IJFANS INTERNATIONAL JOURNAL OF FOOD AND NUTRITIONAL SCIENCES
ISSN PRINT 2319 1775 Online 2320 7876
 UGC CARE Listed (Group -I) Journal Volume 11, Iss 9, 2022

Chandrasekhar limit

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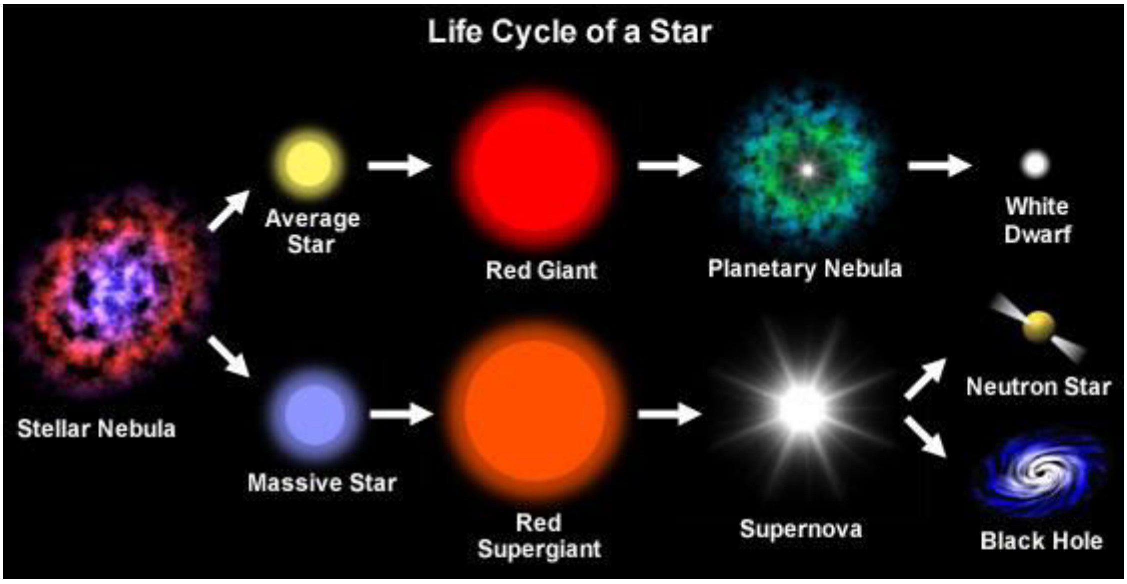
Abstract

The Sun is a star at the centre of our Solar System and is one of the most important source of energy found on earth. A star is born when atoms of light elements are squeezed under enough pressure for their nuclei by fusion process and their life are the result of balance of forces: the force of gravity constantly works to try the star to collapse. The star's core is very hot which creates pressure within the gas. This pressure hinders the force of gravity, putting the star into hydrostatic equilibrium. Different stars take different paths for their life cycle depending on their mass. Though stars shine for many thousands, and even millions of years, stars do not last forever, they also die!. The changes that occur in a star over time and the final stage of its life depends on a star's size. Star, Neutron star, white dwarf also has a limiting value. The Chandrasekhar limit is the maximum mass of a stable white dwarf star. In the beginning of 1930, an Indian-born astrophysicist Subrahmanyan Chandrasekhar was formulated this limiting value. This is the maximum mass theoretically possible for a stable white dwarf star. The currently accepted value of the Chandrasekhar limit is about 1.4 $M_\odot$ (2.765×10^{30} kg). The star turns into a neutron star or a black hole when the limit exceeds. The exact lifetime of a star also depends very much on its size. Using Albert Einstein's special theory of relativity and the principles of quantum physics, Chandrasekhar showed that it is impossible for a white dwarf star, which is supported solely by a degenerate gas of electrons, to be stable if its mass is greater than 1.44 times the mass of the Sun.

