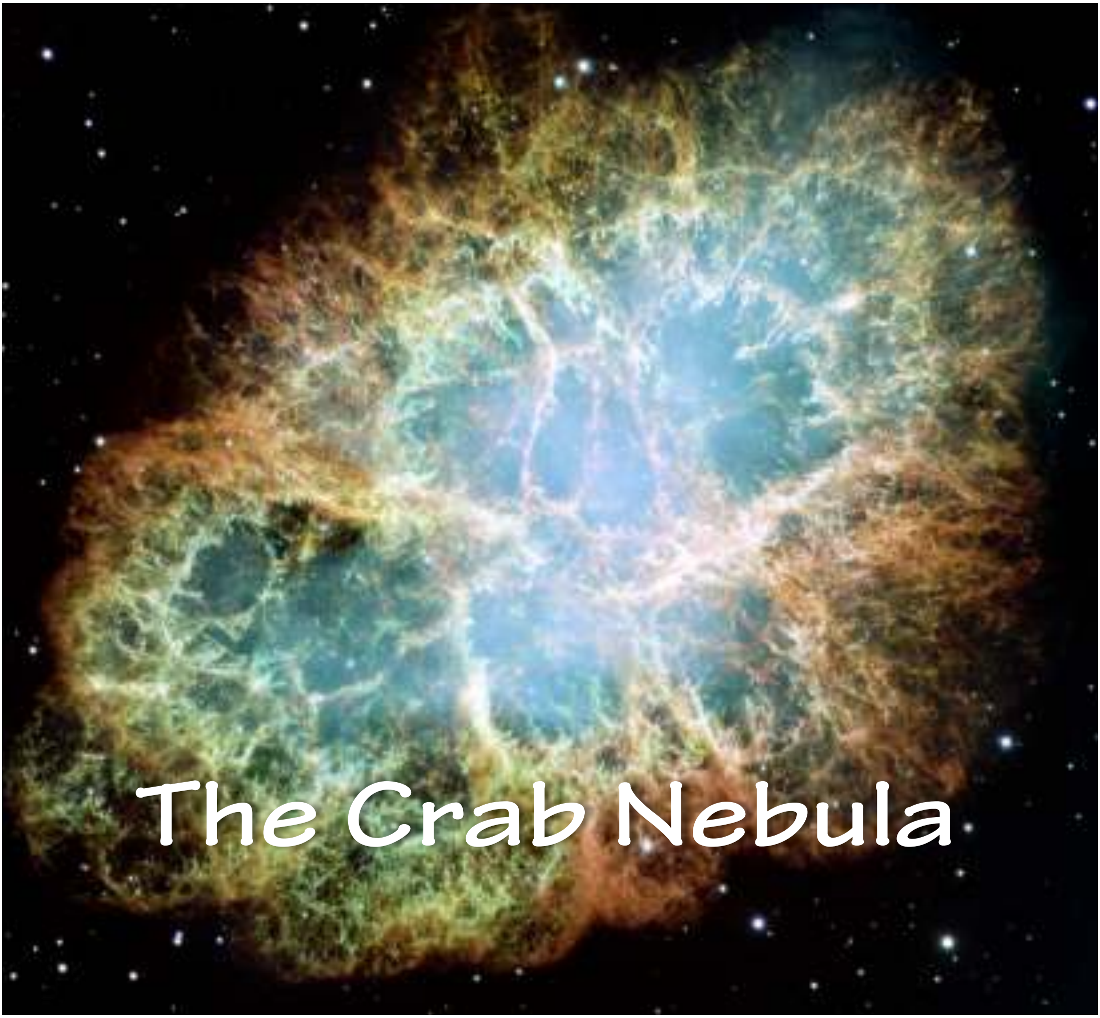
The Universe in my pocket



The Crab Nebula

No. 10

Grażyna Stasińska
Paris Observatory

The first drawing of this object, by Lord Rosse in 1844, as seen through his 90 cm diameter telescope. This drawing gave rise to the name of 'Crab Nebula' (although it looks rather more like a bug). Anyway, the name 'crab' stuck, and is still in use today.

<u>Below</u>: The first photo of the Crab nebula was obtained by Isaac Roberts, a Welsh manufacturer and amateur astronomer, in 1892, with a 3-hour exposure on a 50 cm reflector.

This image hardly looks like the drawing of Lord Rosse. But one already can see some similarity with the detailed Hubble Space Telescope image shown on the cover.

