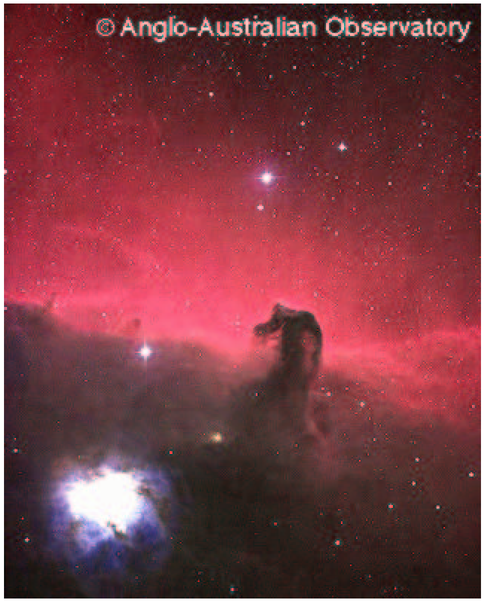
Star Formation (I)

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?

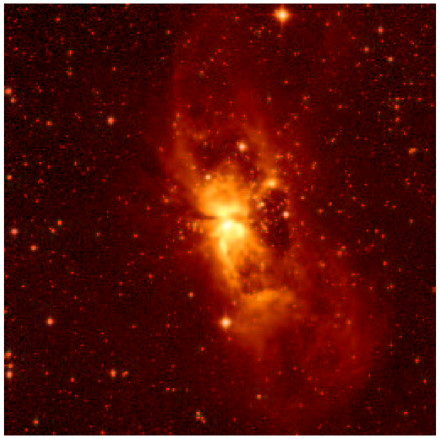
b) Low-mass stars

- born in cold, dark molecular clouds ($T \simeq 10\,\mathrm{K}$)
- 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)

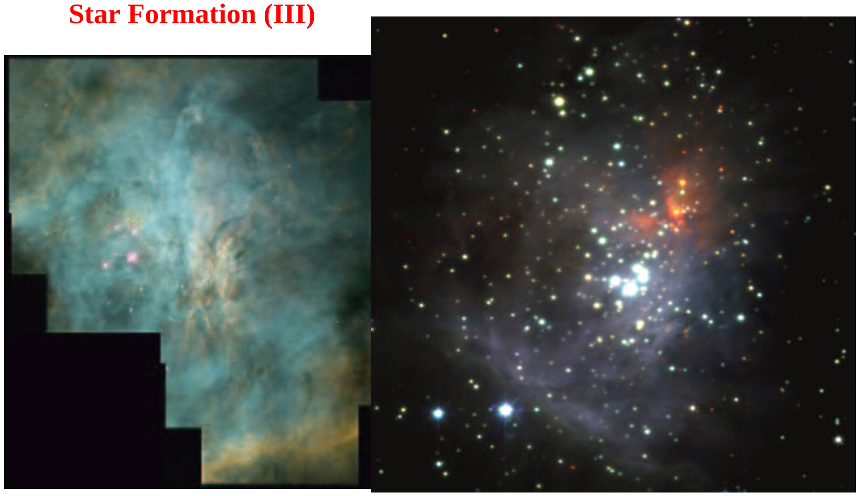


massive star +
cluster of low-mas stars

S 106

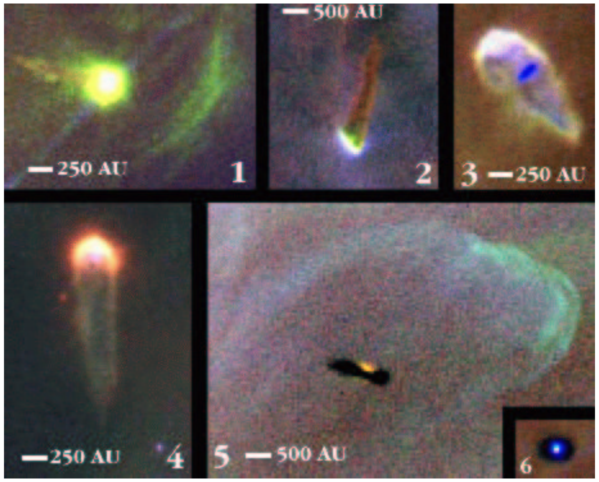
Bok globules

Star Formation (III)

