Exam 1 Logistics

General
- Closed book, closed notes, equation sheet provided
- Bring a calculator (without internet capability)
- Bring two pencils
- Duration will be 75 minutes, same place as we have class

Advice
- Draw pictures, show your work/reasoning/knowledge
- Make sure you attempt every problem! I give partial credit
- Go over your homeworks (one problem is directly from the HW)
- Know the equation sheet
- Read the book (chapters 1, 5, 16, 17, 18, 19, 20,21)
- Review the lecture notes
- Review the worksheets (one problem is directly from a WS)

Important concepts Exam 1:

Ch 1

- Angles, angular measure,
- powers-of-ten

Ch 5

- EM spectrum
- Relations between ν,λ,c and E
- Blackbody (Wien's law, Stefan-Boltzmann law)
- Kirchoff's laws
- Production of spectral lines (energy levels in an atom)
- Doppler shift
- Telescopes, how they work in general, why we want them
- Telescope resolution $\theta = 1.22\ \lambda/D$ where D is the diameter of the primary mirror and λ is the wavelength

Ch 16

- Overall structure of the Sun (see lecture notes)
- What are (and what causes) different features in different layers (granules, sunspots, spicules etc).
- What is the importance of magnetic fields?
- How is the Sun powered (proton-proton chain)?

Ch 17

- How do we describe stars? Knowing the distance is crucial!
- Trigonometric parallax
- Color of stars
- Classifying stellar spectra (HD/Harvard classification)
- Why do the spectra look different?
- HR diagrams (main features)
- How can we determine whether a star is a MS, giant or supergiant (same T)?
- Binary star systems (can provide masses)
- Radial/tangential/space velocity

Ch 18

- The ISM (lecture notes important)
- How does dust affect observations? extinction and reddening.
- How do we form stars?
- Hydrostatic and thermal equilibrium
- Where are the most favorable regions for star formation?

Ch 19

How do stars evolve off the MS?

HR Diagrams, what is the turnoff point?

Variable stars

Ch 20

Stellar remnants – Planetary Nebulae, White Dwarfs, Neutron Stars

What is the iron catastrophe?

Supernovae

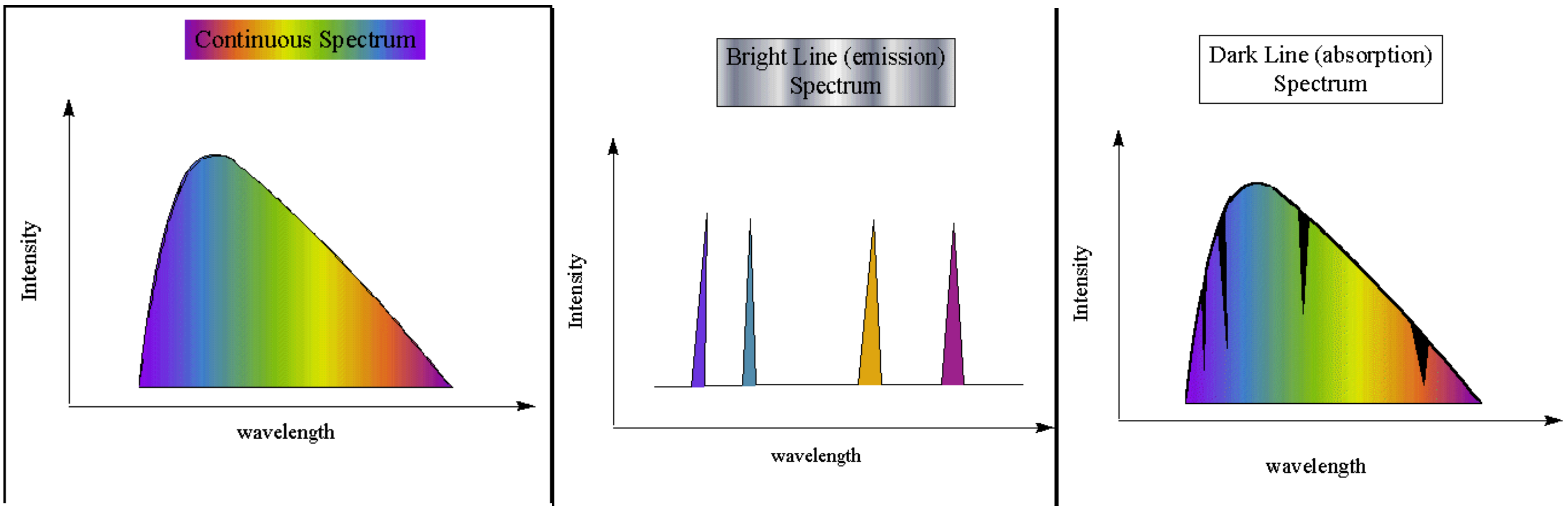
Ch 21

neutron stars

special relativity

Three basic types of spectra

- Kirchoff's laws of spectroscopy:
  1. A hot, opaque body, or a hot, dense gas produces a continuous spectrum.
  2. A hot, transparent gas produces an emission line spectrum.
  3. A cool, transparent gas in front of a source of a continuous spectrum produces an absorption line spectrum.



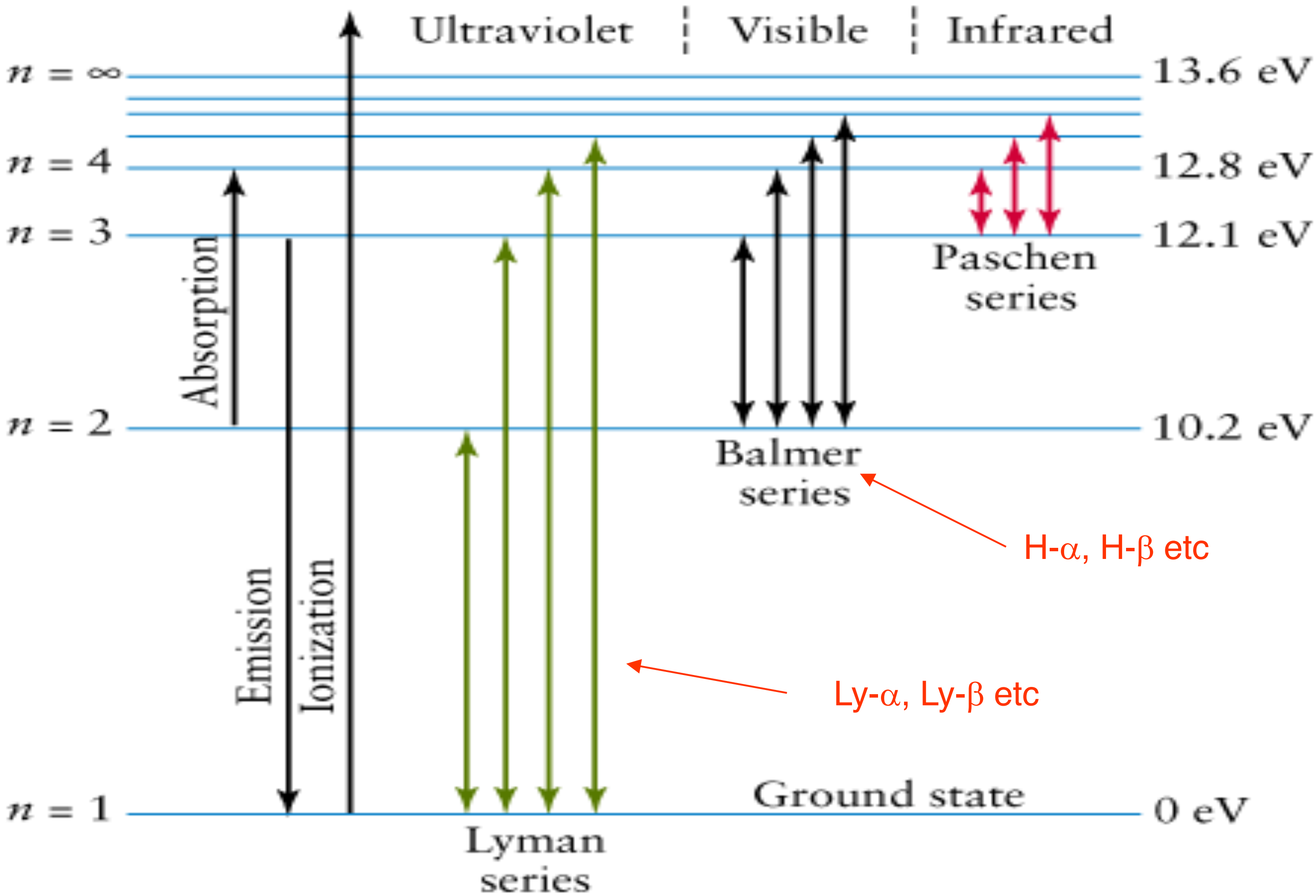
Spectroscopy

The spectrum of an objects tells us:

- Which atoms and molecules are present, and in which proportions
- Which atoms are ionized, and in which proportions
- How excited the atoms are, which tells us about the physical state (cold, hot)

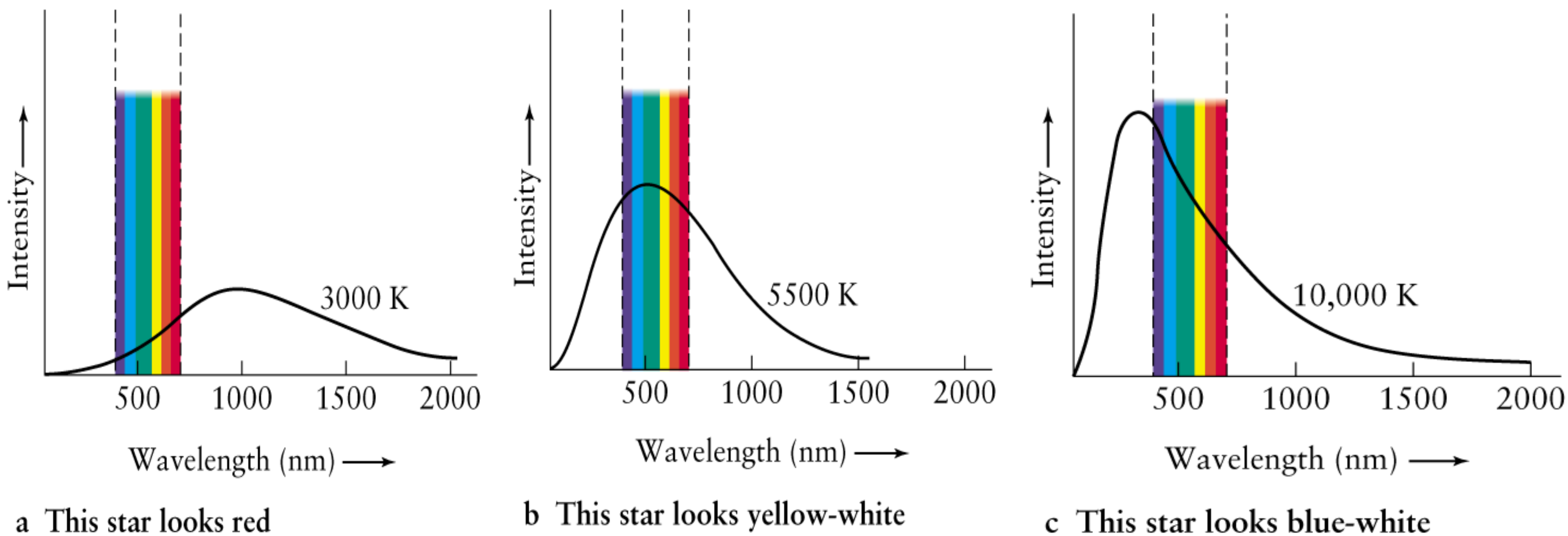
=> Spectroscopy is a very important tool of the astronomer.

Energy level diagram for hydrogen:



Colors of stars

- From Wien's law $\lambda_{max} = 0.0029/T$ we expect hotter objects to be bluer.

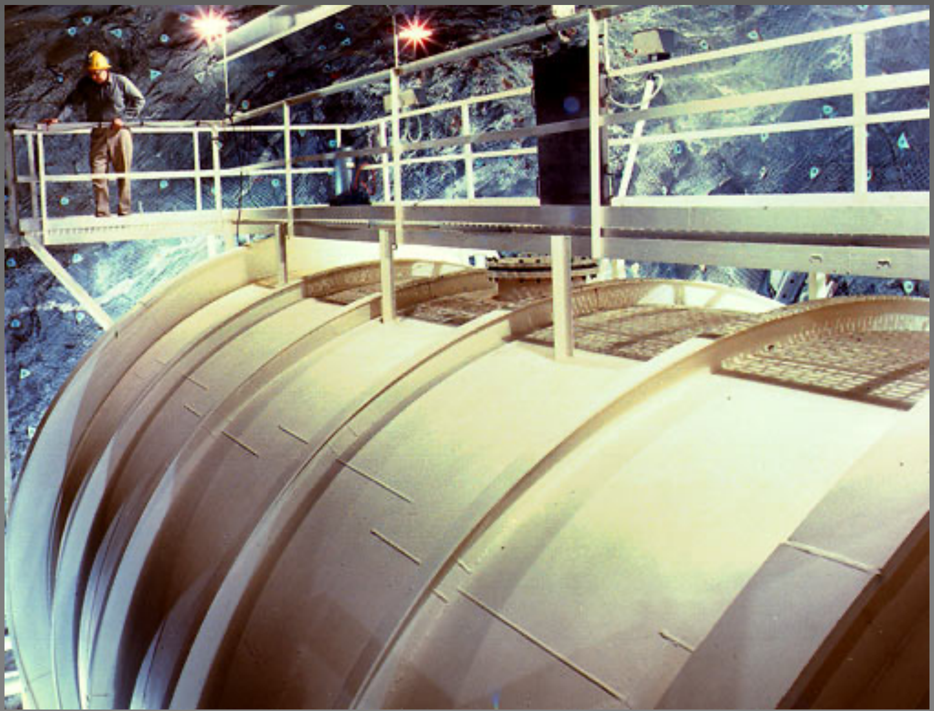


Excited, low-density hydrogen gas.   Red due to “H-alpha” emission line, n = 3 to n = 2.

