Astronomy 162, Week 6
After the Helium Flash: Late Stages of Evolution

Patrick S. Osmer

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Review

- Helium flash – a turning point in evolution
  - produces tremendous energy
  - example of non-equilibrium situation
  - very hard to calculate

What happens after the flash?

- Core has expanded enough to become non-degenerate
- Core hot enough to fuse helium
- Outer layers contract, become hotter

What happens next to sun?

- See Ch. 22-1, Fig. 22-1, 22-2, 22-3
- Converts helium in core to carbon
- After all helium in core is fused,
  core contracts, heats again
- Helium starts to fuse in shell around core

- Hydrogen fuses in shell farther out
- Sun expands almost to size of Earth's orbit
  - outer layers cool, becomes red giant
  - Core temp. increases, heavier elements produced

Mass loss, Planetary Nebulae

- Star sheds mass from surface
  - becomes unstable - a Mira variable
  - produces dust around star
- Hydrogen fusion gets closer to surface

- Surface temperature increases (Fig. 22-10)
- Star ionizes surrounding material
- A planetary nebula becomes visible

Planetary Nebulae

- Ring Nebula in constellation Lyra is classic example (see others in Fig. 22-6)
- Called planetary because they resemble Uranus and Neptune in small telescope
- They surround very hot stars (100,000 deg) (but low luminosity - small in size)
  - (Stars lost much of their mass in arriving at this stage)

- Nebulae have lifetimes about 50,000 years (very short)
- Thus, total observed number not large
- Gas observed to expand at about 30 km/sec
  - Evidence for ejection during red giant phase (otherwise expansion would have to be much faster)

Effect of mass loss on ISM

- Gas ejected from star has more heavy elements because of nuclear processing
- Thus, interstellar medium gets enriched, abundance of heavy elements increases
- Next generation of stars to form in ISM will have more heavy elements
- This recycling necessary for earth to have its heavy elements

The fate of the sun

- As it runs out of nuclear fuel,
  - contracts
  - becomes white dwarf
  - slowly cools
  - that will be the end of its life

White dwarfs

- Composed of degenerate matter
  - except for thin surface layer
  - density about a million times water
  - (mass of sun crammed into volume of earth)
  - high surface gravity
  - initially very hot (tens of millions of deg)
  - cannot have hydrogen at this temperature (it would fuse into helium)

White dwarfs, cont.

- Interiors composed of
  - helium (low-mass stars)
  - carbon-oxygen (intermed mass)
- What happens to them?
  - Have no more sources of energy
  - Gradually cool off
  - Become “black dwarfs” after very long time (probably more than age of universe to date)

Physics of white dwarfs

- Pressure depends on density, not temp.
- Density increases toward center
- Chandrasekhar showed
  - radius depends only on mass
  - the larger the mass, the smaller the radius
  - Chandrasekhar limit - 1.4 solar masses
  - above 1.4 solar masses - collapse occurs
  - see Fig. 22-9

Recall Sirius A,B

- Companion of Sirius is white dwarf
- It must have been more massive than Sirius originally
  - but now only half the mass of Sirius A
  - it lost most of its mass
  - some was transferred to Sirius A, rest ejected from system

Variable stars

- Stars that change in brightness
- Some stars become unstable after leaving main sequence
  - begin to pulsate, or expand and contract
  - their brightness (and radial velocity) changes)
  - some show a very regular, periodic change
  - others are irregular (Mira or long-period variables)

Pulsating stars

- Historically very important
  - show a relation between period of variability and absolute luminosity
  - used to establish distance scale of universe
  - good tests of models of stellar evolution

Cepheid variables

- Prototype - Delta Cephei
- Variability discovered in 1784
- Bright enough to see (and measure) with unaided eye
- Polaris is also a Cepheid

Period - Luminosity Relation

- Henrietta Leavitt, 1912, discovered relation between period and brightness of Cepheid variables in Magellanic Clouds
  - stars with longer periods were intrinsically brighter
  - this allows intrinsic luminosity to be determined from measures of light curve
  - see Fig. 21-17

- Important because Cepheids are intrinsically luminous
  - can be up to 10,000 times brighter than sun
- Light curves can be measured at great distances
- Key program with Hubble Space Telescope is using Cepheids to determine distance scale of universe

RR Lyrae Stars (Cluster Variables)

- Pulsating stars with periods less than 1 day
- Found in globular clusters and old populations
- Within cluster, all have about same average brightness
- If all have same absolute brightness, can get distance to clusters
- RR Lyrae stars about 50 times brighter than sun

What is pulsating and why?

