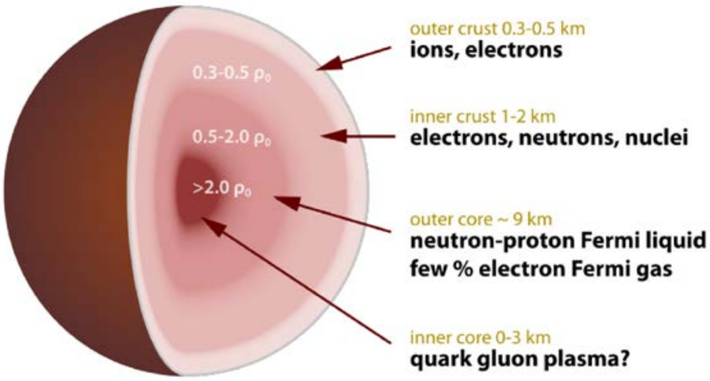
NEUTRON STARS



A neutron star is the collapsed core of a large star, which before a Supernova collapse had a total of between 10 and 29 solar masses. Neutron stars are the smallest and densest stars known to exist. Though neutron stars typically have a radius on the order of 10 kilometres, they can have masses of about twice that of the Sun. They result from the supernova explosion of a massive star, combined with gravitational collapse, that compresses the core past the white dwarf star density to that of atomic nuclei. Most of the basic models for these objects imply that neutron stars are composed almost entirely of neutrons, which are subatomic particles with no net electrical charge and with slightly larger mass than protons. They are supported against further collapse by neutron degeneracy pressure, a phenomenon described by the Pauli exclusion principle. If the remnant has a mass greater than about 3 solar masses, the neutron star continues collapsing to form a black hole (the Pauli exclusion principle states that two or more identical fermions cannot occupy the same quantum state within a quantum system simultaneously). The principle was formulated by Austrian physicist **Wolfgang Pauli** in 1925.

Neutron stars that can be observed are very hot and typically have a surface temperature around 600000 K. **They are so dense that a normal-sized matchbox containing neutron-star material would have a mass of approximately 3 billion tonnes. Their magnetic fields are some 1000 times as strong as that of the Earth. The gravitational field at the neutron star's surface is about 200 billion times that of the Earth.**

Radiation from the pulsar PSR B1509-58, a rapidly spinning neutron star, makes nearby gas glow in X-rays (gold) and illuminates the rest of the nebula in infrared (blue and red).

As the star's core collapses, its rotation rate increases as a result of conservation of angular momentum, hence newly formed neutron stars rotate at up to several hundred times per second. Some neutron stars emit beams of electromagnetic radiation that make them detectable as pulsars. Indeed, the discovery of pulsars by **Jocelyn Bell Burnell** in 1967 was the first observational suggestion that neutron stars exist. The radiation from pulsars is thought to be primarily emitted from regions near their magnetic poles. If the magnetic poles do not coincide with the rotational axis of the neutron star, the emission beam will sweep the sky, and when seen from a distance, if the observer is somewhere in the path of the beam, it will appear as pulses of radiation coming from a fixed point in space (the so-called "lighthouse effect"). **The fastest-spinning neutron star known is PSR J1748-2446ad, rotating at a rate of 716 times a second or 43,000 revolutions per minute, giving a linear speed at the surface of nearly a quarter the speed of light.**

There are thought to be around 100 million neutron stars in the Milky Way, a figure obtained by estimating the number of stars that have undergone supernova explosions. However, most are old and cold, and neutron stars can only be easily detected in certain instances, such as if they are a pulsar or part of a binary system. Slow-rotating and non-accreting neutron stars are virtually undetectable; however a few nearby neutron stars that appear to emit only thermal radiation have been detected. Soft gamma repeaters are conjectured to be a type of neutron star with very strong magnetic fields, known as magnetars, or alternatively, neutron stars with fossil disks around them. Neutron stars in binary systems can undergo accretion which typically makes the system bright in x-rays while the material falling onto the neutron star can form hotspots that rotate in and out of view in identified X-ray pulsar systems. Additionally, such accretion can "recycle" old pulsars and potentially cause them to gain mass and spin-up to very fast rotation rates, forming the so-called millisecond pulsars. These binary systems will continue to evolve, and eventually the companions can become compact objects such as white dwarfs or neutron stars themselves, though other possibilities include a complete destruction of the companion through ablation or merger. The merger of binary neutron stars may be the source of short-duration gamma-ray bursts and are likely strong sources of gravitational waves. In 2017, a direct detection of the gravitational waves from such an event was made, and gravitational waves have also been indirectly detected in a system where two neutron stars orbit each other.

