

Unit 4: Birth of Stars... Lives of Stars

Interstellar Matter

- This is dust & gas that occupy space between the stars
- Stars form in the dust/gas clouds in space

Dust

- Dust is ~1% of the total visible mass in space
- Obscures our view of distant objects
- Is a mixture of elongated, tiny grains of dirty ice, grains of graphite (carbon), silicate particles, complex molecules

Interstellar Reddening

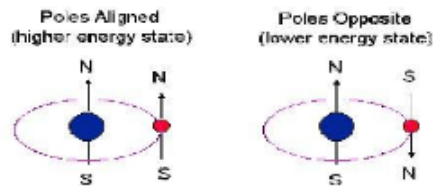
- Light from a star passes through the dust
- The dust particles are ~same length as blue λ 's
- The dust scatters blue λ 's more than red λ 's
- More red photons pass unimpeded through the dust & reach the observer
- Star appears redder than it actually is

Gas

- "☹" *There exists ~ 100 times more gas mass than dust mass in the Universe*
- Gas/Dust ~ 100
- The **visible** Universe contains ~75% Hydrogen, 24% Helium, < 1% Other (*carbon, nitrogen, oxygen, iron*)

H1 Regions

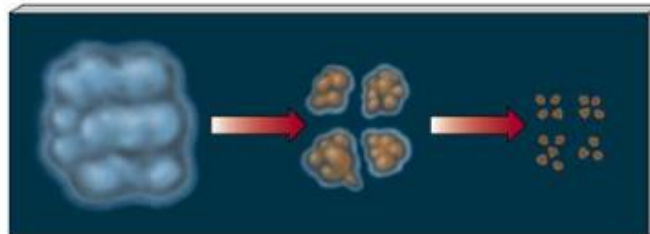
- These are clouds of neutral (= NOT ionized) Hydrogen ; *ionized = take electrons away*
- Contain ~ $1M_{\odot}$ to ~ $100 M_{\odot}$
- The cold Hydrogen gas is in its ground state ($n = 1$ orbit)
- The Hydrogen atom has TWO possible ground state configurations
- The electron may undergo a spontaneous "spin flip"
- From aligned (= parallel) state to the
- Opposed (= anti-parallel) state
- [SPIN FLIP OF HYDROGEN, parallel spins & anti-parallel spins (lower energy state)]



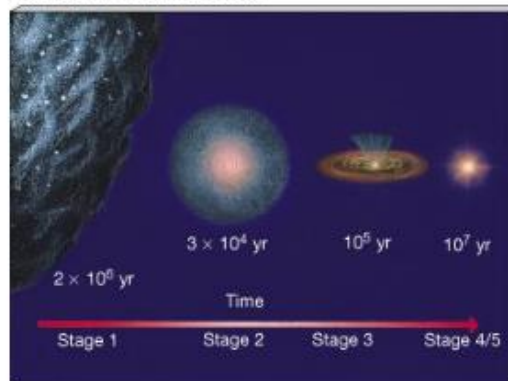
- Excess energy is released as a tiny burst of radiation
- = a photon of definite wavelength: $\lambda = 21\text{cm} = 0.21\text{m}$
- In radio region of Electromagnetic Spectrum
- The corresponding frequency is $f = 1.42 \times 10^9 \text{ Hz} = 1.42 \text{ GHz} = 1.42 \text{ GigaHertz}$
- This wavelength is used to map the Milky Way Galaxy & to search for messages from extra-terrestrials

