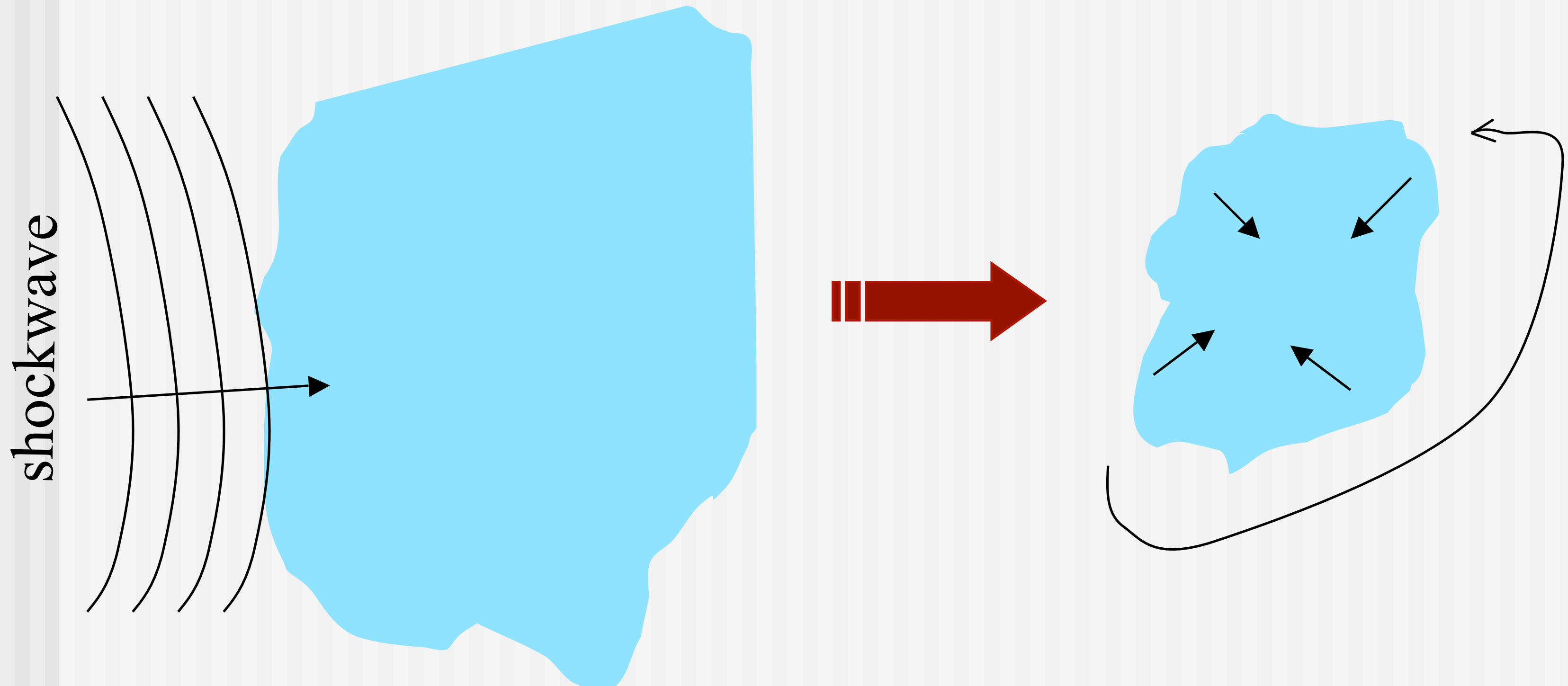
L15: Stellar Evolution

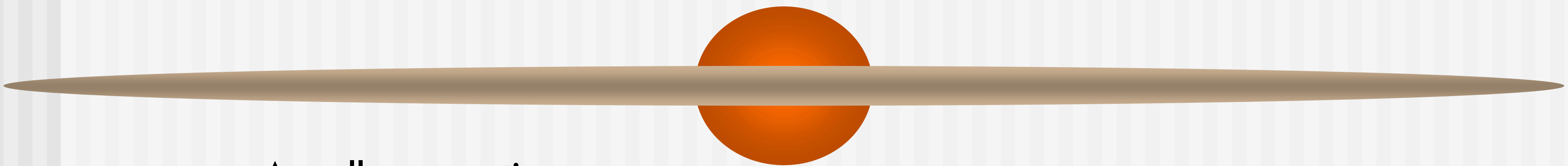
How do Stars Form?

- On macroscopic scale
  - Atoms electrically neutral: no electromagnetic forces over long distances
  - Strong and weak nuclear forces restricted to very small distances
  - Only gravity operates on large scales
- large clouds of gas and dust
  - may start contracting due to passage of shock wave
  - if massive enough, will continue contracting on own due to self-gravity

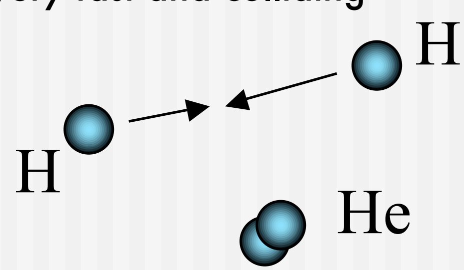


Stellar Birth and Youth

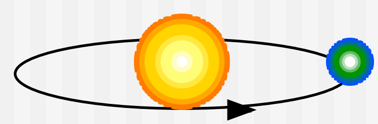
- warm proto-star forms from material collapsing down from cloud
  - May have an associated rotating disk or a condensing companion protostar