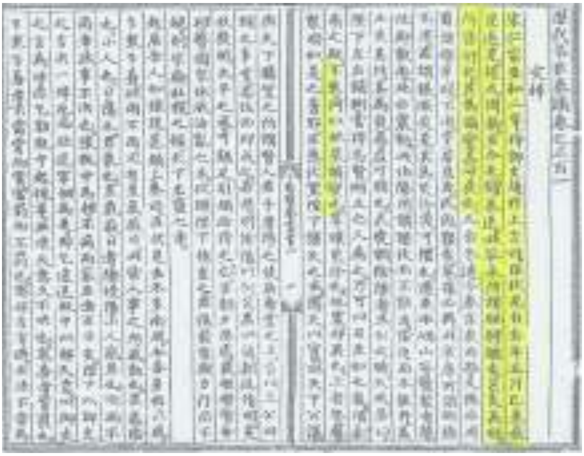
How it was discovered

The English amateur astronomer John Bevis discovered this object in 1731. It was later rediscovered by the French astronomer Charles Messier, while he was searching for comet Halley, whose return in the sky was predicted for 1758. Since this object did not move, it could not be a comet. Messier listed it as number 1 in his 'catalogue of nebulae and star clusters', not to be mistaken for comets.

Around 1800 William Herschel observed it many times with a large telescope and concluded that it was a cluster of stars.

Over a century later, spectra of this object - which enabled astronomers to analyze the nature of its light - showed that it was not an agglomerate of stars but rather was a true nebula, composed of dilute, ionized gas.

In 1054, the Chinese imperial astronomer Yang Weide saw a new star in the sky. This 'guest star', as he called it, could be seen in broad daylight for 23 days and remained detectable in the night sky for over two years.



This event is recorded in old Chinese chronicles, such as the Lidai mingchen zouyi (left). The highlighted passage refers to the guest star.

This event was also witnessed in other parts of the World, for example Japan, Europe and Arabia.

Below: How spectra reveal the motions of astronomical sources.

The shift of the spectral lines is proportional to the velocity of the source with respect to the observer.

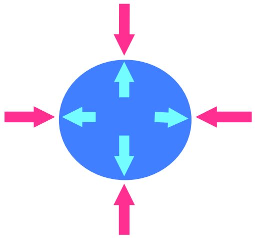
The Crab and the guest star

In the early 1920's, astronomers realized that the position of the Crab Nebula coincided with that of the 'guest star' seen by Chinese astronomers in 1054.

They also noticed that the angular size of the Crab Nebula was growing with time, and the spectra of its filaments indicated that they were moving at a speed of 1500 kilometers per second *. This led them to conclude that the nebula was born and started expanding about 1000 years earlier.

In1928, Edwin Hubble proposed that the Crab Nebula was the remnant of the star whose explosion was seen in 1054. However, the physics of the explosion was not understood at that time and so at first this idea was not accepted.

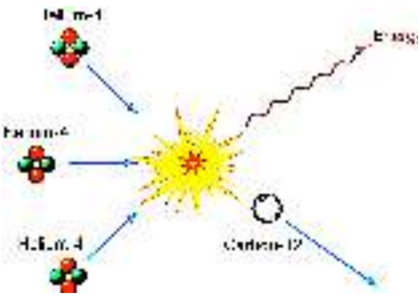
* See page 4

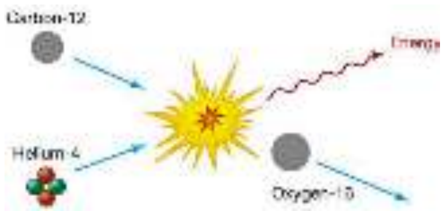


The life of a star is a constant battle between two opposing forces:

- gravity which causes contraction
- and pressure which causes expansion.

In the core of the star, which is the hottest zone, atomic nuclei combine into heavier ones. This process releases energy and creates pressure. When the fuel is exhausted, gravity makes the core contract and its temperature rise, until new nuclear reactions can occur.





First, hydrogen combines with itself to form helium, then helium combines with itself to form carbon, carbon combines with helium to form oxygen and so on. In massive stars this can go until the formation of iron. If the process continues until the stellar core has become pure iron, such reactions cannot occur anymore, and the core shrinks.

