The Universe in my pocket

Neutron Stars

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THE UNIVERSE IN MY POCKET

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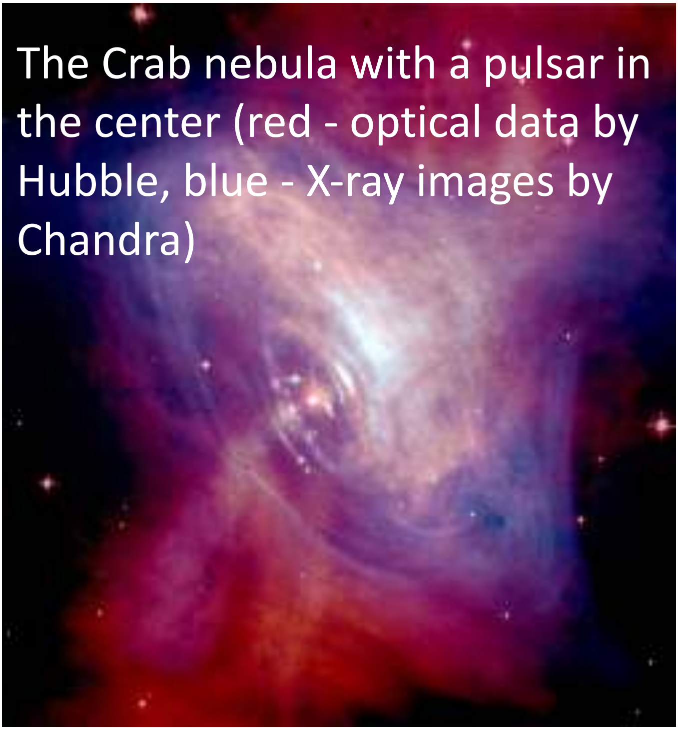
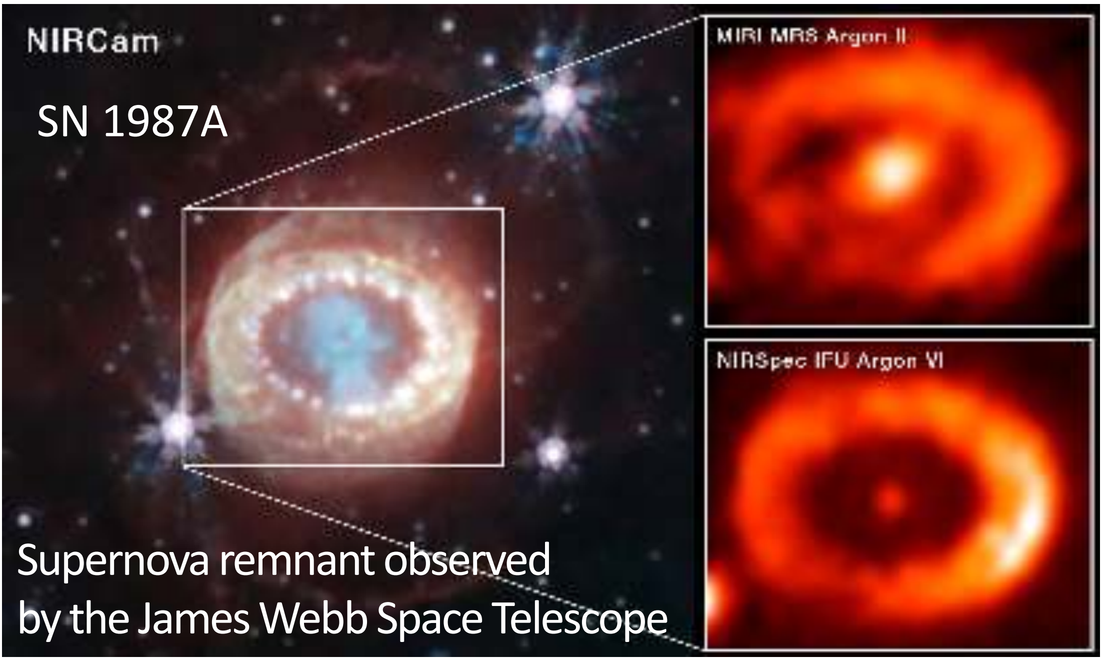
Images of supernova remnants with a neutron star in their center. The Crab nebula is about one hundred trillion km across. The neutron star has a diameter of only about 20 km.



