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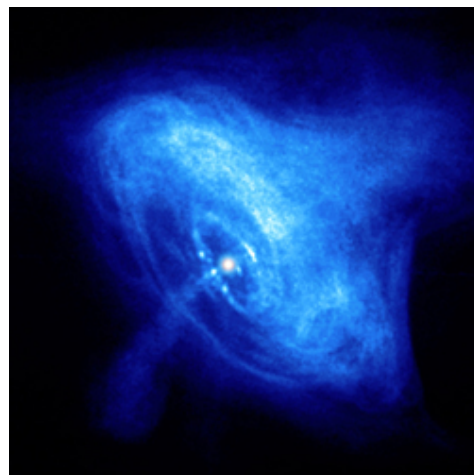
NEUTRON STAR

Neutron stars comprise one of the possible **evolutionary end-points** of high **mass** stars. Once the core of the **star** has completely burned to iron, energy production stops and the core rapidly **collapses**, squeezing **electrons** and **protons** together to form neutrons and neutrinos. The neutrinos easily escape the contracting core but the neutrons pack closer together until their **density** is equivalent to that of an atomic nucleus. At this point, the neutrons occupy the smallest **space** possible (in a similar fashion to the electrons in a **white dwarf**) and, if the core is less than about 3 **solar masses**, they exert a **pressure** which is capable of supporting a star. For masses larger than this, even the pressure of neutrons cannot support the star against **gravity** and it collapses into a **stellar black hole**. A star supported by neutron degeneracy pressure is known as a '**neutron star**', which may be seen as a **pulsar** if its magnetic field is favourably aligned with its spin **axis**.

Neutron stars are extreme objects that measure between 10 and 20 km across. They have densities of 10^{17} kg/m³ (the Earth has a density of around 5×10^3 kg/m³ and even **white dwarfs** have densities over a million times less) meaning that a teaspoon of neutron star material would weigh around a billion tonnes. The easiest way to picture this is to imagine squeezing twice the mass of the **Sun** into an object about the size of a small city! The result is that gravity at the surface of the neutron star is around 10^{11} stronger than what we experience here on Earth, and an object would have to travel at about half the **speed of light** to escape from the star.

Born in a core-collapse supernova explosion, neutron stars rotate extremely rapidly as a consequence of the conservation of **angular momentum**, and have incredibly strong magnetic fields due to conservation of magnetic **flux**. The relatively slowly rotating core of the massive star increases its rotation rate enormously as it collapses to form the much smaller neutron star. This is analogous to the increased spin of an iceskater if she concentrates her mass around her spin axis by bringing her arms close to her body. At the same time, the magnetic field lines of the massive star are pulled closer together as the core collapses. This intensifies the magnetic field of the star to around 10^{12} times that of the Earth.

The result is that neutron stars can rotate up to at least 60 times per **second** when born. If they are part of a **binary system**, they can increase this rotation rate through the accretion of material, to over 600 times per second! Neutron stars that have lost energy through radiative processes have been observed to rotate as slowly



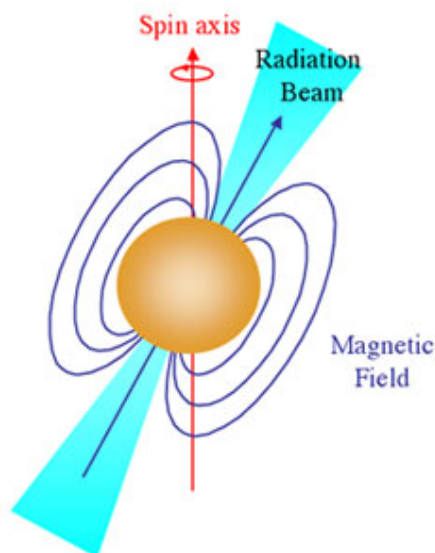
The Crab pulsar and **nebula** formed in a **supernova** explosion first noted by Chinese **astronomers** in 1054. This X-ray image shows the pulsar and the nebula which is powered mostly through

as once every 8 seconds while still maintaining radio pulses, and neutron stars that have been braked by **winds** in X-ray systems can have rotation rates as slow as once every 20 minutes.

the loss of rotational energy by the neutron star.

Credit: NASA/CXC/ASU/J. Hester et al.

Observations also reveal that the rotation rate of isolated neutron stars slowly changes over time, generally decreasing as the star ages and rotational energy is lost to the surroundings through the magnetic field (though occasionally **glitches** are seen). An example is the Crab pulsar, which is slowing its spin at a rate of 38 nanoseconds per **day**, releasing enough energy to power the Crab nebula.



Schematic of a pulsar showing the misalignment between the rotation axis and the radiation beams emitted from the magnetic poles.

Astronomers measure these rotation rates by detecting **electromagnetic radiation** ejected through the poles of the magnetic field. These magnetic poles are generally misaligned with the rotation axis of the neutron star and so the radiation beam sweeps around as the star rotates. This is much the same as the beam of light from a lighthouse sweeping around. If the Earth lies in the path of the beam, we see the neutron star/pulsar. If not, we see only the **supernova remnant**. This also nicely accounts for the fact that we do not see a pulsar in every supernova remnant.

Neutron stars do not necessarily exist in isolation, and those that form part of a binary system usually emit strongly in **X-rays**. **X-ray binaries** typically result from the transfer of material from a main sequence companion onto the neutron star, while **short-duration gamma ray bursts** are thought to result from the merger of two neutron stars.

The existence of neutron stars as a result of supernova explosions was tentatively predicted in 1933, one **year** after the discovery of the neutron as an elementary particle. However, it was not until 1967 that Jocelyn Bell observed the periodic pulses of radio emission characteristic of **pulsars**. There are now over 1,300 neutron stars known and about 10^5 predicted to exist in the disk of the **Milky Way**.

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