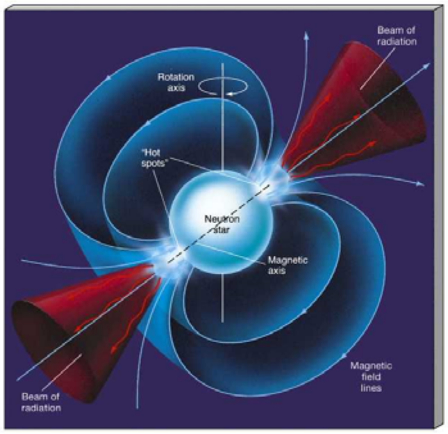
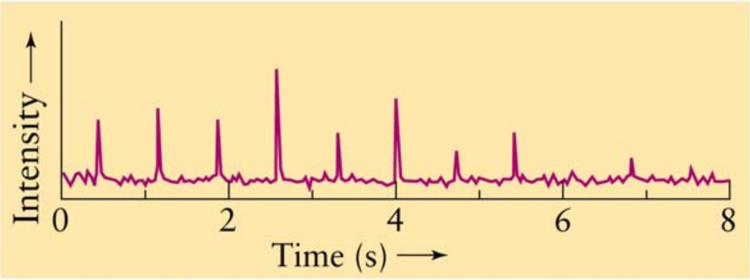
Pulsars and Neutron Stars



History

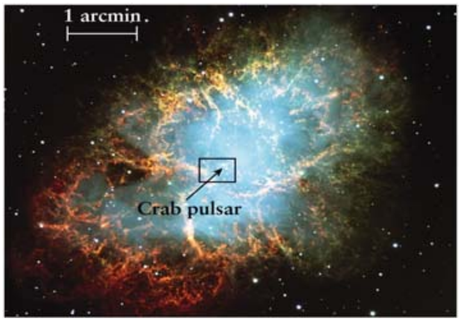
The **neutron** was discovered in 1932. In 1933 a prediction (largely ignored) was that supernovae could form "neutron" stars. First one was discovered 1967 by Jocelyn Bell; period was 1.3373 seconds. Three more pulsars were quickly found after the first.



Pulse Frequency Indicates Size

1. Not an ordinary star or nebula because they do not pulsate.
2. Not an eclipsing binary because the orbital period would have to be under 1 second.
3. Not a variable star because they are too large to pulsate this quickly.
4. Not a rapidly rotating white dwarf with a “hot spot” because it would fly apart.

Relationship with Supernovae

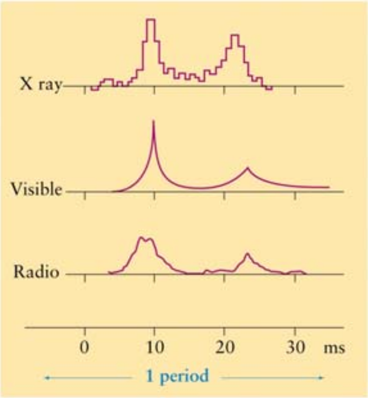


It was not until the discovery of the pulsar (P = 0.033 sec) in the Crab Nebula in 1968 that the association with SN remnants was confirmed.

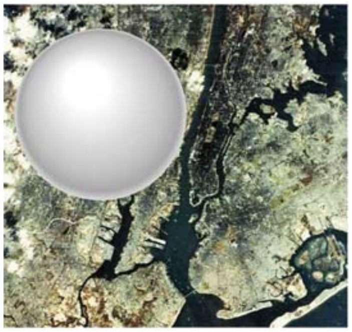
Observations

More than 2000 pulsars have been discovered since Bell and Hewish's first one in 1967. Pulses range from a little longer than 0.001 seconds to nearly 10 seconds. The current fastest is P = 0.00113 sec or 885 rotations/sec.

Multi-Wavelength Pulses

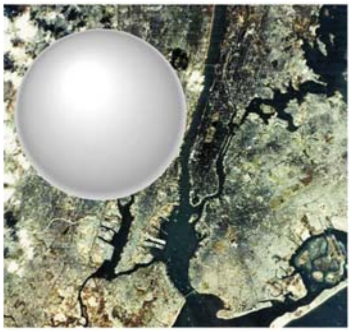


Mass and Density



Neutrons, like electrons, **obey the Pauli exclusion principle** and can become degenerate if crowded into a sufficiently small volume for a given momentum range. Degenerate neutrons cannot decay into protons and electrons, for by the time the star is that collapsed, the allowable states for neutrons are filled.

