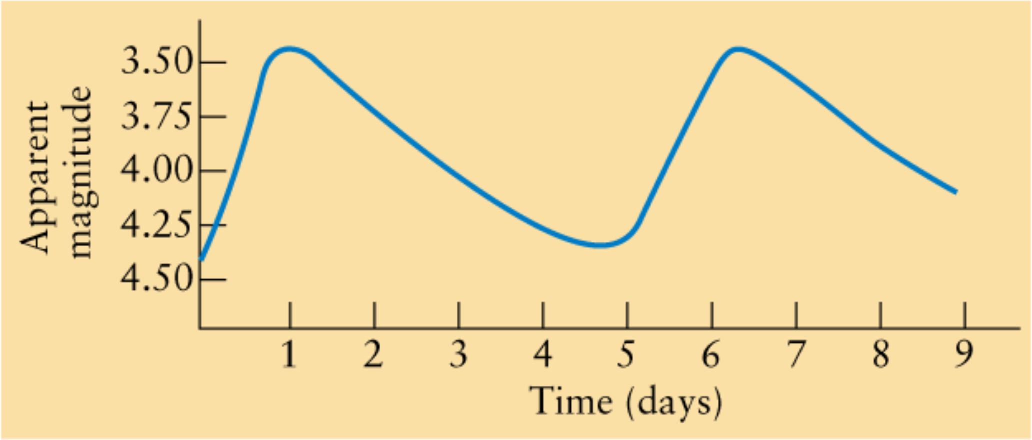
Cause of pulsations

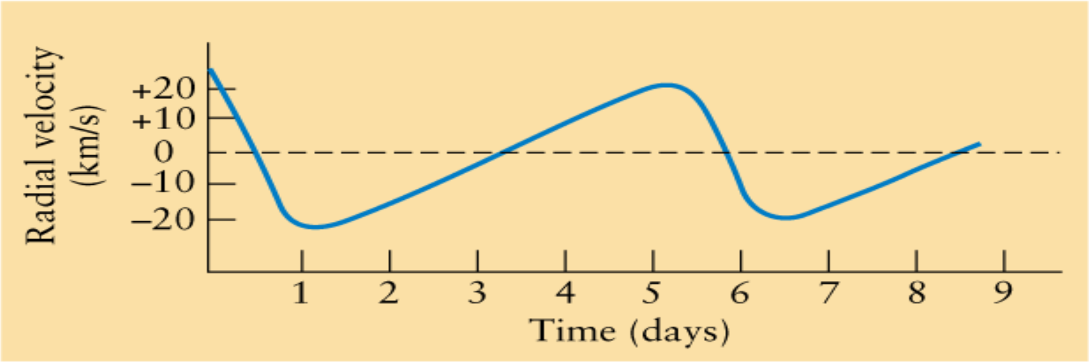
- Stars are variable because they are unstable in one way or another: they lack hydrostatic equilibrium beneath surface.
- Miras are not well understood, but other, more periodically varying stars are better understood, like the Cepheids:
- The ionization zone of He lies at a distance from the center of the star, close to the surface.
- When He gas is ionized, it is opaque to radiation, thus effectively absorbing photons, trapping the heat.
- Radiation will push the surface layer outward, and cooling will begin.
- As the gas cools, it will recombine. Neutral He is transparent, ceasing the outward push and layers fall back as a result of gravity.
- Heating of those layers causes the process to repeat.

How to study variable stars



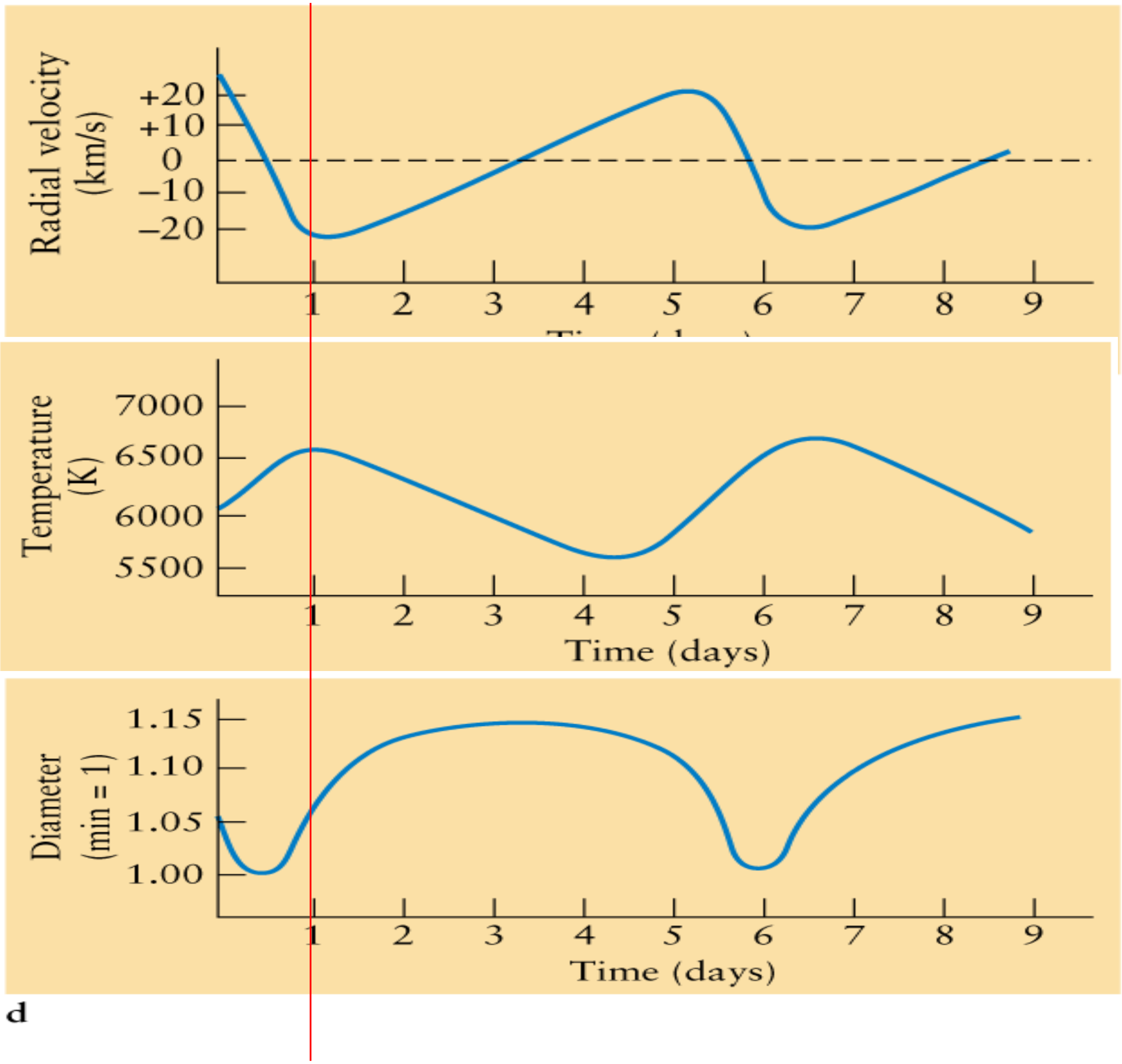
a

We use lightcurves, which show the brightness versus time for the star.



b

We can also look at the periodic change of other properties, such as the radial velocity, surface temperature, and size.



Max brightness

At max brightness, the star expands most rapidly. As it cools, the outer layers will start falling back onto the star.

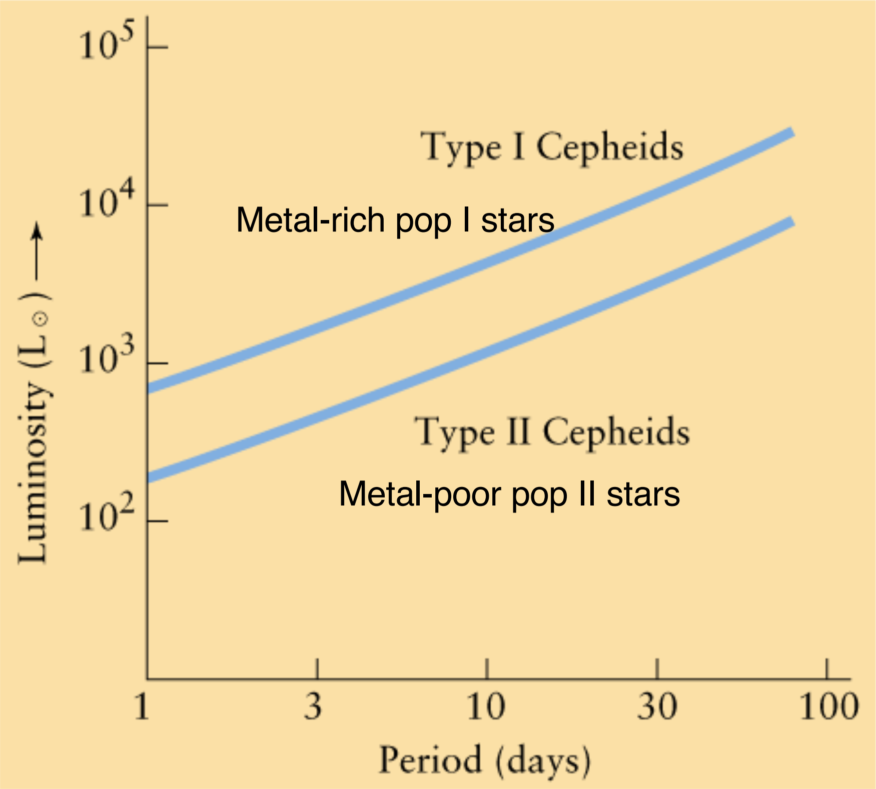
The surface temperature will vary with the brightness.

The star reaches its minimum size *before* maximum brightness, since it will take a little time to transport the radiation to the surface. A *time lag*.

Distance indicators

- Variable stars like Cepheids, and RR Lyrae stars can be used as distance indicators. How?
- The exhibit a relation between their period and their luminosity.

  => if we can measure the period of the star, then we know its luminosity (or absolute magnitude).



The period-luminosity (P/L) relationship for Cepheids

Type I and II Cepheids behave differently because they have different abundances of heavy elements in their atmospheres, affecting the opacity.

- The P/L relationship for RR Lyrae stars is trivial: all have M=+0.5.

- For Cepheids, the relation is fitted by:

$$M_{<V>} = -2.81 \log_{10} P_d - 1.43$$

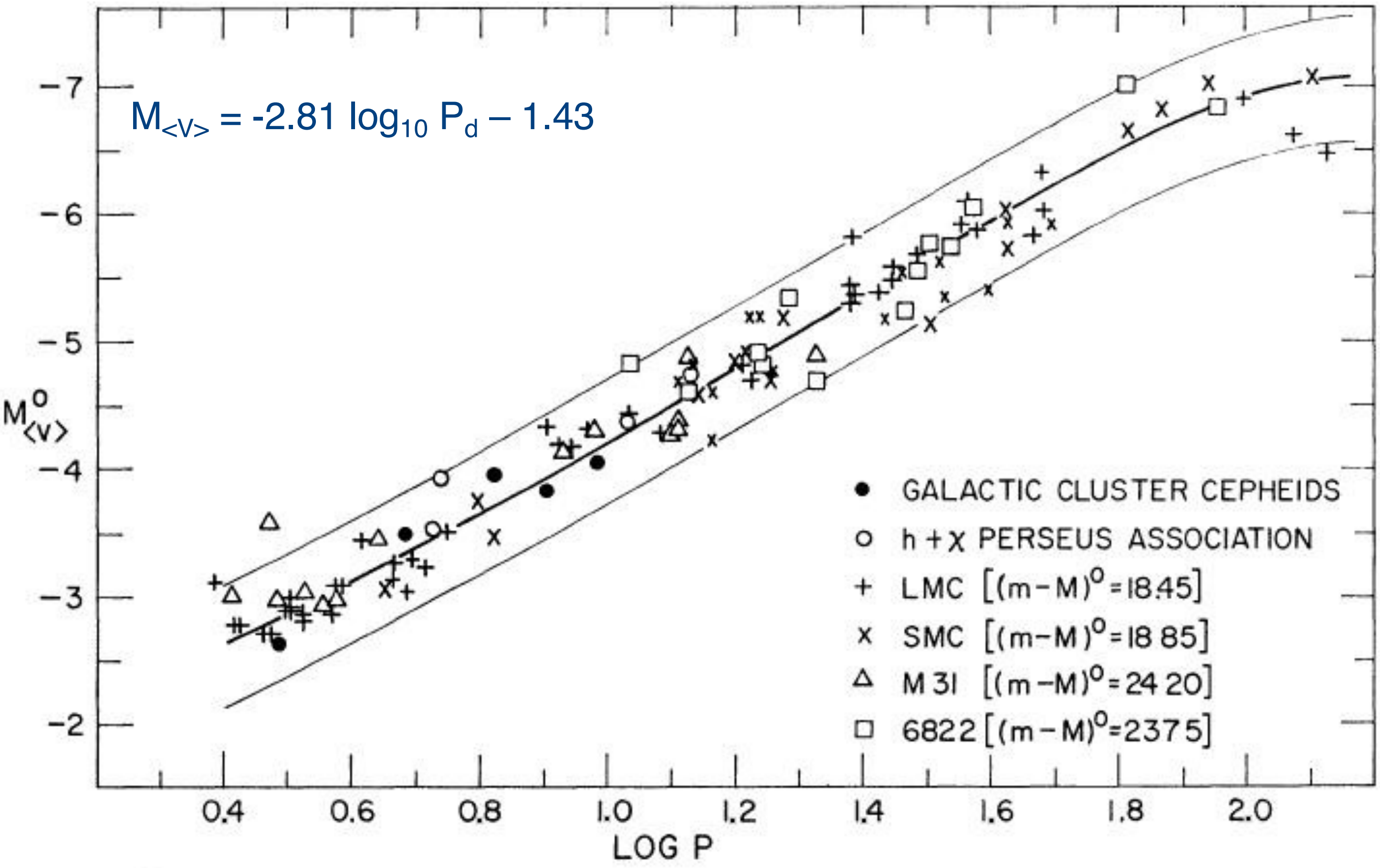
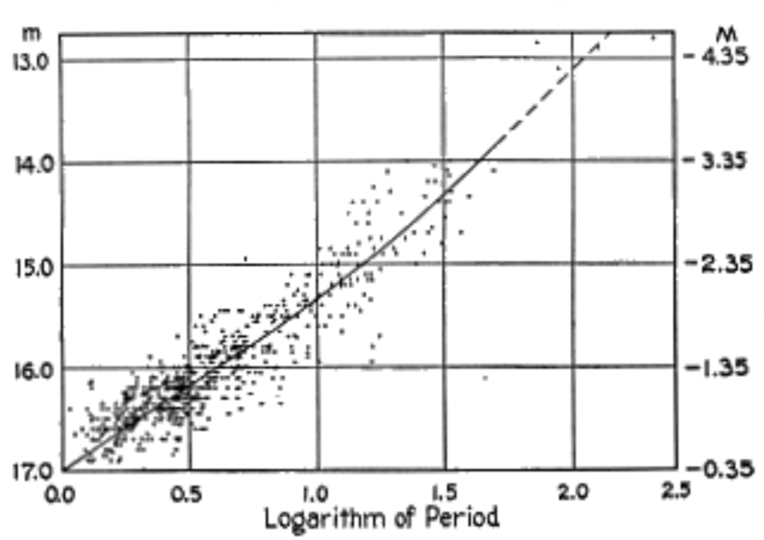


FIG. 1.—The composite period-luminosity relation at mean intensity in B and V wavelengths derived from the sources indicated at the lower right. The absolute calibration was made by using the nine Cepheids of the galactic system shown as open and filled circles. The photographic data from the SMC are plotted with smaller crosses than the Gascoigne and Kron photoelectric data.

- Knowing *L* or *M*, we can calculate the distance. Apparent magnitude (*m*) is always easy.

$$m - M = 5\log(d) - 5$$

- Important relation: Cepheids and RR Lyrae stars are giant and thus very luminous. We can see them as individual stars in other galaxies.