Starbirth Scenario – 179

- Consider a giant interstellar cold molecular H_2 cloud
- $> \sim 10$ of light-years across, contains $(10^4 - 10^6) M_\odot$
- Gravitational force \propto mass
- Random particle fluctuations in the cloud act as gravitational foci (*focus*) to attract more material
- Contracting condensates in cloud dissipate their gravitational energy as heat (infrared radiation)
- Material falling onto a condensate \rightarrow internal heat & shock waves $\rightarrow H_2$ molecules dissociate
- This contracting object is a PROTOSTAR (*contract through infrared*)
- Core of protostar = the central 10%-15%
- Core reaches 10 million K = 10×10^6 K = 1×10^7 K ; *minimum temperature needed for nuclear fusion*
- \rightarrow Hydrogen-based nuclear reactions begin in the core \rightarrow A STAR IS BORN
- A Main Sequence Star has H-based nuclear reactions in the core
- The entire birth process for an *average* star takes 10^6 to 10^7 years
- The process is faster for a massive star ... $\sim 10^5$ years
- [Cloud Fragmentation]



- [Interstellar Cloud Evolution]



The Main Sequence Stage – 185

- $T_{\text{core}} \geq 10 \times 10^6$ K \rightarrow Hydrogen fusion nuclear reactions in the core
- A star spends its life in a delicate balance between outward radiation pressure & inward gravitational pull
- $\sim 90\%$ - 95% of stars are Main Sequence... including our Sun

Hydrogen Fusion Reactions = Proton-Proton Chain

- ${}^2\text{H} + {}^1\text{H} \rightarrow {}^3\text{H} + e^+ + \nu$ (deuterium, positron, neutrino)
- ${}^2\text{H} + {}^1\text{H} \rightarrow {}^3\text{He} + \gamma$ (helium isotope, radiation burst)
- ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + {}^1\text{H} + {}^1\text{H}$ (helium, hydrogen) ; left side always have higher mass
- Overall, 4 Hydrogen nuclei fuse to form 1 Helium nucleus & a small amount of mass is released as energy (4.3×10^{-12} J)
- BUT... a typical star has 10^{25} such reactions each second!
- $(4.3 \times 10^{-12} \text{ J}) \times (1 \times 10^{25}) = \sim 4 \times 10^{13} \text{ W}$
- This is the Luminosity (energy per second) observed for our Sun (a typical star)
- Luminosity = $L = 4 \pi R^2 \sigma T^4$ = energy / s

Life on the Main Sequence – 191

- Star fuses Hydrogen nuclei into Helium nuclei deep in its core via p-p chain
- Core temperature must be at least $10 \times 10^8 \text{ K} = 10$ million K ; Sun is 15mil K
- $4\text{H} \rightarrow 1 \text{He}$
- $\sim 10^{25}$ such reactions occur each second
- MASSIVE STARS: greater core densities & greater core pressures
- Faster rate of Hydrogen fusion \rightarrow shorter Main Sequence lifetime of only few million years

The Sun – 193

- Massive stars only live for a few million years
- Normal stars live for billions of years
- Our Sun is a normal star & will fuse Hydrogen in its core for a total of ~ 10 billion years
- Our Sun is now 4.5 billion years old

Nemesis

- $\sim 55\%$ of stars have a companion
- Mass extinctions occur on Earth \sim every 25-30 million years
- Perhaps the Sun has never-observed companion which comes near to the Sun periodically
- It disturbs the orbits of nearby comets, asteroids, meteors
- These may crash into Earth & precipitate mass extinctions

Characteristics of Nemesis

- If it exists, Mass $\sim 0.01 M_{\odot}$, Distance $\sim 89 \times 10^5 \text{ AU} \sim 90,000 \text{ AU}$, Period ~ 26 million – 30 million years

The Red Giant Phase – 196

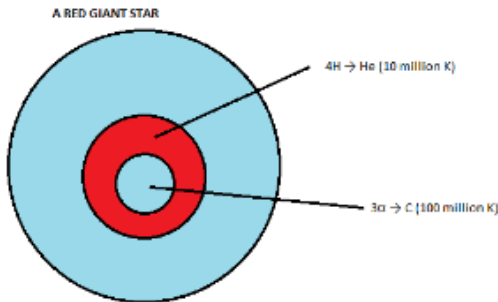
- Core runs low on Hydrogen fuel & contracts dramatically
- Core contraction \rightarrow temperature rises in core
- At $T = 100 \times 10^8 \text{ K} = 1 \times 10^9 \text{ K} = 100$ million Kelvins
- Helium-based nuclear fusion reactions take place in the core

