Chapter 12: Stellar Evolution

Notes and Sketches

12.1: Leaving the Main Sequence

Stars and the Scientific Method

- You cannot observe a single star from birth to death
- You can observe a lot of stars in a very short period of time
- Compare/contrast/classify
- Wait for the physics to catch up, and explain

Structural Change

- Main sequence: Star burns hydrogen (fuses into He)
- Hydrostatic equilibrium: Gravitational collapse balanced by outward thermal pressure
- Star stays on main sequence while in hydrostatic equilibrium
- What happens when hydrogen core is consumed depends almost entirely on mass
- Low mass stars end very differently than super-massive stars

12.2: Evolution of a Sun-Like Star

Stages 8 and 9—Subgiant to Red Giant

Hydrogen Core to Helium Core

- When hydrogen at core fuses to He, fusion stops (need greater temp and pressure to fuse He)
- When fusion stops, He pressure decreases slightly
- Pressure decrease creates gravitational contraction
- Core heats up as He is squeezed gravitationally

Hydrogen Shell Burning

- Underlying He core releases heat, enough to create hydrogen fusion is layers above core
- Rate of hydrogen fusion is faster than before
- More energy produced means star gets brighter

Outer Layer Expansion

- Shell burning creates outward pressure on upper layers
- Upper layers expand and start to cool
- Time frame from main sequence to red giant ≈ 100 million years

Red Giant

- Typically by Stage 9, size increase ≈ $100R_\odot$
- Helium core radius ≈ radius of Earth, but contains about 25% of the star's mass
- Density of helium core ≈ 10^8 kg/m^3 (water = 10^3 kg/m^3)

Stage 10—Helium Fusion

Helium Flash

- When core temp reaches 10^8K, helium can fuse
- Happens rapidly and violently: Uncontrolled core fusion for ≈ hours
- Core expands, density drops, new equilibrium of He → carbon fusion at core

Less Luminosity

- Energy from He flash does not generate increased brightness
- Energy used to expand core (causes cooling)
- Surface temp increases, but luminosity does not
- Takes about 10^5 years

Horizontal Branch

- Star stays stable with He fusing core and hydrogen fusing shell
- Radius shrinks back down to ≈ $10R_\odot$
- Location on HR determined by what mass remains after red giant phase

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Stage 11—A Red Giant Again

Helium Core to Carbon Core

- He at core will eventually all fuse into carbon
- Same sequence starts to repeat again
- Core fusion ceases, core gravitational collapse generates heat

Helium Shell Burning

- Underlying carbon core releases energy, ignites the layer of He above it
- Now there is a layer of helium fusion surrounded by a layer of hydrogen fusion above it
- Same sequence of rapid expansion as before

Asymptotic Giant Branch

- Radius and luminosity both greater than previous red giant stage
- Carbon core begins to shrink

12.3: The Death of a Low Mass Star

Stage 12—A Planetary Nebula

Everything Falls Apart

- Carbon core: No fusion, just residual heat
- H and He shells burning, expanding
- Expansion causes cooling
- Gas envelope escapes (very rapidly, ≲ million years)

Planetary Nebula

- Carbon core continues to shrink
- Temperature increases (moves from visible to UV)
- Higher energy radiation ionizes surrounding gas

Planetary Nebula ≠Emission Nebula

- Both glow via the same physical mechanism (electrons absorb/emit)
- Cloud of gas & dust does not exist for the same reason
- Emission nebula = region of star formation
- Planetary nebula = small star's end of life

The Shape of Things to Come

- Most planetary nebulae are not spherically symmetric: Rings jets, etc.
- Shape can be influenced by many factors
- Cat's Eye: Two stars (binary) both shedding envelopes simultaneously

Galactic Fertilizer

- Remember that, even though it's mostly H and He, all the other elements are present as well
- As the majority of the mass escapes, the heavier elements are escaping as well
- This enriches the interstellar medium, provides the seed material for the next generation of star formation

Dense Matter

- That carbon core—what happens to it?
- Not massive enough to sustain further fusion (temperature/pressure insufficient)
- Core will reach an equilibrium between gravitational collapse and electron repulsion
- Final result is very, very dense ($\approx 10^{10}$ kg/m^3)
- Final result is very, very hot ($300\text{x}10^6$ K), but still insufficient for further fusion

Stage 13—A White Dwarf

White Dwarf

- Glows (in the visible part of the spectrum) because of residual heat
- Can be seen outside planetary nebulae: Globular clusters, binary companions

Black Dwarf
- Residual heat dissipates: Glow will diminish over time
- White dwarf will gradually just keep getting cooler and dimmer
- Becomes "black" when it no longer glows visible
- Gravitational/electron pressure equilibrium can be maintained almost forever (almost)

Helium Dwarf
- Stars much smaller than the sun do not have enough mass to fuse helium
- Convection keeps core supplied with hydrogen until ALL the H fuses into He
- The natural evolution of this would be longer than the age of the universe, so none have been observed
- You can create this artificially with a binary companion that strips outer mass from smaller star

Nova (Plural: Novae)
- Sudden burst of energy from a white dwarf
- The star should not have enough mass to explode
- The star is still there even after the explosion

Star Thief
- A white dwarf with a main sequence binary companion
- When dwarf is close enough, it can steal mass away from the other star
- Dwarf will gradually accumulate an accretion disk (in the plane of rotation)

