τ_{KH}.

Dissociation and ionization

- The gas initially consists of molecular hydrogen and behaves like an ideal gas, such that $\gamma > 4/3$ and the protostellar core is dynamically stable:

$$M_J \propto \rho^{\frac{(3\gamma - 4)}{2}}$$

- Eventually, the core reaches a temperature of ~ 2000 K and begins to dissociate the molecular hydrogen, which is analogous to ionization and leads to a strong increase of the specific heat and a decrease of γ_{ad} below the critical value of $4/3$.

- Hydrostatic equilibrium is no longer possible, and a renewed phase of dynamical collapse follows. The collapse releases energy, which further dissociates molecules without a significant rise in temperature. When H_2 is completely dissociated into atomic hydrogen, the star settles into a new hydrostatic equilibrium. Somewhat later, the same thing happens when the temperature rises enough to ionize hydrogen (and then helium, at $\sim 10^4$ K, and then helium again, at $\sim 8 \times 10^4$ K).

- When ionization of the protostar is complete it settles back into hydrostatic equilibrium at a **much reduced** radius.

- Note also that the temperature required to doubly ionize helium (~ 80000 K) is far less than that required to fuse hydrogen.

Pre-main sequence phase

- Finally, the accretion slows down and eventually stops and the protostar is revealed as a pre-main sequence star. Its luminosity is now provided by gravitational contraction and, according to the virial theorem, its internal temperature rises as

$$T \propto M^{2/3} \rho^{1/3}$$ **Prove it!**

- The surface cools and a temperature gradient builds up, transporting heat outwards.

- Further evolution takes place on the thermal timescale τ_{KH}.

- The temperature of this early-evolution proto-star is roughly 4000 K. A size of $R \sim 35\, R_\odot$. Then it implies a luminosity of $\sim 10^3\, L_\odot$. Note however, that observed pre-main sequence stars have radii substantially smaller than $35\, R_\odot$, indicating that additional energy must have been radiated (or otherwise lost) in the contraction process.

- At these low temperatures, the opacity is very high – the dominant source of opacity is H^- (**hydrogen with two electrons** rather than one) – rendering radiative transport inefficient and making the protostar convective throughout.

- The properties of such fully convective stars must be examined more closely.

Summary of star formation on large scales

If the internal gas pressure is not strong enough to prevent gravitational collapse of a region filled with matter, then the Jeans instability may occur, causing the collapse of interstellar gas clouds and subsequent star formation.

Jeans' mass - minimum mass of a gas cloud of temperature T and density ρ that will collapse under gravity:

$$M_J = \left(\frac{\Re}{\mu G}\right)^{3/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{3/2} \rho^{-1/2}$$

Several stages of collapse:

- Initial isothermal collapse - still optically thin
- The creation of proto-stellar cores with surrounding discs
- Collapse slows or halts once gas becomes optically thick - heats up so pressure becomes important again
- Second phase of free-fall collapse as hydrogen molecules are broken up - absorbs energy and robs cloud of pressure support
- Finally forms protostar with radius of 5 - 10 $R_\odot$ and the remnants of a disc.

All this happens very rapidly – $t_{dyn} \sim 10^5$ yr – not easy to observe

Identification of Young Stars

Observationally, young stellar objects (YSOs) can be classified

- By infrared excess in their spectral energy distributions (SEDs): Young stars are built up by accretion, and the accretion disc can linger for some time after the nuclear reactions have started. The dust and material in the disk can reprocess some of the light into the IR.

- By X-ray identification: Conservation of angular momentum guarantees that young stars will be rotating quickly. If the star has a convective envelope, then differential rotation will cause an increased magnetic dynamo effect, leading to increased flare activity and X-rays.

- Hα emission: The same mechanism that can create X-rays may also result in Hα emission. In addition, there may still be residual Hα emission from the accretion disc.

