Astronomy 404
October 28, 2013

Chapter 12. The ISM and Star Formation

HII Regions

Massive stars' UV radiation can photo-ionize the ambient gas into HII regions. The Strömgren sphere (a spherical ionized gas cloud) has a radius of :

$$r_S \simeq \left(\frac{3N}{4\pi\alpha}\right)^{1/3} n_H^{-2/3}.$$

Note that this equation works only when the HII region is optically thick to the ionizing UV radiation.

α_B = 3.1 x 10^{-19} m^3 s^{-1} at 8000 K

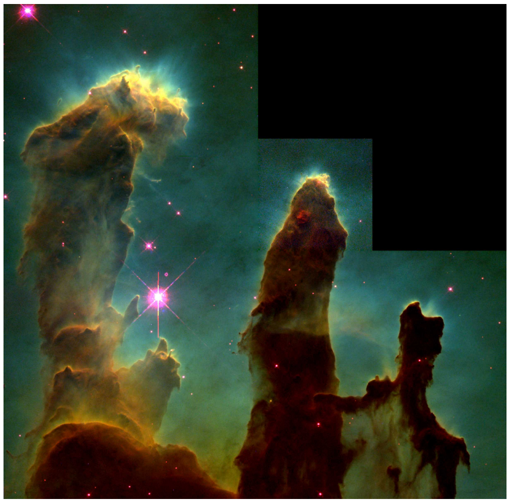
α_B = 2.6 x 10^{-19} m^3 s^{-1} at 10,000 K

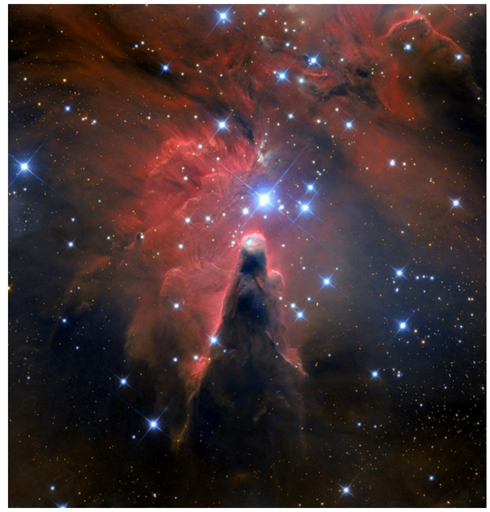
α_B is the recombination coefficient for recombinations to excited state, i.e., n= 2 or higher.

Massive stars are rarely formed in isolation. They are born in clusters or OB associations. They photoionize the ambient medium into HII regions.

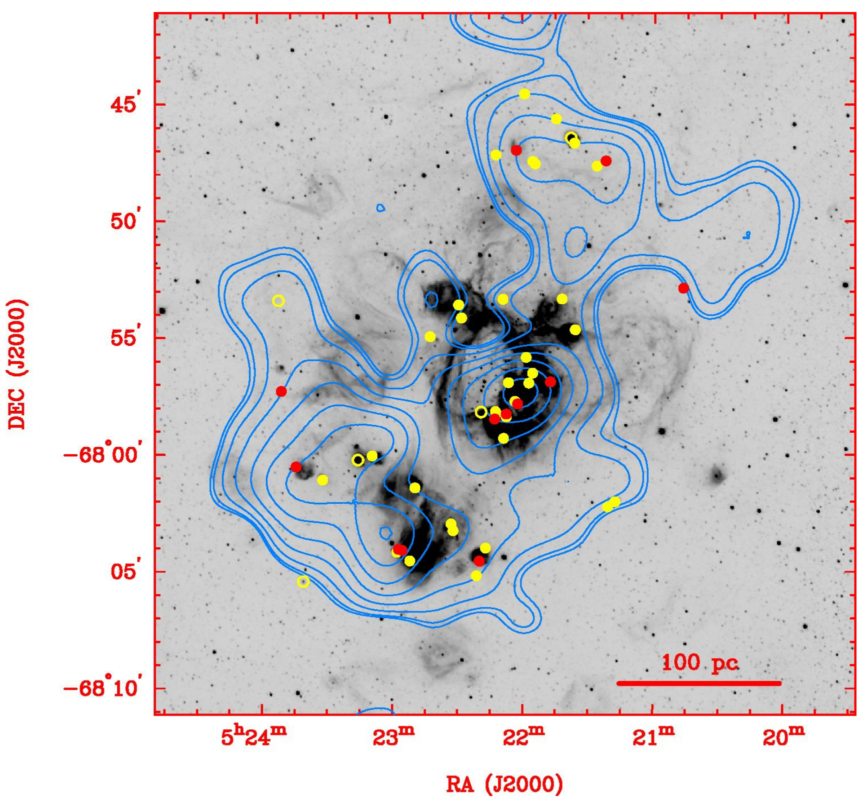
HII regions are often referred to as "star-forming regions" because O stars have short life-time and must be formed within the last few Myr and the low-mass stars are still in their contracting phase being formed.

