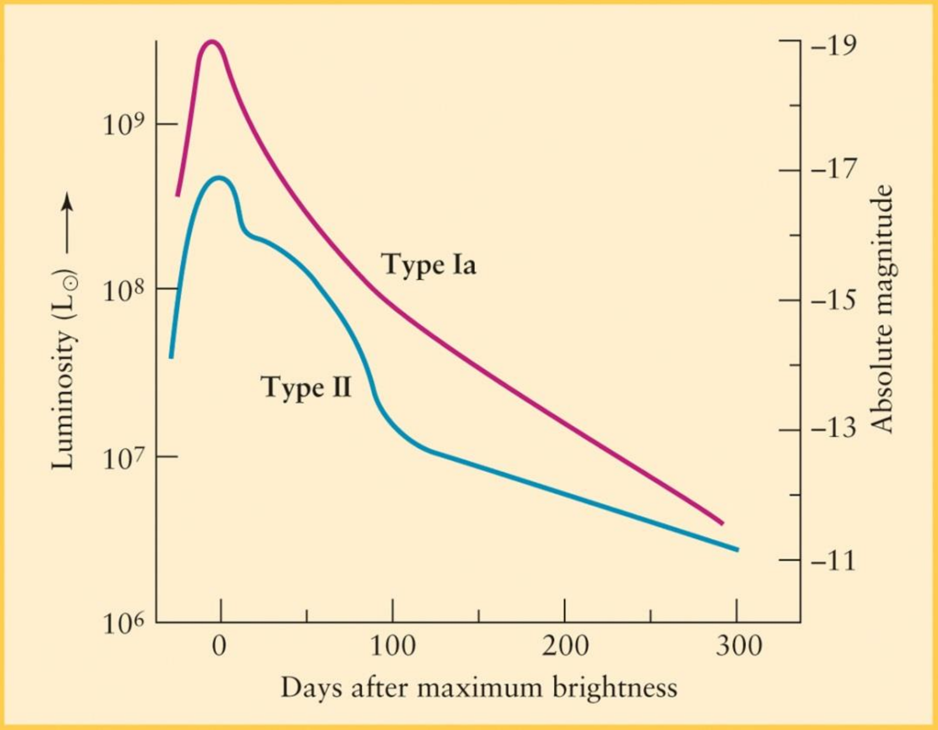
Dead & Variable Stars

Supernovae – Death of massive Stars

- As the core collapses, it overshoots and "bounces"
- A shock wave travels through the star and blows off the outer layers, including the heavy elements – a supernova
- A million times brighter than a nova!!
- The actual explosion takes less than a second

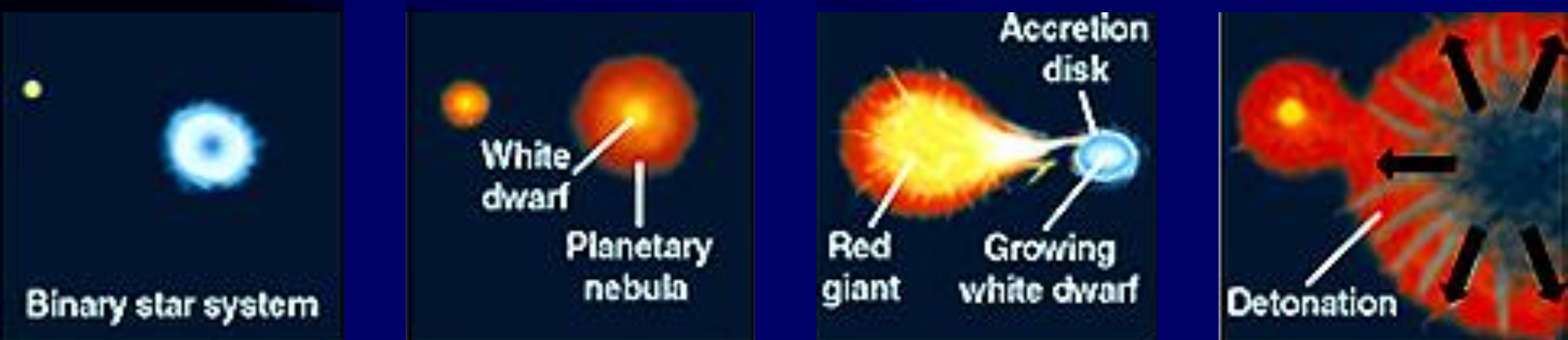
Type I vs Type II Supernovae

- Different light curves (patterns of Nature)
- Different processes produce these patterns
  - Type Ia: White dwarf "overeats"
  - Type II: massive star's core collapses because fusion of iron sucks up energy



SN Type Ia – "Assisted Suicide"

- Implosion of a white dwarf after it accretes a certain amount of matter, reaching about 1.4 solar masses → can only happen in binaries
- Very predictable; used as a standard candle
  - Estimate distance to host galaxy



Extra mass comes from companion star

- Reason for instability: failure of quantum pressure of electrons (gravity wins!)
  - Was worked out by Chandrasekhar (age 19) on the boat from India to Britain 1930
  - Implies Black Holes

