Evolution of Stars

RAC Presentation

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Outline

- Overview
- Star Formation
- Evolution Paths
- Remnants
- Summary
- Questions

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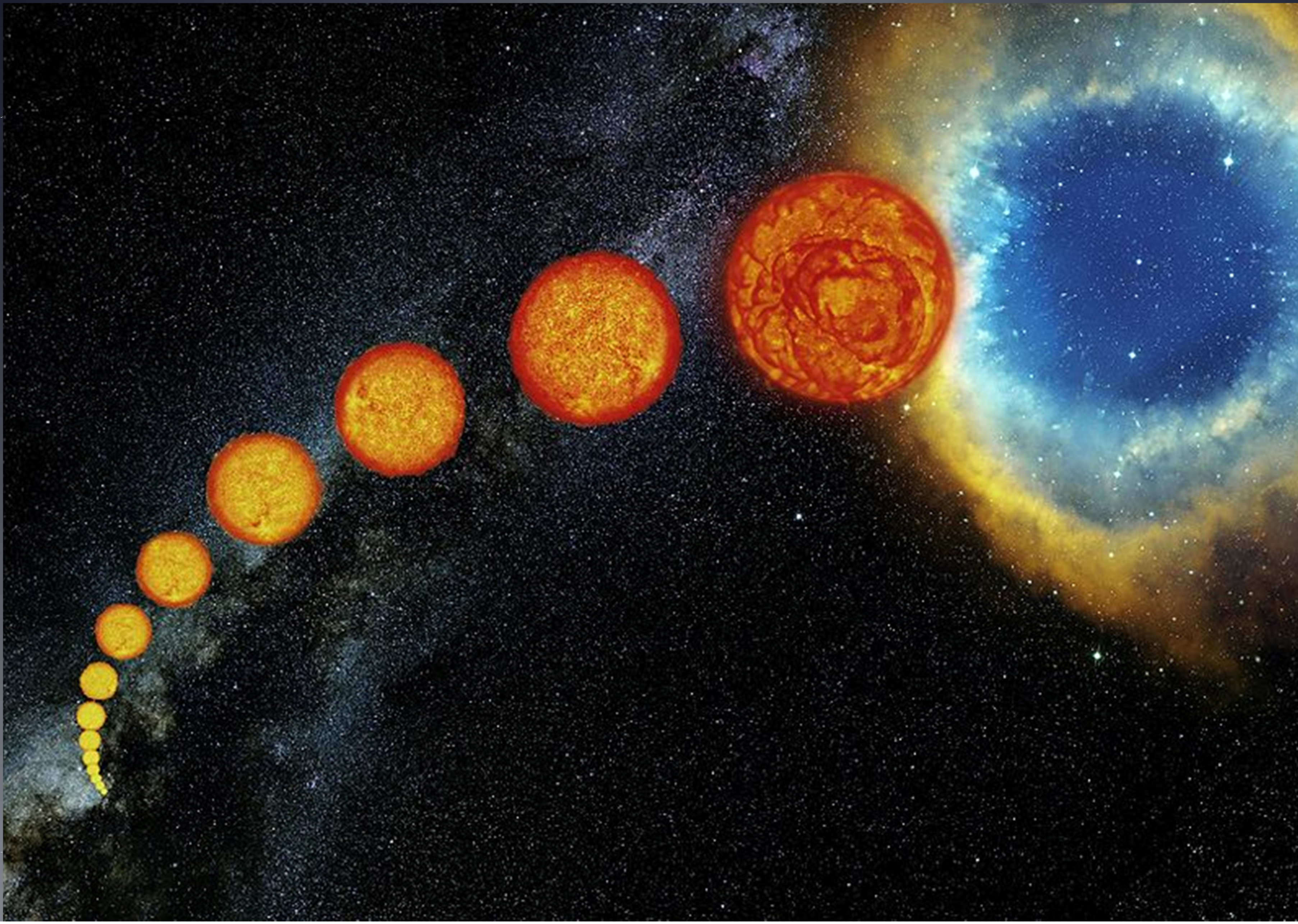
Introduction



Stellar Overview

- Stellar evolution is dominated by initial mass
  - Composition plays a secondary role
- Fusion is the primary energy source
- Stars spend most of their time on the "main sequence", burning hydrogen
- Stellar evolution stabilized by hydrostatic equilibrium
  - Changes happen when stars fall out of equilibrium
- Stellar interiors behave like ideal gases in *most circumstances*

Stellar Overview 2

- Final states:
  - 85% of stars will end as Red Dwarfs,
  - Most of the rest will end as White Dwarfs.
  - A few stars go Supernova
  - Massive stars go through core collapse to neutron stars or black holes
  - White dwarfs in close binary systems suffer thermonuclear explosion and total disruption

Introduction

- Born from clouds of gas and dust
  - Stars like our Sun burn Hydrogen in nuclear fusion
  - Burning Hydrogen for several billion years to make Helium
  - As Hydrogen is used up they swell to large Red Giants
    - 100 times larger
  - Red Giants oscillate slowly in brightness
  - Then die as planetary nebulae
    - Usually a white dwarf is left
- Stars lifetime:
  - Giant stars live Millions of years
  - Small Stars live Trillions of years
  - (Universe is 13.7 Billion yrs. old)

A Star is Born

- Stellar evolution begins with the gravitational collapse of a Giant Molecular Cloud (GMC)
- Typical GMCs are about 100 light-years across
  - Contain up to 6,000,000 solar masses
  - As it collapses, a GMC breaks into many smaller pieces.
  - In each of these fragments, gravity compresses the gas, which heats the gas
  - As its temperature and pressure increase, a fragment condenses into a rotating sphere of superhot gas known as a Protostar
  - Protostars start fusion of Hydrogen to become stars

Fusion

- Fusion is the primary power source for stars
- Only power source capable of sustaining stellar structure against gravity for the time scales needed.
  - 4 1H to 4He + neutrinos + gamma rays
  - E = mc2 in action!
  - 0.7 % of mass of hydrogen ions is converted to energy during fusion into helium

Stellar Interiors

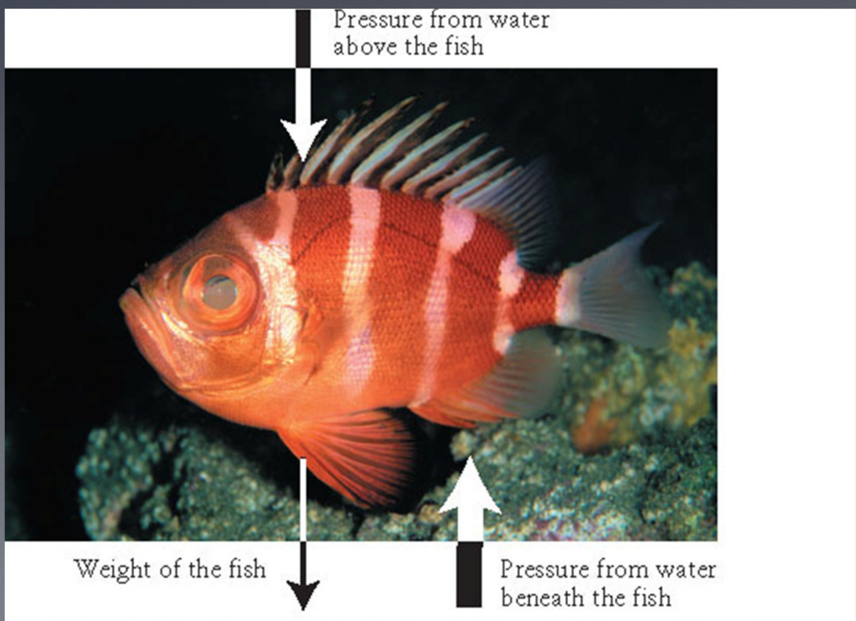
- Stellar Interiors Act Like Ideal Gases (usually)
- In an Ideal Gas, there is a simple relationship between pressure, temperature, and density:
  - Pressure is proportional to Density x Temperature
- This implies:
  - As a gas expands, it cools
  - As a gas is compressed, it heats up
- In a star, this provides a safety valve:
  - If the rate of fusion rises, the temperature tends to rise
  - The temperature rise increases the pressure, expanding the gas just enough to cool the gas back down and stabilize the rate of fusion
- Thermal equilibrium is maintained