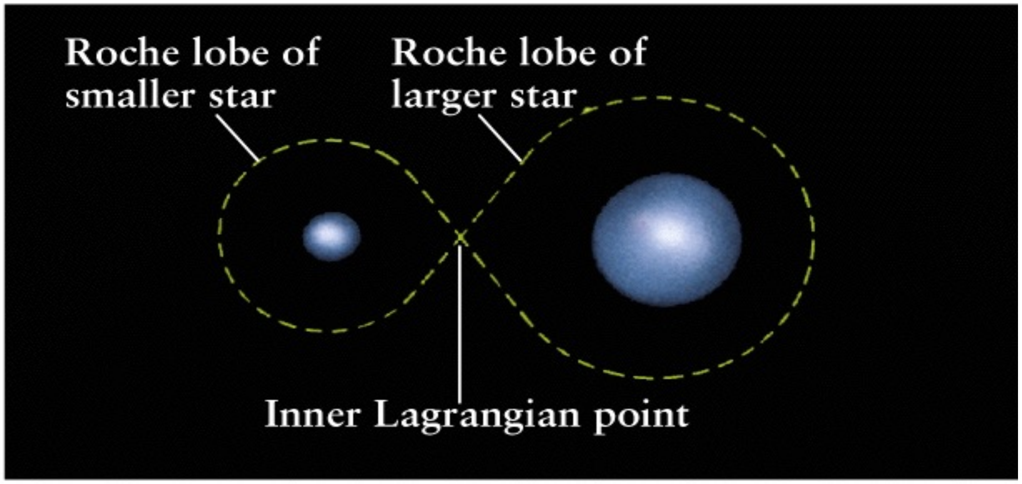
Cepheids in the Small Magellanic Cloud

Announcements

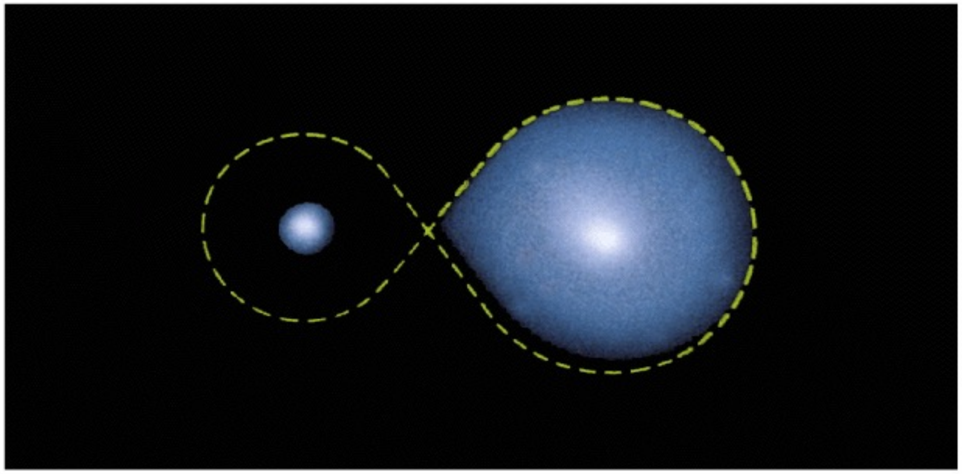
- Today – Finish low mass stellar evolution
- Thursday – High mass stellar evolution and
  HW#4 is due
- Saturday 28 Sept – VLA/LWA tour

Mass transfer can affect stellar evolution

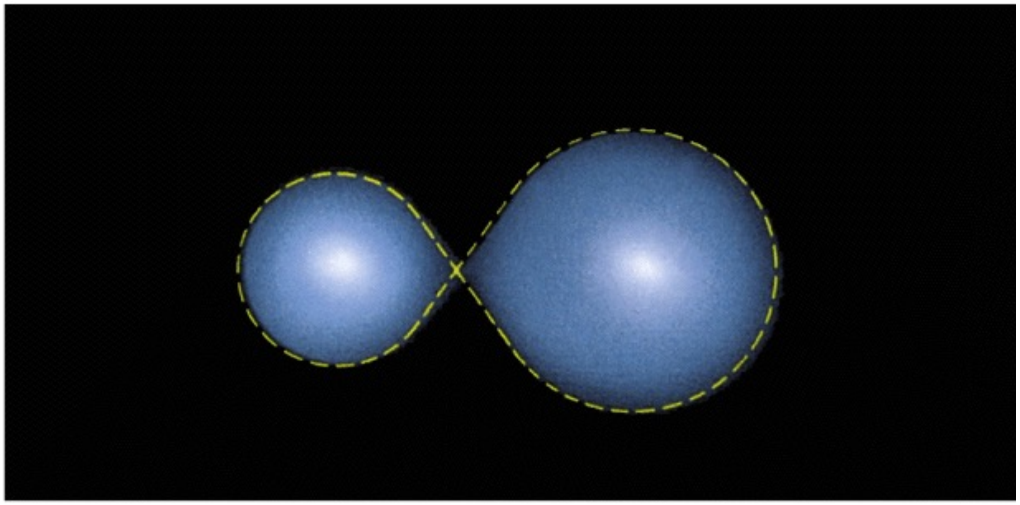
- Close binary systems - some binary systems are so close they are in contact.



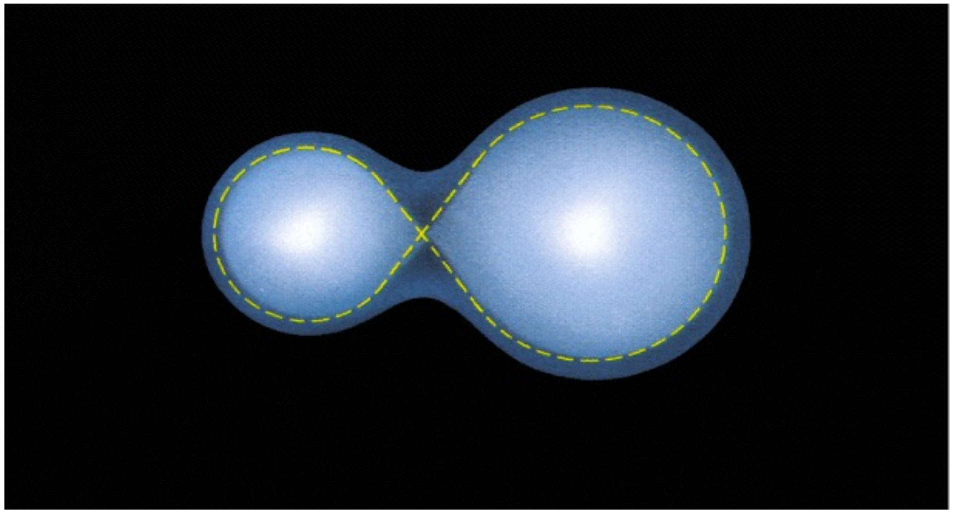
a Detached binary



b Semi-detached binary

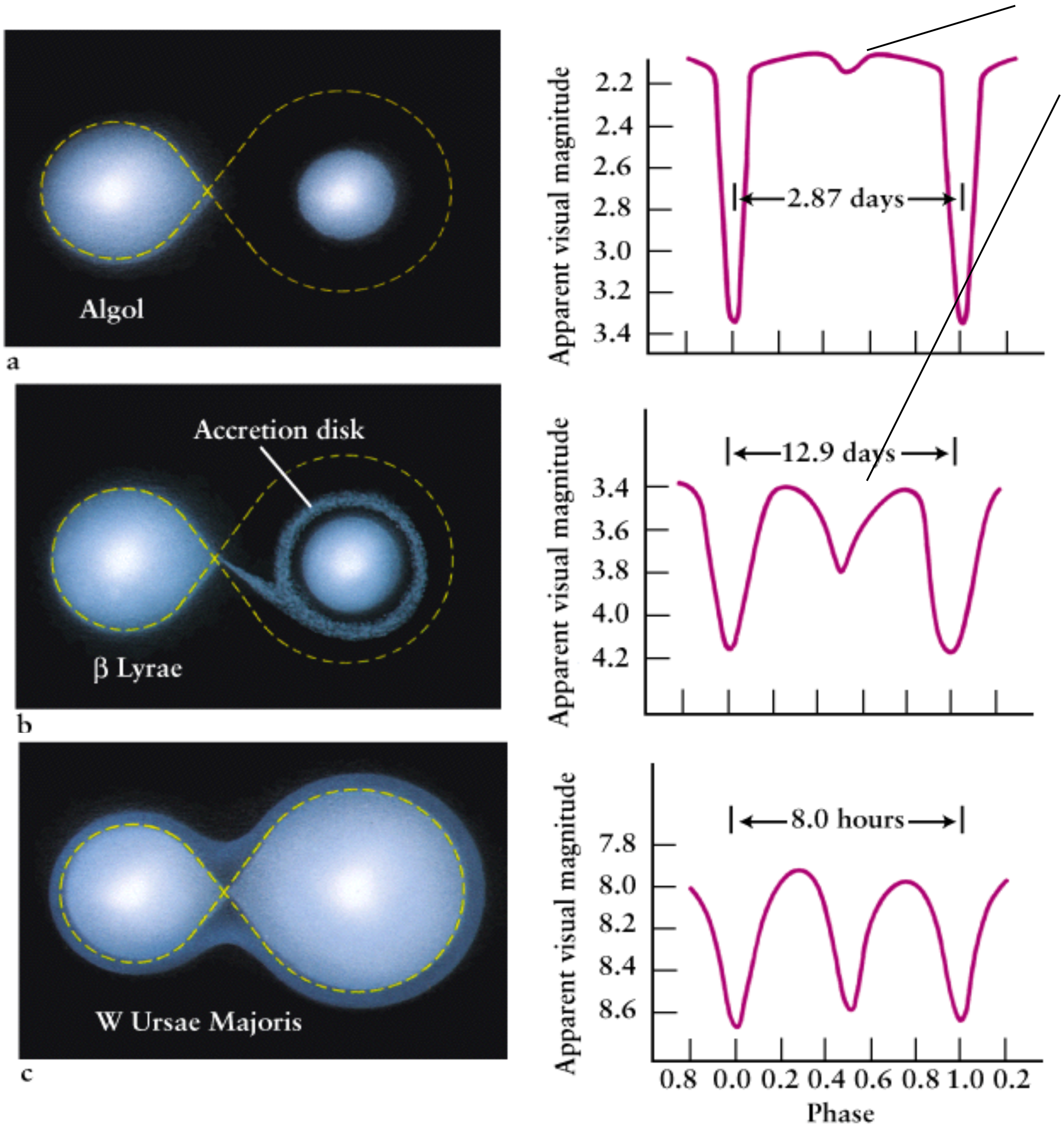


c Contact binary



d Overcontact binary

Gas may flow from one star to another in close systems. This can alter the standard evolutionary pattern.



Small star eclipses large one

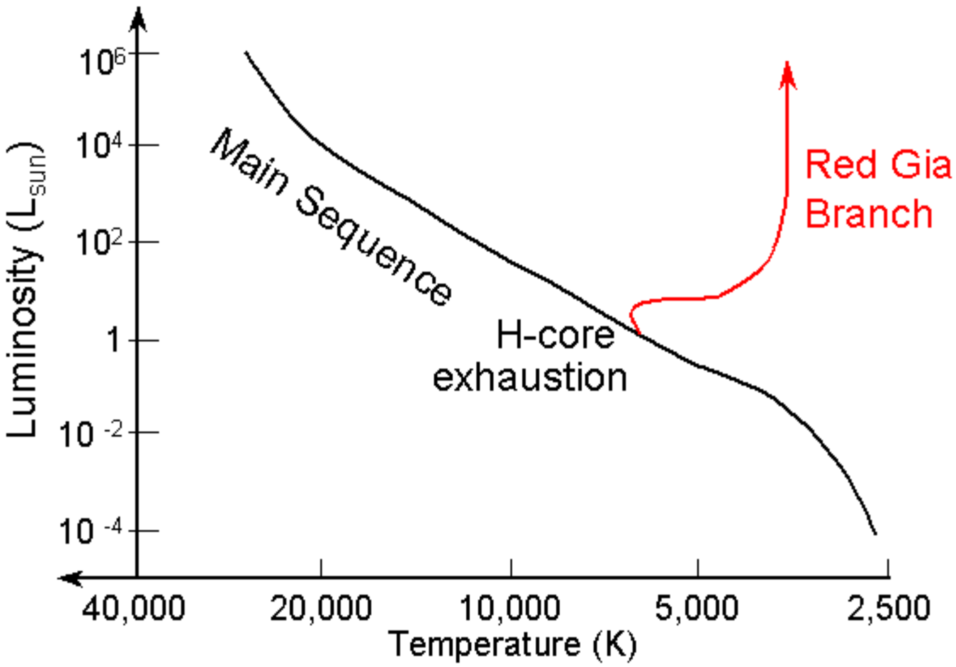
Last time: post-main sequence evolution

- Core hydrogen exhaustion => inert He core, contracting and heating.

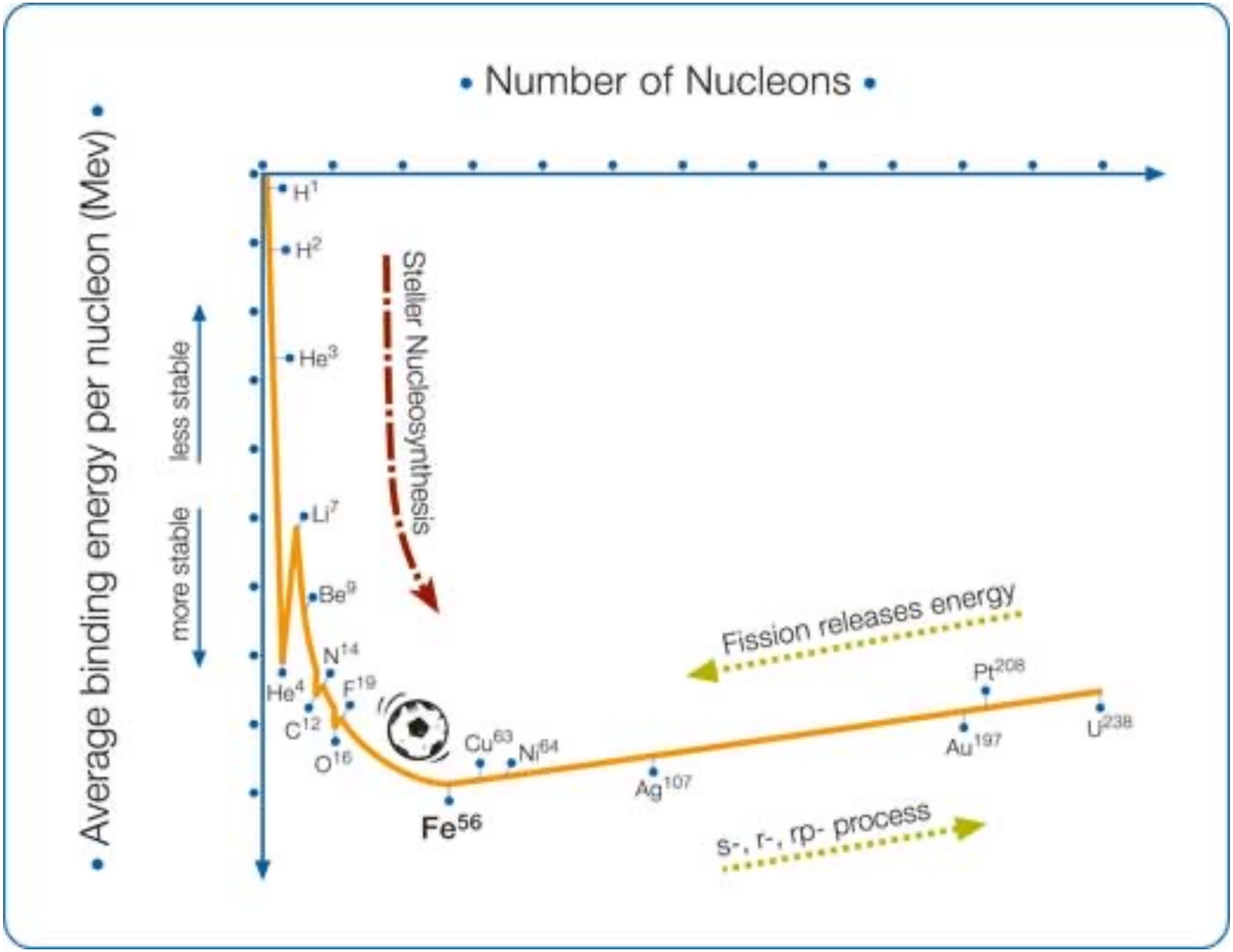
- Pushes outer layers outwards => expansion, and cooling (to the right in H-R diagram)

- Shell H fusion starts => luminosity increase (upwards in H-R diagram)

- Helium fusion starts (the triple alpha process, producing C and O) => the core expands and cools



Binding Energy per nucleon



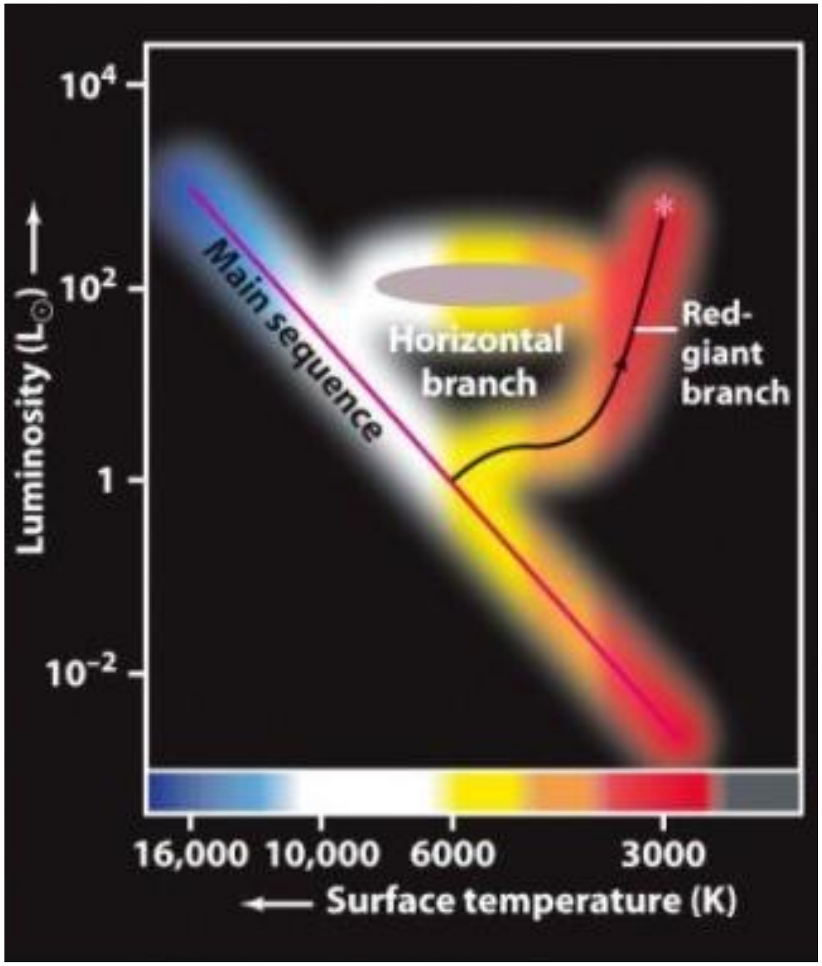
Death of a Low Mass Star

PRC00-12 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)