Mass and Density



A neutron star of one solar mass would have a diameter of only about 20 km.

The density would be 10^{14} to 10^{15} g/cm^3:

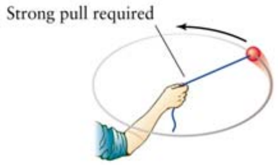
1 sugar cube = 100 million tons
> all of humanity.

The mass limit for neutron stars is believed to be from 2 to 3 solar masses.

Why So Fast?

Angular Momentum = Mass x Radius x Angular velocity

$= \mathcal{M} R^2 \omega$



where $\omega = v / R$

which is proportional to 1 / Period

Solar Example

$$\mathcal{M} R_1^2 \omega_1 = \mathcal{M} R_2^2 \omega_2$$

$$\omega = v / R = 1 / P$$

$$R_1^2 / P_1 = R_2^2 / P_2$$

$$P_1 / P_2 = R_1^2 / R_2^2 = [\, 7 \times 10^5 \text{ km} / 10 \text{ km} \,]^2 = 4.9 \times 10^9$$

Period_1 (current) = 30 days = 2.59×10^6 sec

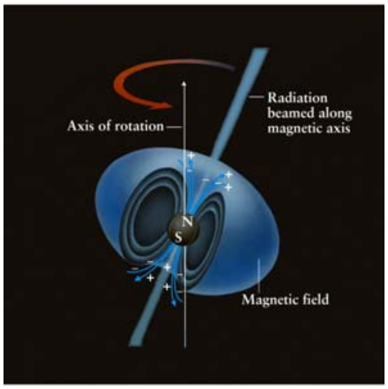
Period_2 (new) = $2.59 \times 10^6 \;/\; 4.9 \times 10^9$ = 0.0005 sec

The Sun’s new rotation rate would be 0.0005 sec if it had D = 20 km.

Magnetic Strength

Any magnetic field that existed in the original star is highly compressed, so a field of (typically) 1 gauss in a star the size of the Sun increases to the order of 10^{10} to 10^{12} gauss around the neutron star.

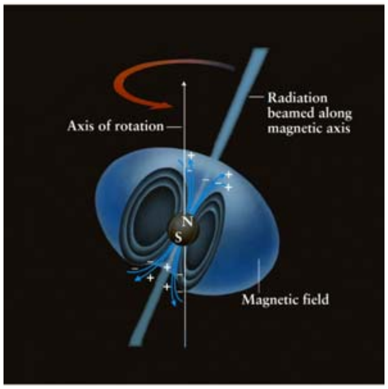
At the surface, neutrons decay into protons and electrons. The electrons move in the intense magnetic fields at close to the speed of light and emit energy by the synchrotron mechanism.



Magnetic Strength

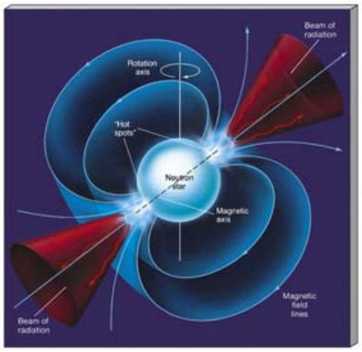
The radiation is very directional, however, and if the magnetic poles happen not to coincide with the poles of the axis of rotation, the star becomes like a lighthouse. But the beam is hollow.

Neutron Star Interactive



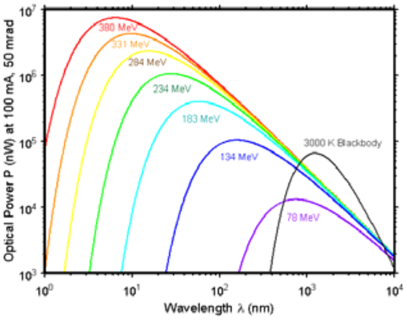
Synchrotron Radiation

As relativistic electrons follow the curved magnetic field lines, they accelerate and emit light. It is called synchrotron radiation if the circular motion *around* the field lines dominates, and curvature radiation if the motion is primarily *along* the field lines.