HII regions commonly show dust pillars, remnants from the natal molecular clouds. See the two examples below.



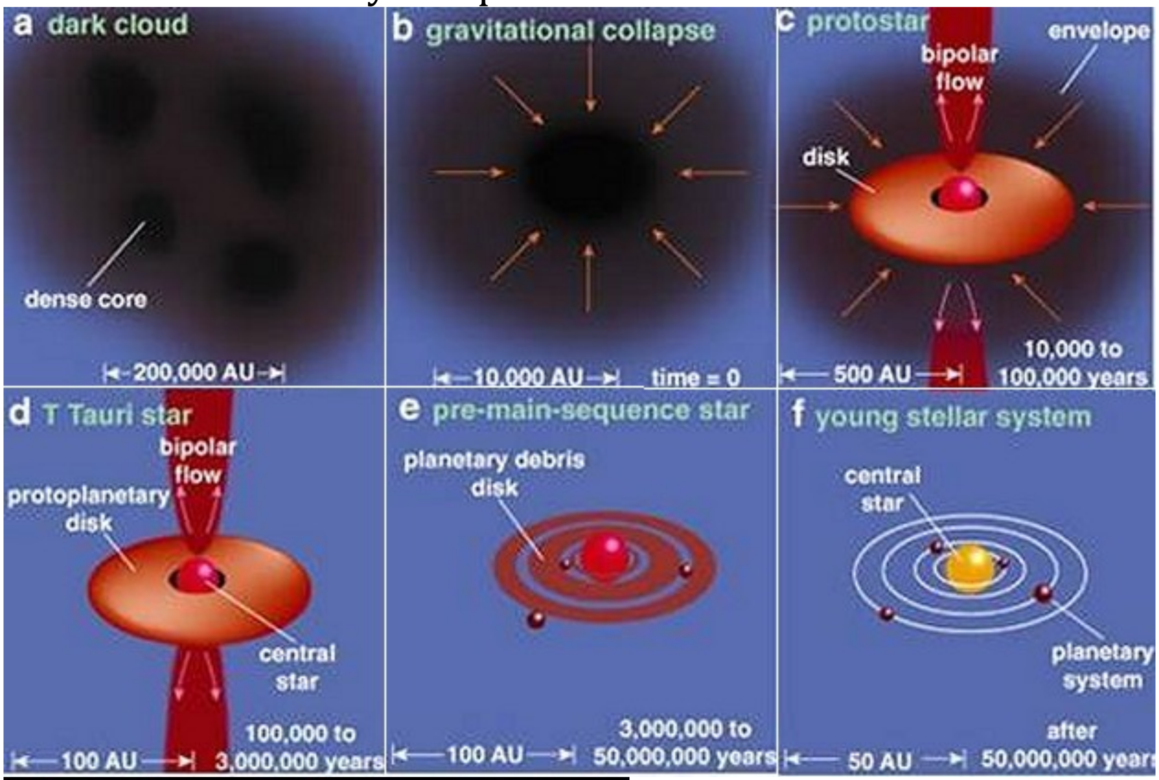


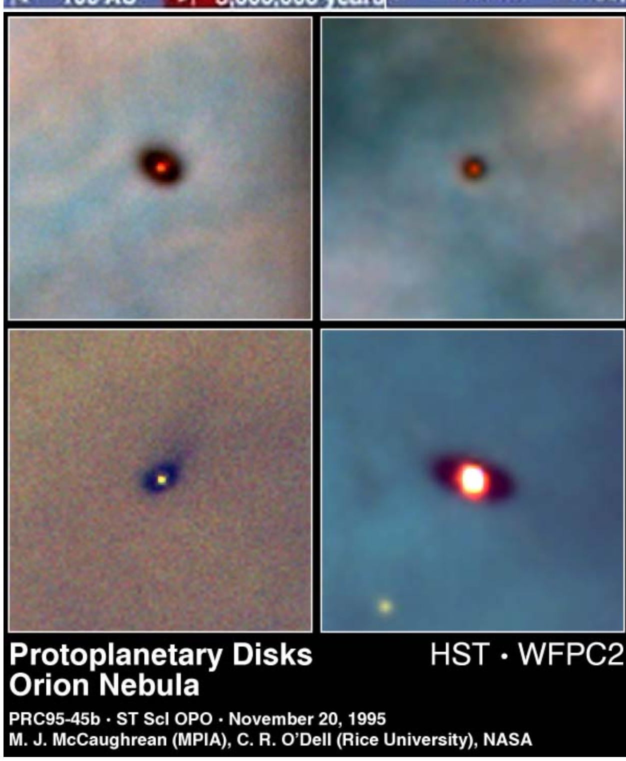
In the image below, you see HII regions (black), young stellar objects (red dots for massive stars, and yellow dots for intermediate mass stars), and molecular clouds (cyan contours) in the star-forming region N44 in the LMC.