Protostars

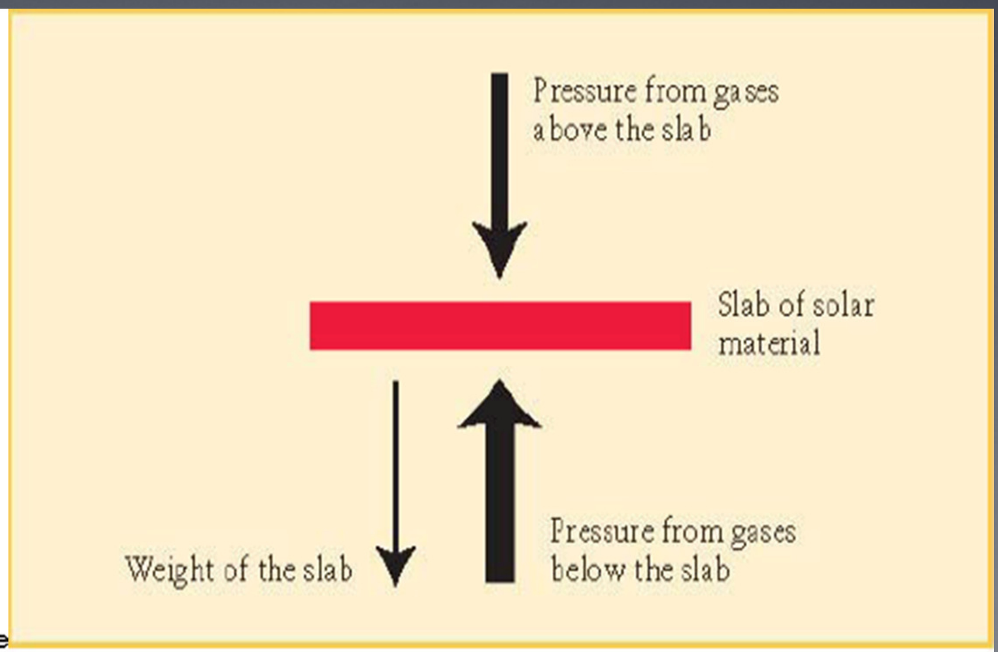
- Protostars with masses below 0.08 $M_\odot$ NEVER become stars
  - They never start fusion of Hydrogen to Helium
  - They become BROWN DWARFS
  - They shine dimly and die away slowly, cooling gradually over hundreds of millions of years.
- More Massive Protostars reach a core temperature of 10 million degrees Kelvin (K)
  - Proton-Proton chain reaction begins: Hydrogen becomes Deuterium, then Helium
  - The star core quickly heats from the nuclear energy
  - Hydrostatic equilibrium brings the star to a stable state (core fusion exerts a "outward thermal pressure" balancing the weight of the star's matter)
  - Beginning the "main sequence" phase of its life
  - Energy generation is strongly dependant on temperature & pressure
  - Massive stars burn faster

Hydrostatic Equilibrium

- Hydrostatic equilibrium is the balancing of the downward pull of gravity by the gas pressure below (pressure gradient)
- Gravity + P above = P below



(b) A fish floating in water is in hydrostatic equilibrium, so forces balance



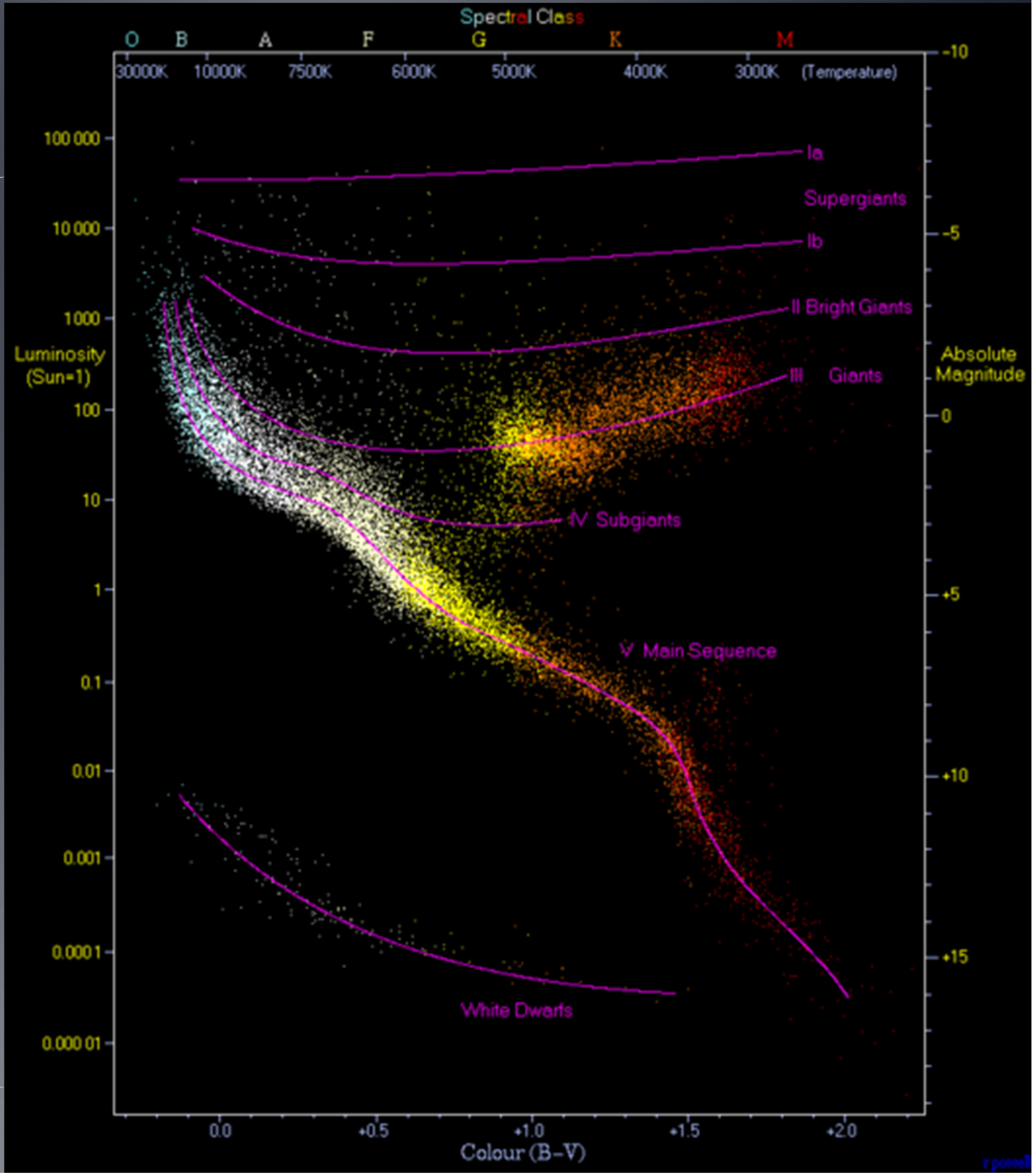
HR Diagram

Hertzsprung-Russell

diagram plots the actual brightness or absolute magnitude of a star against its color index. The "main sequence" is visible as the diagonal band that runs from the upper left to the lower right.