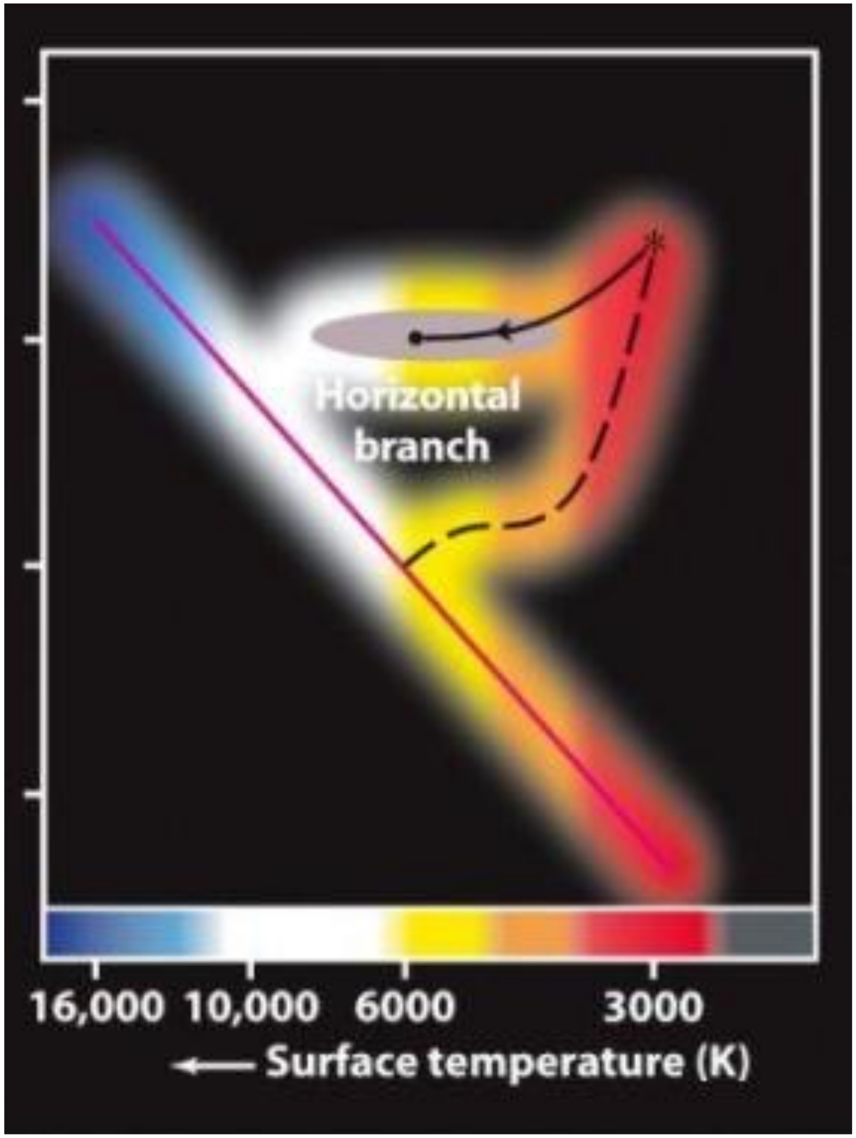
Low mass stars

- How stars live and die depends entirely on their masses
- Today: low mass stars ($< 4M_\odot$), when they evolve off the main sequence
- These stars have two, distinct red giant phases

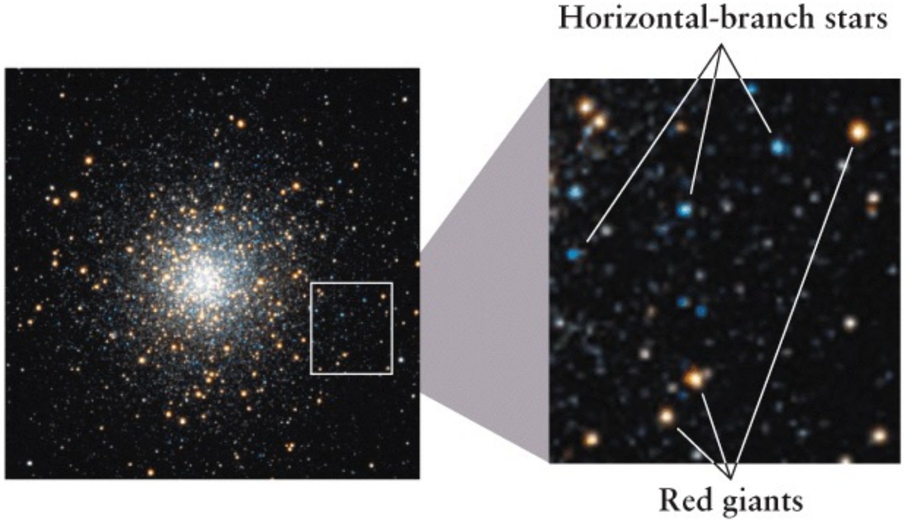
On the red giant branch



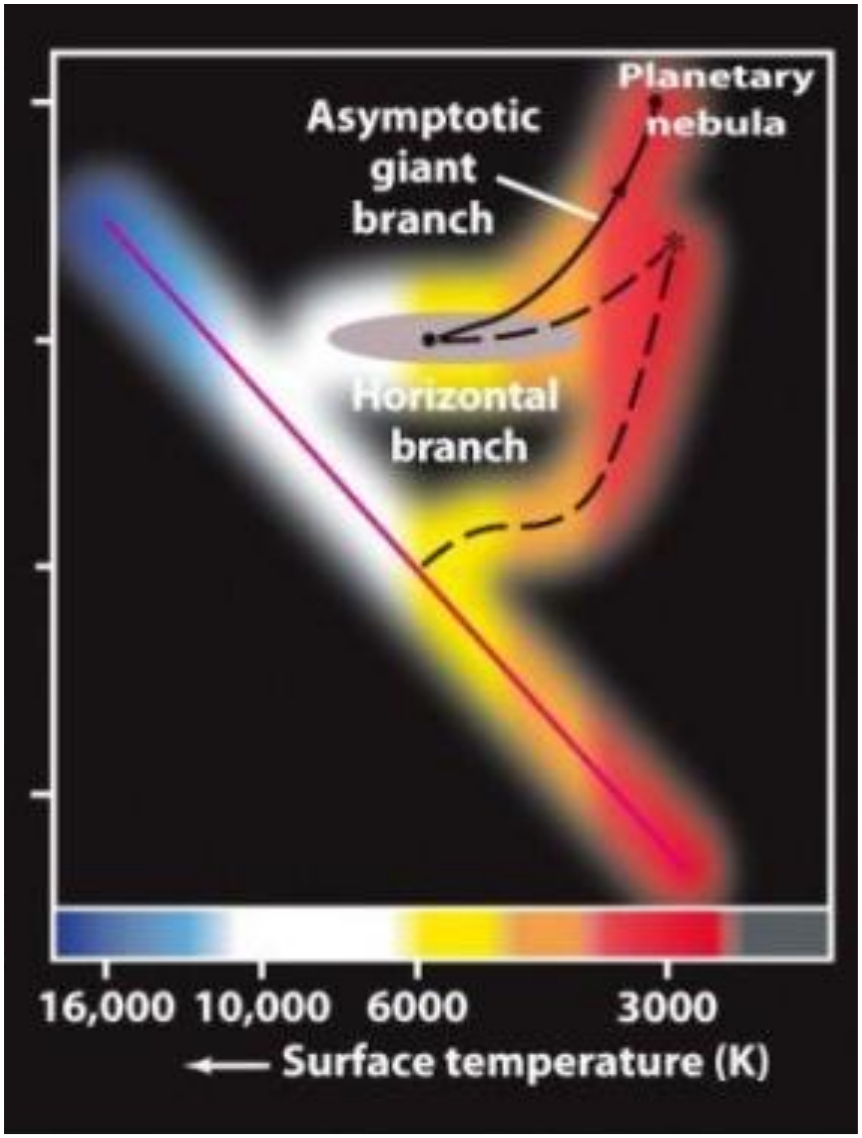
- Shell H burning continues after core H burning stops (core now filled with He).
- Outer layers expand and cool.
- As core contracts and heats, He burning starts with a flash (triple alpha process).
- The triple alpha process less efficient, can only last for about 10^8 yr.



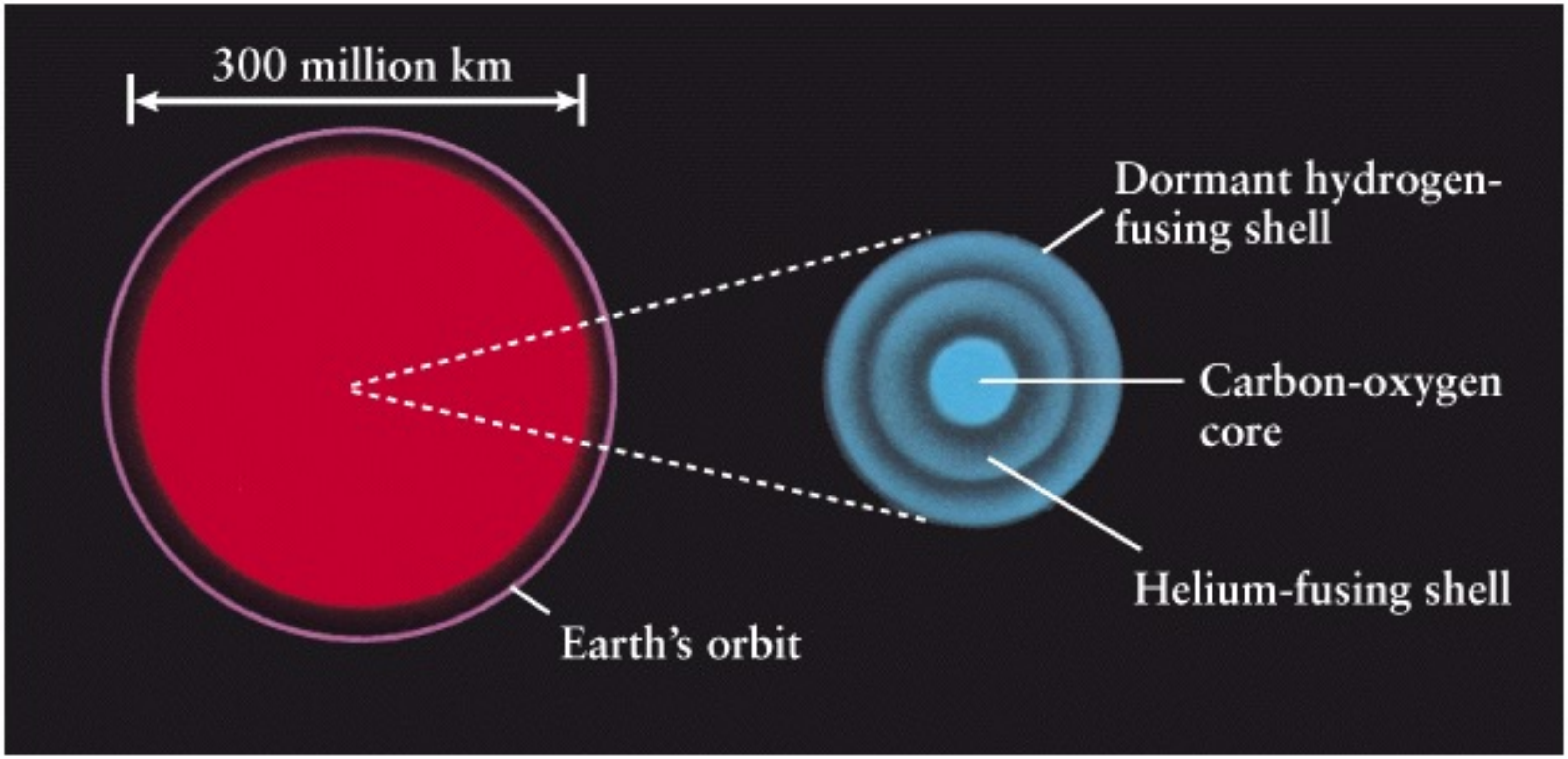
- Core expands and cools when core He burning starts.
- H burning slower => lower luminosity. This means downwards in the H-R diagram.
- With less internal pressure, the outer layers shrink and heat up => to the left in the H-R diagram.
- Now the star is on the *horizontal branch.*



On the asymptotic giant branch



- After some time, the core will fill with C and O.
- Core He burning stops, core contracts => shell He burning
- Produces a lot of energy => outer layers expand and cool. Red giant again!
- This is an AGB (*asymptotic giant branch)* star.

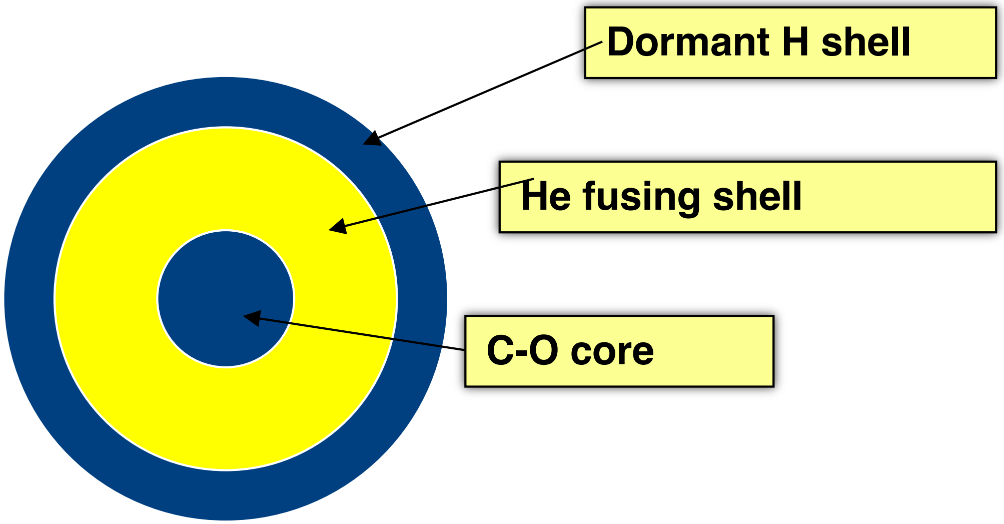

300 million km
Dormant hydrogen-fusing shell
Carbon-oxygen core
Helium-fusing shell
Earth's orbit

Mass loss

- Sun loses 4 x 10^9 kg/s (4 million tons/s) on MS
- Up to AGB, stars lose mass very slowly (e.g. via the solar wind).
- After AGB, mass loss is more extreme and stars are shedding their outer layers. Could reach 10^{-4} M_sun/year
- Produces *Planetary Nebulae* (PN), and PN central stars that cool to become *White Dwarfs*.

What is going on? Instabilities!

