

The following is a summary of the gravitational and nuclear fusion processes in stars and galaxies.

Interstellar space is not truly empty, but consists of clouds of gas and dust with a density of about $10^{-21} \text{ kg m}^{-3}$. This amounts to about one atom in every cubic centimetre of space. The gas is mainly hydrogen and helium, with other elements making up less than 1% of the gas clouds by mass.

Stars form when hydrogen gas clouds in interstellar space collapse under their own gravitation. Whether an interstellar gas cloud will collapse into a star depends on the temperature and mass of the gas cloud. If the temperature of the gas molecules is too high, the molecules of the gas cloud will have sufficient kinetic energy to escape the gravitational pull of the gas cloud, and the cloud will not collapse. However, if a gas cloud is sufficiently massive and sufficiently cool (10 – 100 K), the cloud can collapse into a star.

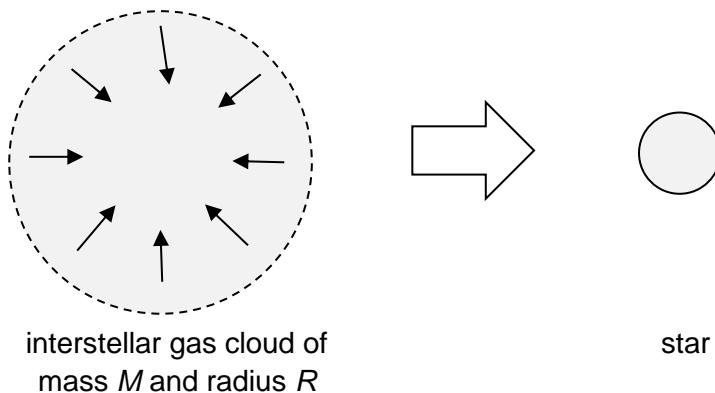


Fig. 8.1

Fig. 8.1 shows a spherical interstellar gas cloud. If the total gravitational potential energy of a given gas cloud exceeds the average kinetic energy of the thermal random motion of its molecules, the gas becomes unstable and tends to collapse. This is known as the Jeans criterion, given by the equation:

$$\frac{3}{2} NkT \leq \frac{GM^2}{R}$$

where M is the total mass of the cloud and R is the radius, N is the number of molecules of gas, k is Boltzmann's constant, and T is the maximum average temperature of the molecules which will allow the gas cloud to collapse into a star.

- (a) A spherical interstellar gas cloud has the following properties:

uniform density of 100 hydrogen atoms per cm^3
total mass M of 10^{33} kg

The mass of a hydrogen atom is 1.66×10^{-27} kg.

Show that the radius R of the spherical gas cloud is 1.1×10^{17} m.

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- (b) Calculate the maximum average temperature T for the interstellar gas cloud in (a) to collapse into a star.

maximum temperature = K [2]

- (c) A second interstellar gas cloud is observed to have the same volume as the gas cloud in (a), but with higher density. Explain how this difference in density affects the maximum average temperature for this gas cloud to collapse.

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[2]



Stars radiate an enormous amount of power into space. The source of this energy is nuclear fusion in which hydrogen nuclei fuse to produce helium and energy. This process can only take place in the core of the star, as that is where the temperatures and pressures are high enough for the nuclei to come sufficiently close together, frequently enough to react.

The sequence of nuclear fusion reactions that take place in smaller stars is called the proton-proton chain, as shown in the equations below. Most of the energy released in this nuclear fusion chain is produced in the third step of the series of nuclear equations below.

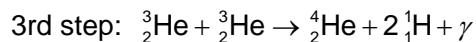
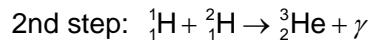
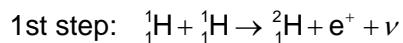


Fig. 8.2 Proton-proton chain

However, in stars which are much more massive than our Sun, the core's temperature and pressure is high enough to allow the fusion of heavier elements: neon, oxygen, magnesium and silicon in turn, with each step in the fusion chain producing heavier elements. Eventually, iron is produced in the core of these massive stars and that is where the fusion chain stops.

- (d) Explain why high temperatures are required for nuclear fusion to occur.
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- (e) The binding energy per nucleon of helium-3 and helium-4 are 2.57 MeV and 7.07 MeV respectively.

Determine the energy released in the third step of the proton-proton fusion chain.

energy released = MeV [2]



- (f) Calculate the maximum frequency of the gamma photon emitted in the third step of the proton-proton fusion chain.

frequency = Hz [2]

- (g) Explain why the fusion chain in massive stars does not progress past iron.

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Galaxies are made up of a huge number of stars held together by mutual gravity. There is some debate about how mass is distributed in different galaxies which astronomers hope to resolve by taking measurements of the orbital velocity of stars around the galactic centre of various galaxies.

