Protostars and Pre-Main Sequence Evolution

José Garmilla

Princeton University

October 16, 2012

Outline

Bonnor-Ebbert Mass

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

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

Three phases of collapse

- Isothermal Collapse
- Adiabatic Collapse
- Envelope Accretion

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

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

with bc: $r = L_r = 0$ at $m = 0$, $P = P_\mathrm{o}$ $L_R = 4\pi R^2 \sigma T_\mathrm{eff}^4$ at $m = M$

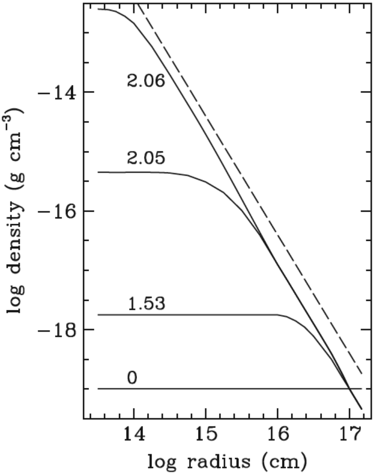
$\tau \approx \kappa_R \rho R$, $t_\mathrm{diff} \approx 3\kappa_R \rho (\Delta r)^2 / c$, $t_\mathrm{ff} \approx (G\rho)^{-1/2}$

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

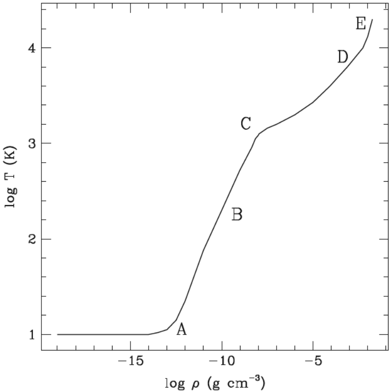
Adiabatic Phase: $\tau \gtrsim 1$, $t_\mathrm{diff} \gg t_\mathrm{ff}$, infrared radiation gets trapped, can ignore heat term in energy equation.

Protostars

Isothermal and Adiabatic Collapse

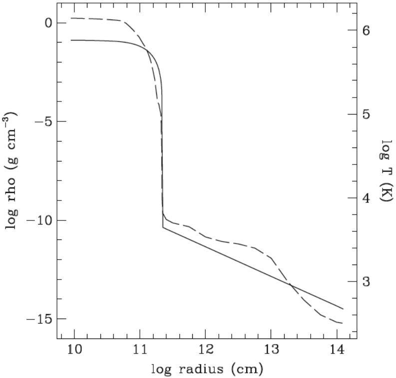


Larson, 1969



Bodenheimer, 2011

Protostars
Accretion Phase



Stahler et al., 1980

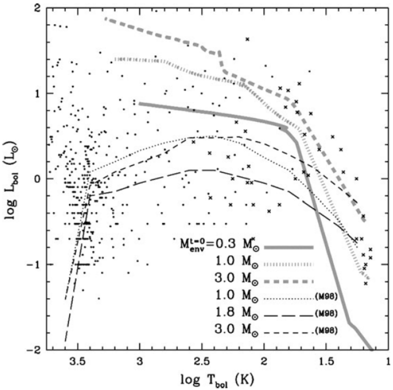
The central part of the core reaches *quasi-hydrostatic* equilibrium while the outer regions are still in isothermal collapse.

$t_{\rm KH} \approx GM^2/RL \sim$ Myr
$t_{\rm acc} \approx M/\dot{M} \sim 10^5$ yr
$t_{\rm diff} \ll t_{\rm acc} \ll t_{\rm KH}$, therefore
$L \approx L_{\rm acc}$.

Dust sublimates at $T \approx 1500$ K.

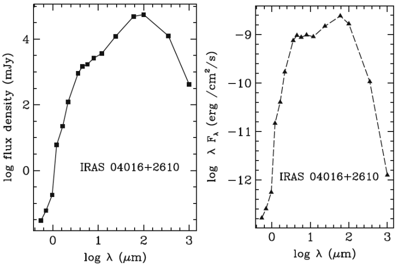
Protostars

Comparissons to Observations



Bodenheimer, 2011

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

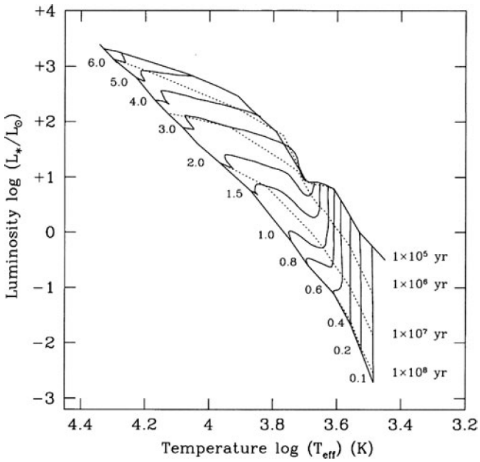


Kenyon et al., 1993
Bodenheimer, 2011

Non-thermal spectrum due wavelength dependent opacity.