Keywords Neutron star; white dwarf; Limiting value; Solar mass; Chandrasekhar limit; hydrostatic equilibrium; Fermi gas.

The Sun is a star at the centre of our Solar System and is one of the most important source of energy found on earth. A star is born when atoms of light elements are squeezed under enough pressure for their nuclei to undergo fusion and its life is a constant struggle against the force of gravity. The force of gravity compresses atoms in interstellar gas until the fusion reactions begin. Stars populate the universe with elements through their “lifecycle” - an ongoing process of formation, burning fuel, and dispersal of material when all the fuel is used up. Different stars take different paths, however, depending on how much matter they contain their mass.

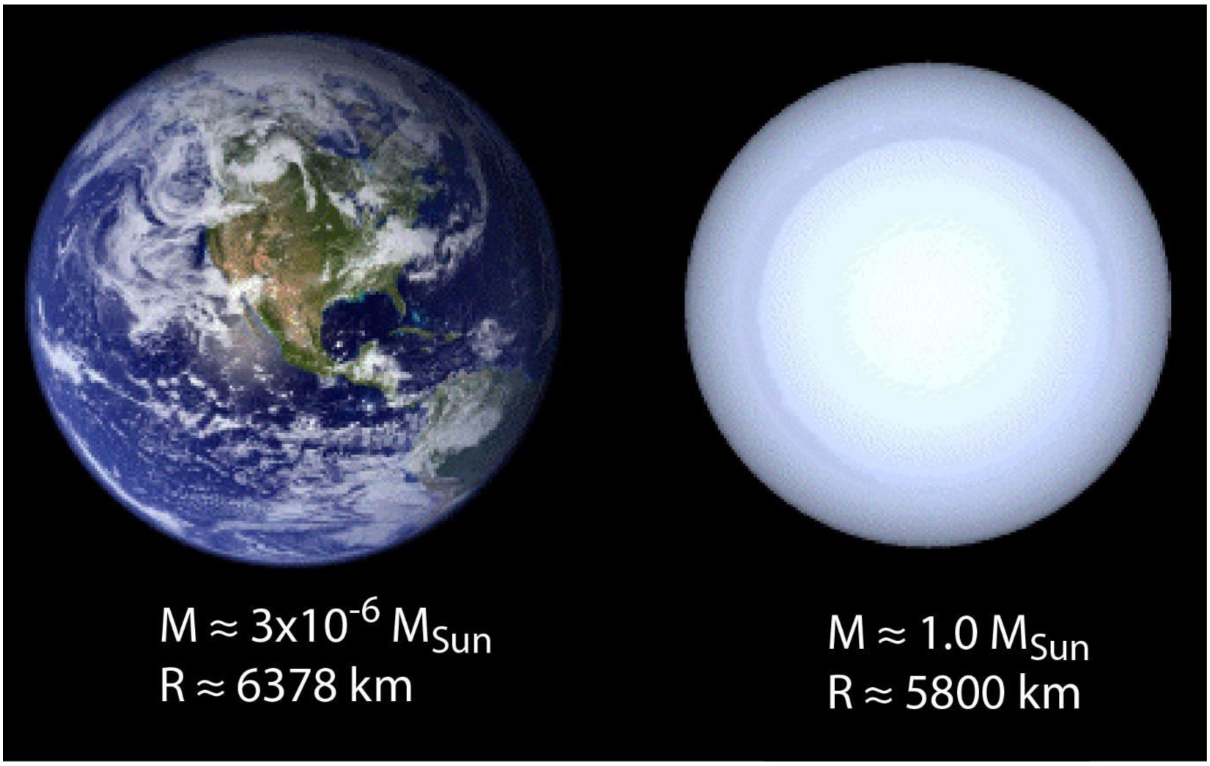
All stars form in nebulae, which are huge clouds of gas and dust. Though they shine for many thousands, and even millions of years, stars do not last forever. The changes that occur in a star over time and the final stage of its life depend on a star's size. Stars also die! The end life of 97% star along with the sun, as a white dwarf surrounded by a disappearing planetary nebula, while massive stars transform into supernovae, neutron stars and black holes.