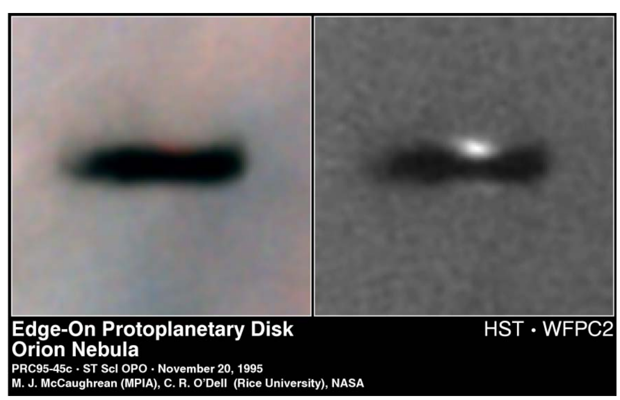


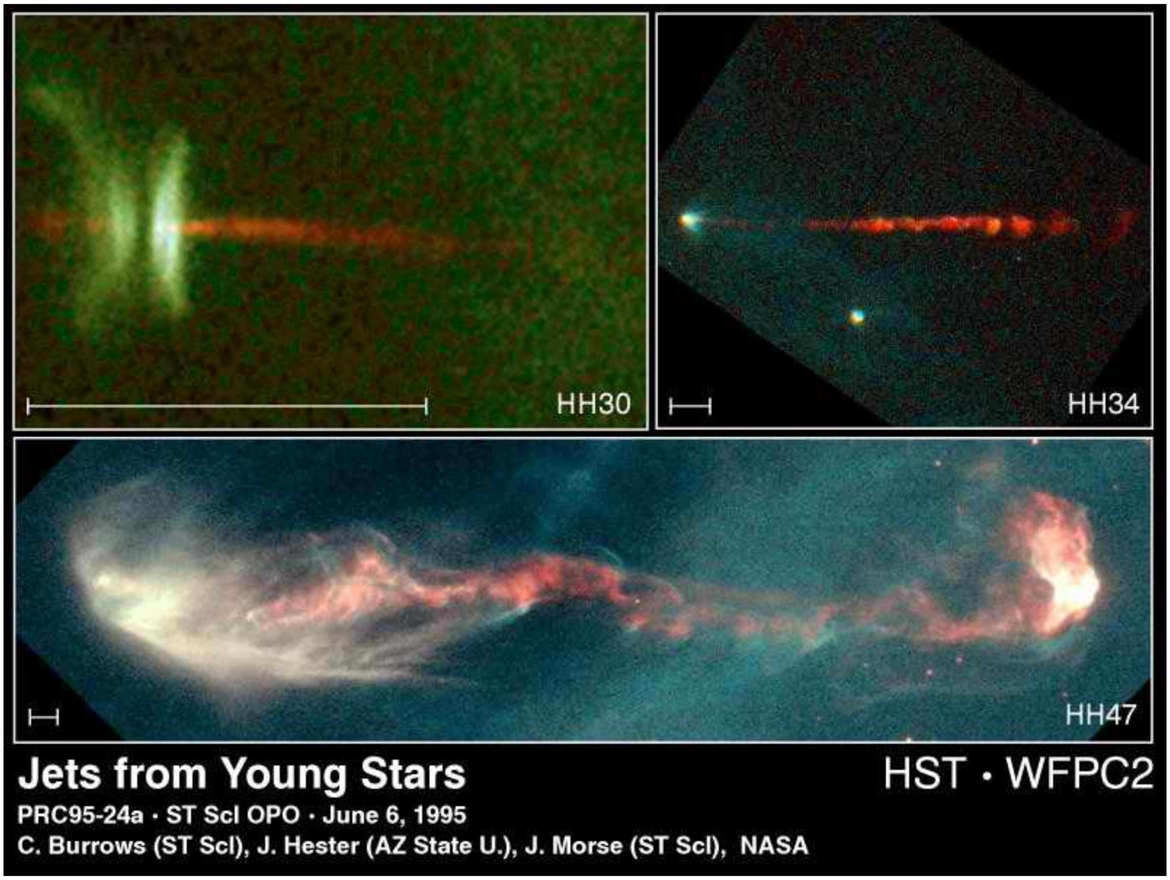
Low-mass pre-main sequence stars

Below is a commonly accepted model for low-mass star formation.









