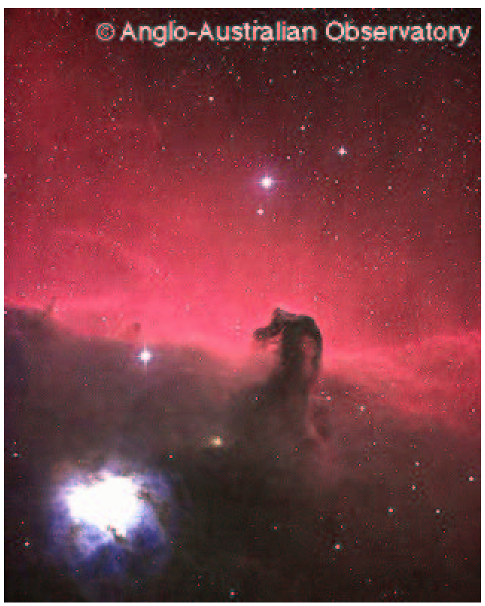
Star Formation (I)

Orion Nebula



STAR FORMATION (ZG: 15.3; CO: 12)

Star-Forming Regions

a) *Massive stars*

- born in *OB associations* in warm molecular clouds
- produce *brilliant HII regions*
- shape their environment
  - ▷ photoionization
  - ▷ stellar winds
  - ▷ supernovae
  - → induce further (low-mass) star formation?

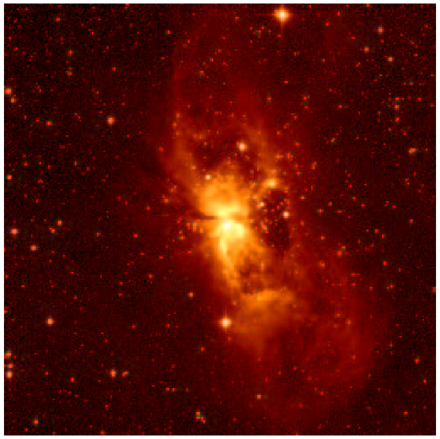
b) *Low-mass stars*

- born in *cold, dark molecular clouds* ($T \simeq 10\,K$)
- Bok globules
- near massive stars?
- *recent:* most low-mass stars appear to be born in *cluster-like environments*
- *but:* most low-mass stars are not found in clusters → embedded *clusters do not survive*

  Relationship between massive and low-mass star formation?

  - ▷ massive stars trigger low-mass star formation?
  - ▷ massive stars terminate low-mass star formation?

Star Formation (II)

