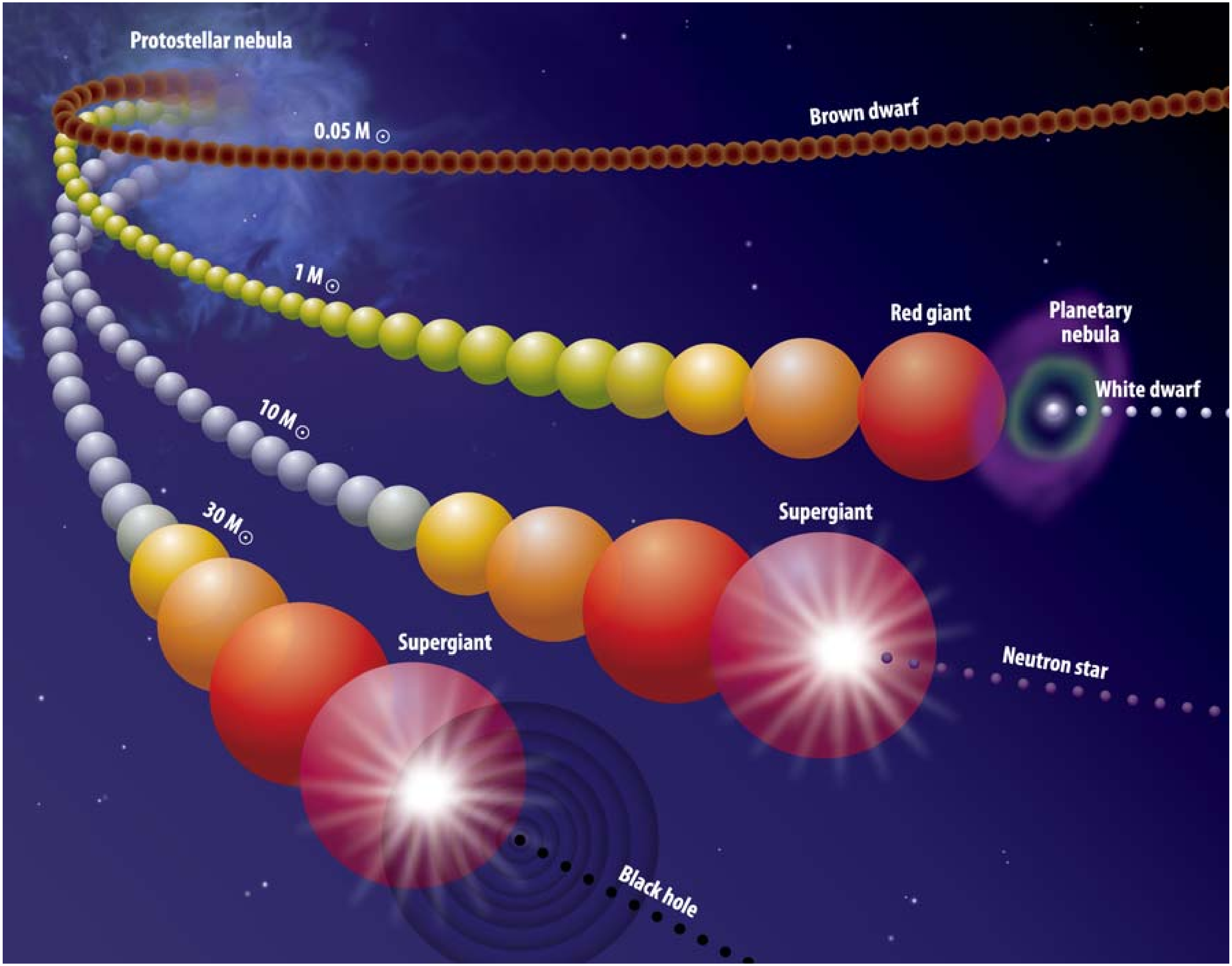

Protostellar nebula
Brown dwarf
0.05 M ⊙
1 M ⊙
Red giant
Planetary nebula
White dwarf
10 M ⊙
30 M ⊙
Supergiant
Supergiant
Neutron star
Black hole

Neutron Stars

Neutron Stars

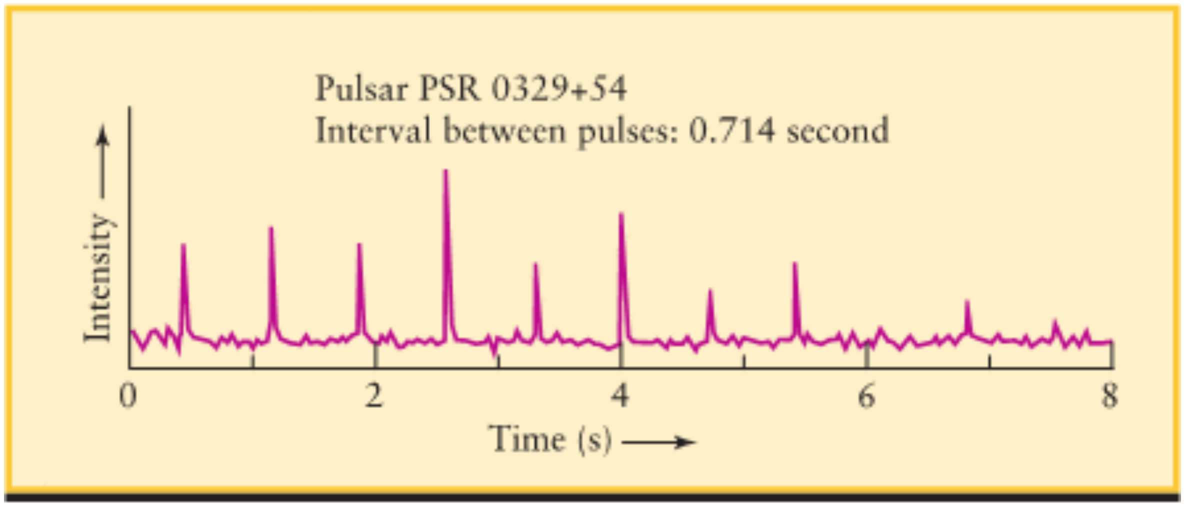
The emission from the supernova that produced the **crab nebula** was observed in 1054 AD by Chinese, Japanese, Native Americans, and Persian/Arab astronomers as being bright enough in the night sky for almost 2 years.

We now know that **SN 1054 was a Type II supernova** that ended the life of a massive star and left behind a neutron star.

English physicist **James Chadwick** discovered the neutron in 1932. The neutron is a subatomic particle with a mass similar to that of a proton and with no electric charge.

Astronomers **Zwicky** and **Baade** first suggested that the collapse of a massive star could lead to an object made up primarily of neutrons (neutron star).

Neutron Stars



Graduate student Jocelyn Bell from Cambridge University was working on a project to detect fluctuations of radio signals caused by motion of gas between the source and observer.

While searching for these random fluctuations she detected radio regular (periodic) pulses from a particular location in the sky. Many similar sources with periodic pulses were soon discovered and such objects were called **pulsars**.

Neutron Stars

We now know that **pulsars are just rotating neutron stars**.

The **neutron star spins up** when it forms **during the collapse** of a spinning star. (a figure skater on ice can increase spin by bringing in their arms).

One year after the discovery of the first pulsar the **central object in the crab nebular** was found to be pulsating at ~30 times a second.

The spinning neutron star in the middle of the Crab nebula explained the origin of its glow. The energy source of its glow is the rotational energy of the neutron star.

Properties of Neutron Stars

Rapid rotation. **Conservation of angular momentum** implies that a neutron star should be rotating very fast. The NS spins up when it forms during the collapse of a spinning star.

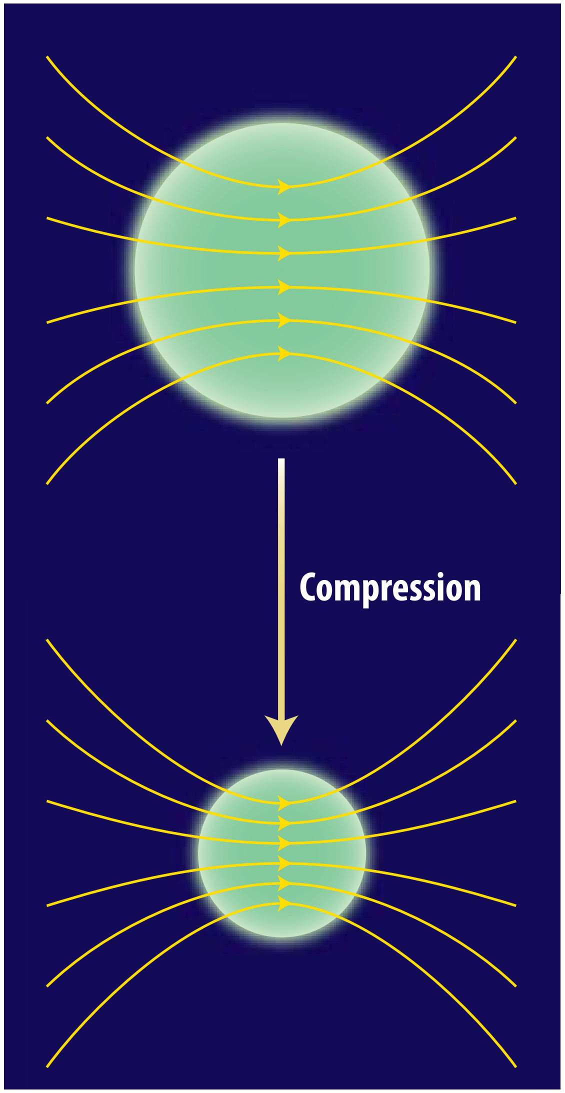
Angular momentum before collapse = Angular momentum after

$$\frac{2}{5}MR_1^2\omega_1 = \frac{2}{5}MR_2^2\omega_2 \Rightarrow R_1^2\omega_1 = R_2^2\omega_2$$

where R_1 and ω_1 are the radius and angular speed of the star before collapse and R_2 and ω_2 are the radius and angular speed of the star after collapse.