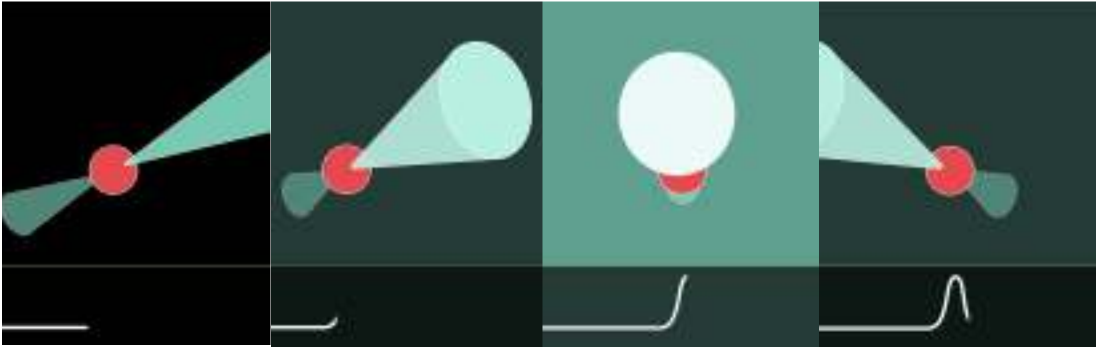
The Crab nebula with a pulsar in the center (red - optical data by Hubble, blue - X-ray images by Chandra)



Supernova remnant observed
by the James Webb Space Telescope

What are neutron stars?

A neutron star is a stellar remnant: the end of a massive star, which - at the beginning of its life - had a mass larger than about 8 solar masses, and less than 25 solar masses. At the end of its life, a massive star explodes as a supernova and the remaining material subsequently collapses due to the loss of energy production. As a result the star's core is compressed to densities greater than that of atomic nuclei. Neutron stars are the second most dense objects currently known to science. Their *compactness* (the ratio between mass M and radius R) is second only to black holes. Neutron stars have a radius of about 10 kilometers and a mass between 1 and 2 solar masses. For comparison, a black hole of 1 solar mass has a radius of about 3 km. They were only a theoretical concept until their discovery in 1967.



The majority of known neutron stars are radio pulsars rotating about their axes. The beam they emit is detected by radio antennae when the beam is directed towards the Earth.