Sudden Surface Explosion
- Accreted mass gets hotter as more mass gets added
- Sudden helium flash at the surface (corresponding sudden increase in brightness)
- Accreted matter gets violently blown away

Recurrent Novae
- As long as the binary companion has mass to share, the process will repeat
- A star that "goes nova" will do it again after accreting enough matter
- How much time this takes depends on how massive/close the companion star is

12.4: Evolution of Stars More Massive Than the Sun

Formation of Heavy Elements

Stars A Bit More Massive Than The Sun
- Stars up to about 10 $M_\odot$ form white dwarfs
- Fusion stops at either carbon, or with increasing mass oxygen

Ten Solar Masses and More
- Fast paced evolution: Multiple fusion shells
- Heavier and heavier elements forming at core
- Red supergiant: Cool (≈4000K) and huge (> 100$R_\odot$)

Observations of Supergiants
- Supergiants shed mass at a very, very rapid rate
- Stellar wind: ≈3000 km/s, up to an Earth's worth of mass loss every year
- Huge mass ejections possible as star approaches end of life
- Star can eject the equivalent of 1000 Earth masses per year

The End of the Road
- When the end comes, it comes FAST
- Each heavier core burns for a shorter period than the previous (lighter) core
- Core can only fuse into heavier elements up to iron

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The Iron Curtain

- Atomic structure of iron means that it is not possible to continue fusion at core
- Once the core becomes iron, there's no regaining an equilibrium
- Outward pressure from core fusion stops, gravity is unopposed
- Star starts to collapse under its own weight
- Core temperature shoots up as high as 10 billion K

Particle Soup

- Photodisintegration: Energetic photons break the iron nuclei into small and smaller pieces
- Ultimately, nuclei are split into constituent particles: Loose protons and neutrons
- Takes energy to split nuclei: Core heat decreases, collapse speeds up
- Particles are squeezed until electrons + protons start to form neutrons (releases neutrinos)

Incomprehensible Density

- Neutrino release carries away more energy, again speeds up collapse
- Core is almost entirely neutrons by this point
- Density about 10^{15} kg/m^3 as neutrons brought into contact

Core Collapse Supernova

- Neutron repels neutron when you try to compress them closer together than they can actually get
- Result is a "rebound," or outward pressure
- "Pressure" would be an extreme understatement
- Star explodes
- This whole process happens faster than you can imagine: Less than a day to grow the iron core, and from there it takes only a second or two to collapse and explode

12.5: Supernova Explosions

Novae and Supernovae

- These are not the same thing at all, even though at a distance they may look alike: sudden dramatic brightening, followed by gradual dimming
- Novae can be recurrent (not so with supernovae)
- Supernovae release many, many, many times more energy

Type I and Type II Supernovae Explained

- Mass is the key
- Type I is a low-mass/binary system event
- Type II is core collapse event (higher mass stars)

Type I: Carbon Detonation Supernova

- White dwarf accretes mass from its main-sequence partner
- Nova: Surface explosion as helium ignites
- Not all the accreted mass is blown away: star ends up a bit more massive than before
- White dwarf gradually grows more massive
- Chandrasekhar limit: $1.4M_\odot$
- Above this limit, white dwarf collapses suddenly, carbon fusion begins throughout

White Dwarf Collision

- Type I supernova can also happen when two binary white dwarfs collide
- Two low-mass stars combine to form single unstable star
- Whatever way you do it, the result is essentially hydrogen-free

Supernova Remnants

- Crab Nebula: Remnant from 1054 CE Type II explosion
- Vela Remnant: About 9000 BCE
- Curiously, no supernovae in our own galaxy for at least 400 years (you would expect, on average, one exploding star about every 100 years)

Notes and Sketches

Formation of the Heavy Elements

- Fusion factories (stars!) can make elements up to iron
- Elements heavier than iron created during supernova explosions
- We are all made of stars...literally

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12.6: Observing Stellar Evolution in Star Clusters

Cluster Evolution

- Clusters: Stars that formed at the same time in the same region of space
- Mass of star determines its evolutionary track and where it ends up on the zero-age main sequence (ZAMS)
- Even if stars form at the same time, they do not age at the same rate

Main Sequence Turn-Off

- Plot stars of cluster on HR diagram to determine age of cluster
- The younger the cluster, the more hot blue giants on ZAMS
- The older the cluster, the fewer blue giants on the ZAMS (increasing number of white dwarfs)
- As cluster ages, more and more stars leave main sequence
- Main sequence turn-off: Where do you stop seeing stars on the ZAMS?

Blue Stragglers

- Anomalous presence of hotter, more massive stars at an inconsistent cluster age
- These stars appear to have formed via mergers and collisions
- These stars did not form at the same time as the rest of the cluster: Late arrivals

Globular Clusters

- Composed of mostly aging stars
- Appear to contain multiple generations of stars
- Older stars will have fewer heavy elements in their spectra
- Younger stars form from death of initial generation of giant stars
- As older stars explode, they seed the cluster with heavier elements
- Younger stars will have different proportions of heavy elements than older stars
- Evidence = multiple main sequence tracks

12.7: The Cycle of Stellar Evolution

The Ultimate Recycling Program

- Conservation of Mass: However much there is, that's how much there is
- Matter is continually being rearranged into new atoms and recycled into new stars
- Not just stars; literally everything. As in EVERY. THING.
- Process in cyclic: All of this has happened before, and all of it will happen again.