Solar neutrino problem

In 1960s Ray Davis and John Bahcall measured the neutrino flux from the Sun and found it to be lower than expected (by 30-50%)

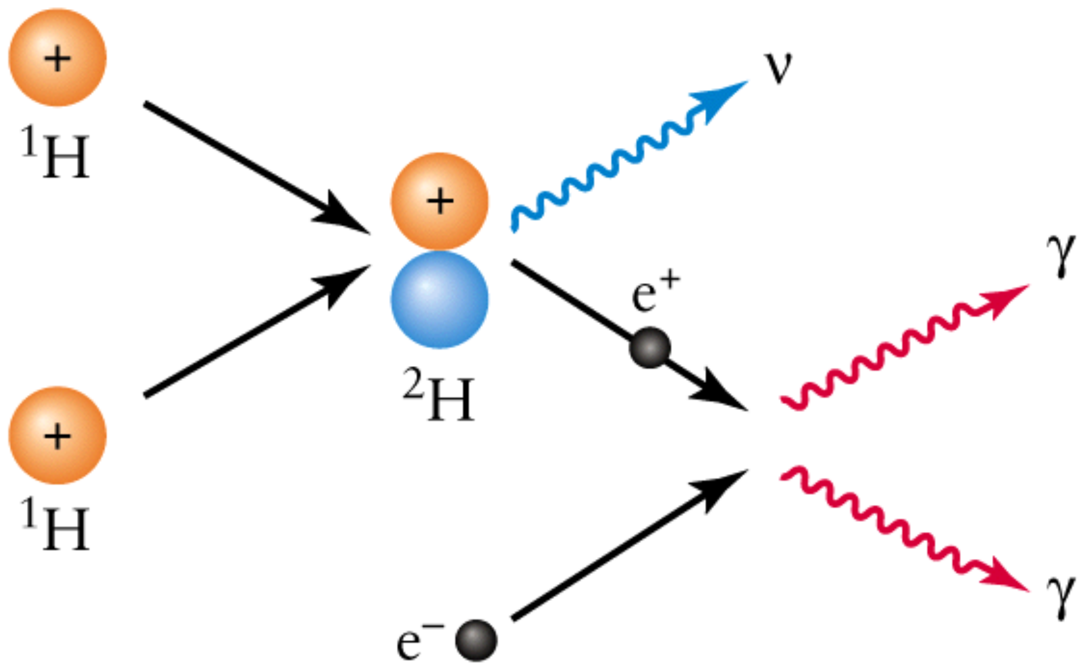
Confirmed in subsequent experiments
Theory of p-p fusion well understood
Solar interior well understood



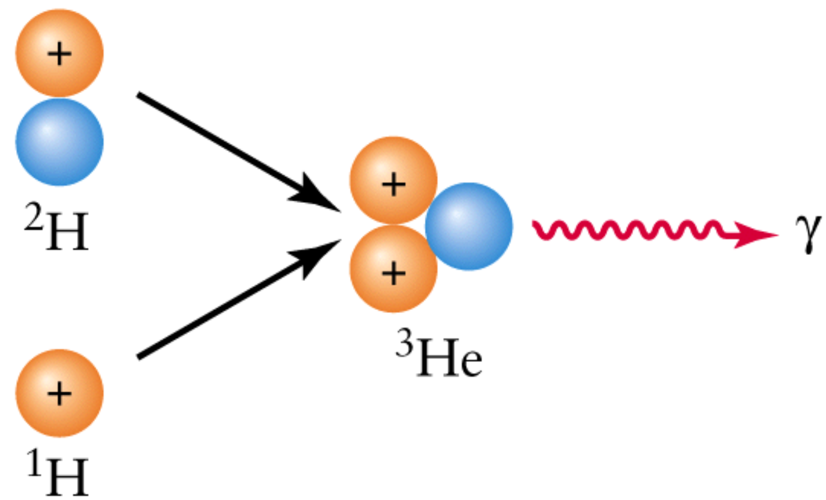
The proton-proton chain in pictures

- Starting point: at 1.5×10^7 K, hydrogen in the core of the Sun is completely ionized, thus a mixture of free electrons and protons (plasma)

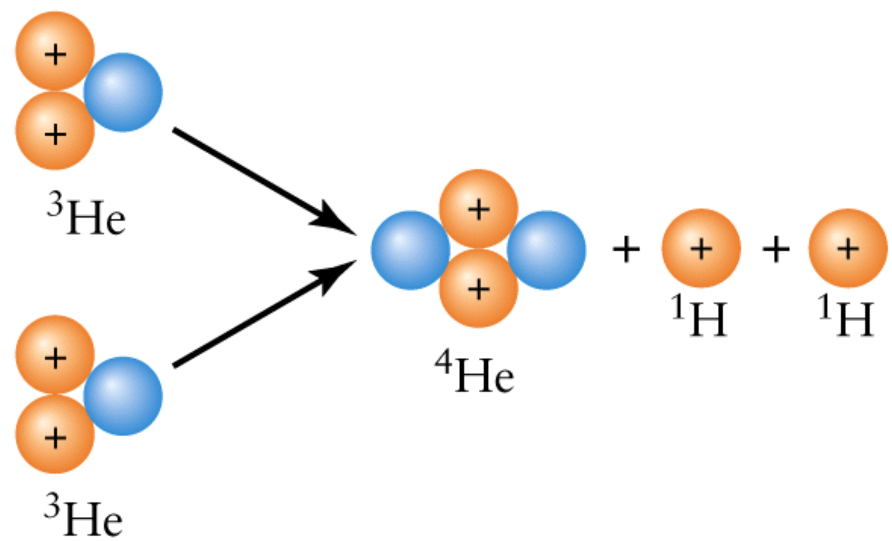
- Step 1:



Once the deuterium has been created, step 2 happens:



In step 3 common helium is formed:



Proton-proton chain

$$p + p \rightarrow {}^2H + e^+ + \nu_e \qquad \text{(twice)}$$

$$p + {}^2H \rightarrow {}^3He + \gamma \qquad \text{(twice)}$$

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

Note the six important byproducts: is that enough to do the job?

Calorimetry

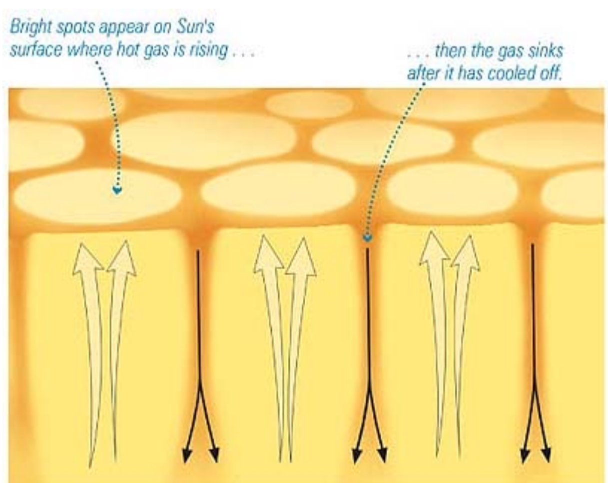
- The 4 protons have 4.8×10^{-29} kg more mass than the He nucleus (0.7% of the total mass has disappeared).
- $E=mc^2$ => 4.3×10^{-12} J is released by the formation of a single He nucleus.
- $L_\odot = 3.9 \times 10^{26}$ J/s => 6×10^{11} kg of H is converted to He every second.

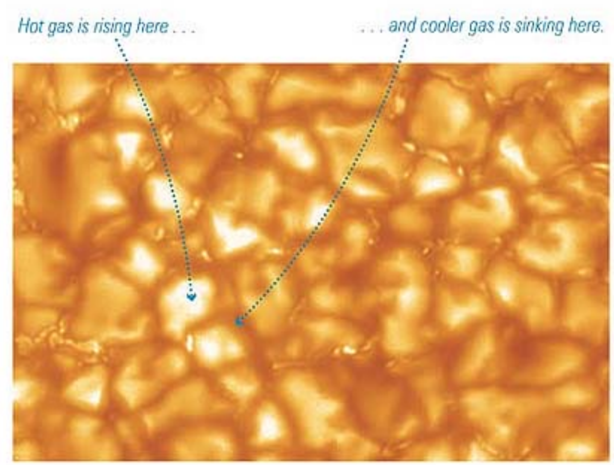
See box 16-1 for details

How does energy get to the surface?

- Radiation, or "radiative diffusion"
  - Photons created in core diffuse outward toward surface. Individual photons are quickly absorbed and reemitted by atoms and electrons in the Sun.

- Convection
  - Mass motion of gas, takes over where the Sun is too opaque for radiation to work well.

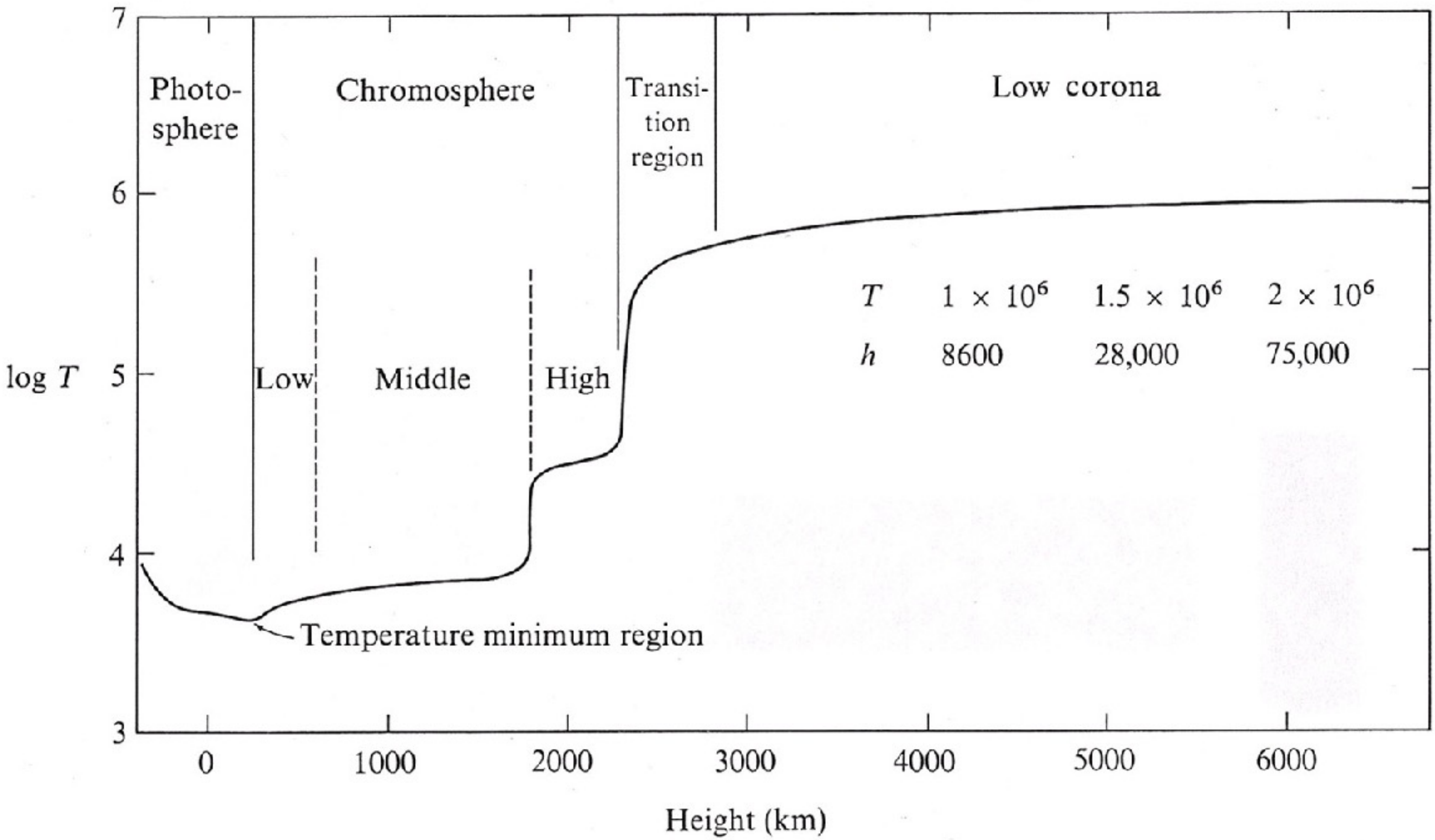




The Sun's atmosphere

- Photosphere: yellowish color. The part we see, T=5800 K.
- The Sun is a giant sphere or gas - so it doesn't have a well defined surface
- Talking about the surface: we mean the photosphere
- The point where atmosphere becomes completely opaque is the photosphere (defines diameter of the Sun)

Thermal Profile of the Sun



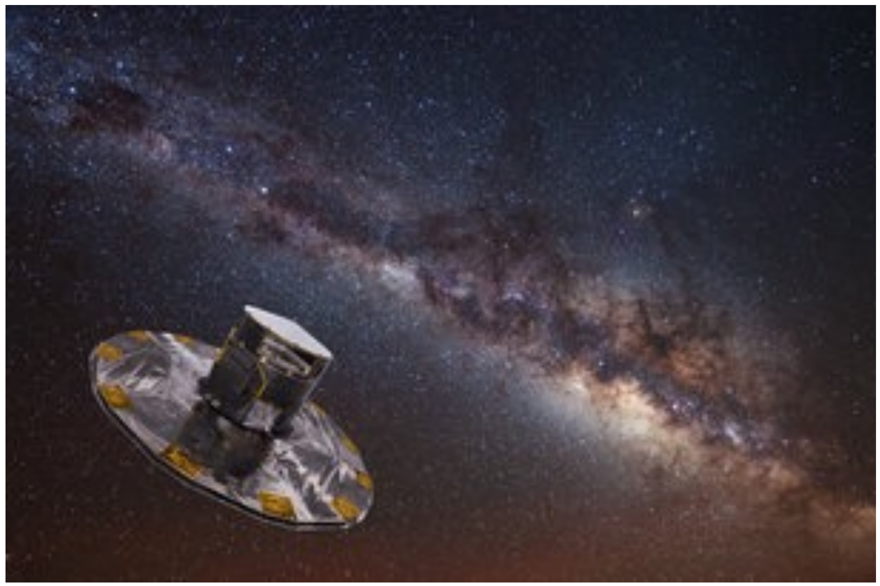
The parallax formula for distance

- $d\,[\mathrm{pc}] = \dfrac{1}{d\,[''] }$ where *p* is the parallax angle and *d* is the distance.
- Distance units: 1 pc = 3.26 ly = 3.09×10^{16} m = 206,265AU
- It took us until 1838 to measure stellar parallaxes since the stars are so far away => small parallax angles

Limitations

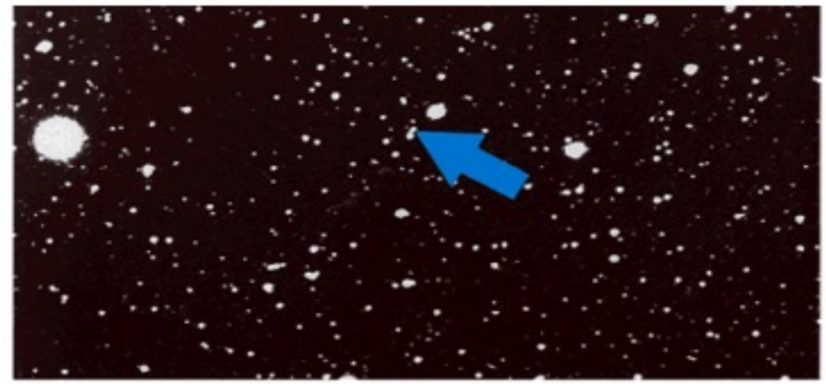
- Until recently we only knew accurate (0.01") parallaxes for a few 100 stars (=> d~100pc)
- In the 1990's the ESA satellite Hipparchos measured over 100,000 parallaxes with an accuracy of 0.001”
- Gaia has measured over a billion stars to 2 kpc
- With VLBI we can measure 10μas parallaxes