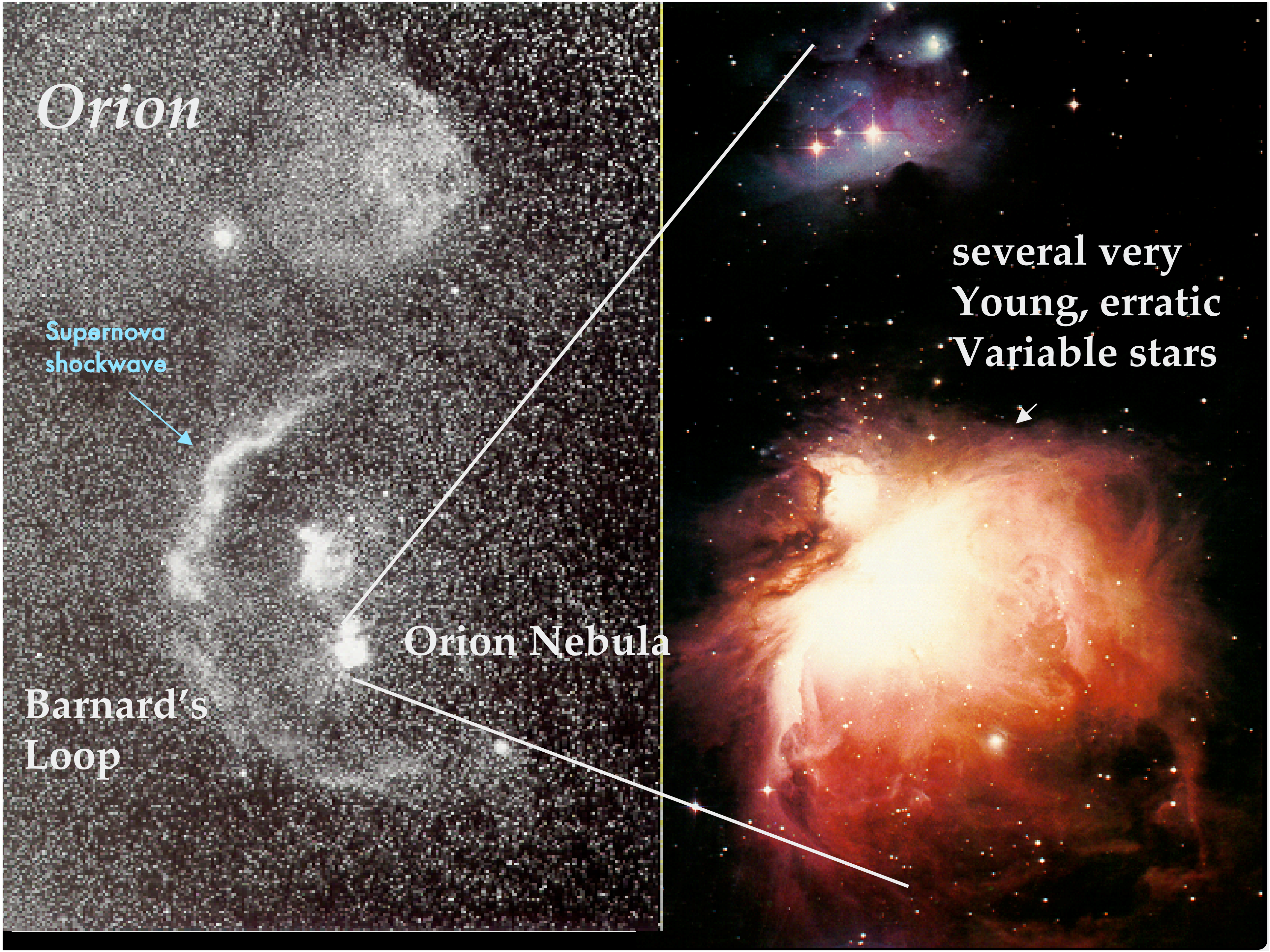
  - As collapse continues
    - Tremendous heat generated in center
    - Heat from contraction leaks away, so more contraction – the core gets very hot
      - This means atoms in the core are traveling very fast and colliding
  - thermonuclear reactions start
    - start by fusing Hydrogen into Helium
    - tremendous amount of energy produced
      - gas and radiation pressure
      - balances weight of overlying layers



… a star + planets:

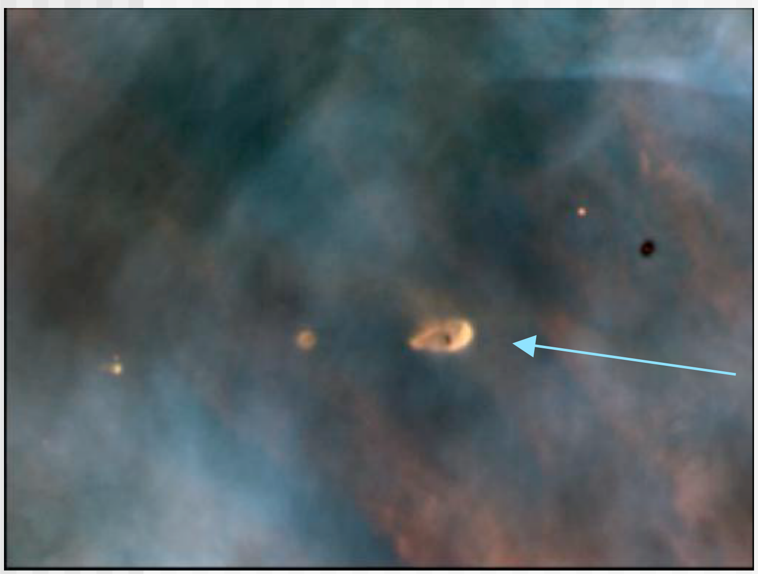


- Early in life, light output may be unstable
  - But collapse stops for most of star's life


Orion
Supernova shockwave
Orion Nebula
Barnard's Loop
several very Young, erratic Variable stars

The Orion Complex

- enormous star-forming region
  - 300 light-years across
  - surrounded by Barnard's Loop
  - collapse start 3 to 5 million years ago
- Orion Nebula
  - in front of the larger nebula
  - can see many young variable stars