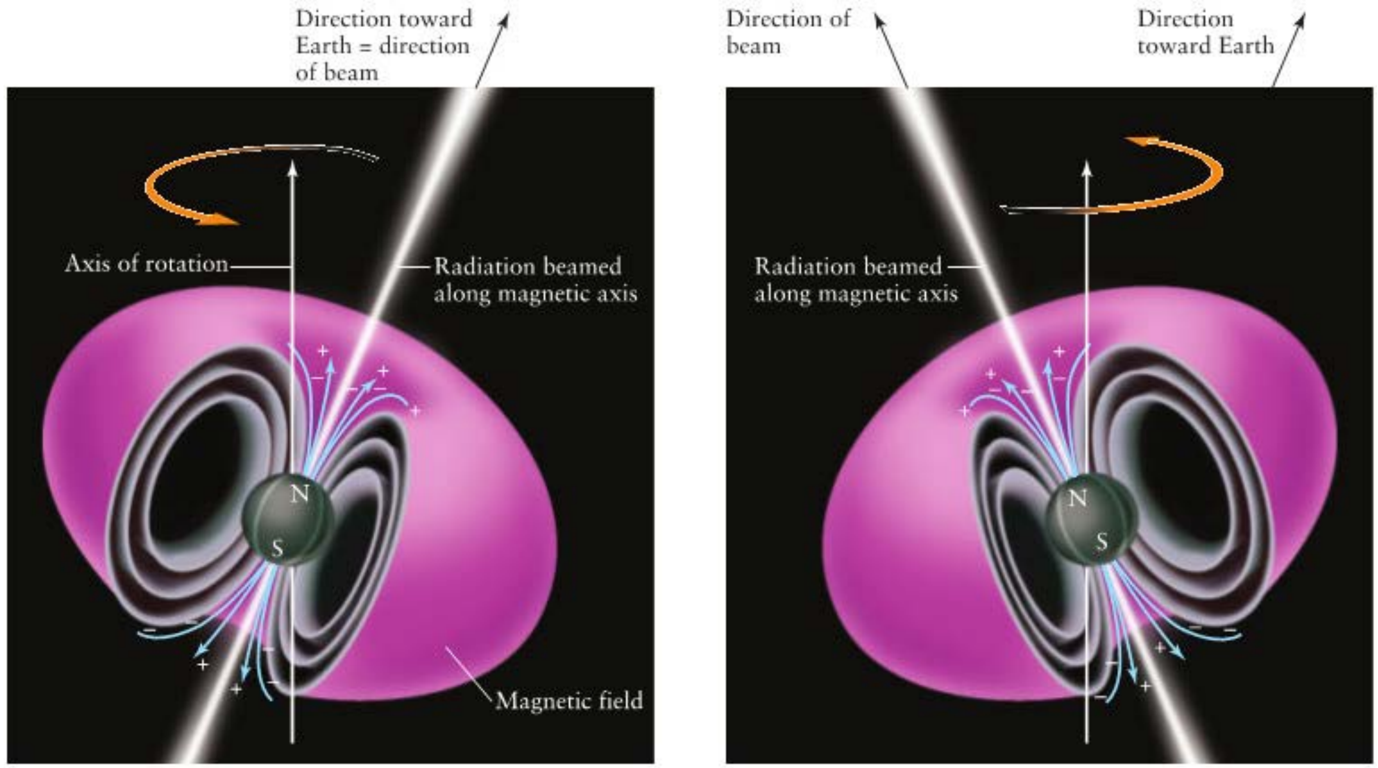
Properties of Neutron Stars

As the star collapses, the plasma drags the magnetic field lines with it (surface area shrinks by a factor of 10^{10}). This implies that the magnetic field of a NS would be at least 10^{10} times larger than that of the ordinary star from which it collapsed from.



Earth's magnetic field ~ 0.5 Gauss
WD magnetic field ~ 10^6 Gauss
NS magnetic field ~$10^{12\text{-}15}$ Gauss

Neutron Stars

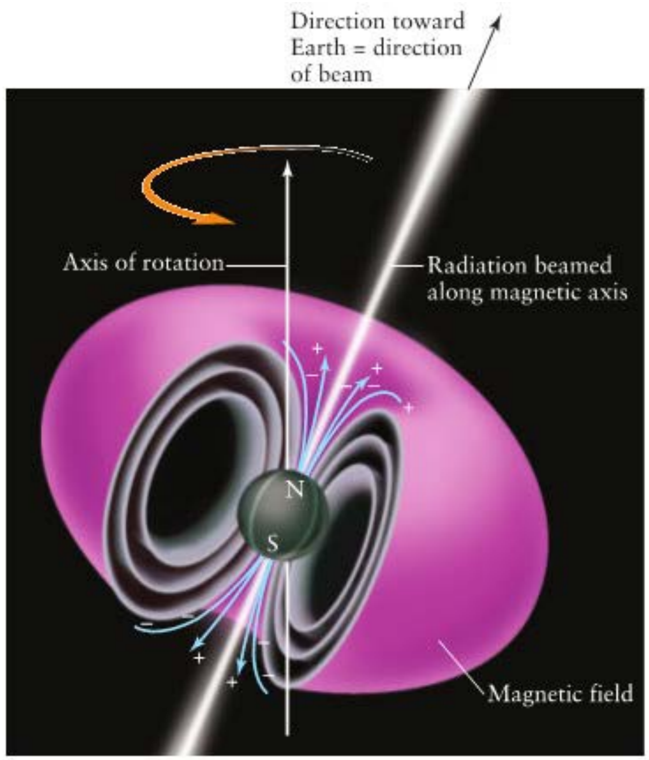


(a) One of the beams from the rotating neutron star is aimed toward Earth: we detect a pulse of radiation.

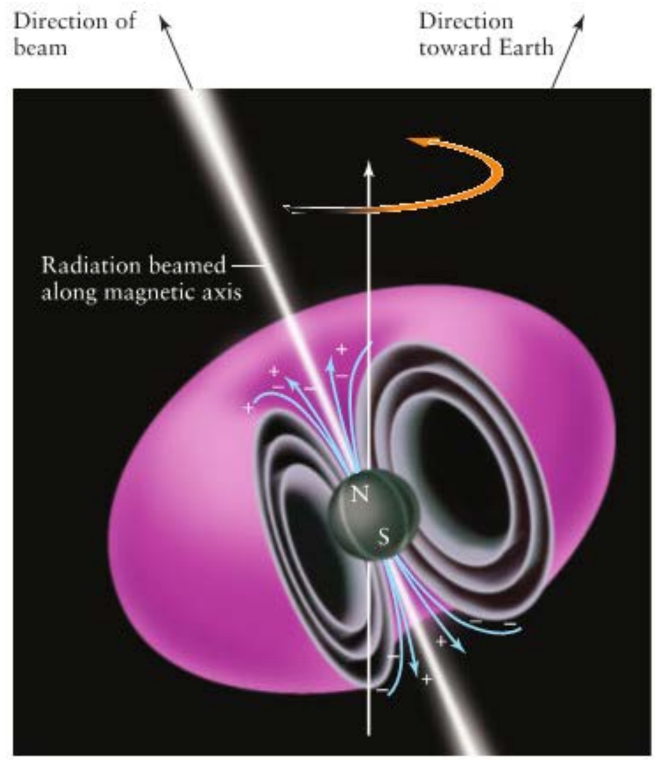
(b) Half a rotation later, neither beam is aimed toward Earth: we detect that the radiation is "off."

The neutron star's magnetic axis is titled with respect to its rotational axis. The rotating magnetic fields create electric fields. The strong **electric field** near the poles **accelerates electrons and ions** from the neutron star's surface to near relativistic speeds. As these fast electrons spiral around magnetic field lines they are accelerated and emit **synchrotron radiation** in the form of **gamma rays**. Because of the relativistic e^- velocities the **gamma rays are beamed** along the poles.

Neutron Stars



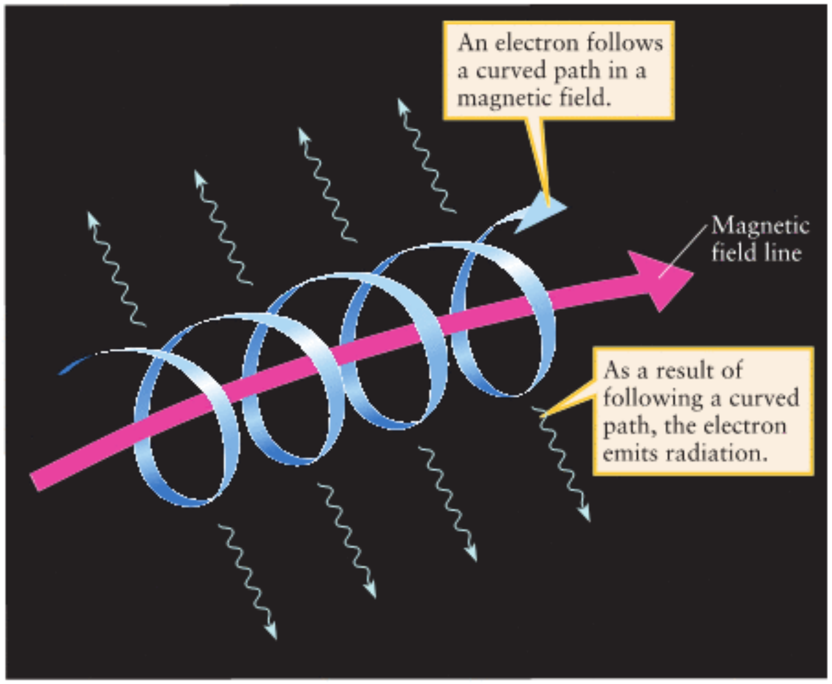
(a) One of the beams from the rotating neutron star is aimed toward Earth: we detect a pulse of radiation.



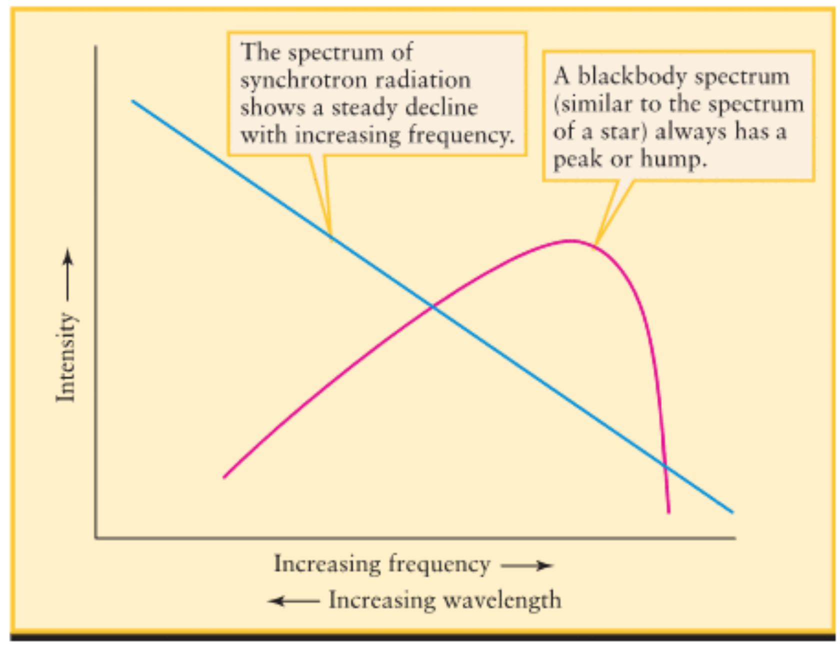
(b) Half a rotation later, neither beam is aimed toward Earth: we detect that the radiation is "off."