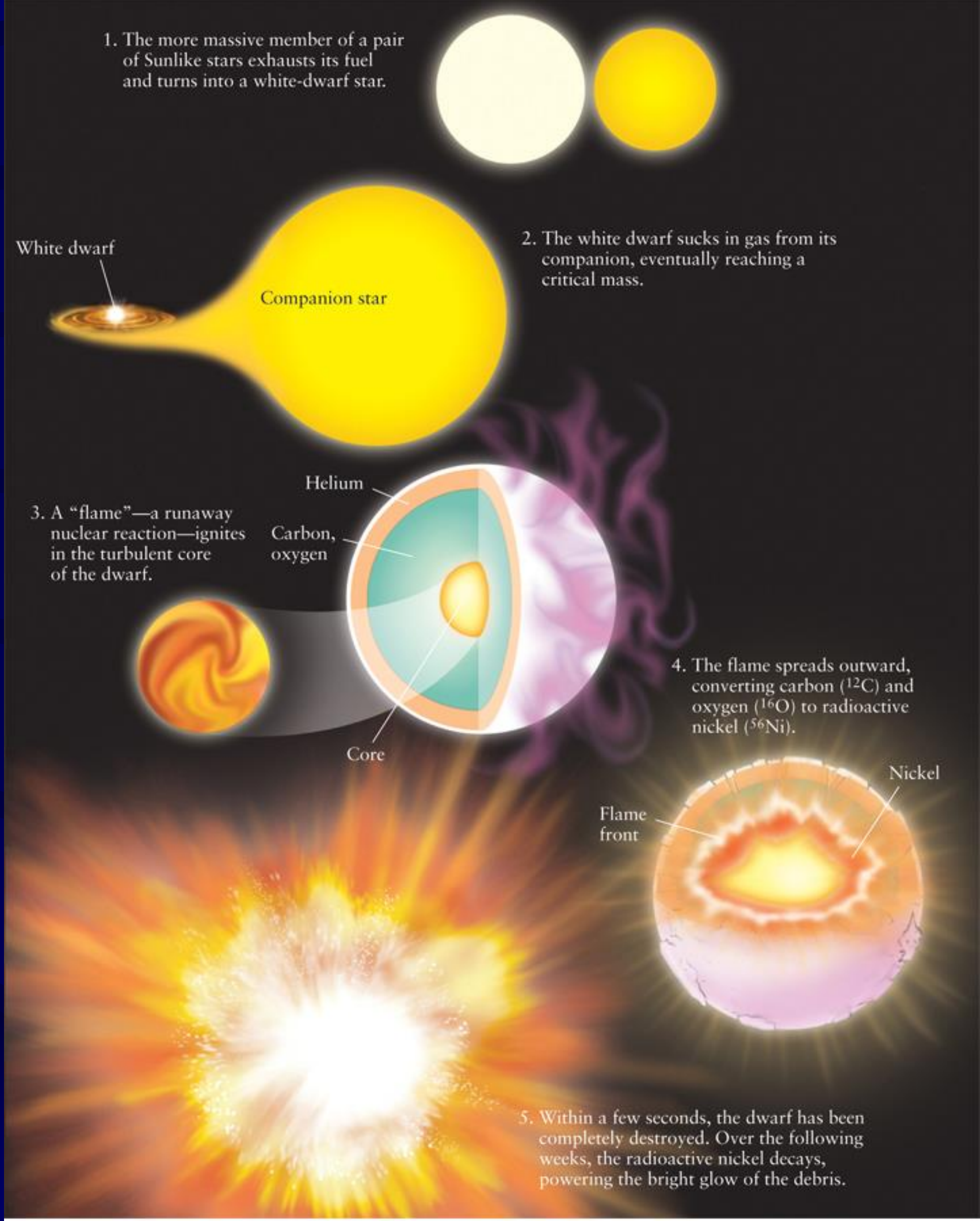
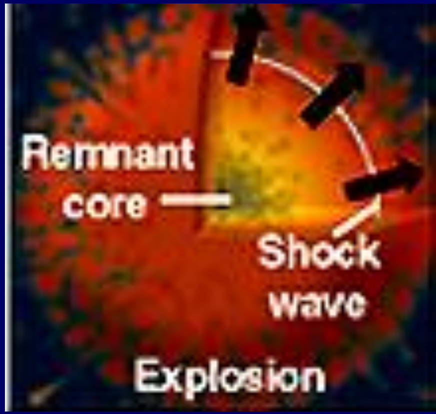


Illustration by Don Dixon, adapted from Wolfgang Hillebrandt, Hans-Thomas Janka, and Ewald Müller, "How to Blow Up a Star," Scientific American, October 2006

Type II – “Normal Supernova”

- Implosion of a massive star, as we already saw
- Expect one in our galaxy about every hundred years
- Six in the last thousand years; none since 1604



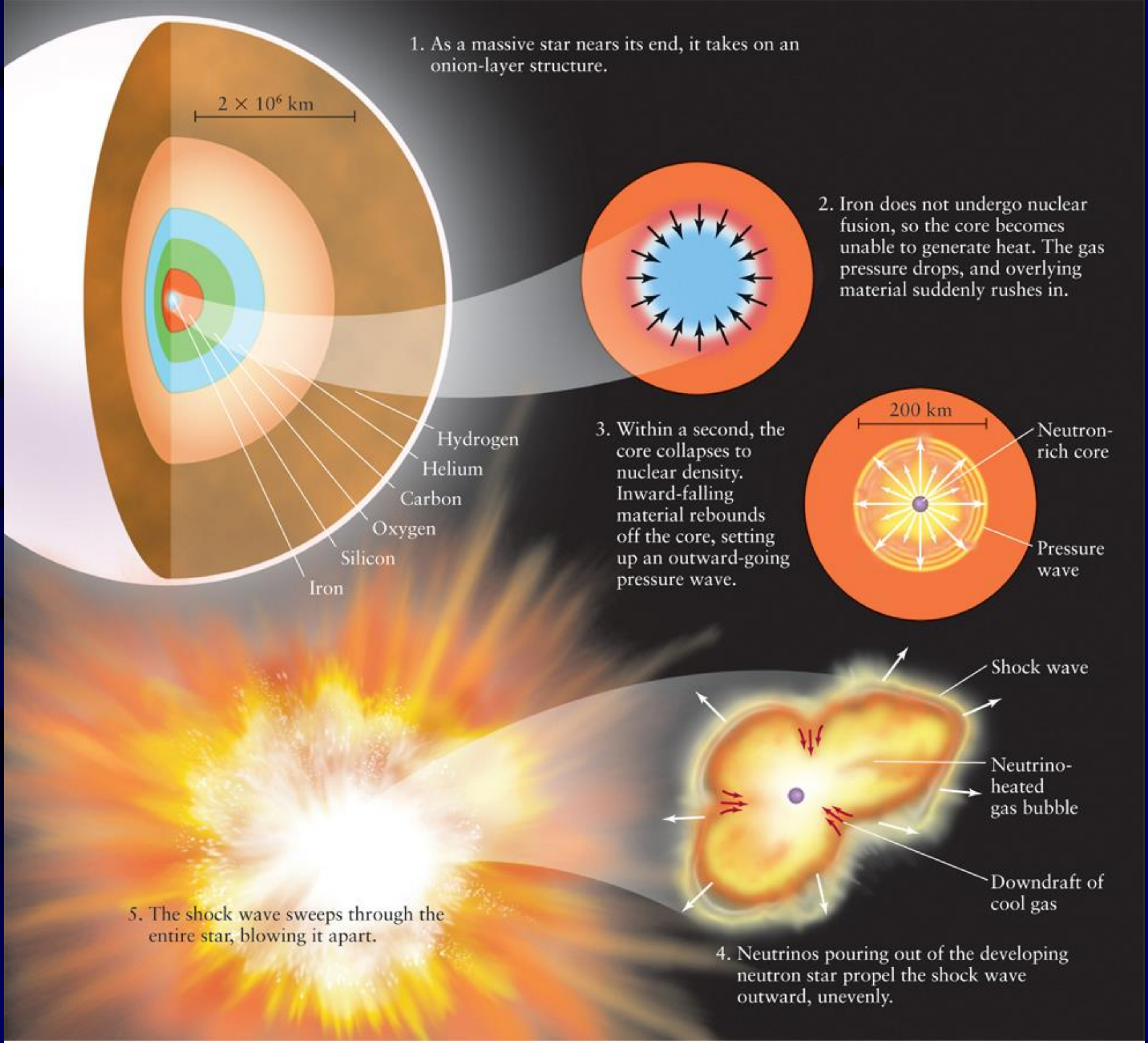
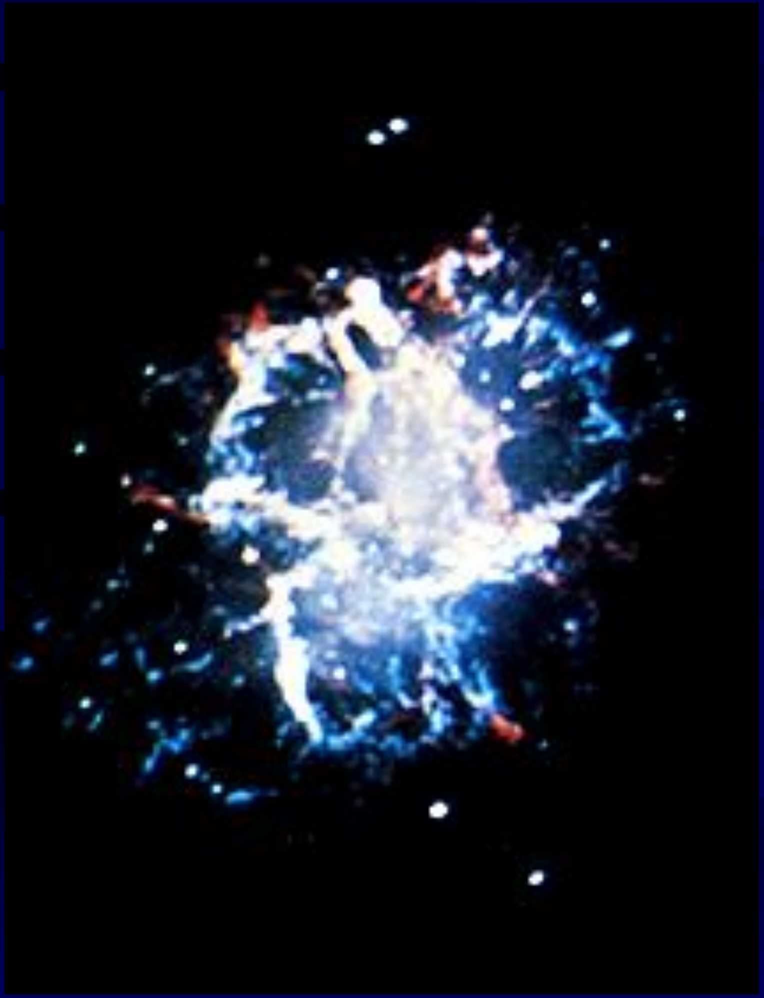