- He burning very temperature sensitive, triple-alpha fusion rate $\sim T^{40}$
- Small changes in T => large changes in fusion output
- Star experiences thermal pulses, destabilizing the outer envelope



Dormant H shell

He fusing shell

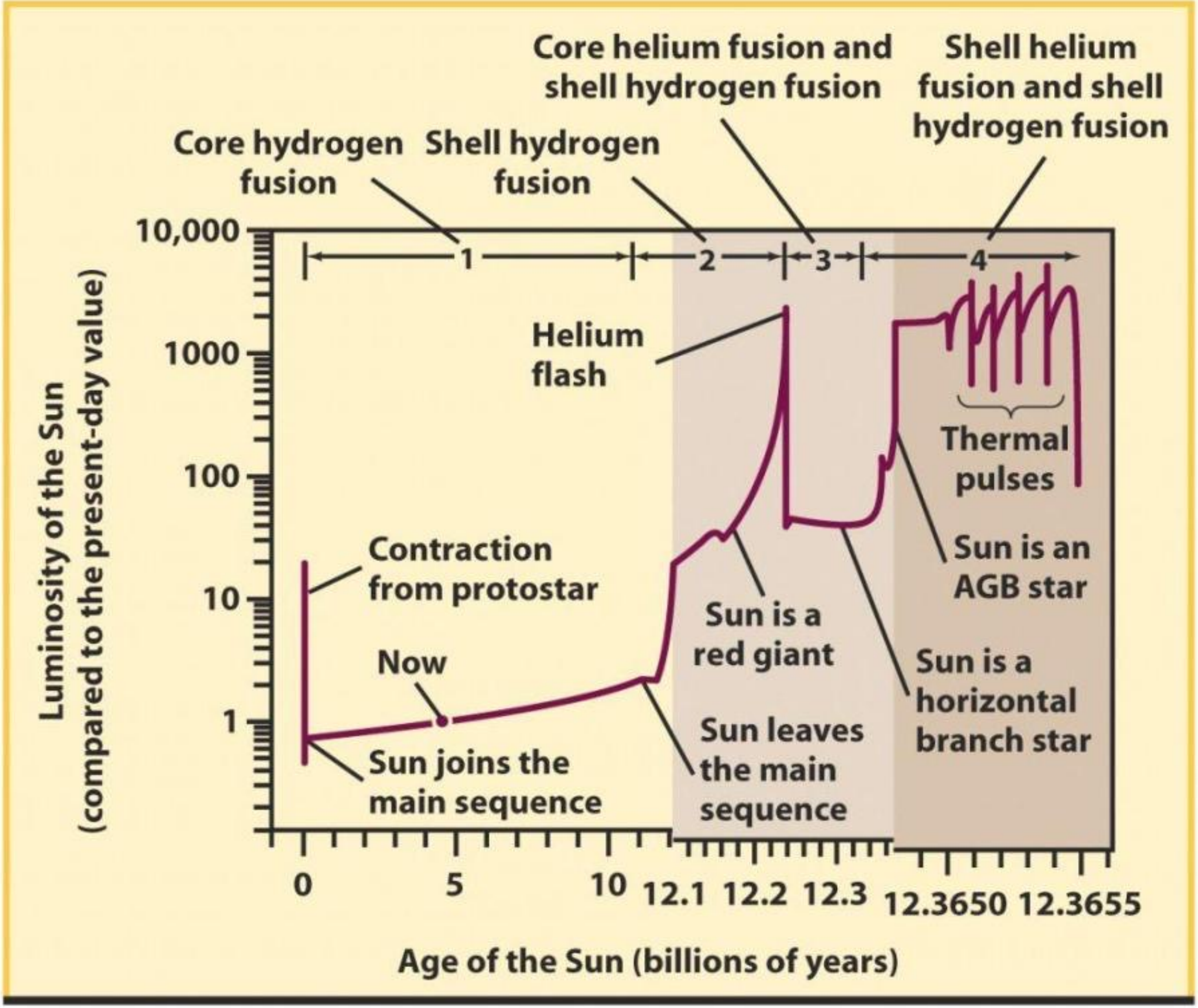
C-O core

When He burning shell is depleted, the triple-alpha process stops and He shell starts contracting.

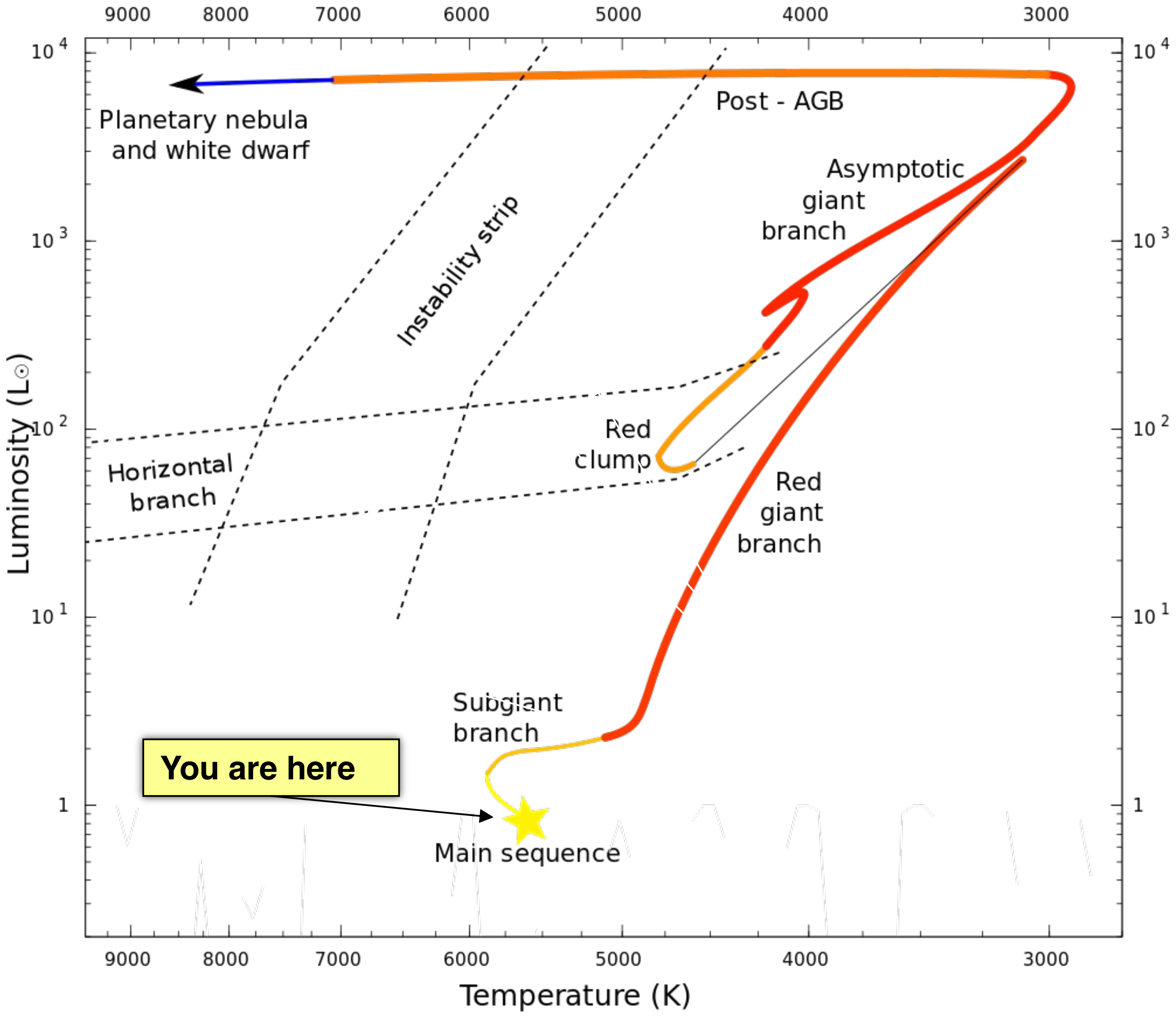
H shell also contracts, heats up => H fusion starts again

The p-p produced He replenishes the He shell, which will cause another He flash => pushes material outwards

Cools off H shell, which then becomes dormant again => cycle

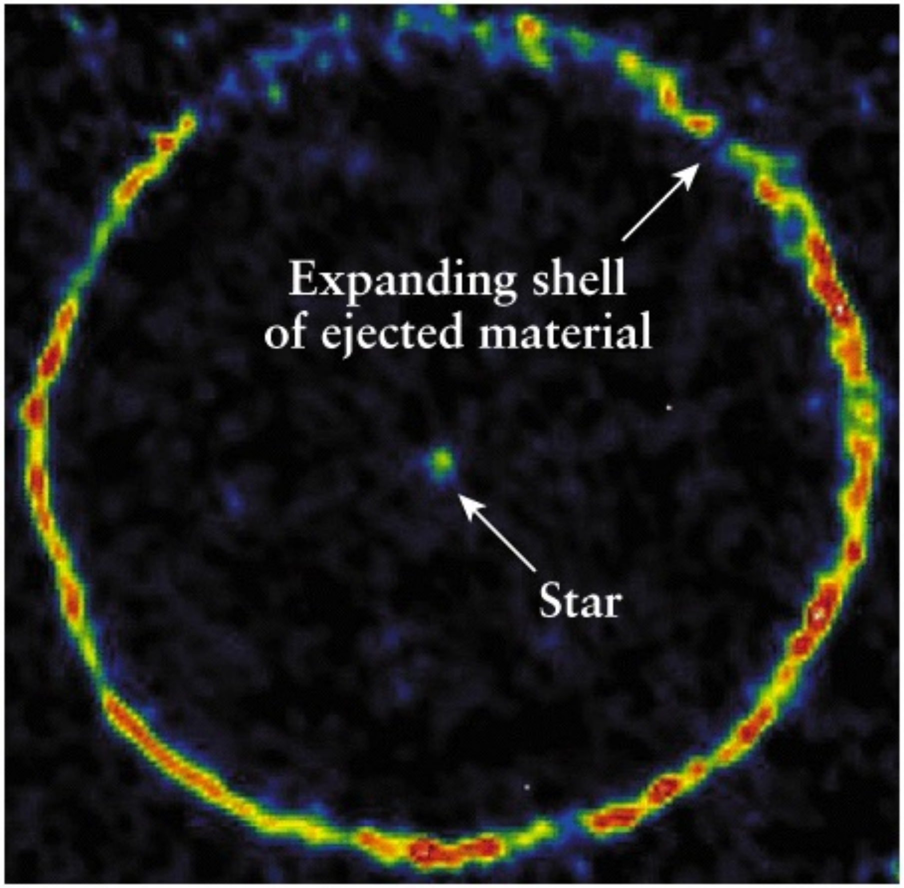

Core hydrogen fusion
Shell hydrogen fusion
Core helium fusion and shell hydrogen fusion
Shell helium fusion and shell hydrogen fusion
1
2
3
4
Helium flash
Thermal pulses
Contraction from protostar
Now
Sun joins the main sequence
Sun is a red giant
Sun leaves the main sequence
Sun is a horizontal branch star
Sun is an AGB star
10,000
1000
100
10
1
Luminosity of the Sun (compared to the present-day value)
0
5
10
12.1
12.2
12.3
12.3650
12.3655
Age of the Sun (billions of years)

Evolution of a 1 M☉ star



Dredge-up

- Convection zone may extend down to core: convection brings enriched core material to surface.
- Produces objects like *carbon stars*.
- These stars are important sources for replenishing the ISM.



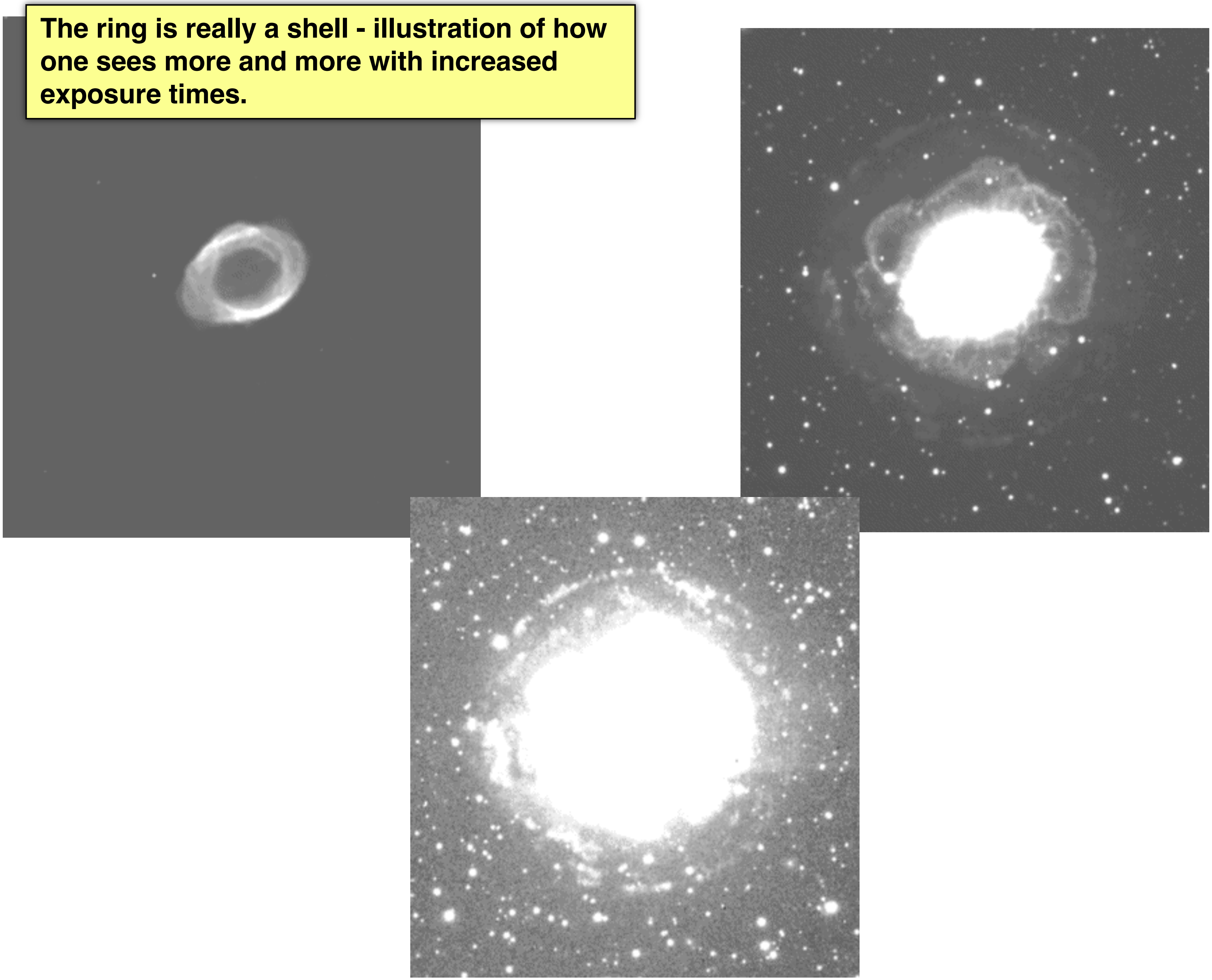
Molecular CO emission from shell surrounding the carbon star TT Cygni.

Core-envelope separation

- Rapid process (~10^5 yr), outer envelope gets ejected
- C-O core still contracts, but less weight of envelope results in a core that never gets hot enough for C to ignite (600M K)
- Core and envelope separate physically, expanding envelope forms a nebula around the C-O core (*planetary nebula*)

M57, the Ring Nebula. Located in Lyra.

The ring is really a shell - illustration of how one sees more and more with increased exposure times.



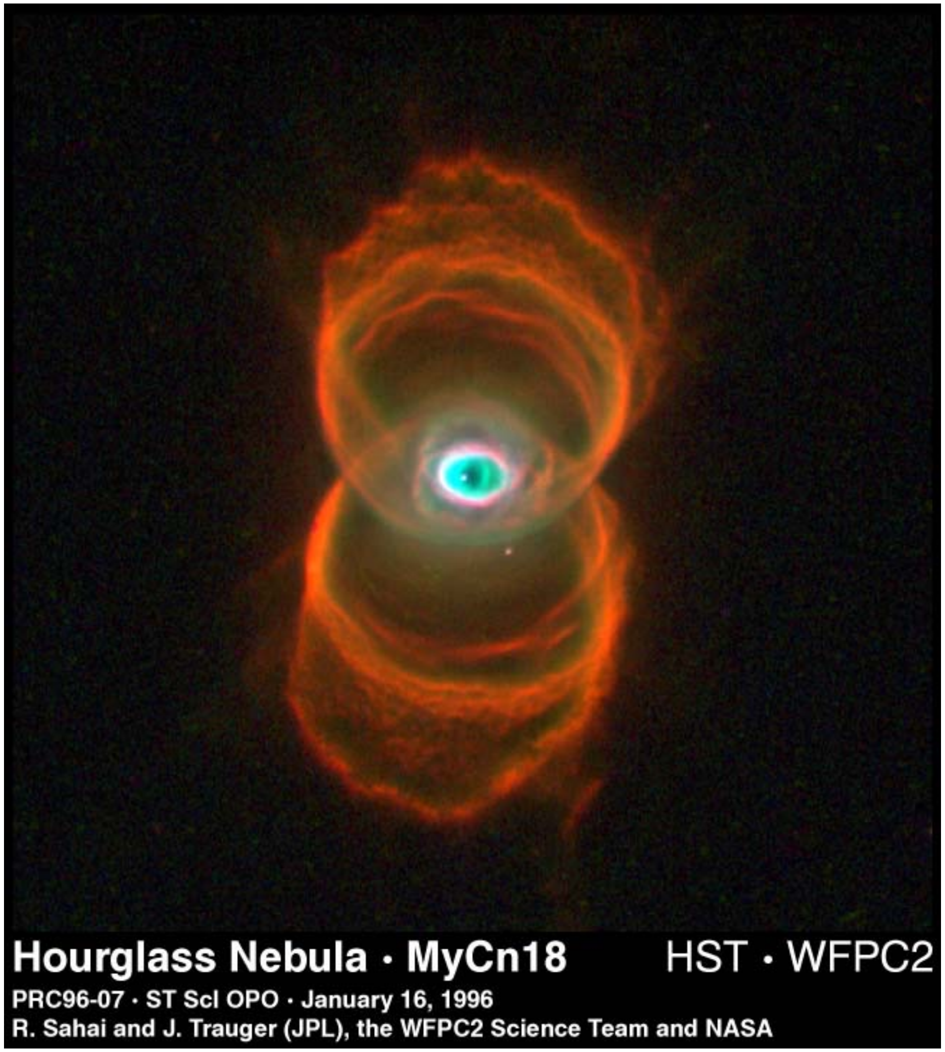
Why do planetary nebulae shine so brightly?