Jocelyn Bell in 1968

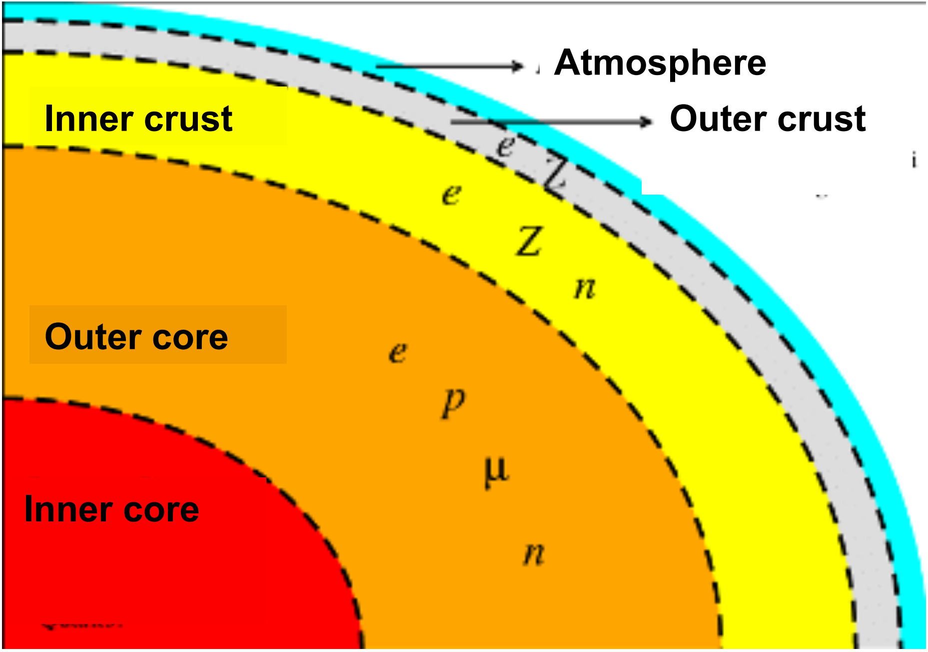
Jocelyn Bell, a student of Antony Hewish in Cambridge (England) discovered these objects in 1967. This discovery was first understood as due to pulsations of compact stars. In 1974 the Nobel Prize was awarded to Hewish for this discovery.

How can they be observed?

Considering the number of stars that explode as supernovae there should be about one billion neutron stars in the Milky Way. However, astronomers directly observe only about 3000 of them in our Galaxy.

In most neutron stars a beam of radio emission is created by the magnetic field at their poles. This magnetic field is extreme - 10^{15} times stronger than Earth's magnetic field. As the neutron star spins, a radio signal can be detected when the beam is directed towards us, mimicking pulses.

Shortly after their discovery, the properties of these objects (named pulsars) were explained by this lighthouse effect. Only neutron stars - then merely a theoretical concept - had properties that could explain the observations.



The conjectured structure of a neutron star of 1.4 solar masses, adapted from Jorge Piekarewicz. The various components are:

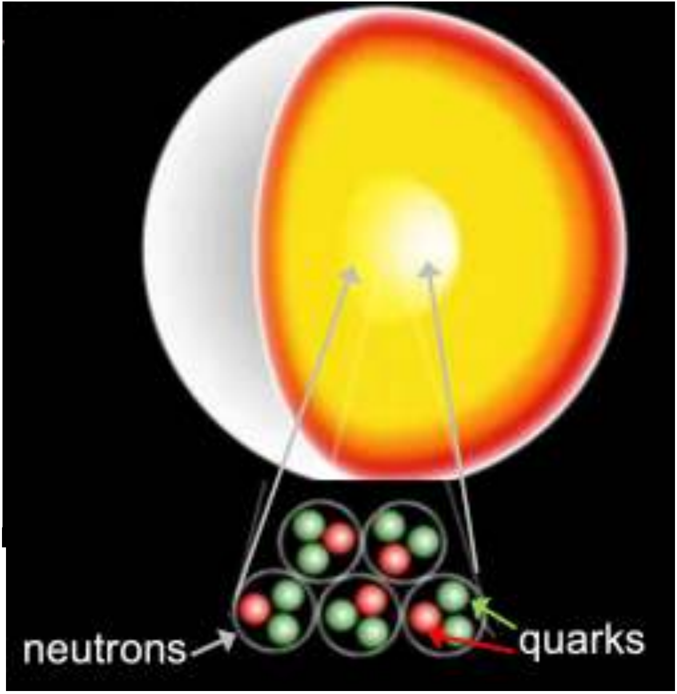
- The gaseous atmosphere (a few cm thick).
- The liquid « ocean » (10 m deep).
- The solid crust (1 km thick) consists of an outer crust (nuclei forming a crystal embedded in electron gas) and an inner crust (nuclear crystal embedded in electron and neutron gas).
- The liquid core. Its outer shell (about 7 km thick) consists of neutrons, protons, electrons and muons. The inner core of some 4 km radius is a mystery, and may contain exotic particles.

What is inside a neutron star?