- Lithium absorption: Lithium can be burned during the pre-main sequence phase. Stars with lithium absorption in their spectrum must be young (see below).

Four main classes of object have been identified.
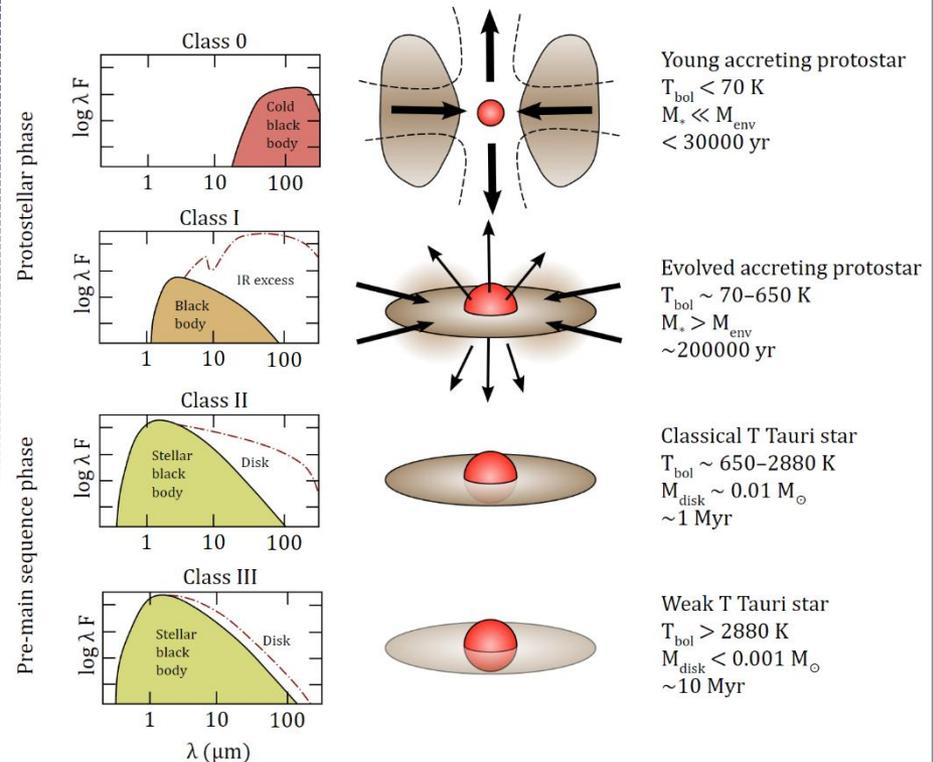
On the left, the stellar flux is depicted (shaded area) and the contribution from the disc (dotted line). On the right the corresponding geometry of the object is shown.
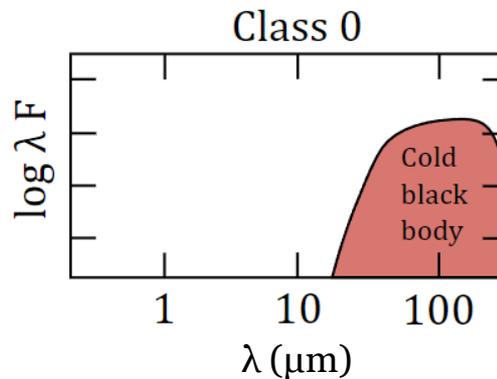
Class 0 source

Young accreting protostars. Observationally, this is a source whose SED peaks in the far-infrared or mm part of the spectrum. No flux in the near-infrared (at a few microns). Effective temperature is several tens of degrees Kelvin.

What are **Class 0** sources? Earliest observed stage of star formation...

- Still very cool - not much hotter than molecular cloud cores. Implies extreme youth.
- Deeply embedded in gas and dust, any shorter wavelength radiation is absorbed and re-radiated at longer wavelengths before escaping.
- Fairly small numbers - consistent with short duration of the initial collapse.
- Outflows are seen - suggests a protostar is forming.