The position of the star on the main sequence is determined primarily by its mass

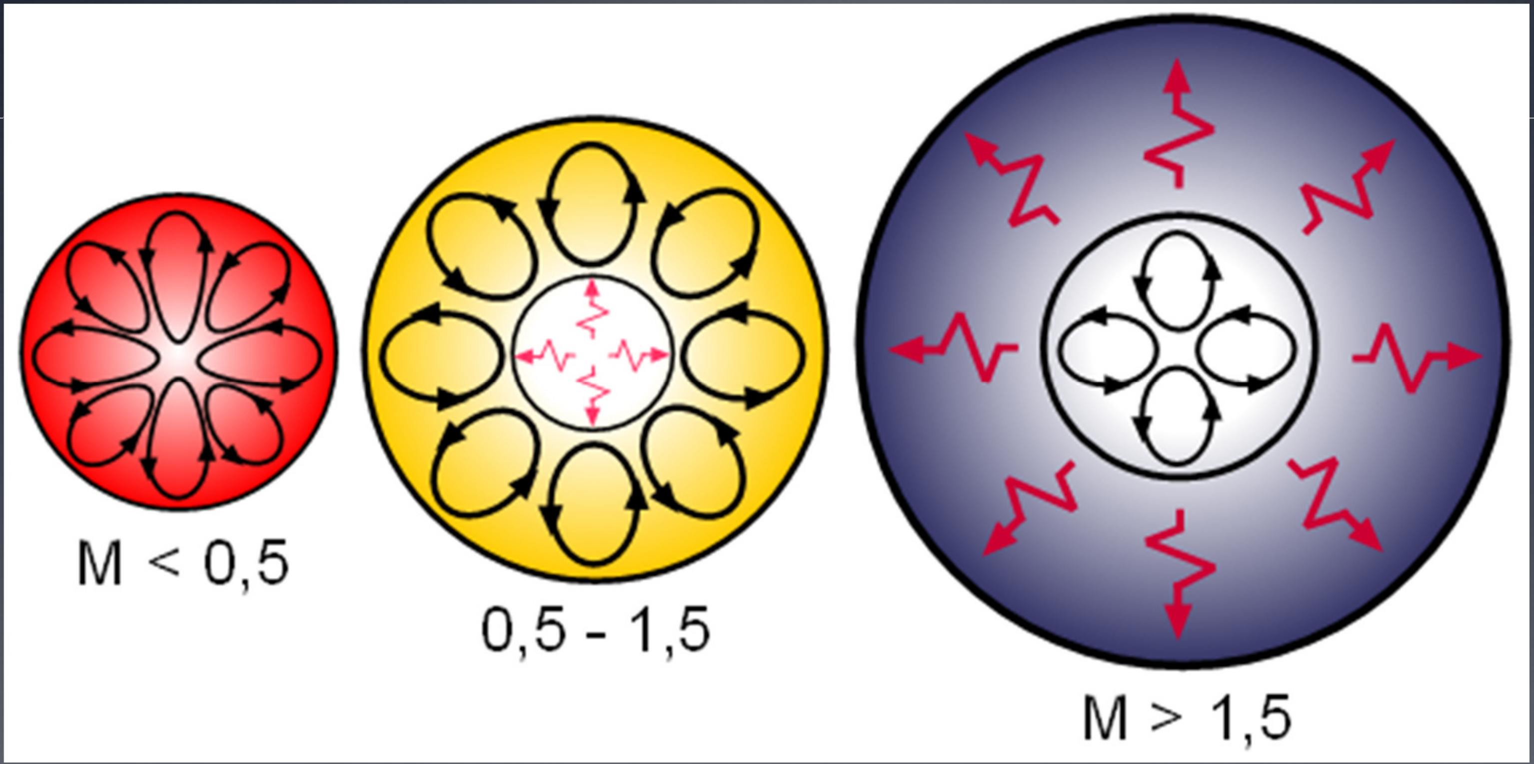
After the hydrogen fuel at the core has been consumed, the star evolves away from the main sequence



Behavior of Stars

- The behavior of a star now depends on its mass
- Stars below 0.23 solar masses become WHITE DWARFS directly
- Stars less than 0.5 solar masses never fuse Helium—RED GIANTS (Aldebaran & Arcturas) live on main sequence for up to 6 Trillion years, then become WHITE DWAFS
- Stars up to ten solar masses pass through a RED GIANT stage
- More massive stars can explode as a SUPERNOVA
- OR Collapse directly into a BLACK HOLE
- OR collapse into a Neutron Star if mass < 2-3 solar masses