Helium Fusion Reactions = Triple α Process – 197

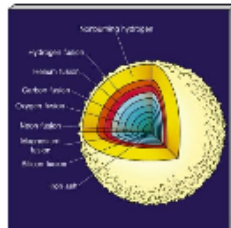
- ${}^4\text{He} + {}^4\text{He} \rightarrow {}^8\text{Be} + \gamma$ (beryllium, radiation burst)
- ${}^4\text{He} + {}^8\text{Be} \rightarrow {}^{12}\text{C} + \gamma$ (carbon, radiation burst)
- Note that 3 Helium nuclei fuse to form one Carbon nucleus. ; $3 \text{He} \rightarrow 1 \text{C}$
- A small amount of mass is converted to energy & released

- [triple-alpha process]

Shell Fusion



- Successive core contractions can produce He, C, O, Ne, Mg, Si in the core & in surrounding shells



[FIG: Heavy- element Fusion]

; Silicon makes iron = death of star since no fuse.

- H fusion: $T_{\text{core}} = 10$ million Kelvins = 10×10^6 K
- He fusion: $T_{\text{core}} = 100$ million Kelvins = 100×10^6 K
- \exists a temperature gradient from the core to the surface
- AROUND the He-fusing core, there is a shell of stellar material which is at 10 million Kelvins = 10×10^6 K
- Hydrogen fusion takes place in this shell
- Core energy + Shell energy \rightarrow increased radiation pressure outward
- Star expands & surface reddens = a Red Giant
- A Red Giant star is NOT fusing Hydrogen in its core
- A very massive star can undergo SEVERAL Red Giant phases

Evolutionary Stages of a Massive Star (~25 M_{\odot})

- Hydrogen fusion: 7×10^5 years
- Helium fusion: 7×10^3 years
- Carbon fusion: 600 years
- Oxygen fusion: 6 months
- Silicon fusion: 1 day ; produces iron
- Core collapse: $\frac{1}{4}$ second
- Explosive supernova: 10 seconds

Evolutionary Stages of a Normal Star (<~4 M_{\odot})

- Our Sun is a normal star & is NOT massive
- Our Sun & stars of similar mass can ONLY fuse H \rightarrow He & He \rightarrow C
- When our Sun has a core consisting of Carbon (& a little bit of Oxygen), it will DIE because our Sun has insufficient mass to perform C-based nuclear reactions needed to generate outward pressure & balance the inward pull of gravity

End of Star Formation – 209

- Stars FORM in vast interstellar Hydrogen & Helium clouds
- As the Universe ages, Hydrogen is being transformed into heavier elements inside the stars

- The Hydrogen component of the Universe is always declining
- The abundances of heavier elements are increasing
- Eventually new stars will cease to form & the stelliferous era will end

Unit 5: Measuring Stellar Properties (5Qs on test)

- Light year = ly: Distance that light travels in one year $1 \text{ ly} = 9.5 \times 10^{15} \text{ m}$
- Parsec = pc: $1 \text{ pc} = 3.26 \text{ ly}$
- Astronomical Unit = AU: Average distance between Earth & Sun

Distance via Parallax Method (only for nearby stars) – 225

- $\sin \Theta \approx \text{opposite} / \text{hypotenuse} = 1 / d = \Theta$ (for small angles)
- $D = 1 / \Theta$ If Θ is in seconds of arc ("), then d is in parsecs (pc)
- $D = 3.26 / \Theta$ If we multiply by 3.26, then d is in light years (ly)
- Method only good for stars $d < \sim 50 \text{ pc}$ (163 ly), only good for nearby stars

Apparent Magnitude (m)