The internal structure of a neutron star is layered like an onion. The solid crust contains only 1% of the star's mass, while some 99% of the mass is contained in the liquid core and the very mysterious inner core. The density increases with depth, from 10 g/cm^3 in the gaseous atmosphere (with a typical temperature of 1-2 million K) up to more than

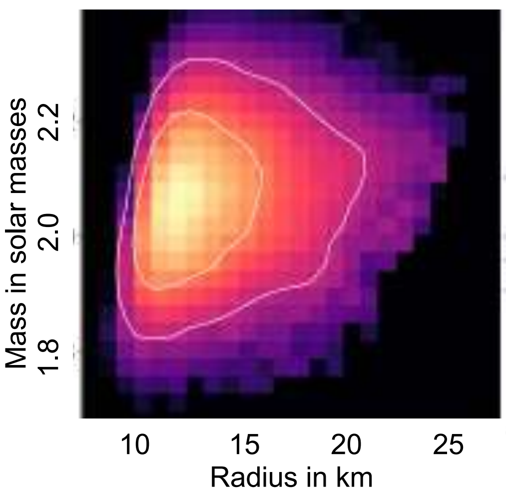
100 000 000 000 000 kilograms/cm^3 at its center, some 4-6 times denser than atomic nuclei. A teaspoon of neutron star material on Earth would weigh as much as the entire human population!

Their interiors are not only hot and dense, but also very magnetized, superfluid and superconductive. By observing them we may learn about their internal features, and use them as extreme cosmic laboratories.



The properties of dense matter are encoded in the equation of state which can be determined by studying the mass-radius relation of neutron stars. (Figure after CXC/M. Weiss).

The mass and radius of neutron stars masses can be estimated from observations of pulsars in binary systems.
The figure below shows the relation between the mass and the radius of the neutron star PSR J0740+6620 as obtained from observations. The lightest zone corresponds to the most probable values: 2.08 solar masses and 12.35 km (Miller et al. 2021),



The Equation of State

Only the outermost part of a neutron star (corresponding to 0.01 percent of its mass) can be described using experiments on atomic nuclei made on Earth. Most of the nuclei that are present in the neutron star crust and core can only be studied theoretically.

Within neutron stars, the pressure must increase rapidly enough with density to support the mass of the neutron star. Using this condition, theoretical physicists estimate the relation between the density and the pressure. From this Equation of State they can derive the relation between the mass and the radius of a neutron star and compare it with observations. By successive approximations they can determine the actual Equation of State of dense matter, thus unveiing the properties of the most extreme state of the matter known today.

This is the screen of the first pulsar clock in the World, which was installed in the Tower Clock museum in Gdańsk, Poland in 2011.

This unique clock uses the impulses of pulsars as a basis for keeping time.

It consists of a radiotelescope with 16 antennas which receive signals from six pulsars.

Neutron stars as clocks

The pulses from neutron stars occur in a wide range of periods: from 1.4 milliseconds to about 1 minute.

What is surprising is the remarkable regularity of these pulses: a typical pulsar watch slows down by one second every million years.

Since pulsars are very accurate clocks, they make it possible to measure even very small deviations from the accepted theory describing the motion of stars in a gravitational field. This allows us to test the theory of gravity. It turns out that the General Theory of Relativity, formulated by Einstein in 1915, passes this test perfectly!

An artist's depiction of two merging neutron stars. The narrow beams are the gamma-ray bursts. Swirling clouds of material ejected from the merging stars are also shown. These clouds emit in visible light as well as other wavelengths.