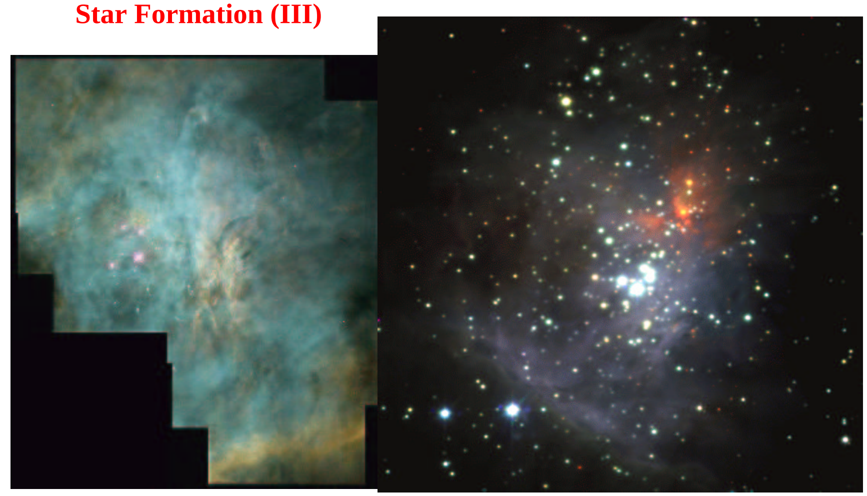


massive star +
cluster of low-mas stars

S 106

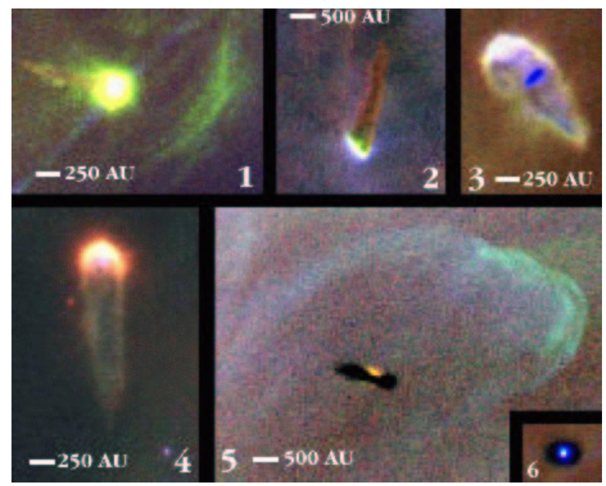
Bok globules

Star Formation (III)

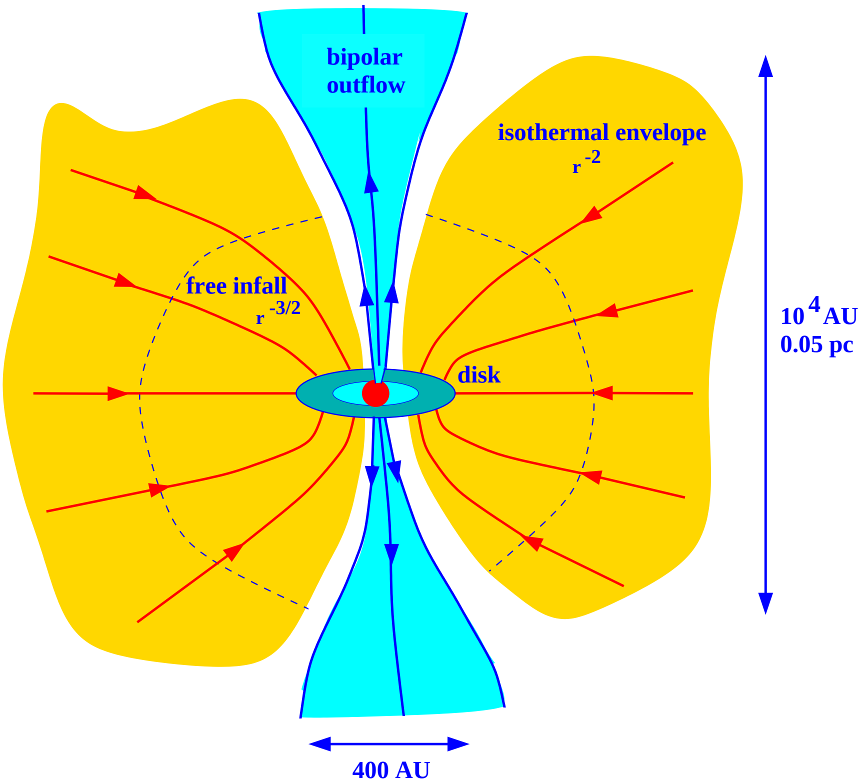


The Trapezium Cluster (IR)

HST



Dusty Disks in Orion (seen as dark silhouettes)



Protostar Structure

The Jeans Mass

- cool, *molecular cores* (H_2) can collapse when their mass exceeds the *Jeans Mass*
  - ▷ no thermal pressure support if $P_c = \rho/(\mu m_H) kT < GM^2/(4\pi R^4)$
  - ▷ or $M > M_J \simeq 6\,M_\odot \left(\frac{T}{10\,K}\right)^{3/2} \left(\frac{n_{H_2}}{10^{10}\,m^{-3}}\right)^{-1/2}$

What triggers star formation?