Clumps of cloud condensing to protostars

Newly born stars

The Life of a Star

"Change is the essential fact of all existence."
Mr. Spock, Star Trek III

- Radiation from burning Hydrogen to form Helium in star's core
  - Light, massive particles, neutrinos
  - When interacts with other matter, it causes changes in motion
    - Layers above core are heated, and the greater motion/velocity of these atoms exerts a pressure
    - This outward pressure balances the relentless pull of gravity toward collapse
- This state can only be maintained so long as fuel exists
  - Luckily, 90% of raw material in stars is Hydrogen, so there's lots of fuel
  - For a star the mass of the Sun, lifetime expected to be 10 billion years
    - So we have 5 more billion years, don't worry!
  - Much more massive stars
    - Internal temperature hotter
    - A larger fraction of their volume harbors nuclear reactions
    - Burn much faster
      - Blue giant might live 10 million years, or 1000x shorter!
- Stars do not live forever…

Variability

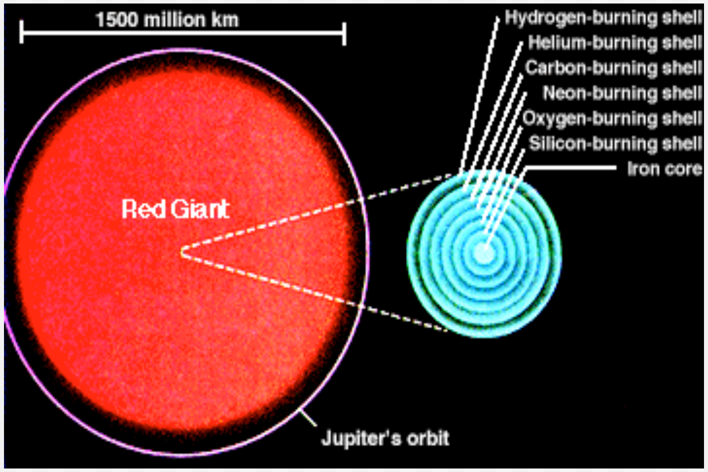
- An uneasy stability exists
  - from radiation pressure for most of a star's life
  - Many stars 'pulsate'
  - as burn fuel
    - star makes slight adjustments to internal structure
      - may upset balance of gravity and pressure
  - sometimes changes deviate significantly from stability
    - might generate somewhat more energy
    - outer layer absorbs more radiation
    - star expands and overshoots stable point, so that…
    - outer layers absorb less energy and star contracts
  - very regular variations
    - pulsations occur in extreme outer layers
  - brightens when densest, smallest

Regular Variables - δ Cephei

- variations first recorded in 1784
- period 5.36 days
- variation due to alternating expansion and contraction of outer regions
- Henrietta Leavitt at Harvard
  - 1912 realized period-luminosity relation
    - longer variation means a brighter star
    - if know apparent magnitude and period, distance can be calculated
  - permits construction of distance ladder
- several related types of variable
  - also allow determination of intrinsic luminosity

Stellar Old Age

- initial fuel runs out in core
  - Core collapses and gets much hotter
  - If star massive enough, heat can be sufficient to burn new fuels, such as Helium
  - Intense radiation generated causes outer layers to expand enormously -- red giant or supergiant stars



- very massive stars
  - exhaust Helium,
    - so further core collapse and heating
  - burn Carbon, then Neon, then Oxygen, then Sulfur
    - shorter and shorter intervals
  - Silicon burning to Iron in about 1 day

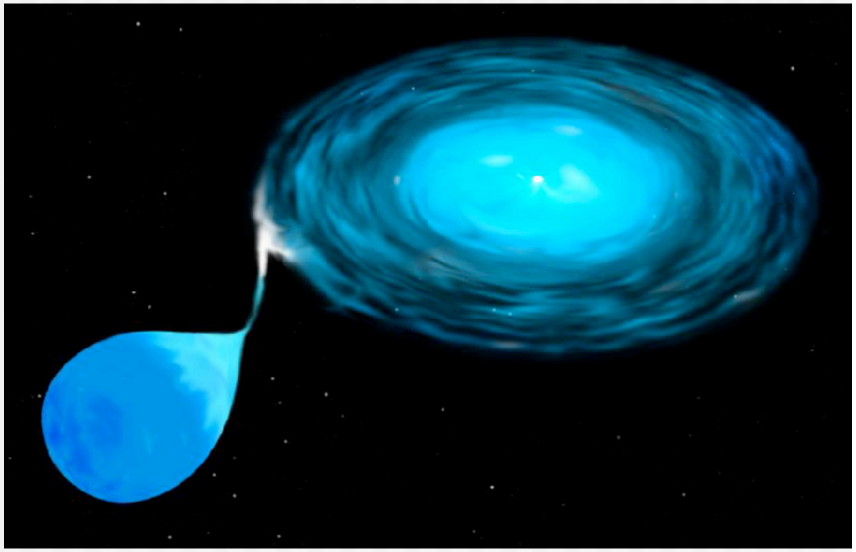
L17: Stellar Death

White Dwarfs

- For solar mass stars, cannot get hot enough after Helium burning to ignite Carbon burning to Oxygen
  - collapse ensues
  - A lot of star's outer layers still Hydrogen
    - enough burns to eject large amount of this into interstellar medium (process not well understood)
    - 'planetary nebula' formed
- The core collapses
  - Atoms pushed closer together (normally in matter, they are very far apart)
  - Electrons in atoms
    - Don't like to be in same energy state as another (exclusion principle)
    - When they start to overlap, a pressure is exerted to stop core collapse
  - Collapse stops with a large body of atoms in close proximity ('almost touching')
    - A 'white dwarf' – diameter about size of Earth
    - But it has 1 million times the mass of the Earth!
    - Can support stars < 1.4 solar masses