Nuclear reactions at the centre or core of a star gives energy which makes it shine brightly. This stage is called the 'main sequence'. The exact lifetime of a star depends very much on its size. Very massive stars use up their fuel quickly. This means they may only last a few hundred thousand years. Smaller stars use up fuel more slowly so will shine for several billion years.
Ultimately, the hydrogen which powers the nuclear reactions inside a star begins to give out. The star then enters the final phases of its lifetime. All stars will expand, cool and change colour to become a red giant. What happens next depends on how massive the star is. A smaller star, like the Sun, will gradually

ISSN PRINT 2319 1775 Online 2320 7876
 UGC CARE Listed (Group -I) Journal Volume 11, Iss 9, 2022

cool down and stop glowing. During these changes it will undergo the planetary nebula phase, and white dwarf phase. After many thousands of millions of years, it will stop glowing and become a black dwarf.
When stars run out of hydrogen, the nuclear fusion reactions at their core stop and become unstable and collapse. It is important that not all stars collapse the same way. Stars do explode, and when that happens, they're known as supernovae. A supernova creates an explosion billions of times brighter than our sun, with enough energy to outshine its own galaxy for weeks. Stars do explode, and when that happens, they're known as supernovae. A supernova creates an explosion billions of times brighter than our sun, with enough energy to outshine its own galaxy for weeks.



Comparison of Earth to a white dwarf star with a mass equal to the Sun. They have comparable radii but radically different densities. An Earth-sized white dwarf has a density of 1×10^9 kg/m^3. Earth itself has an average density of only 5.4×10^3 kg/m^3. That means a white dwarf is 200,000 times as dense. This makes white dwarfs one of the densest collections of matter, crossed only by neutron stars.

Nuclear fusion reactions are the power of the Sun and other stars. In a fusion reaction two light nuclei merge to form a single heavier nucleus. The process releases energy because the total mass of the resulting single nucleus is less than the mass of the two original nuclei. In 1920, British astrophysicist Sir Arthur Stanley Eddington first suggested that stars draw their apparent endless energy from the fusion of hydrogen into helium. After converting all of their hydrogen to helium, stars lose energy and contract under the influence of their own gravity. These stars, known as white dwarf stars, contract to about the size of Earth, and the electrons and nuclei of their constituent atoms are compressed to a state of extremely high density. But Indian-born astrophysicist Subrahmanyan Chandrasekhar determined that a star having a mass more than 1.44 times that of the Sun does not form a white dwarf but instead continues to collapse, blows off its gaseous envelope in a supernova explosion, and becomes a neutron star. An even more massive star continues to collapse and becomes a black hole. These calculations contributed to the eventual understanding of supernovas, neutron stars, and black holes. Chandrasekhar came up with the idea for a limit on his voyage to England in 1930. However, his ideas met strong opposition, particularly from Arthur Eddington, and took years to be generally accepted. Chandrasekhar's work on the limit of the maximum mass of a stable white dwarf star irradiated disagreement, due to the opposition of the Sir Eddington. Eddington was aware that the existence of black holes were theoretically possible, and also believed that the existence of the limit made their formation possible. However, he was unwilling to accept that this could happen. After a talk by Chandrasekhar on the limit in 1935, he replied: The star has to go on radiating and radiating and contracting and contracting until, I suppose, it gets down to a few km radius, when gravity becomes strong enough to hold in the radiation, and the star can at last find peace. ... I think there should be a law of Nature to prevent a star from behaving in this absurd way!