Illustration by Don Dixon, adapted from Wolfgang Hillebrandt, Hans-Thomas Janka, and Ewald Müller, "How to Blow Up a Star," *Scientific American*, October 2006

Supernova Remnants



Crab Nebula

From Vela Supernova

Formation of the Elements in SN

- Light elements (hydrogen, helium) formed in Big Bang
- Heavier elements formed by nuclear fusion in stars and thrown into space by supernovae
  - Condense into new stars and planets
  - Elements heavier than iron form during supernovae explosions
- **Evidence:**
  - Theory predicts the observed elemental abundance in the universe very well
  - Spectra of supernovae show the presence of unstable isotopes like Nickel-56
  - Older globular clusters are deficient in heavy elements

What's Left?

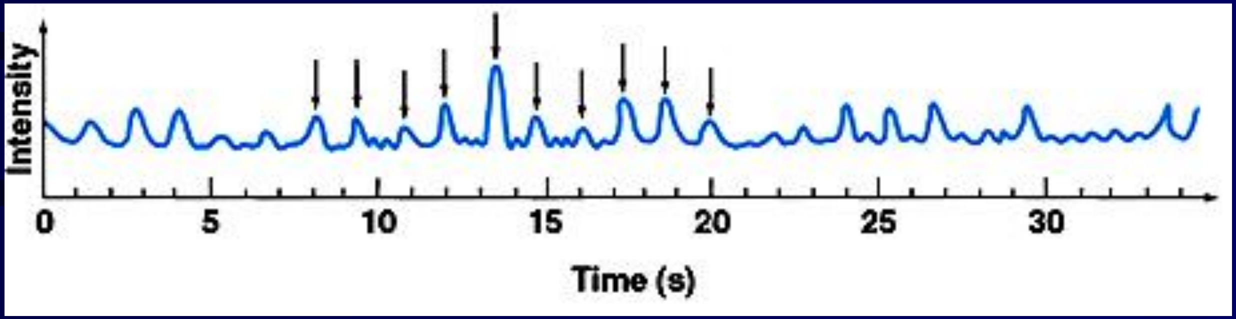
- Type Ia supernova
  - Nothing left behind
- Type II supernova
  - While the parent star is destroyed, a tiny ultra-compressed remnant may remain – a neutron star
  - This happens if the mass of the parent star was above the Chandrasekhar limit

More Massive Stars end up as **Neutron Stars**

- The core cools and shrinks
- Nuclei and electrons are crushed together
- Protons combine with electrons to form neutrons
- Ultimately the collapse is halted by neutron pressure, the core is composed of neutrons
- Size ~ few km
- Density ~ 10^{18} kg/m^3; 1 cubic cm has a mass of 100 million kg!

