# PHY 474/374 – Stellar Astrophysics

## *Spring 2021*

## Week 9, Day 1

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# Announcements

- In-class Exam is Wednesday (next class meeting).
- You must be present on the Zoom session in order to take the exam, otherwise you'll have to take a make-up exam.
- All class summaries, worksheets, videos, homework solutions have been posted.
- Special Office Hour is 9 PM on Tuesday, the night before the exam.

# Stellar Evolution: The Complete Picture

- Everything we have learned has been with the purpose of understanding what goes on inside a star and how it evolves.

- Let's remind ourselves of the most important parts.

# Stars and Stellar Evolution

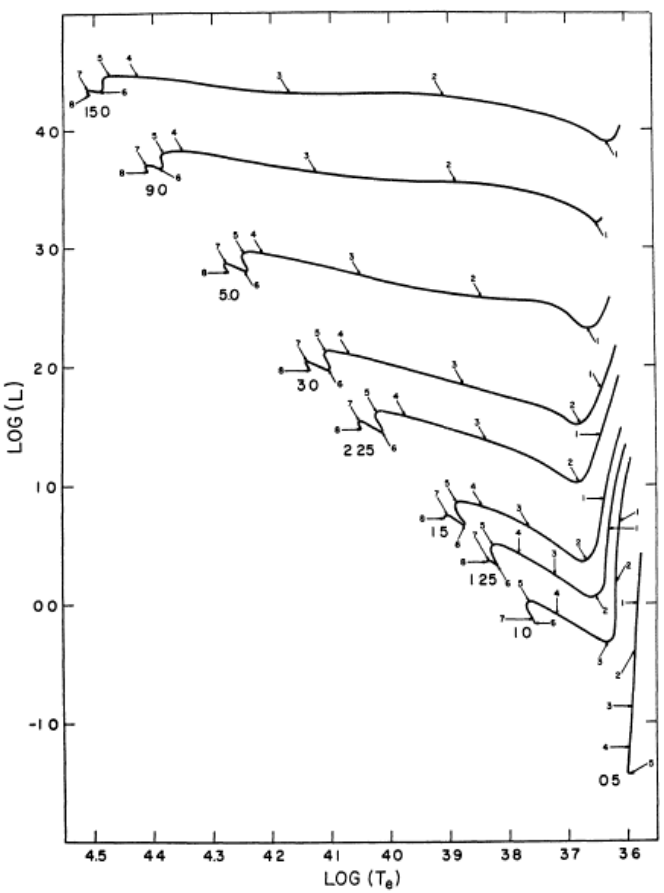
- Stars form in sub-pc scale dense cores inside Giant Molecular Clouds (GMCs).

- Gravitational collapse of these cores results in a protostar forming at the center, and this is accompanied by disks and outflows.

Image of propylds in Orion and Herbig-Haro objects removed to limit file space.

# Stars and Stellar Evolution

- When the protostar makes its appearance in the HR diagram, it is fully convective.
- Depending on mass, stars follow different routes to the Main Sequence (MS) stage.




High mass stars spend very little time on the convective Hayashi track.

Low mass stars ~1 $M_\odot$ become radiative and approach the MS on the Henyey track.

Very low mass stars ~0.5 $M_\odot$ reach the MS while still on the Hayashi track.

# Stellar Evolution

- Stars arrive on the ZAMS when they attain hydrostatic equilibrium after igniting H fusion.

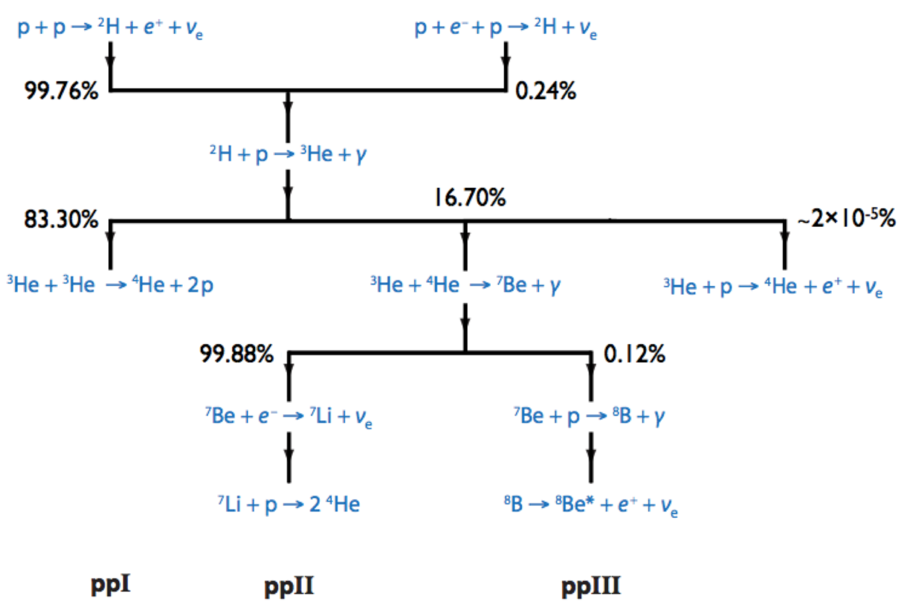
Dalsgaard, Figure 11.1
removed to limit file space.