Although Niels Bohr, Fowler, Wolfgang Pauli, and other physicists agreed with Chandrasekhar's analysis, at the time, owing to Eddington's status, they were unwilling to publicly support Chandrasekhar. Through the rest of his life, Eddington taken to his position in his writings, including his work on his fundamental theory. Chandrasekhar's discovery might well have transformed and accelerated developments in both physics and astrophysics in the 1930s. Instead, Eddington's heavy-handed intervention lent weighty support to the conservative community astrophysicists, who steadily refused even to consider the idea that stars might collapse to nothing. As a result, Chandra's work was almost forgotten. However, in 1983 in recognition for his work, Chandrasekhar shared a Nobel prize "for his theoretical studies of the physical processes of importance to the structure and evolution of the stars" with William Alfred Fowler. Using Albert Einstein’s special theory of relativity and the principles of quantum physics, Chandrasekhar showed that it is impossible for a white dwarf star, which is solely by a degenerate gas of electrons, to be stable if its

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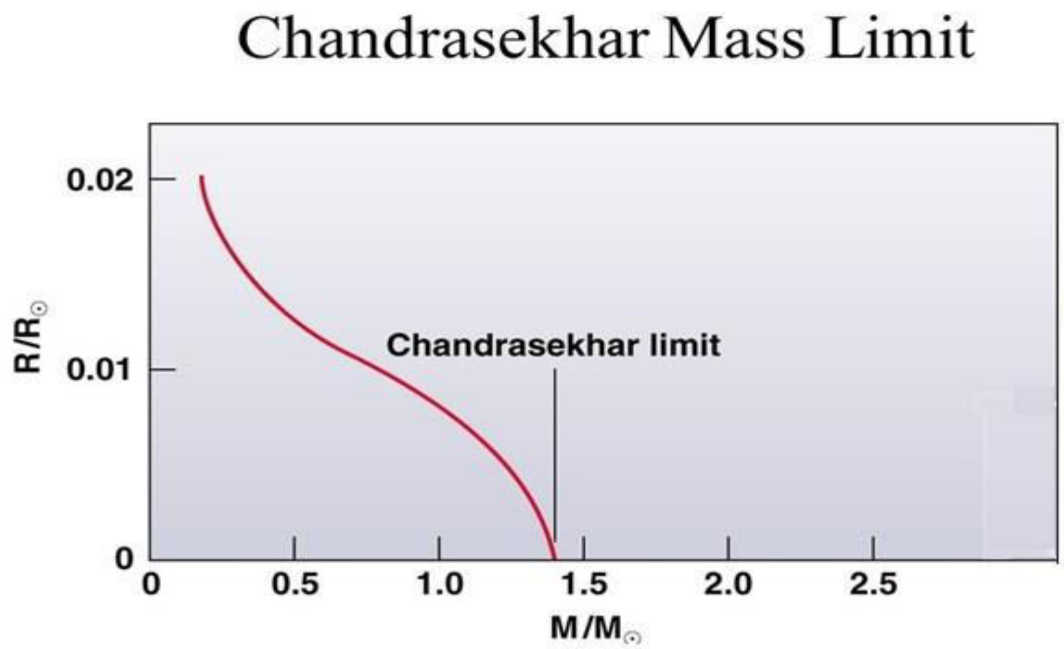
mass is greater than 1.44 times the mass of the Sun. This is the maximum mass theoretically possible for a stable white dwarf star. Primarily white dwarfs resist gravitational collapse through electron degeneracy pressure, compared to main sequence stars, which resist collapse through thermal pressure. Electron degeneracy pressure is a quantum-mechanical effect arising from the Pauli's exclusion principle. According to Pauli's exclusion principle electrons cannot have the same state or the minimum-energy level. This is because they are fermions**.** A spectrum of energy levels exists, and electrons should be distributed throughout them. When the electron gas is compressed, the number of electrons in a specific volume increase, and so does the energy level of the band that has been occupied. Thus, to produce the electron degeneracy pressure, pressure must be applied for the compression of the electron gas as their energy increases when compressed. Electron capture occurs when that pressure is so high that the electron goes into the nuclei. That is to say, once the lowest energy level is filled, the other electrons are forced into higher and higher energy states resulting faster speeds. These fast-moving electrons create a pressure called electron degeneracy pressure. Electron degeneracy pressure is the pressure that prevents a white dwarf star from collapsing.