The gamma-rays produce electrons and positrons **(pair production)** that get accelerated and in turn emit their own gamma-rays, which create more electron-positron pairs, and so on. This cascade creates a continuous synchrotron spectrum including radio waves that get beamed along the magnetic axis direction. **When this beam of radio waves crosses the direction towards Earth we detect the beamed emission from the pulsar.**

Neutron Stars



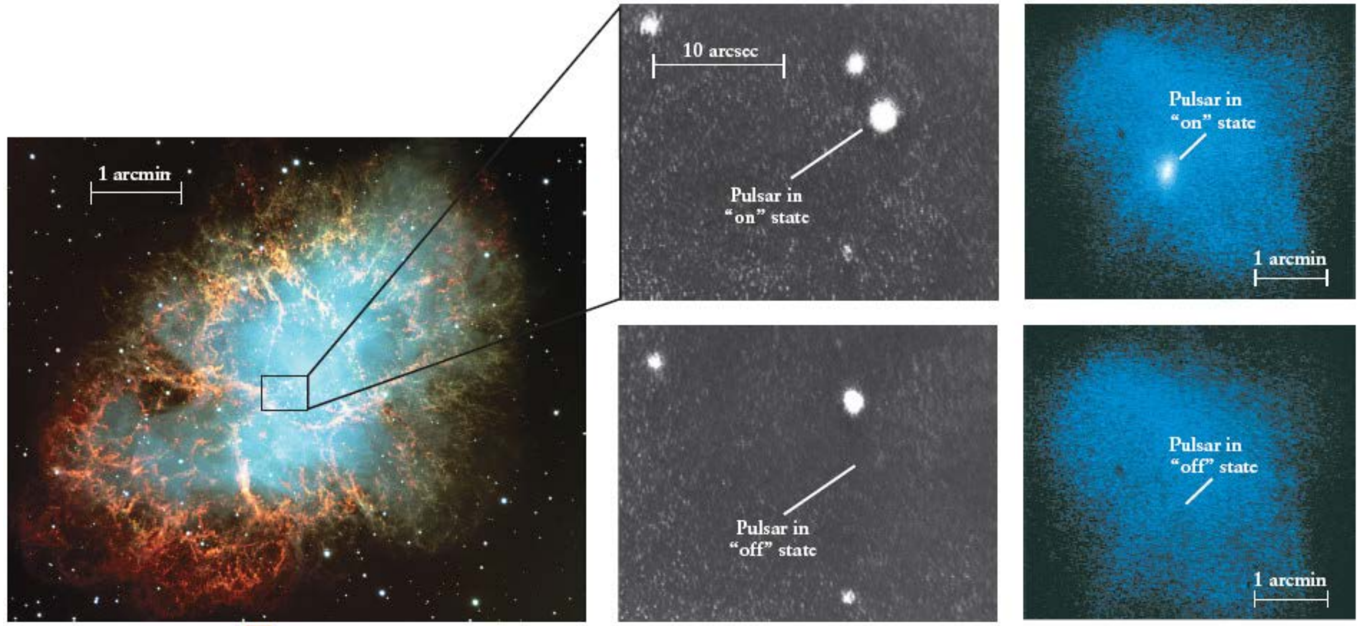
(a)



(b)

The neutron star uses some of its rotational energy to accelerate electrons. These electrons radiate as they spiral around magnetic fields lines. This transfer of energy gradually slows down the neutron star.

Kinetic Energy of Neutron Star



(a) The Crab Nebula R I V U X G

(b) The Crab pulsar in visible light R I V U X G

(c) The Crab pulsar in X rays R I V U X G

The Crab Nebular is about 6,500 ly away and can be viewed even with a small telescope. In 1966 John Wheeler and Fanco Pacini proposed **that the source of the Crab Nebula's immense energy output is the spin of a neutron star** at the center of the nebula .

$E = \frac{1}{2} I\omega^2$, E = energy due to NS spin, I = moment of intertia, ω = angular momentum

Their idea has been confirmed with the discovery of the pulsar and the discovery that its rotation is slowing down.

How Do Pulsars Lose Energy?

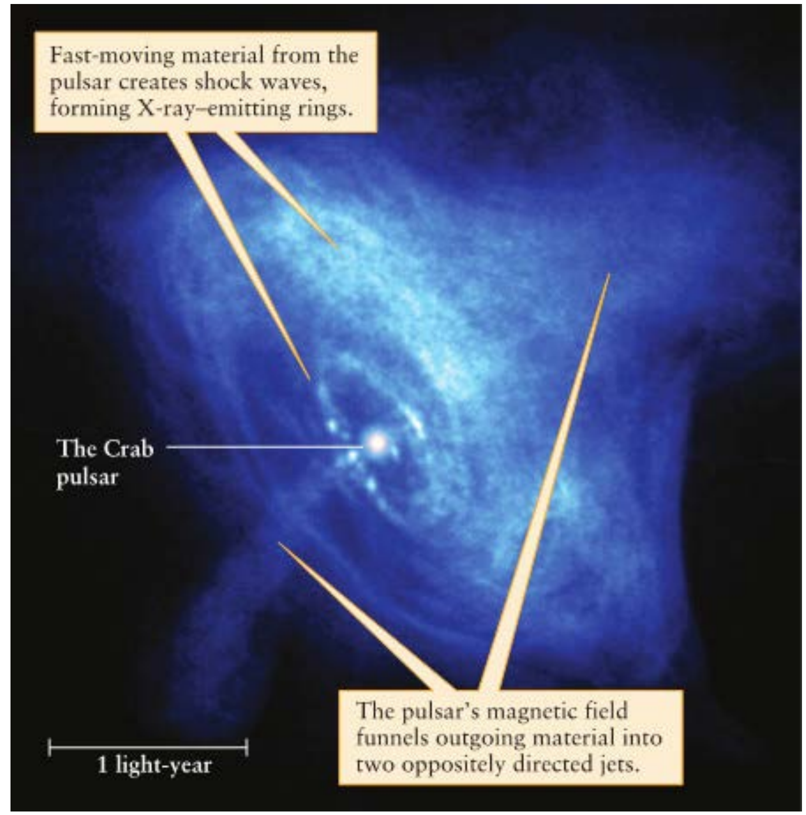
The energy source of a pulsar is kinetic energy of the spinning neutron star. Energy losses that result in the slowing down of a pulsar are:

1) The **pulsar radiates magnetic radiation** as the magnetic dipole rotates about the rotational axis.

2) Production of a **pulsar wind** from accelerated electrons that reach the **light cylinder.**

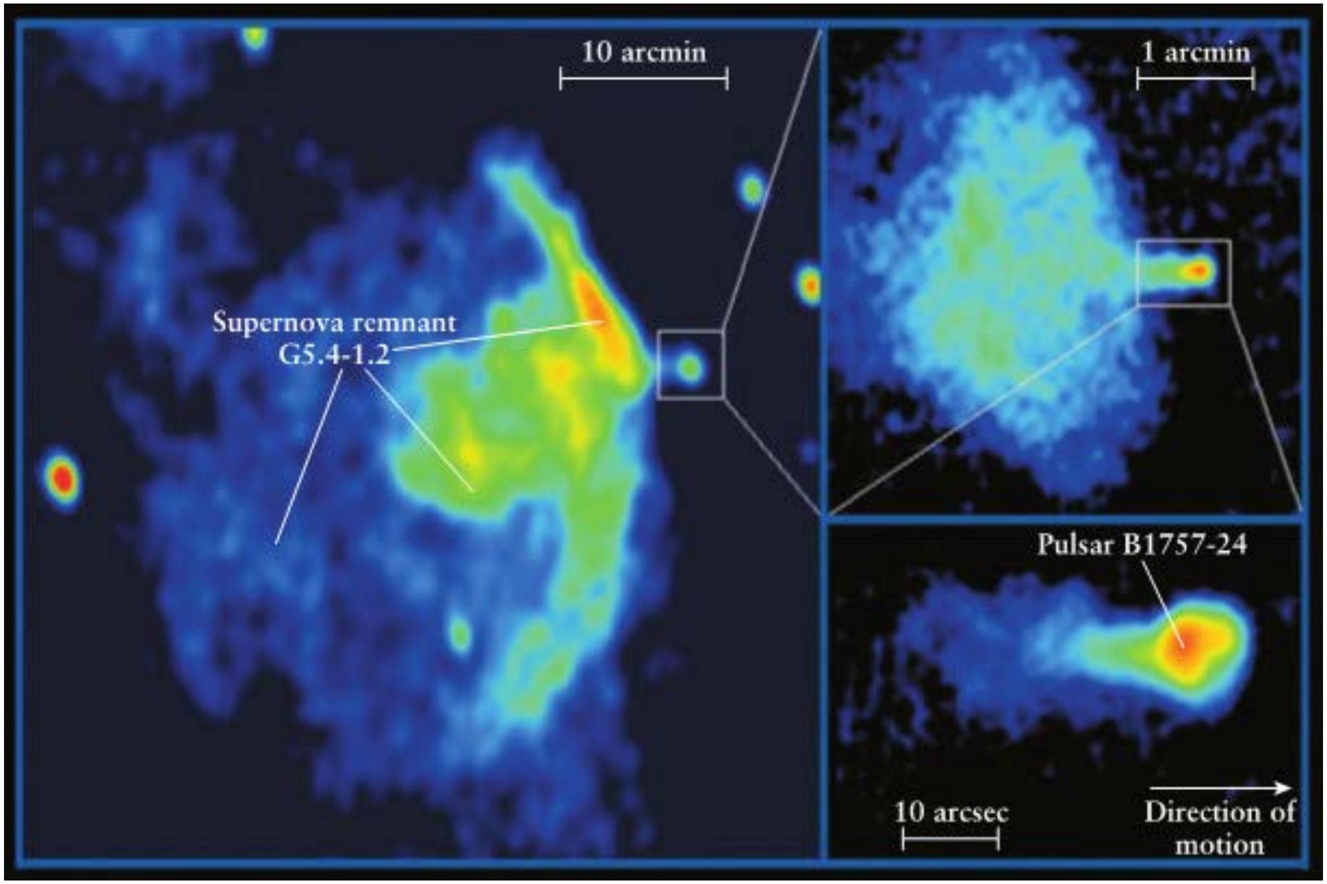
3) **Synchrotron emission** emitted by electrical charges accelerated in the magnetic field of the neutron star.

An isolated pulsar slows down as it ages, so its pulse period increases.