- Hipparchus (Hipparchos) of Greece (2nd century B.C.) divided the VISIBLE stars into 6 groups
- $M = 1$ (brightest star in Greek sky) 2...3...4...5... $m = 6$ (barely visible)
- $M = 1$ is 2.5 times brighter than $m = 2$
- The more negative m , more brighter the star

Determination of Apparent Magnitude (m)

- Star \rightarrow star light \rightarrow photocell \rightarrow current \rightarrow meter \rightarrow computer
- **Problem:** W Pegasi is an 8th magnitude ($m = 8$) star. Formalhaut is 1st magnitude ($m = 1$)
Which star appears to be brighter? $M = 6$ is barely visible, $m = 8$ is even fainter
 \rightarrow Formalhaut ($m = 1$) is brighter than W Peg.

How MUCH brighter?

- $\Delta m = 8 - 1 = 7$
- Ratio of brightness = $R = 2.5^{\Delta m}$ $R = 2.5^7$ $R = \sim 610$ times brighter

Absolute Magnitude (M)

- Absolute magnitude (M) = apparent magnitude (m) of star AT a distance of 10 parsecs (= 32.6 ly) from us
- To convert m to M : $M = m + 5 - 5 \log (d)$ The distance, d , MUST be in parsecs
- **Problem:** What is the absolute magnitude of the Sun?
 $d_{\odot} = 4.7 \times 10^{-6} \text{ pc}$; apparent magnitude = -26.5 (= brightest celestial object)
 - $M = m + 5 - 5 \log (d)$ $M = -26.5 + 5 - 5 \log (4.7 \times 10^{-6})$ $M = 5.14$
 Today's smog & air pollution \rightarrow the Sun would be barely-visible at 10 pc from us
- **Problem:** What is the absolute magnitude of Alpha Centauri? Parallax?
 $d_{\alpha\text{cen}} = 4.4 \text{ ly}$; apparent magnitude is $m = -0.01$

- We must convert the distance to parsecs
 $4.4 \text{ ly} \times 1 \text{ pc} / 3.26 \text{ ly} = 1.35 \text{ pc}$
 $M = m + 5 - 5 \log (d) \quad M = -0.01 + 5 - 5 \log (1.35) \quad M = 4.34$
 αCen is dimmer if pushed out to 10 pc (= 32.6 ly)
- Its parallax angle Θ (in arcsec = seconds of arc) is
 $\Theta = 1/d = 1/1.35 = 0.74''$

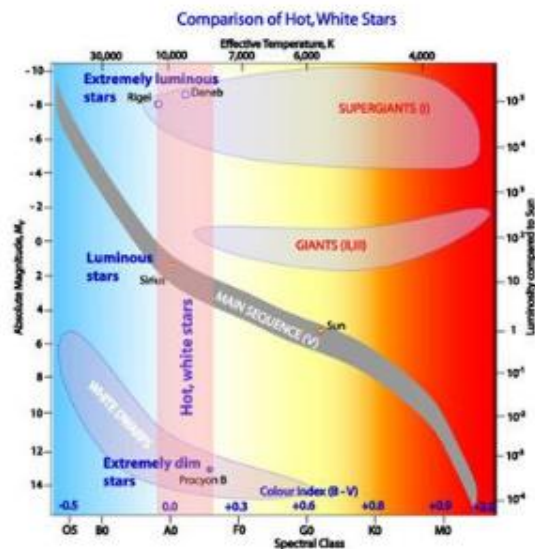
Radius Determination Problem – 235

- The surface temperature of the Sun is 5800K. R_{\odot} in m?
- If $L = 4 \pi R^2 \sigma T^4$, then

$$R = \left(\frac{L}{4\pi\sigma T^4} \right)^{\frac{1}{2}} \quad \text{** NOT ON FORMULA SHEET} \quad R = \left(\frac{3.9 \times 10^{26}}{4\pi(5.67 \times 10^{-8})(5800)^4} \right)^{\frac{1}{2}} = R \approx 7 \times 10^8 \text{ m} = R_{\odot}$$