At present, there are about 2000 known neutron stars in the Milky Way and the Magellanic Clouds, the majority of which have been detected as radio pulsars. Neutron stars are mostly concentrated along the disk of the Milky Way although the spread perpendicular to the disk is large because the supernova explosion process can impart high translational speeds of up to 400 km/s to the newly formed neutron star.

BINARY NEUTRON STARS

About 5% of all known neutron stars are members of a binary system. The formation and evolution of binary neutron stars can be a complex process. Neutron stars have been observed in binaries with ordinary main-sequence stars, red giants, white dwarfs or other neutron stars. According to modern theories of binary evolution it is expected that neutron stars also exist in binary systems with black hole companions. **The merger of binaries containing two neutron stars, or a neutron star and a black hole, are expected to be prime sources for the emission of detectable gravitational waves.**

HISTORY OF DISCOVERIES

In 1934, **Walter Baade** and **Fritz Zwicky** proposed the existence of neutron stars, only a year after the discovery of the neutron by **Sir James Chadwick**. In seeking an explanation for the origin of a supernova, they tentatively proposed that in supernova explosions ordinary stars are turned into stars that consist of extremely closely packed neutrons that they called neutron stars. Baade and Zwicky correctly proposed at that time that the release of the gravitational binding energy of the neutron stars powers the supernova: "In the supernova process, mass in bulk is annihilated".

Neutron stars were thought to be too faint to be detectable and little work was done on them until November 1967, when **Franco Pacini** pointed out that if the neutron stars were spinning and had large magnetic fields, then electromagnetic waves would be emitted. Unbeknown to him, radio astronomer **Antony Hewish** and his research assistant **Jocelyn Bell** at Cambridge were shortly to detect radio pulses from stars that are now believed to be highly magnetized, rapidly spinning neutron stars, known as pulsars. Antony Hewish was awarded the Nobel Prize in Physics "for his decisive role in the discovery of pulsars"

In 1965, Antony Hewish and Samuel Okoye discovered "an unusual source of high radio brightness temperature in the Crab Nebula". This source turned out to be the Crab Pulsar that resulted from the great supernova of 1054.

In 1974, **Joseph Taylor** and **Russell Hulse** discovered the first binary pulsar, PSR B1913+16, which consists of two neutron stars (one seen as a pulsar) orbiting around their centre of mass. **Einstein's general theory of relativity predicts that massive objects in short binary orbits should emit gravitational waves, and that their orbit should decay with time. This was indeed observed, precisely as general relativity predicts, and in 1993, Taylor and Hulse were awarded the Nobel Prize in Physics for this discovery.**

In 1967, **Iosif Shklovsky** examined the X-ray and optical observations of Scorpius X-1 and correctly concluded that the radiation comes from a neutron star at the stage of accretion.

In 2003, **Marta Burgay** and colleagues discovered the first double neutron star system where both components are detectable as pulsars. The discovery of this system allows a total of 5 different tests of general relativity, some of these with unprecedented precision.

In 2010, **Paul Demorest** and colleagues measured the mass of the millisecond pulsar PSR J1614–2230 to be 1.97$M_\odot$. This was substantially higher than any previously measured neutron star mass and places strong constraints on the interior composition of neutron stars.

In 2013, **John Antoniadis** and colleagues measured the mass of PSR J0348+0432 to be 2.01$M_\odot$. using white dwarf spectroscopy.

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