Gaia satellite

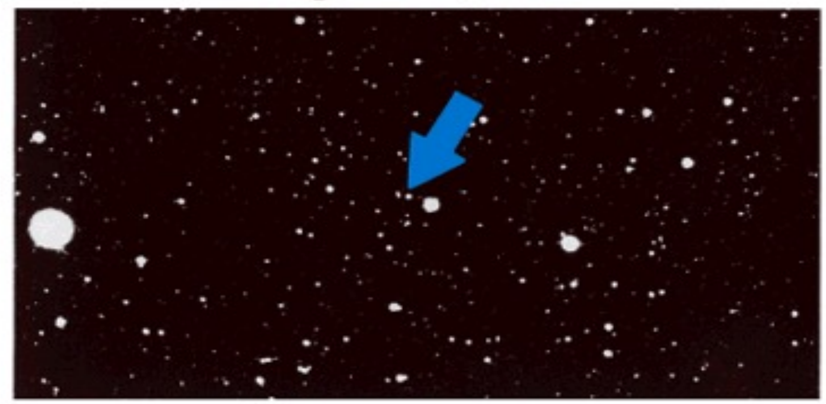


Proper motion

- Caused by physical movement of a star with respect to our Solar system
- This is in contrast to parallax which is an apparent motion of the star due to the motion of the Earth
- Proper motion is the angle a star moves per year (angular motion on the sky), and it is a linear drift
- The superposition of this linear drift and the elliptical motion from the parallax effect leads to a 'wavy' path on the sky



August 24, 1894



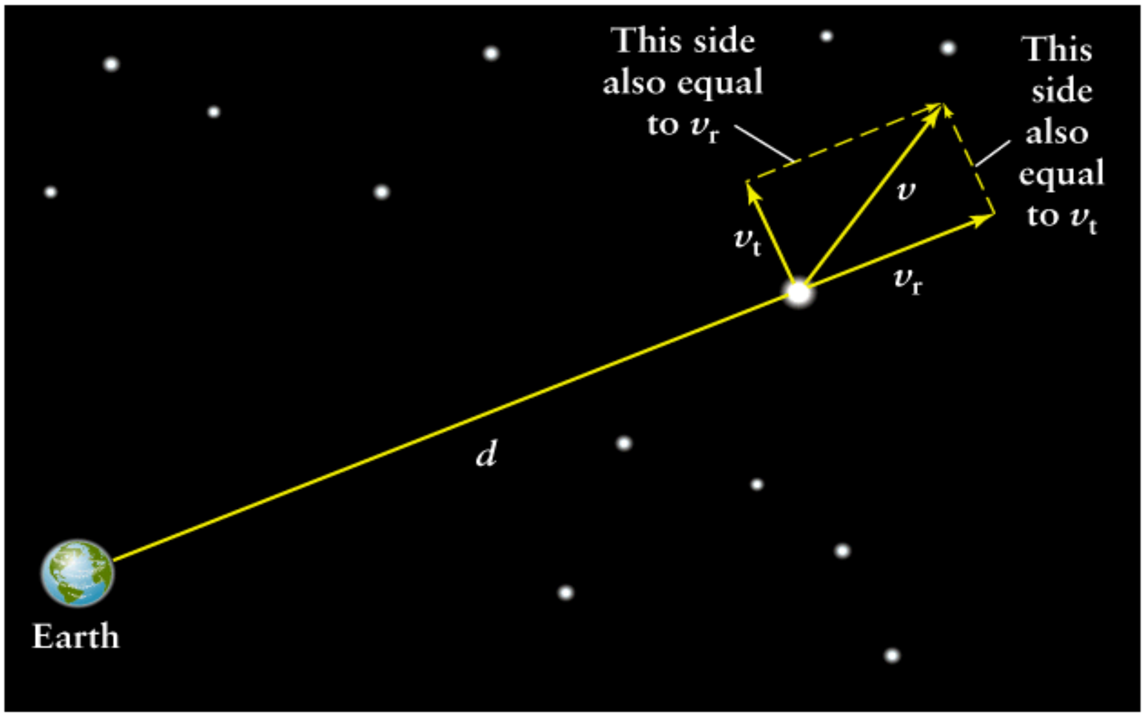
May 30, 1916

This star moved 4' over this time - a huge proper motion of 10″.9/yr.

Space Velocity

Speed and direction of star. From Pythagorean theorem

$$V = \sqrt{V_t^2 + V_r^2} = \sqrt{(4.74\mu d)^2 + V_r^2}$$



Typical stellar space velocities are 20-100 km/s.

Three quantities need to be measured - distance is the most difficult one.

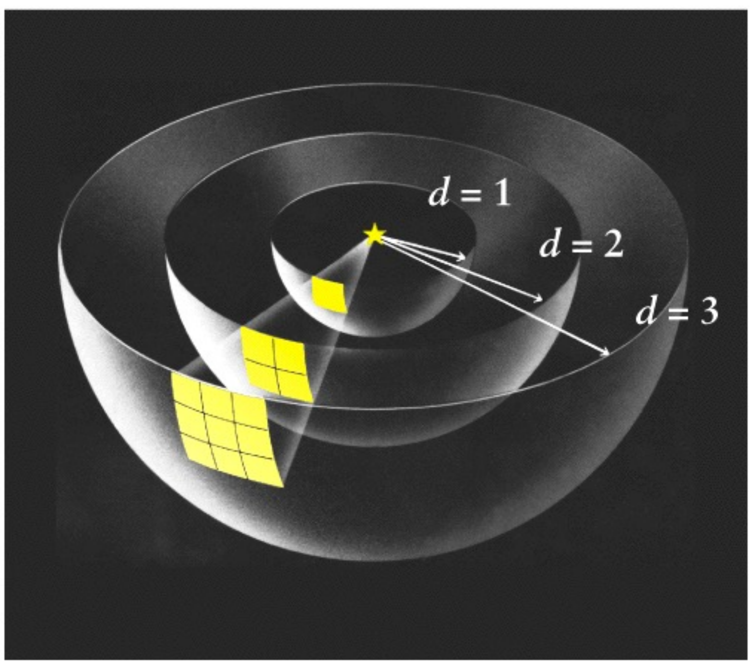
How bright is a star?

- Luminosity (*L,* intrinsic property): the total energy output, a physical property of the star. Doesn't depend on distance.

- Apparent brightness (*F,* or *b*): measures how bright a star appears to be on a distance. Does depend on distance!

- The brightness, or intensity, of light diminishes as the inverse square of the distance.

$$F = L/4\pi d^2$$



Same amount of radiation from a star must illuminate a bigger area as distance from star increases.The area increases as the square of the distance.

Apparent magnitudes

- Measurement of brightness of stars as they seem from Earth.

- Smaller magnitudes mean brighter stars and defined such that 5 magnitude differences implies a factor of 100 in brightness

- Magnitude difference related to brightness ratio:

$$m_2 - m_1 = 2.5\log\left(\frac{b_1}{b_2}\right)$$

- Also note: if $\frac{b_1}{b_2} = 100$, then $2.5\log\left(\frac{b_1}{b_2}\right) = 5$

- This is a logarithmic scale - no zero point is defined. Done by defining certain stars to have zero magnitude.

Absolute magnitude

Caution:

Apparent magnitude is NOT power output! A star may have bright (small) apparent magnitude because it is close to us, or it might have a bright (small) magnitude because it produces a huge amount of light.

As scientists, we want a brightness scale that takes distance into account and measures the *total* energy output of the star.

Absolute magnitude:

Definition: the apparent magnitude a star would have if it were precisely 10 pc away from us

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

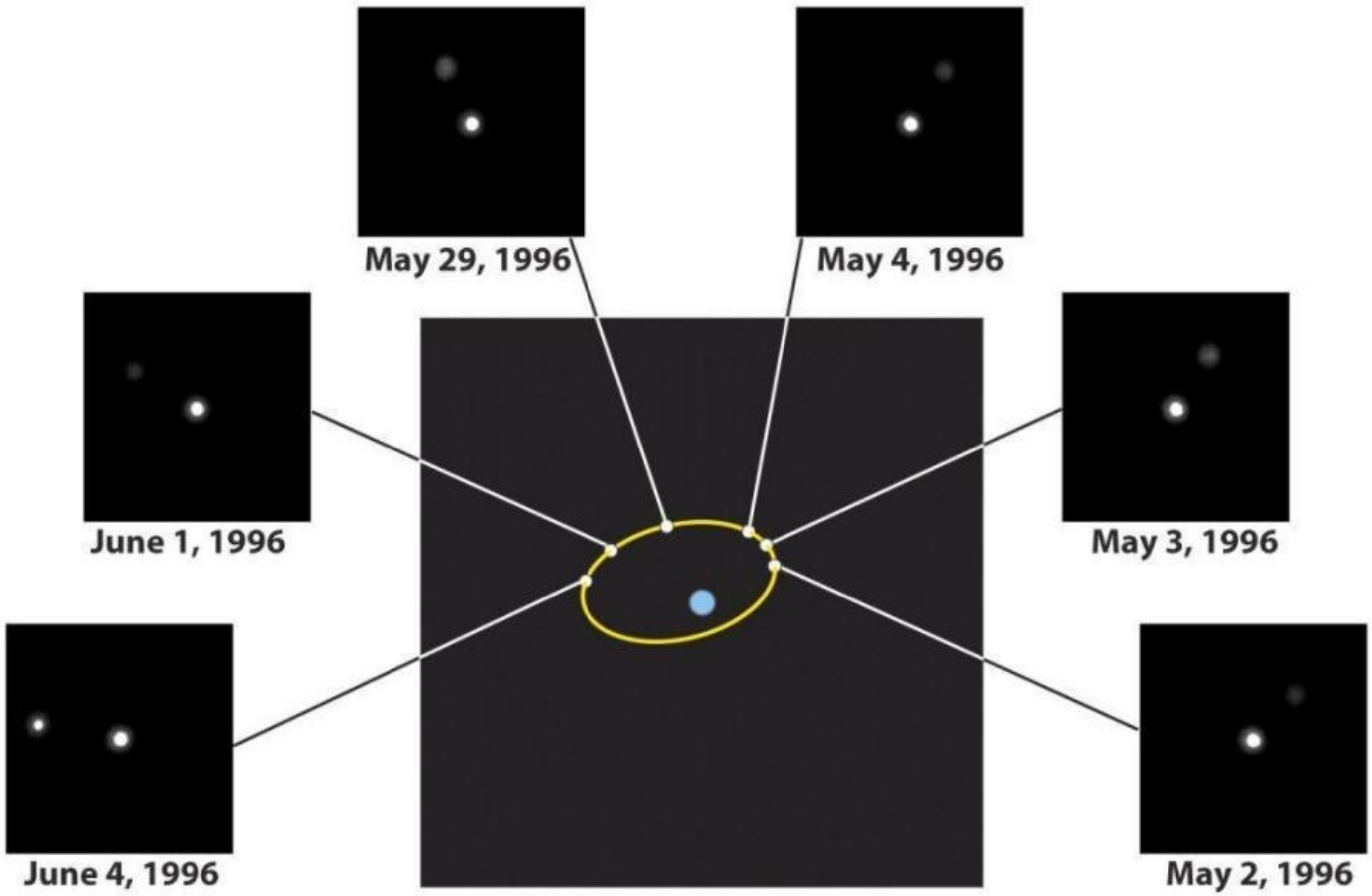
m is apparent magnitude (measured)

d is distance (calculated from parallax)

