Unit – II
Astrophysical Objects
B.Sc Physics Fifth Semester
By Dr Priya Bharali (MGGAC)
Part I

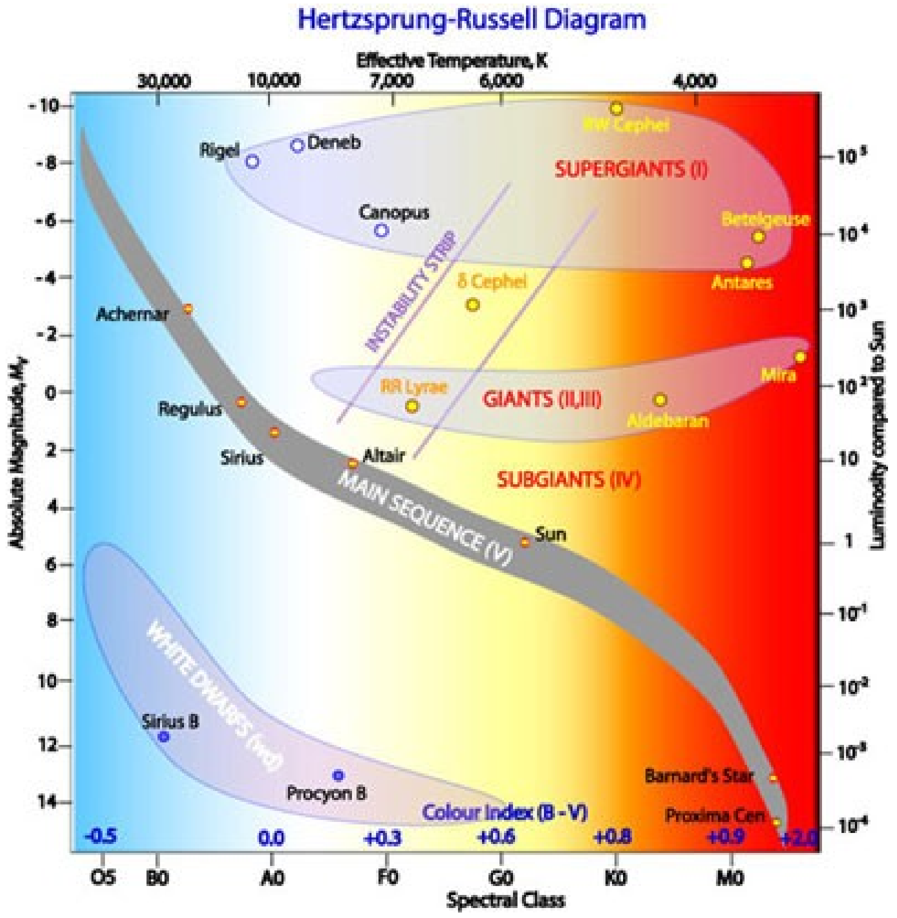
Luminosity of a star

Luminosity is the total energy that a star produces in one second. It depends on both the radius of the star and on its surface temperature. Our Sun's luminosity is about 3.84×10^{26} W.

$$L = 4\pi R^2 \sigma T^4$$

HR Diagram (Hertzsprung-Russell Diagram)

The HR diagram is one of the most important tools in the study of stellar evolution. It plots the temperature of stars against their luminosity. Depending on its initial mass, every star goes through specific evolutionary stages dictated by its internal structure and how it produces energy. Each of these stages corresponds to a change in the temperature and luminosity of the star, which can be seen to move to different regions on the HR diagram as it evolves. Astronomers can know a star's internal structure and evolutionary stage simply by determining its position in the diagram.



To understand the HR Diagram in detail, let us discuss star formation in detail.

- **Star Formation :** Stars form in the dense molecular clouds within galaxies. These clouds of dust and gas obscure the early stages of stellar formation. The space between the stars is filled with a tenuous range of material that provides the building blocks of stars. This material is gas and dust and collectively is known as the ***interstellar medium*** (*ISM*). The ISM gas is predominantly hydrogen whilst the dust is about 1% by mass and includes carbon compounds and silicates. Dust is responsible for the interstellar reddening and extinction of starlight. The more of the ISM a star's light travels through on its way to an observer on Earth the more it gets scattered and absorbed, decreasing the star's apparent brightness and reddening its appearance. Properties of the ISM vary widely depending upon its location within a galaxy. At its most tenuous, in hot regions between denser clouds, it may have a density of only 100 particles per cubic metre, mostly ionised hydrogen atoms. In the inner regions of shells of gas surrounding stars the density can be as high as 10^{17} particles per m^3 although this is still a million times less dense than a normal vacuum on Earth. Stars form in regions of the ISM where there is sufficient material available. These are the ***giant molecular clouds*** or ***GMCs.***