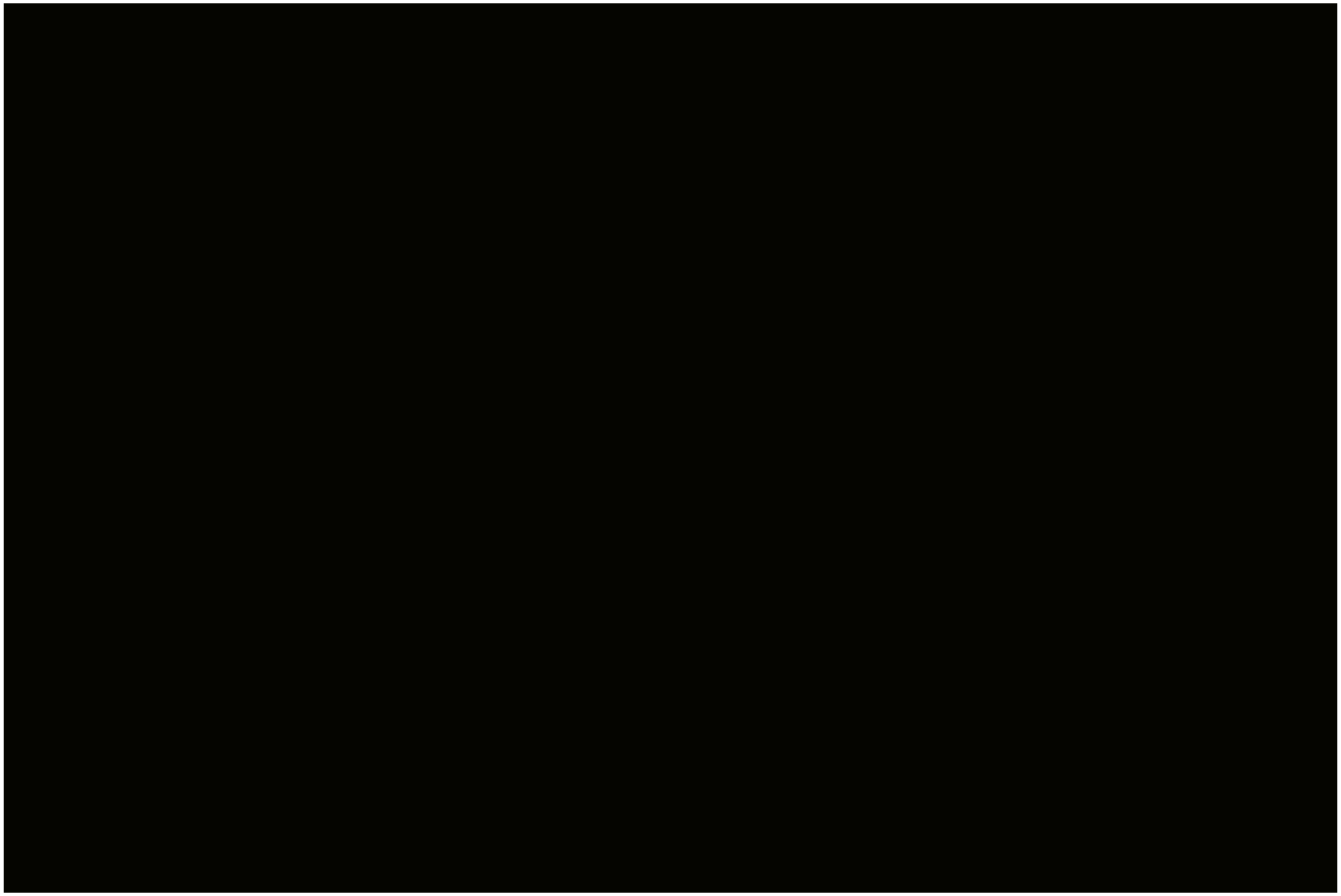


X-ray image of the Crab pulsar.

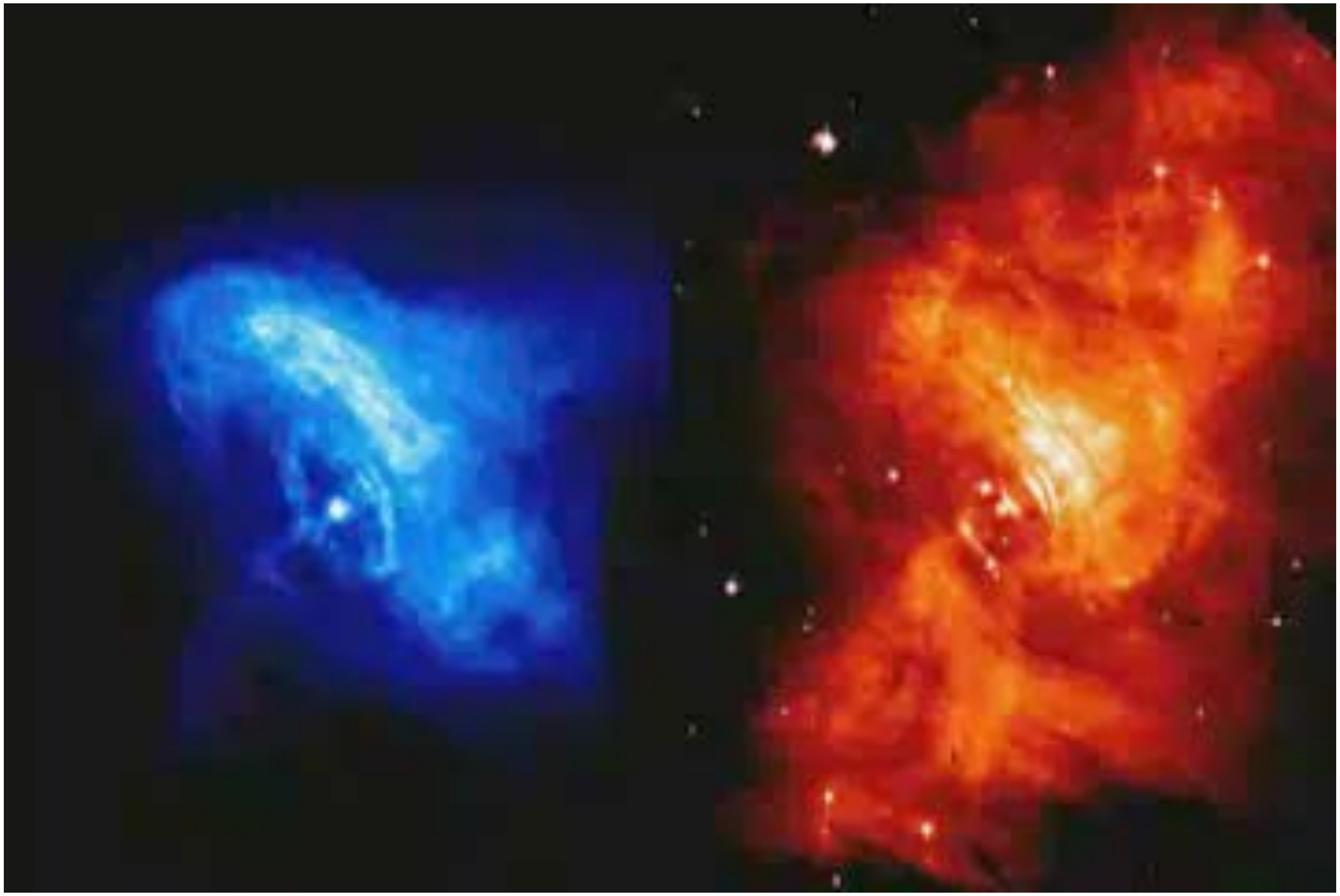
Pulsars Moving Through Space



Occasionally the pulsar is not found at the center of the remnant. This may happen if the explosion was much more powerful on one side of the core than the other. Pulsar B 1757-24 is moving at ~ 600 km/s.



This animation shows material being ejected from the vicinity of the rotating, magnetized neutron star at the heart of the Crab Nebula. Under the influence of the neutron star's magnetic field, the ejected material forms a thick ring and a pair of oppositely-directed jets.



This movie shows dynamic **rings and jets** around the pulsar in the Crab Nebula. The left half of the movie (in blue) shows observations at X-ray wavelengths from the Chandra X-ray Observatory; the right half (in red) shows observations at visible wavelengths from the Hubble Space Telescope. The inner ring is about one light-year across.

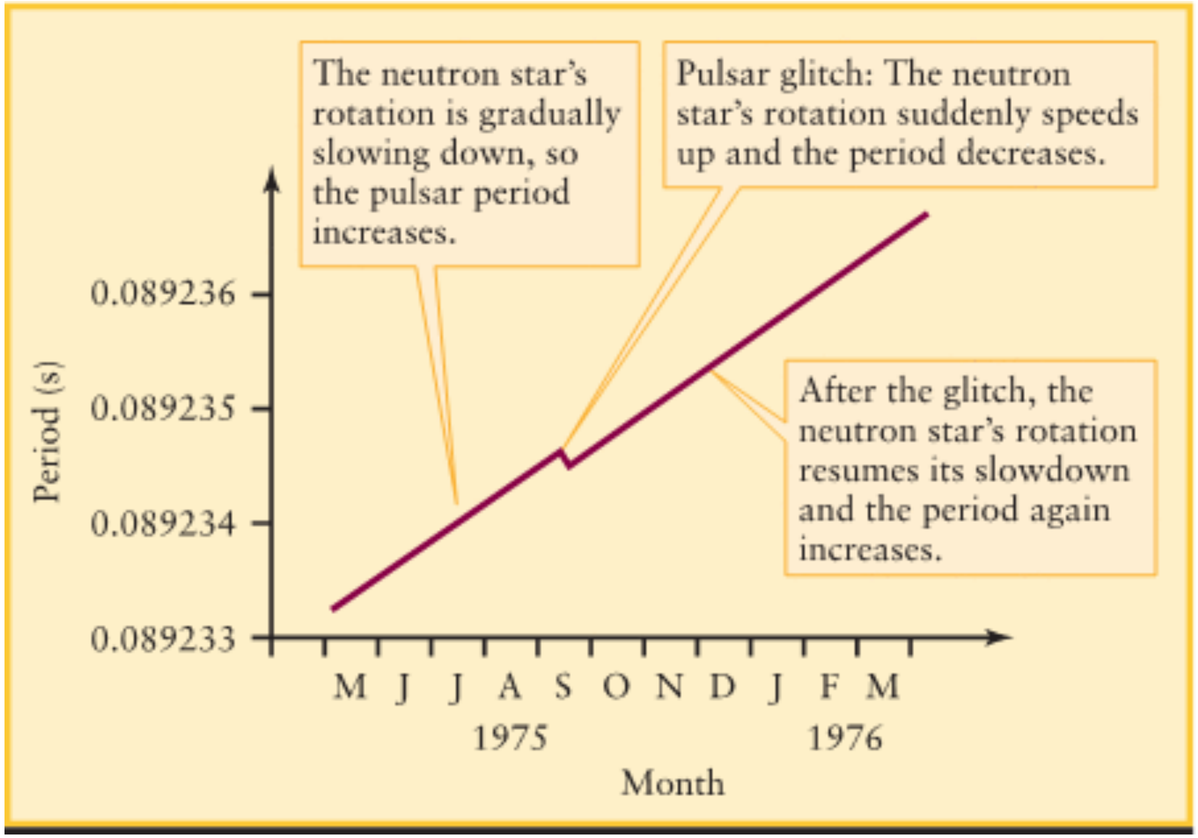
Neutron Stars

A neutron star has a solid crust on its surface and an interior sea of **degenerate neutrons**. The crust is made mostly of Fe, with some nickel, germanium and krypton.

As one goes into the NS more free neutrons are present. These free neutrons move around with no friction (**superfluid**).

Friction-free **whirlpools of superfluid neutrons** may form in the interior. The interaction of these whirlpools with the crust may be the cause of the observed sudden changes in the pulsar's rotation.