T Tauri stars

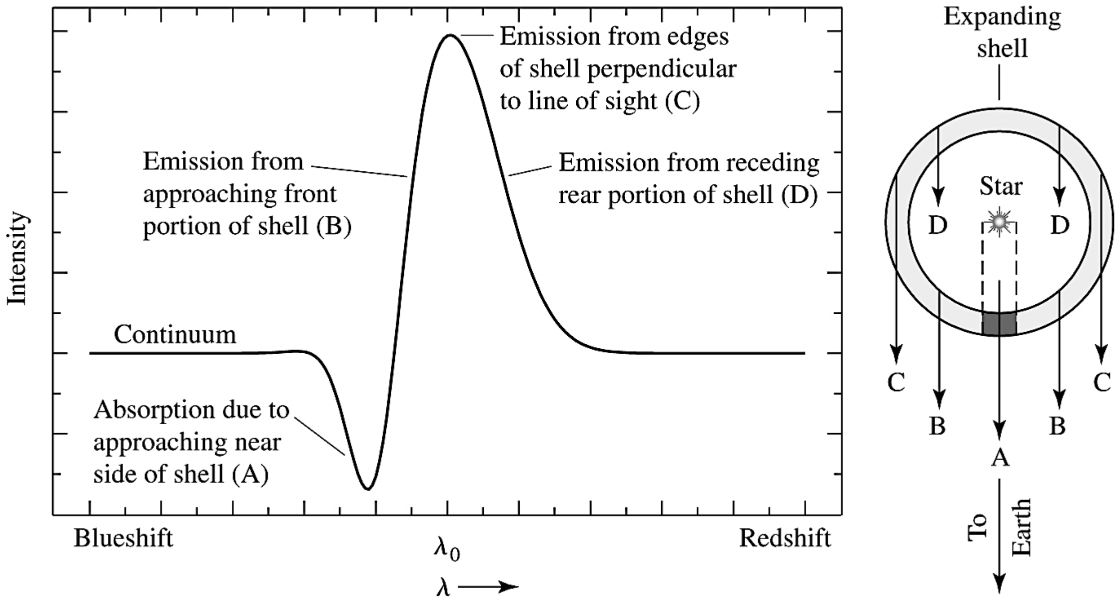
These are young stars in the process of getting rid of the accretion disk. Their masses range from 0.5 to 2 $M_\odot$.

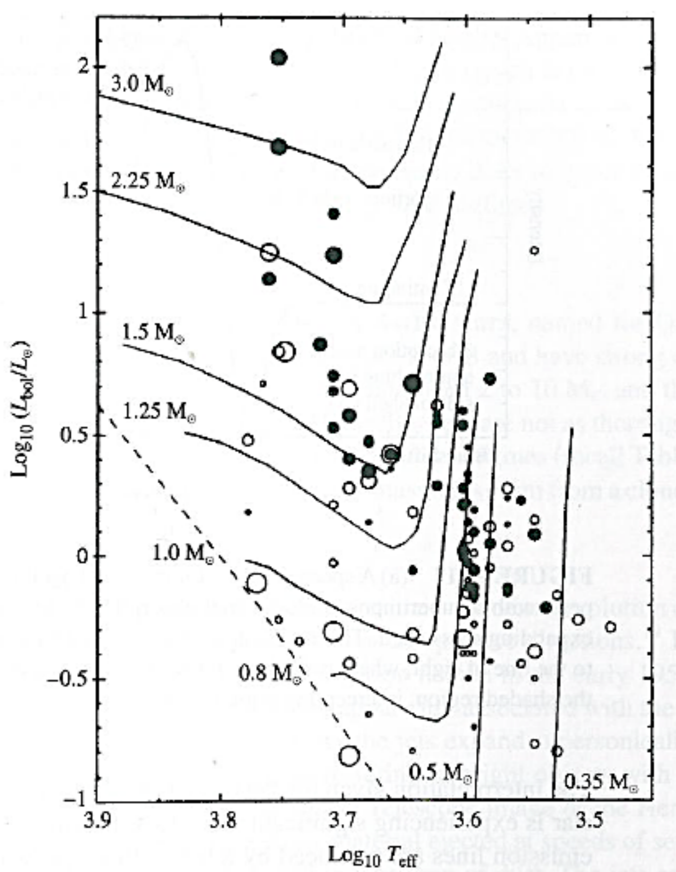
T Tauri stars with strong Hα emission line are "classical" T Tauri stars; their accretion disks are still significant.