- *observed molecular clouds* often have masses $\gg$ Jeans mass
- but: no evidence for large-scale collapse

→ support required

  - ▷ cannot be thermal (Jeans mass! $v_{th} \ll v_{virial}$)
  - ▷ *supersonic turbulence:* possible, but: rapid shock dissipation
  - ▷ *magnetic fields:* requires $\rho v_{virial}^2 \sim B^2/2\mu_0 \rightarrow B \sim 1 - 10\,nT$ (o.k. consistent with observations)

- stars can form in regions that lose *magnetic support*
- *collisions* of cores (compression reduces Jeans mass)
- *compression* by nearby supernovae

Stellar Collapse

- ***inside-out isothermal collapse*** (i.e. efficient radiation of energy) from $\sim 10^6\,R_\odot$ to $\sim 5\,R_\odot$ (note this decreases the Jeans mass and possibly allows further fragmentation of the core)
- ***timescale:*** $t_{dyn} \sim 1/\sqrt{4\,G\rho} \sim 10^5 - 10^6$ yr
- collapse ***stops*** when material becomes ***optically thick*** and can no longer remain isothermal ***(protostar)***
- ***central accretion rate:*** $\dot{M}$
  - ▷ hydrostatic equilibrium of an ***isothermal sphere:*** $c_s^2 = \frac{kT}{\mu m_H} = \frac{GM(r)}{r}$, where c_s is the sound speed of the material, $M(r)$ the mass enclosed in radius r.
  - ▷ c_s =constant implies $M(r) \propto r$

  → for the density $\rho(r) = \frac{M_0}{4\pi r^2 R_0} = \frac{c_s^2}{4\pi r^2 G}$, where M_0 and R_0 are the total mass and total radius of the collapsing core.
  - ▷ at radius r: mass-inflow rate $\dot{M}$ is given by $\dot{M} = 4\pi r^2\,\rho\,c_s$ (inflow velocity = sound speed)
  - ▷ combining these equations, one obtains for the central accretion rate
    $$\dot{M} = \frac{c_s^3}{G} = 2\times10^{-6}\,M_\odot\,yr^{-1}\left(\frac{T}{10\,K}\right)^{3/2},$$
    where $\mu = 2$ (molecular hydrogen) and
    $$c_s = 0.2\,km\,s^{-1}\left(\frac{T}{10\,K}\right)^{1/2}.$$
  - ▷ note: $\dot{M}$ depends strongly on T, which in turn depends on the ***cooling mechanisms*** (CO molecules, dust, H_2, etc.) and is dependent on the environment and metallicity.
- ***the angular-momentum problem***
  - ▷ each molecular core has a small amount of angular momentum (due to the velocity shear caused by the Galactic rotation)
  - ▷ characteristic $\Delta v/\Delta R \sim 0.3$km/s/ly

  → characteristic, specific angular momentum $j \sim (\Delta v/\Delta R\,R_{cloud})\,R_{cloud} \sim 3\times10^{16}\,m^2\,s^{-1}$
  - ▷ cores cannot collapse directly

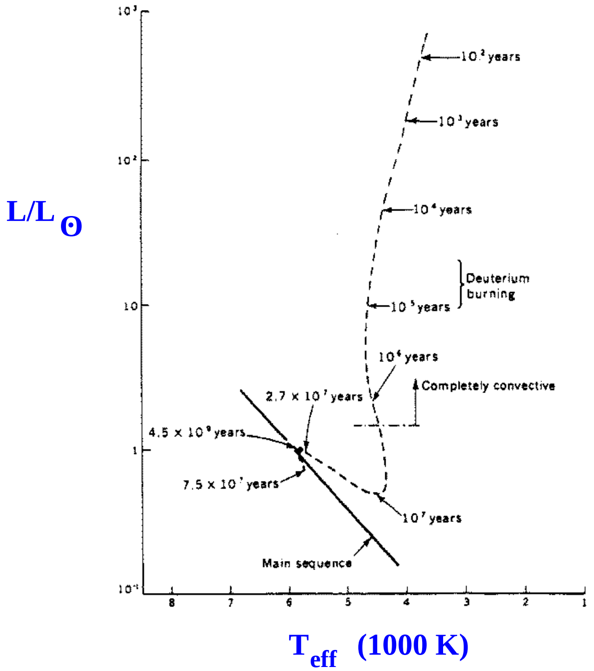
  → formation of an ***accretion disk***
  - ▷ characteristic disk size from angular-momentum conservation $j = rv_\perp = rv_{Kepler} = \sqrt{GMr}$