Pulsar Glitch

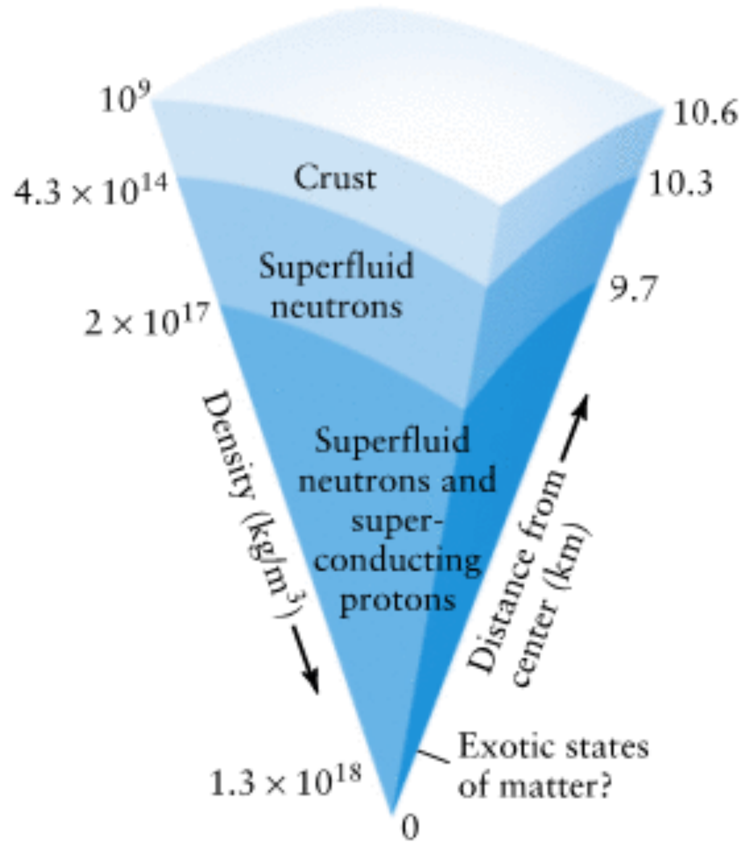


The rotational speed of a pulsar can suddenly increase. This is called a **pulsar glitch**.

Neutron Stars

Models of the internal structure of a neutron star strongly suggest that the **protons in the core experience no electrical resistance** moving around. This phenomenon, is called **superconductivity**.

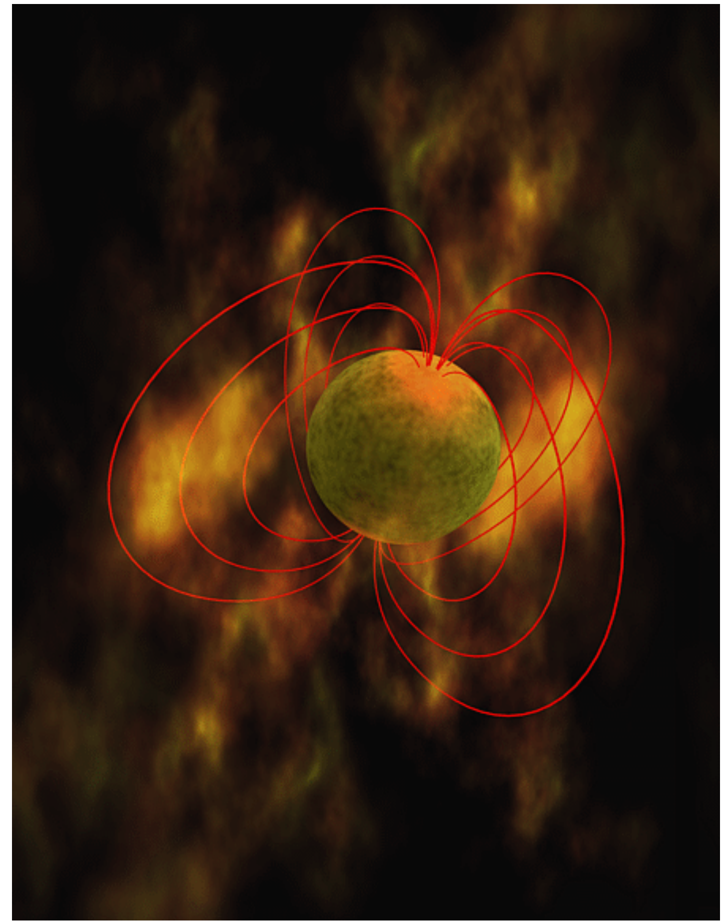
It has been speculated that near the core the pressure reaches a few $\times 10^{18}$ kg/m^3 at which levels the neutrons and protons dissolve into more fundamental particles called **quarks**.



A model of a neutron star.

Magnetars

As a supergiant collapses to form a neutron star its magnetic field moves along with the infalling material and increases significantly up to values of 10^{12} Gauss.

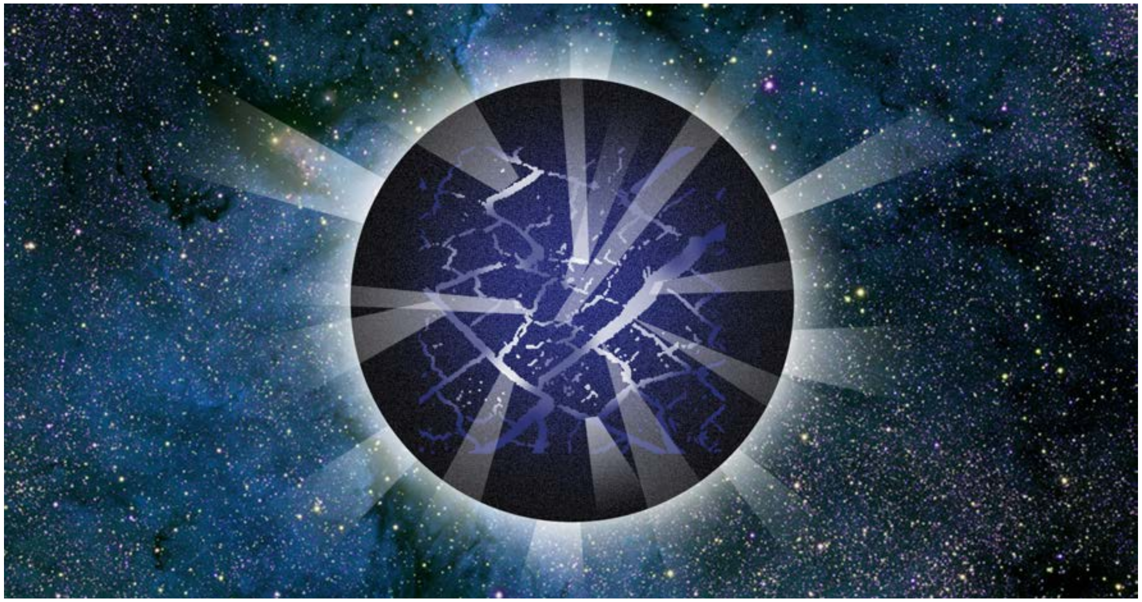


If during the collapse the NS is spinning fast enough that the rotation time is much less than the time for a convection cell to rise and fall then the magnetic field can reach 10^{15} G. These **highly magnetized neutron stars** are called **magnetars**.

Starquakes

The strong magnetic field of a magnetar can exert stresses on the star's surface that can lead to fractures called **starquakes**.

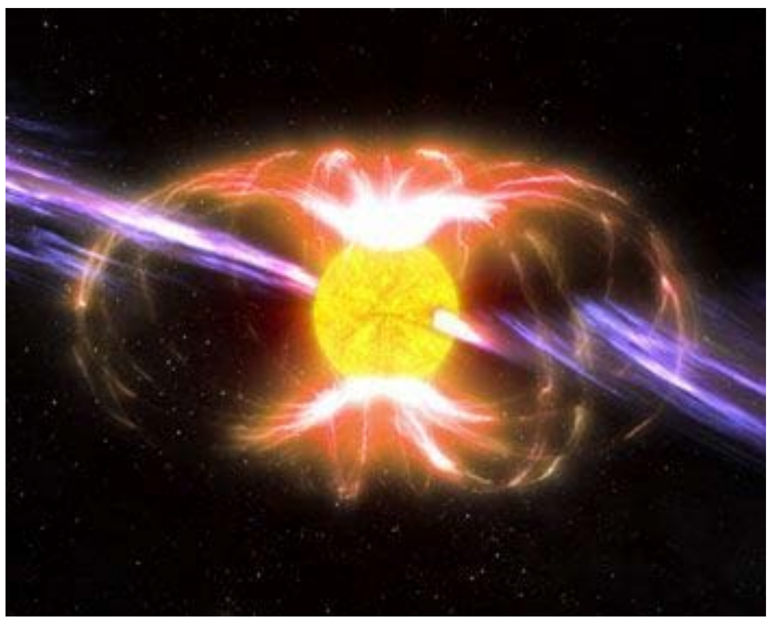
A starquake results in the rearrangement of the magnetic field and the reconnection of magnetic field lines. This reconnection results in **a burst of gamma rays**.



Starquakes

In rare occasions almost all of the magnetars surface may fracture resulting in the production of a very large burst of gamma rays and X-rays.

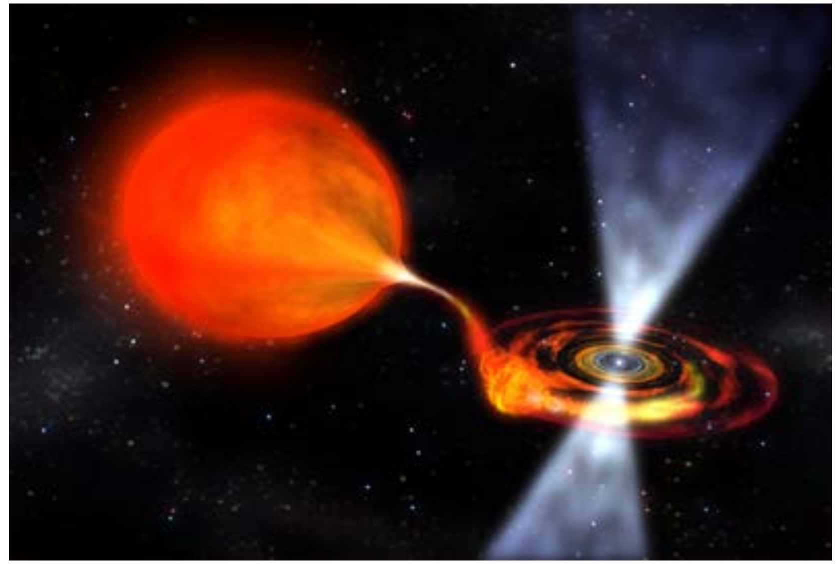
On Dec 27, 2004 a huge burst of gamma rays and X-rays was detected from the magnetar SGR 1806-20. $L_{burst} \sim 10^{14} L_{\odot}$.



Millisecond Pulsars

Pulsars should slow down with age due to loss of kinetic energy. So at first one might think that millisecond pulsars are young. But a young pulsar should be slowing down very quickly.