Three models are proposed. The first model assumes that most of the mass of a galaxy is concentrated in a supermassive point-like galactic core, with the other stars orbiting around it. The second model assumes that the mass of a galaxy is uniformly distributed in a sphere of stars. The third model assumes that the mass of a galaxy is distributed in a non-uniform sphere of stars such that the total mass increases proportionally with distance from the centre.

Plotting the orbital velocity of stars in a galaxy against distance from the galactic centre gives what is called a **rotation curve**. The three different models of galactic mass distribution give rise to three different possible rotation curves, shown in Fig. 8.3.

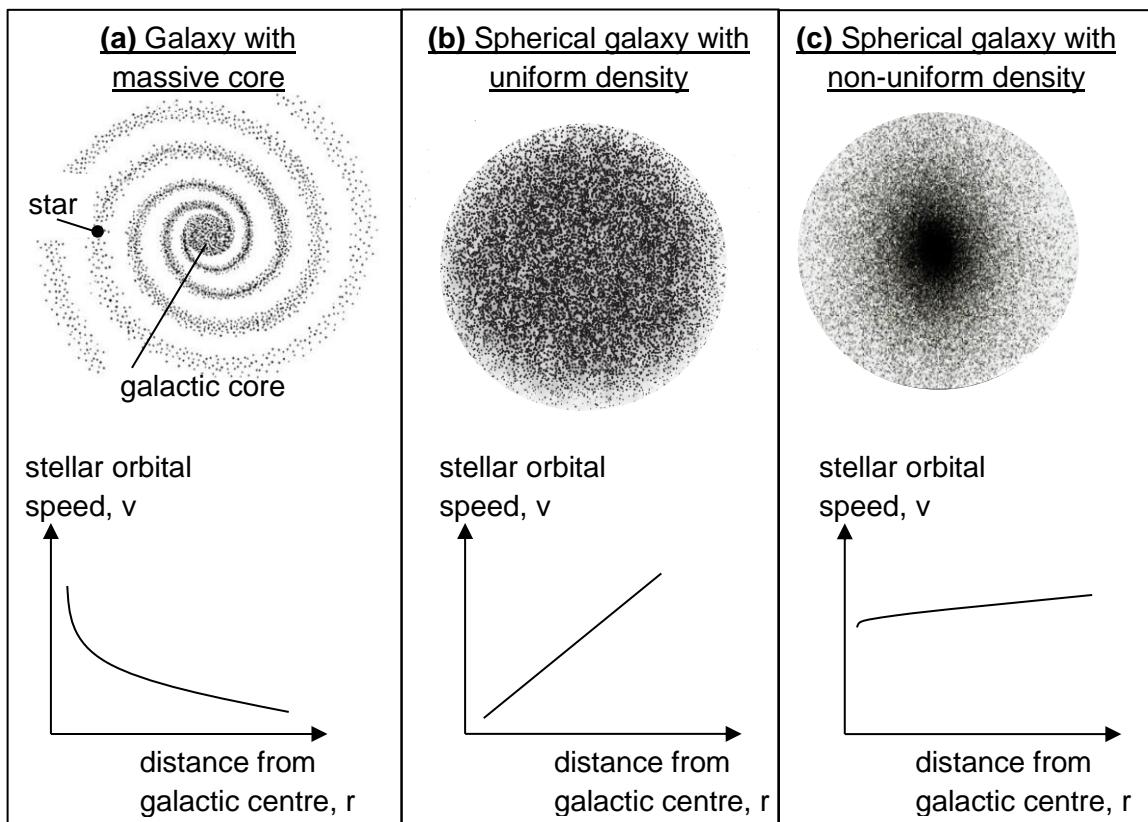


Fig. 8.3 Three models of galactic mass distribution and their associated rotation curves

- (h) The first model of galactic mass distribution assumes that most of a galaxy's mass is concentrated in its galactic core.

Fig. 8.3(a) shows a star orbiting a galactic core, with an orbital speed v and an orbital radius r . The mass of the galactic core is M .

By considering gravitational and centripetal forces on the star, show that the orbital speed of the star is given by:

$$v = \sqrt{\frac{GM}{r}}$$

[2]

- (i) The second model of galactic mass distribution assumes that a galaxy's mass is distributed as a large sphere of uniform density ρ , as shown in Fig. 8.3(b).

Using the equation in (h), show that the orbital velocity of a star orbiting at the edge of a spherical galaxy of uniform density with a mass M and radius r is given by the relationship:

$$v \propto r$$

[2]



Measurements were made of the orbital velocity of stars in a distant galaxy, Messier 33. The rotation curve obtained from these measurements is shown in Fig. 8.4.



Fig. 8.4 Rotation curve of stars in Messier 33

- (j) With reference to Fig. 8.3 and Fig. 8.4, suggest the possible distribution of mass in the galaxy Messier 33.

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