The Hertzsprung Russel (HR) Diagram – 236

- HR diagram for the brightest stars in the sky – handout



- White dwarfs, faint, but very hot ; super giants not hot... very bright
- Spectra class "O B A F G K M" oh be a fine girl/guy kiss meo_o

The H-R Diagram

- A plot of stellar luminosities or magnitudes vs. surface temperature or spectral type
- The Harvard Spectral Classification System (= spectral type) is O B A F G M
- The HR diagram has distinct regions: Giants, Main Sequence, White Dwarfs

Spectroscopic "Parallax" Problem 1

- Find the distance (in pc & in ly) to a main sequence star with apparent magnitude of -1.1 & a surface temperature of 10000K
- HR diagram → absolute magnitude, $M = -2$
- Recall: $M = m + 5 - 5 \log(d)$ → $\log(d) = [m - M + 5] / 5$
 $D = 10^{(m - M + 5)/5}$ ** NOT ON FORMULA SHEET
- Note that this formula is NOT on your formula sheet. You must derive/know it for your test.
- $D = 10^{(-1.1 - (-2) + 5)/5}$ $d = 10^{2.25}$ $d = 2.4 \text{ pc} = 7.8 \text{ ly}$

Spectroscopic Parallax Problem 2

- Spica is a main-sequence star, spectral class B0, apparent magnitude 0.91. How far is Spica (in pc)?
- HR Diagram → $M = -3.5$ $d = 10^{(0.91 - (-3.5) + 5)/5}$ $d = 10^{2.882}$ $d = \sim 76 \text{ pc}$

Period-Luminosity Curve for Cepheid Variable Stars – 250

- A Cepheid variable star grows larger & brightens
- It then grows smaller & dimmer
- The entire cycle occurs over a time span of days
- Henrietta Leavitt produced a plot of Period vs. Magnitude (M)
- Period = time duration of one cycle
- Cepheids can be used as farther distance indicators to other galaxies
- A Cepheid varies in brightness → we use an average absolute magnitude, \bar{M}
- **Problem:** A Cepheid in another galaxy has an average magnitude of 15 & a period of 10 days
 - Is the Cepheid visible to the naked eye? What is the distance (in pc & in ly) to the Cepheid/galaxy?
- $d = 10^{(m - \bar{M} + 5)/5}$ ** NOT ON FORMULA SHEET
- $d = 10^{(15 - (-3) + 5)/5} = 10^{22/5} = 10^{4.4} = \sim 4 \times 10^4 \text{ pc} \sim 1.3 \times 10^5 \text{ ly}$ (Large Magellanic Cloud)

Velocity – 257

- Recall that radial velocity (v_r) is the component of the star's velocity along our line of sight $v_r = \frac{c \Delta \lambda}{\lambda_{lab}}$
- Proper Motion (μ) is the star's angular displacement perpendicular to (across) our line of sight
- It is measured in arcseconds per year (" / year) (= seconds of arc per year)

Tangential Velocity – 258

- Tangential velocity is the component of the star's velocity perpendicular to our line of sight
- $V_t = 4.74 \times 10^5 \mu d$
- Where v_t is in m/s, d is in pc, μ is in arcsec per year (" / year)

Space Velocity – 259

- Space velocity (v_s) is the actual velocity of the star in space

Typical White Dwarf – 273

- Mass $\sim 0.8 M_{\odot} \rightarrow 1 M_{\odot}$
- Mass limit is $1.4 M_{\odot}$, the Chandrasekhar Limit
- Size \sim same size as Earth
- Density $\sim 10^9 \text{ kg/cm}^3$
- Magnitude = $M \sim +11$ (very dim)
- Temperature $\sim 15000 \text{ K}$ on surface
- No longer has a central energy source
- We can detect ~ 500 White Dwarfs \rightarrow our Milky Way galaxy must contain billions of them
- The brightest star in our sky is Sirius A & it has a faint White Dwarf companion, Sirius B.