- **Stars & Their Energy Sources :** Stars are not fixed and unchanging. Stars are formed, evolve and eventually exhaust their energy sources to end up as some type of stellar remnant. Gravity is the force responsible for stellar formation. **Protostars** form when sections of giant molecular clouds start to collapse. Clouds are initially diffuse enough, so that they do not contract. Triggers for this initial collapse may include nearby supernovas or compression due to the motion of the arms in a spiral galaxy, though other mechanisms are also possible. The gravitational collapse of a giant molecular cloud does not result in a single, massive star. Instead the cloud tends to fragment into smaller denser regions that each collapse to form star systems. The dense regions collapse due to gravitational attraction between the particles. Individual gas or dust particles move in towards the centre of the collapsing region, losing gravitational potential energy. As the total energy of the system is conserved, the loss of gravitational energy is balanced by an increase in the kinetic energy of the particles. These particles then undergo more collisions, which in turn raises the temperature of the gas. At this stage further collapse is only possible, if the cloud can radiate away the thermal energy so that the radiation pressure outwards remains lower than the inward gravitational pull. This is achieved via convection cycling warm material upwards within the cloud, making the collapsing cloud visible in the infrared region.

The stages in the formation of a one solar mass star are:

1. Initial collapse of a cloud causes it to heat up and become a **protostar.** Although cool, it is very large, perhaps 20 times the diameter of the Sun, thus its surface area is so great that its overall luminosity is very high.
2. As it radiates away energy, gravitational collapse pulls the **protostar** inwards rapidly. Its temperature rises but this is offset by the decrease in size so that overall luminosity decreases significantly.
3. Once the core temperature reaches **10 million K**, coulombic repulsion between the now ionised hydrogen atoms (protons) is overcome and nuclear fusion commences. Hydrogen

fuses to form helium nuclei, releasing energy in the process. Initially the increased outward radiation pressure is still insufficient to halt gravitational collapse but it does slow it down. The star's surface temperature increases significantly, compensating for the drop in size so that its luminosity increases slightly. The star's track moves up slightly and to the left on the H-R diagram over 10 million years.

4. As the rate of core fusion increases due to higher core temperature, the outward gas and radiation pressures eventually match the inward gravitational force. The star attains a state of hydrostatic equilibrium and settles down onto **the main sequence.** This stage may take a few tens of million years.

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Various stages of Stars during stellar evolution

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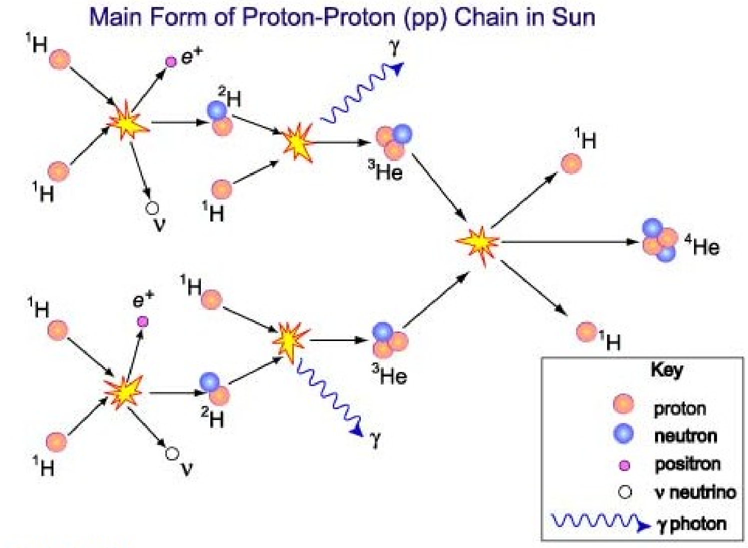
- **Main Sequence Stars**

The core temperature of main sequence stars is hot enough (> about 10 million K) that hydrogen nuclei (protons) can overcome coulombic repulsion and fuse together. The net result of this is that through several steps, hydrogen is fused to form helium nuclei. In the process a small amount of mass is converted into energy, released in the form of ***high-energy gamma photons.*** This hydrogen **fusion** provides the radiation pressure that supports main sequence stars against further gravitational collapse and ultimately is the source of energy fuelling life on Earth.