- Outer layers of stars are expanding and contracting, not the core
- Under certain conditions, there is an ionization zone of helium in outer regions of star. It can absorb or release energy as it is compressed or it expands
- This can drive the pulsations

Instability strip in H-R diagram

- When stars lie in certain band in H-R diagram, they will pulsate (Fig. 21-15)
- Stars at top are more luminous
  - they also pulsate more slowly (have longer periods)
  - thus have theoretical explanation of period-luminosity relation

Astronomy 162, Week 6, Part 2
Evolution of Massive Stars

Patrick S. Osmer

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Evolution and Death of Massive Stars

- Consider O-type stars
  - masses more than 15 solar masses
  - very young
  - concentrated to plane of Milky Way
  - mass loss very important
- What is origin of heavy elements (iron)?
  - not in stars like sun

Supergiants

- Evolve differently
  - At first evolve to right in H-R diagram
  - Do not develop degenerate core
  - Hot enough to fuse helium directly
  - when helium fusion starts, move back to left in H-R diagram
  - Also shed much mass from outer envelope

O-stars, cont

- How does their evolution differ from stars like sun?
  - much faster (few million years)
  - no helium flash (no degenerate core, temperature hot enough to fuse helium)
  - horizontal tracks on H-R diagram
  - nuclear reactions produce elements up to iron

O-stars, cont.

- What happens after they leave main sequence?
- Nuclear reactions continue in core
  - Helium is converted to carbon, oxygen
  - Core temperature keeps increasing
  - Neon gets produced, then silicon, finally iron
  - Core becomes onion like
  - Temperature reaches 3 billion degrees!

End of Silicon Burning Phase:

Burn out!

- Once iron is produced - big problem!
  - iron is end point of fusion reactions
  - need to add energy to iron to make heavier elements (nuclear binding energy curve)
  - nuclear reactions stop in iron core
  - core becomes degenerate, mass keeps building up from reactions further out

- We are about to see finale of contest between gravity and gas pressure
- Does gravity win?
  - Not for outer layers
  - Yes for core
- Final act is the most spectacular in the universe!

Time scale for Reactions

- 25 solar mass star (Table 22-1)
- Reaction Time (yrs)
  - H to He 7 million
  - He to C/O 700,000
  - C to Ne ...Mg 600
  - Ne to O, Mg 1
  - O to Si, S, P 6 months
  - Si to Ni … Fe about 1 day

Then what?

- Reactions stop in core
- Core is degenerate, cannot increase pressure to resist inward pull of gravity
- More iron is produced from reactions in shell around core
- Core mass increases, approaches 1.4 solar masses (Chandrasekhar limit)

Collapse

- Core collapses in about 1/4 sec at speed of about 1/4 the speed of light
- Shrinks to about 100 km radius
- During collapse, all nuclei are destroyed, all particles converted to neutrons
- Tremendous flux of neutrinos emitted

Rebound

- Core density reaches 10^{14} times water, about that of atomic nucleus
- Neutron core has tremendous pressure, stops further collapse, produces rebound
- The neutrino flux produces tremendous shock wave
- Shock wave turns collapse around, starts explosive expansion

Kaboom!!!

- Explosive nucleosynthesis produces elements heavier than iron
- Shock blows outer part of star completely away
- We see the supernova explosion
- A neutron star is left as remnant. Its radius is only 10km

Supernova!- Explosion and Destruction of a Star

- Most violent event in universe!
  - for a few milliseconds, collapse/explosion releases more energy than all stars/galaxies in visible universe
  - Later, the visible light can be up to 10^{10} solar luminosities, as much as many galaxies
  - Material is ejected at speeds up to 10,000 km/s

History

- Chinese noted a "guest star," bright enough to be seen in daytime, in the year 1054
  - Today we see an expanding nebula at position of the star, the Crab Nebula
  - Other "guest stars" were seen in 1006, 1181
  - Tycho saw a new star in 1572
  - Kepler, another one in 1604
  - Five seen in galaxy in last thousand years

History, cont.

- Tycho's discovery helped make him very famous
  - gained enough support from King of Denmark to build first great observatory of modern times
- Recall that was the time of alchemy
  - but chemical reactions cannot turn lead into gold
  - but supernovae can produce gold

Supernova 1987A

- Feb. 1987 - Duhalde and Shelton discover supernova in Large Magellanic Cloud
  - visible to unaided eye
  - was found within about 8 hours of core collapse
  - neutrinos from explosion were detected under Lake Erie and in Japan in physics experiments

Fig. 22-16 - SN 1987A, Before and After

Fig. 22-15, SN1987A

SN1987A, cont.

- Discovery sparked feverish activity by observers and theorists
- Produced most complete record ever for a SN
- Brilliant interplay of theory and observation
  - led to development and confirmation of our current picture of the explosion

What did we learn?