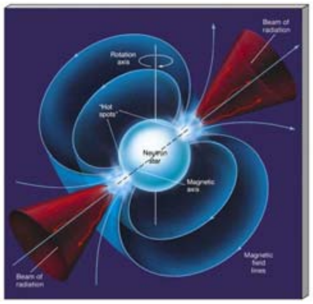


Synchrotron Radiation

In both cases, the shape of the continuous spectrum depends on the energy distribution of the emitting electrons, and so is easily distinguished from the spectrum of blackbody radiation.



The Electric Field



The rapidly changing magnetic field near the rotating pulsar induces a huge electric field at the surface. The electric field easily overcomes the pull of gravity on charged particles in the neutron star's crust.

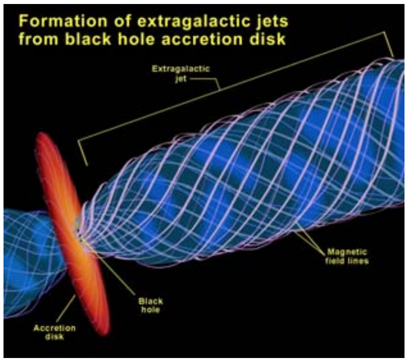
For example, the electric force on a proton is about 300 million times stronger than the force of gravity, and the ratio of the electric force on an electron to the gravitational force is even more overwhelming.

The Jets

The charged particles ejected from the vicinity of the pulsar's magnetic poles are quickly accelerated to relativistic speeds by the induced electric field.

As the electrons follow the curved magnetic field lines, they emit curvature radiation in the form of energetic gamma-ray photons.

This radiation is emitted in a narrow beam in the instantaneous direction of motion of the electron.

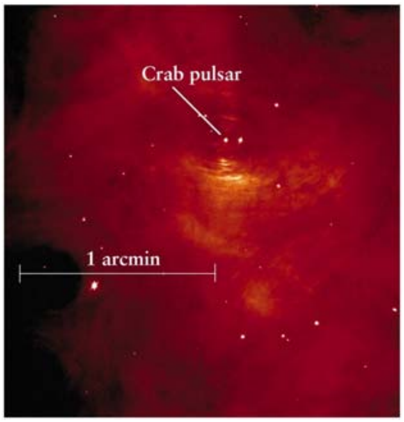


Synchrotron Radiation

Pulsars continue to evolve, for they give off synchrotron radiation (relativistic, circular electrons).

Crab Nebula E = 3×10^{31} W

Sun E = 4×10^{26} W



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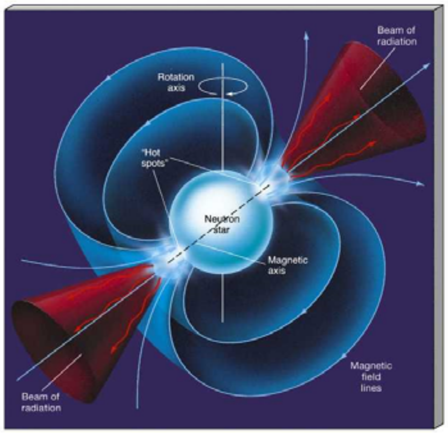
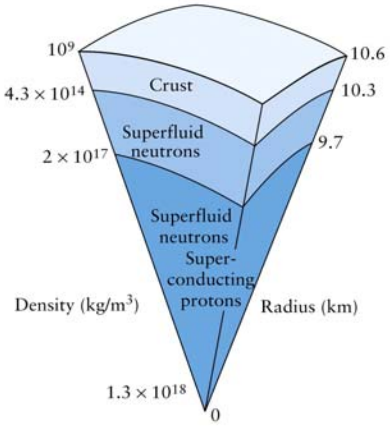


Internal Structure



10.3 to 10.6 km

rigid crystal – 10^{16} times that of steel – mountains are a few mm high

9.7 to 10.3 km

liquid state with superfluid neutrons

0.0 to 9.7 km

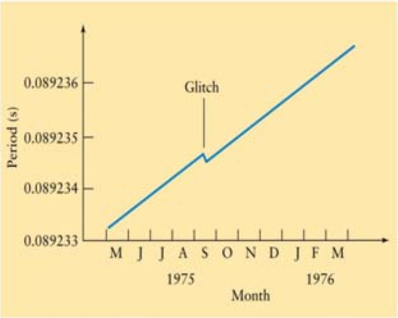
liquid state with superconducting protons and superfluid neutrons

Rotational Changes

1. Many are slowing down by a billionth of a second per day. This energy is 10^5 times that of the Sun. This is the source of energy for the synchrotron radiation that illuminates the nebula.