It turns out that **PSR 1937+21 is slowing down very gradually** which is characteristic of a pulsar that is hundreds of millions of years old.



In 1982 astronomers discovered **millisecond pulsar** PSR1937+21 (P =1.558 ms).

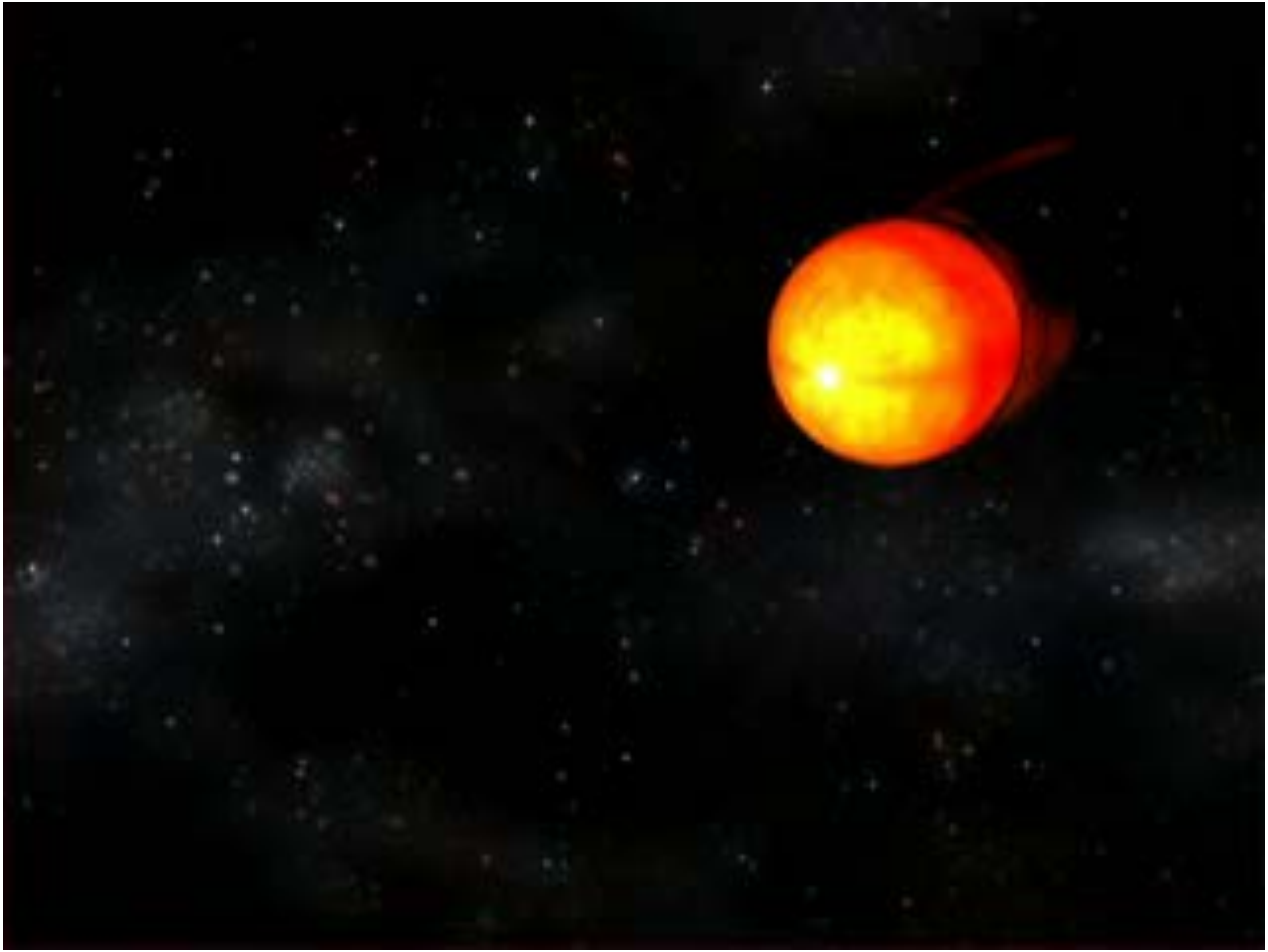
Explanation: Observations indicate that millisecond pulsars have been **spun-up in binary systems**!

Origin Millisecond Pulsars

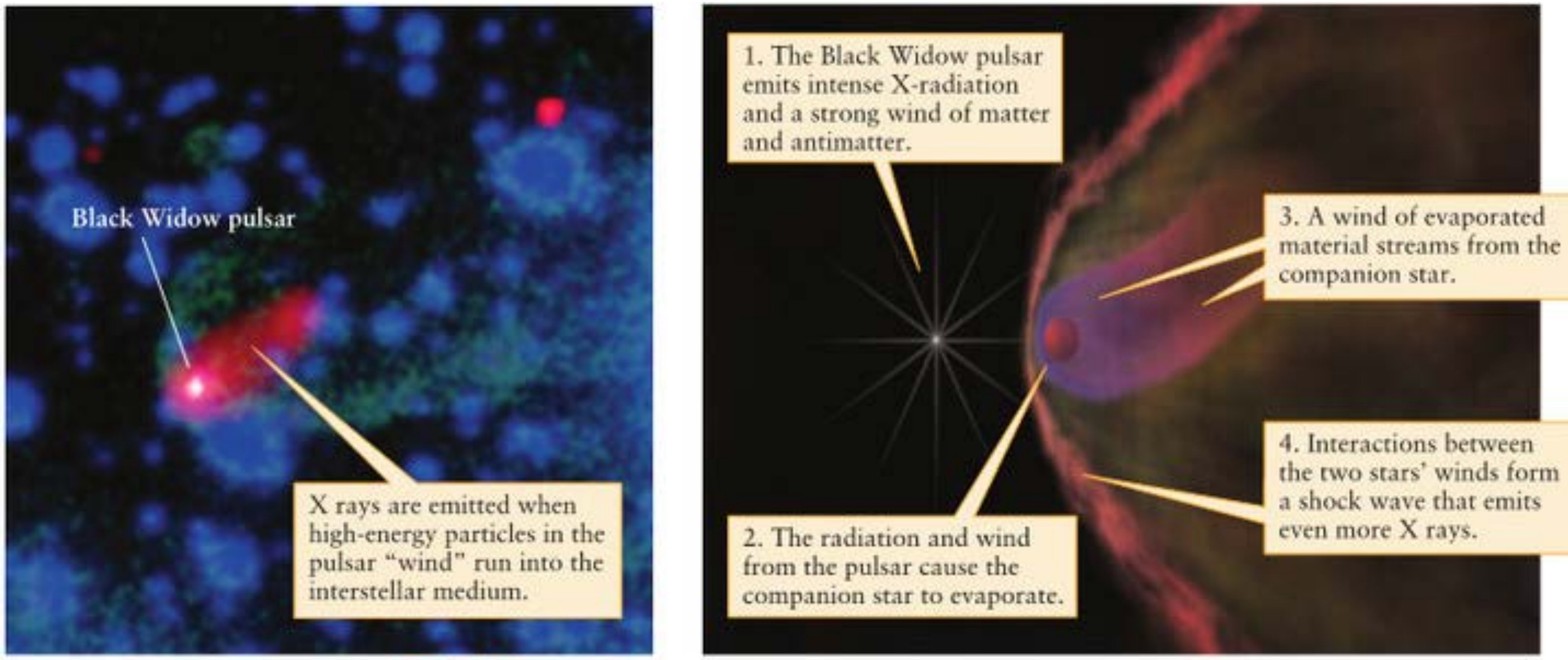
Consider a **binary system consisting of a high-mass star and a low-mass star.** The **high-mass star will evolve faster** and in a few million year becomes a Type II supernova forming a neutron star.

Over the next billion years the low mass star will evolve to become a red giant filling its Roche lobe and transferring material to the NS.

The infalling gas strikes the neutron star’s surface at high speed and at an angle that causes the star to spin faster. In this way, a slow, aging pulsar is “spun up” by mass transfer from its bloated companion.