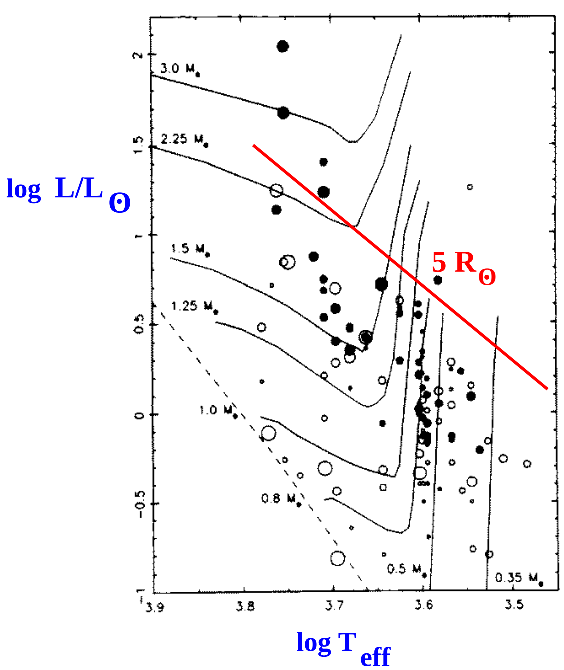
  → $r_{min} = j^2/GM \sim 10^4\,R_\odot \simeq 50$AU
- ***Solution:*** Formation of ***binary systems and planetary systems*** which store the angular momentum (Jupiter: 99 % of angular momentum in solar system)

  → ***most stars should have planetary systems and/or stellar companions***

  → stars are initially ***rotating rapidly*** (spin-down for stars like the Sun by magnetic braking)
- inflow/outflow: $\sim 1/3$ of material accreted is ejected from the accreting protostar → bipolar jets
- ***the magnetic field problem***
  - ▷ using ***magnetic flux conservation*** $B(star) = B(cloud)\,(R_{cloud}/R_{star})^2 \sim 10^3 - 10^4\,T$ ***(!)***, many order larger than observed
  - ▷ efficient loss of magnetic field, perhaps related to bipolar jets