Main Form of Proton-Proton (pp) Chain in Sun

Credit: *CSIRO*

The **proton-proton** chain is the **main hydrogen fusion sequence** powering main sequence stars such as our Sun and those of lower mass. The net result is that four protons are fused to form a He-4 nucleus, gamma photons, positrons and neutrinos. The total mass of the products is slightly less than the constituents - the difference being converted to and released as energy.

A different sequence, the CNO cycle (for carbon-nitrogen-oxygen) dominates in higher mass main sequence stars. In the CNO cycle carbon-12 nuclei act as nuclear catalysts but the overall result is much the same as for the proton-proton chain, four protons are converted into a He-4 nucleus, releasing energy, primarily as high-energy gamma photons.

The main factor that determines where a star lays on the main sequence is its **mass.** A star with a mass of about **one-tenth that of the Sun** has just enough gravitational force to heat the core to about **10 million K,** the temperature needed for hydrogen fusion to start. If a protostar is less massive than this, fusion cannot be triggered and it becomes a ***brown dwarf*** or a **"failed" star**, emitting energy in the infrared.

The greater the mass of a main sequence star, the higher its core temperature and the greater the rate of its hydrogen fusion. Higher-mass stars therefore produce more energy and are thus more luminous than lower mass ones. This comes at a cost though. High mass stars consume their core hydrogen fuel much faster than lower-mass ones. **Therefore high mass stars are short-lived in comparison to low mass stars.** Our Sun has sufficient hydrogen in its core to last about 10 billion years (10^{10} years) on the main sequence.

- **Red Giants**

Eventually the hydrogen fuel in the core of a main sequence star runs out and the fusion reaction stops, shutting off the outward radiation pressure. Inward gravitational attraction causes the helium core to contract, converting gravitational potential energy into thermal energy. Although fusion is no longer taking place in the core, the rise in temperature heats up the shell of hydrogen surrounding the core until it is hot enough to start hydrogen fusion again, producing more energy than when it was a **main sequence star**.

This shell-burning causes some interesting effects. The increased radiation pressure actually causes the outer layers of the star to expand to maintain the pressure gradient. As the gas expands it cools. This expansion and cooling causes the effective temperature to drop and the star thus appears redder. Convection transports the energy to the outer layers of the star from the shell-burning region. The star's luminosity eventually increases by a factor of 1000 × or so as the size has increased. During this stage of expansion, the star will move up and to the right on the HR diagram. Our Sun may end up as a red giant. Such stars are commonly referred to as **red giants.**

- **Supergiants & Supernovae**

High-mass stars consume their core hydrogen at tremendously higher rates so may only survive on the main sequence for millions rather than billions of years. Once this fuel is used up, the core contracts due to gravity and heats up. This triggers helium-burning in the core. Unlike lower-mass stars, this helium fusion (triple-alpha process) starts gradually rather than in a helium flash. In moving off the main sequence, the effective temperature of the star drops as its outer layers expand. The decrease in temperature balances the increased radius so that the overall luminosity remains essentially constant. Energy liberated by helium fusion in the core raises the temperature of the surrounding hydrogen shell so that it too begins fusing.

In time the core helium is used up resulting in further core collapse and gravitational heating. This then triggers carbon fusion to produce sodium, neon and magnesium.
Depending on the mass of the star, as each core fuel is used up further collapse leads to even higher temperatures that can trigger fusion of heavier elements. Through a combination of fusion and photodisintegration a range of heavier nuclei are formed up to iron for the most massive stars. The core region of a supergiant eventually resembles the layers of an onion

with a dense iron core surrounding by shells of silicon and sulfur, oxygen and carbon, helium and an outer shell of hydrogen as shown in the diagram below. The final core temperature reaches about 7 × 10^9 K.