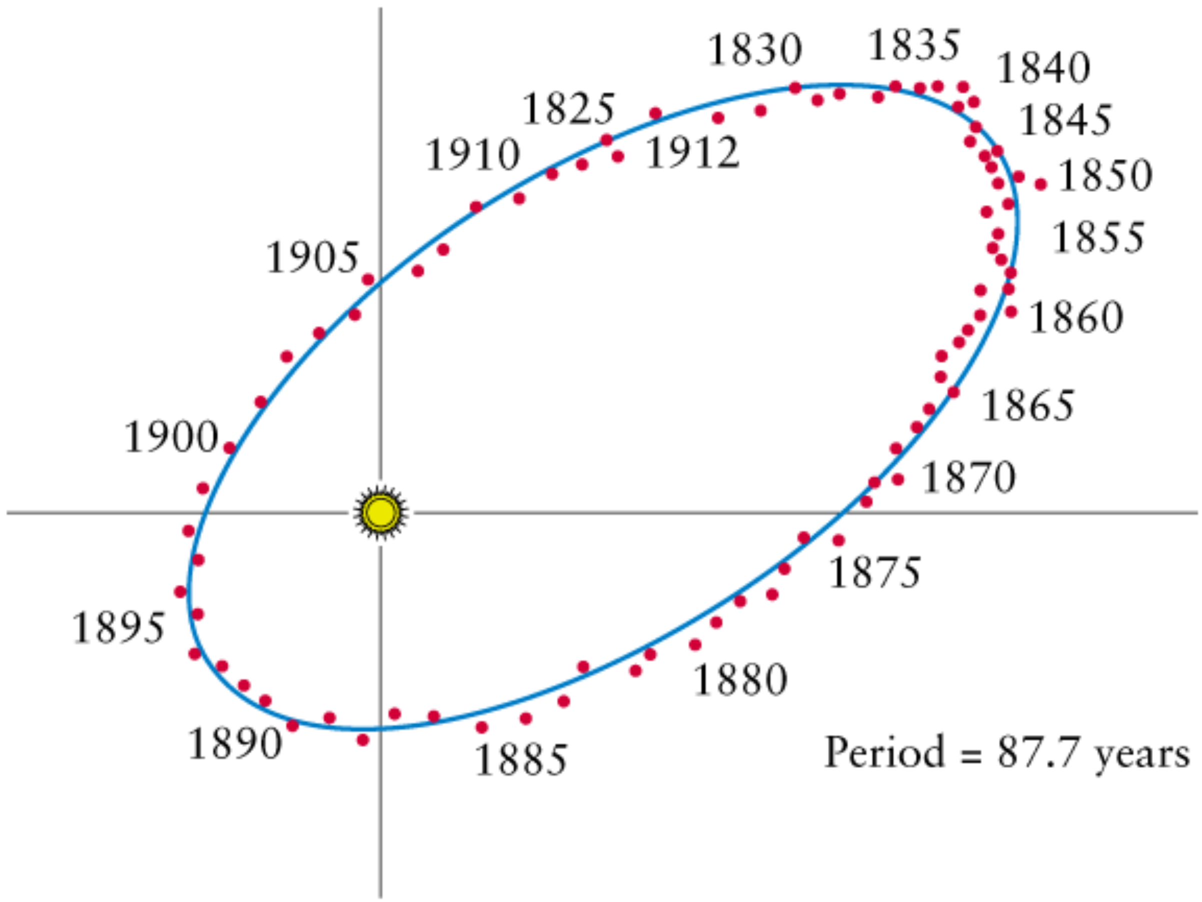
M is absolute magnitude

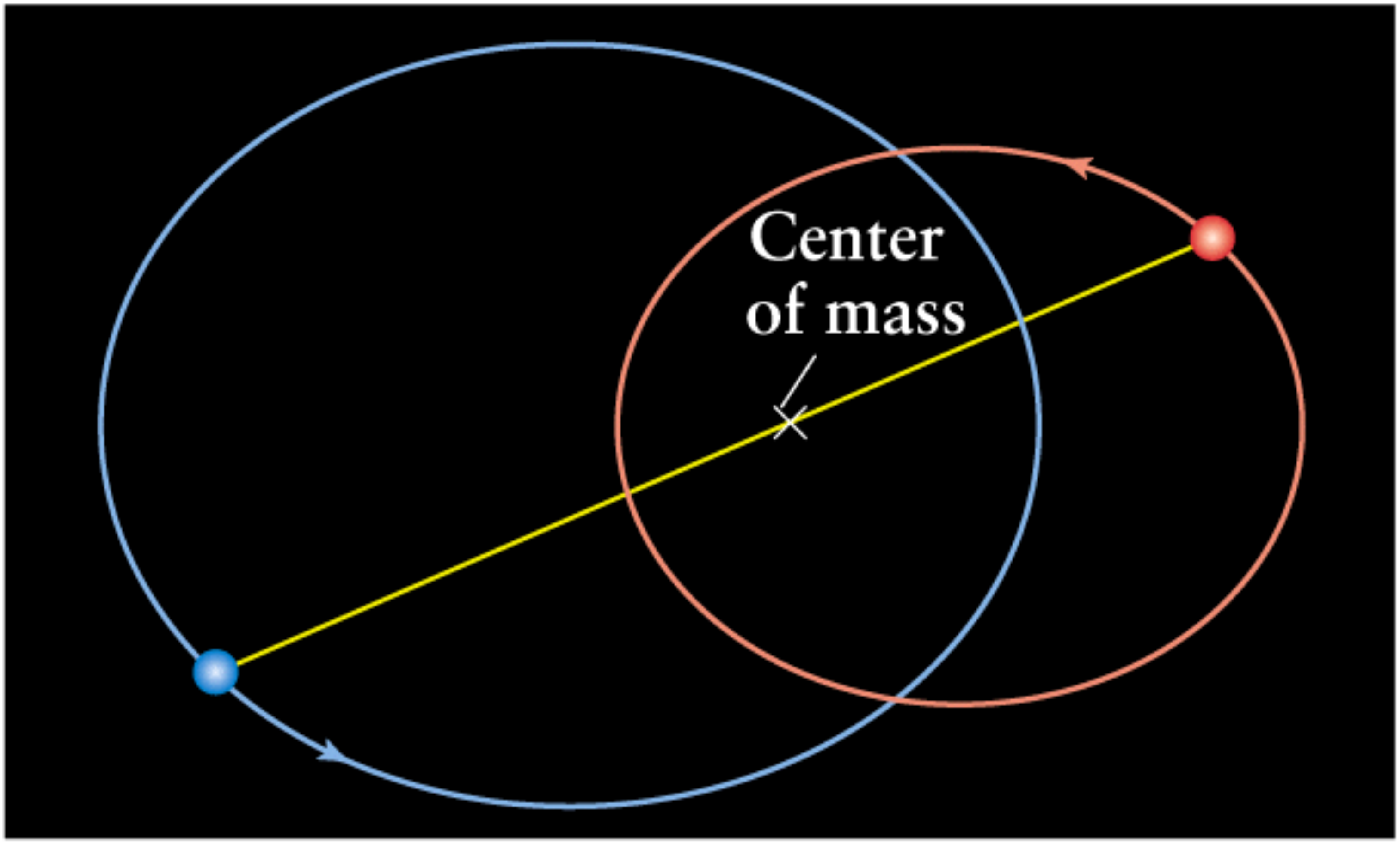
Binary stars

1. Visual binaries - can see both stars. Binaries (any type) always orbit around the mutual center of mass.



Can plot orbit of either star around the other, treated as stationary.





b

$$a_1M_1=a_2M_2$$

where a = semimajor axis, M = mass

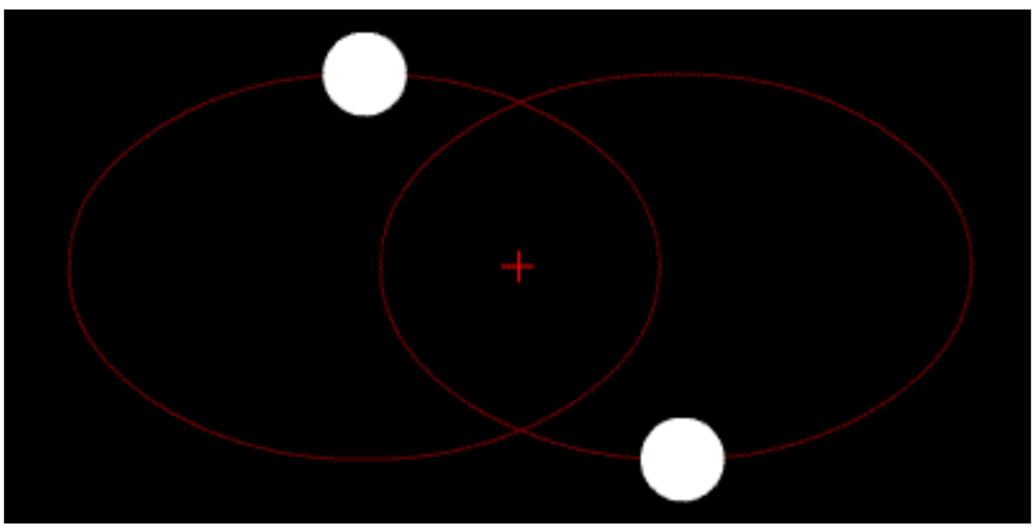
Recall semimajor axis = half of the long axis of ellipse

Newton's version of Kepler's third law:

- Universal, that is we can use it in any system

$$P^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3$$

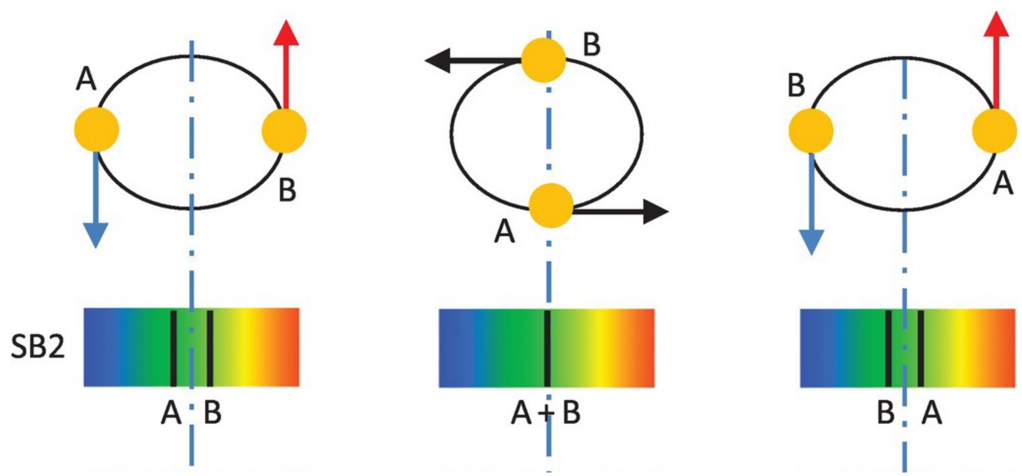
Here, *a* is the average distance between their centers.



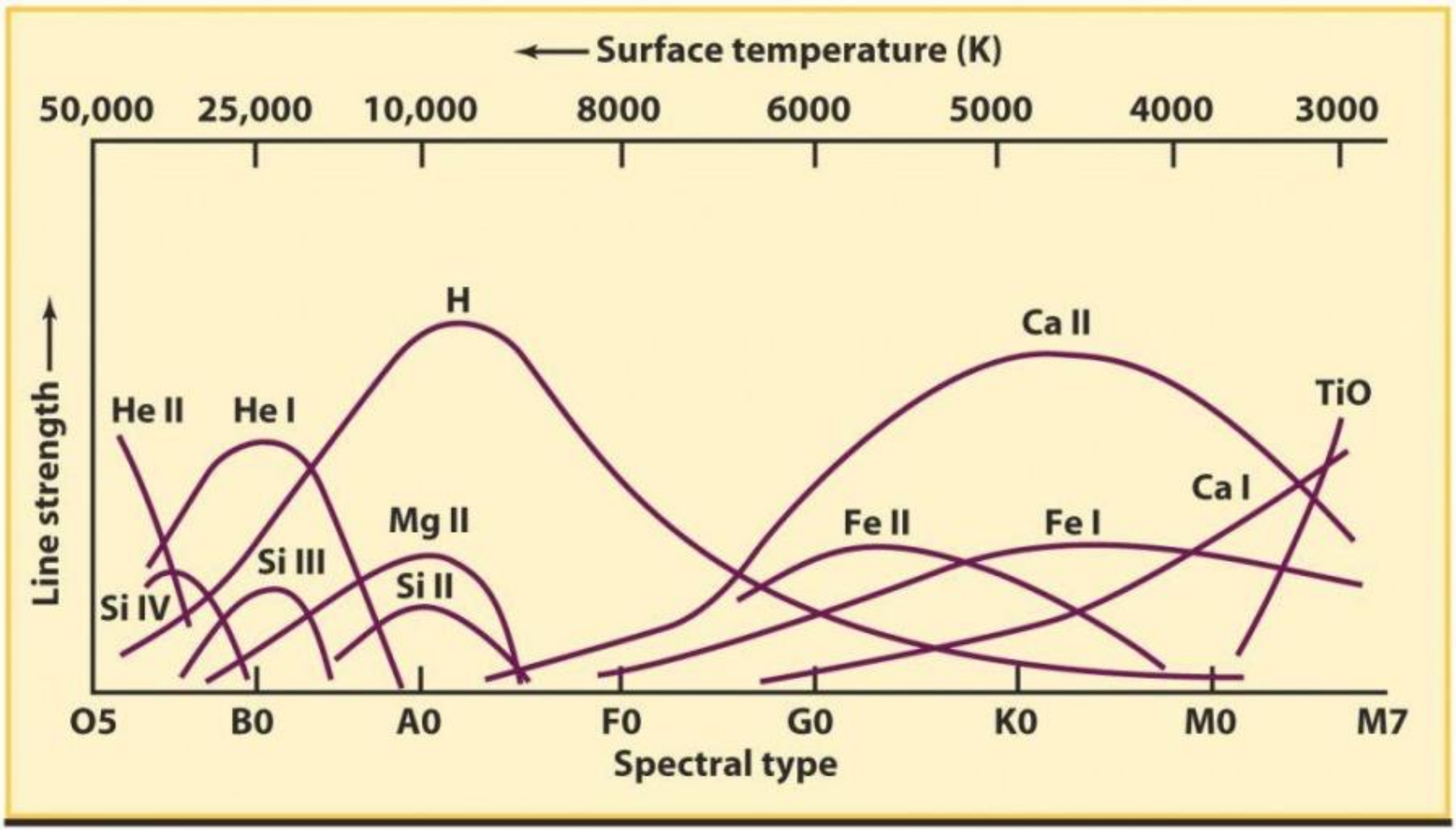
Spectroscopic binary example

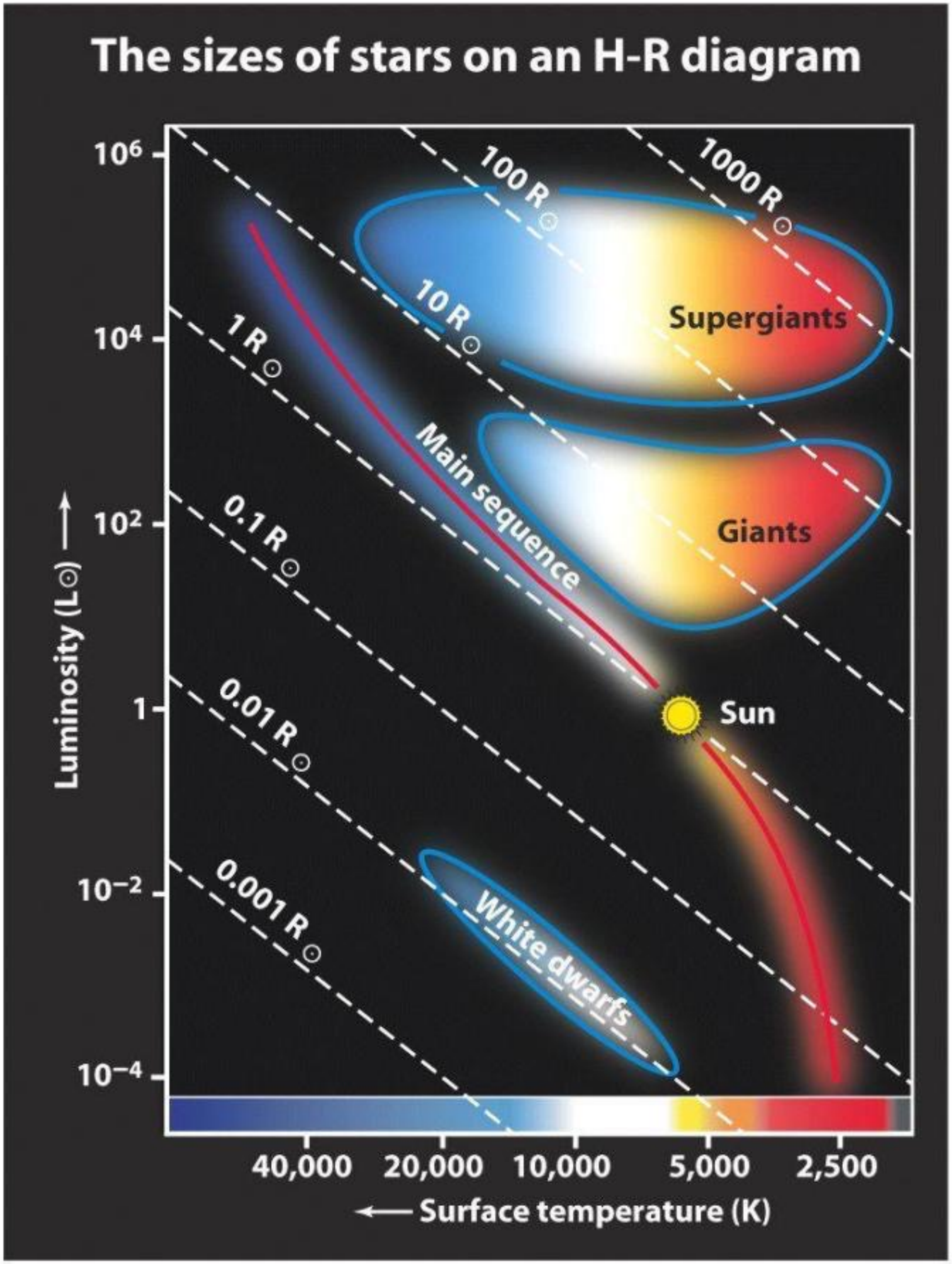
- The components (A and B) of a binary star move along circular orbits. The distance between them is 1AU. You are observing this system in the plane of the orbit, and observe a periodic, maximum separation of the Hγ lines from the rest wavelength (434.04 nm) of 0.061nm as shown below. The shift is the same for both components.