T Tauri stars without Hα emission can be diagnosed by their X-ray emission; these are "naked" or "weak-lined" T Tauri stars.

T Tauri stars' X-ray emission can originate from their corona or accretion.

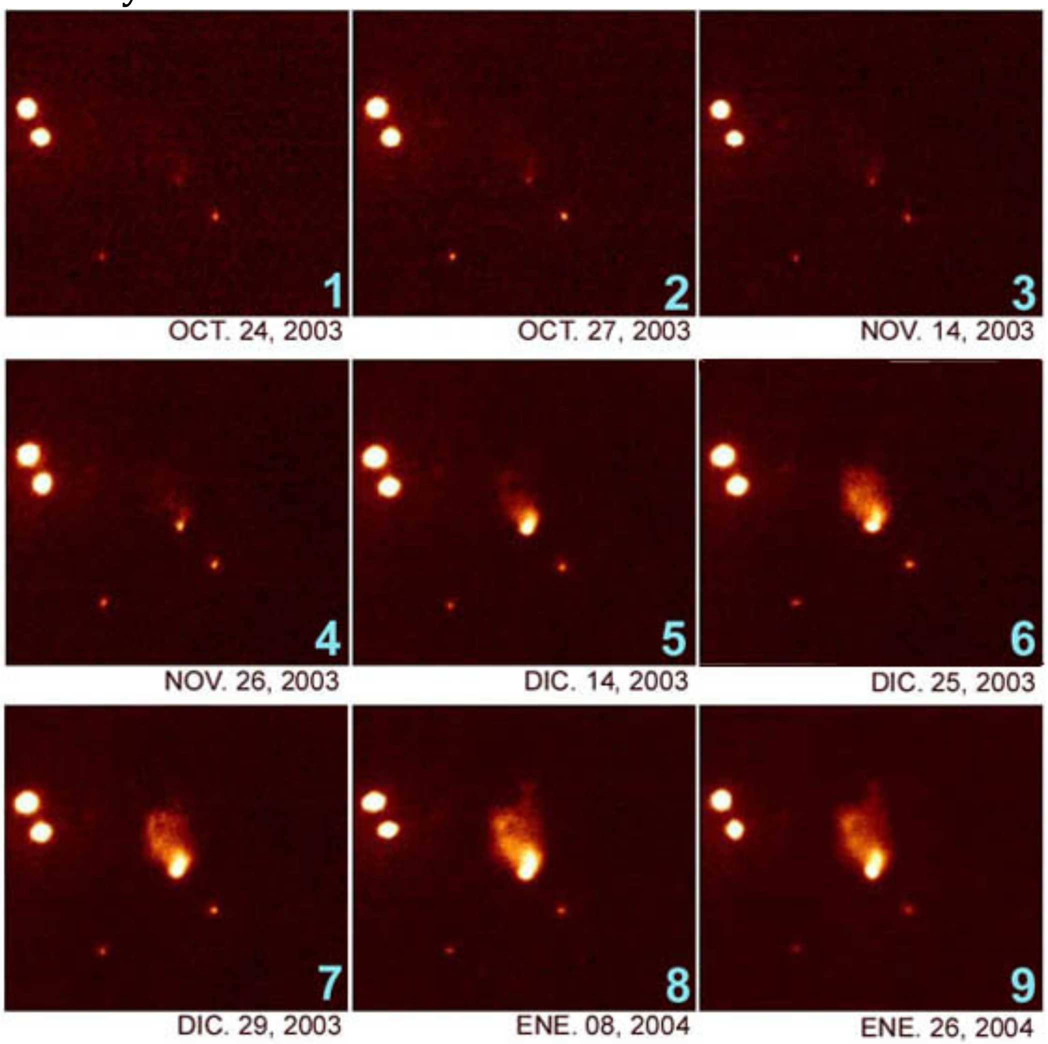
T Tauri stars can exhibit either P Cygni profiles (wind/outflow) or inverse P Cygni profile (accretion), depending on viewing angle.





T Tauri stars in the H-R diagram. Size of the circle indicates the rate of rotation. Filled circles for strong-lined T Tauri, and open circles for weak-lined T Tauri.

FU Orionis Stars are T Tauri stars that go through periods of significant increase in accretion rates, reaching accretion rates of 10^{-4} $M_\odot$ yr^{-1}. The inner disk can outshine the star and strong high-velocity winds occur. Below shows an outburst of a FU Ori star.



Herbig-Haro objects are young stars that show outflows.

Herbig Ae/Be stars are the higher-mass counterparts of T Tauri stars. HAeBe stars have spectral types of A or B with strong emission lines. Their masses range from 2 to 10 $M_\odot$.