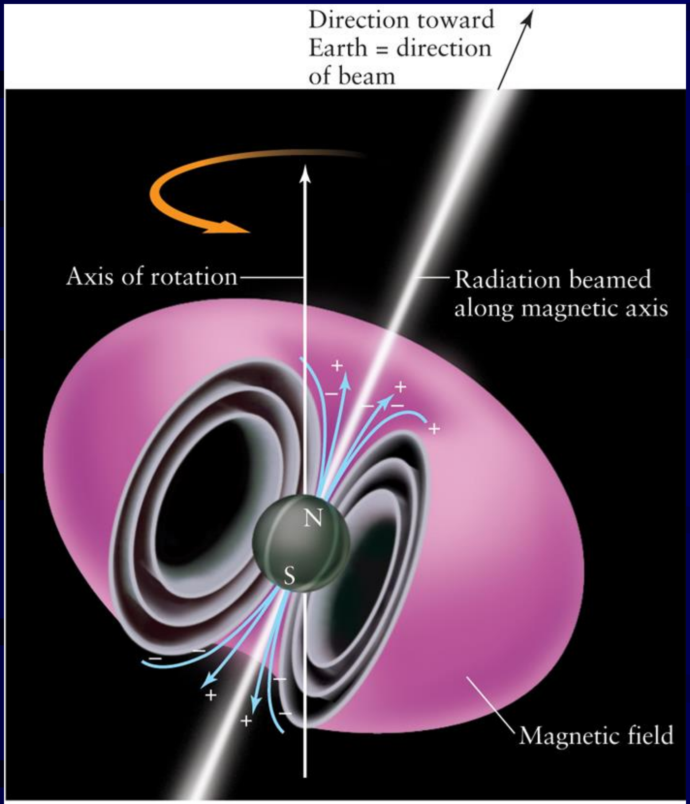
Manhattan

How do we know Neutron Stars exist? →Pulsars



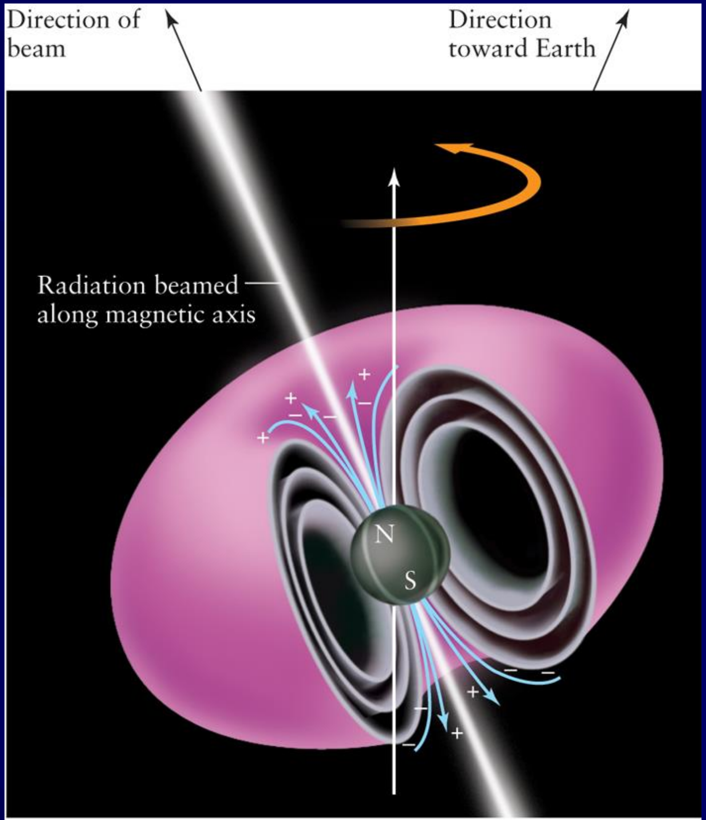
- First discovered by Jocelyn Bell (1967)
  - Little Green Men?!? Nope…
- Rapid pulses of radiation
- Periods: fraction of a second to several seconds
- Small, rapidly rotating objects
- Can't be white dwarfs; must be neutron stars

The “Lighthouse Effect”



(a) One of the beams from the rotating neutron star is aimed toward Earth: We detect a pulse of radiation.

- Pulsars rotate very rapidly
- Extremely strong magnetic fields guide the radiation
- Results in “beams” of radiation, like in lighthouse



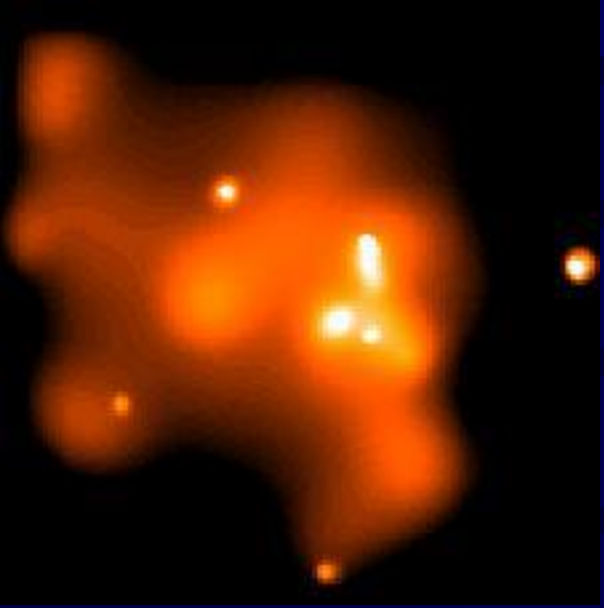
(b) Half a rotation later, neither beam is aimed toward Earth: We detect that the radiation is “off.”

Super-Massive Stars end up as **Black Holes**

- If the mass of the star is sufficiently large ($M > 25\ M_{Sun}$), even the neutron pressure cannot halt the collapse – in fact, no known force can stop it!
- The star collapses to a very small size, with ultra-high density
- Nearby gravity becomes so strong that nothing – not even light – can escape!
- The edge of the region from which nothing can escape is called the event horizon
  - Radius of the event horizon called the Schwarzschild Radius

Table 12-1 Evolutionary Stages of a 25-$M_{\odot}$ Star

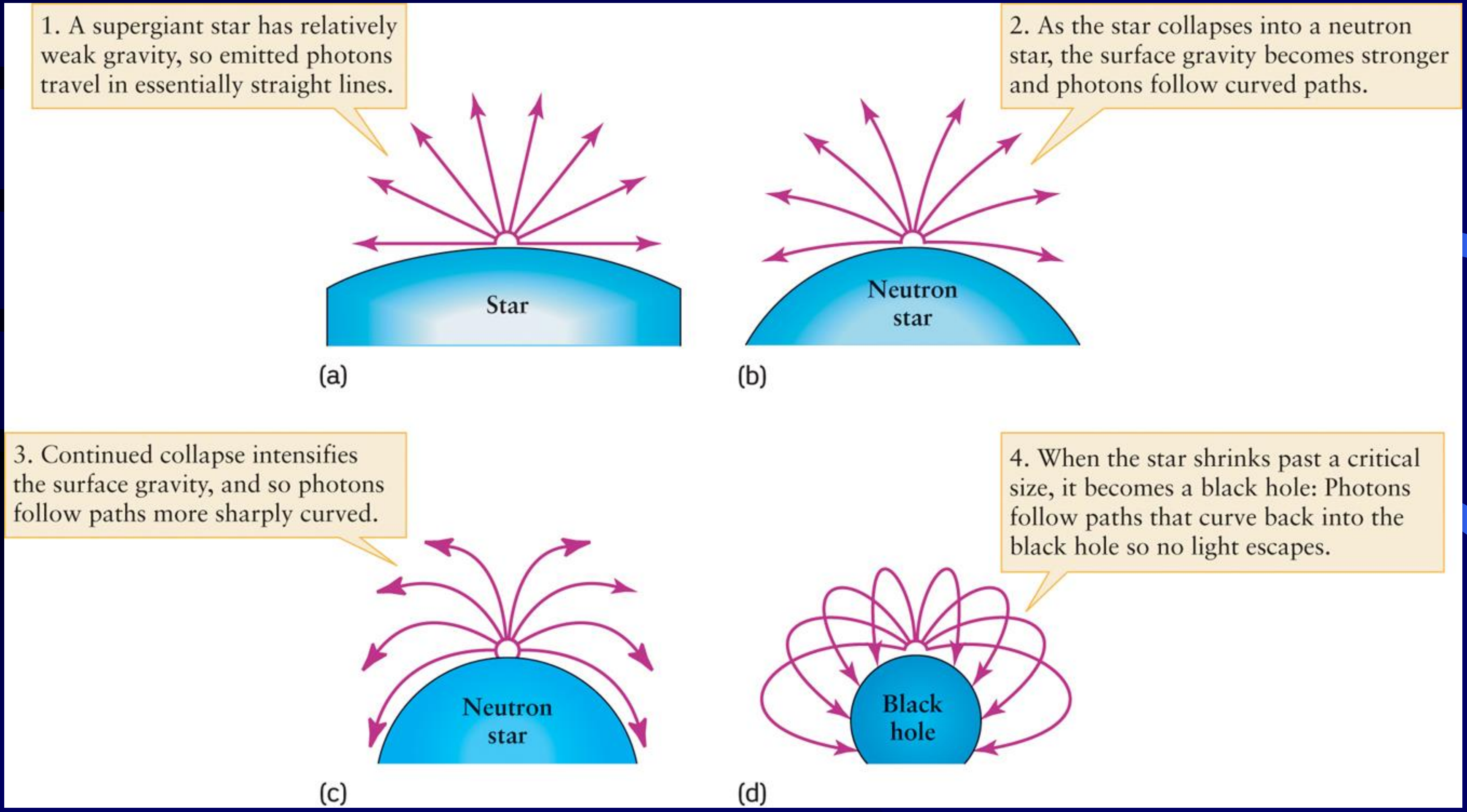
Stage	Core temperature	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{17}	milliseconds
Explosive supernova	about 10^9	varies	10 seconds