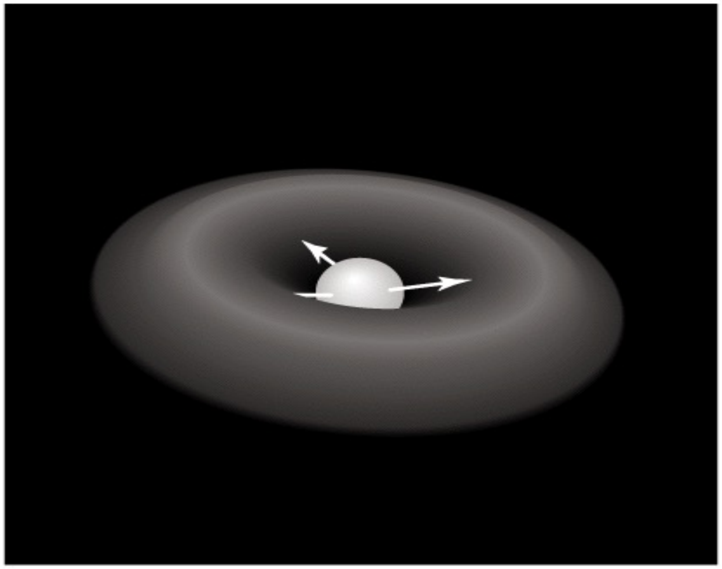
- Dying star ejects outer layers and exposes the hot core.
- The hot core emits UV radiation => excites and ionizes the surrounding low density gas

…what kind of spectrum would a planetary nebula show?

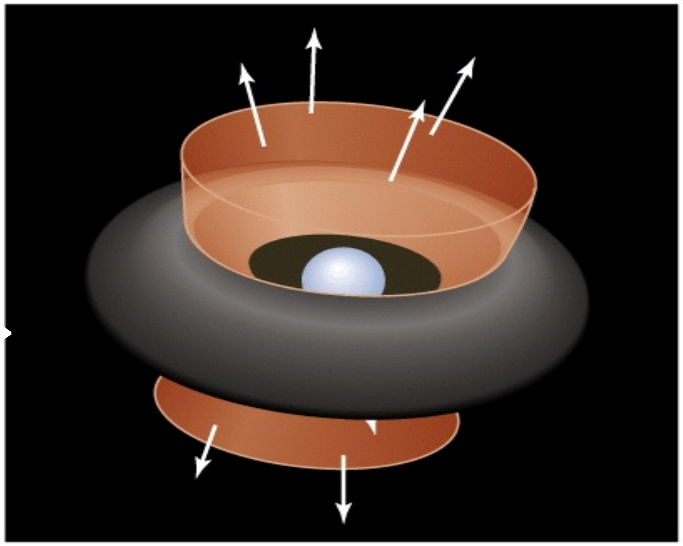
The Spirograph Nebula

Not all are spherical: bipolar shapes are common

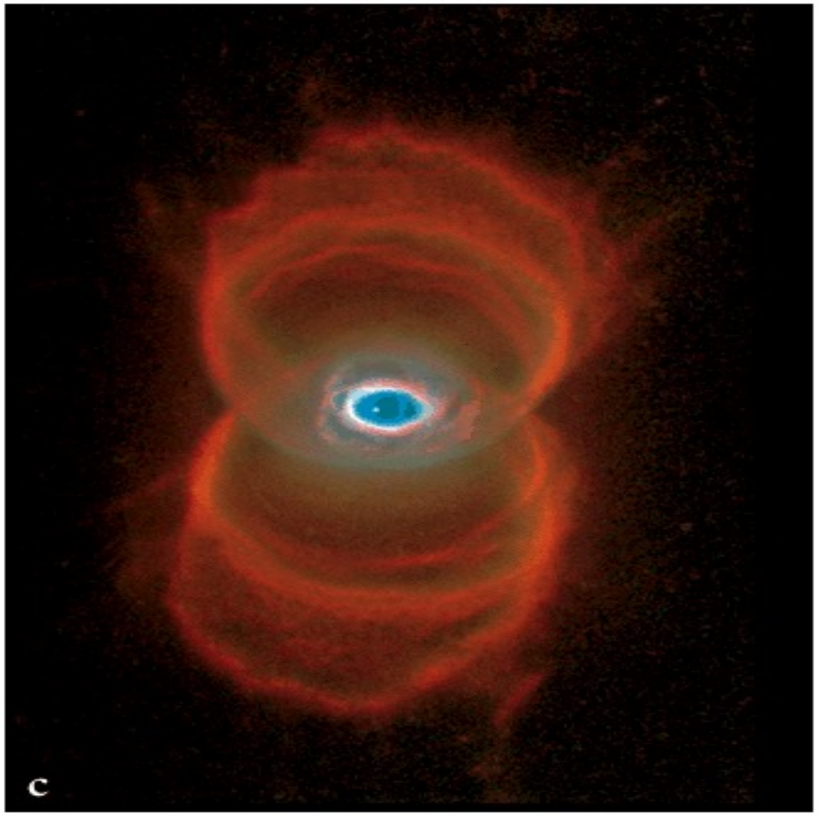


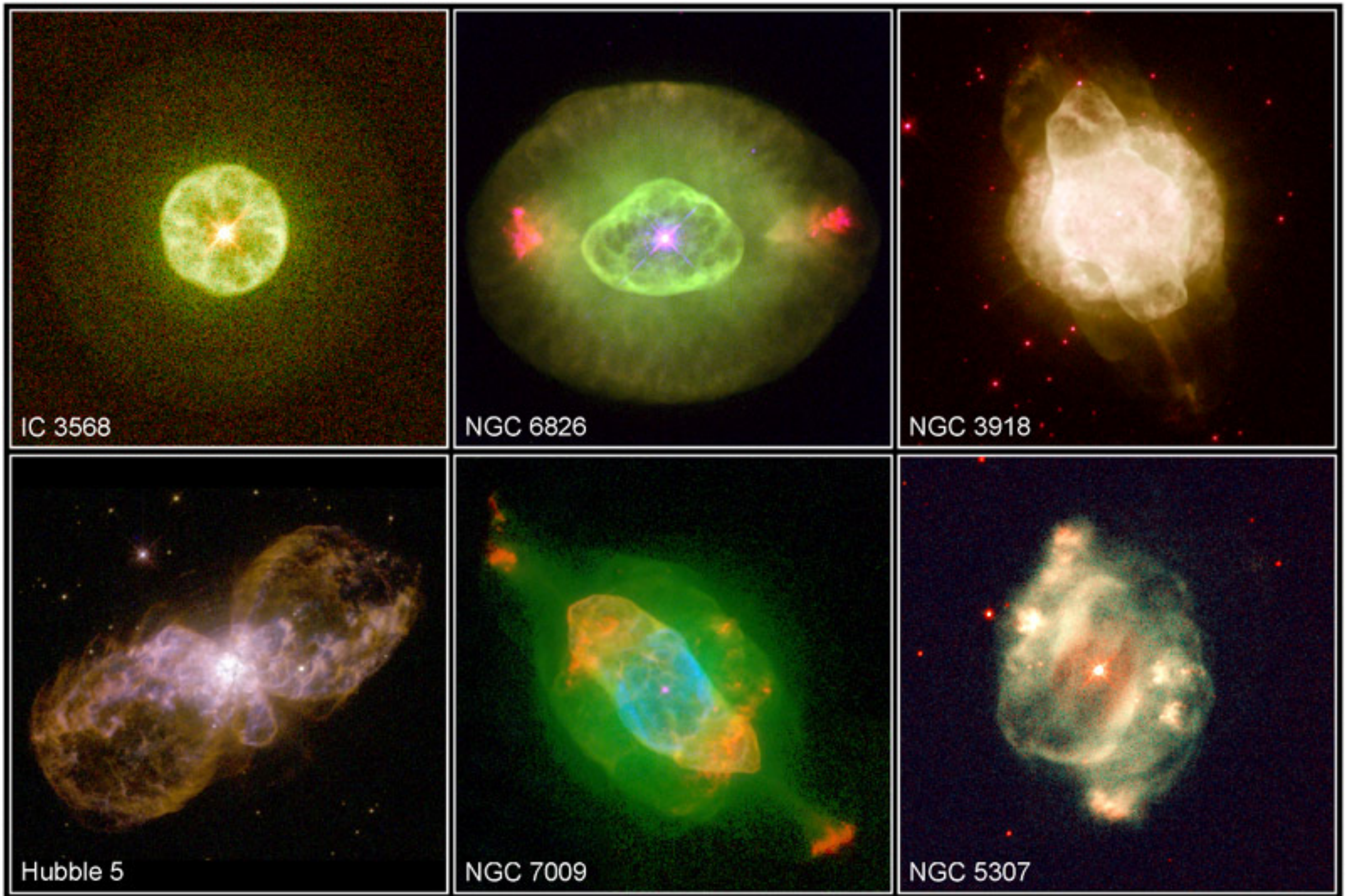


a



b





IC 3568

NGC 6826

NGC 3918

Hubble 5

NGC 7009

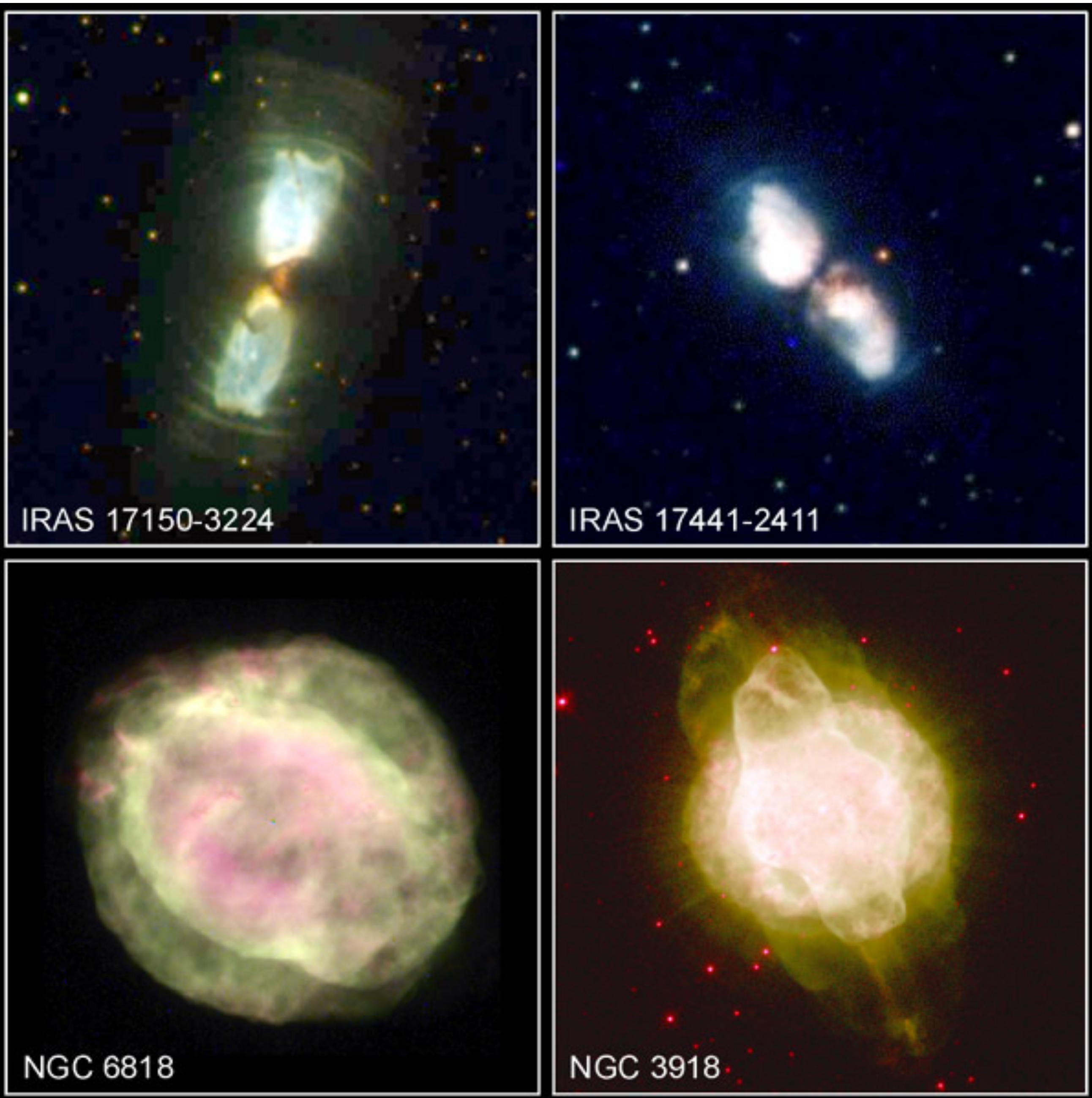
NGC 5307

Planetary Nebula Gallery

HST • WFPC2

PRC97-38b • ST ScI OPO • December 17, 1997

H. Bond (ST ScI), B. Balick (University of Washington) and NASA

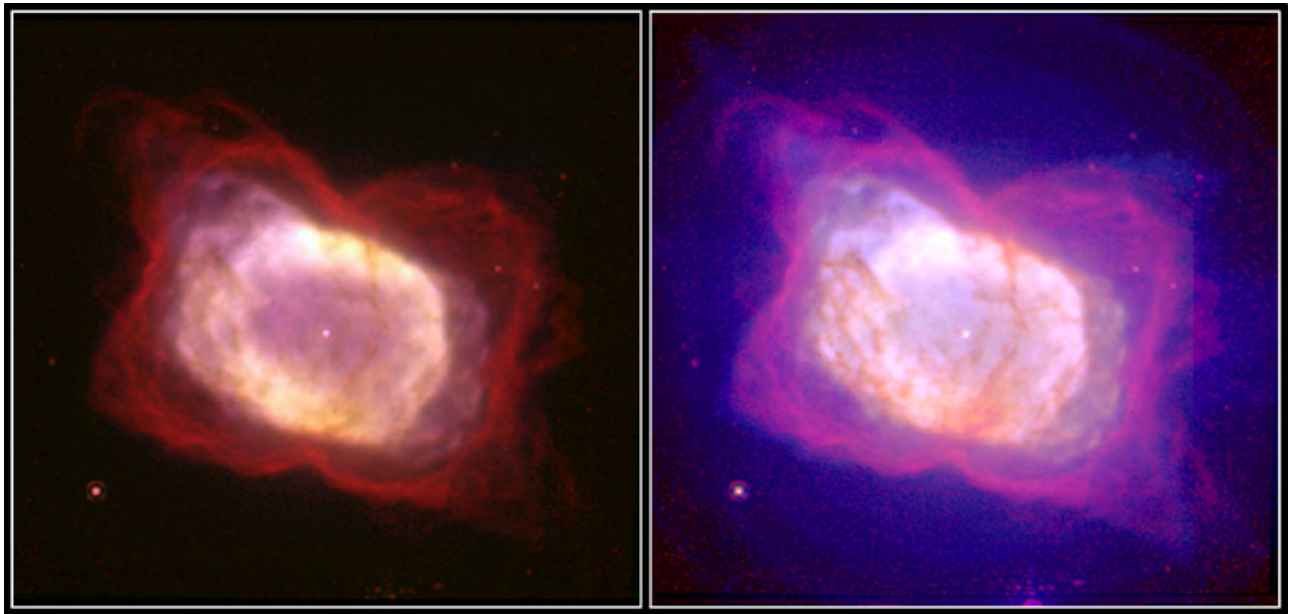


Planetary Nebulae HST • WFPC2

PRC98-11b • ST ScI OPO • March 12, 1998
S. Kwok (University of Calgary),
R. Rubin (NASA Ames Research Center),
H. Bond (ST ScI) and NASA

What happens to the core?

- For stars with original mass < $4M_\odot$, the central temperature never becomes hot enough for C or O to fuse.
- The central star of the PN is a *White Dwarf*. No more nuclear fusion processes occur.
- Shines because it is hot, and doesn't collapse because of pressure of degenerate matter.