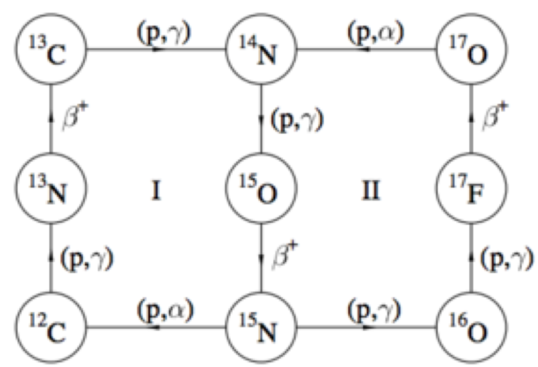
HR diagram of the zero-age main sequence computed for the composition $X = 0.685$, $Y = 0.294$. The location of several models with masses between 0.1 and 22 $M_\odot$ are indicated below the sequence.

*Dalsgaard*, Figure 11.1

# Stellar Evolution

- Stars spend the majority of their lifetime on the Main Sequence fusing H to He.
- For lower mass stars, the dominant process is the PP chain.
- For higher mass stars, the CNO cycle dominates.

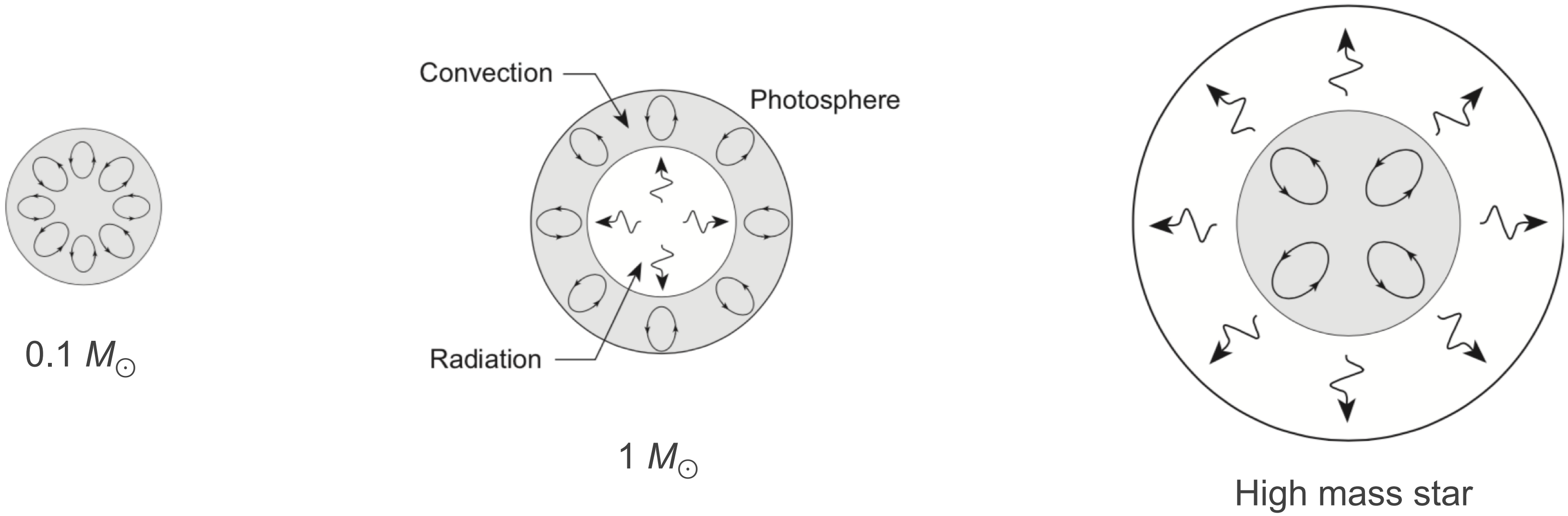



J. Li, *Stanford*

# Energy Transport in Stars

- Energy produced in the core is conveyed to the surface.
- The mode of transport depends on the mass of the star.