Proplyds are protoplanetary disks around young low-mass stars. They are illuminated by radiation and blasted by stellar winds of nearby massive stars. Here are 30 proplyds from the Orion Nebula.

Chapter 13. Main Sequence and Post-Main Sequence Stellar Evolution

Timescales to pay attention to:

Free-fall timescale	--	pre-main sequence	(~0.4 Myr)
Kelvin-Helmholtz timescale	--	pre-main sequence	(10 Myr for Sun)
Nuclear timescale	--	main sequence	(10 Gyr for Sun)

The nuclear timescale is the longest, during which a star is stable and is located in the main sequence in an H-R diagram.

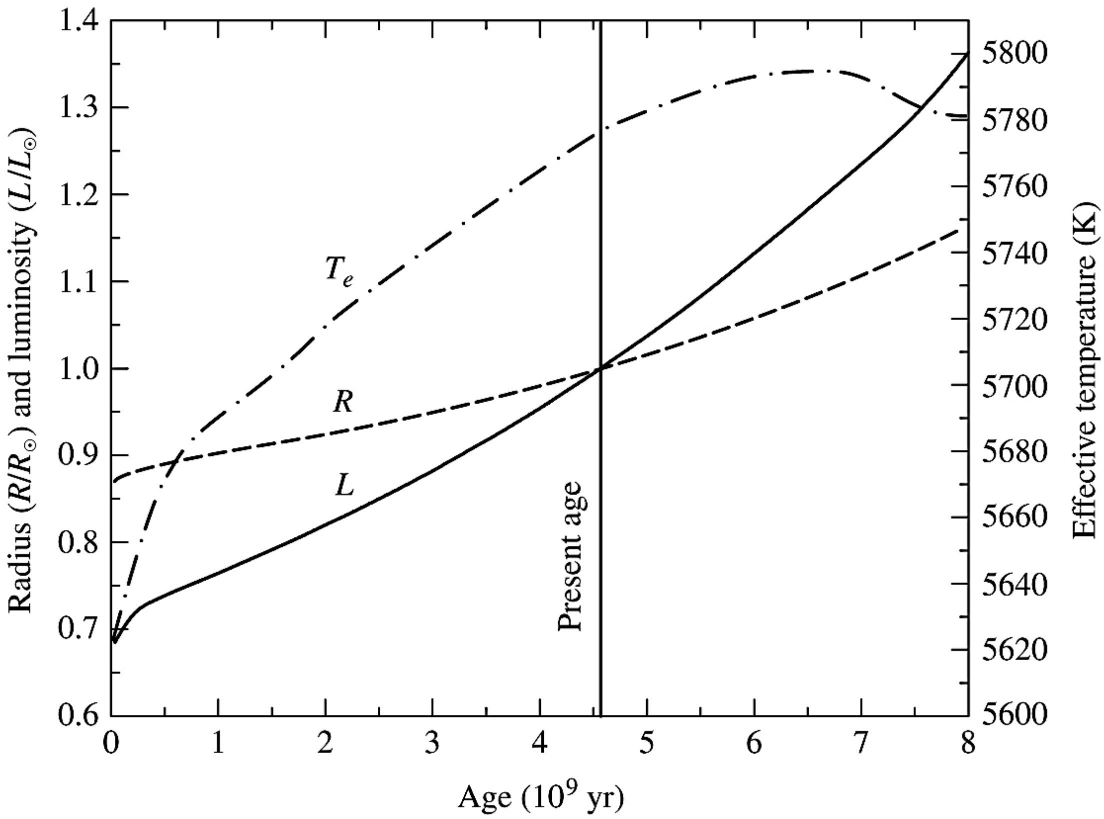
The main sequence is not a thin line; its widths are caused by the stars adjusting their internal structure as nuclear reactions go on.

Remember that H-burning in stars more massive than 1.2 $M_\odot$ is dominated by CNO cycle and the lower mass stars PP chain. These different reactions have different energy production rates, which lead to different internal structures and different evolution paths.

Stellar evolution is a saga of stars fighting the gravitational force!

For a low-mass main sequence star like the Sun,
PP chain converts H into He in the stellar core => μ increases
As $P = (\rho/\mu\, m_H)\, k\, T$, ρ and/or T need to increase to maintain the pressure. Therefore, the core must be compressed.

