Protostars and Pre-Main Sequence Evolution

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Outline

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Bonnor-Ebert Mass

\[ M_{\text{crit}} = 1.18 \frac{c_s^4}{P_{\text{surf}}^{1/2} G^{3/2}} = 1.82 \left( \frac{n}{10^4 \text{cm}^{-3}} \right)^{-1/2} \left( \frac{T}{10 \text{ K}} \right)^{3/2} M_\odot \]

The process starts with cores of \( M \sim M_\odot \), and \( R \sim 0.1 \text{ pc} \).

Three phases of collapse
  
  Isothermal Collapse
  
  Adiabatic Collapse
  
  Envelope Accretion
Protostars
Isothermal and Adiabatic Collapse

\[
\frac{Gm}{4\pi r^4} + \frac{dP}{dm} = -\frac{1}{4\pi r^2} \frac{d^2r}{dt^2}, \quad L_r = -\frac{64\pi^2 acr^4}{3\kappa_R} T^3 \frac{dT}{dm}
\]

\[
\frac{dr}{dm} = \frac{1}{4\pi r^2 \rho}, \quad \frac{dL_r}{dm} = -\frac{dE}{dt} - P \frac{dv}{dt}
\]

with bc: \( r = L_r = 0 \) at \( m = 0 \), \( P = P_0 \) \( L_R = 4\pi R^2 \sigma T_{\text{eff}}^4 \) at \( m = M \)

\[\tau \approx \kappa_R \rho R, \quad t_{\text{diff}} \approx 3\kappa_R \rho (\Delta r)^2 / c, \quad t_{\text{ff}} \approx (G\rho)^{-1/2}\]

Isothermal Phase: \( \tau \ll 1 \), \( \rho = 10^{-19} - 10^{-13} \text{gcm}^{-3} \), efficient cooling, can assume constant temperature (\( T \approx 10 \text{ K} \)).

Adiabatic Phase: \( \tau \gg 1 \), \( t_{\text{diff}} \gg t_{\text{ff}} \), infrared radiation gets trapped, can ignore heat term in energy equation.
Protostars
Isothermal and Adiabatic Collapse

Larson, 1969

Bodenheimer, 2011

Bodenheimer, 2011
The central part of the core reaches quasi-hydrostatic equilibrium while the outer regions are still in isothermal collapse.

\[ t_{KH} \approx \frac{GM^2}{RL} \sim \text{Myr} \]
\[ t_{\text{acc}} \approx \frac{M}{\dot{M}} \sim 10^5 \text{ yr} \]
\[ t_{\text{diff}} \ll t_{\text{acc}} \ll t_{KH}, \text{ therefore} \]
\[ L \approx L_{\text{acc}}. \]

Dust sublimates at \( T \approx 1500 \text{ K} \).
Protostars
Comparisons to Observations

Bodenheimer, 2011
Luminosity Problem, for $M = 0.5M_\odot$
$L_{\text{acc}} \sim 10L_\odot$. 

Kenyon et al., 1993
Bodenheimer, 2011
Non-thermal spectrum due wavelength dependent opacity.
In the interior,\[
\frac{3}{16\pi Gac} \frac{\kappa_R L_r P}{mT^4} > \left( \frac{\partial \ln T}{\partial \ln P} \right)_S
\]
\(\kappa_K \propto \rho T^{-3.5}\)

Thin Outer Radiative Zone with \(H^-\),
\(\kappa_{H^-} \propto Z\rho^{0.5} T^9\)

\(\kappa_p P_p = \frac{2}{3} g\)
Stars above $6M_\odot$ are already in the main sequence when the accretion phase is over.
Deuterium Burns at $10^6$ K

$^1H + ^2D \rightarrow ^3He + \gamma$

$\epsilon \propto f \left[ \frac{D}{H} \right] \rho T^{11.8}$

$[D/H] = 2 \times 10^{-5}, f = 1$

Stahler, 1988
Pre-Main Sequence Evolution
Deuterium Burning and the Stellar Birthline

Burrows et al., 2003
Cores with $M < 0.08 M_\odot$, can’t burn Hydrogen

Lithium Burns at $2.5 \times 10^6$ K

$^1H + ^7Li \rightarrow ^4He + ^4He$

Burrows et al., 2003
Pre-Main Sequence Evolution
Degeneracy

\[ P_e = 1.004 \times 10^{13} (\rho/\mu_e)^{5/3} \text{ dyne cm}^{-2} \]

\[ \rho = 2.4 \times 10^{-8} \mu_e T^{3/2} \text{ g cm}^{-3} \]

Bodenheimer, 2011

Burrows et al., 2003
Pre-Main Sequence Evolution
T Tauri Stars

$L_{\text{H}\alpha}$, high $Li$ abundance ($\sim 10^{-9}H$), nearby dark clouds, X-rays emission, strong magnetic fields (Zeeman splitting $\sim$ kilogauss).

Infrared excess in CTTS, due to dusty disk.

Lada et al., 1999
Pre-Main Sequence Evolution

T Tauri Stars

Lamm et al., 2005

Contraction, magnetic star disk interaction, stellar winds.
Conclusions

We have made a lot of progress in understanding the protostar and pre-main sequence phase of star formation.

Many challenges remain: The luminosity problem, the role of magnetic fields, star disk interaction, stellar winds.