Type I Supernovae

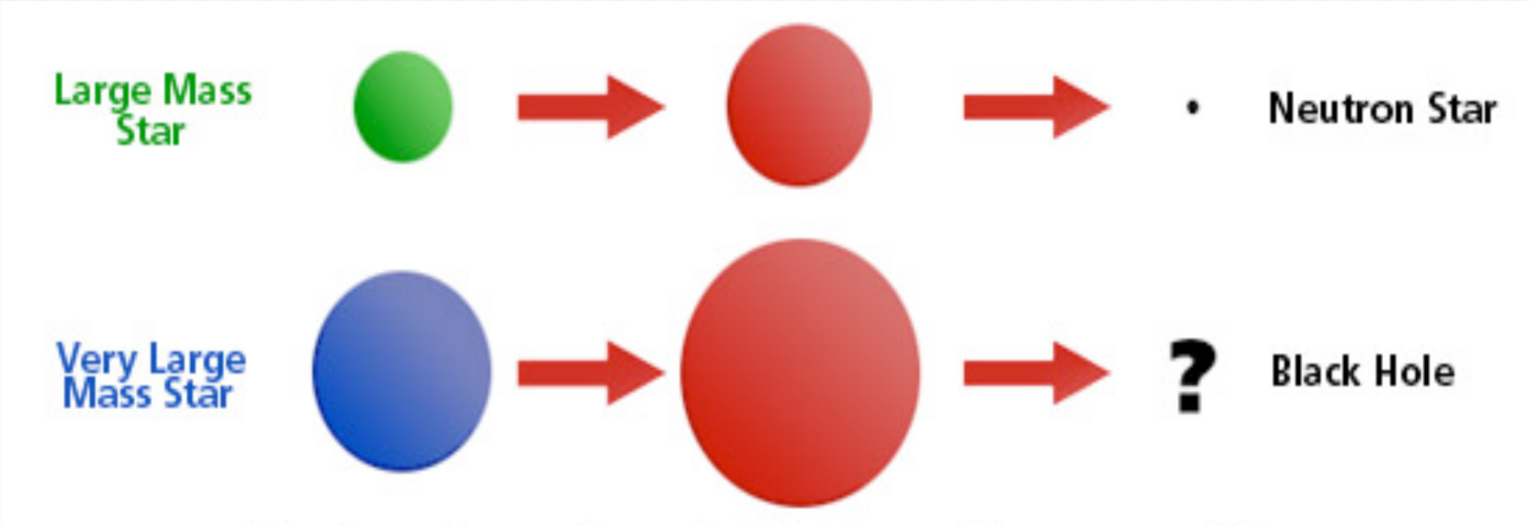
- binary systems – white dwarf and a giant
- White dwarf may pull matter from companion
  - get more and more massive



- after about 100,000 of years
  - pass point where degeneracy can support star
    - I.e. mass is > 1.4 solar masses
  - fatal collapse in < 1 second
  - all degenerate matter explodes

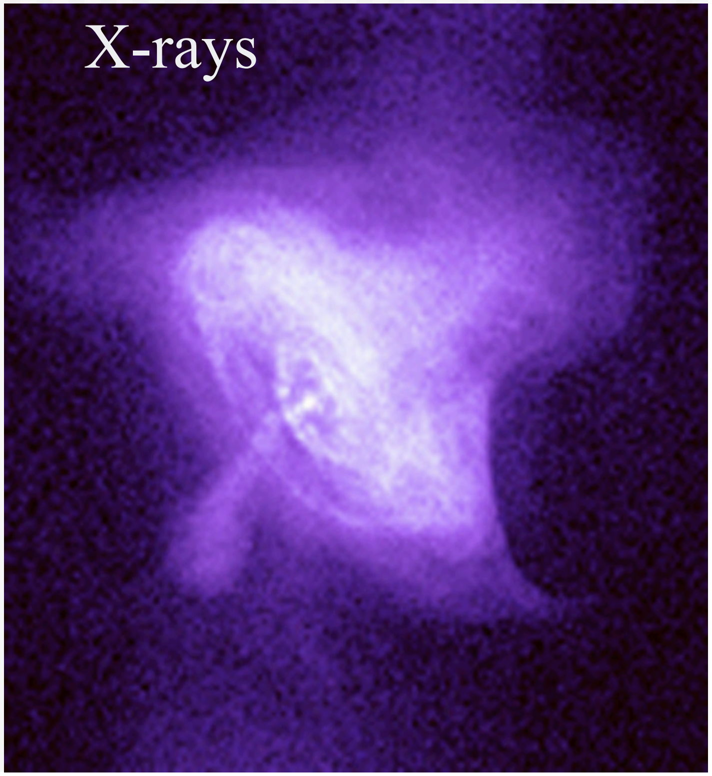
Type II Supernovae

- BIG PROBLEM: cannot release energy by burning Iron
  - just get hotter and hotter
  - in < 1 second core crashes in on itself
- detonate alot of unburnt fuel
  - blow away outer layers
  - can outshine a galaxy
  - elements heavier than Iron produced



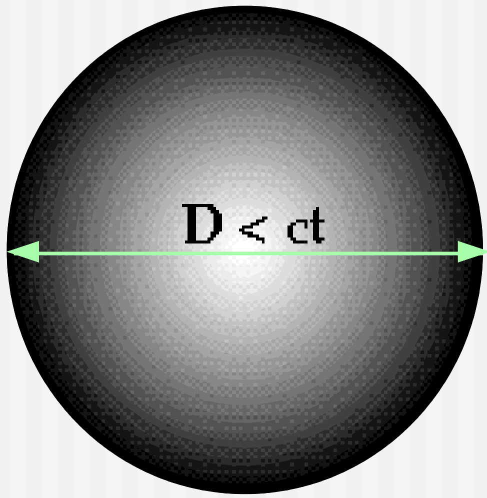
The Guest Star - Supernova 1054

- Chinese observed previously unkown star
  - July 4, 1054
  - peak magnitude about -5
    - brighter than all stars and planets
  - apparently visible in daytime
  - visible for almost 2 years
- ‘Crab Nebula’ found in same location



