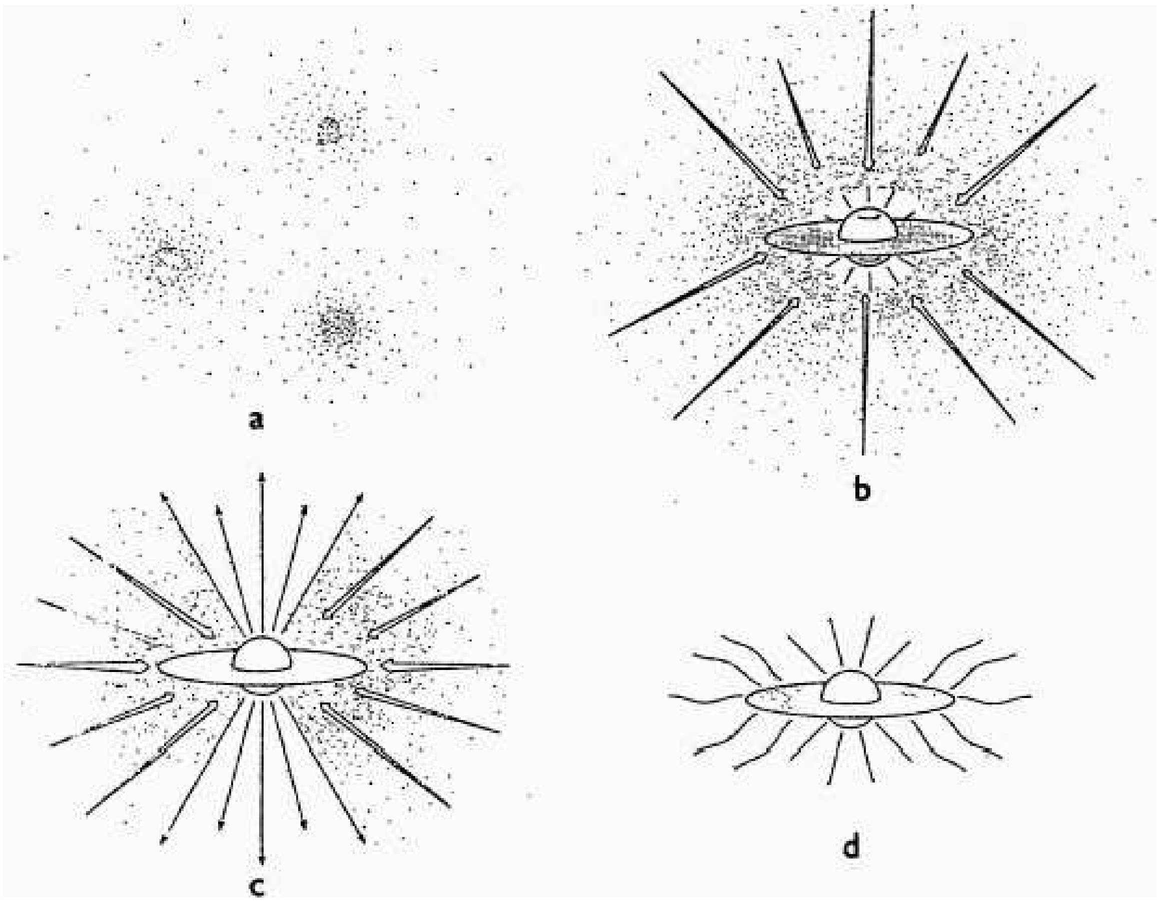
Pre-main-sequence stellar evolution

Classic picture of (single) star formation from Shu, Adams & Lizano (ARAA, 1987):



Nomenclature for roughly Solar mass objects:

- Class 0 and Class I sources: rising spectra in the near and mid infrared. Embedded sources with ages of $\sim 10^5$ yr that may still need to accrete substantial fraction of their final mass. Ouflows already common.

- Class II sources – **classical T Tauri stars**. Optically visible pre-main-sequence stars surrounded by circumstellar disks. Identified by Joy (e.g. ApJ, 1945).
- Class III sources – **weak-lined T Tauri stars**. Pre-main-sequence stars without disks.

Main difficulty with pre-main sequence evolution: models are limited by poor knowledge of the initial conditions (principally, $\dot{M}(t)$ resulting from star formation). Star formation is much less well understood than stellar evolution:

- Observationally: brief (and therefore nearest examples distant) phase with forming stars highly embedded in dusty gas.
- Theoretically: role of turbulence, rotation, and magnetic fields. Large dynamic range. Earlier initial conditions (formation of molecular clouds) themselves uncertain.