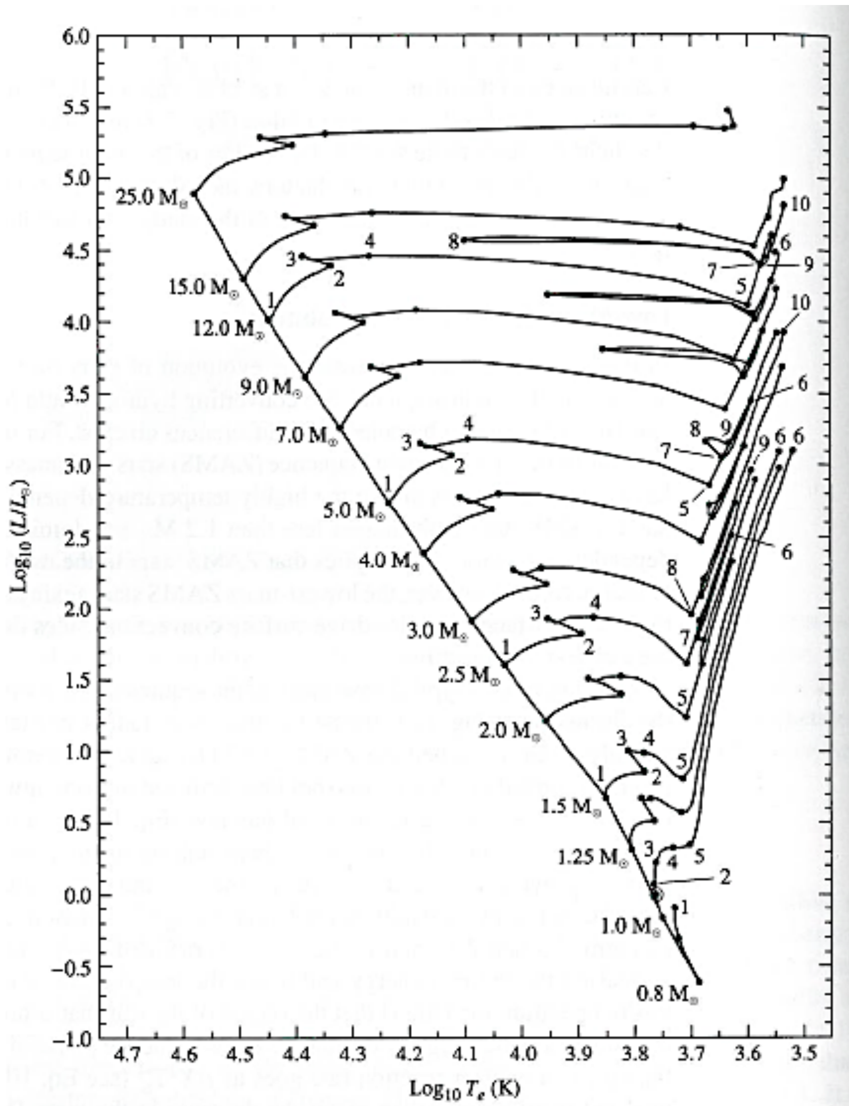
The compressed core raises the density, and ½ of the gravitational energy released is radiated away and ½ is retained to heat the core. The raised density and temperature in the core raises the nuclear reaction rate and energy production rate, although the fraction of H is lower than before. (reaction rate $\propto \rho X^2 T^4$)
Therefore, stellar luminosity slowly increases.



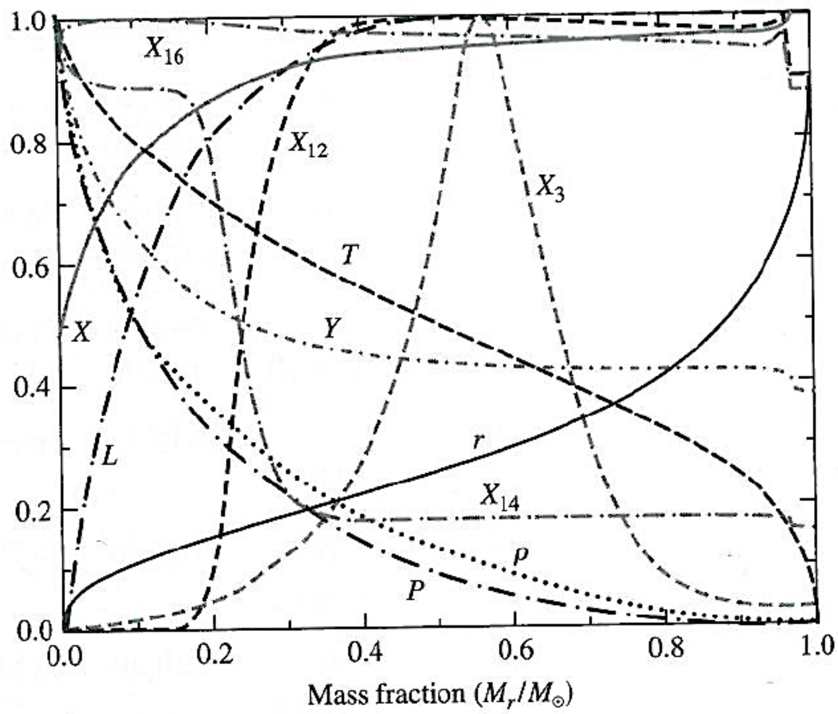
For the Sun, luminosity, radius, and temperature all increases.