Guidry, *Stars & Stellar Processes*

# Energy Transport in Stars

- More quantitative representation of convective and radiative zones in stars.
- *y*-axis is fraction of mass from center to surface, *x*-axis is mass of star in $M_\odot$

*Cloudy areas* indicate extent of convection zones.

The two solid lines give the mass values at which *r* is 1/4 and 1/2 of the total radius R.

Dashed lines show the mass values inside which 50 per cent and 90 per cent of the luminosity $L_s$ are produced.

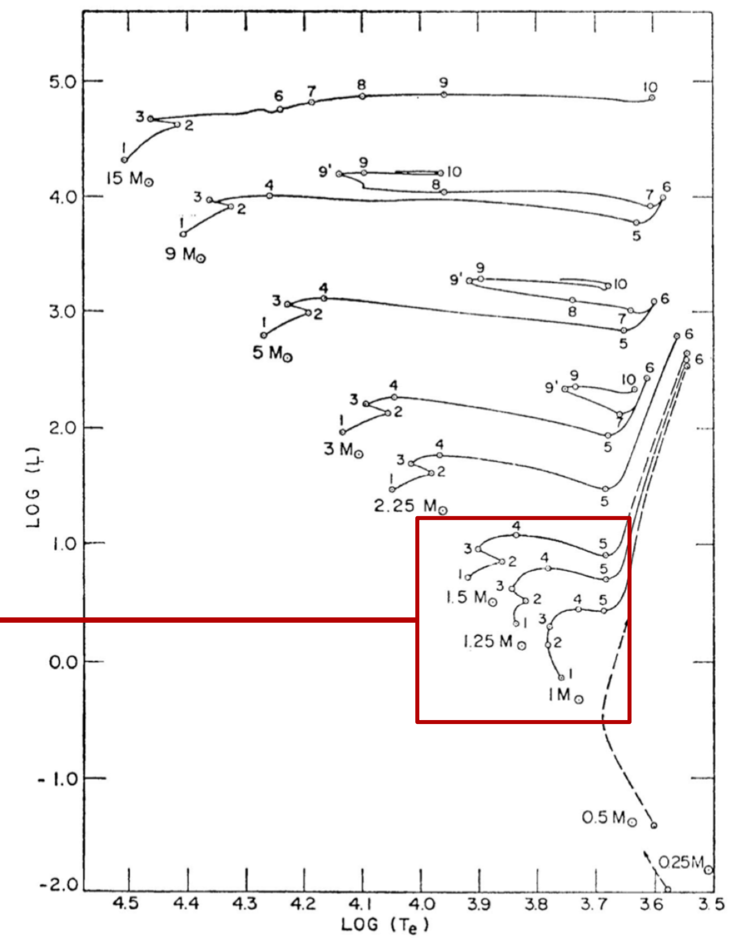
Dalsgaard, Figure 11.4 removed to limit file space.

*Dalsgaard*, Figure 11.4

# Post-Main Sequence Evolution

Stars then evolve off the Main Sequence. The details again depend on mass.