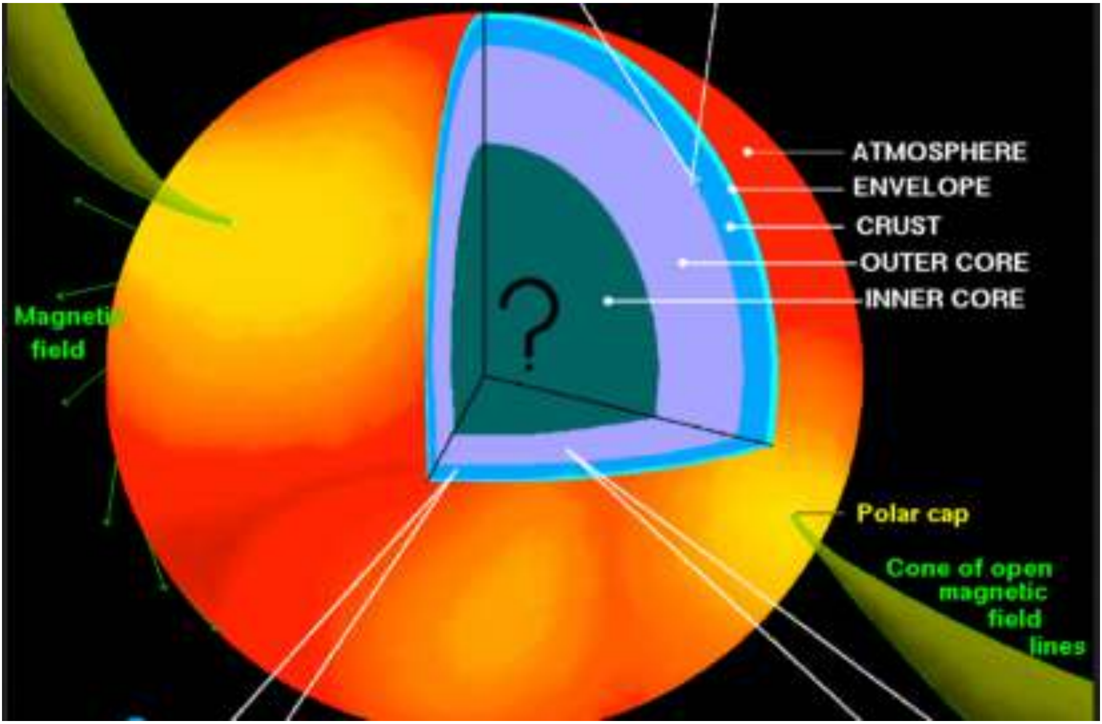
Supernova

In 1934 Baade and Zwicky suggested that such stellar explosions - which they called supernovae - could occur during the transition from a normal star to a star with a very small radius and large density.

The cause of such a transition, however, was still not understood.

In 1957, Burbidge, Burbidge, Fowler & Hoyle explained in a fundamental article how in the very hot interior of massive stars, the chemical elements gradually transform into heavier ones, until the core is entirely made of iron. Then the core collapses while the outer layers explode and eject the newly formed elements into interstellar space.

Anatomy of a neutron star as pictured by Dany Page (Univ. of Mexico)



Going from the outside to the inside one finds a hot 'atmosphere' whose temperature is about one million degrees; then a cooler envelope; then a crystalline crust of iron nuclei; next an outer core made of neutrons, protons and electrons in solid state; and finally the inner core composed of the same particles but in liquid state and, perhaps, of free quarks, the fundamental particles that combine to form protons and neutrons.

Neutron stars

When the core of a star has been converted to iron, further nuclear reactions cannot take place and gravitational collapse occurs on a time scale of seconds. The pull of gravity is so strong that the atoms are squeezed together. Electrons are forced to fuse with protons, resulting in a very dense sphere of neutrons.

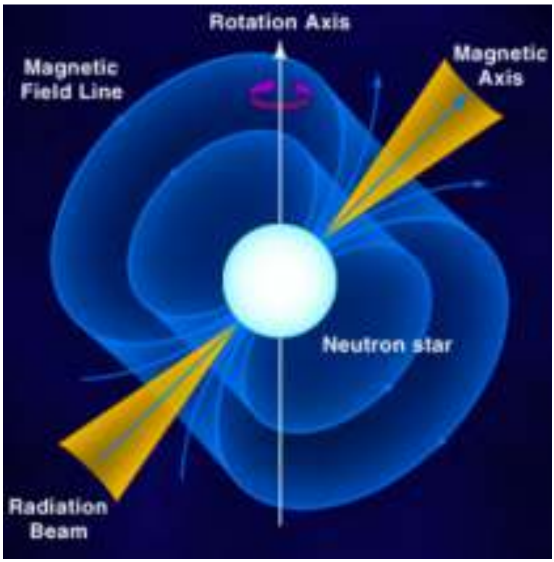
The neutron star within the Crab nebula is more massive than the Sun but its diameter is only about 20 km. A sugar cube of its material on Earth would weigh as much as the entire human population.