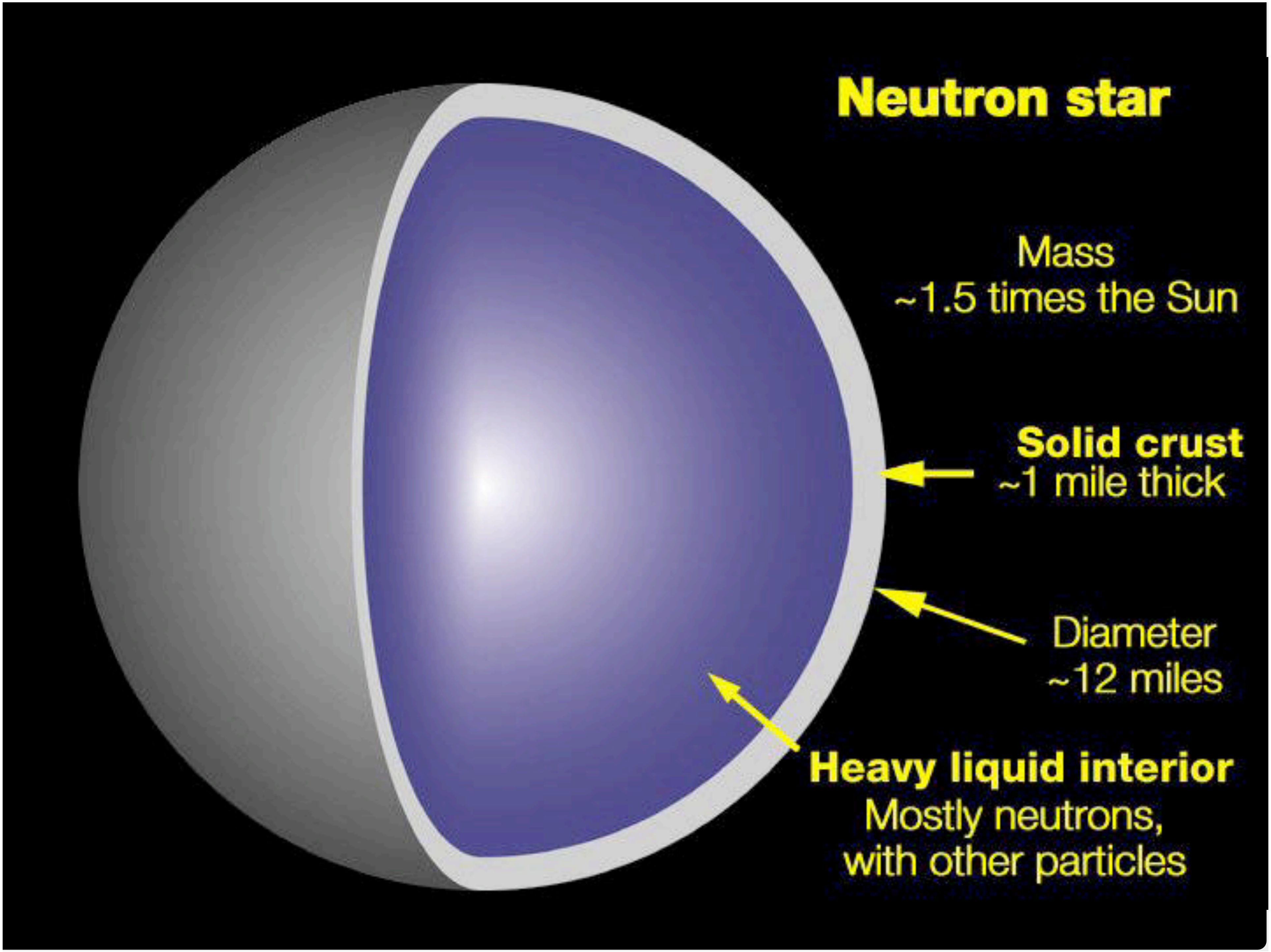
The Crab Pulsar

- accidentally found weak radio pulses, 1949
  - period 1/30 second



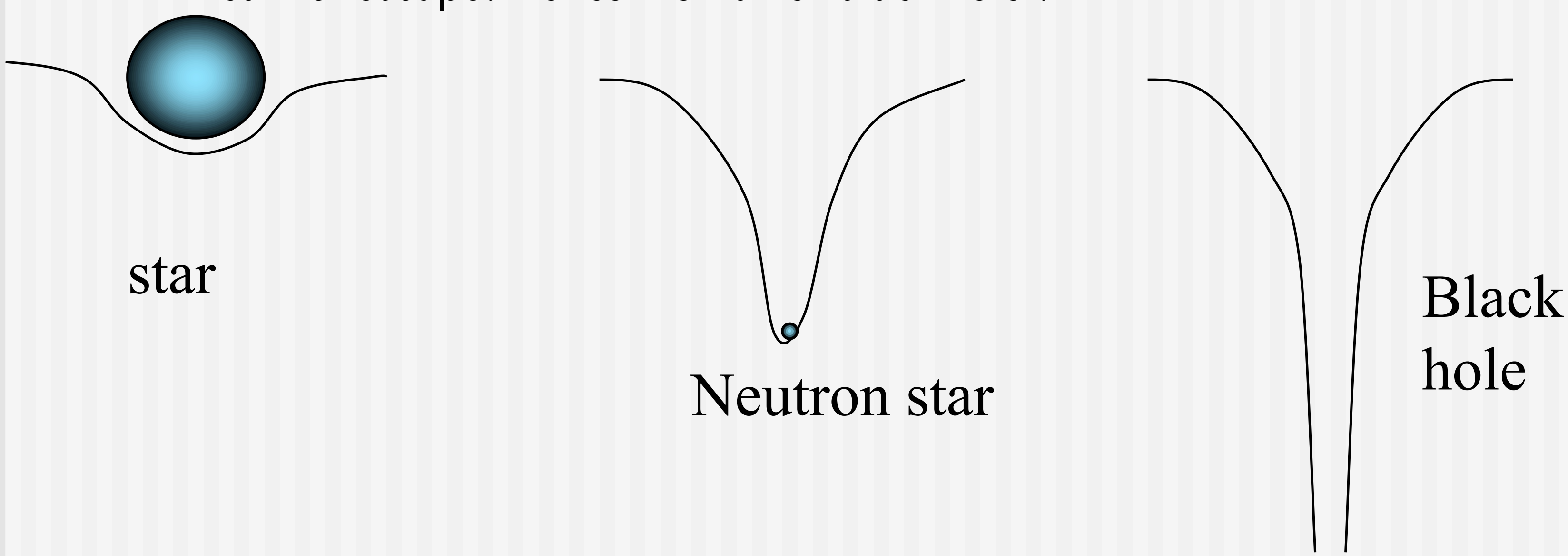
time scale, t, indicates maximum source size