Evidence for the existence of Black Holes

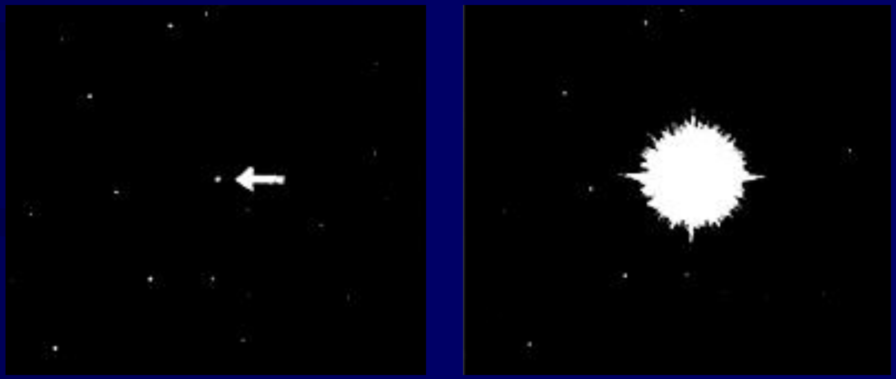
- Fast Rotation of the Galactic Center only explainable by Black Hole
- Other possible Black Hole Candidates:
  - Cygnus X-1 (X-ray source), LMC X-3
- Observational evidence very strong

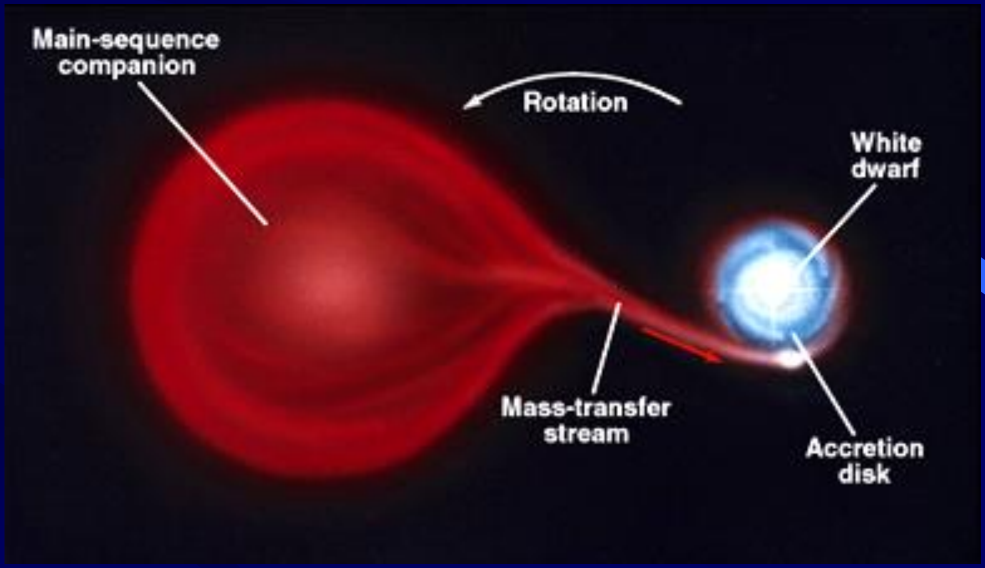
Surface Gravity is strongest if mass is concentrated in a small volume



Novae – “New Stars”

- Actually an old star – a white dwarf – that suddenly flares up
  - Accreted hydrogen begins fusing
- Usually lasts for a few months
- May repeat (“recurrent novae”)



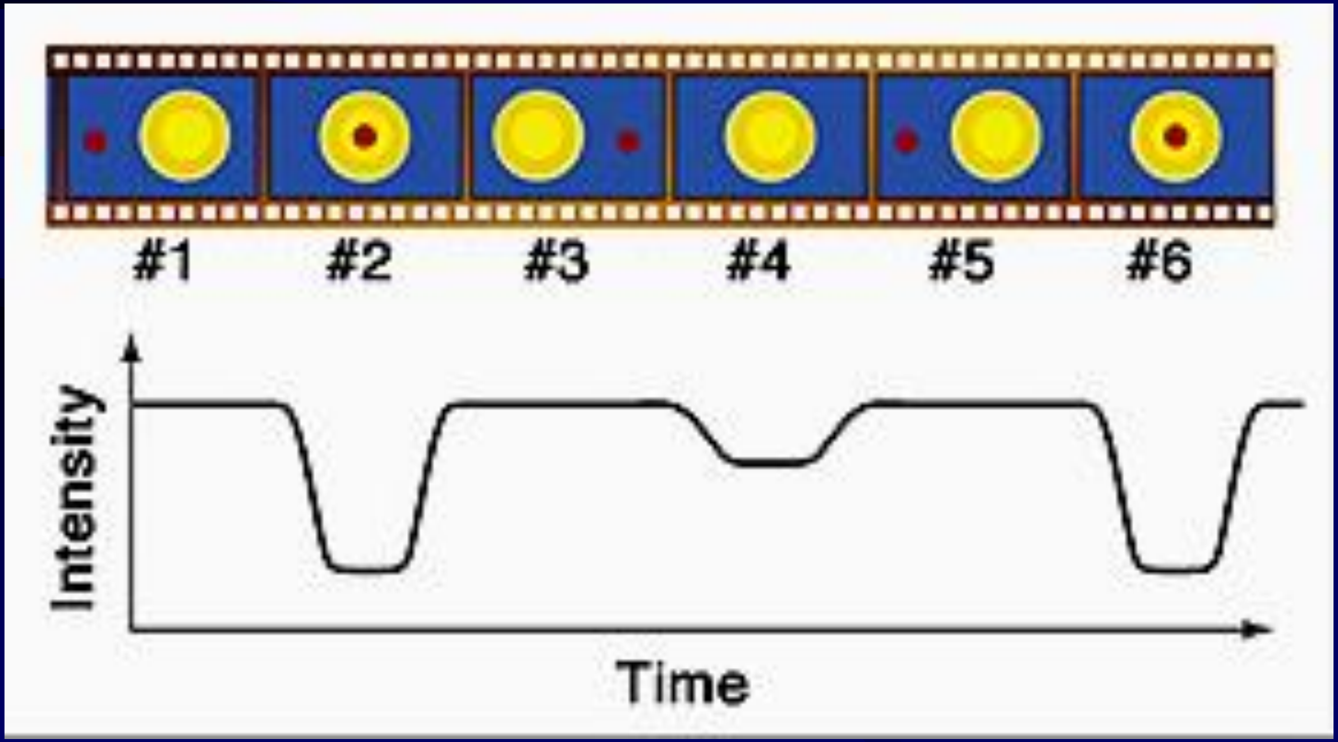


Variable Stars

- Eclipsing binaries (stars do not change physically, only their relative position changes)
- Nova (two stars "collaborating" to produce "star eruption")
- Cepheids (stars do change physically)
- RR Lyrae Stars (stars do change physically)
- Mira Stars (stars do change physically)

Eclipsing Binaries (Rare!)