At the extreme densities of neutron stars, the physical processes are very different from those occurring elsewhere in the Universe. With the help of theoretical physics it is possible to deduce the internal structure of a neutron star.

During the gravitational collapse that produces the neutron star, the rotation speed of the star increases tremendously because the star shrinks.

This is the same phenomenon as when an ice skater spinning with her arms outstretched pulls her arms inwards: she then spins much faster.

Neutron stars have a very strong magnetic field and emit radiation only in narrow beams from their magnetic poles. The radiation is observed only when the beam points toward the Earth.

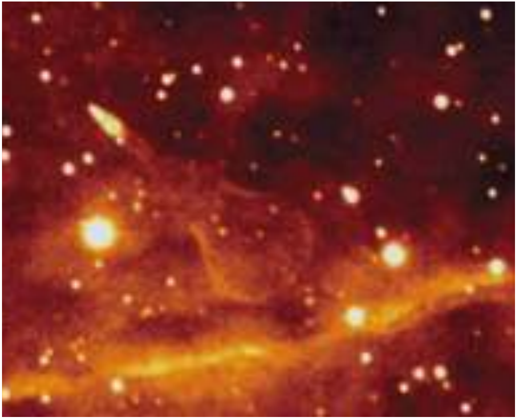


As the neutron star rotates and the beam sweeps past the Earth, pulses of radiation, equally spaced in time, are observed.

The Crab pulsar

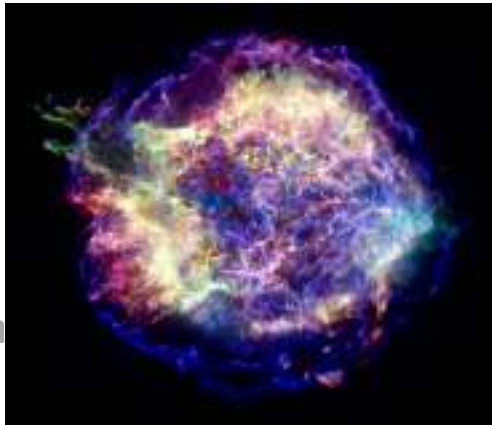
In the 1960's, radio-astronomers observed strange, regularly pulsating radio signals in the sky. They demonstrated that these pulses came from astronomical sources. Such radio-sources were named pulsars. The Crab pulsar was one of the first to be discovered.

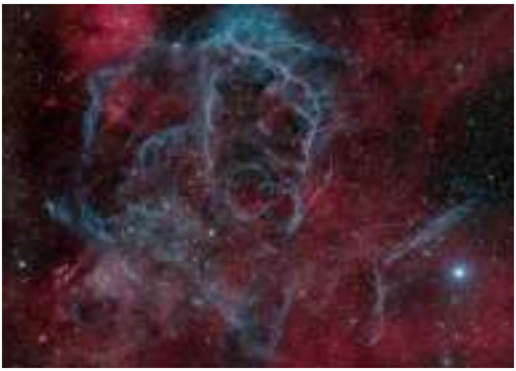
However, it was soon understood that the radio emission did not come from a pulsating object, but rather from a rapidly spinning neutron star, emitting radiation in two narrow beams. The beams sweep through space as the star rotates, just like beams from a lighthouse.



The Guitar nebula in visible light. It is produced by an otherwise ordinary neutron star, which is travelling at high speed.

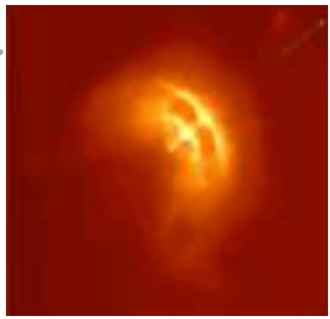
An X-ray image of Cas A. It is estimated that light from the stellar explosion reached Earth about 300 years ago, but there are no written records of the event.





An image of the Vela supernova remnant, taken by the amateur astronomer Marco Lorenzi in visible light.