Death of Middleweight Stars – 278

- These are $\sim (8 - 20) M_{\odot}$
 - $< \sim 5\%$ of stars are $> \sim 4 M_{\odot}$
1. Star undergoes several Red Giant Phases, producing ever-heavier elements in the core

Evolutionary Stages of a Massive Star ($\sim 25 M_{\odot}$)

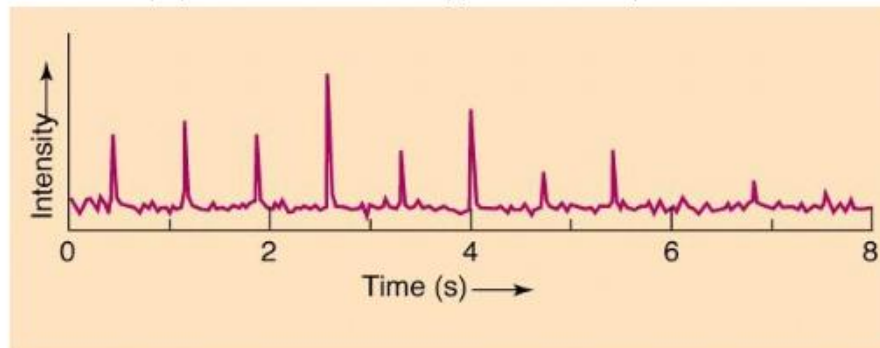
- | | |
|-----------------------|-----------------------|
| - Hydrogen fusion | 7×10^5 years |
| - Helium fusion | 7×10^3 years |
| - Carbon fusion | 600 years |
| - Oxygen fusion | 6 months |
| - Silicon fusion | 1 day |
| - Core collapse | $\frac{1}{4}$ second |
| - Core bounce | milliseconds |
| - Explosive supernova | 10 seconds |
2. When star has an Iron core, Iron will NOT fuse \rightarrow outward radiation pressure decreases
 3. Star collapses inward, squashing core to fantastic densities
 4. This inward pressure dissociates the core Iron into constituent particles: neutrons, protons & electrons
 5. Protons & electrons are forced to merge to produce neutrons
 6. Neutrons reach max density & collapsing layers of star strike this tight ball of neutrons & star's layers are ejected into space... core bounce
 7. Star dies violently in a Supernova explosion
 8. High temperatures & densities in the ejecta support ALL known nuclear reactions
 9. ALL elements created & ejected into space
 10. Huge neutrino production... most neutrinos escape into space
 11. The elements $>$ Hydrogen in our bodies etc. came from the violent death of a star/stars
- We observe very few supernovae in our Milky Way Galaxy
 - Only $\sim 5\%$ of stars have sufficient mass
 - The Supernova event is relatively short-lived, the Milky Way is a very dusty galaxy
 - We observe ~ 2 Supernovae every hundred years in other galaxies

Supernovae in the Milky Way Galaxy – 286

- 1) 1054 A.D. Chinese QUEST Star as bright as our full moon... could read at night
- 2) 1572 observed by Tycho Brahe... some remnants remain
- 3) 1604 observed by Johannes Kepler

Light Curve

- 1967: Jocelyn Bell (graduate student at Cambridge) used a radio telescope to search/study Quasars
- She detected very rapid fluctuations in radio intensity (1.3 seconds interval)



- Original data of Jocelyn Bell → Discovery of first Neutron “Star”

Neutron “Stars”

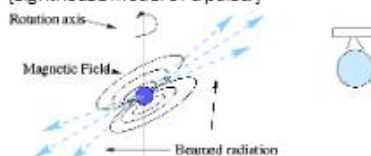
- Pulsar = Neutron “star” = the collapsed core remnant of a Supernova explosion
- This tight ball of closely-packed neutrons is only ~ (20-100) km across & has ~ same density as an atomic nucleus
- A Neutron Star has other characteristics similar to atomic nuclei

Earth’s Magnetic Poles

[Insert Pictures?]