Solitary millisecond pulsars

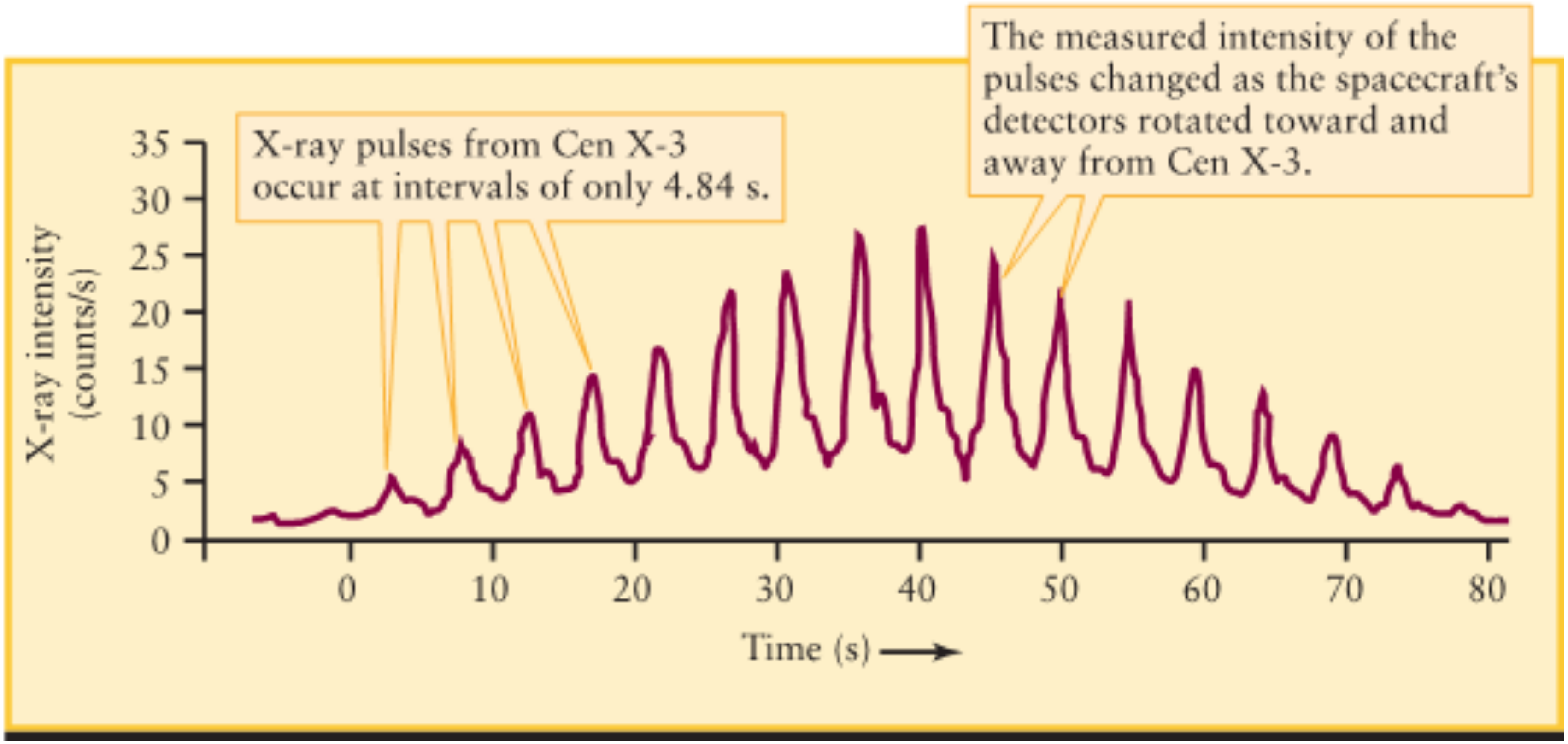


(a) The Black Widow pulsar R I V U X G

(b) An illustration of the pulsar and its companion

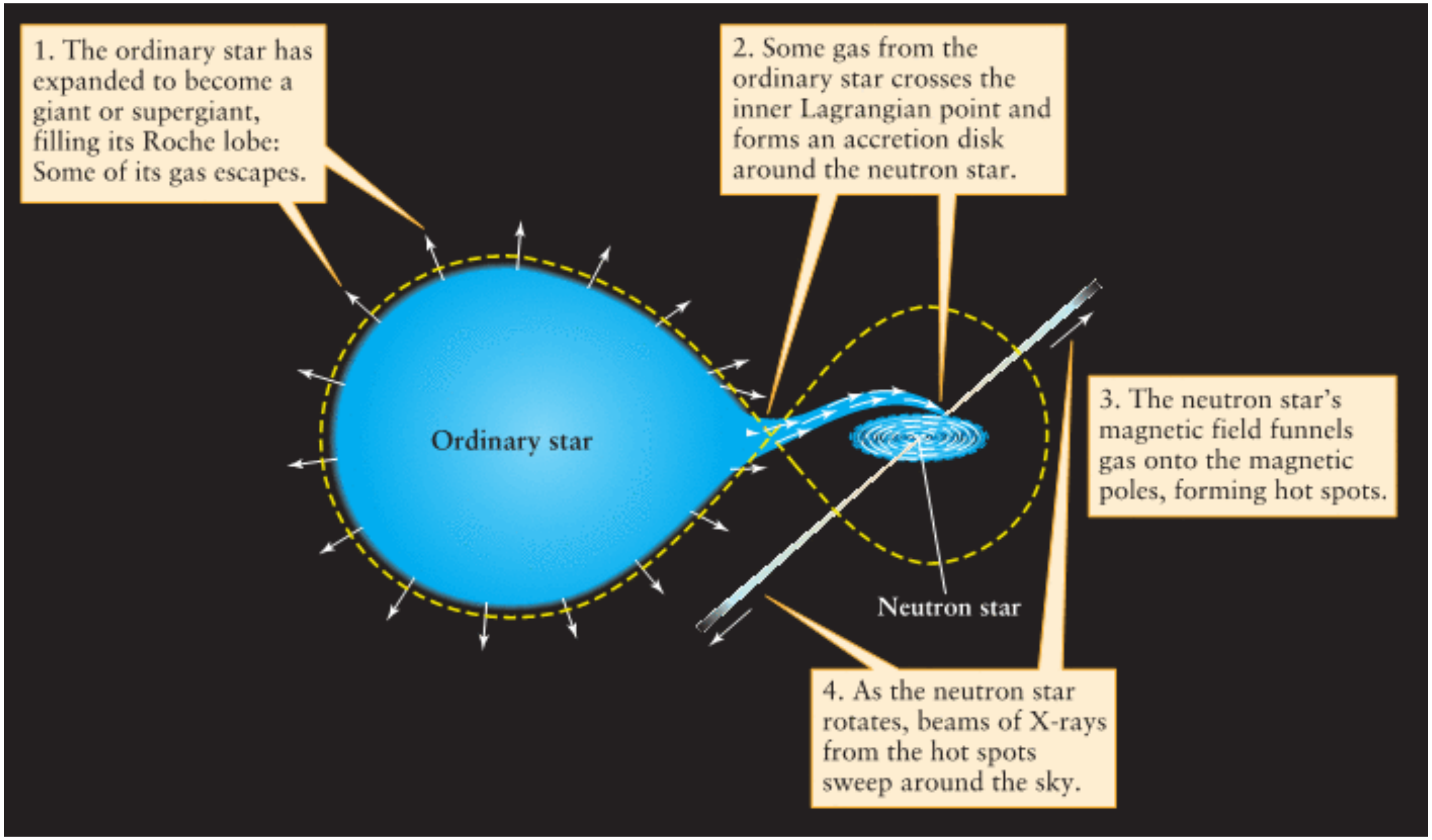
A solitary millisecond pulsar is thought to have been part of close binary system, but the companion star was eroded away by the high-energy particles emitted by the pulsar after it was spun up. The **Black Widow pulsar** may be caught in the act of destroying its companion in just such a process.

Pulsating X-ray Sources



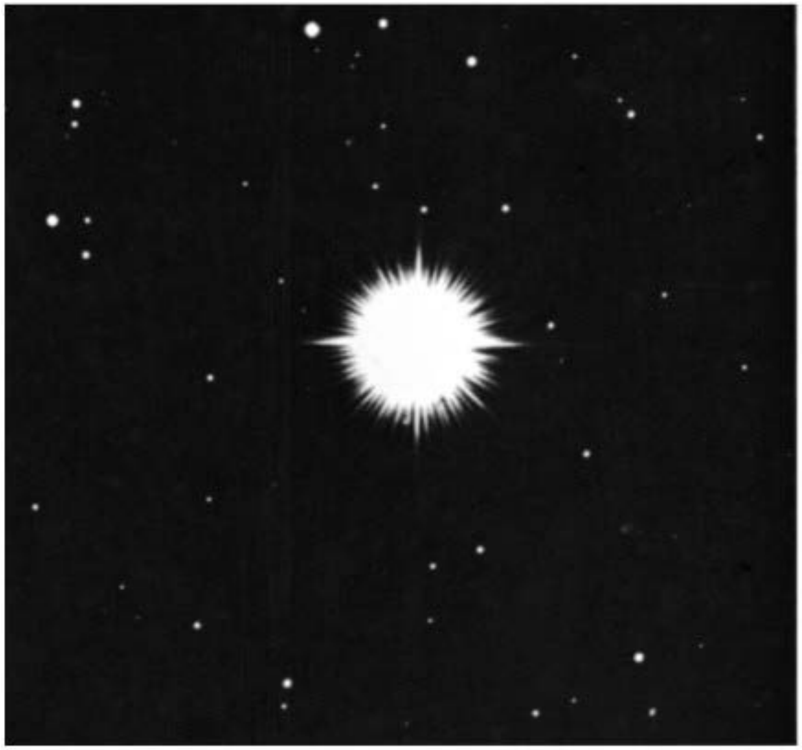
X-ray pulses from Centaurus X-3. Centaurus X-3 is a neutron star in a binary system.

Pulsating X-ray Sources

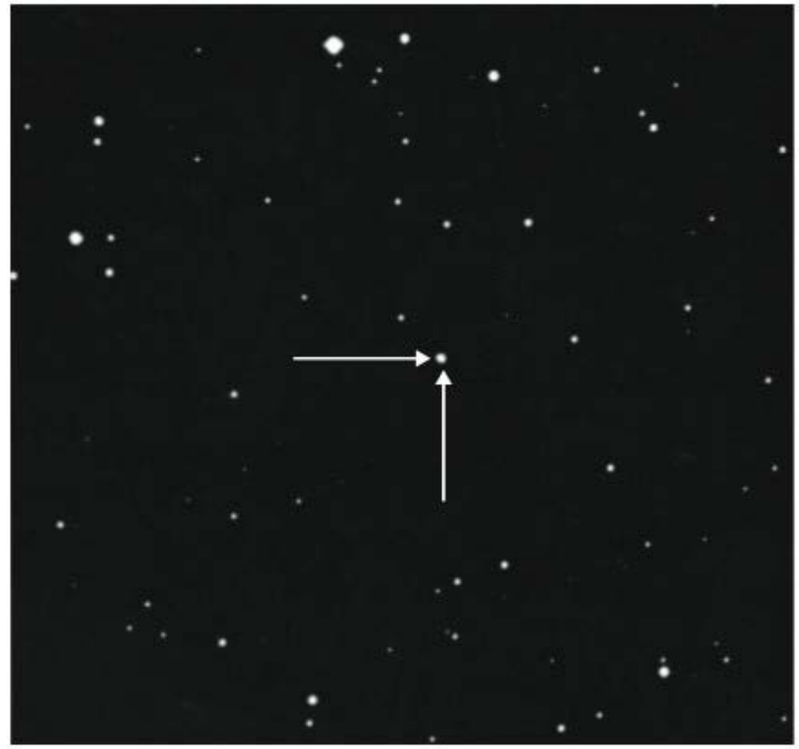


In an X-ray binary pulsar, gas from a companion star is funneled to the magnetic poles of the neutron star, forming hot spots that emit X-rays rather than radio waves.

Novae



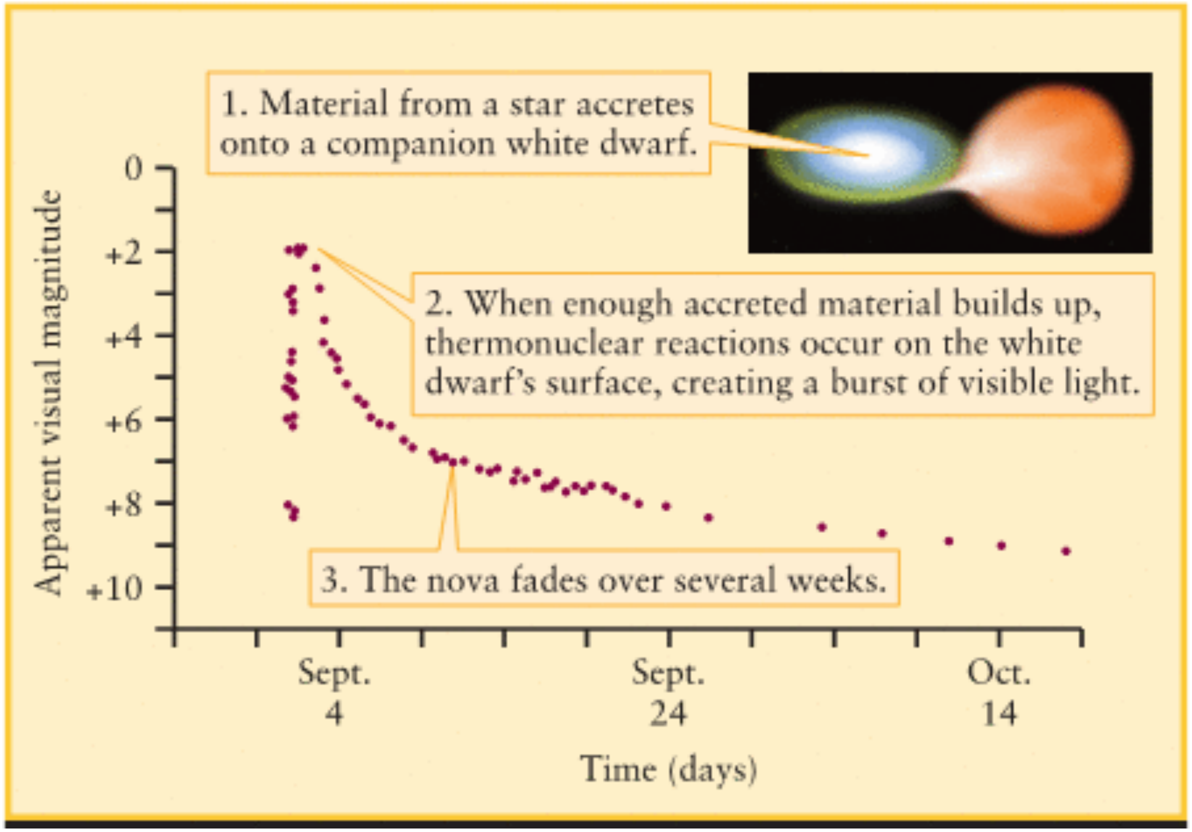
(a) Nova Herculis 1934 shortly after peak brightness



(b) Two months later

A nova is an explosion that occurs in a binary system comprised of a white dwarf and a companion star overflowing its Roche lobe. Mass transfer deposits hydrogen on the white dwarf. As the hydrogen is compressed on the surface its temperature rises and when it reaches 10^7 K fusion of hydrogen begins.

