From interstellar medium to stars

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Outline

- The Interstellar medium
- Gravitational collapse
- Protostellar phase
- Pre-Main Sequence

The interstellar medium

$$10 \lesssim T \lesssim 10^6 \ [\mathrm{K}]$$

$$10^{-3} \lesssim \mathrm{n} \lesssim 10^3 \ \ [1/cm^3]$$

Phase	n_{tot} (cm^{-3})	T (K)	M ($10^9 M_\odot$)
molecular	> 300	10	2.0
cold neutral	50	80	3.0
warm neutral	0.5	8×10^3	4.0
warm ionized	0.3	8×10^3	1.0
hot ionized	3×10^{-3}	5×10^5	–

Stahler and Palla (2004)

Molecular clouds

Mostly molecular hydrogen

$n \sim 10^{2-3}\, cm^{-3},\ T \sim 10 - 30\, K$

Interstellar dust

Silicates and carbon $\sim 0.1\ \mu m$

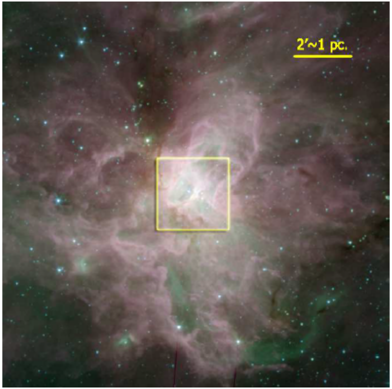
Molecular cloud and initial collapse

$$M \sim 10^5 - 10^6 \ M_\odot$$
$$T \sim 10 - 30 \ K$$
$$\rho \sim 10 - 100 \text{ particles}/cm^3$$

Cloud of molecular hydrogen

- Isothermal phase
- Free-fall collapse

$$\tau_{ff}^{Sun} \sim \frac{1}{\sqrt{G\overline{\rho}}} \sim 10^5 yr$$

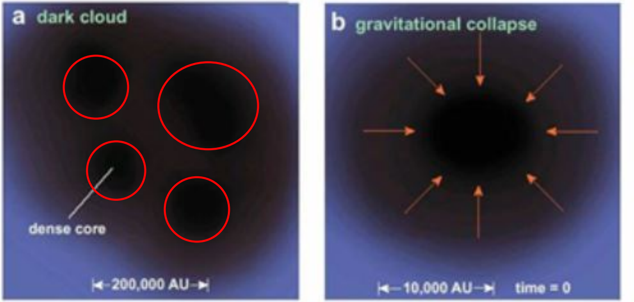


Wolk *et al.* (2008)

Fragmentation

$$M_J = 1\,M_\odot \left(\frac{T}{10\,K}\right)^{3/2} \sqrt{\frac{10^4\,cm^{-3}}{n}}$$

$$M_{Cloud} >> M_J \longrightarrow \text{Instability}$$



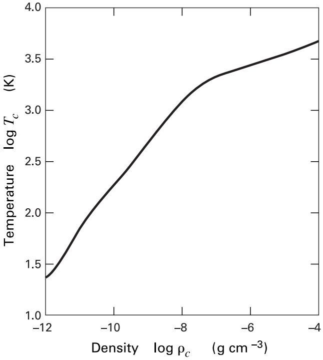
Fragmentation of the cloud

First protostellar core

Opaque central region

Rise of the central temperature

$$M_{core}^{Sun} \sim 5 \times 10^{-2} \ M_{\odot}$$
$$R_{core}^{Sun} \sim 10^{3} \ R_{\odot}$$



Stahler and Palla (2004)

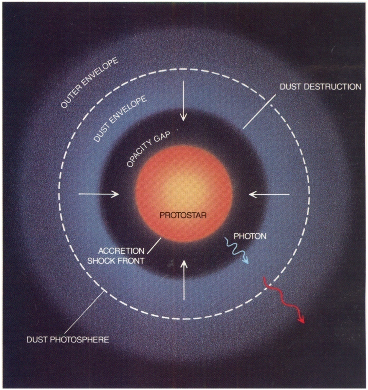
Dissociation of H_2 ($\sim 2000 \ K$) and collapse of the core

Stellar core

Rise in central temperature and pressure

Main accretion phase (free-fall velocity of the gas)