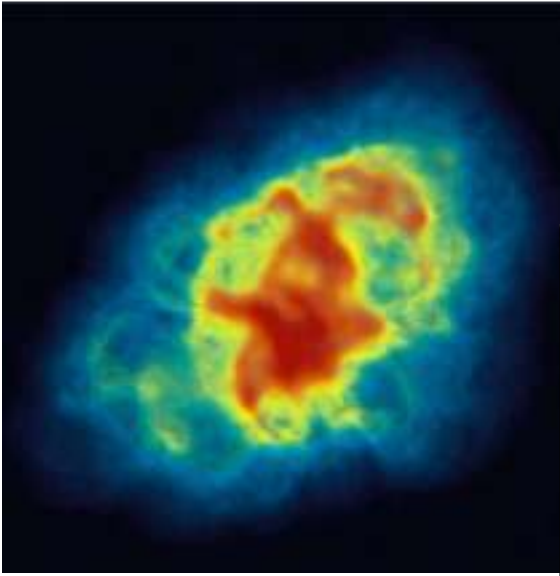
An X-ray image of the compact nebula surrounding the Vela pulsar. The bow-like structures are produced by high-energy particles emitted by the neutron star.



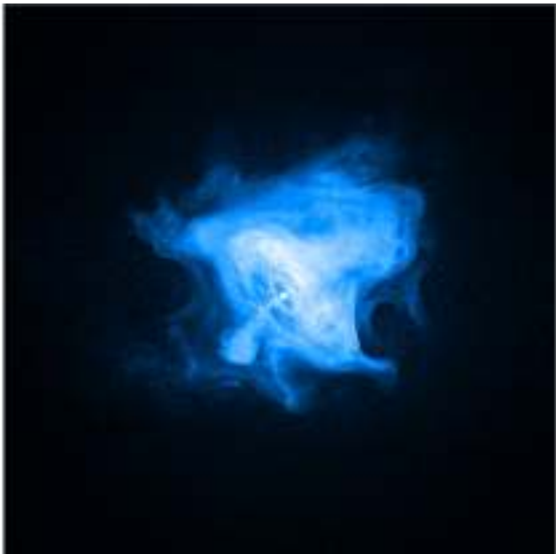
Other 'Crabs' in the Universe

Given the number of stars that have died in our Galaxy, it should contain billions of neutron stars. However, most of these are old and cold and undetectable. Even hot neutron stars can only be detected when their pulsar beam is directed towards the Earth or when they are in a binary system. In the latter case, X-rays are often emitted by hot gas as it falls towards the surface of the neutron star.

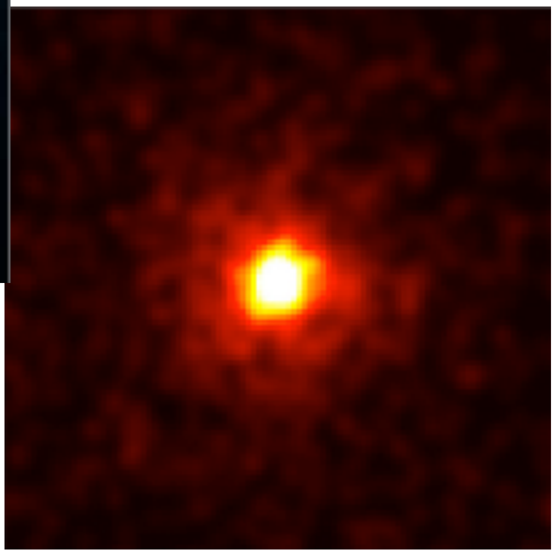
At present, there are almost 3000 known neutron stars in the Milky Way, most of which have been detected as radio pulsars. The opposite page shows images of some of them.



Quiz



Do all these images represent the Crab nebula?



Answers on overleaf

Infrared image taken by the Spitzer telescope

Radio image taken by the VLA

All the images represent the Crab nebula

X-ray image taken by Chandra

Gamma-ray image taken by Fermi

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This booklet was written in 2018 by Grażyna Stasińska from Paris Observatory (France) and revised by Fabrice Mottez, Mikaela Oertel and Silvano Bonazzola (all from Paris Observatory).

Cover image: The Crab Nebula taken by the Hubble Space Telescope. Image Credit: NASA, ESA, J. Hester, and A. Loll (ASU). Other images in this booklet are from HST, VLA, Spitzer, ALMA, Chandra and Fermi.

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