For stars of different masses, the evolutionary tracks are different.

The first evolutionary tracks of low-mass stars were calculated by Professor Icko Iben, Jr., an emeritus professor of our department.

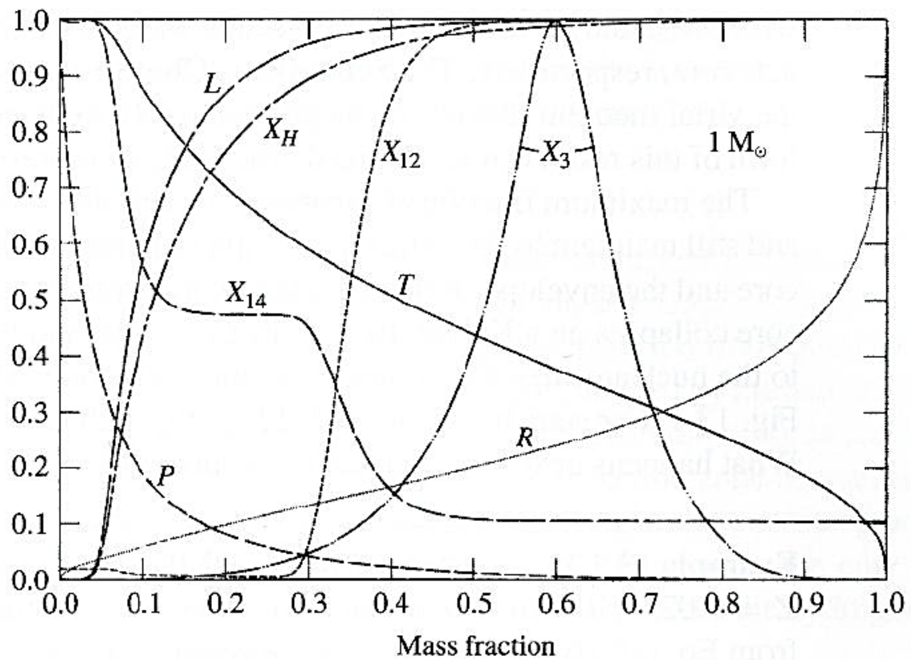


After core H is exhausted, H-burning occurs in a shell around the He core. The core (with 3% of the mass) has zero luminosity and is isothermal.



Above is the present-day Sun’s structure.

Below is the Sun’s structure near point 3 of the evolutionary track.



Initial Mass	1	2	3	4	5
($M_\odot$)	6	7	8	9	10
25	0	6.33044	6.40774	6.41337	6.43767
	6.51783	7.04971	7.0591		
15	0	11.4099	11.5842	11.5986	11.6118
	11.6135	11.6991	12.7554		
12	0	15.7149	16.0176	16.0337	16.0555
	16.1150	16.4230	16.7120	17.5847	17.6749
9	0	25.9376	26.3886	26.4198	26.4580
	26.5019	27.6446	28.1330	28.9618	29.2294
7	0	42.4607	43.1880	43.2291	43.3388
	43.4304	45.3175	46.1810	47.9727	48.3916
5	0	92.9357	94.4591	94.5735	94.9218
	95.2108	99.3835	100.888	107.208	108.454
4	0	162.043	164.734	164.916	165.701
	166.362	172.38	185.435	192.198	194.284
3	0	346.240	352.503	352.792	355.018
	357.310	366.880	420.502	440.536	
2.5	0	574.337	584.916	586.165	589.786
	595.476	607.356	710.235	757.056	
2	0	1094.08	1115.94	1117.74	1129.12
	1148.10	1160.96	1379.94	1411.25	
1.5	0	2632.52	2690.39	2699.52	2756.73
	2910.76				
1.25	0	4703.20	4910.11	4933.83	5114.83
	5588.92				
1	0	7048.40	9844.57	11386.0	11635.8
	12269.8				
0.8	0	18828.9	25027.9		

The **Schonberg-Chandrasekhar Limit**
The maximum factional mass that can exist in the isothermal core.

$$\left(\frac{M_{ic}}{M}\right)_{\rm SC} \simeq 0.37\left(\frac{\mu_{\rm env}}{\mu_{ic}}\right)^2,$$