- The orbital plane of the pair almost edge-on to our line of sight
- We observe periodic changes in the starlight as one member of the binary passes in front of the other

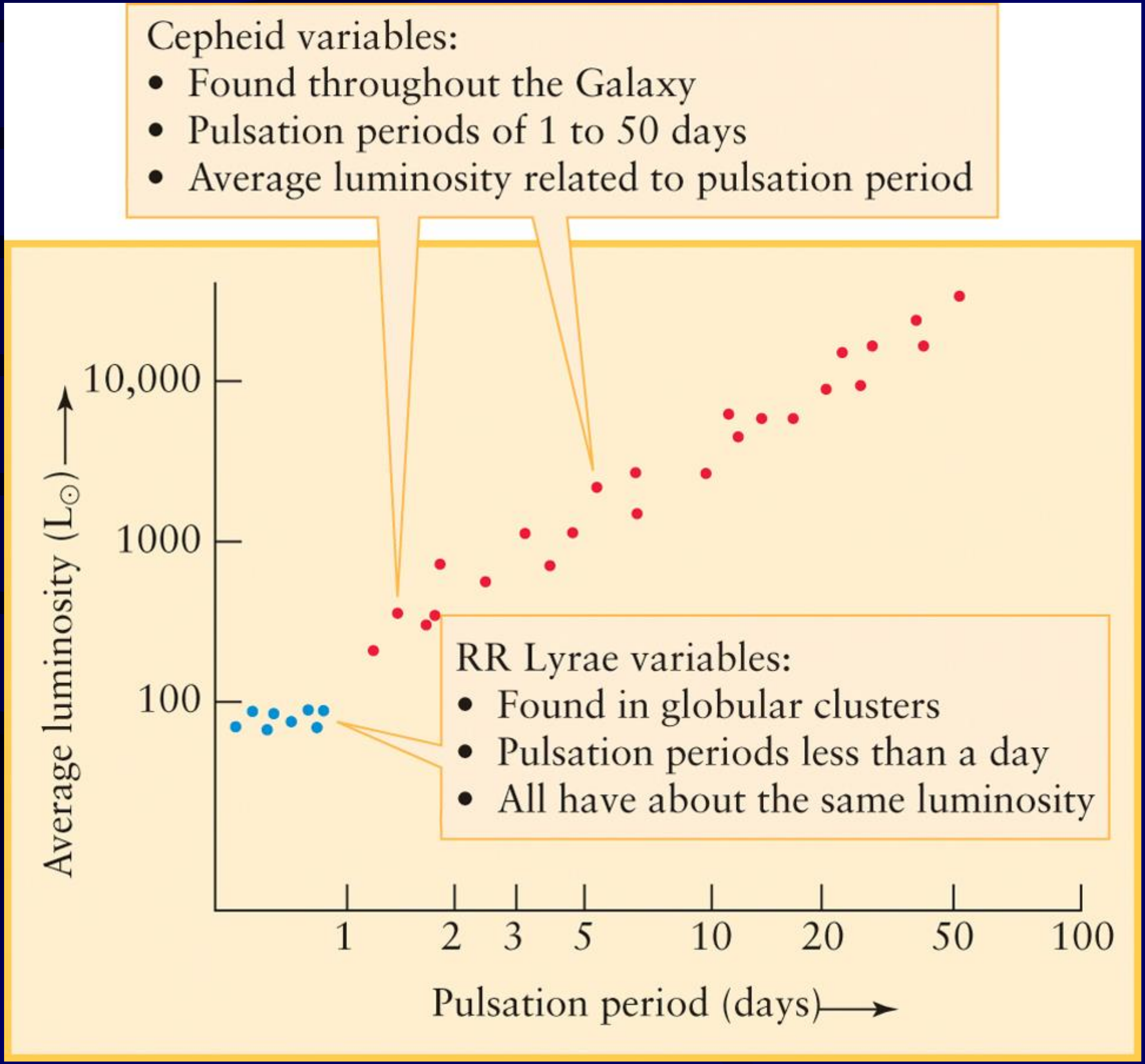


Cepheids

- Named after δ Cephei
- Period-Luminosity Relations
- Two types of Cepheids:
  – Type I: higher luminosity, metal-rich, Pop. 1
  – Type II: lower lum., metal-poor, Population 2
- Used as “standard candles”
- “yard-sticks” for distance measurement
- Cepheids in Andromeda Galaxies established the “extragalacticity” of this “nebula”

Cepheids

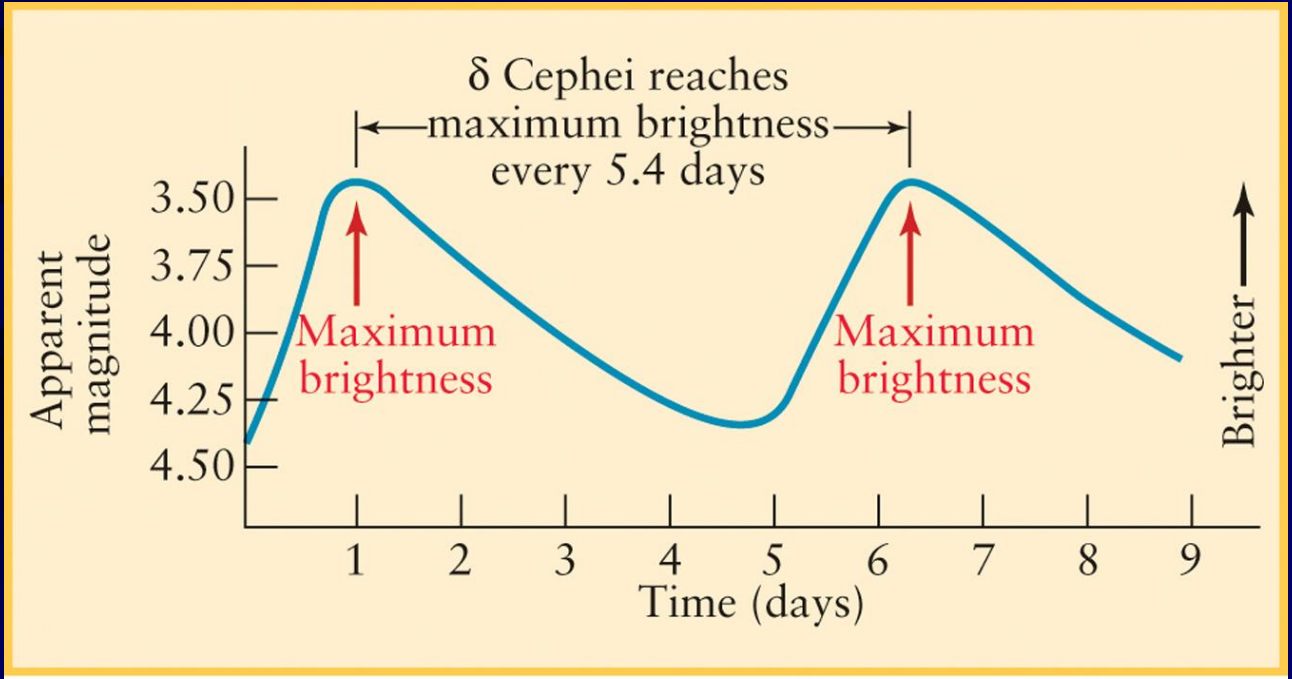
- Henrietta Leavitt (1908) discovers the period-luminosity relationship for Cepheid variables
- Period thus tells us luminosity, which then tells us the distance
- Since Cepheids are brighter than RR Lyrae, they can be used to measure out to further distances