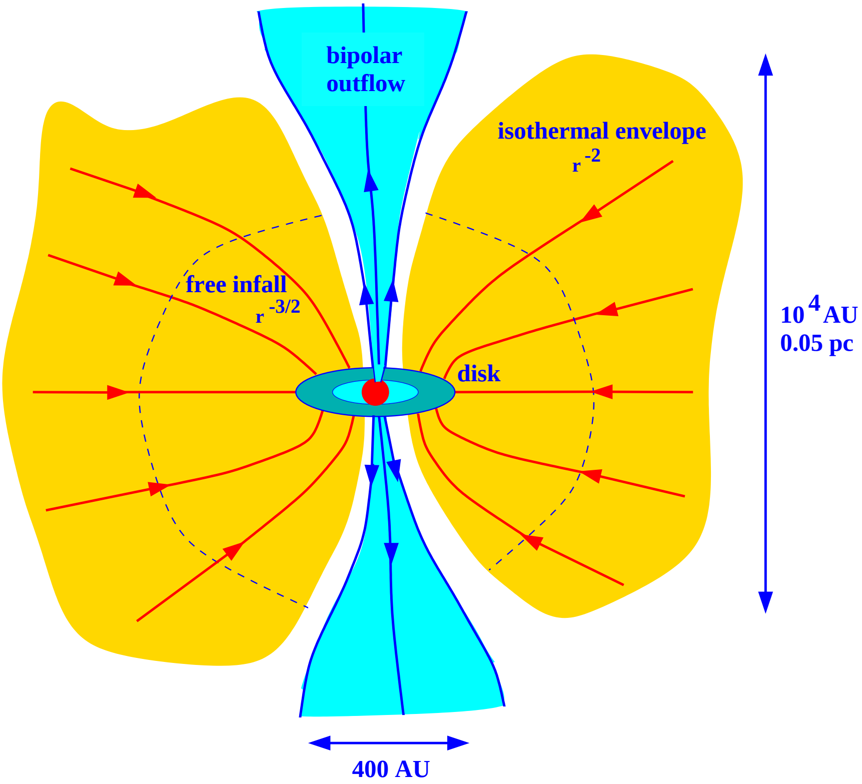


The Trapezium Cluster (IR)

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 ≫ 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 $\rho v_{virial}^2 \sim B^2/2\mu_0$ → $B \sim 1 - 10\,nT$ (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: $t_{\rm dyn} \sim 1/\sqrt{4\,G\rho} \sim 10^5 - 10^6\,{\rm yr}$
- 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: $c_s^2 = \dfrac{kT}{\mu m_H} = \dfrac{GM(r)}{r}$, 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 $\rho(r) = \dfrac{M_0}{4\pi r^2 R_0} = \dfrac{c_s^2}{4\pi r^2 G,}$ 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

    $$\dot{M} = \frac{c_s^3}{G} = 2\times 10^{-6}\,M_\odot\,{\rm yr}^{-1}\left(\frac{T}{10\,{\rm K}}\right)^{3/2},$$

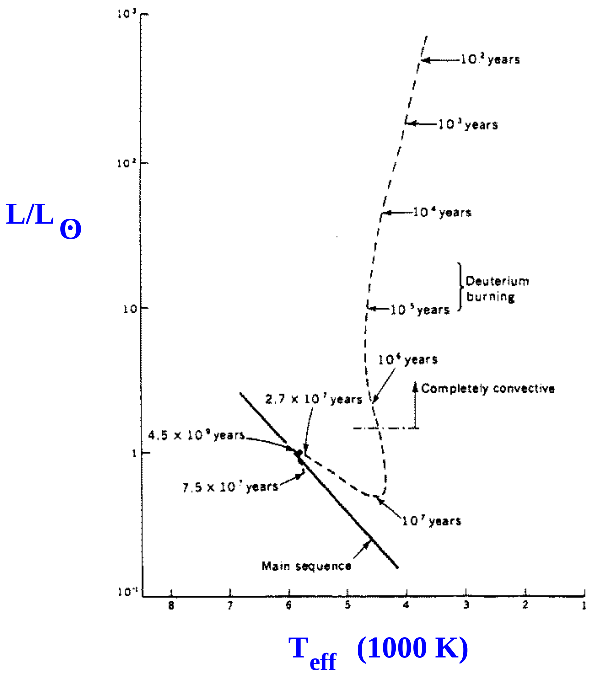
    where $\mu = 2$ (molecular hydrogen) and