Describe here two simple models:

1 Hayashi – fixed mass of gas contracts from large radius.

2 Stahler (1983) – stars build up mass from intially small (in mass *and* radius) cores at rate set by spherically symmetric models of single star formation.

Rule of thumb: quantitative conclusions about low mass stars with claimed ages below 1 Myr should be regarded cautiously.

Classical theory of protostars

Consider a protostar of mass M_* and radius R_* forming from a cold, static cloud with $R \gg R_*$. Initial energy (thermal, kinetic, gravitational) is ≈ 0, while star is bound (negative total energy).

ΔE can be:

- Radiated into space during collapse.
- Absorbed into dissociating and ionizing gas.

Internal component,

$$E_{\text{int}} = \frac{XM_*}{m_H}\left[\frac{E_{\text{diss}}^{H_2}}{2} + E_{\text{ion}}^{H}\right] + \frac{YM_*}{4m_H}E_{\text{ion}}^{He},$$

where,

- $E_{\text{diss}}^{H_2} = 4.48$ eV.
- $E_{\text{ion}}^{H} = 13.6$ eV.
- $E_{\text{ion}}^{He} = 75.0$ eV.

If the average luminosity during the formation time t is L_{rad}, then the virial theorem gives,

$$0 = -\frac{1}{2}\frac{GM_*^2}{R_*} + E_{\text{int}} + L_{\text{rad}}t.$$

Set $L_{\rm rad} = 0$ to get an estimate of the *maximum* radius $R_{\rm max}$ of a protostar as a function of mass,

$$R_{\rm max} = \frac{GM_*^2}{2E_{\rm int}} \simeq 60 R_\odot \left(\frac{M_*}{M_\odot}\right),$$

where we have assumed roughly Solar composition.

Classical theory assumes *no further accretion*. Luminosity is,

$$L_{\rm surf} = 4\pi R_*^2 \sigma T_{\rm e}^4.$$

Know that for a fully convective star, track in HR diagram is almost vertical. Thus using observed $T_e \approx 4000$ K values (for smaller stars), infer that initially,

$$L_{\rm surf} \sim 10^3 \; L_\odot.$$

Note: this is $\gg L_{\rm max}$, the maximum radiative luminosity, so assumption of convection is self-consistent.

For a polytrope with $n = 3/2$, gravitational energy,

$$\Omega = -\frac{3}{5-n}\frac{GM_*^2}{R_*} = -\frac{6}{7}\frac{GM_*^2}{R_*}.$$

The virial theorem (cf Problem set 1) gives,

$$L_{\rm surf} = -\frac{1}{2}\frac{d\Omega}{dt} = -\frac{3}{7}\frac{GM_*^2}{R_*^2}\frac{dR_*}{dt},$$

so the star contracts with a characteristic timescale,

$$t_{PMS} \equiv -\frac{R_*}{dR_*/dt} = \frac{3}{7}\frac{GM_*^2}{R_* L_{\rm surf}} = t_{\rm KH}.$$

Since $t_{\rm KH} \gg t_{\rm dyn}$, contracting stars can be considered to be in hydrostatic equilibrium at each instant – ie quasi-static contraction.