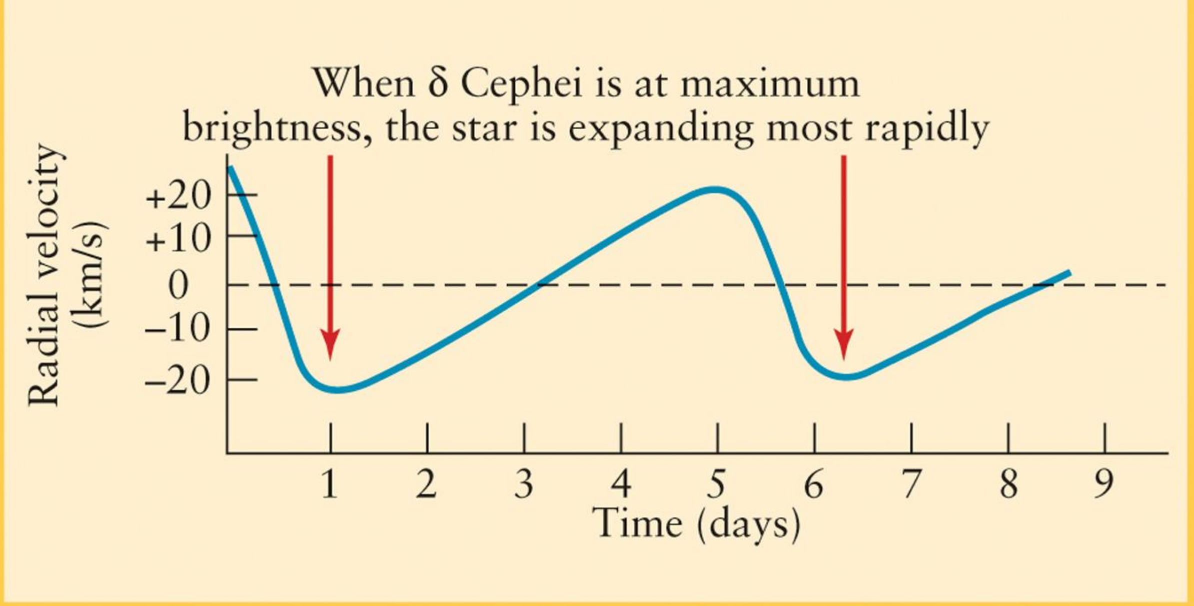
Cepheid variables:
• Found throughout the Galaxy
• Pulsation periods of 1 to 50 days
• Average luminosity related to pulsation period
10,000
1000
100
Average luminosity (L☉)
RR Lyrae variables:
• Found in globular clusters
• Pulsation periods less than a day
• All have about the same luminosity
1
2
3
5
10
20
50
100
Pulsation period (days)

Properties of Cepheids

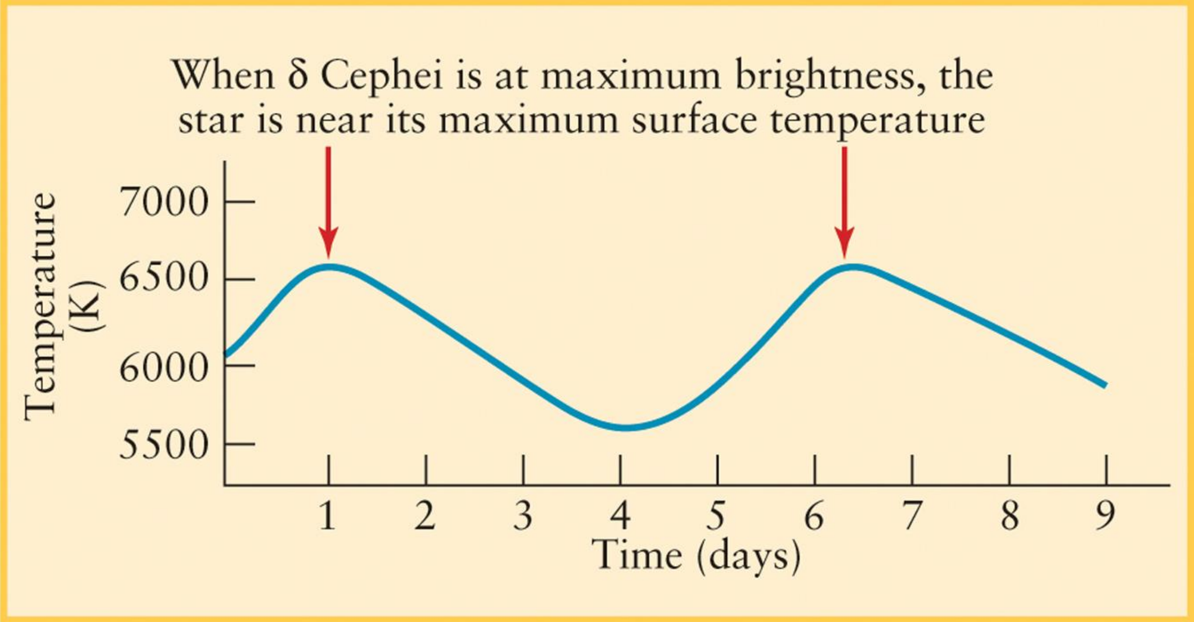
- Period of pulsation: a few days
- Luminosity: 200-20000 suns
- Radius: 10-100 solar radii



(a) The light curve of δ Cephei
(a graph of brightness versus time)



(b) Radial velocity versus time for δ Cephei
(positive: star is contracting; negative: star is expanding)