Star Types



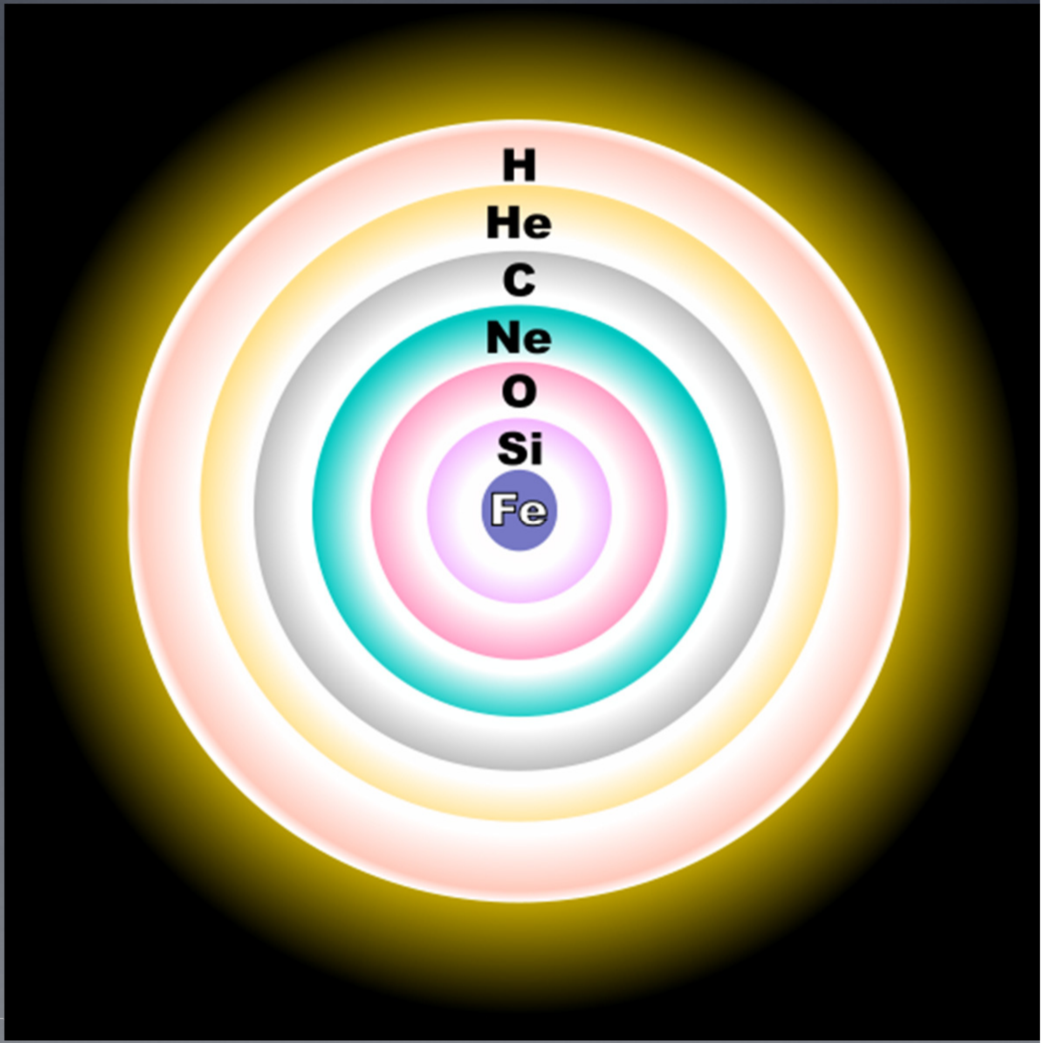
- Low-mass stars, less than half a solar mass, are fully convective from core to the surface
- In intermediate-mass stars (such as the sun), radiation transport works well-- a stagnant core develops, surrounded by a convective region -- stars' surfaces are like the GMC
- At 1.5 solar masses, the convective layer has almost disappeared and the star is almost fully radiative.
- Above 1.5 solar masses, the CNO cycle contributes the majority of the energy

Star Fusion Shells

Once the the fusion process reaches Iron-56 it consumes energy and the star collapses to form a Neutron Star or a Black Hole

Through a process that is not completely understood, some of the gravitational potential energy released by this core collapse is converted into a Type Ib, Ic or II Supernova

A a spectrum of heavier-than-iron material including the radioactive elements up to uranium are created by this "explosion"



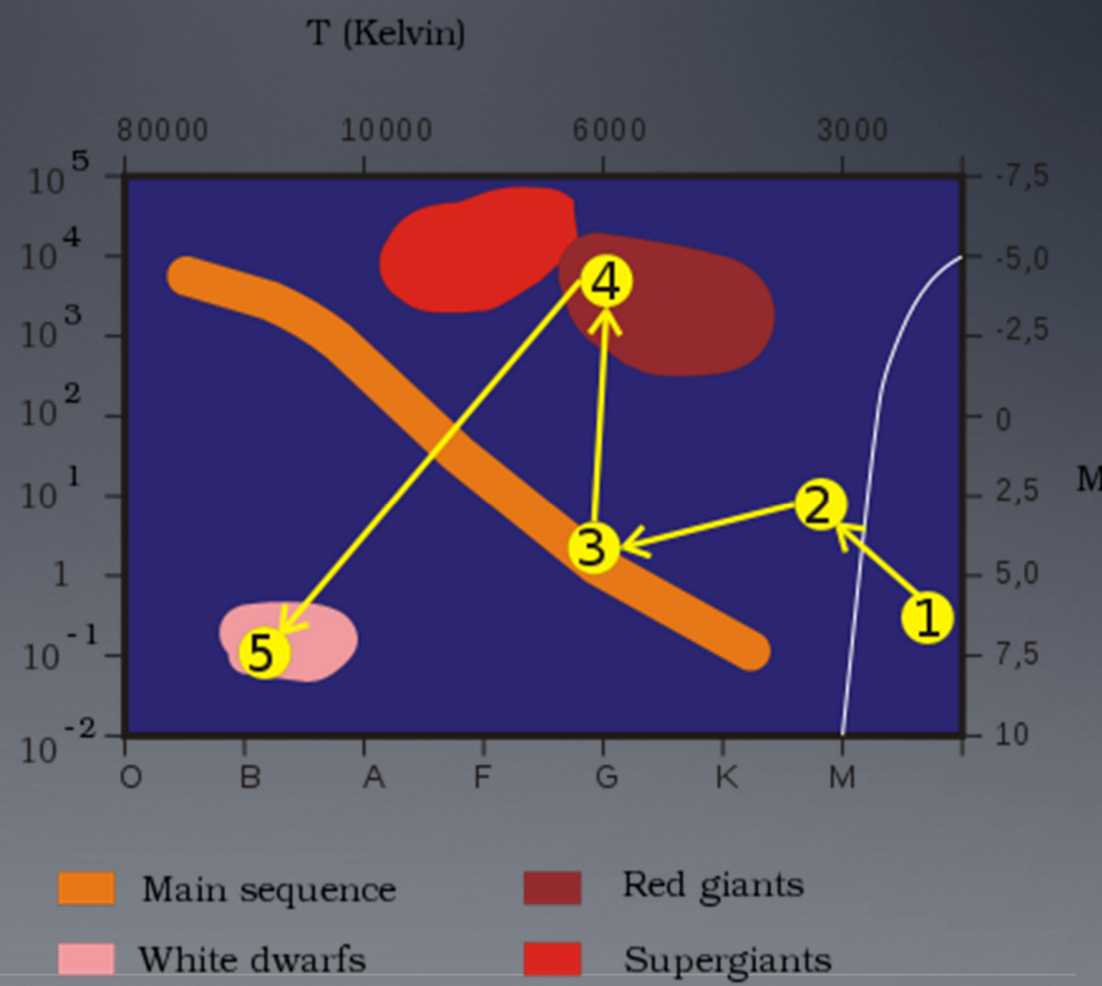
Evolution
Small & Medium Stars

- Eventually, the core exhausts its supply of hydrogen, and without the outward pressure generated by the fusion of hydrogen to counteract the force of gravity, it contracts until either electron degeneracy opposes gravity or the core becomes hot enough (100MK) for Helium fusion

- Which of these depends on the star mass
  - Electron degeneracy will halt the collapse of a star if its mass is less than 1.38 solar masses– it goes to a WHITE DWARF
  - Larger MEDIUM stars collapse to NEUTRON STARS
  - Stars less than 0.5 solar masses never fuse Helium—RED GIANTS
  - Red Giants leave the main sequence on the HR Diagram