Emission in extreme ultraviolet and X-ray

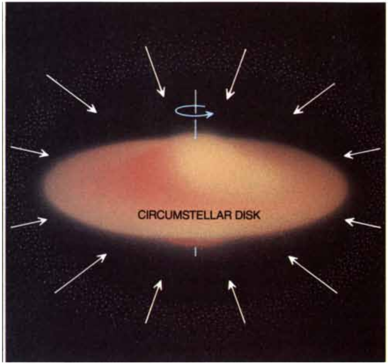


Stahler (1991)

Redshift due to scattering (visible in infrared)

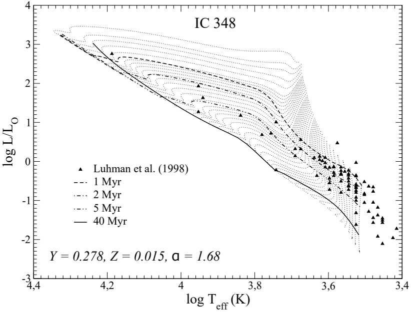
Birthline

The locus in the HR diagram where Pre-MS stars of various masses should first appear as visible objects (Stahler, 1983)



Stahler (1991)

Observative evidence in star forming regions



Tognelli *et. al* (2011)

Deuterium ignition

$$T \sim 10^6 \ K$$

Deuterium ignition

$$efficiency \propto T^{12}$$

Strongly dependent from temperature

$$p + D \longrightarrow {}^3He + \gamma$$

Equilibrium of the stellar structure

Expansion:

- decreasing temperature
- decreasing efficiency

Contraction:

- increasing temperature
- increasing efficiency

Hayashi track

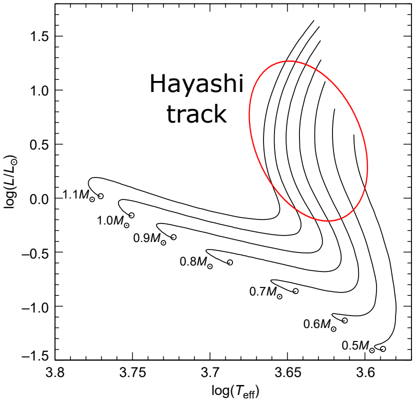
Convective star

Kelvin-Helmholtz timescale

$$t_{KH} \approx 3 \times 10^7 \text{ yr} \left(\frac{M_\star}{M_\odot} \right)^2 \frac{R_\odot L_\odot}{R_\star L_\star}$$

Constant effective temperature

Decreasing luminosity



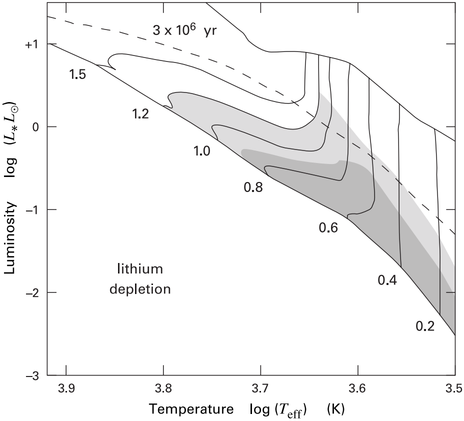
Salaris and Cassisi (2005) - Adapted

Lithium burning

$$T \sim 3 \times 10^6 \; K$$

Lithium ignition

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



Stahler and Palla (2004)

No influence on contraction

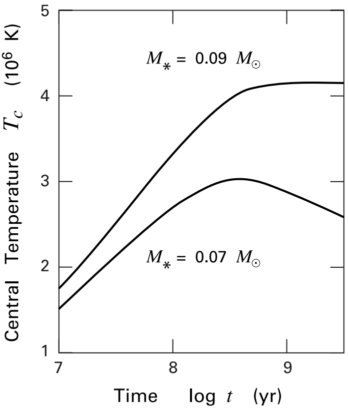
Contraction and temperature rise

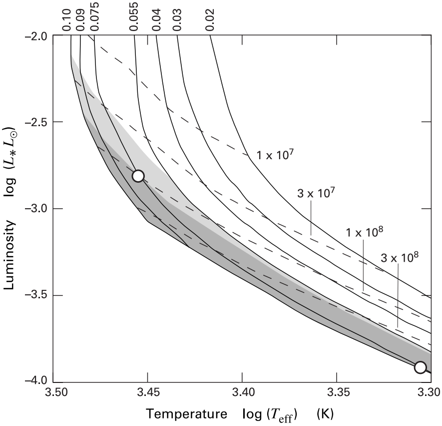
What happens next?