- dim in optical, bright in other wavelengths
  - X-rays seen, 1964
  - visible in gamma-rays
  - synchrotron from fast electrons moving thru mag. field


Neutron star
Mass
~1.5 times the Sun
Solid crust
~1 mile thick
Diameter
~12 miles
Heavy liquid interior
Mostly neutrons,
with other particles

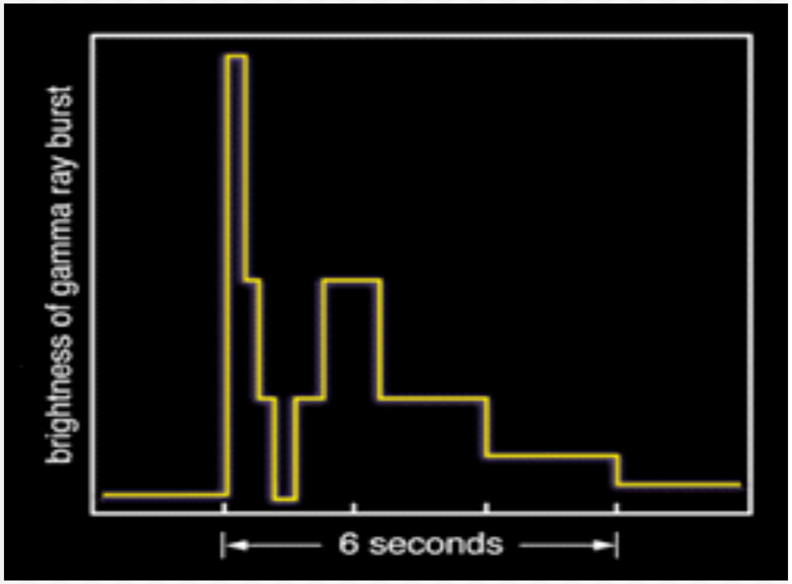
Black Holes

- For very mass stars
  - mass of core is too great even for the exclusion principle
  - Matter compresses further without end
  - Perhaps to infinite density
- Far away from a 1 solar mass sized objects, gravity feels the same
  - But size of the object takes effect when get closer
  - Curvature of spacetime is severe near a neutron star surface
  - A black hole causes such severe curvature, that if light gets too close, it cannot escape! Hence the name 'black hole'.



Gamma-Ray Bursts

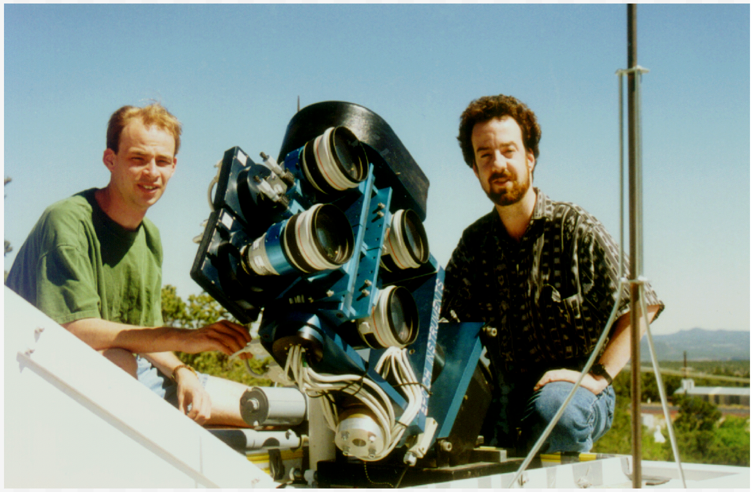
- accidental discovery 1967 by test-ban treaty spacecraft
  - bursts of very high energy X-rays and gamma-rays
  - brighter than the rest of the gamma-ray sky when at peak
  - celestial origin determined, 1973



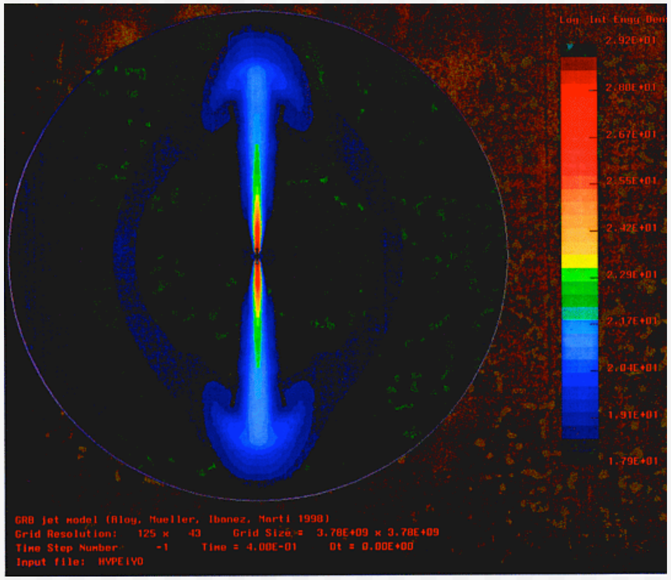
- They last a few seconds
- very erratic behavior
  - variations as short as milliseconds observed
    - places a limit on source size ($D < ct$) of < 100 km!

What Are They?