Pre-Main Sequence Evolution

Convective and Radiative Contraction



Palla & Staller, 1999

In the interior,

$$\frac{3}{16\pi Gac}\frac{\kappa_R L_r P}{m T^4} > \left(\frac{\partial \ln T}{\partial \ln P}\right)_s$$

$$\kappa_K \propto \rho T^{-3.5}$$

Thin Outer Radiative Zone with H^-,

$$\kappa_{H-} \propto Z\rho^{0.5}T^9$$

$$\kappa_p P_p = \frac{2}{3}g$$

Table 8.1 Evolutionary times (years)

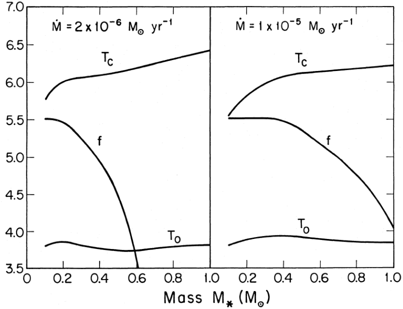
Mass ($M_\odot$)	Pre-main-sequence time	Mass ($M_\odot$)	Pre-main-sequence time
0.1	1.2×10^9	1.2	3.4×10^7
0.2	5.1×10^8	1.4	1.6×10^7
0.3	3.8×10^8	1.6	1.1×10^7
0.4	2.3×10^8	1.8	9.0×10^6
0.5	1.5×10^8	2.0	7.0×10^6
0.6	1.0×10^8	2.5	4.0×10^6
0.7	7.5×10^7	3.0	2.0×10^6
0.8	6.5×10^7	4.0	5.0×10^5
0.9	5.5×10^7	5.0	2.0×10^5
1.0	4.0×10^7	6.0	1.0×10^5

Bodenheimer, 2011

Stars above $6M_\odot$ are already in the main sequence when the accretion phase is over.

Pre-Main Sequence Evolution

Deuterium Burning and the Stellar Birthline

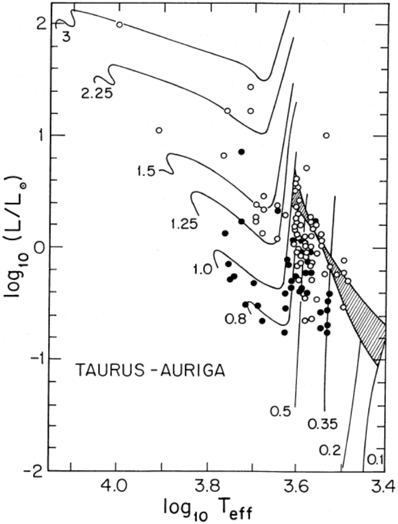


Stahler, 1988

Deuterium Burns at 10^6 K

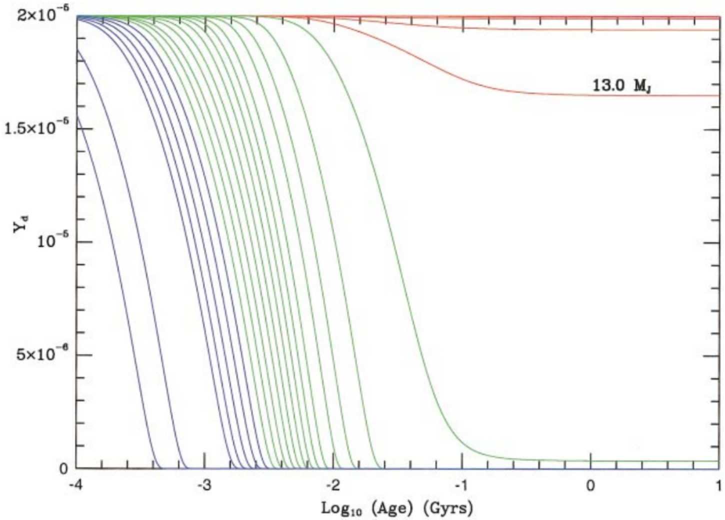
$$^1H + {}^2D \rightarrow {}^3He + \gamma$$

$$\epsilon \propto f\,[D/H]\,\rho T^{11.8}$$
$$[D/H] = 2 \times 10^{-5},\ f = 1$$