$t < 30000$ yr

$T_{bol} < 70$ K
$M_* \ll M_{env}$

Class 0

Cold black body

$\log \lambda F$

1   10   100

λ (µm)
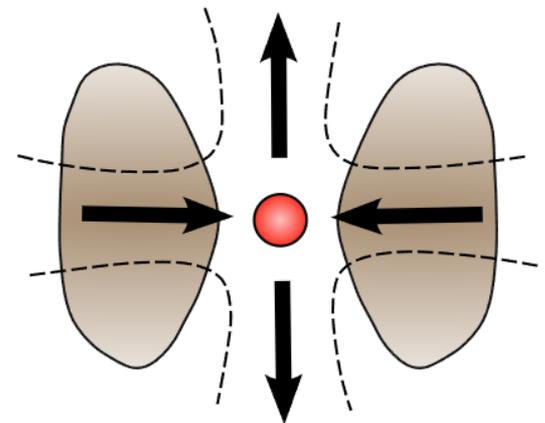
Class I source

Class I sources – evolved accreting protostars – also have SEDs that rise into the mid and far IR. But they differ from Class 0 in having detectable near infrared flux.
Still not seen at visible wavelengths.

$t \approx 200000$ yr

$M_* > M_{env}$

$T_{bol} \sim 70 - 650$ K
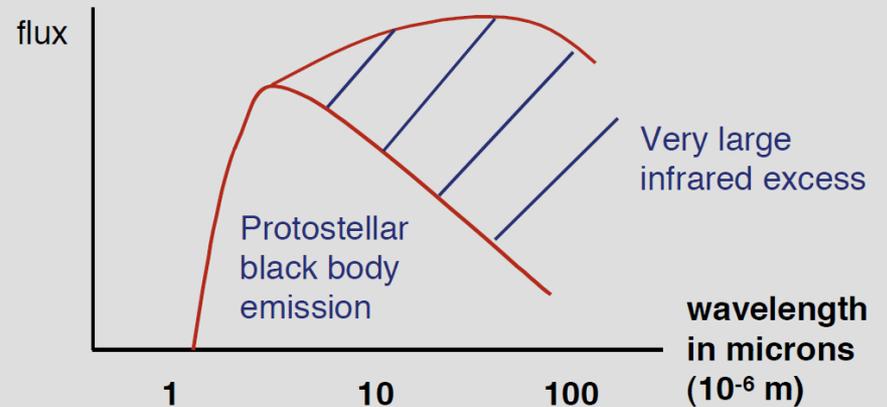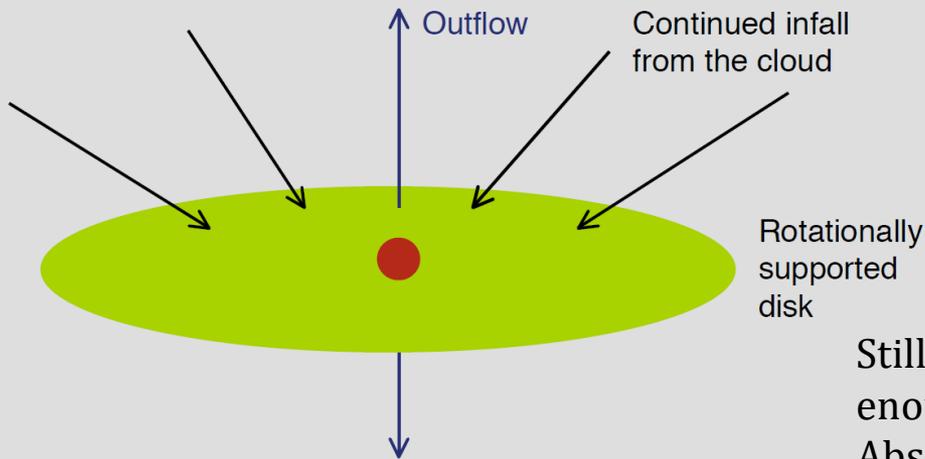
Still can't see the star itself, but dust has cleared enough to see the hot gas and dust close to the star. Absorption and re-radiation of this near-infrared flux by the dust in the envelope produces the far-infrared peak.

