Stellar Evolution

The Main Sequence
- Stars eventually burn their nuclear fuel
- Lifetime
  - Depends on luminosity
  - Depends on amount of energy
- Stars spend about 80% of lifetime on MS
  - 10 Billion years for sun
  - 10 Million years for a 10 $M_{\odot}$ star
  - 10 Trillion years for a 0.1 $M_{\odot}$ star

Core Hydrogen Exhaustion
- He core
- H burning zone moves into a thin shell surrounding the core
- Collapsing core heats the H shell above it, driving the fusion faster.
- More fusion = more heating, so that Pressure > Gravity

Outside Core
- Subgiant branch:
  - Convective Envelope
  - Envelope expands and cools
  - R-increases; T-decreases; L-increases slightly
- Red Giant
  - Envelope becomes most convective at point 8
  - R-increases; T-same; L-increases

Red Giant
- It takes a star about 1 Gyr to climb the Red Giant Branch
  - He core contracting & heating, but no fusion - density rises, core becomes degenerate gas
  - H burning to He in a shell around the core
  - Huge, puffy envelope > size of orbit of Venus
The Evolution to Horizontal Branch

- He core temperature reaches $10^8$ K at tip of Red Giant branch
  - Helium Flash - Helium quickly begins to fuse into carbon in the core
  - Sudden release of energy

The Evolution to Horizontal Branch

- Inside:
  - Starts generating primary energy from He burning in the core.
  - Gets additional energy from an H burning shell surrounding the core.
- Outside:
  - Gets hotter and bluer.
  - Star shrinks in radius, getting fainter.
- The new energy source helps the star begin to regain Hydrostatic and Thermal Equilibrium. As it does so, it moves onto the Horizontal Branch

Horizontal Branch Phase

Structure:

- He-burning core
- H-burning shell
- The Triple-alpha Process is very efficient at producing energy, so it can only last for about 100 Myr.
- While it goes on, the star steadily builds up a C-O core, but it is still too cool to ignite Carbon fusion

Evolution Off the Horizontal Branch

- The Helium in the core becomes depleted after ~100Myr
  - C-O core contracts and heats up
  - He burning shell outside core
  - H burning shell outside the He shell
  - Hotter shells produce more energy
  - Pressure expands star
  - Core never gets hot enough to fuse Carbon

The Instabilities of Old Age

- He burning is very temperature sensitive: Triple-alpha fusion rate $\sim T^{40}$

Consequences:

- * Small changes in T lead to
- * Large changes in fusion energy output
- Star experiences huge Thermal Pulses that destabilize the outer envelope.
Proto-Planetary Nebula
• Large pulsations blow off outer layers of star
• The entire outer part of the star is stripped off
• Hot dense Carbon core left behind

Planetary Nebula
• Shell is atmosphere of star
• Very hot core photo-ionizes the gas and makes it glow

White Dwarf
• The carbon core = white dwarf
  – Typically 0.5 \( M_{\odot} \)
  – Very, very hot initially 100,000K
  – Very, very dense 10^6 kg/m^3
    • So dense that pressure comes from the electrons in the gas rather than normal pressure (degenerate)
    • Pressure does not change with temperature
  – Very small - size of earth
    • 1/100 of \( R_{\odot} \)
    • Radius set only by the mass
  – Has no fusion - slowly cools

Evolution of Binary Stars
• Remember: Most stars are in binary systems
• Common envelope evolution
  – Higher mass star becomes giant first
    • companion orbits inside the giant’s atmosphere
  – Stars move close together due to drag
  – Higher mass star becomes white dwarf

Nova
• White dwarf draws hydrogen from main sequence companion
• As hydrogen accumulates it becomes denser and hotter
• Hydrogen fuses into He in a very rapid explosion
• Cycle begins again
Type Ia Supernova

- White dwarf collects too much matter
- Electron pressure can not hold up the WD mass - exceed Chandrasekhar (1910-1995) limit = 1.4 $M_{\odot}$
  - $e^- + p = n$
- Star collapses in a massive explosion
  - Most luminous events in the universe
    - $10^8$ L$_{\odot}$: Can out shine an entire galaxy
    - Decays away for years
  - Energy from collapse of star
  - Heavy elements generated

Evolution of Massive Stars

- Evolution of stars with $M > 5 M_{\odot}$ differs from low mass stars
  - Higher core temperatures so they fuse heavier elements easily
- Main sequence is still fusion of Hydrogen - much shorter life
- He core immediately starts burning into carbon
- No "red giant phase"

Evolution of Massive Stars

- Hot enough to fuse carbon into oxygen
- Hot enough to fuse oxygen into silicon
- Hot enough to fuse silicon into iron
- Iron is the most stable element
  - Lose energy breaking it apart into lighter element
  - Lose energy fusing it into heavier elements

Supergiants

- So much energy is generated that massive stars swell to tremendous sizes
- These are called supergiants
- They are 1000-10000 times larger than the Sun