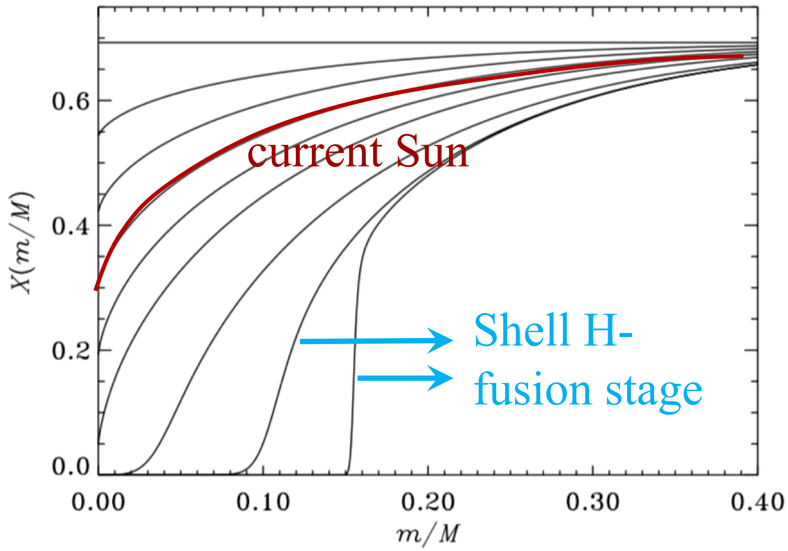
For example, we've learned how 1 $M_\odot$ stars don't show the overall collapse phase from points 2 to 3.



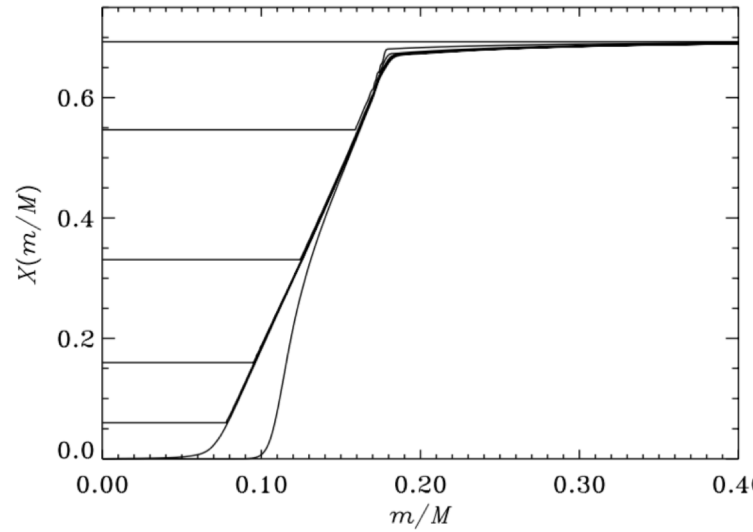

*Dalsgaard*, Figure 11.5

# Post-Main Sequence Evolution

- 1 $M_\odot$ stars don't show the overall collapse phase from points 2 to 3.




Hydrogen profiles showing the gradual exhaustion of hydrogen in a star of 1 $M_\odot$. $X$ as a function of the mass fraction $m/M$ is plotted for nine models which correspond to ages of 0, 2.0, 3.6, 5.0, 6.2, 7.5, 9.6, 11.0 and 11.6 times $10^9$ yr after the onset of H fusion.