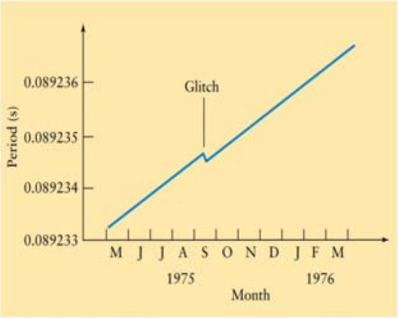
2. There are **glitches** in the regularity of the pulses.

Rotational Glitches



Rotational glitches are caused by superfluid neutrons. As a neutron star radiates, the rotation of its crust slows down, but the neutron whirlpools in the star's interior continue to rotate with the same speed.

Rotational Glitches



Some of these whirlpools cling to the crust as though they were bungee chords with one end attached to the crust and the other end to the star's interior. As the crust slows down relative to the interior, these superfluid bungee cords are stretched out. When the tension in them gets too great, they deliver a sharp jolt that makes the crust speed up suddenly.

Lifetimes

Most pulsars lie fairly close to the plane of the Galaxy.

Lifetimes must be about 10 million years.

Pulsars should all be slowing down.

Only 3 of more than 1000 pulsars discovered so far are embedded in visible nebulae.

The lifetime of the pulsar is about 100 times longer than the length of time required for the expanding gas to disperse.

Evolution of Pulsars

Pulsars initially spin at a period of about 0.01 seconds. As it rotates, it gives off radiation. So, in turn, it slows and the magnetic field decreases.

Not every pulsar is in a supernova remnant, and only 3 supernova remnants have pulsars (which have short periods). This could be due to:

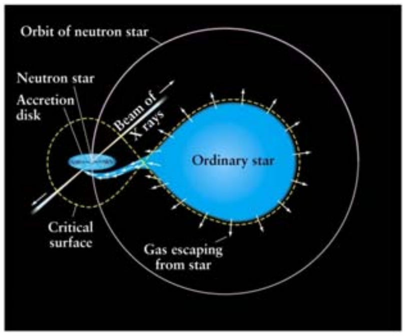
1. The beams do not sweep the Earth,
2. They have high proper motion away from the remnant,
3. SNRs last for 50,000 years, whereas pulsars last for 2 million years,
4. SNR are seen out to 10 kpc, but pulsars are detected only to 1 kpc.

Millisecond Pulsars

There are ~133 known X-ray binaries.

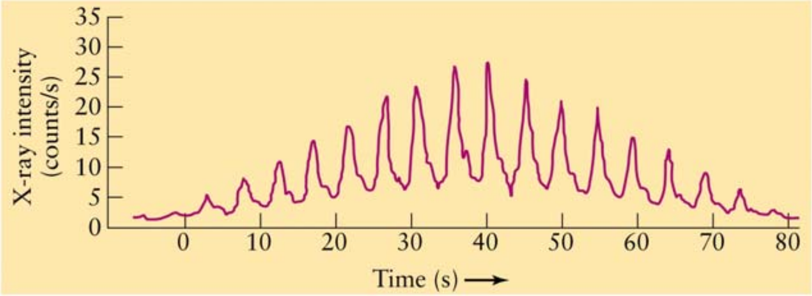
1. A weak field indicates that they are old, but the extremely fast rotation rate suggests they are very young.

2. It is believed that mass transfer causes the pulsar to spin up. [Once again, an interesting binary star system.]



Binary Pulsars

The first binary pulsar, PSR 1913+16 or the "Hulse-Taylor binary pulsar" was discovered in 1974 at Arecibo by Joseph Taylor, Jr. and Russell Hulse, for which they won the 1993 Nobel Prize in Physics. Pulses from have been tracked, without glitches, to within 15 μs since its discovery.



Typical Comparison

	White Dwarf	Neutron Star
Mass	0.6 - 1.0	2 - 3
Diameter	10,000 km	20 km
Density	5×10^5 g/cm^3	10^{14} g/cm^3