Class II source: classical T Tauri stars

Class II: Flat or falling SEDs in the mid-infrared. Optically visible pre-main-sequence stars. Also called classical T Tauri stars, after the prototype star T Tauri in the Taurus star forming region.
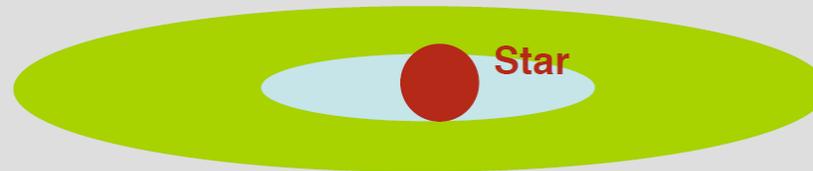
- By this stage almost all of the collapsing cloud has settled onto the star or onto a disc surrounding the star.
- From most angles we can see the young star directly.
- Disk slowly drains onto the star over several million years.
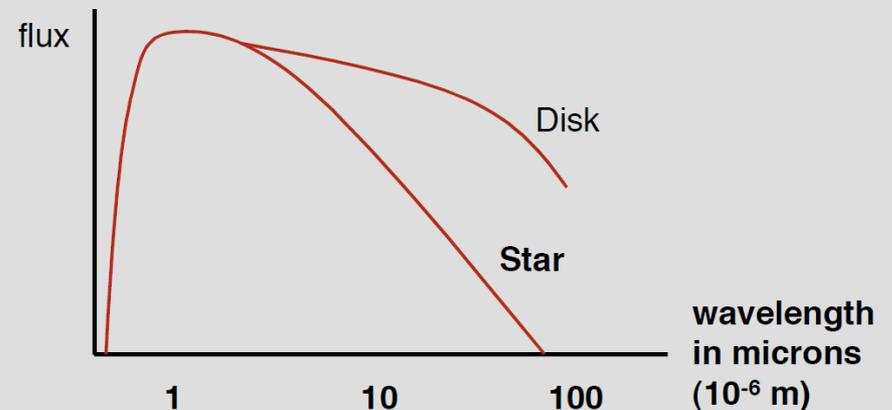
$t \approx 1$ Myr

$M_{disk} \sim 0.01\ M_{\odot}$

$T_{bol} \sim 650 - 2880$ K

Protostellar or protoplanetary disk of gas and dust

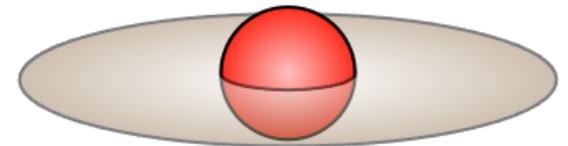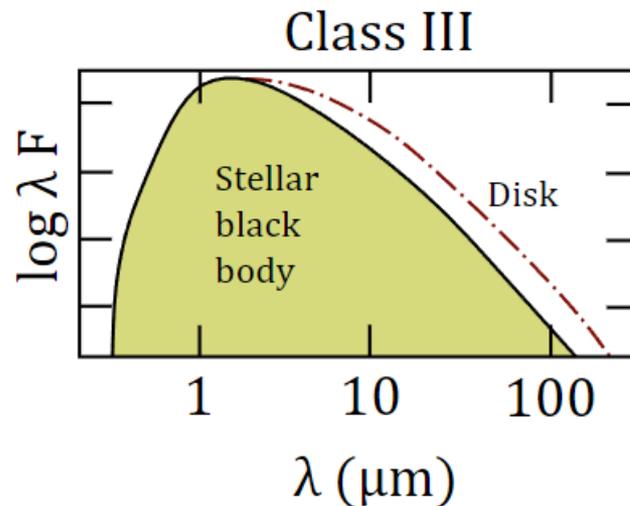# Class III source: weak-lined T Tauri stars

Class III sources: Fairly normal stellar SEDs, but more luminous than main-sequence stars of the same effective temperature (i.e. they lie above the main sequence).