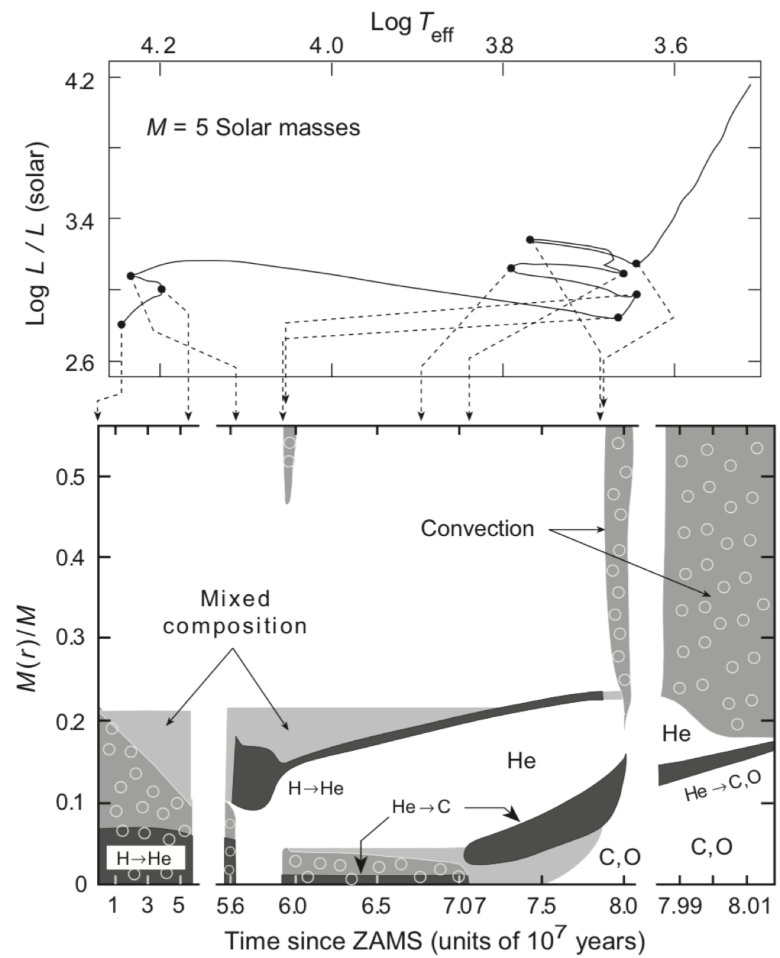

Hydrogen depletion in a 2.5 $M_\odot$ star with a shrinking convective core. $X$ for age 0, 1.5, 3.1, 4.0, 4.4, 4.6, and 4.8 times $10^8$ years. Since H-fusion is negligible at the edge of the convective core during the MS phase, the H-profile reflects the decrease in the extent of the core. In contrast, the last model is in the H shell-fusion phase, the He core having grown substantially beyond the smallest extent of the convective core.

*Dalsgaard*, Figure 11.6 & 11.7

# Post-Main Sequence Evolution

I've written up the details of post-MS evolution of lower mass stars in the class summary and posted video, and today you'll get a chance to go over them using a device called a Kippenhahn diagram (bottom panel).

Today's Worksheet, Question 5




Post main-sequence evolution of a 5 $M_\odot$ star. Darkest shading in the bottom panel indicates regions of energy production and regions with circles are convective. The upper panel shows the evolutionary track on the HR diagram. Note the breaks in scale for the time axis in the bottom panel.

Guidry, *Stars & Stellar Processes*

# Post-MS: High Mass Stars

- High Mass stars can go beyond C-fusion up to Si-fusion, and assemble elements up to Fe.

- Let's look in more detail at their end stage.

- The exact details can be broken up into $8\ M_\odot < M < 25\ M_\odot$, $M > 25\ M_\odot$, etc.

- Let's fast-forward and look at the final spectacular stage.

# Supernovae

- When the star has an onion-skin core with Fe in the innermost core, it runs out of fusion stages, and there is no more energy production.
- Core collapses. As it collapses, temperatures becomes high enough (> $10^{10}$ K) that photons can break up heavier nuclei into lighter ones.
- These are endothermic reactions that cost energy rather than produce it, so core quickly cools, and collapse accelerates.
- Collapse is halted when core becomes a neutron star. Three mechanisms work together to eject the envelope in an explosion known as a supernova.

# Supernovae

Three mechanisms work together to eject the envelope in an explosion known as a supernova.

- One is the bouncing shock on matter rapidly falling on the neutron star. This shock is so strong that it runs outward against the infalling material and helps to eject it.

- Another is that during infall the temperature is so high that photons create neutrinos (photon + electron gives electron + neutrino + anti-neutrino). In the layers just above the neutron star, the density is so high that these neutrinos can be captured by the infalling gas. This heats up the infalling layers so much that infall stops and is converted into an explosion with mass ejection.

- Increasing T reignites very efficient fusion in the infalling fusion shells in the core, producing a large amount of energy that also heats the infalling layers and creates enough gas pressure to make them explode.

Today's Worksheet,
Questions 1 & 2

# Black Holes

- If the collapsing core gathers more mass than 2-3 $M_\odot$, it will form a Black Hole.

- Very interesting objects, we will do some calculations.

Today's Worksheet,
Question 4

# Post-Main Sequence Evolution

- So, how do we check if all that has been modeled is correct?
- One easily available test, of course, is to see if it works for our Sun, the nearest available star!
- Both helioseismology and solar neutrino observations allow for such tests, along with directly measuring the solar luminosity and surface temperature.
- We've also referred to other observational consequences as we have learned about different aspects.
- One such test that is worth looking at in greater detail is the observation of clusters of stars.

# Stellar Clusters

- All stars in a stellar cluster can be assumed to have formed out of the same gas cloud.
- Thus, they presumably have the same age and chemical composition.
- This means that the observed properties of all the stars in a stellar cluster are determined by only one parameter: mass.
- Therefore, stellar clusters provide an important test of stellar evolution models.

Today’s Worksheet, Question 3

# Today's Worksheet