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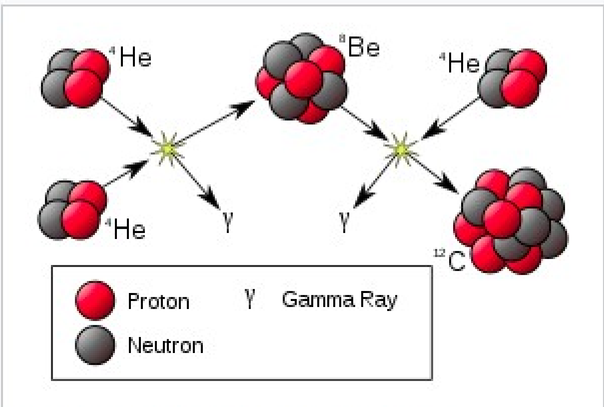
- **White Dwarfs**

White dwarfs are thought to be the final evolutionary state of stars whose mass is not high enough to become a neutron star (1.4 times one solar mass). After the hydrogen fusing period of a main sequence star of low or medium mass ends, such a star will expand to a **red giant** during which it fuses helium to carbon and oxygen in its core by the ***triple alpha process***. If a red giant has insufficient mass to generate the core temperatures required to fuse carbon (around 1 billion K), an inert mass of carbon and oxygen will build up at its center. After such a star sheds its outer layers and forms a planetary nebula, it will leave behind a core, which is the remnant **white dwarf**.



Overview of the triple-alpha process.

Stars with masses similar to our Sun will end up as white dwarfs. These stellar remnants have unusual properties. Firstly, they are very small but the more massive white dwarfs are actually smaller than less massive ones. With their fuel used up, no further fusion takes place so there is no outward radiation pressure to withstand gravitational collapse. More massive stellar cores experience stronger gravitational force, hence compress more. A white dwarf is composed of carbon and oxygen ions mixed in with a sea of degenerate electrons. It is the degeneracy pressure provided by the electrons that prevents further collapse.

Additional Information on White Dwarf

A white dwarf, with a mass roughly that of the Sun packed into a volume not much greater than the Earth must have an extremely high density. At 10^9 kg m^{-3} its density is one million times greater than that of water. Although its surface temperature is about 10,000 K, the core temperature may be as high as 10^7 K. The heat trapped within a white dwarf will gradually be radiated away by it but with its small radius, a white dwarf has only a small surface area. Heat therefore cannot escape quickly. In fact it will take tens to hundreds of billions of years for a white dwarf to radiate away its heat and cool down to a black, inert clump of carbon and degenerate electrons. As the Universe is not yet old enough for this to have happened, all the white dwarfs that have ever formed in single-star systems are still white dwarfs.

Typical luminosities are less than 10^{-3} that of our Sun. More massive white dwarfs, having smaller surface areas but more trapped heat, take longer to cool down than lower-mass ones. As white dwarfs are so faint they are also hard to detect. We are only able to observe relatively close ones. Nonetheless white dwarfs are thought to comprise about 10% of the stars in our galaxy. Nearby examples are Sirius B and Procyon B, both of which are found in binary systems.

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- **Neutron Stars and Black Holes**

At the end of its life, a massive star explodes as a supernova, its core can *collapse* to end up as a tiny and superdense object. These small, incredibly dense cores of exploded stars can become either a *neutron stars* or *black hole* depending on the mass of the remnant star.

If it is in the range (1.4-3.0) $\mathbf{M}_{\odot}$, the small and dense core will turn into a **neutron star** and if it is greater than 3.0 $\mathbf{M}_{\odot}$, then it will become a **black hole.**

Throughout much of their lives, stars maintain a delicate balancing act. Gravity tries to compress the star while the star's internal pressure exerts an outward push. The outward pressure is caused by nuclear fusion at the star's core. This fusion "burning" is the process by which stars shine.

Neutron Star :

In a supernova explosion, gravity suddenly and catastrophically gets the upper hand in the war it has been waging with the star's internal pressure for millions or billions of years. With its nuclear fuel exhausted and the outward pressure removed, gravity suddenly compresses the star inward. A shock wave travels to the core and rebounds, blowing the star apart. This whole process takes perhaps a ***couple of seconds.*** But gravity's victory is not yet complete. With most of the star blown into space, the core remains, which may only posses masses in the range (1.4-3.0) $\mathbf{M}_{\odot}$. Gravity continues to compress it, to a point where the atoms become so compact and so close together that electrons are violently thrust into their parent nuclei, combining with the protons to form neutrons.

Black holes :

Black holes are the extremely dense region in the space, with such strong gravitational attraction that even light cannot escape their grasp if it comes near enough. The strong gravity occurs because matter has been pressed into a tiny space. This compression can take place at the end of a star's life. Some black holes are a result of dying stars if the mass of the remnant core is greater the 3.0 $\mathbf{M}_{\odot}$. As no light can escape, black holes are invisible (**black**). However, space telescopes with special instruments can help find black holes. They can observe the behavior of material and stars that are very close to black holes. (***How can we see a black hole if they don't emit anything ?)***

Chandrasekhar Limit

White dwarf stars are the end products of the stellar evolution of low to medium mass stars like our Sun. They are extremely dense objects and are supported against further gravitational collapse by electron degeneracy pressure.