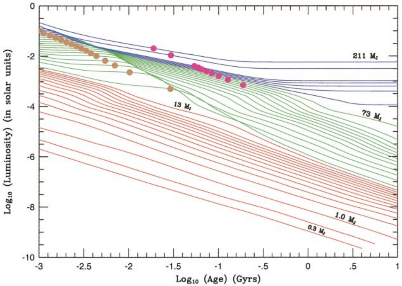
Stahler, 1988

Pre-Main Sequence Evolution
Deuterium Burning and the Stellar Birthline



Burrows et al., 2003

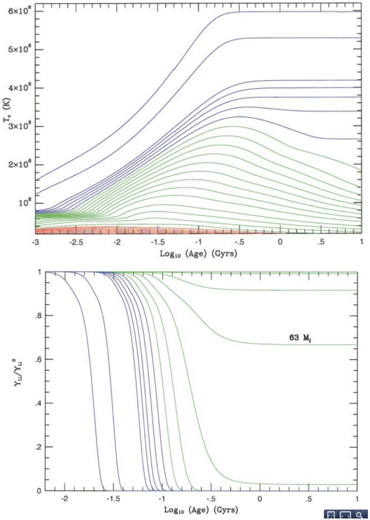
Pre-Main Sequence Evolution
Lithium Burning and Substellar Objects



Burrows et al., 2003

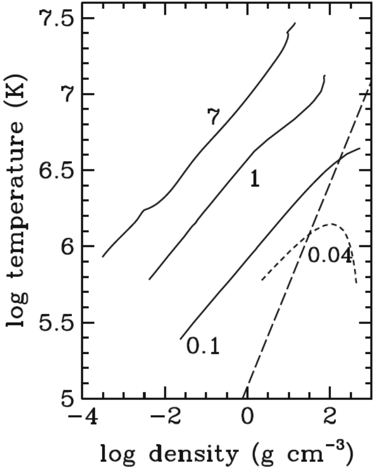
Cores with $M < 0.08 M_{\odot}$, can't burn Hydrogen

Lithium Burns at 2.5×10^6 K
$^1H + {}^7Li \rightarrow {}^4He + {}^4He$

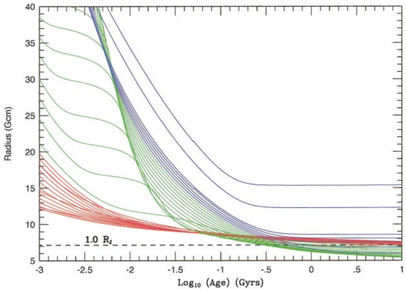


Burrows et al., 2003

Pre-Main Sequence Evolution
Degeneracy



Bodenheimer, 2011

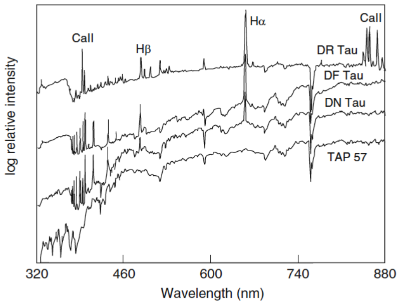


Burrows et al., 2003

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

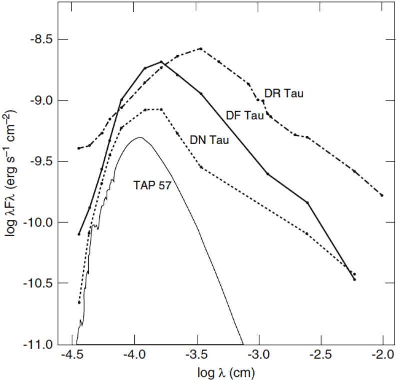
$$\rho = 2.4 \times 10^{-8} \mu_e T^{3/2} \text{g cm}^{-3}$$

Pre-Main Sequence Evolution
T Tauri Stars



Lada et al., 1999

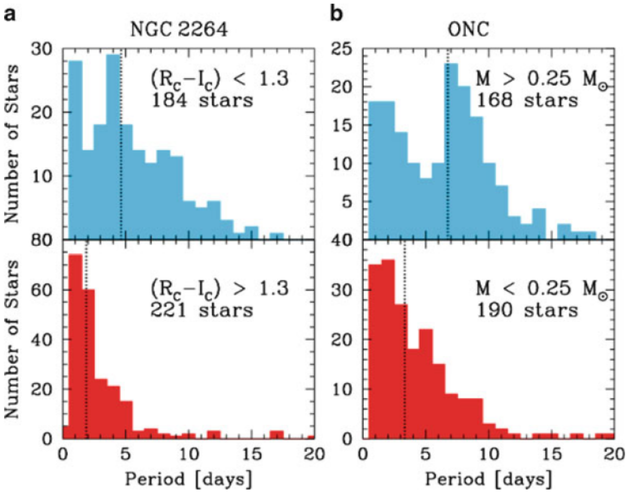
Hα, high *Li* abundance ($\sim 10^{-9}H$), nearby dark clouds, X-rays emission, strong magnetic fields (Zeeman splitting$\sim$kilogauss).



Lada et al., 1999

Infrared excess in CTTS, due to dusty disk.

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 foramtion.

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

References

Stahler, S. W., ApJ 332, pp. 804, 1988.

Palla, F., Stahler, S., ApJ 525, pp. 772, 1999.

Burrows, A., Hubbard, W., Lunine, J., Liebert, J., Rev. of Modern Physics 73, pp. 719, 2001.

Bodenheimer, Pirnciples of Star Formation, Springer, 2011.