Pulsation Explanation – 300

- A neutron “star” (NS) = compacted core of an exploded star that had a magnetic field
- A neutron “star” has a strong magnetic field which directs charged particles to the North or South magnetic poles
- The particles continually strike the surface of the neutron star, creating polar “hot spots”
- These “hot spots” radiate over a wide range of wavelengths... visible & invisible
- [Lighthouse model of a pulsar]



- If the rotating neutron star is properly oriented with respect to Earth, we detect the beams of radiation emitted by the “hot spots”

- This is the "Lighthouse Effect"
- We call the object a "pulsar"
- A pulsar is a neutron "star" BUT every neutron "star" is NOT a pulsar
- There are probably many unobserved neutron "stars", undetectable because their North/South poles are NOT oriented toward Earth

Typical Neutron "Star" – 307

- Mass range: $1.4 M_{\odot} < M_{NS} < \sim 3 M_{\odot}$
- Size: ~ 20 to 100km across \sim about the size of a city
- Density is similar to that of an atomic nucleus
- Temperature: $\sim 10 \times 10^8 \text{ K}$ on surface
- Period: 0.1 to 4 seconds
- We know of ~ 500 pulsars

Sanduleak

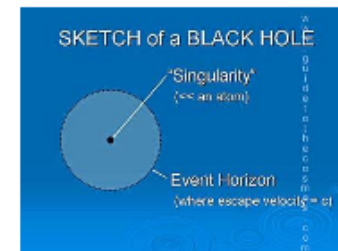


Supernova 1987A

- Discovered/reported from Chile by Ian Shelton, an observer from the University of Toronto
- SN1987A occurred in the Large Magellanic Cloud = an irregular galaxy near Milky Way at $\sim 170,000 \text{ ly}$ distance
- The progenitor star was a blue giant star, Sanduleak
- Huge neutrino bursts detected by Earth-based equipment
- This particular SN event has been studied from the actual explosion to the present day

Death of Very Massive Stars – 315

- These are $> \sim 25 M_{\odot}$
- $< \sim 5\%$ of stars are $> \sim 4 M_{\odot}$
- Star undergoes several Red Giant phases, producing ever-heavier elements in the core
- When star has an iron core, it "goes Supernova" ... BUT if the collapsed core is $3 M_{\odot}$, it cannot resist the pull of gravity & collapses to a Black Hole Singularity



Black Hole – 316

- A Black Hole consists of the central singularity & the Event Horizon Boundary
- Event Horizon is where an object must travel at c to escape
- Inside the Event Horizon, an object must exceed c to escape
- Light itself cannot escape the Black Hole
- The Event Horizon of a Black Hole is the "point of no return"

The Event Horizon – 318

- The spherical Event Horizon (EH) is non-tangible, non-visible location in space that surrounds/hides the singularity (= collapsed core)
- Events that occur within the Event Horizon cannot send information to the outside Universe
- Radiation & matter cannot escape from within the Event Horizon unless they exceed c

Escape Velocity – 325

- Minimum velocity required to escape the gravitational pull of a massive object
- The gravitational constant is $G = 6.67 \times 10^{-11} \text{ n}\cdot\text{m}^2/\text{kg}^2$; on formula sheet
- $v_{esc} = \left(\frac{2GM}{R}\right)^{\frac{1}{2}}$ M is mass of object in kg & R is radius in m

Escape Velocity for Earth

- $M_{Earth} = 6 \times 10^{24} \text{ kg}$ $R_{Earth} = 6.4 \times 10^6 \text{ m}$ Determine the escape velocity in km/s
- $v_{esc} = \left(\frac{2GM}{R}\right)^{\frac{1}{2}} = \left(\frac{2(6.67 \times 10^{-11})(6 \times 10^{24})}{6.4 \times 10^6}\right)^{\frac{1}{2}}$ $v_{esc} = 11,183 \text{ m/s} \approx 11 \text{ km/s}$