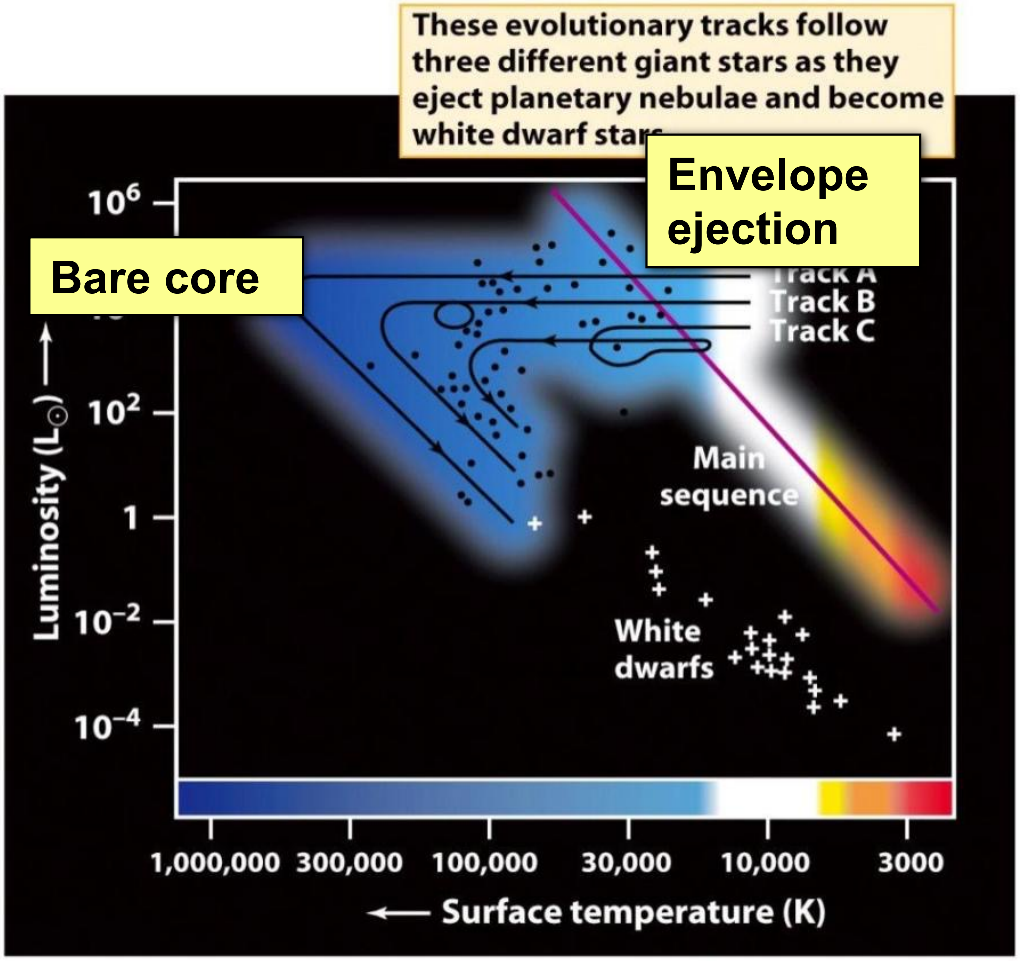
Planetary Nebula NGC 7027

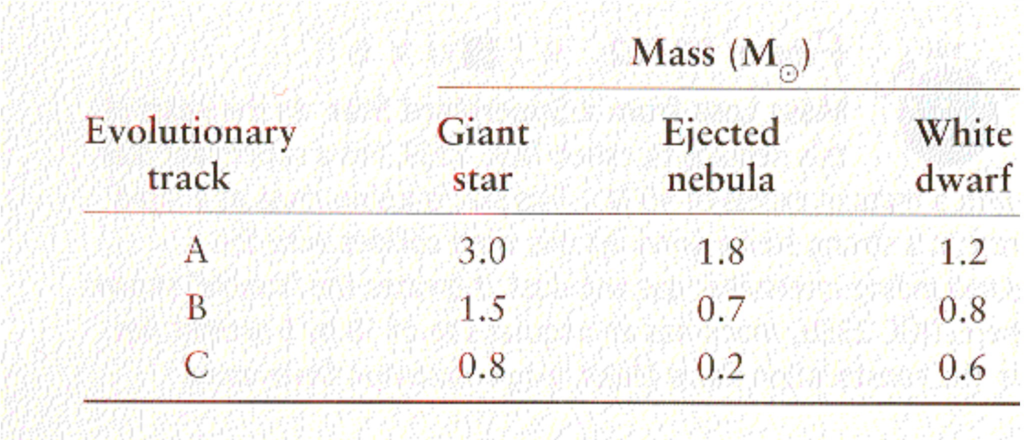
PRC98-11a • March 12, 1998 • ST ScI OPO

W. Latter (SIRTF Science Center/IPAC/Caltech) and NASA

HST • NICMOS • WFPC2

These evolutionary tracks follow three different giant stars as they eject planetary nebulae and become white dwarf star



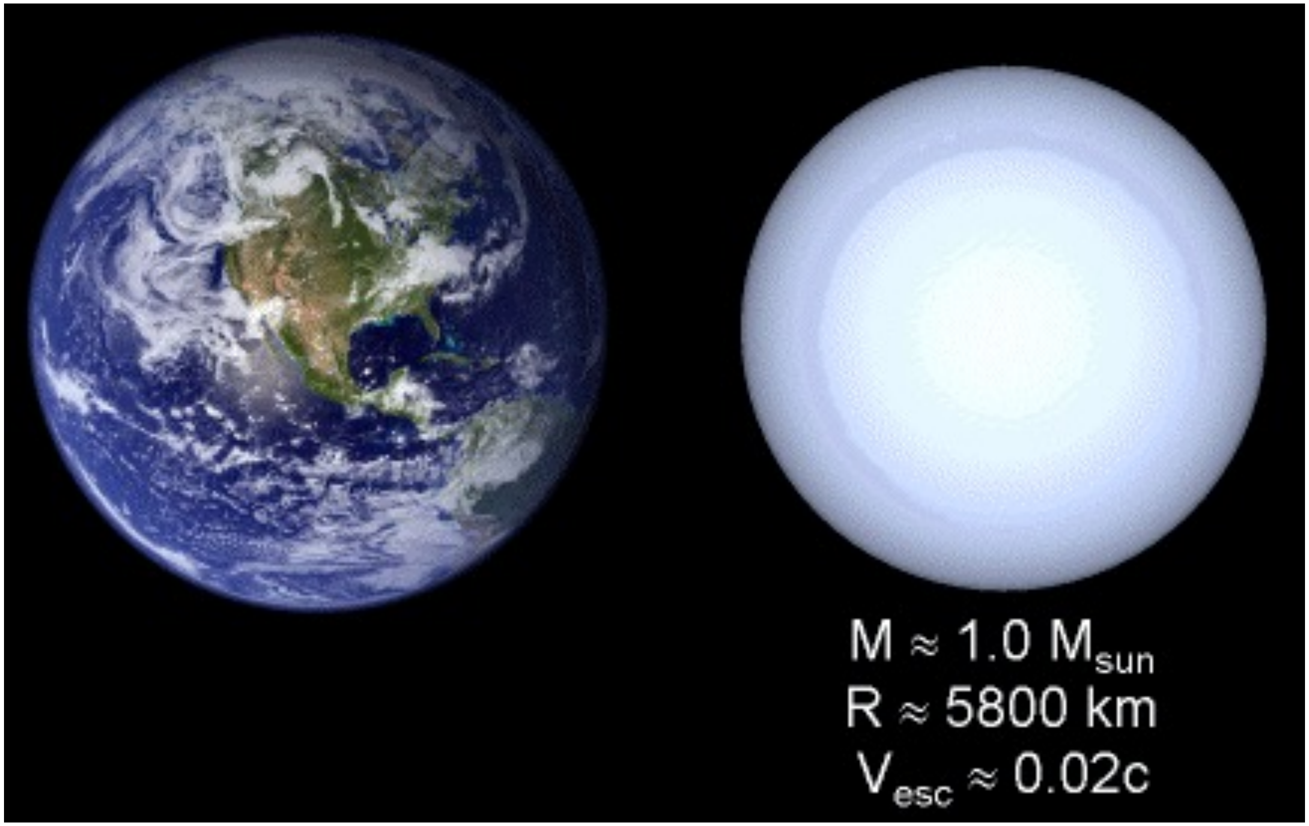


Evolutionary track	Mass ($M_\odot$)		
	Giant star	Ejected nebula	White dwarf
A	3.0	1.8	1.2
B	1.5	0.7	0.8
C	0.8	0.2	0.6

- Core contracts until degenerate (P independent of T)

- Then P grows fast, halting contraction (when $R \sim R_{\text{earth}}$)

- => Bare core = white dwarf

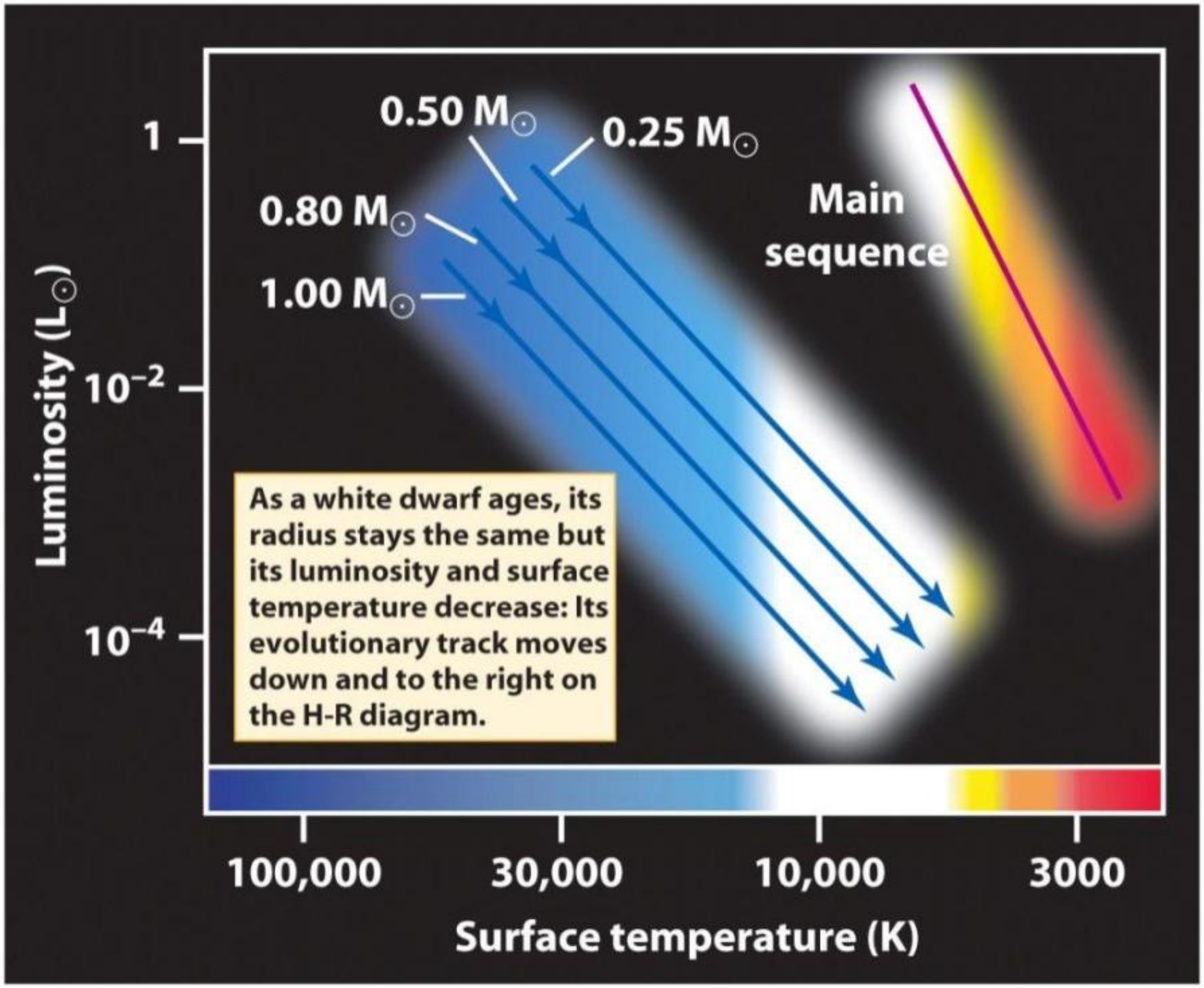


White dwarfs are of the size of the Earth, with the mass of the Sun. Much denser than anything ever made on Earth.

Density ~ 1.9 billion times the density of water

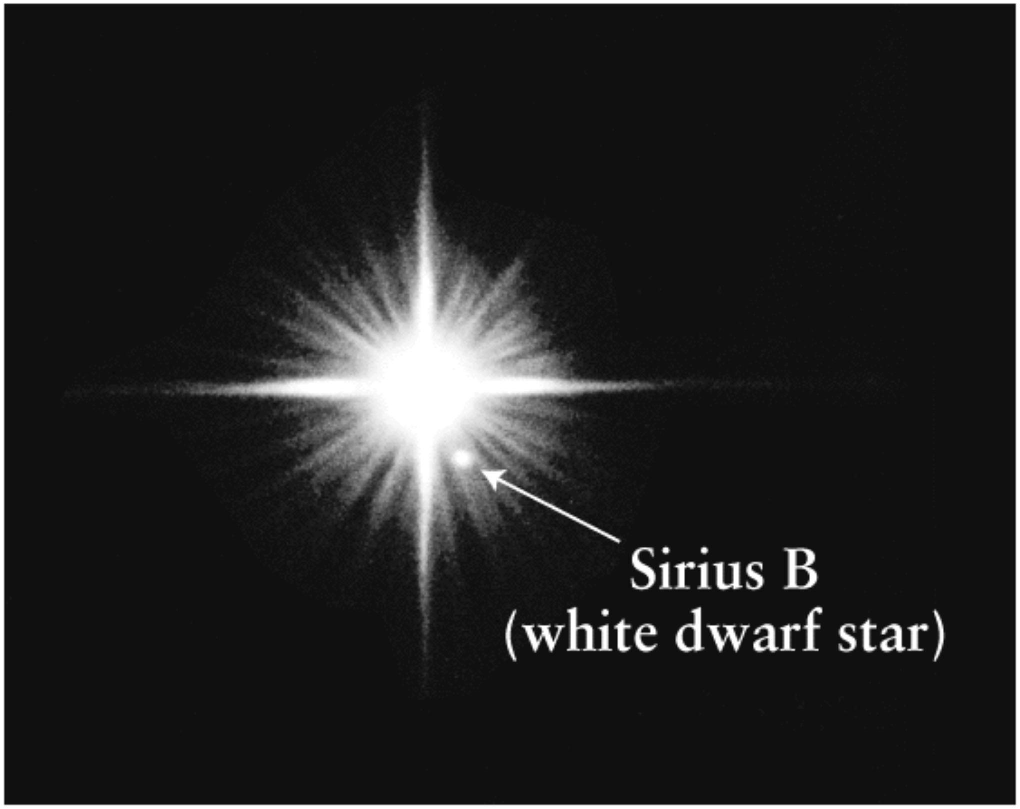
Made of C and O with possibly a thin atmosphere of H.

Where are white dwarf stars on the H-R diagram as they cool? Follow “Cooling Curves”:

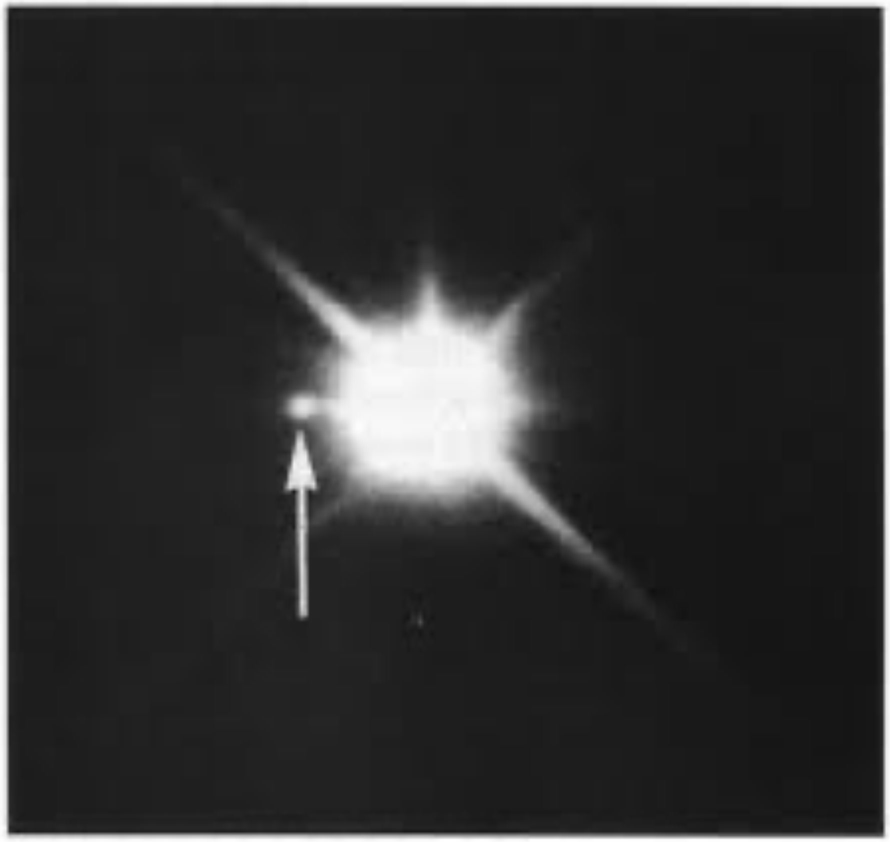


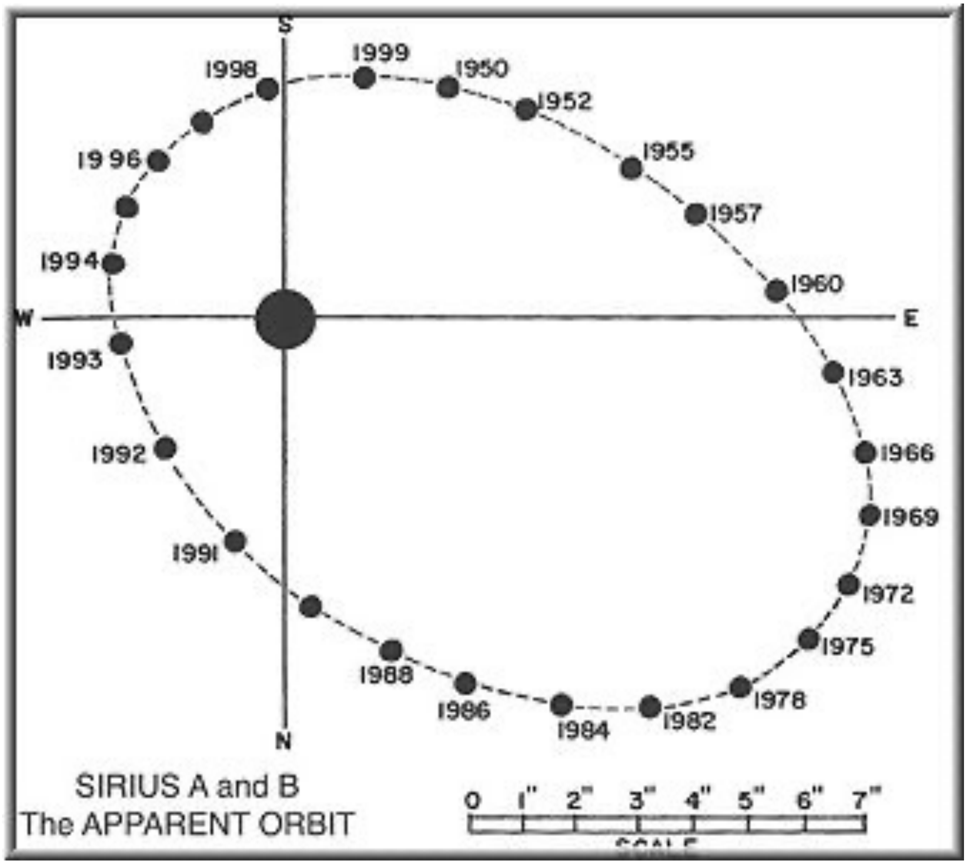
As a white dwarf ages, its radius stays the same but its luminosity and surface temperature decrease: Its evolutionary track moves down and to the right on the H-R diagram.