  What are the masses of the individual stars in the system?



Balmer lines of hydrogen are most prominent about 10,000 K, peaking around A0. Other lines peak at different temperatures.





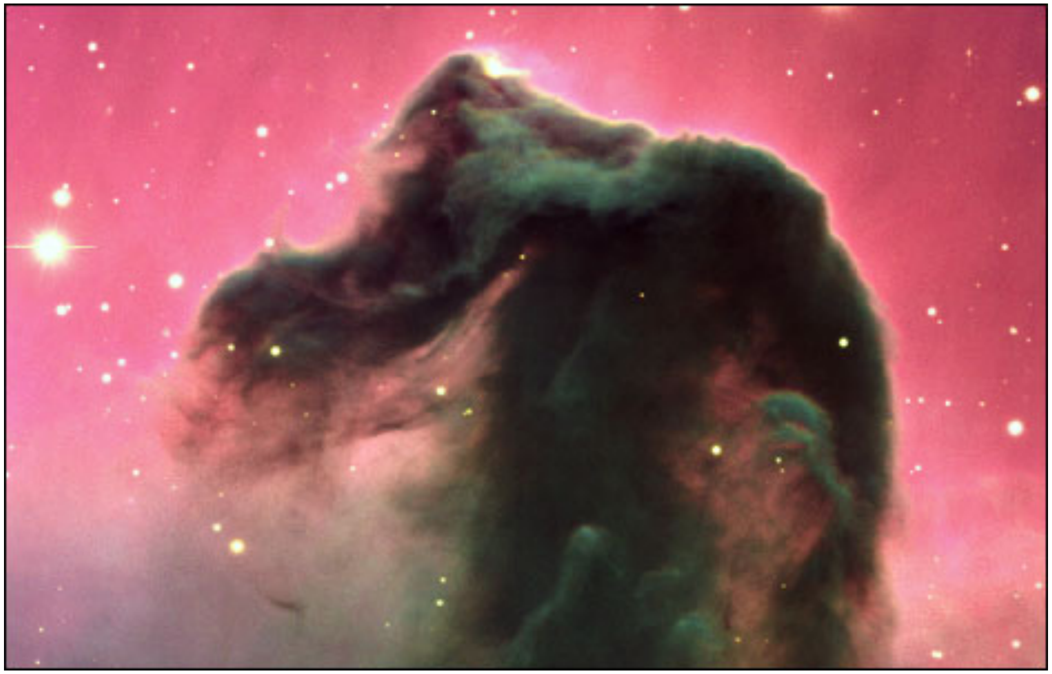
The sizes of stars on an H-R diagram
10^6
10^4
10^2
1
10^{-2}
10^{-4}
Luminosity ($L_\odot$)
1000 $R_\odot$
100 $R_\odot$
10 $R_\odot$
1 $R_\odot$
0.1 $R_\odot$
0.01 $R_\odot$
0.001 $R_\odot$
Supergiants
Giants
Main sequence
Sun
White dwarfs
40,000
20,000
10,000
5,000
2,500
Surface temperature (K)

Overview of the ISM

- The ISM is a multi-component, multi phase medium

- The *components* are gas and dust, with dust comprising 1-2% of the ISM mass.

- The *phases*, meaning different kinds of clouds of gas and dust – hot, warm, cold, dense, rarefied.



Component	Phase	T(K)	$n(cm^{-3})$
Neutral	Cold (molecular)	10-50	10^3-10^7
	Cool (atomic)	100	1
	Warm	$8x10^3$	10^{-1}
Ionized	Warm	10^4	10^0-10^4
	Hot	$5x10^5$	10^{-3}

Stages of star formation

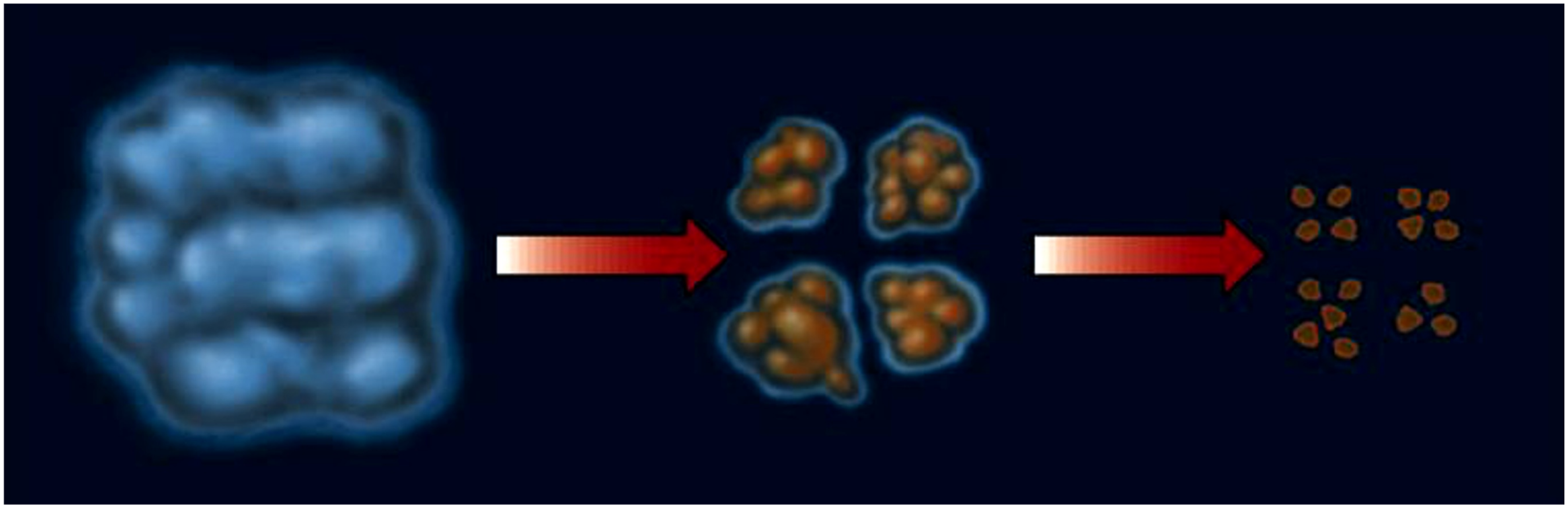
- Start with a large, cold cloud: 0.1pc diameter, T~100 K, M=10-100$M_{\odot}$.
- First, gravity dominates and collapse is *free-fall* (like falling from the top of a building).
- As n and T increases, pressure begins to slow collapse. This is slower than free-fall, and outer gas is held up by a slower, inner gas core.
- K-H process converts gravitational energy to heat, and some radiated into space, rest heats up core.
- Outer parts spin-up to form a protostellar disk, slowing the collapse since protostar can only get new material through inner parts of disk (which has lost angular momentum from gas friction and magnetic diffusion).

- The protostar becomes hot enough to blow gas from the poles, and twisted B-fields help spew out gas in bipolar jets (v=200km/s).

- Finally, protostar core hot enough to ignite nuclear fusion and becomes a star.

- At some point the luminosity is large enough to blow away most of the surrounding gas, and accretion stops. The star is now visible.

- Very little of the original cloud mass makes it into the star itself. Some of the protostellar disk remains, which might stay around long enough to form a planetary system.



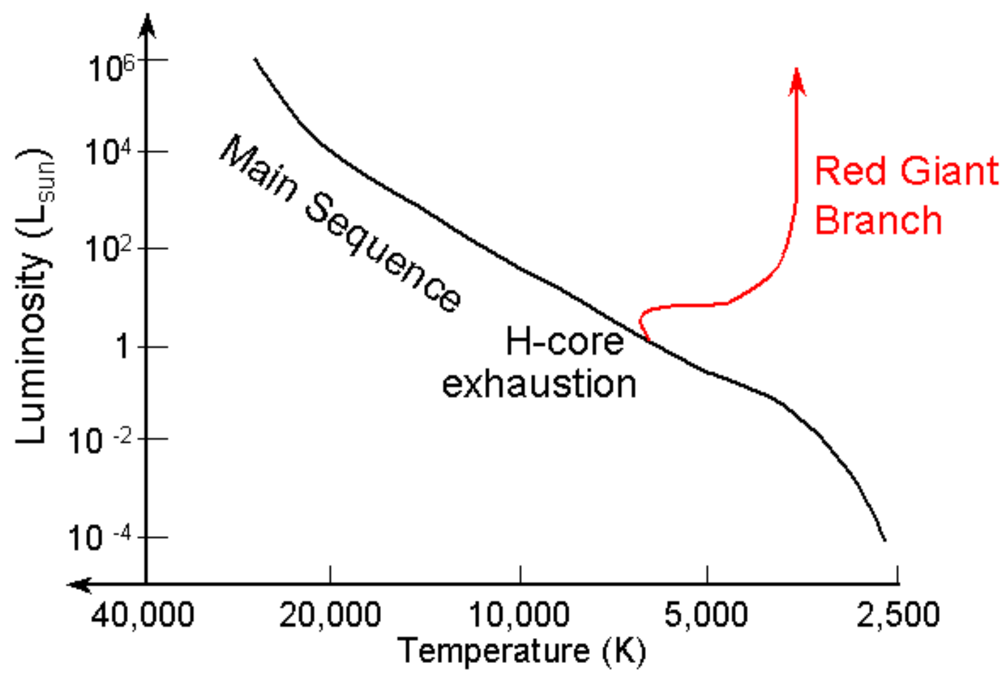
- Clouds are inhomogeneous - clumpy.

- Clumps start to collapse, densest clumps collapses first and fastest => fragmentation.

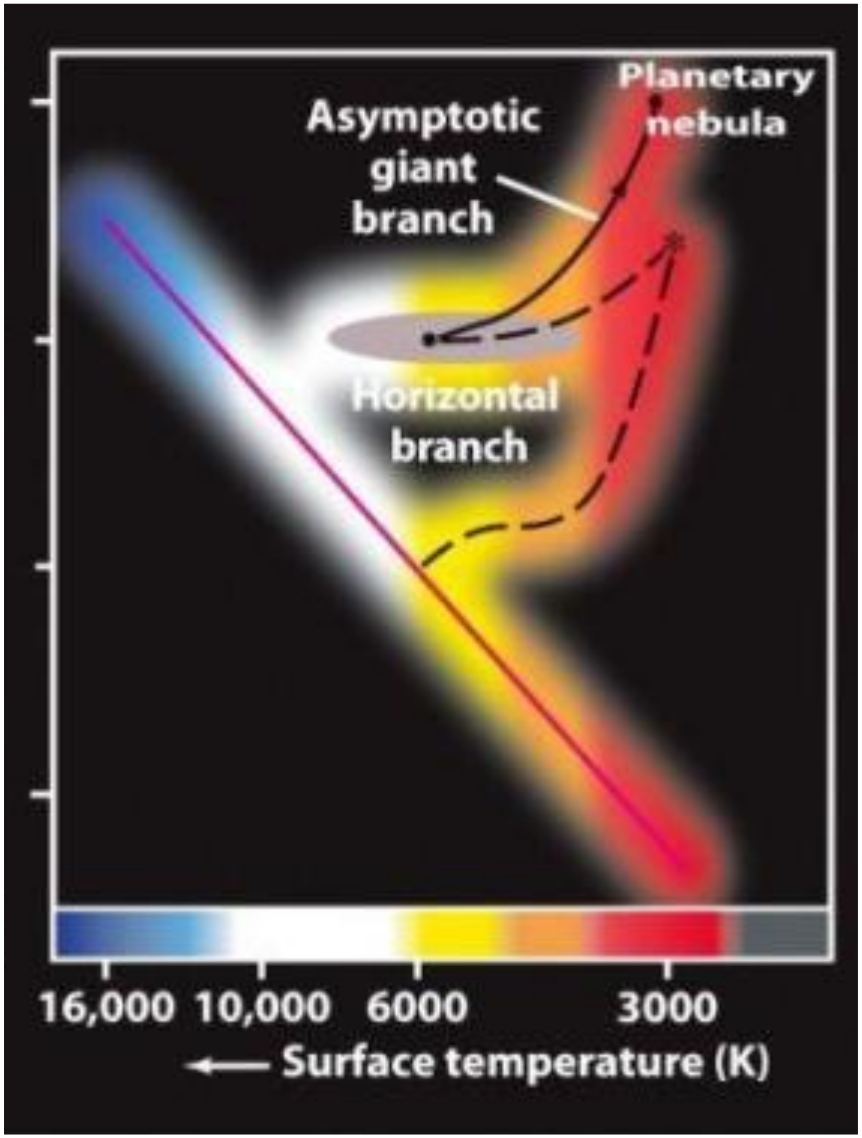
- 100s to 1000s of fragments may exist in one collapsing molecular cloud.