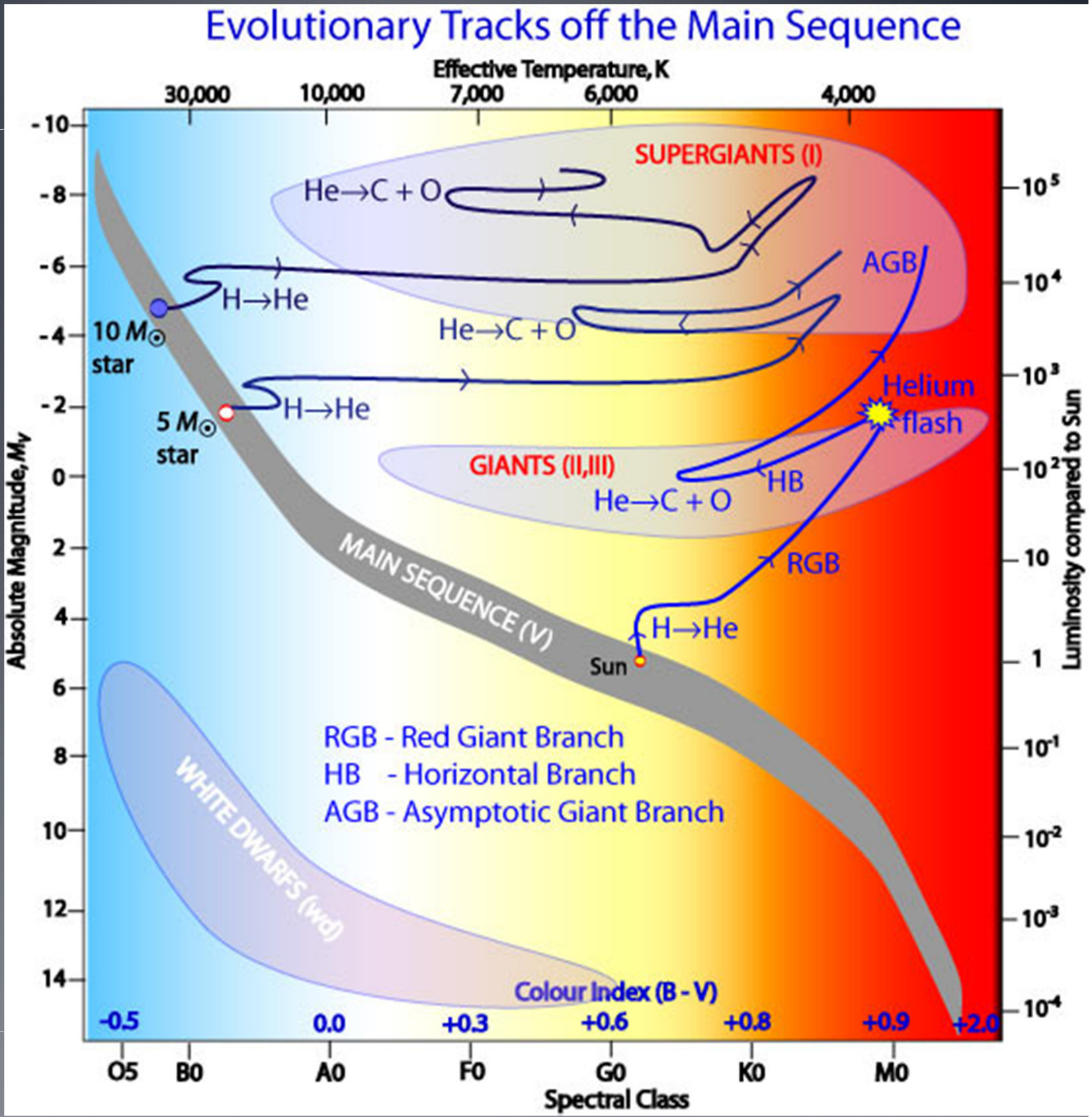
Evolution of a Star (Mass of the Sun)

- Star forms from a collapsing cloud of gas (1)
- Then contraction as a Protostar (2)
- Then joins the main sequence (3)
- Once the Hydrogen at the core is consumed it expands into a Red Giant (4)
- Then sheds its envelope into a planetary nebula and degenerates into a White Dwarf (5).



Stellar Evolution

- More Examples



Mid-sized Stars

- In either case (1) the star beginning Helium fusion OR (2) halting fusion due to hydrostatic equilibrium from electron degeneracy pressure:
  - The accelerated fusion in the hydrogen-containing layer immediately over the core causes the star to expand.
  - This lifts the outer layers away from the core, reducing the gravitational pull on them
  - They expand faster than the energy production increases.
  - This causes them to cool, which causes the star to become redder than when it was on the main sequence.
  - They become RED GIANTS
- Helium burning reactions are extremely sensitive to temperature. Huge pulsations build up and give the outer layers of the star enough kinetic energy to be ejected, potentially forming a planetary nebula. The core of the star cools down to a WHITE DWARF

Evolution, Larger Stars

- A star of up to a few solar masses will develop a Helium core supported by electron degeneracy pressure, surrounded by layers which still contain hydrogen.
- Its gravity compresses the hydrogen in the layer immediately above it, causing it to fuse faster than hydrogen would fuse in a main-sequence star of the same mass.
- This in turn causes the star to become more luminous (from 1,000–10,000 times brighter) and expand; the degree of expansion outstrips the increase in luminosity, causing the effective temperature to decrease

Massive Stars

- In massive stars, the core is already large enough at the onset of Hydrogen burning shell that Helium ignition will occur before electron degeneracy pressure becomes prevalent.
- When these stars expand and cool, they are brighter than the red giants formed from less massive stars.
- These stars are unlikely to survive as Red Supergiants, instead they will destroy themselves as Supernovae Type II

Extremely Massive Stars

- Extremely massive stars: > 40 Ms and < 120 Ms
- Extremely massive stars are very luminous and thus have very rapid stellar winds, lose mass so rapidly due to radiation pressure that they tend to strip off their own envelopes before they can expand to become RED SUPERGIANTS
- They retain extremely high surface temperatures (and blue-white color) from their main sequence time onwards
- Stars cannot be more than about 120 Ms because the outer layers would be expelled by the extreme radiation

The Nuclear Impasse

- Fusion of light elements releases nuclear binding energy
- Iron (Fe) is the most tightly bound nucleus
- Fusion of nuclei lighter than Fe releases energy
- Fusion of nuclei heavier than Fe absorbs energy
- Once an Fe core forms, there are no new fusion reactions left for the star to tap

End of the Road

- At the end of Silicon Burning:
  - Build up an inert Fe core and Onion Skin of nested nuclear burning shells
  - Finally, the Fe core exceeds 1.2-2 M_{sun}
  - Fe core begins to contract & heat up
  - Collapse is final & catastrophic