In the beginning of 1930, Subrahmanyan Chandrasekhar was formulated this limiting value and the currently accepted value of the Chandrasekhar limit is about 1.4 $M_\odot$ (2.765×10^{30} kg), where $M_\odot = (1.98847\pm0.00007) \times10^{30}$ kg. If such a star does not completely exhaust its thermonuclear fuel, then this limiting

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 UGC CARE Listed (Group -I) Journal Volume 11, Iss 9, 2022

mass may be slightly larger. The significance of this limit is the mass above which electron degeneracy pressure in the star's core is inadequate to balance the star's own gravitational self-attraction or the limit is accepted to be 1.4 times the sun's mass, such that the white dwarf is within the limit, they stay permanent and if the star that exceeds the limit is subject to further gravitational collapse, evolving into a different type of stellar remnant, such as a neutron star or black hole and will experience explosions, turning into a supernova.

Calculated values for the limit vary depending on the nuclear composition of the mass. Chandrasekhar gives the following expression, based on the equation of state for an ideal Fermi gas:

$$M_{\text{limit}} = \frac{\omega_3^0 \sqrt{3\pi}}{2} \left(\frac{\hbar c}{G} \right)^{\frac{3}{2}} \frac{1}{(\mu_{\text{e}} m_{\text{H}})^2}$$

where:

- $\hbar$ refers to the reduced Planck constant.
- c is the speed of light.
- G stands for the gravitational constant.
- μ_e is the average molecular weight per electron, which depends upon the chemical composition of the star.
- m_H is the mass of the hydrogen atom.
- $\omega^0{}_3 \approx 2.018236$ is a constant connected with the solution to the Lane–Emden equation.

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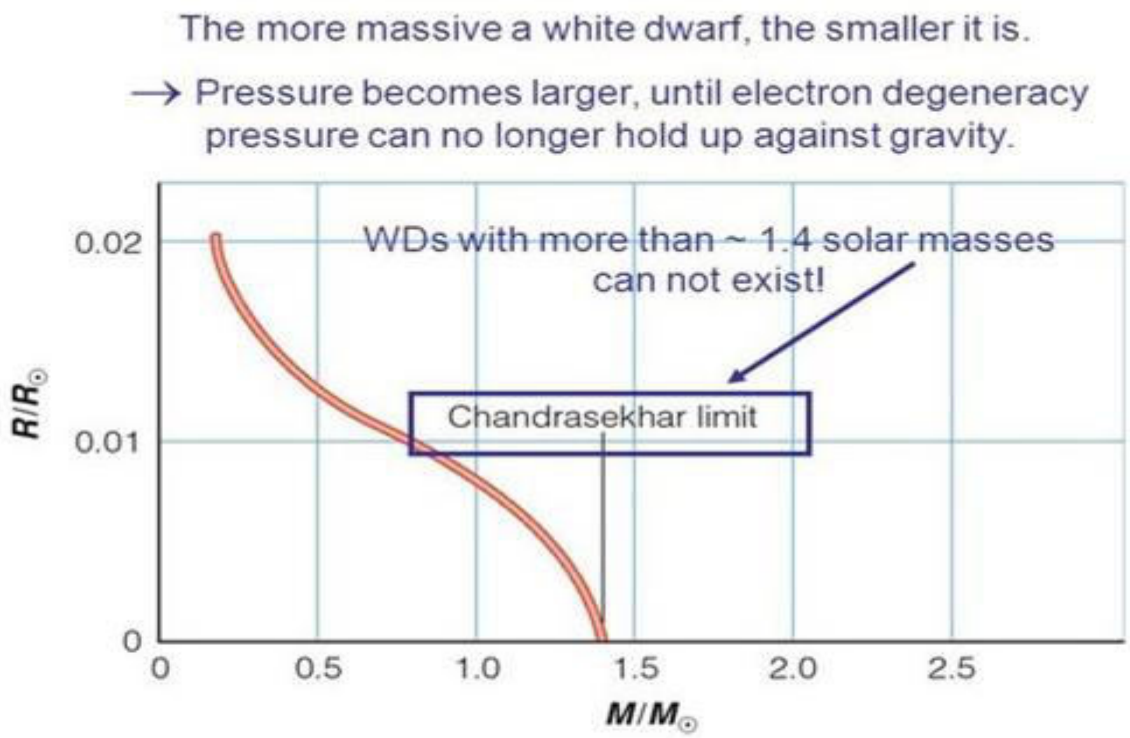