The Chandrasekhar mass limit of 1.4 solar masses, is the theoretical maximum mass a white dwarf star can have and still remain a white dwarf (though this limit does vary slightly depending on the metallicity). Above this mass, electron degeneracy pressure is not enough to prevent gravity from collapsing the star further into a neutron or black hole.

Electron Degeneracy Pressure

The Pauli exclusion principle states that no two electrons with the same spin can occupy the same energy state in the same volume. Once the lowest energy level is filled, the other electrons are forced into higher and higher energy states resulting in them travelling at progressively faster speeds. These fast moving electrons create a electron degeneracy pressure which is capable of supporting a star.

In particular, electron degeneracy pressure is what supports white dwarfs against gravitational collapse, and the Chandrasekhar limit (the maximum mass a white dwarf can attain) arises naturally due to the physics of electron degeneracy. As the mass of a white dwarf approaches the Chandrasekhar limit, gravity attempts to squeeze the star into a smaller volume, forcing electrons to occupy higher energy states and attain faster velocities. At the Chandrasekhar limit, the pressure exerted by the electrons travelling at close to the speed of light becomes insufficient to support the star, and the white dwarf collapses into a much denser state.

Electron degeneracy occurs at densities of about 10^6 kg/m^3.

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Black Hole

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A black hole is a region of space within which the force of gravity is so strong that nothing, not even light, can escape. The existence of such objects was first suggested as far back as the late 1700s. However, it was ***Karl Schwarzschild*** (1873-1916), a German astronomer, who basically developed the modern idea for a black hole.

Using Einstein's theory of general relativity, Schwarzschild discovered that matter compressed to a point (now known as a **singularity**) would be enclosed by a spherical region of space from which nothing could escape. The limit of this region is called the **event horizon**, a name which signifies that it is impossible to observe any event taking place inside it.

Since the black holes are formed from the death of stars which are rotating, almost all the black holes are supposed to have angular momentum (rotating).

For a non-rotating black hole (*no experimental evidence of non rotating black hole is found yet*), the radius of the event horizon is known as the **Schwarzchild radius**, and marks the point at which the escape velocity from the black hole equals the speed of light. In theory, any mass can be compressed sufficiently to form a black hole. The only requirement is that its physical size is less than the Schwarzschild radius. For example, our Sun would become a black hole if its mass was contained within a sphere about 2.5 km across.

Well inside the event horizon lies the heart of the black hole – the **singularity (**singuarity is point which is unsolvable**)**. Everything within the event horizon is irreversibly drawn towards this point where the curvature of spacetime becomes infinite and gravity is infinitely strong. An interesting dilemma for astrophysicists is that the physical conditions near a singularity result in the complete breakdown of the laws of physics.

Types of Black holes :

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Black holes are completely characterised by only three parameters: **mass, rotation and charge**. There are now thought to be 4 main types of black holes if classified by **mass**:

1. **Primordial Black Holes** have masses comparable to or less than that of the Earth. These purely hypothetical objects could have been formed through the gravitational collapse of regions of high density at the time of the Big Bang.
2. **Stellar Mass Black Holes** have masses between about 4 and 15 solar masses and result from the core-collapse of a massive star at the end of its life.

3. **Intermediate Mass Black Holes** of perhaps a few thousand solar masses may also exist. Sketchy evidence suggests that they may be found in some clusters of stars, and may eventually grow into supermassive black holes.
4. **Supermassive Black Holes** weigh between 10^6 and 10^9 solar masses and are found at the centres of most large galaxies.

Alternatively, black holes can be classified by their two other properties of **rotation and charge**:

1. **Schwarzschild Black Hole**, otherwise known as a ‘static black hole’, does not rotate and has no electric charge. It is characterised solely by its mass.
2. **Kerr Black Hole** is a more realistic scenario. This is a rotating black hole with no electrical charge.
3. **Charged Black Hole** can be of two types. A charged, non-rotating black hole is known as a Reissner-Nordstrom black hole, a charged, rotating black hole is called a Kerr-Newman black hole.