post-main sequence evolution

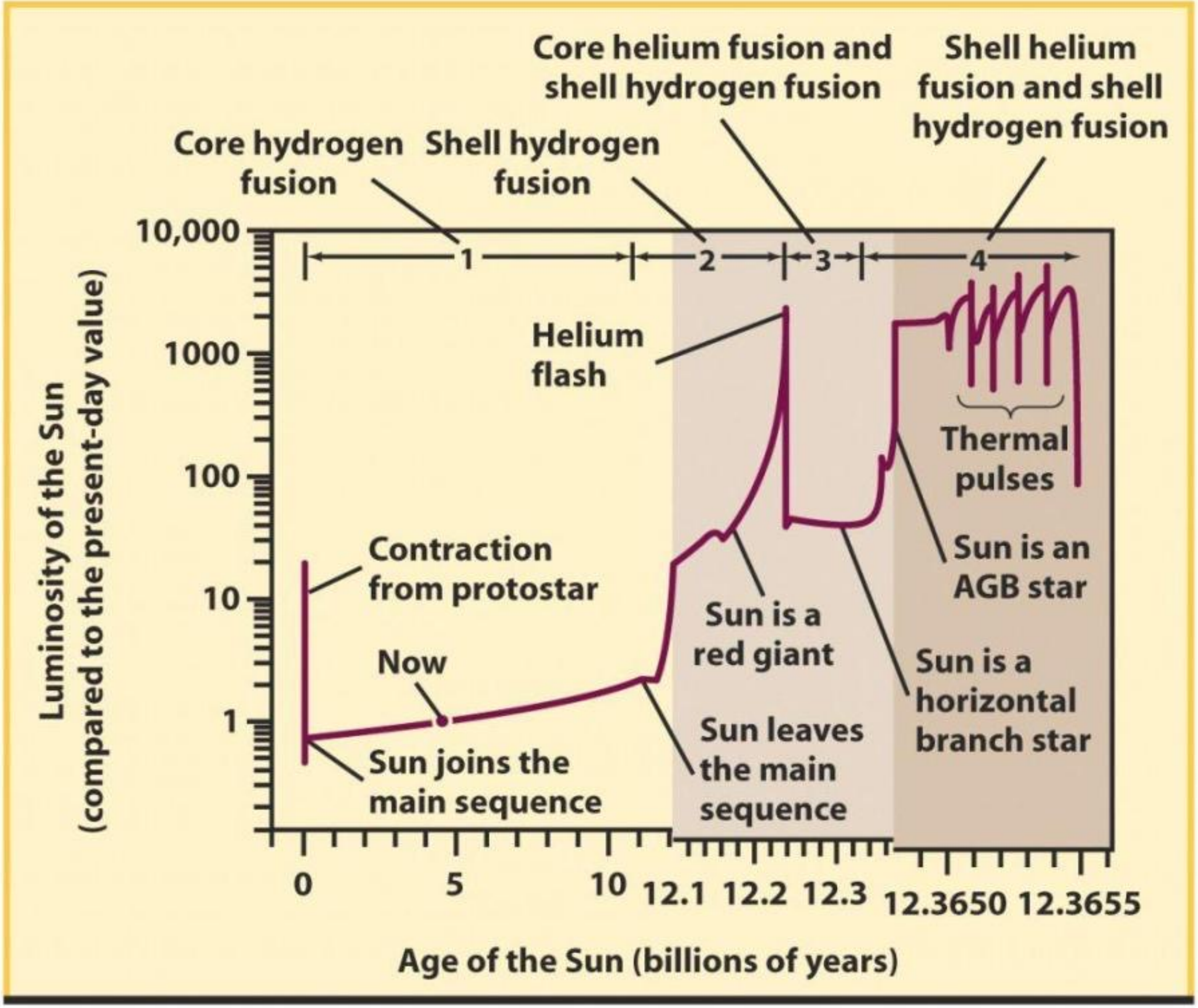
- Core hydrogen exhaustion => inert He core, contracting and heating.
- Pushes outer layers outwards => expansion, and cooling (to the right in H-R diagram)
- Shell H fusion starts => luminosity increase (upwards in H-R diagram)
- Helium fusion starts (the triple alpha process, producing C and O) => the core expands and cools



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.


Core hydrogen fusion
Shell hydrogen fusion
Core helium fusion and shell hydrogen fusion
Shell helium fusion and shell hydrogen fusion
1
2
3
4
10,000
1000
100
10
1
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 an AGB star
Sun is a horizontal branch star
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)

Why do planetary nebulae shine so brightly?

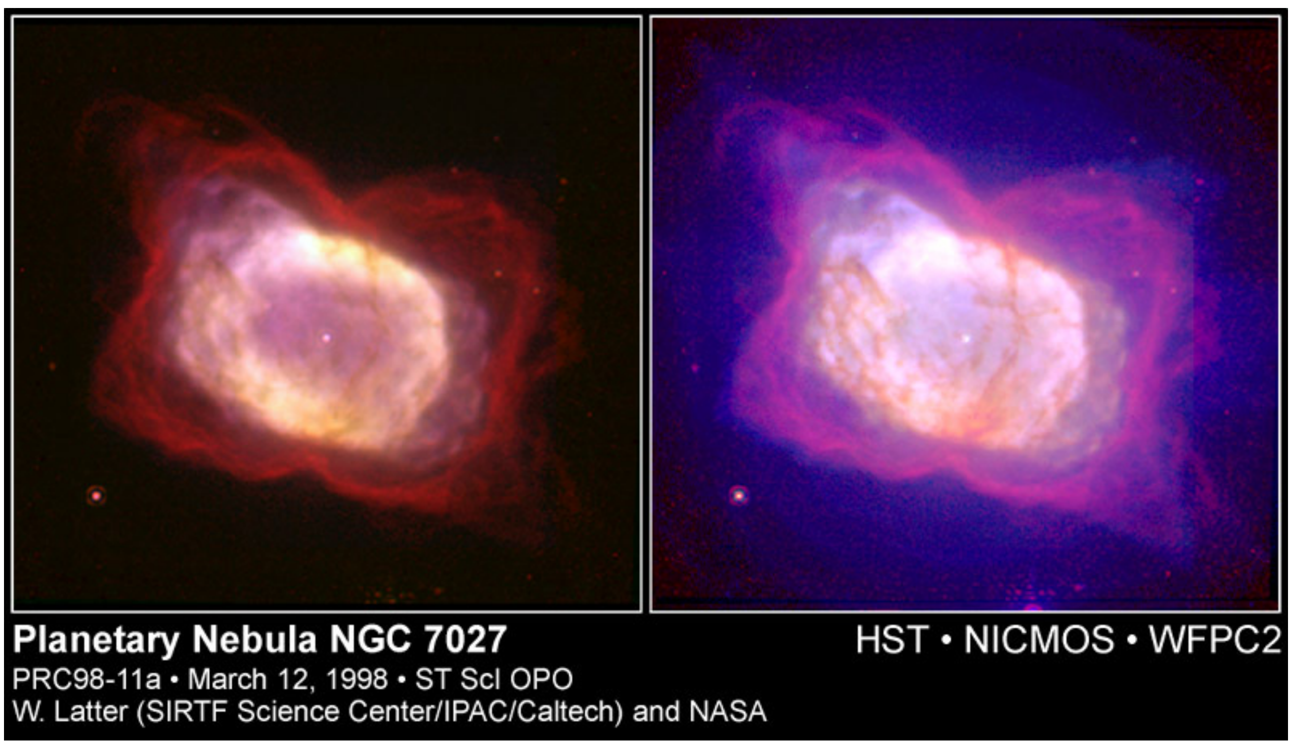
- Dying star ejects outer layers and exposes the hot core.
- The hot core emits UV radiation => excites and ionizes the surrounding low density gas

…what kind of spectrum would a planetary nebula show?

The Spirograph Nebula

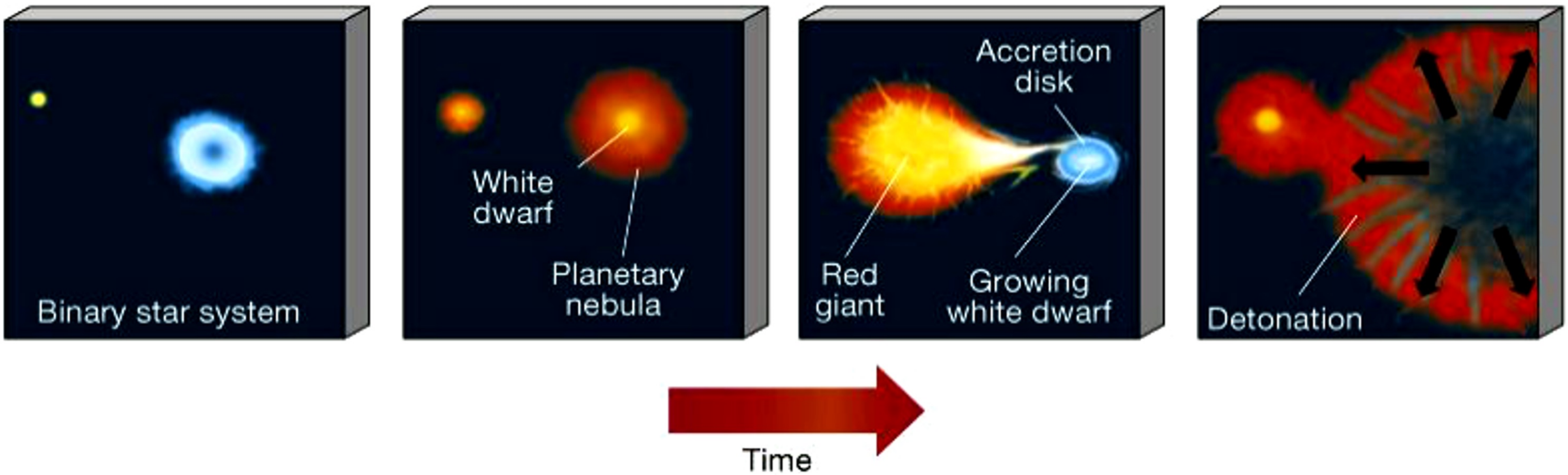
What happens to the core?

- 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.



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)

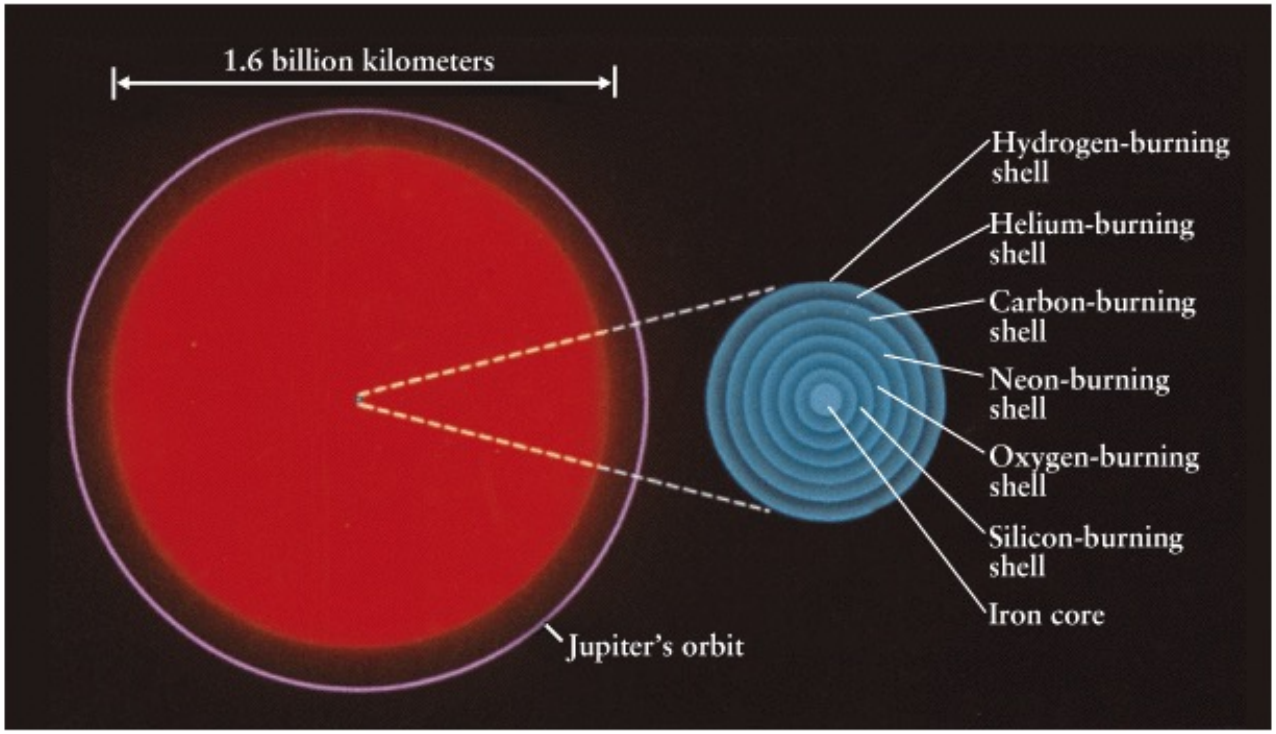
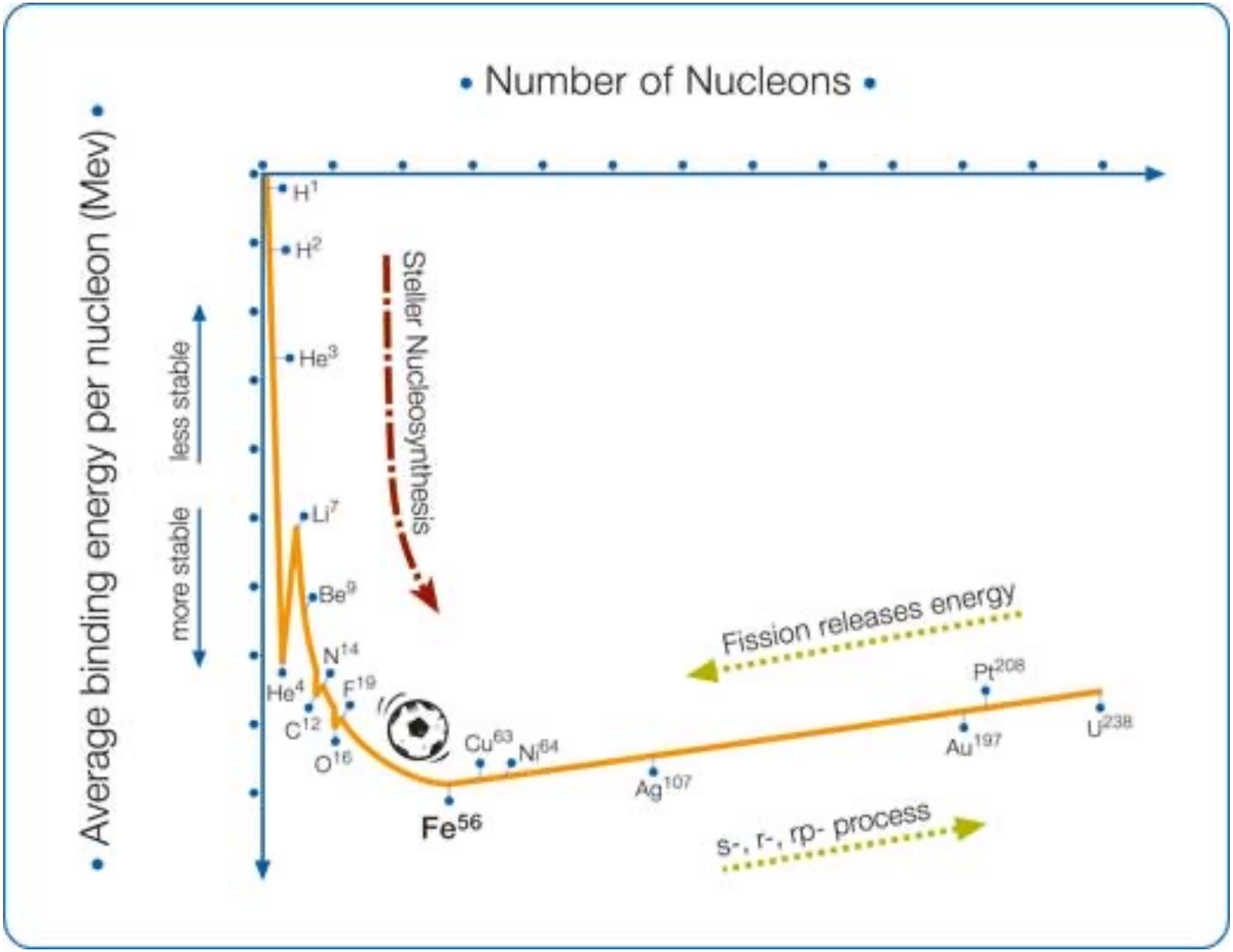