The limit was named after Subrahmanyan Chandrasekhar, who made major independent discoveries on improving the rectitude of computation. Subrahmanyan Chandrasekhar (19 October 1910 – 21 August 1995) was an Indian-American theoretical physicist who spent his professional life in the United States, was born in Lahore on 19 October 1910 of the British Raj (present-day Pakistan) in a Tamil Brahmin family, to Sita Balakrishnan (1891–1931) and Chandrasekhara Subrahmanya Ayyar (1885–1960) who was stationed in Lahore as Deputy Auditor General of the Northwestern Railways at the time of Chandrasekhar's birth. His paternal uncle was the Indian physicist and Nobel laureate Chandrasekhara Venkata Raman. His mother was devoted to intellectual pursuits, had translated Henrik Ibsen's A Doll's House into Tamil and is credited with arousing Chandra's intellectual curiosity at an early age. The family moved from Lahore to Allahabad in 1916, and finally settled in Madras in 1918. Chandrasekhar was tutored at home until the age of 12. In middle school his father taught him mathematics and physics and his mother taught him Tamil. He later attended the Hindu High School, Triplicane, Madras during the years 1922–25. Subsequently, he studied at Presidency College, Madras (affiliated to the University of Madras) from 1925 to 1930, writing his first paper, "The Compton Scattering and the New Statistics", in 1929 after being inspired by a lecture by Arnold Sommerfeld. He obtained his bachelor's degree, BSc. (Hons.), in physics, in June 1930. In July

1930, Chandrasekhar was awarded a Government of India scholarship to continue graduate studies at the University of Cambridge, where he was admitted to Trinity College, secured by R. H. Fowler with whom he communicated his first paper. During his travels to England, Chandrasekhar spent his time working out the statistical mechanics of the degenerate electron gas in white dwarf stars, giving relativistic corrections to Fowler's previous work. Chandrasekhar joined the staff of the University of Chicago, rising from assistant professor of astrophysics (1938) to Morton D. Hull distinguished service professor of astrophysics (1952), and became a U.S. citizen in 1953. He did important work on energy transfer by radiation in stellar atmospheres and convection on the solar surface. He also attempted to develop the mathematical theory of black holes, describing his work in *The Mathematical Theory of Black Holes* (1983). Chandrasekhar was awarded the Gold Medal of the Royal Astronomical Society in 1953, the Royal Medal of the Royal Society in 1962, and the Copley Medal of the Royal Society in 1984. His other books included *An Introduction to the Study of Stellar Structure* (1939), *Principles of Stellar Dynamics* (1942), *Radiative Transfer* (1950), *Hydrodynamic and Hydromagnetic Stability* (1961), *Truth and Beauty: Aesthetics and Motivations in Science* (1987), and *Newton's Principia for the Common Reader* (1995).

In 1983 Subrahmanyan Chandrasekhar was awarded half of the Nobel Prize in Physics with William A. Fowler for "...theoretical studies of the physical processes of importance to the structure and evolution of the stars".

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