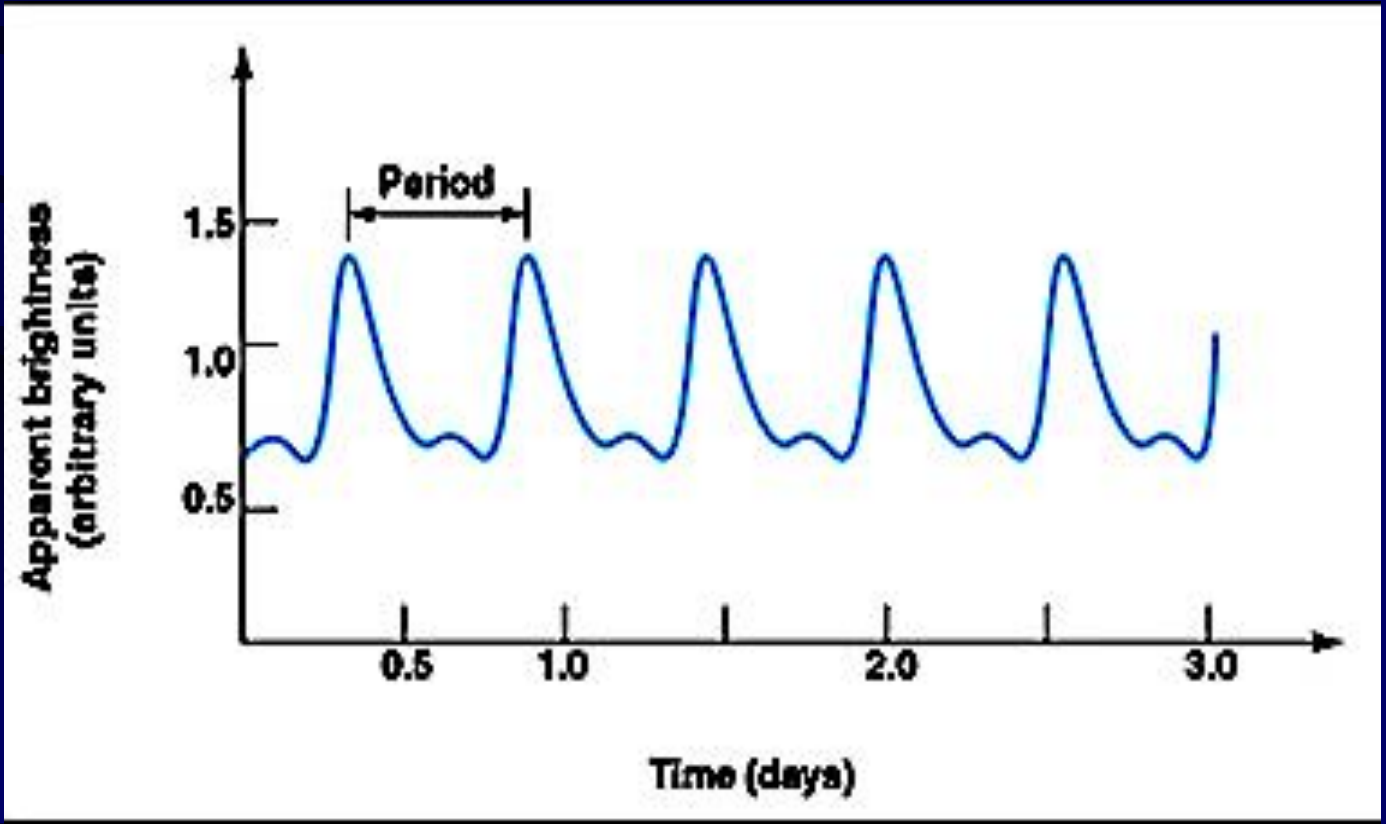


(c) Surface temperature versus time for δ Cephei

The star does change physically: Its radius & surface temperature oscillate

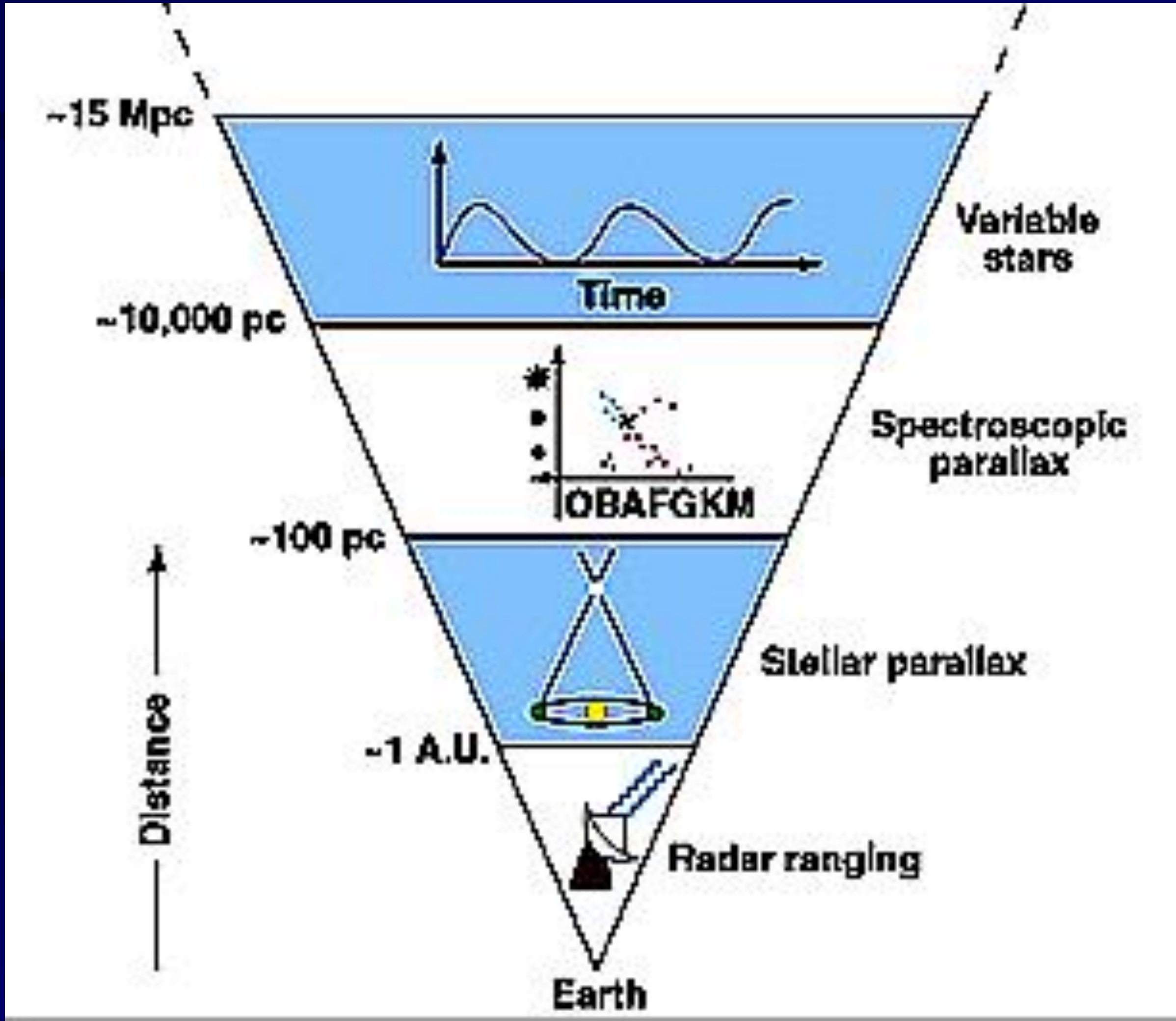
Properties of RR Lyrae Stars

- Period of pulsation: less than a day
- Luminosity: 100 suns
- Radius: 5 solar radii



Distance Measurements with variable stars

- Extends the cosmic distance ladder out as far as we can see Cepheids – about 50 million ly
- In 1920 Hubble used this technique to measure the distance to Andromeda (about 2 million ly)
- Works best for **periodic** variables



Cepheids and RR Lyrae: Yard-Sticks

- Normal stars undergoing a phase of instability
- Cepheids are more massive and brighter than RR Lyrae
- **Note:** all RR Lyrae have the same luminosity
- Apparent brightness thus tells us the distance to them!
  - Recall: $B \propto L/d^2$