- $M \lesssim 0.08\ M_\odot$: Brown dwarf
- $M \gtrsim 0.08\ M_\odot$: Ignition of hydrogen (MS)

Brown dwarfs

Electron degeneracy counteracts gravity and temperature falls





Stahler and Palla (2004)

Approach to Main Sequence Phase

H-ignition

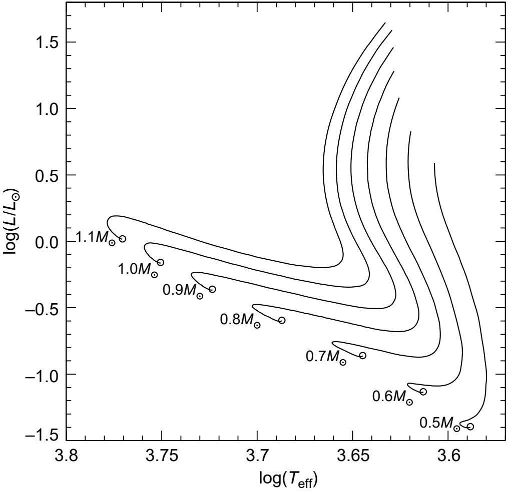
$$T \sim 10^7 \;\; K$$

$$p + p \longrightarrow D + e + \gamma$$

$$D + p \longrightarrow {}^3He + \gamma$$

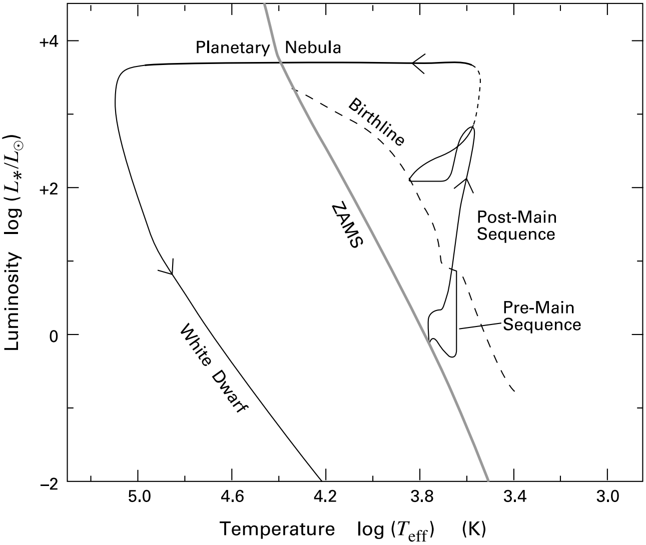
$$^3He + {}^3He \longrightarrow {}^4He + p + p$$

^3He out of equilibrium



Salaris and Cassisi (2005)

Evolution of a star (HR diagram)



Stahler and Palla (2004)

What is neglected?

- Rotation
- Magnetic field
- Chemical composition
- Large- and low-mass stars

G. A. Feyden and B. Chaboyer. The Astrophysical Journal, 779:183 (2013)
G. Somers and M. H. Pinsonneault. The Astrophysical Journal, 807:174 (2015)
L. Amard *et al.* arXiv: 1905.08516v1 (2019)

Thank you
for the attention

References

S. W. Stahler *and* F. Palla. The Formation of Stars, WILEY-VCH (2004)

R. B. Larson. *Mon. Nat. R. astr. Soc.* 145, 271-295 (1969)

M. Salaris *and* S. Cassini. Evolution of Stars and Stellar Populations, John Wiley & Sons (2005)

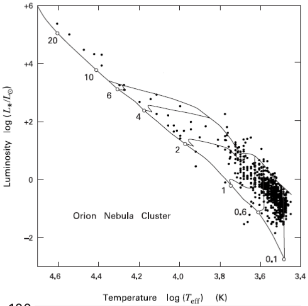
S. W. Stahler. Scientific American 48-55, July 1991

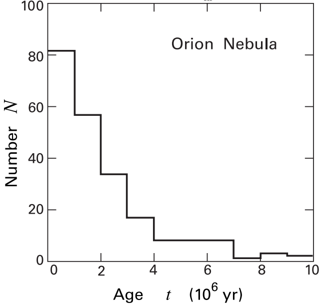
E. Tognelli *et al.* A&A 533, A109 (2011)