Novae



The **fusion of hydrogen in degenerate matter on the white dwarf's** surface results in a reaction rate that increases very rapidly creating a burst of visible light. The optical brightness may increase by a factor of 10^4 to 10^8 reaching a peak luminosity of $\sim 10^5\ L_{\odot}$.

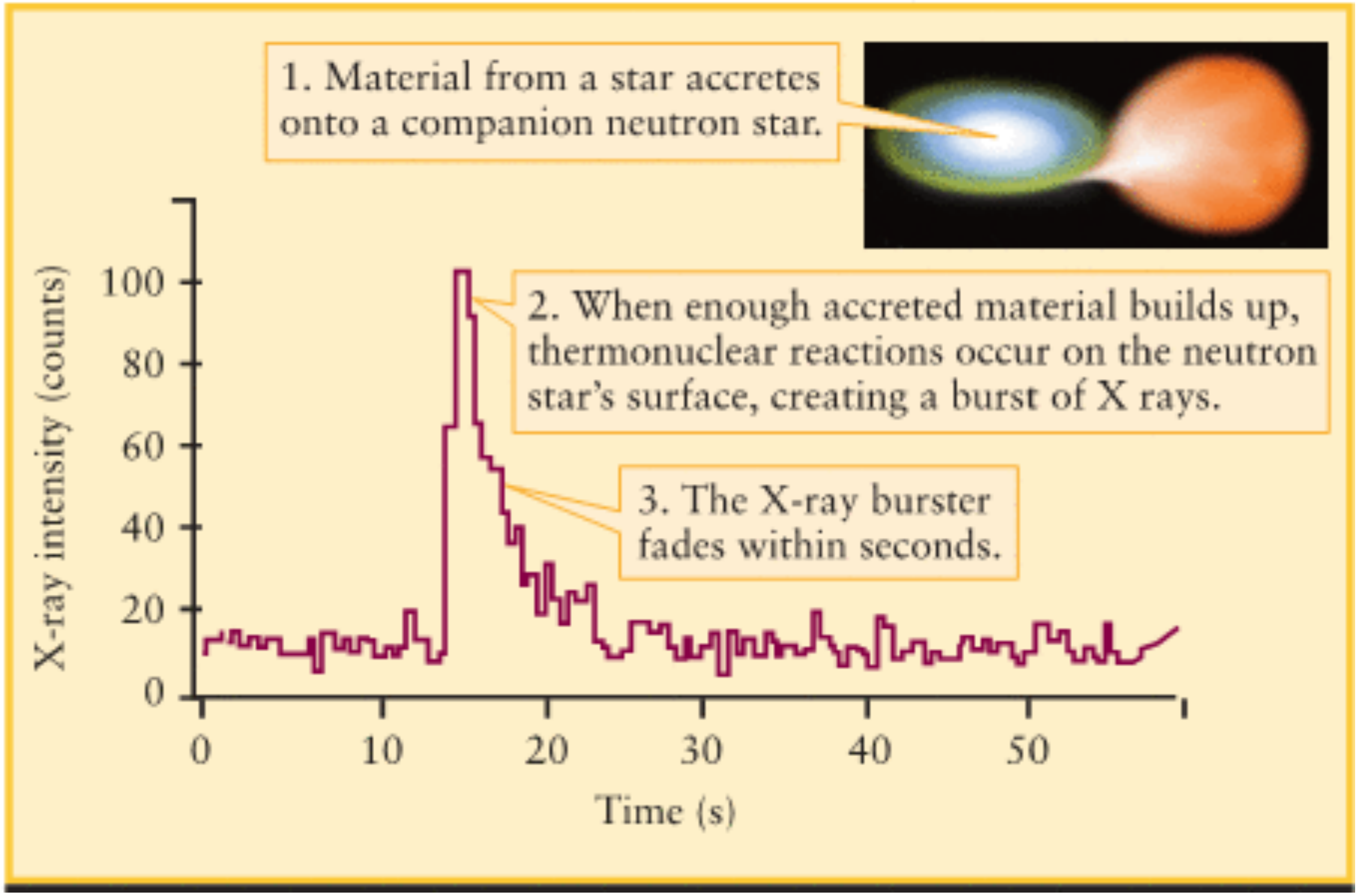
Bursters

A **burster** is an explosion that occurs in a binary system comprised of a neutron star and a companion star overflowing its Roche lobe. Hydrogen transferred from the companion star to the surface of the neutron star is compressed and heated. The fusion of H forms a layer of He that gradually increases in thickness.

When the compressed He layer reaches a thickness of about 1m helium fusion ignites explosively raising the surface temperature of the neutron star to about 3×10^7 K.

At these temperatures the emitted radiation peaks in the X-ray band. As the He is consumed the burst decays in a few seconds.

Bursters



Whereas explosive hydrogen fusion on a white dwarf produces a nova, explosive helium fusion on a neutron star produces an X-ray burster.

Stellar Remnants

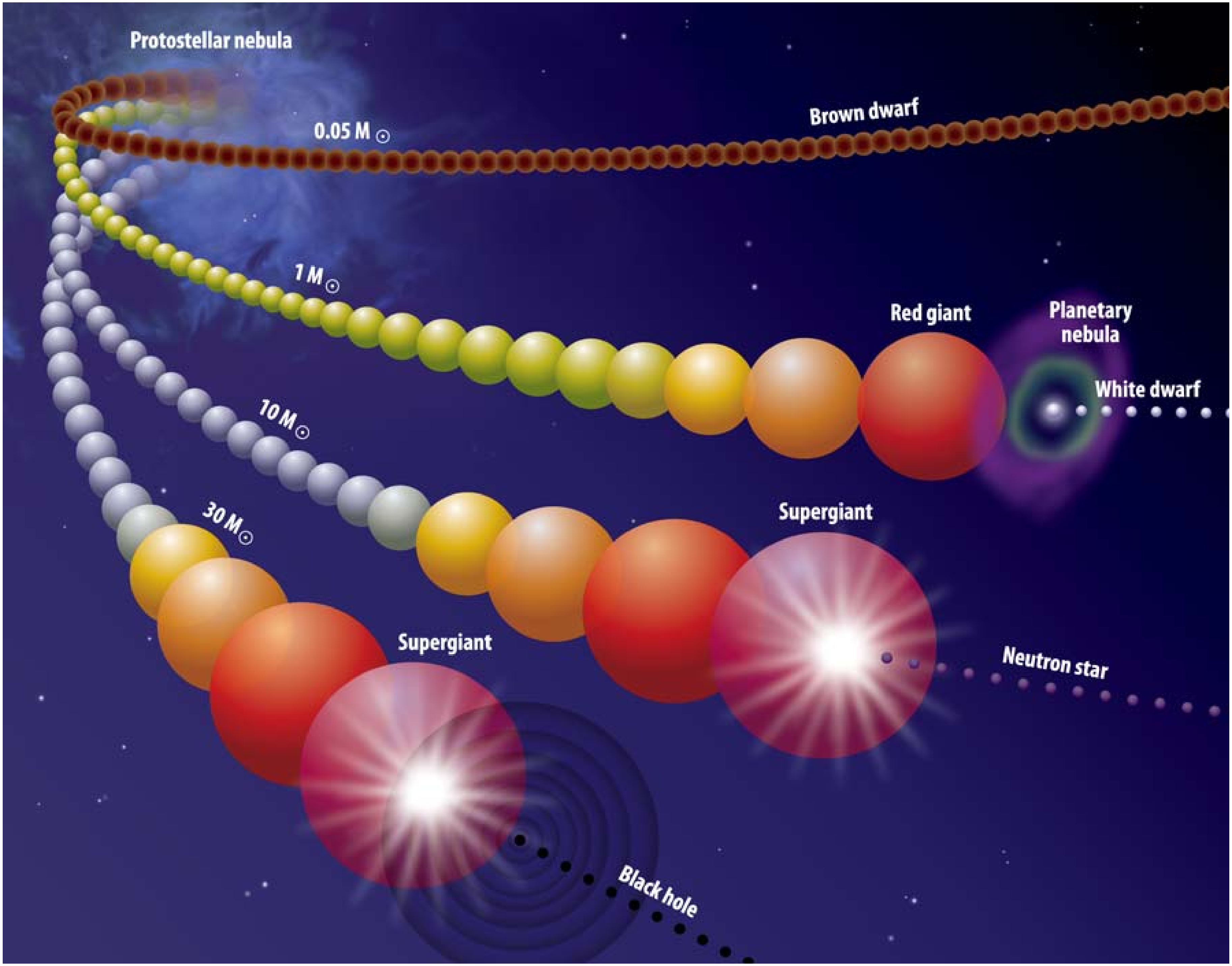
During the course of a stars evolution it will shed a significant fraction of its mass. The mass that is left will determine its fate.

Typically, stars with a initial mass of less than $8M_{\odot}$ will end up as white dwarfs.

Fate depending on the mass of the stellar remnant:

$M_{remnant} < 1.4M_{\odot}$ => White dwarf
$1.4_{\odot} < M_{remnant} < 3M_{\odot}$ => Neutron star
$M_{remnant} > 3M_{\odot}$ => Black hole

It is estimated that there are ~ 100 million neutron stars and ~1 million black holes in our galaxy.



Protostellar nebula
Brown dwarf
0.05 M ⊙
1 M ⊙
Red giant
Planetary nebula
White dwarf
10 M ⊙
30 M ⊙
Supergiant
Supergiant
Neutron star
Black hole