We can see some white dwarfs directly (with telescopes). For example, Sirius has a WD companion Sirius B. You can easily see this from the campus observatory.

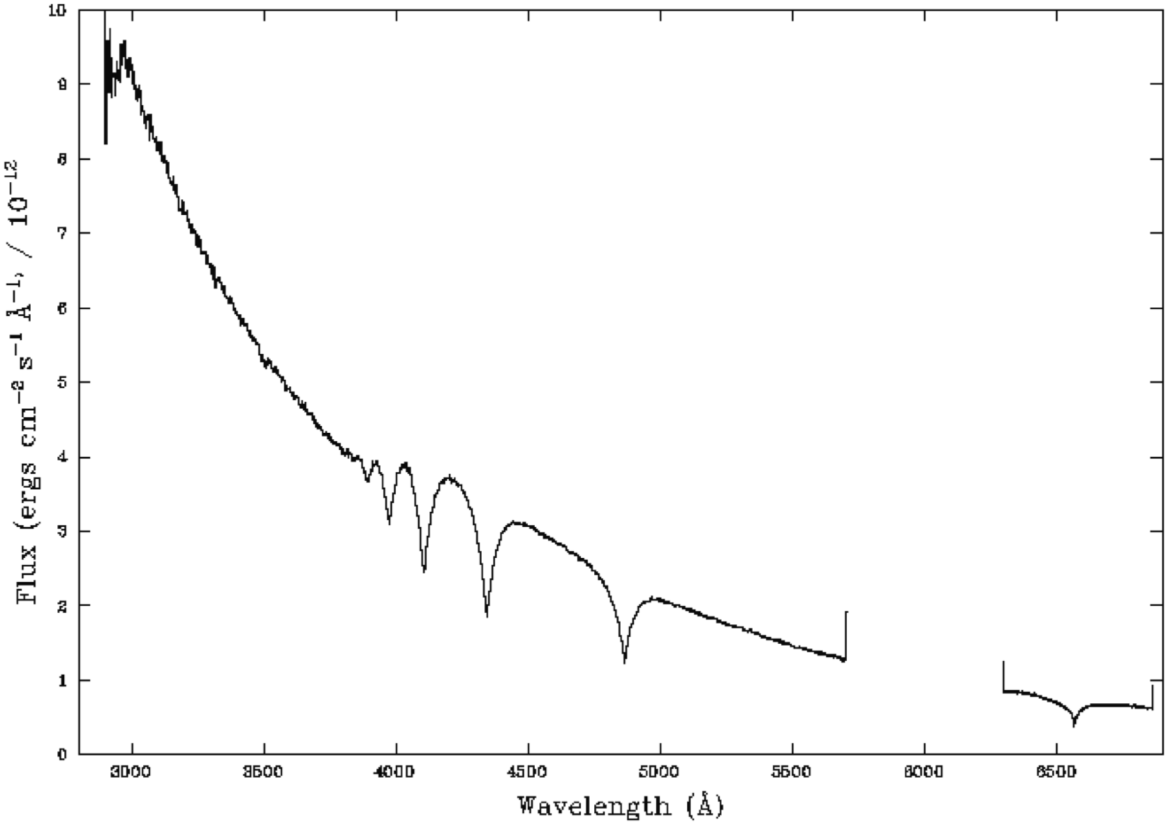


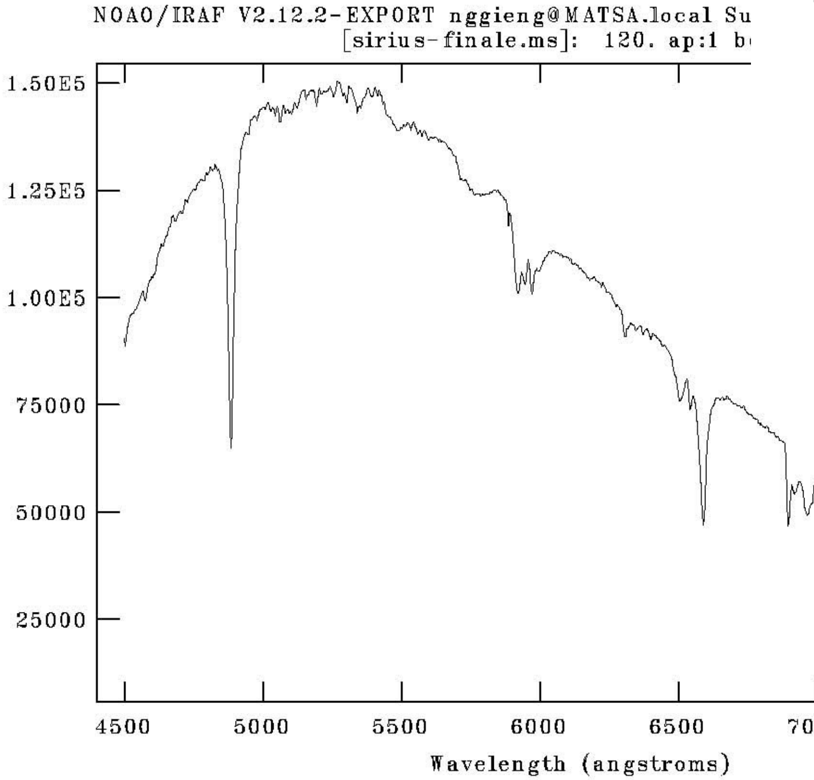
Discovery of Sirius B aka “the pup”



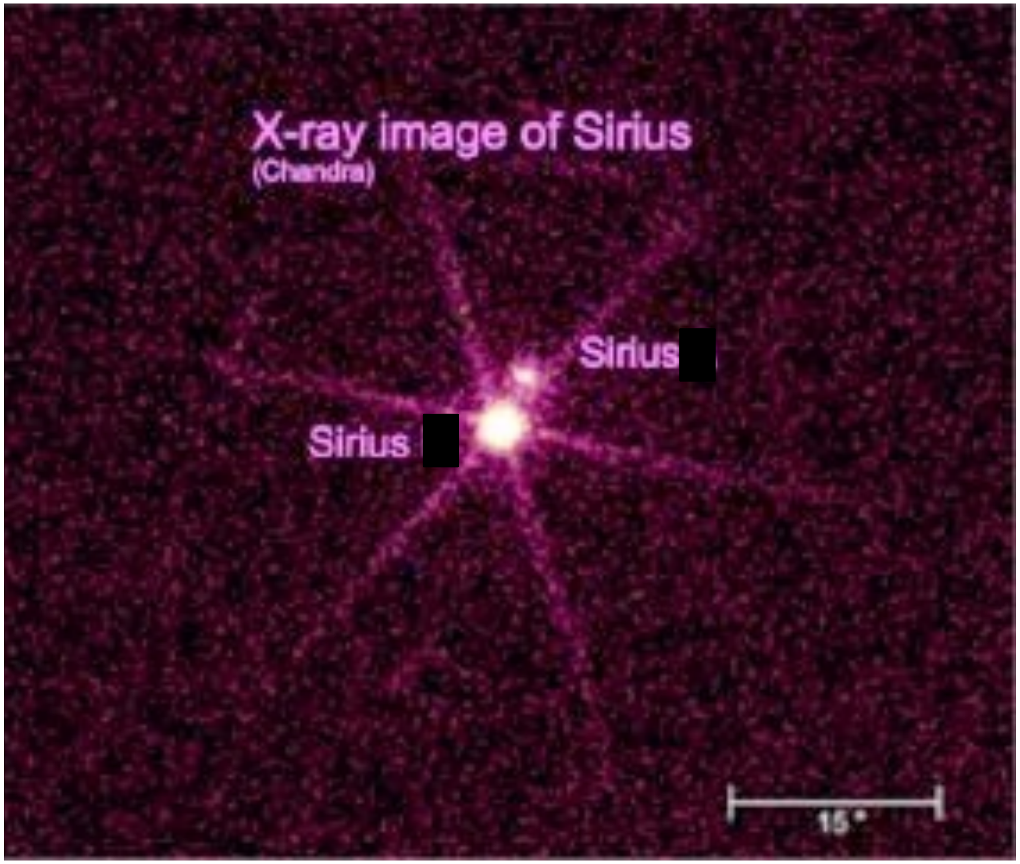


Spectrum of Sirius B and A





X-ray image of Sirius B aka “the pup”



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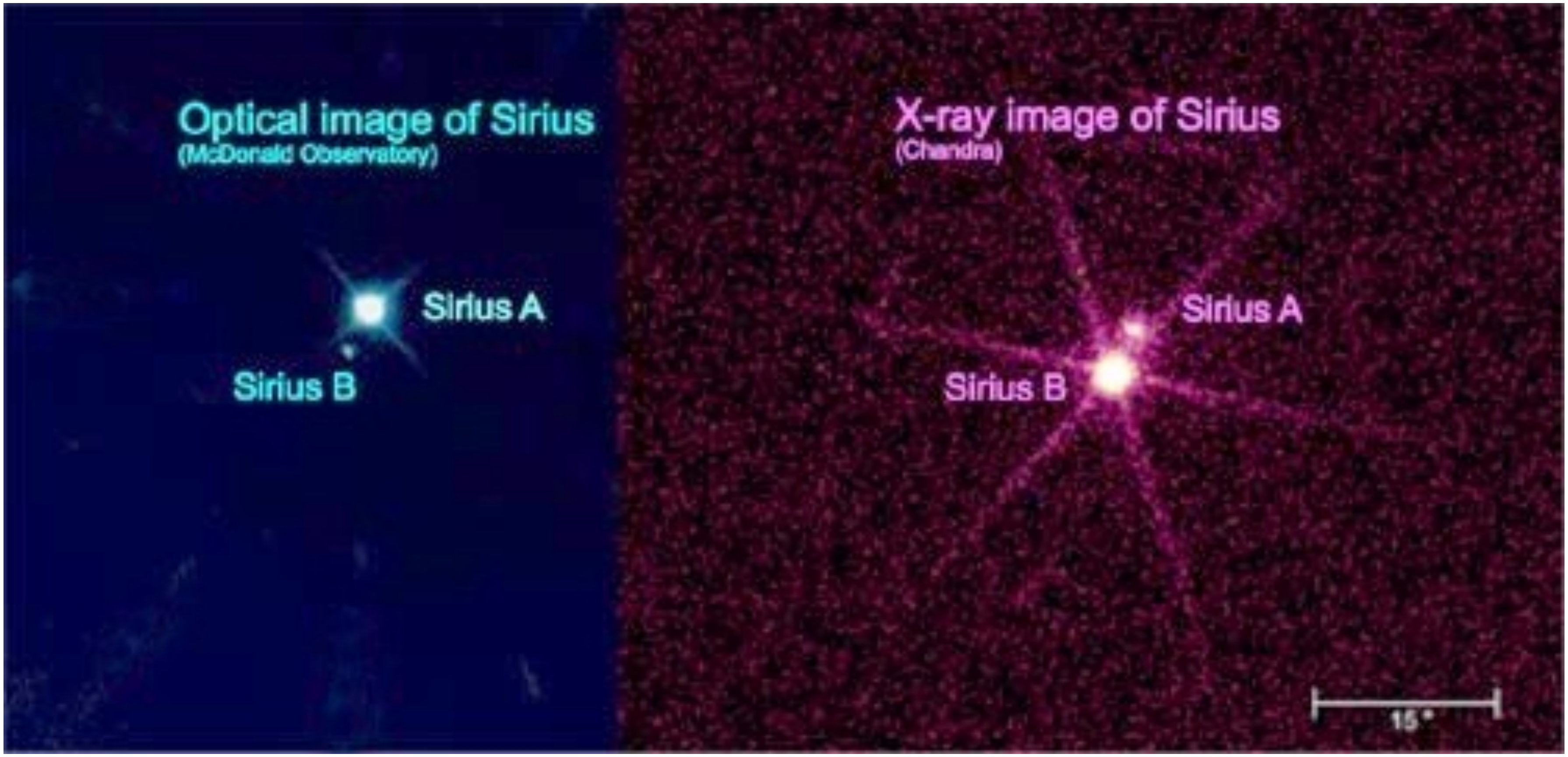
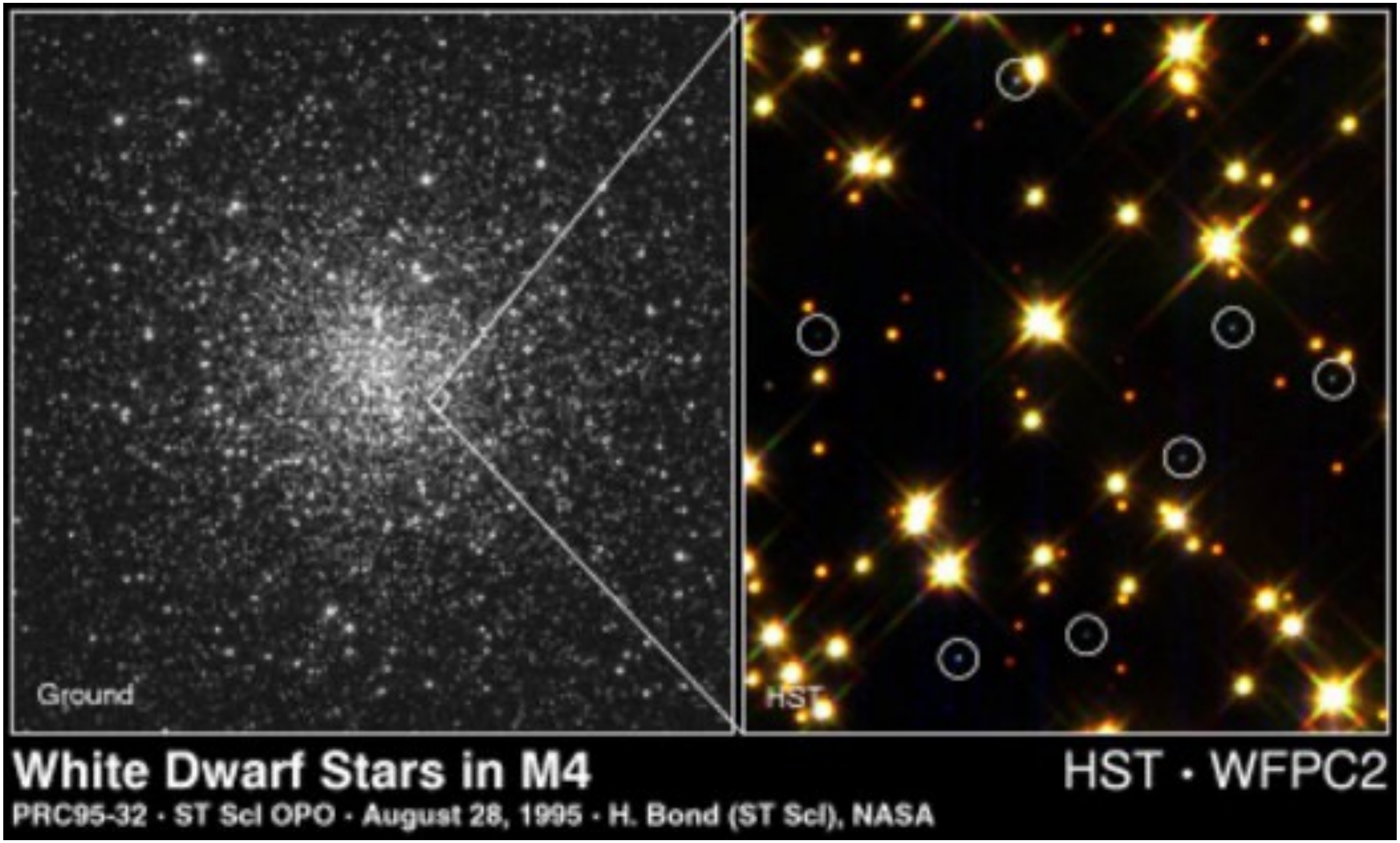


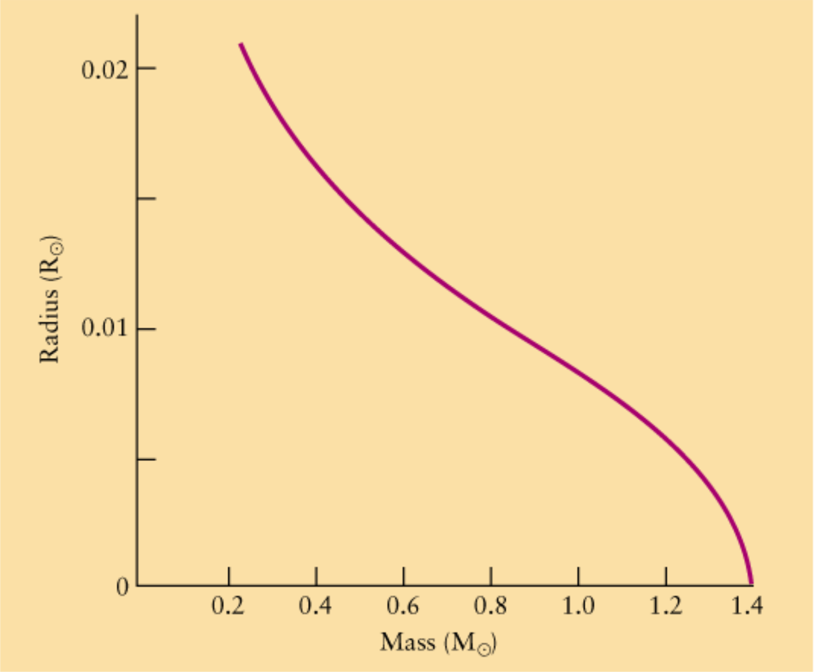
M4, a globular cluster. A stellar graveyard!