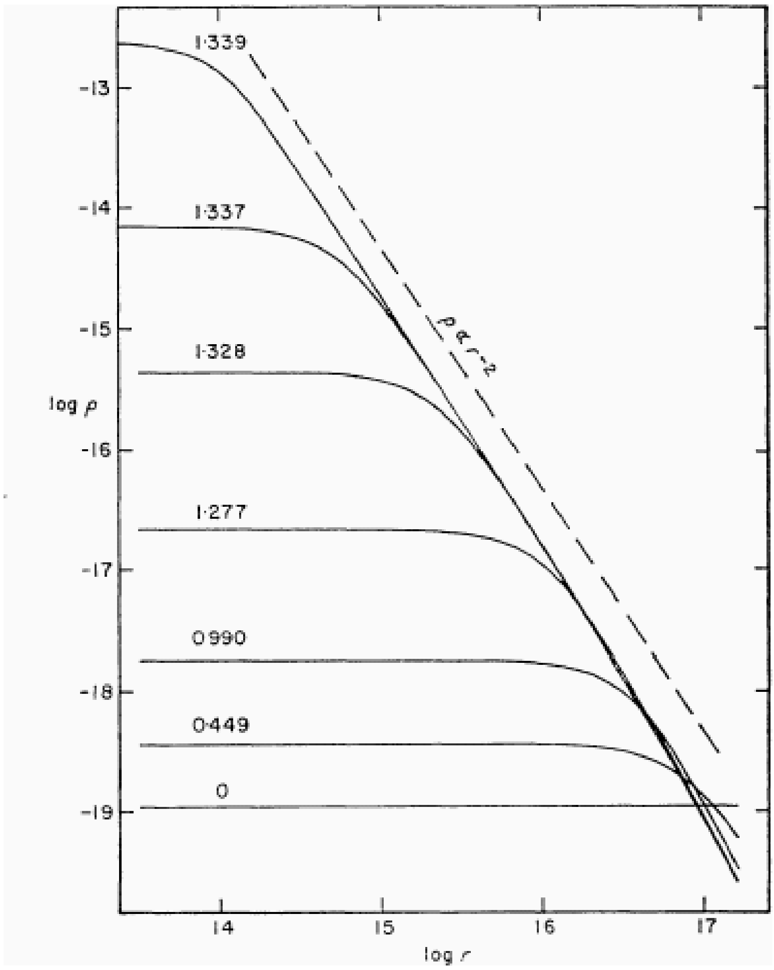
For stars of a Solar mass, subsequently,

- Thermal gradient becomes stable to convection in the core as the luminosity falls.
- Evolution at roughly constant luminosity (*Henyey track*) until hydrogen ignites at the Zero-age main sequence (ZAMS).

Problems with this picture

Observationally: largest T Tauri stars have radii an order of magnitude less than maximum value.

Theoretically: Collapse of molecular clouds does *not* proceed homologously. Larson (1969) found:



Implies that the central regions will reach stellar densities and may start deuterium burning while more mass is still infalling. Initial core will be low mass and small.

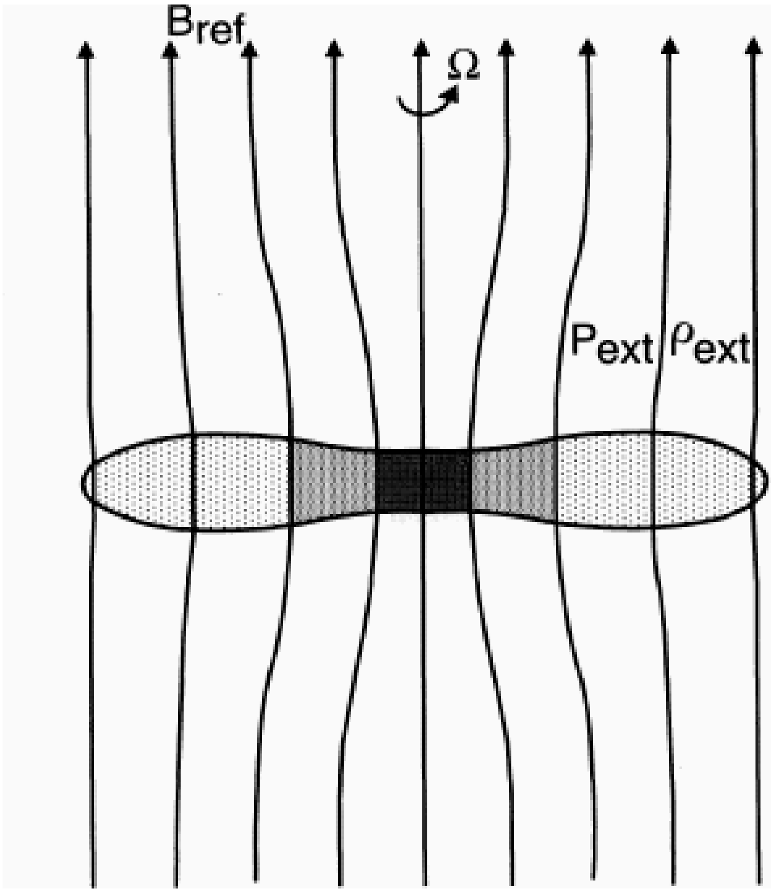
Models for the infall

Basically two schools of thought, which differ as to whether the molecular cloud core prior to collapse can be considered in isolation.