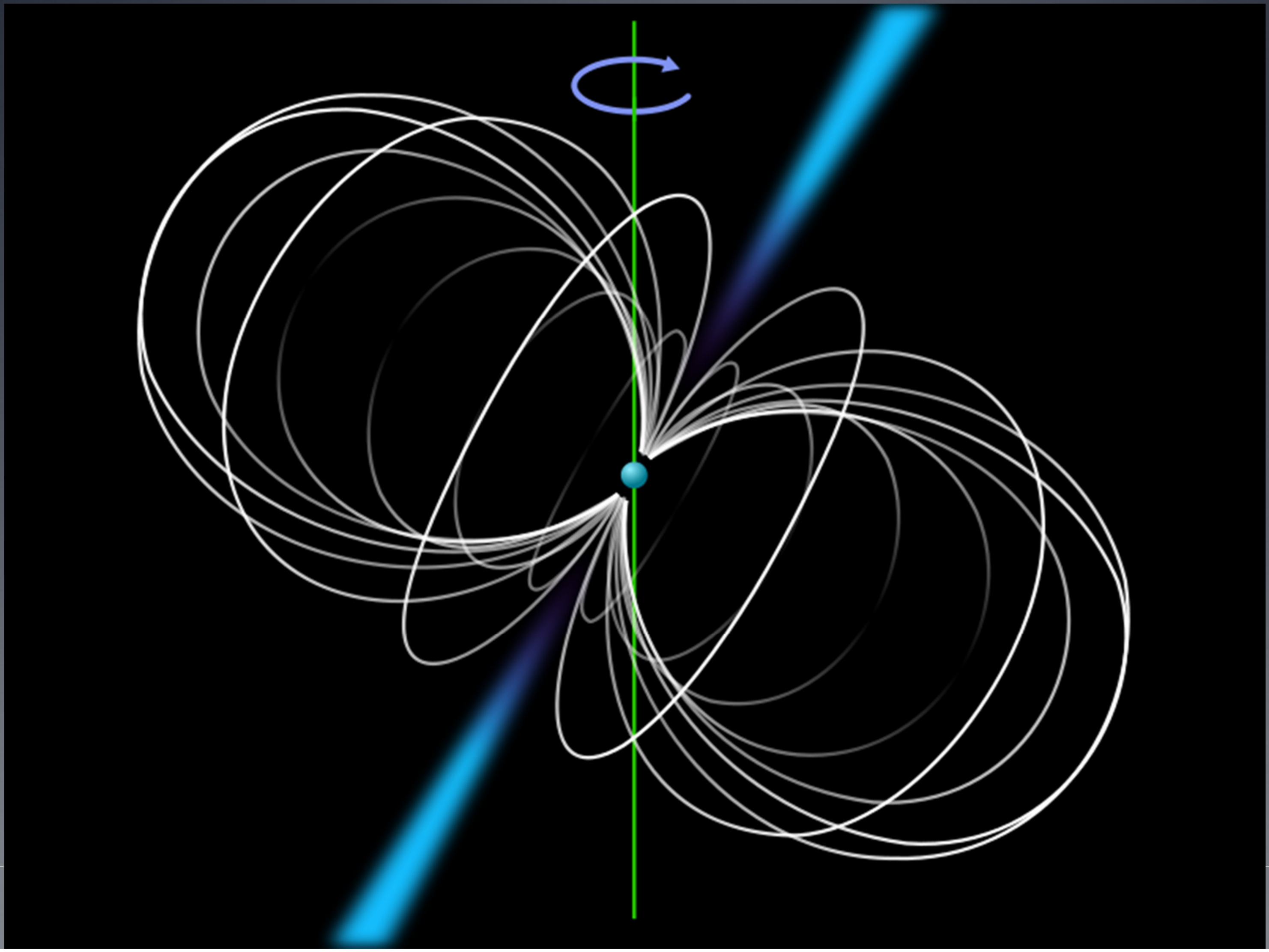
Star Fusion Summary

- Stars with 4 < Mass < 8 M_{sun}
  - Burn through Carbon & Blow off their envelope
  - Core becomes an O-Ne-Mg
- White Dwarf Stars with Mass > 8 M_{sun}
  - Burn Carbon, Neon, Oxygen & Silicon
  - Build up a heavy Iron Core & burning shells.
  - Final stage occurs when the Iron core begins to catastrophically collapse

Star Remnants

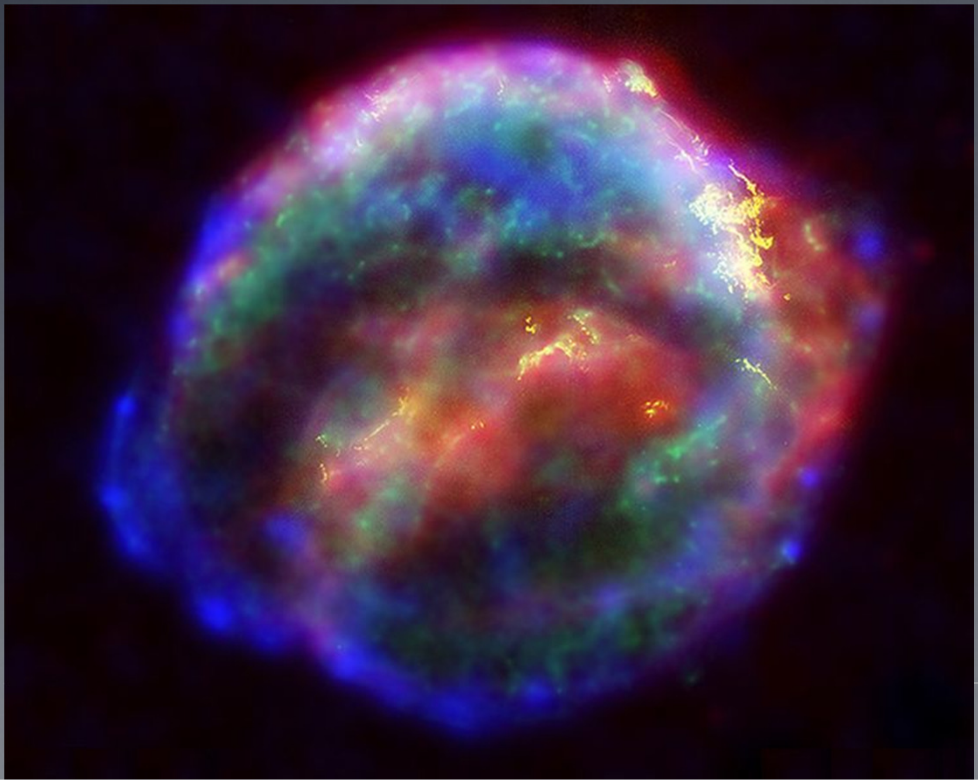
- White Dwarfs:
  - For a star of 1 solar mass (Ms), the resulting white dwarf is of about 0.6 Ms, compressed into approximately the volume of the Earth.
  - White dwarfs are stable because the inward pull of gravity is balanced by the electron degeneracy pressure
  - It radiates remaining heat into space for Billions of years
- Neutron Stars:
  - White Dwarfs of > 1.4 Ms collapse to Neutron Stars
  - Compression limited by Neutron Degeneracy
  - 10km radius
  - Some spin > 600 rev/sec
  - Pulsars
- Black Holes: If the mass of the stellar remnant is high enough (2-3 Ms), the Neutron Degeneracy pressure will not prevent collapse and it becomes a Black Hole