Pre-Main-Sequence Evolution





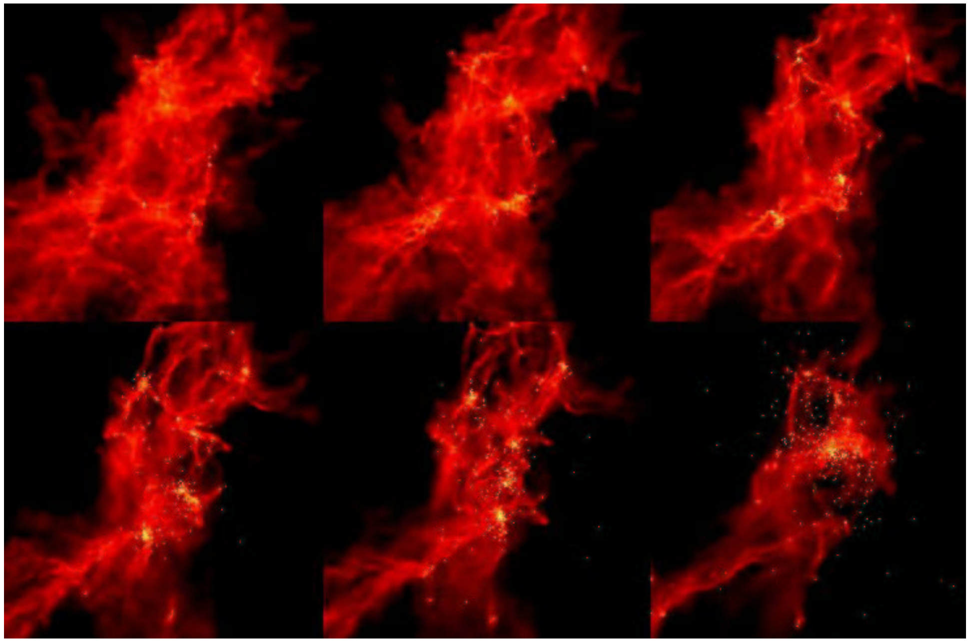
Pre-main-sequence evolution

- Old picture: stars are born with *large radii* ($\sim 100\,R_\odot$) and slowly contract to the main sequence
  - ▷ energy source: *gravitational energy*
  - ▷ contraction stops when the central temperature reaches $10^7\,$K and H-burning starts (main sequence)
  - ▷ note: D already burns at $T_c \sim 10^6\,$K → temporarily halts contraction
- *Modern picture:* stars are born with *small radii* ($\sim 5\,R_\odot$) and small masses
  - → first appearance in the H-R diagram on the *stellar birthline* (where accretion timescale is comparable to Kelvin-Helmholtz timescale: $t_{\dot M} \equiv M/\dot M \sim t_{KH} = GM^2/(2RL)$)
  - ▷ continued accretion as *embedded protostars/T Tauri stars* until the mass is exhausted or accretion stops because of dynamical interactions with other cores/stars

Dynamical Star Formation

- *stars* generally do not seem to form in isolation, but in *dense clusters*
- simulation (Bonnell): $10^3\,M_\odot$ cloud with radius $0.5\,pc$

→ collapse and fragmentation lead to the formation of ~ 400 stars in $\sim 0.5 \times 10^6\,yr$ with broad mass spectrum (but no magnetic fields considered in setting the initial conditions!)



- protostars form in collapsing cores ($R \sim 10^6\,R_\odot$) and accrete from their cores at $\dot{M} \sim 2 \times 10^{-6}\,M_\odot\,yr^{-1}$ till the envelopes are disturbed by a *collision* with another core/star
  - ▷ collision time: $t_{coll} \simeq 1/\sigma n v$
  - ▷ where the collision cross section is given by the size of the core: $\sigma = \pi * (10^6\,R_\odot)^2$,
  - ▷ the number density of colliding objects by $n \sim 10^3/[(4\pi/3) \times (0.5\,pc)^3]$ and
  - ▷ the characteristic velocity by the dynamics of the cloud $v \sim \sqrt{GM/R} \simeq 3\,km\,s^{-1}$.

  → $t_{coll} \simeq 10^5\,yr \rightarrow M_{star} \sim \dot{M} \times t_{coll} \sim 10\,M_\odot$

→ a collisional origin of the initial mass function?

The First Stars

- differences at zero metallicity:
  - ▷ no dust, no CO → higher T of star-forming cloud

  → larger Jeans mass → form very massive stars only?
- at $Z = 0$: very different stellar evolution (no CNO cycle) → different supernovae? Claim: *pair-instability supernova:* complete disruption of star in an energetic supernova (sometimes, also referred to as hypernova, not to be confused with GRB-related hypernova)
- but: observed *nucleosynthesis from Pop III stars* is not consistent with pair-instability supernovae
- formation of intermediate-mass black holes?
- *Problem:* it is not clear whether Pop III stars really should have existed as a significant population