Time Scales for 25 Solar Mass

RR Lyrae Stars

- Horizontal branch stars
  - Brightness varies because they pulsate
  - Periods: ~ 12 to 24 hours
  - All have the same luminosity
  - Found in globular clusters
Cepheid Variables

- Henrietta Leavitt at Harvard College (1908)
  - Studied plates from Peru for variable stars
  - Her plates included the large Magellanic cloud
    - Nearest galaxy to the Sun
    - All stars at the same distance
    - She noted brighter pulsating stars had longer periods
- Period luminosity relationship

Cepheids Variables

- Named after delta Cephei (first discovered)
- Periods ~ 1 to 100 days
- Luminosity is a function of period
- Period-Luminosity relation discovered by Henrietta Leavitt in 1908.
- There are two types (labelled Type I and II Cepheids)
  - Type I Cepheids
    - a.k.a. Classical Cepheids
    - Luminosity: 400 to 20,000 Lsun
    - Location: Open clusters and the galactic disk (Pop I stars)
  - Type II Cepheids
    - a.k.a. W Virginis Stars
    - Luminosity: 100 to 5,000 Lsun
    - Location: Globular clusters (Pop II stars)

Period Luminosity Relation

Stellar Evolution with Star Clusters

- All stars the same age in a cluster
- One mass of star will be ending its main sequence life for a given cluster age
  - More massive stars are gone
  - Lower mass stars still on MS
- Positions of stars beyond main sequence reflect the evolution of a star leaving MS
- Number of stars at each position reflects life time of that phase

Old Globular Cluster 47 Tuc

- 12-15 billion years old
- Turn-off mass 0.5 M\(_{\odot}\)
Open Cluster M67 & Globular Cluster M4
- M67
  - Age - 5 billion years
- M4
  - Age - 12 billion years

Pleiades
- 70 Million years
- Turn-off 5 $M_{\odot}$

The Jewel Box

The Rosette
- Age 3 Million Years old
- Turn-off mass 10-20 $M_{\odot}$

Trapezium
- < 1 million years old
- Low mass stars not on main sequence yet

Supernova Type II: Death of Massive Stars
- Finish with an Fe core
  - Can not produce any energy
- Core contracts and heats
  - Fe disintegrates into $e^-, p & n$ : T<1 second
  - Mass too large to be held up by electron pressure
  - $e^- + p + n$ = neutrinos : T<0.1 second
  - Neutrons degeneracy pressure holds up the core
- Core collapses
  - Star falls onto core releasing lots of energy
  - Envelope "bounces" back into space : T~milliseconds
SN 1987A

Supernova Remnants

- The gas from the stellar atmosphere is launched at high speed into the interstellar medium
- Shocks cause it to emit
  - Radio waves
  - Optical emission lines
  - X-rays

The Remnant of Tycho’s Supernova

The Vela Supernova Remnant

The Crab Nebula

Neutron Stars

- Remnant of Type II supernova
- Composed only of neutrons
  - Typical mass 1.5 $M_{\odot}$
  - Densities $10^{14}$-$10^{18}$ kg/m$^3$
    - like nucleus of atoms
  - Diameter 20 km = Gainesville
  - Temperature 10 million K
- Held up by neutron degeneracy pressure
  - Mass can not exceed 2-3 $M_{\odot}$ or it will collapse
Pulsars: The Detection of Neutron Stars

- Neutron stars were predicted in 1930s
- In 1967 Jocelyn Bell detected the 1st pulsar
  - In the Vela Supernova remnant
  - Emitted a radio pulse exactly every 1.3373011 seconds
  - Jokingly called LGM 1 (Little Green Men)

Pulsars

- Several 100 are now known
  - Periods as short as a few milliseconds
  - Pulse in radio, optical and X-rays
  - There are some binary pulsars
    - Allow measurements of mass
    - Testing of General relativity
- The lighthouse model
  - Pulsar is a magnetic rotating neutron star
  - Beams of light are generated by electrons in the strong magnetic fields and are sent out from poles
  - We see pulses when the beams are toward earth

Black Holes

- What if remnant mass > 3 $M_{\text{sun}}$?
  - Neutron pressure can not hold it up
  - Collapses even further
- Escape velocity is greater than speed of light
  - Density is so high even light can not escape
    - Light & matter go in but they don’t come out
  - Essentially completely cutoff from our universe

Black Holes

- Can only be detected by interaction with another object
- Matter gets very hot falling into black hole
  - Should emit strongly in X-rays
- Binary stars
  - Use Doppler effect & Kepler’s laws to measure mass of star+companion
  - Subtract mass of star
  - Is mass of unseen companion > 3 $M_{\text{sun}}$?
  - Best candidates have M > 9 $M_{\text{sun}}$

Cygnus X-1

- Mass companion = 9 $M_{\text{sun}}$

Cosmic Recycling

- All stellar remnants are much less massive than their parent star
  - Large amounts of material is ejected from the stars into space
- This material is enriched in elements more massive than H and He
  - All elements heavier than H & He came from stars
  - We are made of the ashes of dead stars
- This material is used in subsequent generations of stars