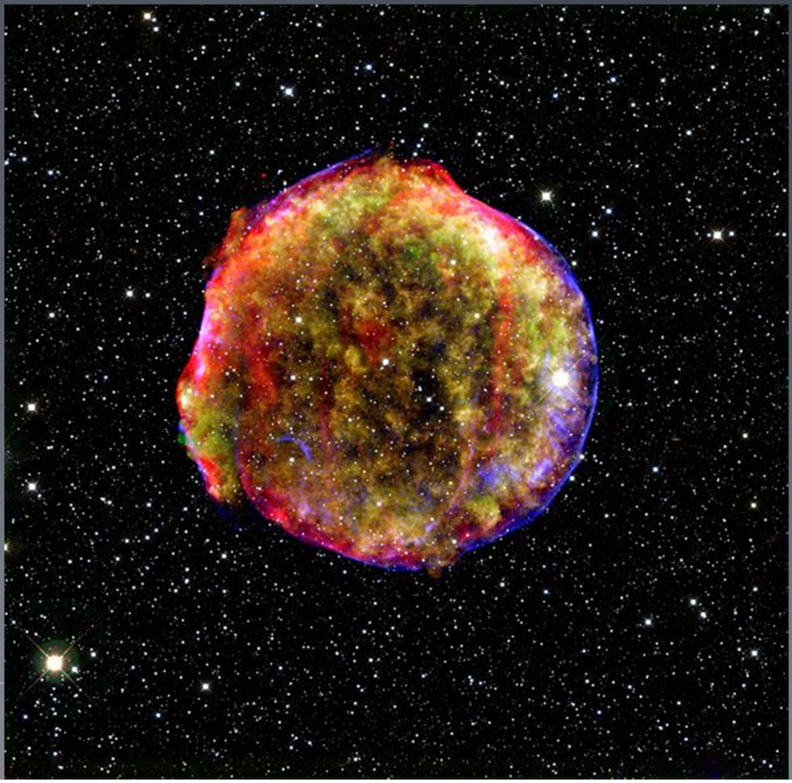
Pulsars



Supernovae or Supernovas

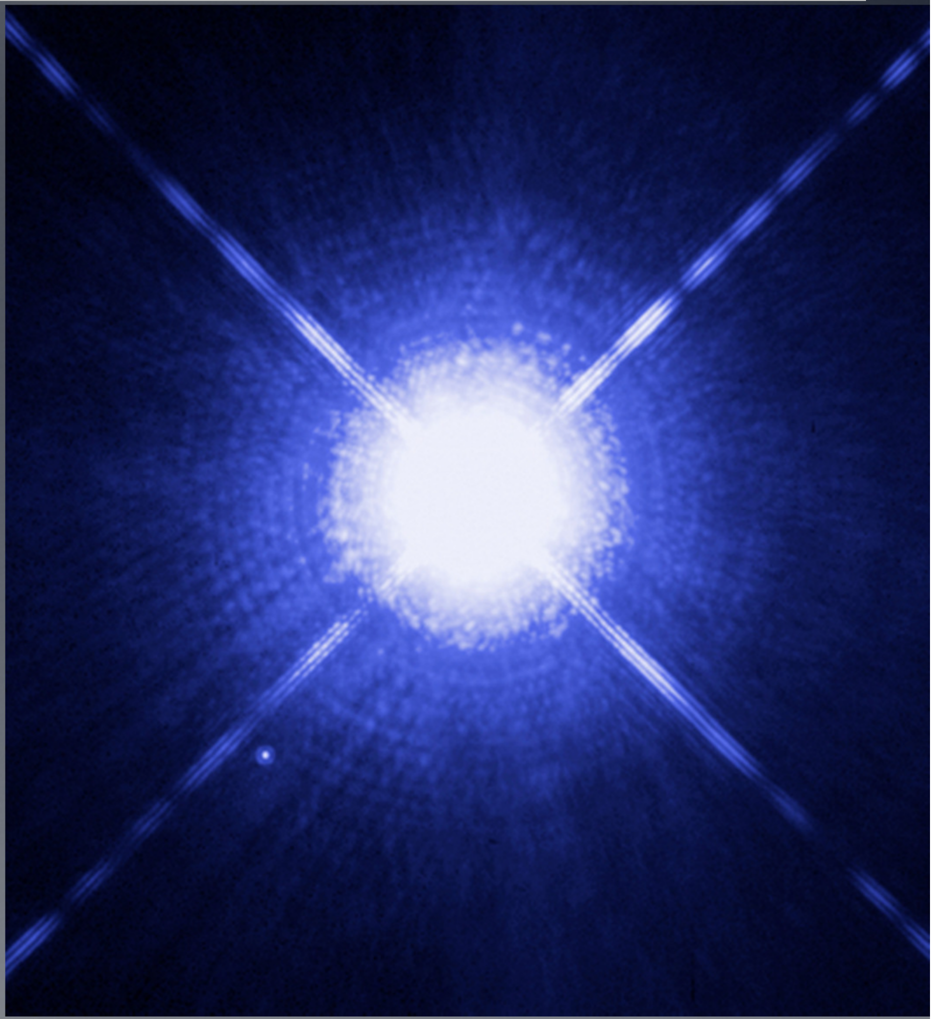
- Supernovae are classified iaw their spectral characteristics:
  - Type II contains Hydrogen
  - Otherwise, it is Type I
- Stars below 9 Ms never go to Supernova– go to White Dwarfs





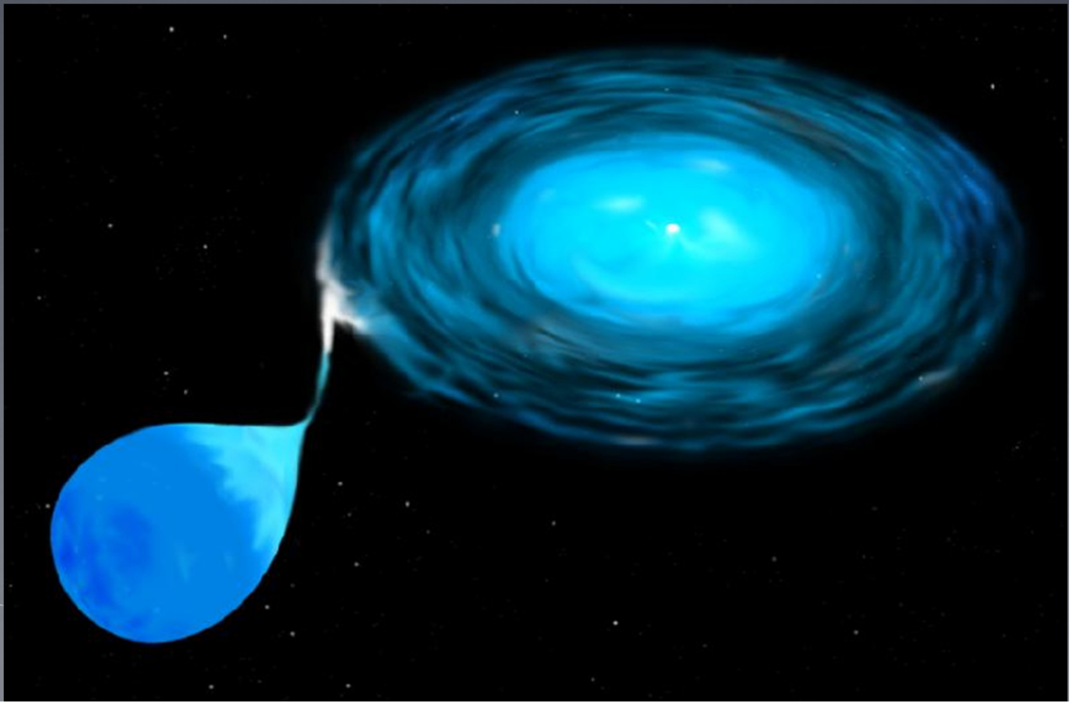
Binary Stars

- Sirius A & B photo
- Most stars are Binary
- Binary stars:
  - Effect star evolution
  - Can form novae & Supernova Ia