- Photos showed which star actually blew up
  - about 15-20 solar masses
  - lived about 10 million years
  - lost mass during its evolution (now lighted up by supernova)
  - reached about 100,000 solar lum. in red supergiant phase
  - was a blue supergiant when it blew up

- The detection of 11 neutrinos in Japan and 8 under Lake Erie confirmed concept of core collapse, neutrino shock wave
- Now, numerical simulations show how shock wave gets out of star
  - previous problem had been “stalling” of shock wave
  - convection, turbulence allow it to get out

Note the boiling currents in the movie

- Also, the incredible conditions that make
- shock wave opaque to neutrinos
  - at that instant - they cannot get out -that’s how hot and dense the matter is
  - (normally they would escape immediately, as in sun)

- Temperature reached something like 200 billion degrees
- Momentarily, the luminosity was about 10^{20} that of the sun (about same as all stars in observable universe)

What’s left?

- A neutron star (we think)
- Rest of star blown away
- Expect to see neutron star when surrounding material clears away
- Note also that explosion produced elements heavier than iron and blew them back into space

Recycling, cont.

- When new stars form from ejected material, will have more heavy elements than previous generation
- Supernova are the origin of the heavy elements on earth
- We were once part of a star

Astronomy 162, Week 6
Supernova Remnants, Neutron Stars

Patrick S. Osmer

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Supernova Remnants

- After explosion
  - central core fades in brightness
  - Outer envelope expands into space
  - forms nebula
  - Crab nebula (from SN1054) is prototype
  - Many others now known
  - Also emit in X-rays and radio waves (from great energy of explosion

Types of Supernovae

- Have covered the death and explosion of massive stars
  - These are called Type II supernovae
  - show hydrogen in the expanding envelope
- Type Is are different
  - No hydrogen in envelope
  - More luminous
  - What are they?

Type I SN

- Believed to originate in binary system
  - one star is a white dwarf
  - it receives mass as its companion evolves
  - eventually gets pushed over Chandrasekhar limit
  - collapses and explodes
  - destroys entire star

- Also consider the star Eta Carina
  - may be close to blowing up
  - (If Rigel goes off, we'll certainly know it - will be visible in the daytime)

What happens to core of SN?

- We saw how it collapsed, reached density of atomic nucleus
- Imagine sun compressed to radius of 10 km
- Protons, electrons forced together to form neutrons
- Even the neutrons are degenerate

- 1938 - Baade, Zwicky postulated that SN could form neutron stars
  - were way ahead of their time, but were right
  - amazing foresight

Pulsars

- Crab nebula is still an emission nebula
  - What is heating it?
- 1967 - Bell, Hewish discover regularly pulsing radio sources, with beeps about every second
- What was going on? Little green men?
- Periods now known to range from 1/1000 of sec to 10 sec

PSR B0329+54
The Vela Pulsar
The Crab Nebula Pulsar
PSR J0437-4715
PSR B1937+21

What can vary so quickly?

- Object must be very small
- Also, signals are very regular
  - pulsars are some of best clocks known
  - regularity means rotation
  - object must be very small
  - thus, can rotate fast

Pulsars, cont.

  – After core collapse, resulting neutron star will
  – rotate very quickly
  – have very strong magnetic field
  – magnetic field can produce beams of radiation
  – neutron star radiates like a lighthouse
  – we detect the pulses when the beam points at us
- Pulsars are rotating neutron stars with beamed radio radiation (Fig. 23-3)

Neutron stars

- Have masses like the sun
- Radius of about 10 km
- So dense, 10^{14} gm/cm^3, that even the neutrons are degenerate
- Best known examples - Crab Nebula
  – has pulsar, which can be seen optically
  – neutron star provides energy to nebula

Planets around pulsars

- Minute changes in arrival times of pulses from pulses indicate that some seem to have planets in orbit around them
- Surprising result - wasn't expected that planets would survive supernova explosion
- Maybe formed from fragments of companion star or material blown off supernova

What happens to pulsars?

- Gradually slow down
- Fade away
- Probable lifetime - about 10 million years

SS433

- Unusual binary system
- Example of mass transfer onto neutron star
- Formation of accretion disk
- Jets of gas ejected from poles of system at 1/4 speed of light (see Fig. 16.30)

Binary Stars and Novae

- Sirius is example of mass loss and transfer
  - White dwarf originally had more mass than Sirius A
- Consider white dwarfs in binary system
  - If companion goes through red giant phase, it can transfer mass to the white dwarf
  - See Fig. 21-17

- As matter containing hydrogen builds up on surface of white dwarf, it gets very hot.
  - Reaches point where fusion starts
  - But matter is degenerate, so nuclear thermostat doesn't work
- Reactions run away, produce explosion, blow material into space
- Explosion we see is called a nova