E. I. Vorobyov *and* Y. N. Pavlyuchenkov. A & A 606, A5 (2017)

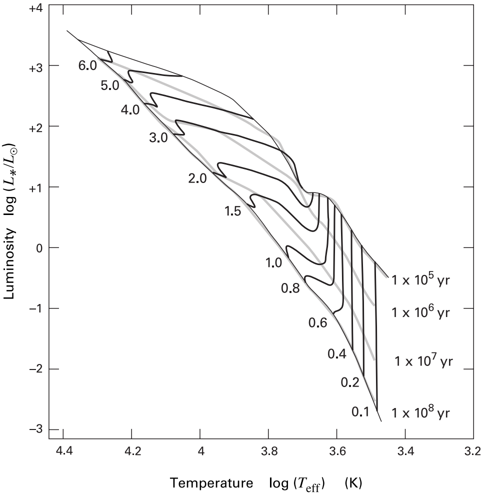
S. J. Wolk *et al.* arXiv: 0808, 3385 (2008)

Birthline





Stahler and Palla (2004)



Birthline

Table 16.1 The Theoretical Birthline

Mass (M)	Radius (R)	log L_* (L)	log T_{eff} (K)	Δt_D (yr)	t_{ZAMS} (yr)
0.1	2.49	−0.28	3.49	1.5×10^6	3.7×10^8
0.2	2.52	−0.01	3.52	8.5×10^5	2.4×10^8
0.4	2.70	+0.27	3.56	3.0×10^5	1.1×10^8
0.8	4.32	+0.78	3.61	2.7×10^4	5.2×10^7
1.0	4.92	+0.85	3.63	6.9×10^3	3.2×10^7
1.5	5.09	+0.89	3.65	0	1.2×10^7
2.0	4.94	+0.90	3.67	0	8.4×10^6
3.0	5.66	+0.94	3.70	0	2.0×10^6
4.0	10.2	+2.09	3.84	1.4×10^4	8.2×10^5
5.0	8.20	+2.83	4.05	8.3×10^3	2.3×10^5
6.0	4.62	+3.24	4.27	1.1×10^3	2.9×10^4
7.0	3.28	+3.40	4.32	7.0×10^1	8.5×10^3
8.0	3.11	+3.55	4.36	0	0

Stahler and Palla (2004)

Pre-Main Sequence

Table 16.2 Evolution of Low-Mass, Pre–Main-Sequence Stars

$M_* = 0.2 M$

Time (yr)	R_* (R)	log T_{eff} (K)	log L_* (L)	log T_c (K)	L_{nuc}/L_*	M_{con} (M)
0	2.55	3.51	+0.02	5.81	0	0.06
1×10^5	2.29	3.51	−0.02	5.92	0.83	0.20
1×10^6	1.89	3.51	−0.57	6.08	0.12	0.20
3×10^6	1.30	3.52	−1.11	6.30	0	0.20
1×10^7	0.61	3.52	−1.40	6.48	0	0.20
3×10^7	0.41	3.52	−1.78	6.64	0	0.20
1×10^8	0.28	3.52	−2.10	6.75	0.40	0.20
2×10^8	0.26	3.52	−2.15	6.78	0.90	0.20

$M_* = 0.6 M$

Time (yr)	R_* (R)	log T_{eff} (K)	log L_* (L)	log T_c (K)	L_{nuc}/L_*	M_{con} (M)
0	4.01	3.59	+0.54	6.04	0.85	0.60
1×10^5	4.00	3.59	+0.53	6.08	0.45	0.60
3×10^5	3.62	3.59	+0.43	6.17	0.09	0.60
1×10^6	2.13	3.59	−0.02	6.35	0	0.60
3×10^6	1.51	3.59	−0.35	6.51	0	0.60
1×10^7	0.90	3.58	−0.78	6.68	0	0.51
3×10^7	0.72	3.59	−0.98	6.77	0.06	0.30
9×10^7	0.58	3.61	−1.08	6.97	0.90	0.10

$M_* = 1.0 M$

Time (yr)	R_* (R)	log T_{eff} (K)	log L_* (L)	log T_c (K)	L_{nuc}/L_*	M_{con} (M)
0	4.80	3.64	+0.85	6.20	0	1.00
1×10^5	4.25	3.63	+0.75	6.22	0	1.00
3×10^5	3.77	3.63	+0.62	6.26	0	1.00
1×10^6	2.59	3.63	+0.28	6.48	0	1.00
3×10^6	1.80	3.63	+0.00	6.64	0	0.78
1×10^7	1.22	3.64	−0.28	6.78	0.01	0.38
3×10^7	1.01	3.75	−0.02	7.09	0.90	0.03

Stahler and Palla (2004)