Star formation from an isolated core

Frank Shu and collaborators (also Mouschovias et al.) have extensively explored models based on:

- Magnetically supported clouds become unstable via ambipolar diffusion → collapse initiated from approximately static, isothermal sphere.



- Inside-out collapse, with fixed accretion rate depending only on the sound speed,

$$\dot{M} = \frac{c_s^3}{G}.$$

- Accretion ceases due to feedback processes (outflows at low stellar masses).

Merits:

- Provides well-defined and calculable initial conditions for star formation (except for feedback).
- Plausible order of magnitude estimate of the accretion rate.
- Consistent answer to important question: how does infalling gas expel its magnetic flux.

Main problem: most stars are found in binaries, and isolated, centrally concentrated cores do not fragment.

Main uncertainty: how long-lived are structures in molecular clouds? Do molecular clouds exist for many free-fall times (perhaps requiring magnetic fields for support)? How rapid is ambipolar diffusion?

Star formation from turbulent initial conditions

Competing view focuses on the initiation of star formation at *large* scales. Several related ideas being explored:

- Molecular clouds on large scales are supported by turbulence, which *decays on a dynamical timescale*. This may be true even if magnetic fields are present.
- Many structures in molecular clouds are transient.
- Star formation proceeds as turbulence decays.
- Accretion onto newly formed protostars ceases due to a combination of dynamical interactions, followed by energy input from outflows or massive stars.

Detailed implications of this picture remain to be worked out. Existing simulations consider low mass star formation only to both simplify the required physics and to reduce the computational cost.

Calculations by Klessen (2001), Padoan & Nordlund (2002), Bate, Bonnell & Bromm (2002). Very similar to cosmological simulations – initial power spectrum of density / velocity perturbations + gravitational evolution.