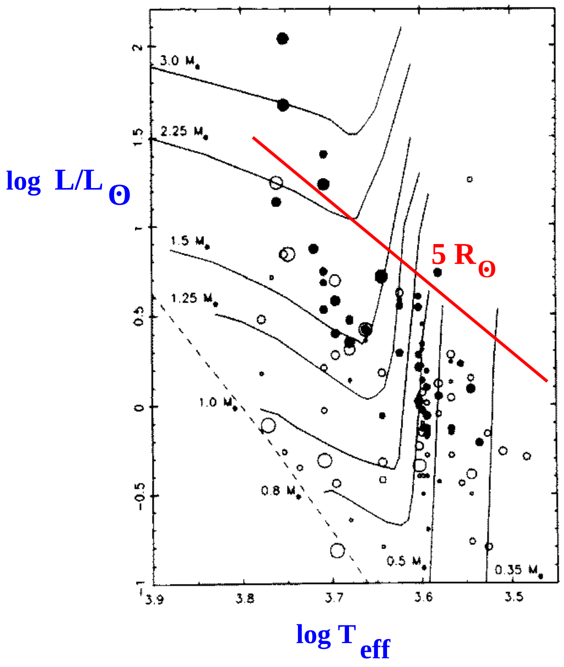
    $$c_s = 0.2\,{\rm km\,s^{-1}}\left(\frac{T}{10\,{\rm K}}\right)^{1/2}.$$

  - ▷ 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 $\Delta v/\Delta R \sim 0.3{\rm km/s/ly}$
  - → characteristic, specific angular momentum $j \sim (\Delta v/\Delta R\,R_{\rm cloud})\,R_{\rm cloud} \sim 3\times 10^{16}\,{\rm m^2\,s^{-1}}$
  - ▷ cores cannot collapse directly
  - → formation of an accretion disk
  - ▷ characteristic disk size from angular-momentum conservation $j = rv_\perp = rv_{\rm Kepler} = \sqrt{GMr}$
  - → $r_{\rm min} = j^2/GM \sim 10^4\,R_\odot \simeq 50{\rm AU}$
- 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 $B({\rm star}) = B({\rm cloud})\,(R_{\rm cloud}/R_{\rm star})^2 \sim 10^3 - 10^4\,{\rm T}$ (!), many order larger than observed
  - ▷ efficient loss of magnetic field, perhaps related to bipolar jets

Pre-Main-Sequence Evolution





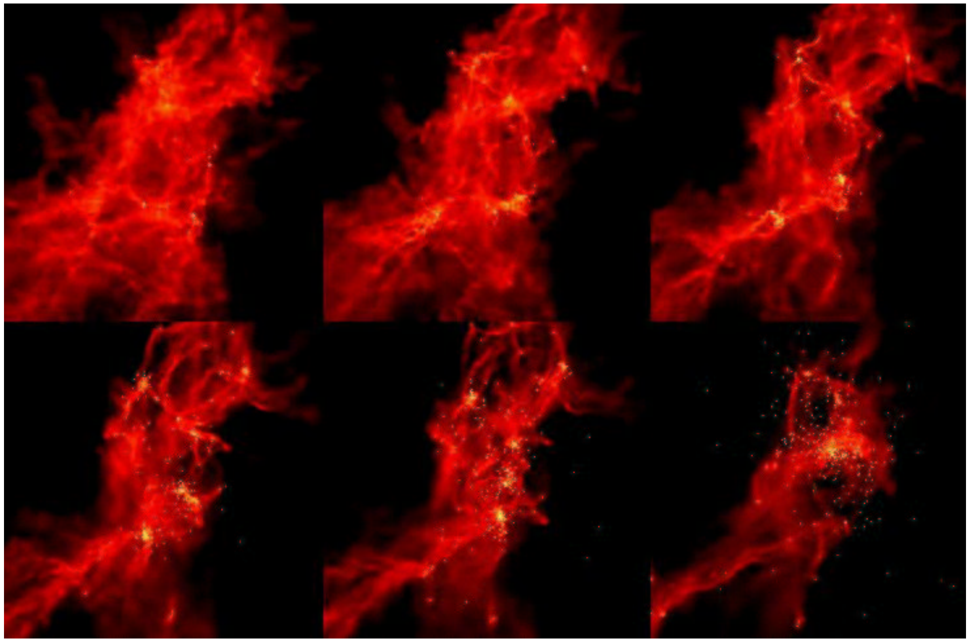
Pre-main-sequence evolution

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

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

→ 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 $\mathrm{Z} = 0$: 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