Observational evidence for black holes is, of course, not straightforward to obtain. Since radiation cannot escape the extreme gravitational pull of a black hole, we cannot detect them directly. Instead we infer their existence by observing high-energy phenomena such as X-ray emission and jets, and the motions of nearby objects in orbit around the hidden mass. An added complication is that similar phenomena are observed around less massive neutron stars and pulsars. Therefore, identification as a black hole requires astronomers to make an estimate of the mass of the object and its size. A black hole is confirmed if no other object or group of objects could be so massive and compact.

Rotating Black Holes :

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There are two types of black holes:

- **Schwarzschild** - Non-rotating black hole
- **Kerr** - Rotating black hole

The **Schwarzschild** black hole is the simplest black hole, in which the core does not rotate. This type of black hole only has a singularity and an event horizon.

The **Kerr** black hole, which is probably the most common form in nature, rotates because the star from which it was formed was rotating. When the rotating star collapses, the core continues to rotate, and this carried over to the black hole.

A non-rotating black hole has a spherical event horizon, whereas a rotating black hole has a slightly oblate (flattened/squashed) ellipsoid event horizon, with a region around the event horizon touching at the poles with respect to the rotation axis known as the *ergosphere* in which no particle can remain at rest but from which it is still possible to escape, if it has the means. Rotating black holes exhibit "frame dragging" effect. While for a Schwarzshild black hole if a particle or photon is shot into the black hole's centre, it will fall in a straight line. For a rotating black hole it will always "spiral" towards it.

The **Kerr black hole** has the following parts:

- **Singularity** - The collapsed core
- **Event horizon** - The opening of the hole
- **Ergosphere** - An egg-shaped region of distorted space around the event horizon (The distortion is caused by the spinning of the black hole, which "drags" the space around it.)

- **Static limit** - The boundary between the ergosphere and normal space

Even though we cannot see a black hole, it does have three properties that can or could be measured:

- **Mass**
- **Electric charge**
- **Rate of rotation** (angular momentum)

As of now, we can only measure the mass of the black hole reliably by the movement of other objects around it. If a black hole has a companion (another star or disk of material), it is possible to measure the radius of rotation or speed of orbit of the material around the unseen black hole. The mass of the black hole can be calculated using Keplar's Modified Third Law of Planetary Motion or Rotational Motion.

Schwarzchild Radius

The Schwarzchild radius is the radius of the event horizon surrounding a non-rotating black hole. Any object with a physical radius smaller than its Schwarzschild radius will be a black hole. This quantity was first derived by Karl Schwarzschild in 1916:

$$R_S = \frac{2GM}{c^2}$$

where R_S is the Schwarzschild radius, G is the universal gravitational constant, M is the mass of the object and c is the speed of light.

The following table gives the Schwarzschild radii of some familiar astronomical objects:

Object	**Mass**	R_S	
Sun	2.0×10^{30} kg	3.0×10^{3} m	= 3 km
Earth	6.0×10^{24} kg	8.7×10^{-3} m	= 8.7 mm
Moon	7.3×10^{22} kg	1.1×10^{-4} m	= 0.11 mm
Jupiter	1.9×10^{27} kg	2.2 m	= 2.2 m
Neutron Star	2.8×10^{30} kg	4.2×10^{3} m	= 4.2 km

Therefore, any mass can become a black hole if it collapses down to the Schwarzschild radius - but if a mass is over some critical value above 3 solar masses and has no fusion process to keep it from collapsing, then gravitational forces alone make the collapse to a black hole inevitable.

Conclusion of HR Diagram

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There are 3 main regions (or evolutionary stages) of the HR diagram:

1. The **main sequence** stretching from the upper left (hot, luminous stars) to the bottom right (cool, faint stars) dominates the HR diagram. It is here that stars spend about 90% of their lives burning hydrogen into helium in their cores.
2. **Red giants** and **supergiant** stars occupy the region above the main sequence. They have low surface temperatures and high luminosities which, according to the Stefan-Boltzmann law, means they also have large radii. Stars enter this evolutionary stage once they have exhausted the hydrogen fuel in their cores and have started to burn helium and other heavier elements.
3. **White Dwarf** stars are the final evolutionary stage of low to intermediate mass stars, and are found in the bottom left of the HR diagram. These stars are very hot but have low luminosities due to their small size.

The Sun is found on the main sequence with a temperature of around 5,400 K. Astronomers generally use the HR diagram to either summarise the evolution of stars, or to investigate the properties of a collection of stars. In particular, by plotting a HR diagram for either a globular or open cluster of stars, astronomers can estimate the age of the cluster from where stars appear to turnoff the main sequence.