- Need to observe visible light
  - to get distance (and therefore actual, or intrinsic, luminosity), or…
  - To understand how explosion occurring
  - Saw one optical burst almost bright enough to see with eyes in 1999 →



- Energy output: > 1000 supernovae
  - Converted > 1 solar rest mass to energy in < 1 minute!
  - largest known explosion since Big Bang
  - Very problematic for theoretical models:
- May be a 'hypernova'
  - Too massive to completely explode, only thru poles
  - we are along beams of intense radiation
  - A black hole would be formed

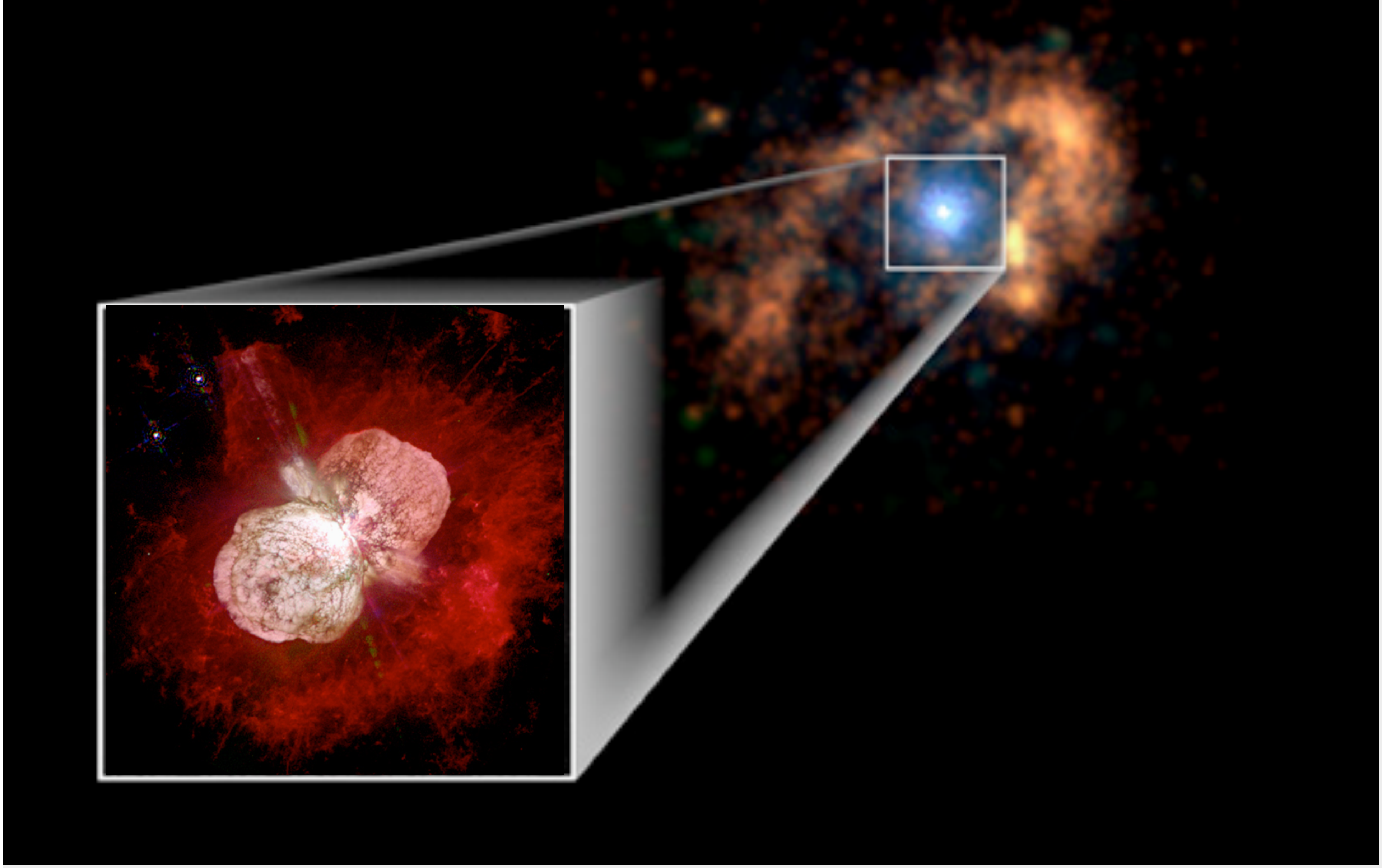


Eta Carinae

- most massive, luminous star in Milky Way
  - beyond limit for star's mass
    - if star mass > 60 times the Sun, radiation pressure pushes it apart
  - mass about 100 times the Sun!
  - 5 million times solar luminosity!
    - We don't see it so brightly because It is embedded in dust
- very unstable star
  - outer layers have been blown off multiple times
  - "Great Eruption" of 1800s – almost as bright as Sirius
  - similar explosion about 1000 years ago
    - X-rays detected in large ring
  - modern observations reveal extended gas regions around star
  - supernovae sized events, except they didn't destroy the star!
- Potential gamma-ray burst coming – Stay Tuned!

"Will it awake, this sun of Argo, will it revive completely and project anew around its brightening sphere the radiation of light and heat which seemed to have departed from it forever? We may, we ought to hope for it."