Also, they are more active (e.g. in X-rays) than ordinary main-sequence stars.
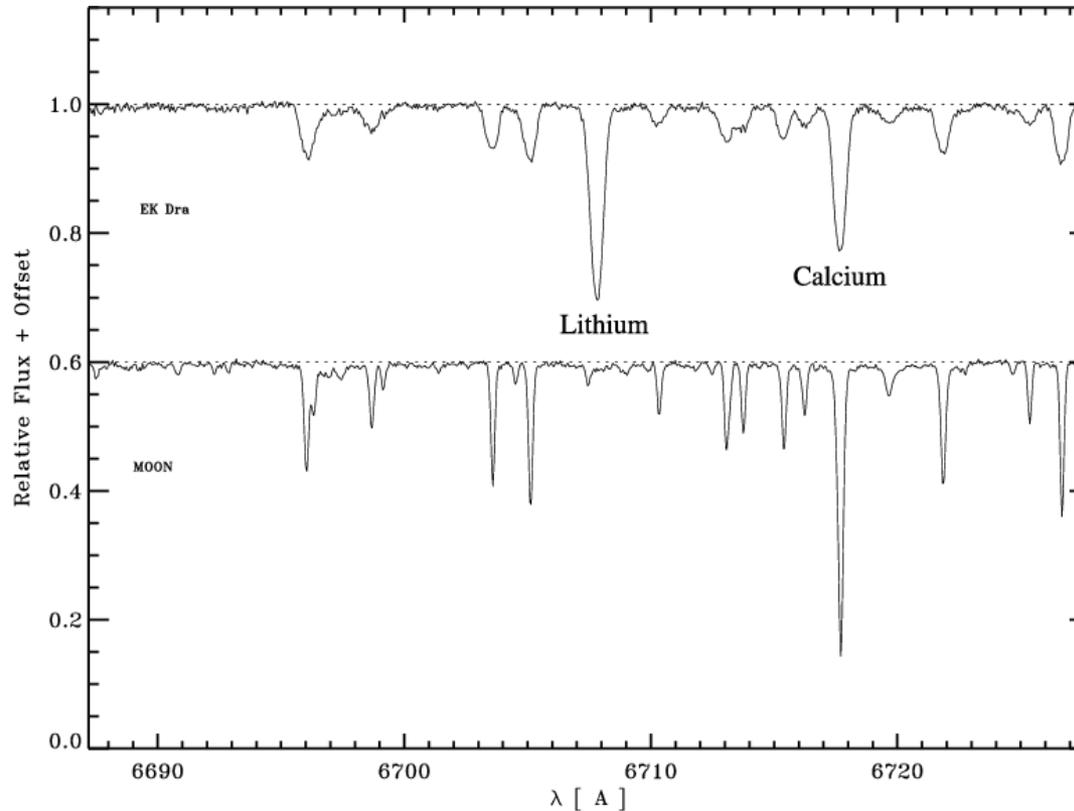
$t \approx 10$ Myr