White Dwarfs as Binary Stars

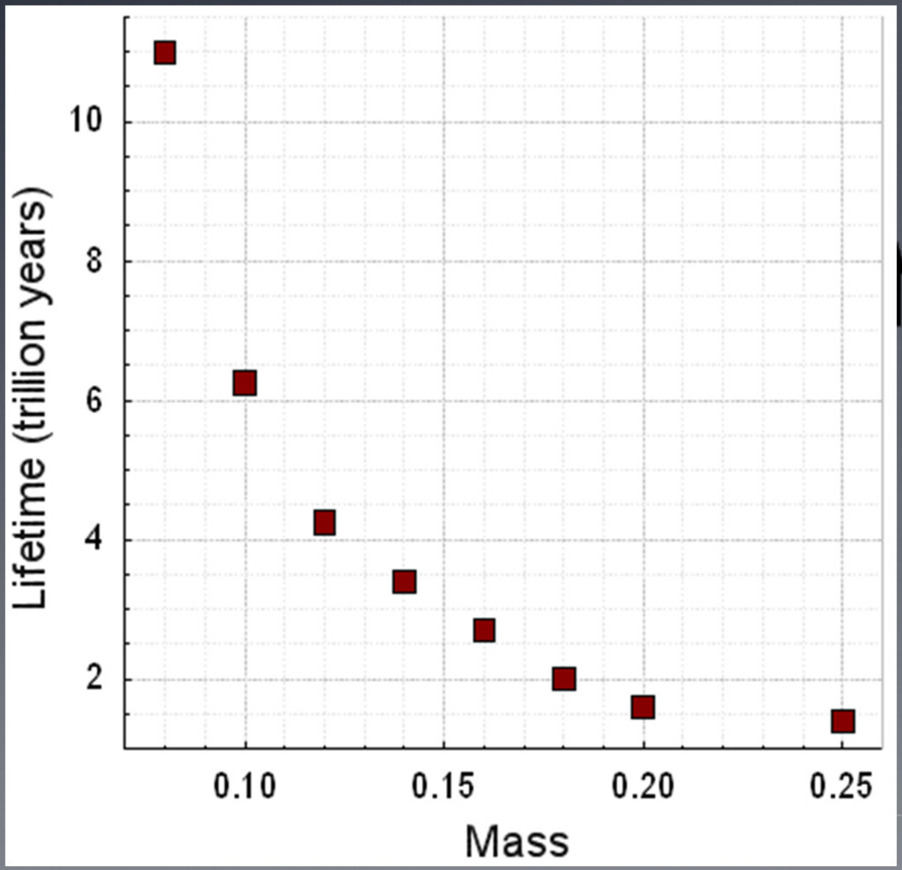
A white dwarf is a stellar remnant that has ceased nuclear fusion (or in final stages). It typically can weigh up to 1.4 times as much as our Sun — a figure called the Chandrasekhar mass. If it gets heavier, from accretion, gravity overwhelms the forces supporting the white dwarf, compacting it and igniting runaway nuclear fusion that blows the star apart--Supernova*

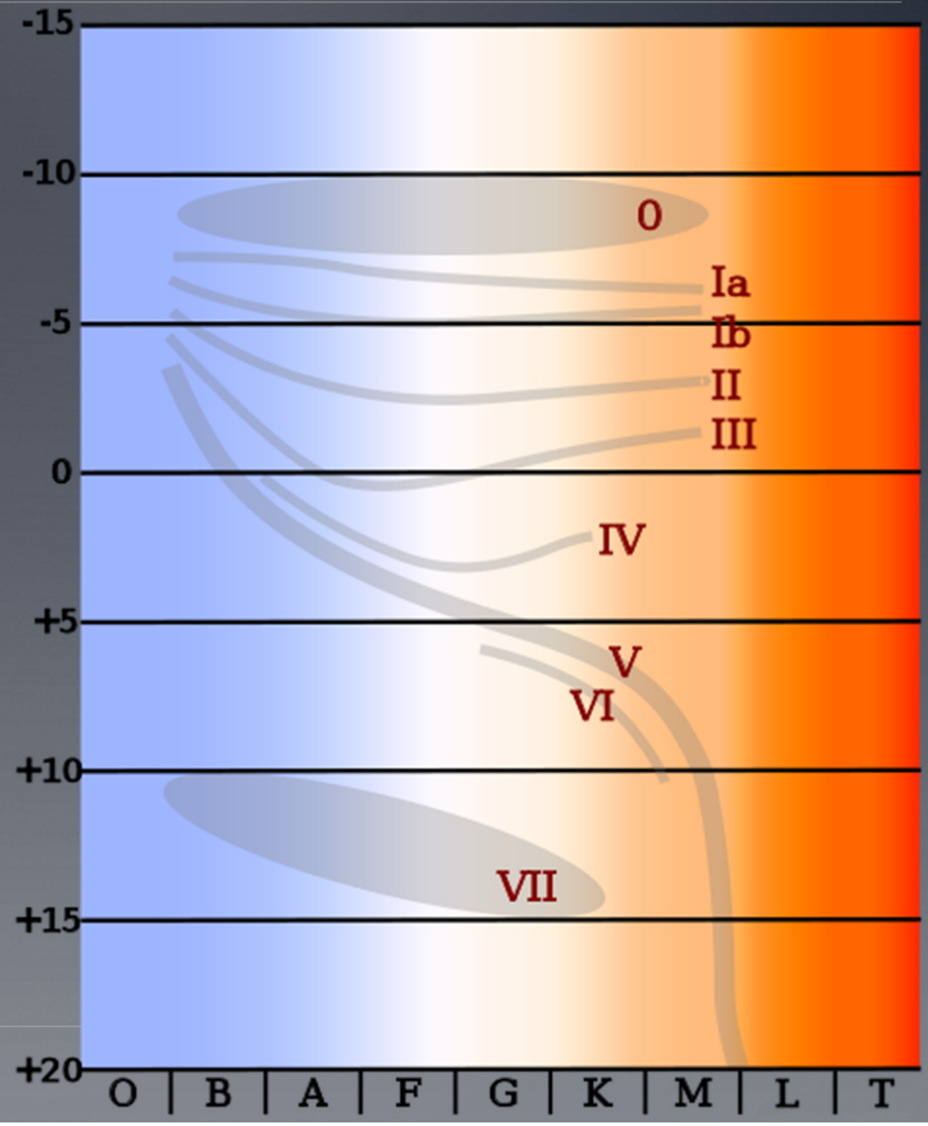


* Astronomy Magazine, 6 Sep 2011

One More Thing

Red Dwarfs Life vs. Mass re. Sun





Summary

- Stars form by gravitational collapse of a Giant Molecular Cloud (GMC)
- The star mass determines its evolution
  - Below 0.08 solar masses (Ms), no fusion, Brown Dwarf
  - Stars below 0.23 Ms become WHITE DWARFS directly
  - Below 0.5 Ms never fuse Helium—RED GIANTS , then White Dwarfs
  - White Dwarfs of > 1.38 Ms collapse to Neutron Stars (can be Pulsars)
  - Neutron Stars > 2-3 Ms collapse to Black Holes
  - Below 9 Ms, Red Giants do not go Supernovae: instead White Dwarfs
  - Stars cannot be more than about 120 Ms
- Stars end as:
  - 85% of stars will end as Red Dwarfs,
  - Most of the rest will end as White Dwarfs.
  - A few stars go Supernova
  - Massive stars go through core collapse to neutron stars or black holes

Questions

Easy Questions Please :-)