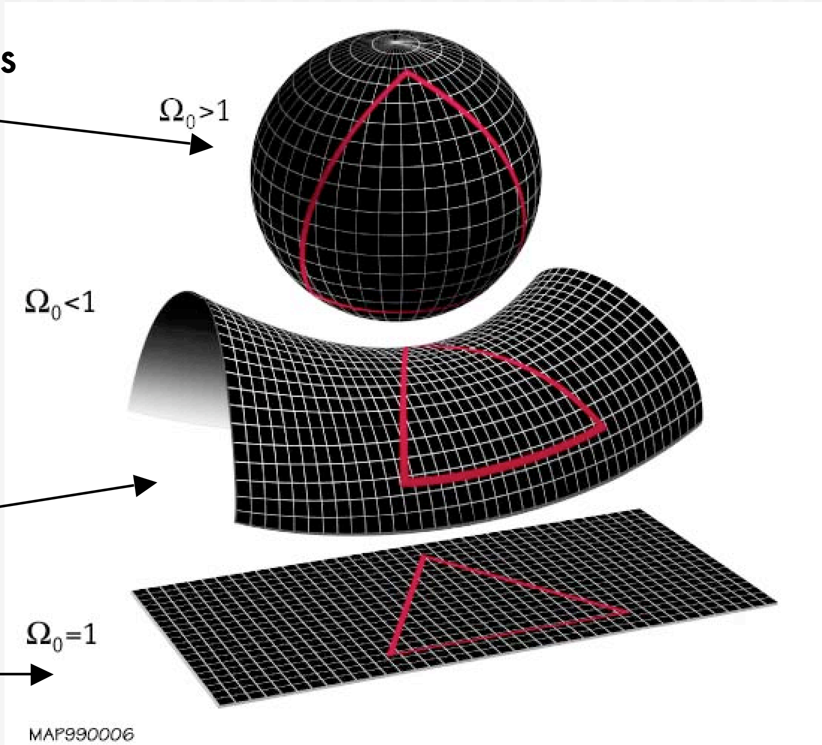
Camille Flammarion on η Car, 19th cent.



Lecture 20

Gravity and Cosmology

- Cosmology = study of the universe as a whole and its origins
- What is the global geometry of spacetime? 3 possibilities
  - Closed: paths 'close' in on themselves
    - Eg. a sphere is a closed 2 dimensional geometry
    - Corresponds to total energy density (Ω) which would cause any expansion to stop and turn into a collapse
  - Open: trajectories diverge from each other
  - Flat: constant velocities, static
    - Eg. a flat sheet



Cosmological Constant

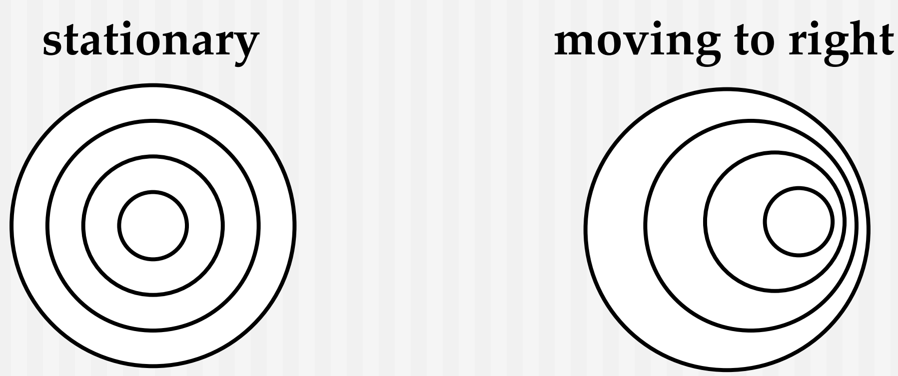
- A priori
  - there is no reason to expect the universe to be a flat, static geometry
    - This would be a 'special case' that needs some explaining
  - In fact, general relativity seems to imply a preference for either an expanding or contracting universe

- The general European predisposition 100 years ago
  - toward a static universe
  - A matter dominated universe

- One problem in such a universe: gravity dominates
  - So spacetime should be closed due to the attractive force of gravity
    - I.e. not static
  - To prevent contraction of spacetime, you need some 'force' to push outward
    - Einstein introduced the 'cosmological constant', Λ, into his equations to express this force

Looking at Cosmological Motion

- Stars in galaxies outside of Milky Way
  - Have optical spectral lines with well-known wavelengths
  - If galaxy moving toward us, lines shifted to blue wavelengths
    - If away, shifted to red (redshifted)



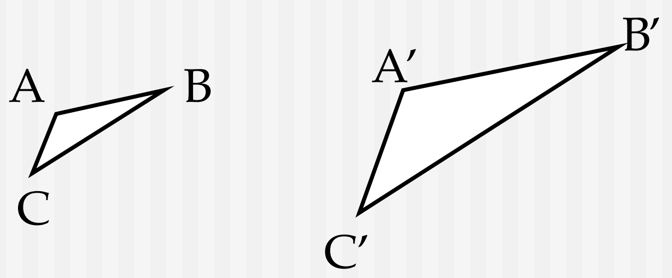
  - If see Cepheid variables, can calculate distance to galaxy because know absolute luminosity

Expansion of the Universe

- In 1912
  - Vesto Slipher observes most galaxies are receding from us
  - Doesn't have great distance measurements

- In 1927, E. Hubble
  - Observed that galaxies that were far away were all moving away from us
    - The farther away, the faster the recession

- This indicates that space itself is expanding!
  - Consider points A, B and C:
    - B recedes from C faster than A recedes from C
    - B is farther from C than A is



  - Einstein: the cosmological constant is "the biggest blunder of my life."

Questions

- Describe the process by which a white dwarf is created. What is preventing further collapse of this object? [10 pts]
- Why is there a problem with burning iron (Fe) within stars to support the weight of their matter? [10 pts]
- What is a 'pulsar'? [10 pts]
- Gamma-ray bursts last 10 seconds. (T or F) [2 pts]
- Describe the processes leading to, during, and after a supernova. Include a description of the progression of fuel burning, what triggers the actual supernova outburst, and why the resulting object develops as it does. [22 pts]
- A normal star's life is spent with the contraction from gravity being balanced by the outward radiation pressure from nuclear reactions. How then does a collapsed star like a white dwarf, or a neutron star, support itself against gravity? [10 pts]
- Describe how redshift measurements of stars in galaxies provided the first observational evidence for the expansion of the universe. [10 pts]
- Gamma-ray bursts occur approximately once per day and are intense bursts of radiation. Why are they not apparent to us visually? Explain the current view of what generates these bursts. [10 pts]