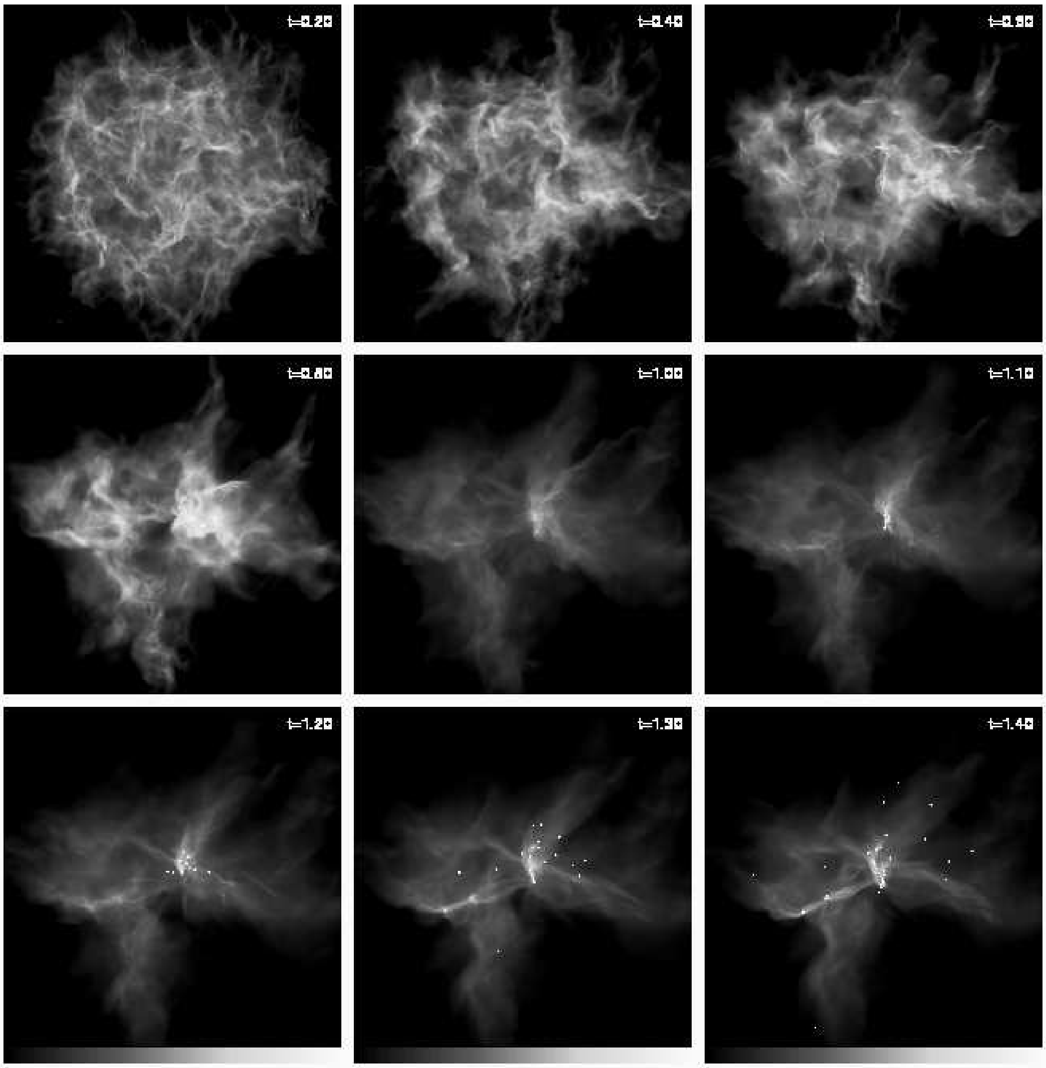
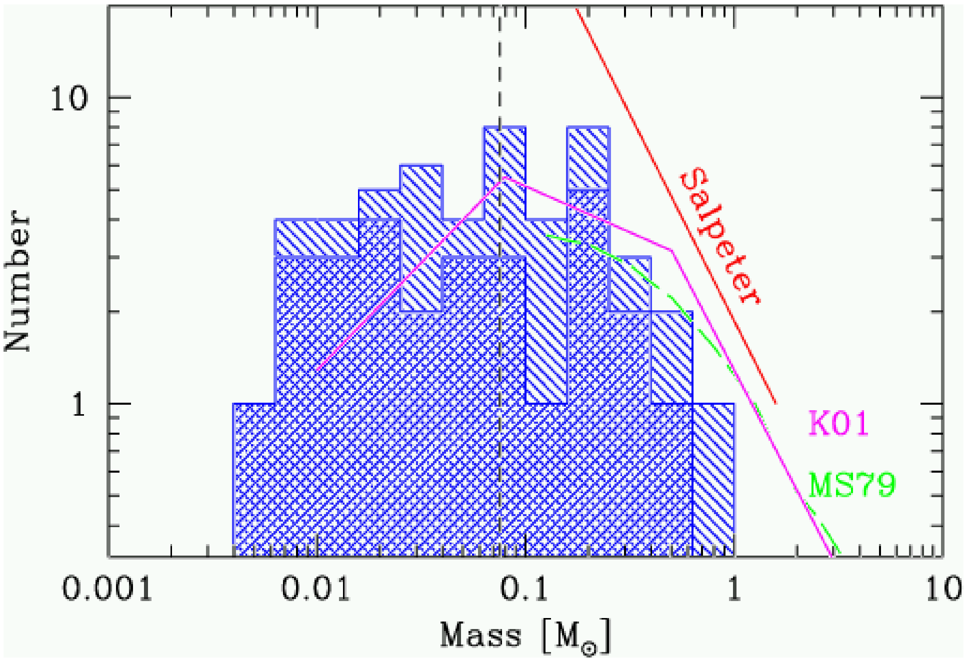


Figure 2. The global evolution of the cloud during the calculation. Shocks lead to dissipation of the turbulent energy that initially supports the cloud, allowing parts of the cloud to collapse. Star formation begins at $t = 1.04 t_{ff}$ in a collapsing dense core. By the end of the calculation, two more dense cores have begun forming stars (lower left of the last panel) and many of the stars and brown dwarfs have been ejected from the cloud through dynamical interactions. Each panel is 0.4 pc (82400 AU) across. Time is given in units of the initial free-fall time of 1.90×10^5 years. The panels show the logarithm of column density, N, through the cloud, with the scale covering $-1.5 < \log N < 0$ for $t < 1.0$ and $-1.7 < \log N < 1.5$ for $t \geq 1.0$ with N measured in g cm^{-2}.

Merits:

- Readily produces binaries (effectively part of the initial conditions).
- In principle a route to calculating the initial mass function. Simple versions seem to be consistent with observations.



Open questions:

- Initial conditions. Some statistical properties of molecular cloud turbulence are known observationally, but *no ab-initio* theory for initial spectrum of perturbations (cf cosmology).
- Role of magnetic fields unclear.