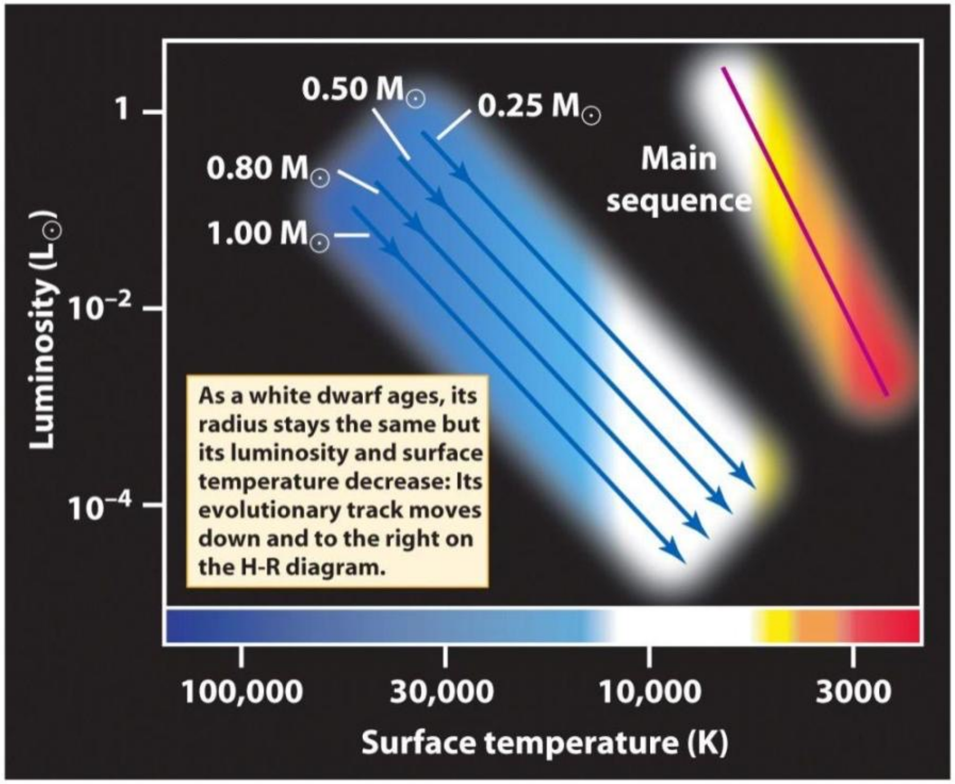
WD represents endpoint of stellar evolution for solar- mass stars.



Mass-radius relation

- Totally different from that for main sequence stars.
- The greater the mass, the smaller the white dwarf.
- This is why more massive WDs are fainter at a given *T*.





As a white dwarf ages, its radius stays the same but its luminosity and surface temperature decrease: Its evolutionary track moves down and to the right on the H-R diagram.

Types of White Dwarf Stars

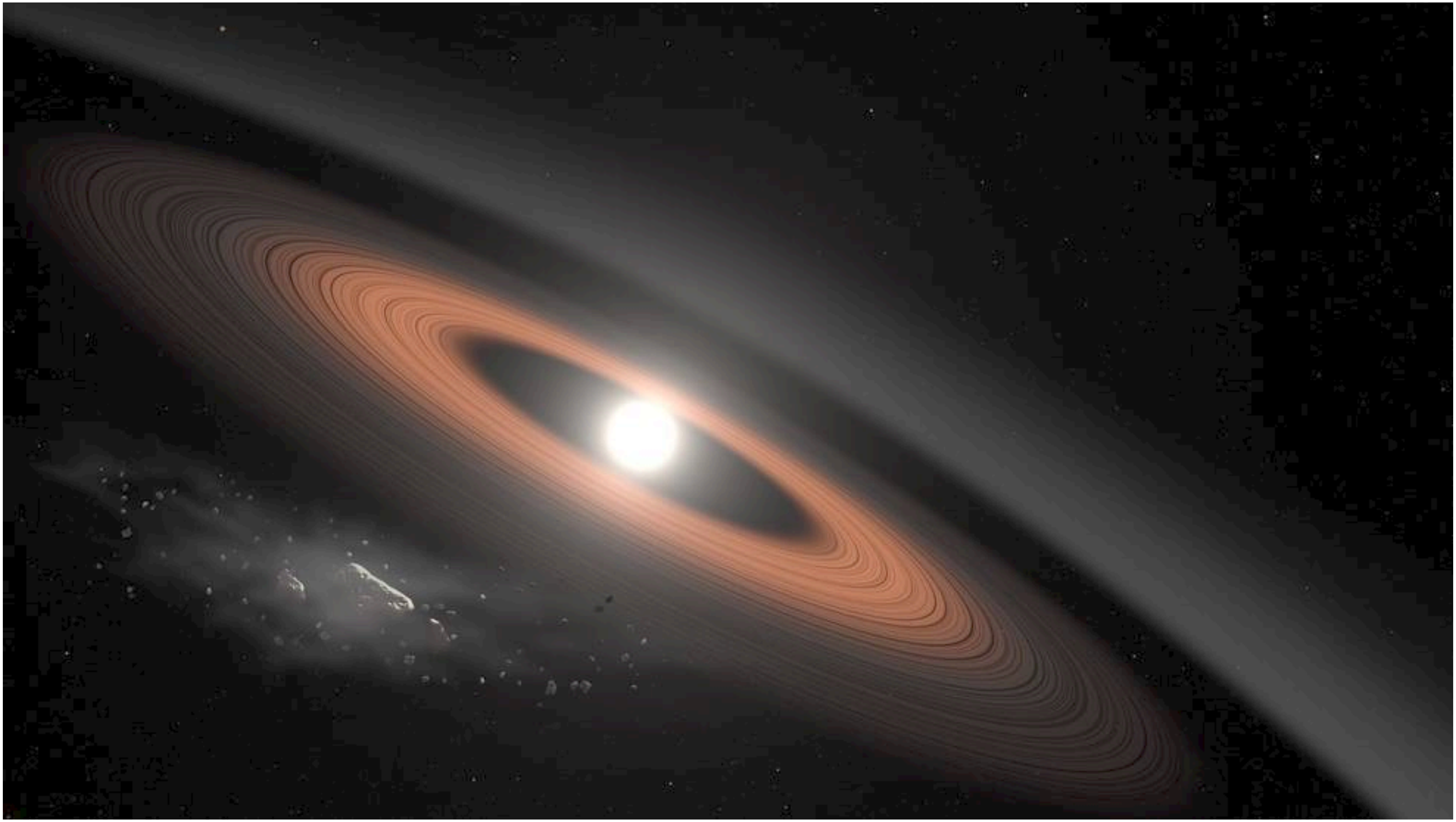
Core:
- Carbon/Oxygen
- Helium
- Oxygen/Neon/Magnesium

Atmosphere
- Hydrogen rich
- Helium rich
- Metal lines

Temperatures 10000 – 50,000 K

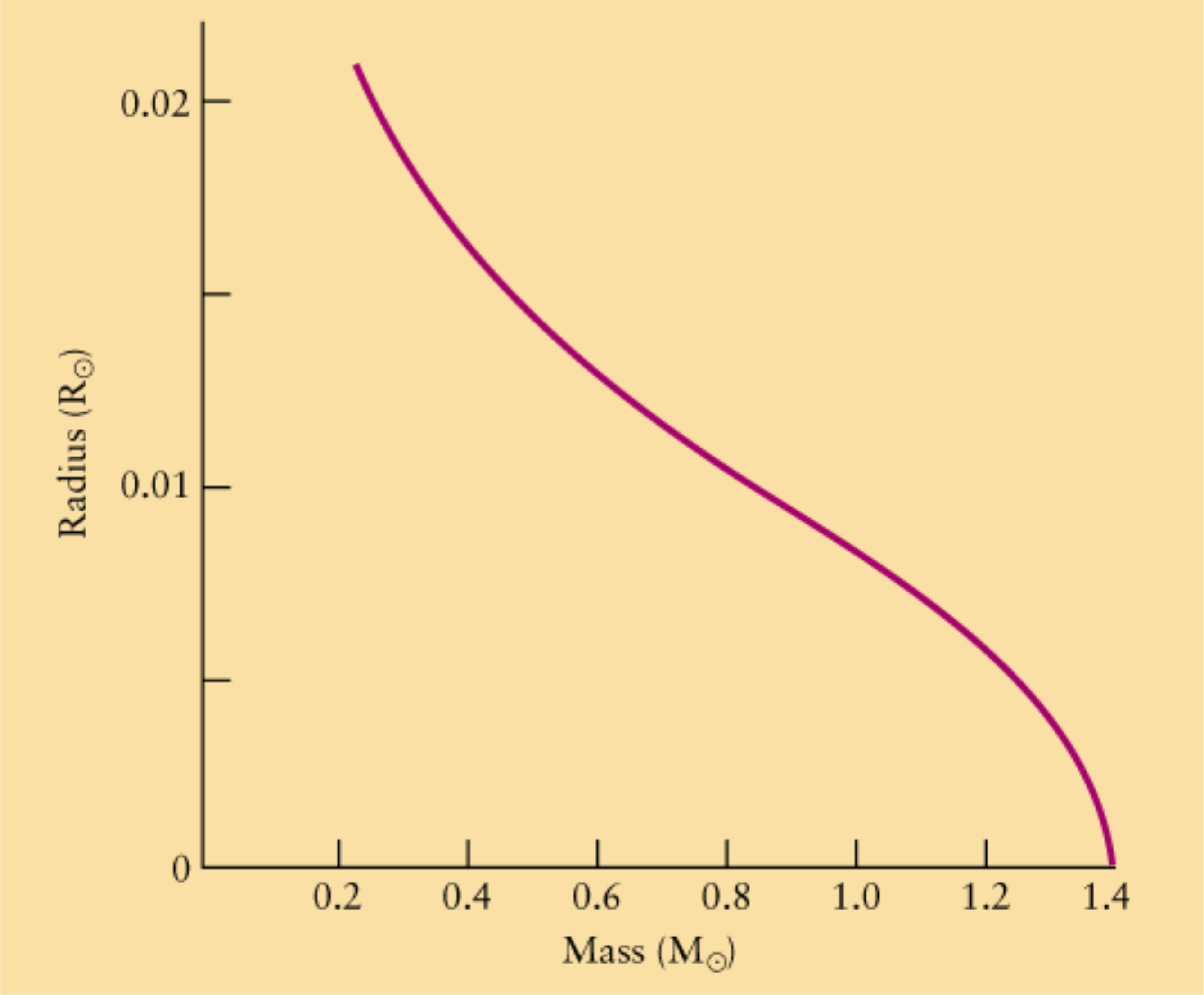
Oldest White Dwarf known

About 3 billion years old, LSPM J0207+3331. with dust disk. Debes et al. 2019



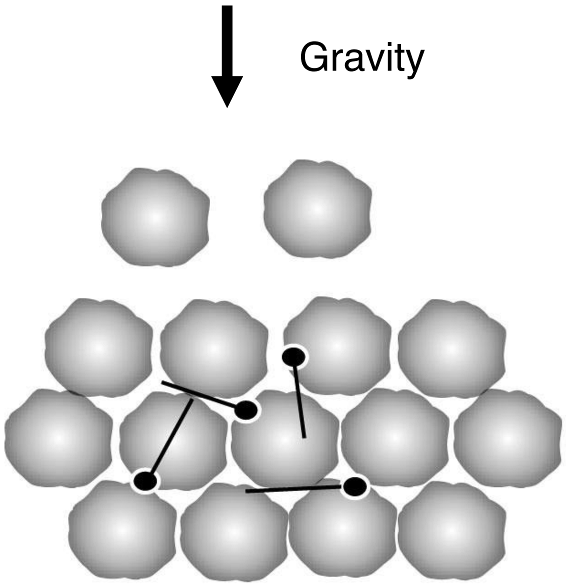
Note the catastrophe at M=1.4 solar masses!

What happens to density as R-> 0?



Electron degeneracy pressure

If the remaining mass of the core is less than $1.4M_{\odot}$, the pressure from degenerate electrons is sufficient to prevent further collapse.



Electrons run out of room to move around, but protons and neutrons are free to move. The electrons create the pressure, and in a WD this balances gravity, keeping the WD from collapsing.

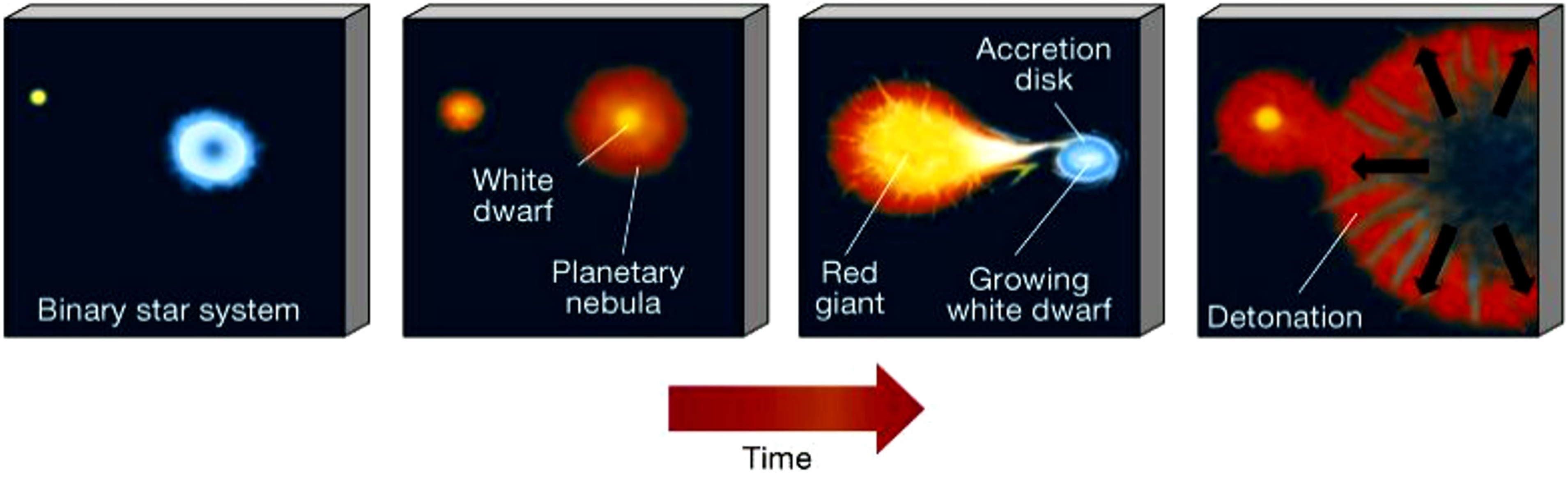
Chandrasekhar limit

- WD starts with C and O ions floating in sea of degenerate electrons
- As the WD cools, C and O form a lattice structure (solid, like a diamond), held up by degeneracy pressure
- Larger masses put more strain on structure. Beyond 1.4 $M_{\odot}$ (*Chandrasekhar limit*) structure collapses.

What does the star become?

Type Ia supernovae

If enough mass dumped onto WD by binary companion to push it over Chandrasekhar limit, starts collapsing until hot enough for C,O fusion. Proceeds rapidly through WD, explosion, no remnant.



Problem, not enough of these systems

New idea: white-dwarf white dwarf merger (the double degenerate)