Black Hole Radius – 327

- We re-arrange the previous equation for radius, R_{BH}
- $R_{BH} = R_{EH} = R_S = \frac{2GM}{(v_{esc})^2}$ We know that at R_{EH} , $v_{esc} = c = 3 \times 10^8$

Black Hole Radius Problem

- A collapsed stellar core is $25 M_{\odot}$ Determine the radius of its Event Horizon (= radius of Black Hole)
- $R_{BH} = R_{EH} = R_S = \frac{2GM}{(v_{esc})^2} = R_{BH} = \frac{2(6.67 \times 10^{-11})(25)(1.99 \times 10^{30})}{(3 \times 10^8)^2} = \sim 74 \times 10^2 \text{ m} = 74 \text{ km}$

The Schwarzschild Radius, R_s

- "There exist" several constants in the previous equation: 2 , G , M_{\odot} , v_{esc} (= c)
- Evaluating these constants gives us $\sim 3000 \text{ m} = 3 \text{ km}$
- The previous equation becomes the Schwarzschild radius **$R_s = 3 M_{\odot} \cdot \text{km}$**
- Where **$M_{\odot} = M_{object} / M_{\odot}$**

Black Hole Radius Problem ... AGAIN ... but with simple formula

- $R_s = 3 M_{\odot}$ $M_{\odot} = 25 M_{\odot} / M_{\odot} = 25$ $R_s = 3 (25) \text{ km} = 75 \text{ km}$ This agrees with previous result.
- Thus if the mass of the singularity is given in solar masses, e.g. $9 M_{\odot}$, $20 M_{\odot}$, $27 M_{\odot}$

- Then R_s is, respectively, 27 km, 60km, 81km
- Note that R_s is in km when you use this simple equation ; on formula sheet

Black Holes

- Generally divided into 4 categories depending on mass
1. Mini Black Hole (= primordial Black Hole):
 - Hawking postulates they might have formed during the Big Bang BUT ... never found
 - $R_s \sim 9 \times 10^{-4}$ km $\sim 9 \times 10^{-2}$ ~ 9 mm
 - But don't try to hold one! Mass \sim Mass of Earth
 2. Stellar Black Hole:
 - Forms from the gravitational collapse of a singular star of large mass
 - Mass $\sim 3 M_\odot$ to $100 M_\odot$ $R_s \sim 9$ km to 300km
 3. Intermediate Black Hole:
 - Forms from the collapse of material equivalent to thousands of solar masses
 - Mass ~ 100 's M_\odot to 1000 's M_\odot $R_s \sim 300$ km to 3000 's km
 - Whether they exist or not is uncertain ... early stages of search
 4. Super massive Black Holes
 - Resides in the centers of most galaxies & power active galactic nuclei (e.g. Quasars)
 - Mass \sim several 10^6 to several $10^9 M_\odot$
 - $R_s \sim 3 \times 10^6$ km to $> 3 \times 10^9$ km
 - Our Milky Way galaxy is believed to have a "sleeping" supermassive Black Hole ($\sim 3 \times 10^6 M_\odot$) at its center

Searching for a Black Hole – 336

- They emit NO light, so we can't see a Black Hole directly
- We seek a stellar Black Hole in a binary system consisting of a visible Giant star & an invisible companion (= BH candidate)
- [Black Hole Binary System]



The Search

- We seek a Giant Star that "wobbles" in its orbit
- The companion causes the "wobble" must be invisible
- The invisible companion must have a mass $> \sim 3 M_\odot$
- The system must be emitting x-rays (from a surrounding Accretion Disk)
- We can use the Wien equation to determine the temperature of the Accretion Disk: $T = 0.0029 / \lambda_{\text{max}}$

Cygnus XI – 341

- Best stellar Black Hole candidate
- We can see a visible supergiant star of $\sim 30 M_\odot$
- The supergiant star is "wobbling" under the influence of an invisible companion
- The system is emitting x-rays
- Mass of invisible companion is $\sim 9.5 M_\odot$
- Recall that a Black Hole singularity has a mass $> \sim 3 M_\odot$