table 22-1 Evolutionary Stages of a 25-$M_\odot$ Star

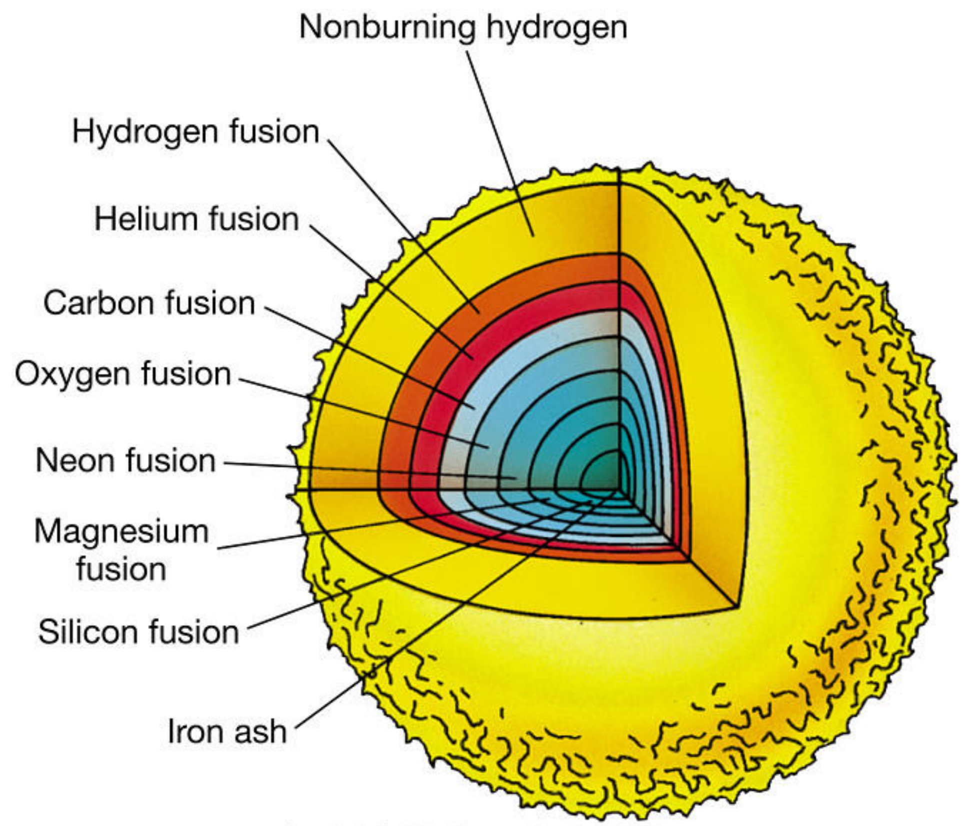
Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

Binding Energy per nucleon



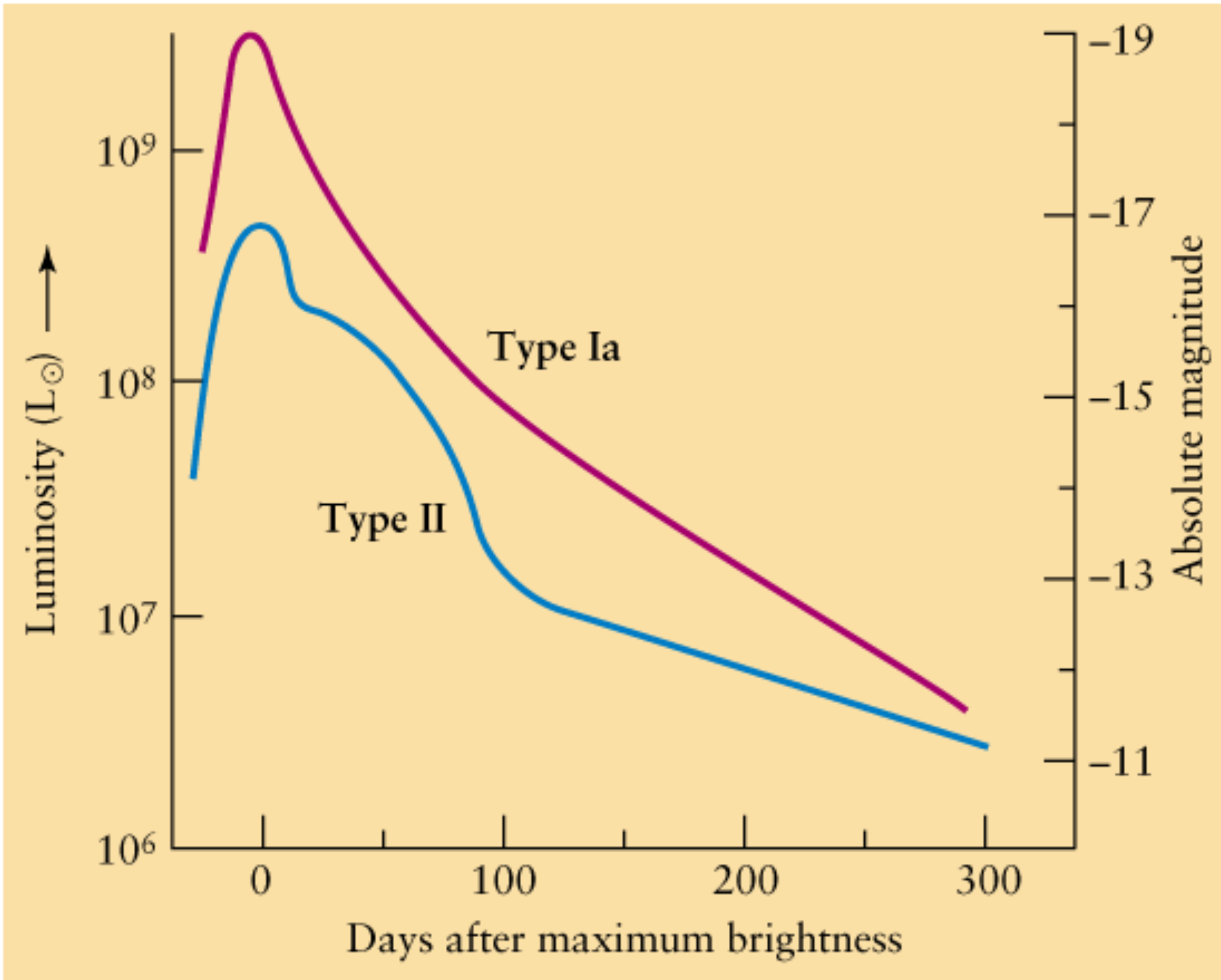
At the end of the road

- End of Si burning day: inert Fe core, and an onion skin of nested nuclear burning shells.
- 1.2-1.4 $M_{\odot}$ Fe core contracts, heats up: a catastrophic collapse is unavoidable.

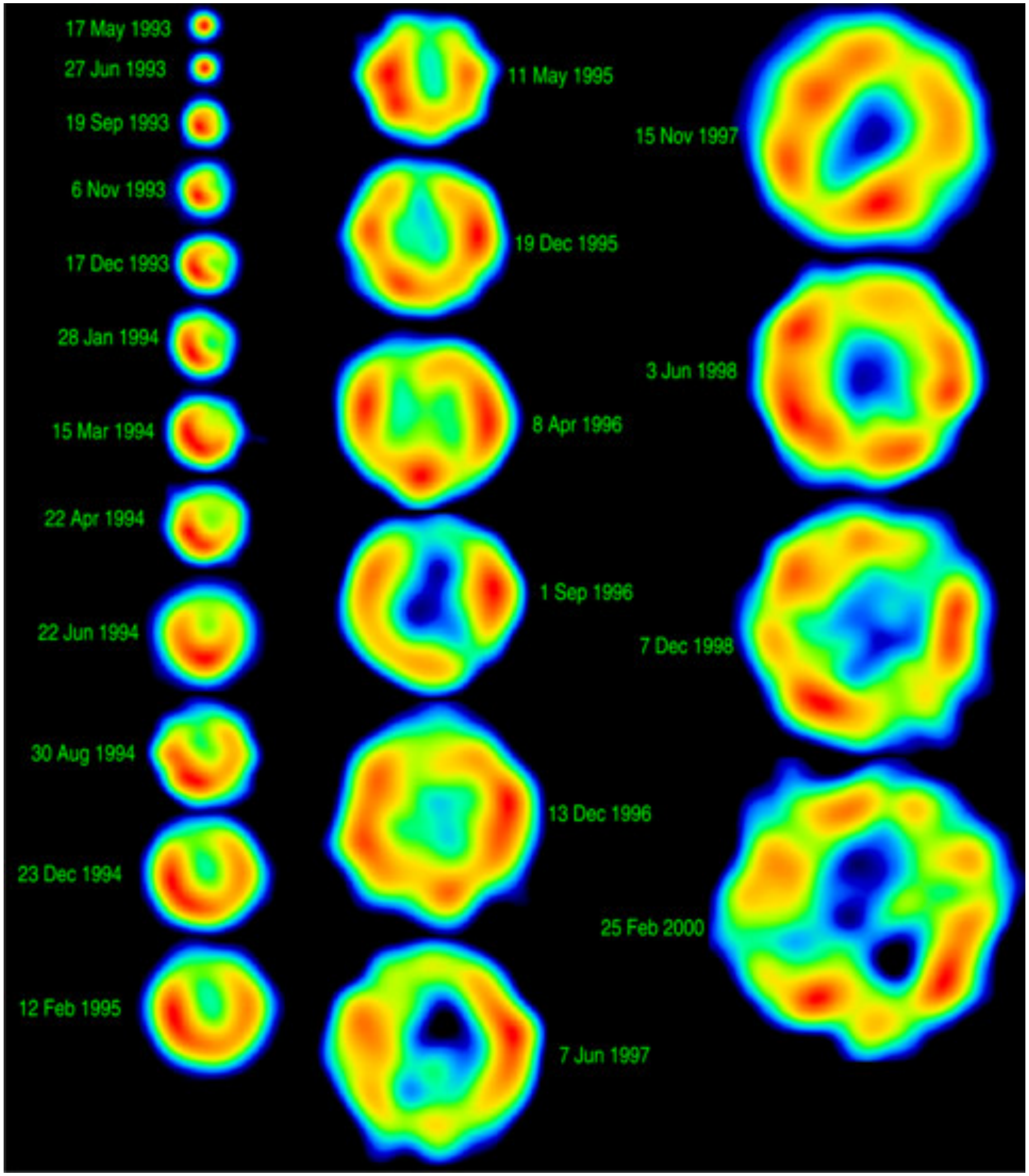


The energy producing region ~ size of Earth (or 10^{-6} of the stellar radius).

Light curves for Type Ia and Type II supernovae



A Young Supernova



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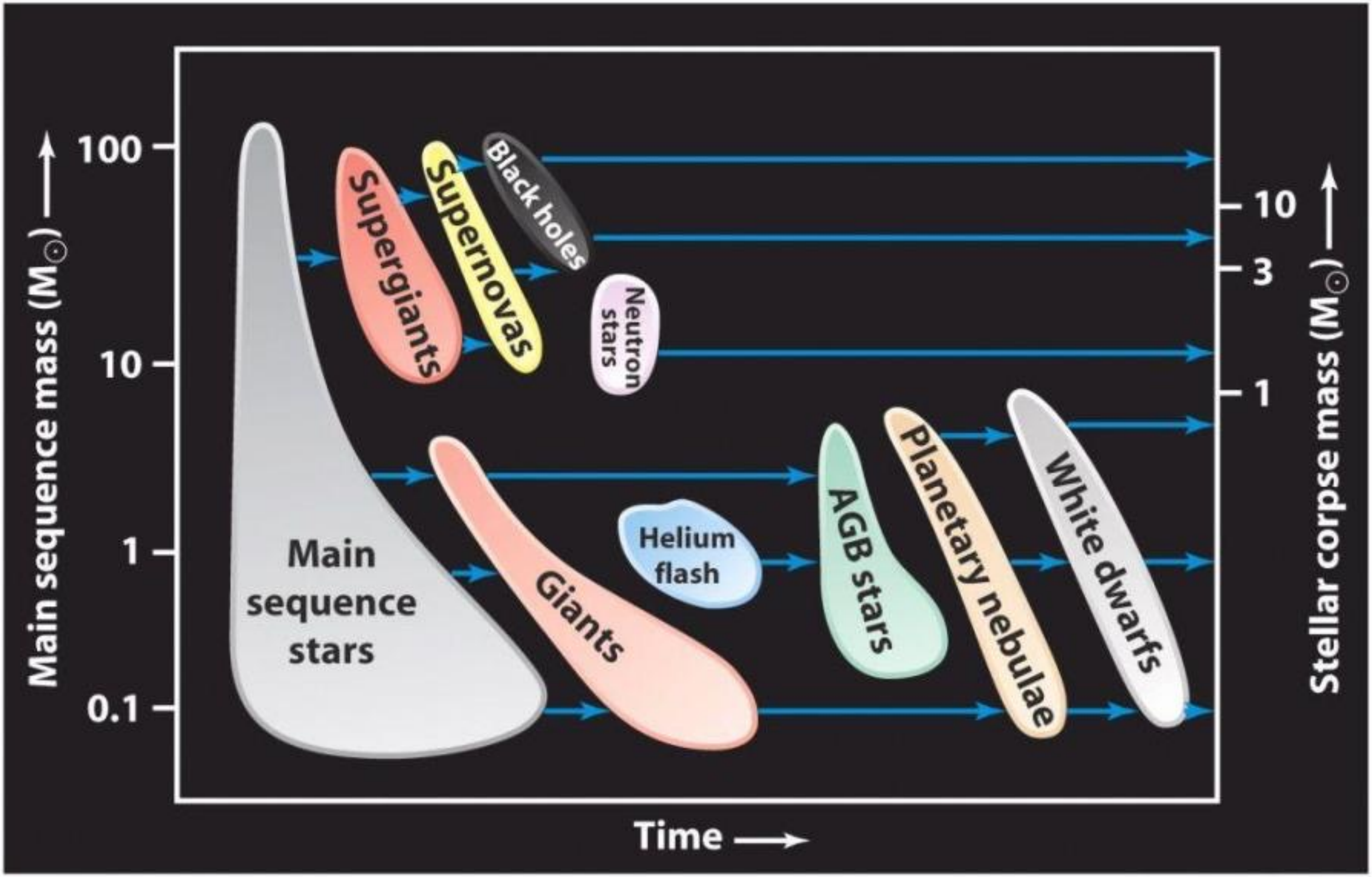
Rupen et al.