$M_{\mathrm{disk}} < 0.001\ M_{\odot}$
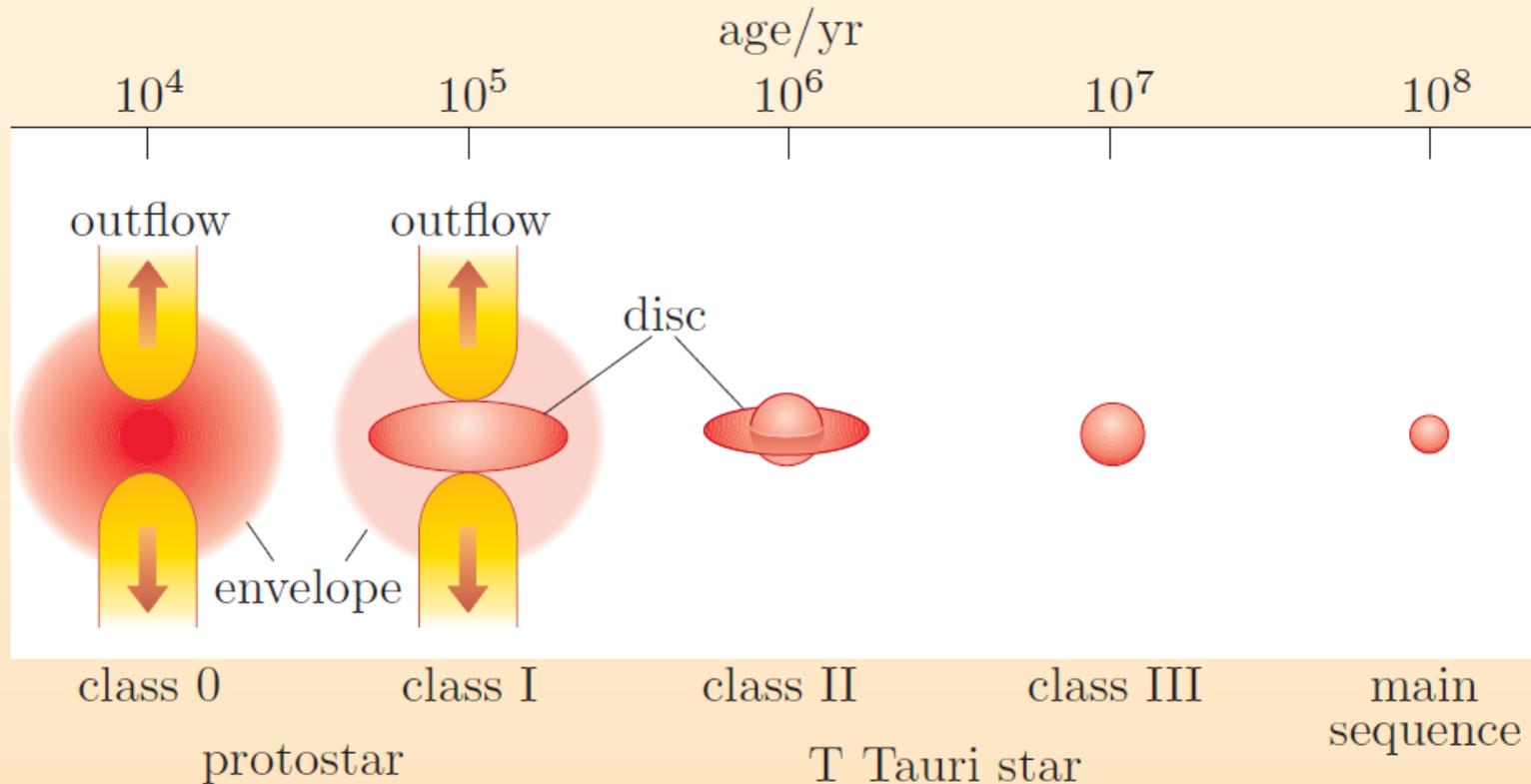
$T_{\mathrm{bol}} > 2880$ K

Lithium absorption

Lithium can be burned during the pre-main sequence phase. Moreover, in stars with convective envelopes, the temperature at the bottom of the convective layers is sufficient for lithium burning. Stars with lithium absorption in their spectrum must be young.

Protostars and pre-main-sequence stars

A schematic diagram (from Ryan & Norton) of the evolution of a pre-main-sequence star from the protostar stage, through the T Tauri stage, to the stage where the star becomes a genuine main-sequence object.