Summary of star deaths



Final States of a Star

1. White Dwarf
   If initial star mass $< 8\ M_{Sun}$ or so

   No Event + PN

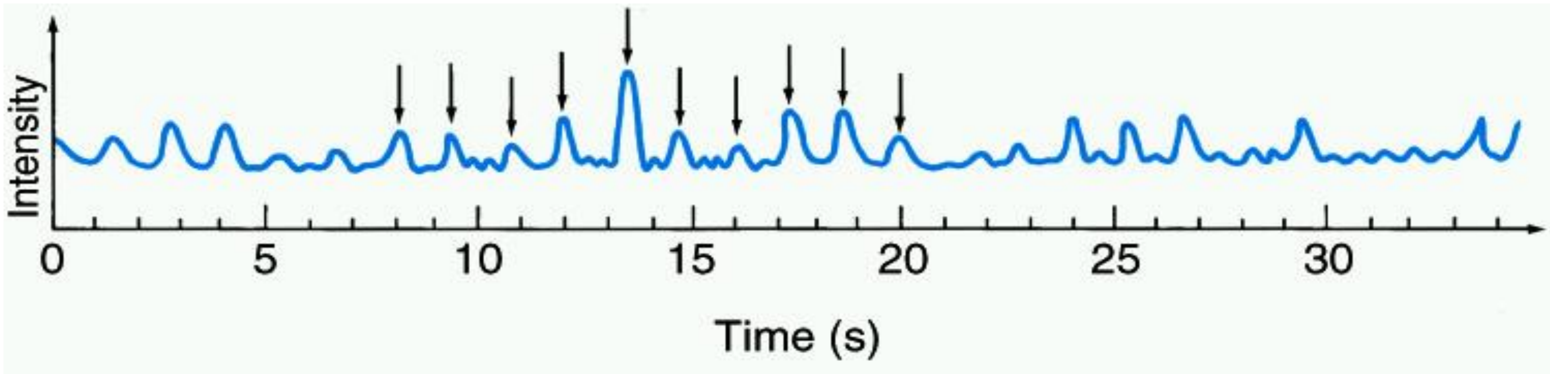
2. Neutron Star
   If initial mass $> 8\ M_{Sun}$ and $< 25\ M_{Sun}$

   Supernova + ejecta

3. Black Hole
   If initial mass $> 25\ M_{Sun}$

   GRB + Hypernova + ejecta

Pulsars



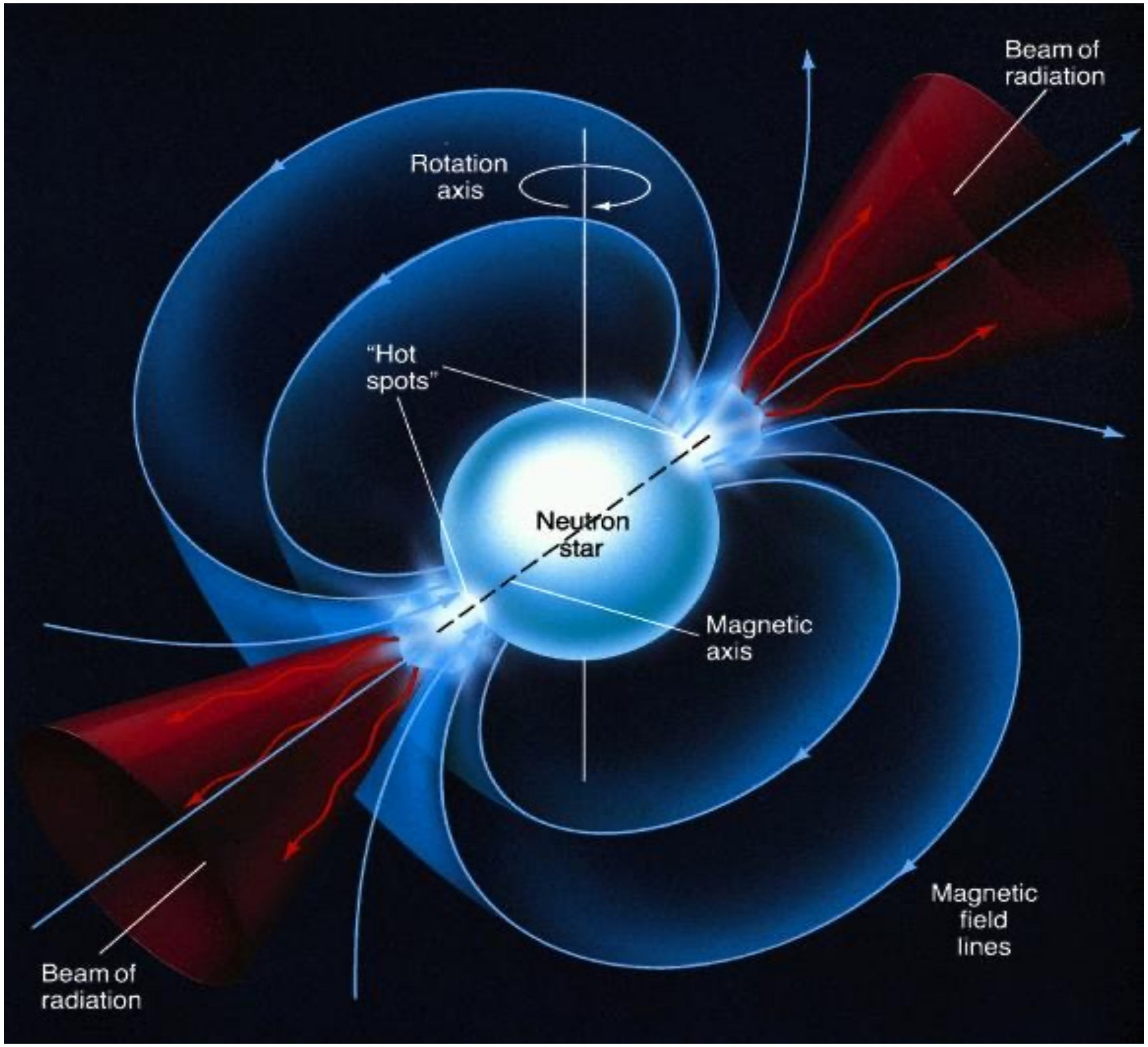
Discovery of LGM1 by Jocelyn Bell and Tony Hewish (Cambridge) in 1967. Nobel Prize to Hewish in 1974.

Pulse periods observed from 0.001 sec to 10 seconds - DEMO

Explanation: "beamed" radiation from rapidly spinning neutron star.

Usually neutron stars are pulsars for 10^7 years after supernova.

The Lighthouse model of a pulsar



Neutron Stars

Leftover core from Type II supernova - a tightly packed ball of neutrons.

Diameter: 20 km only!

Mass: 1.4 - 3(?) M_{Sun}

Density: 10^{14} g / cm^3 !

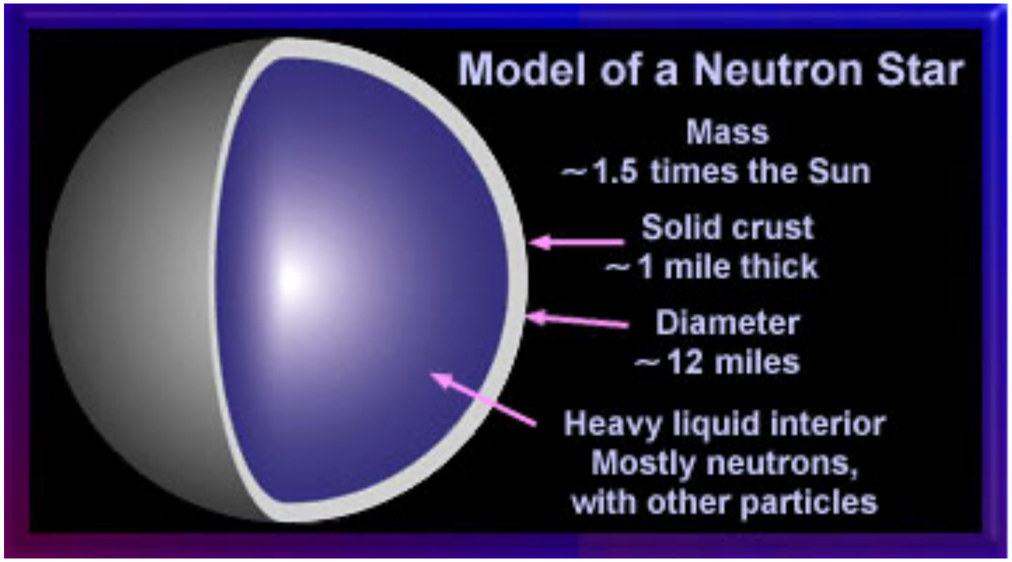
1 teaspoon = 1000 great pyramids

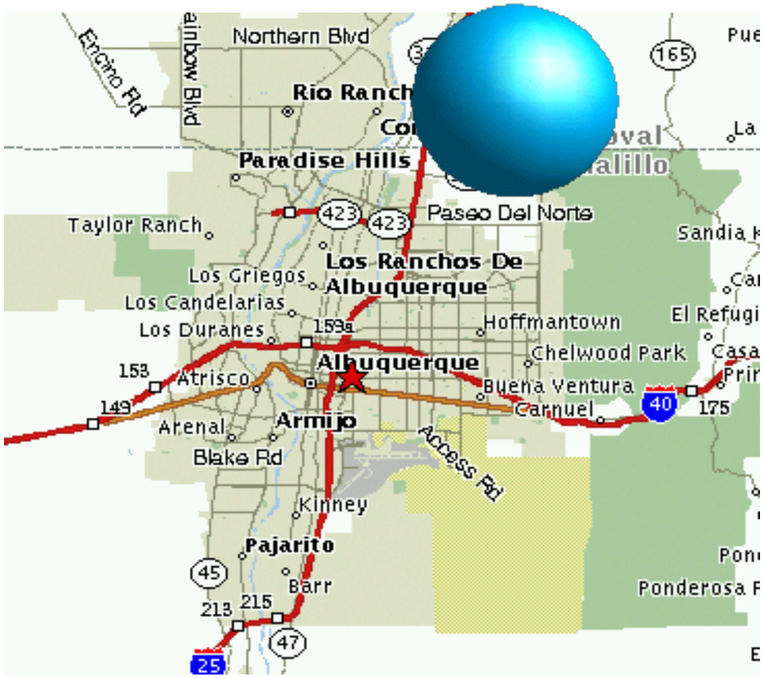
Surface gravity: 10^{12} higher

Escape velocity: 0.5c

Rotation rate: few to many times per second!

Magnetic field: 10^{12} x Earth's





A neutron star over the Sandias?

Pulsars are incredibly accurate clocks!

Example: period of the first discovered "millisecond pulsar" is:

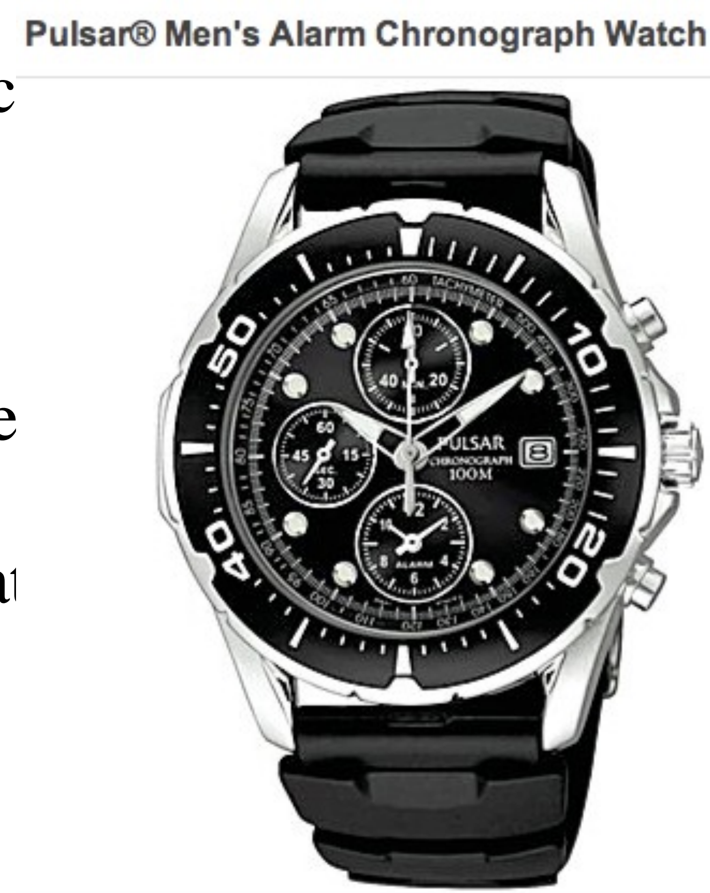
$$P = 0.00155780644887275 \text{ sec}$$

It is slowing down at a rate of

$$dP/dt = 1.051054 \times 10^{-19} \text{ se}$$

The slowing-down rate is slowing down at rate of:

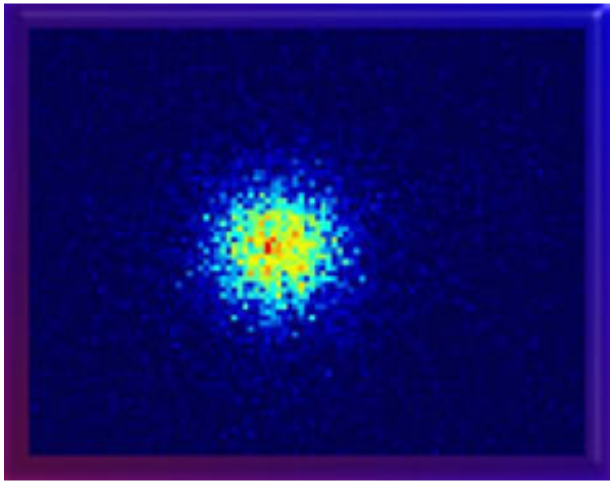
$$d(P)/dt^2 = 0.98 \times 10^{-31} \text{ /sec}$$



Soft Gamma-Ray Repeaters

"E_{iso} ~ a few10^{44} erg in gamma-rays

Where does this energy come from?



X-ray image

- Accretion? No sign of a disk
- Rotation? Not enough energy available
- Magnetic fields?   Yes