Credits:
Image: National Science Foundation/LIGO/Sonoma State University/A. Simonnet

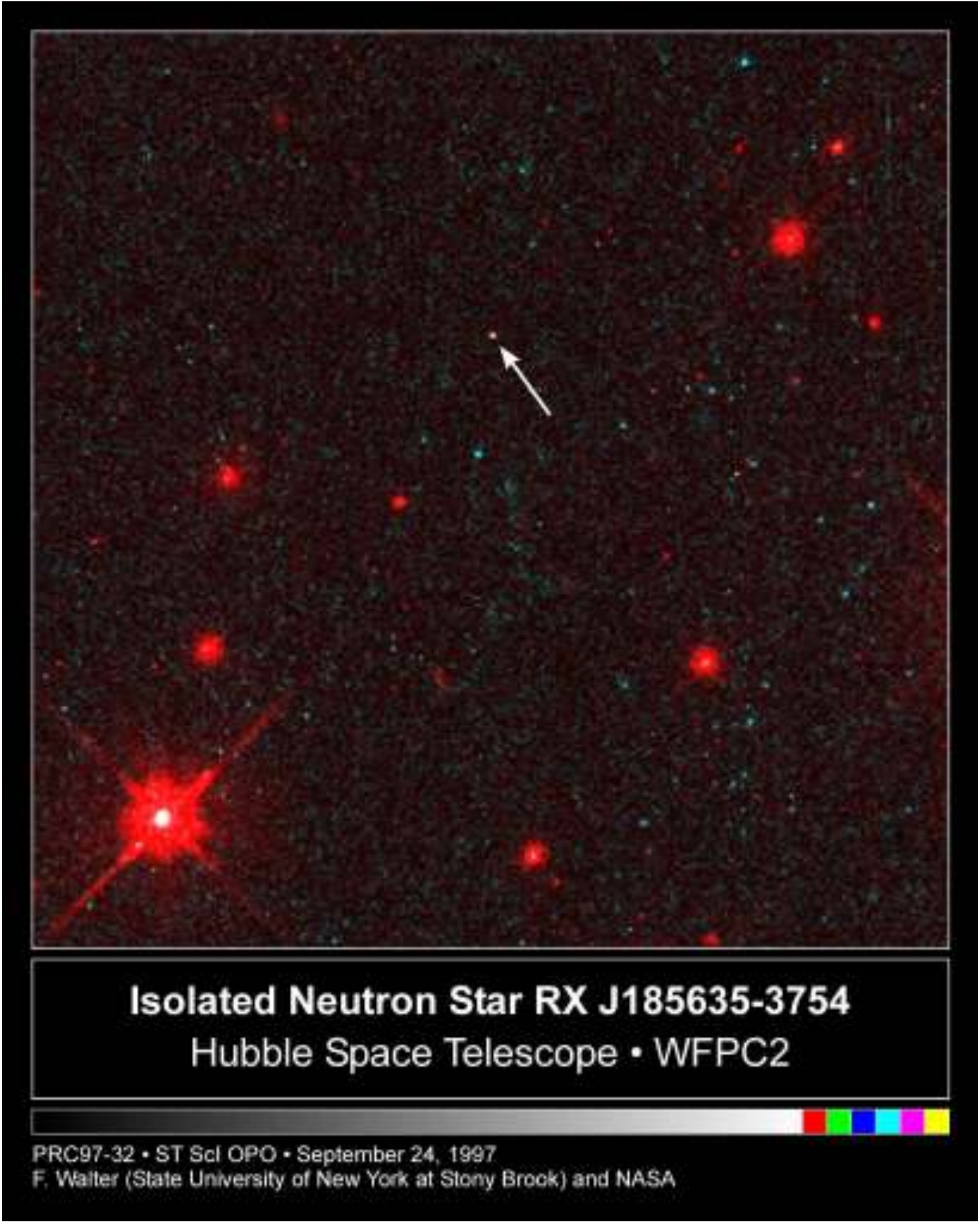
Gravitational waves and gamma-ray bursts

Neutron stars may also be sources of gravitational waves - distortions of spacetime traveling at the speed of light (see TUIMP 18).

On August 17 2017, waves emitted by two colliding neutron stars were registered by the gravitational wave detectors LIGO and Virgo.

In addition, intense light emitted during the collision was observed by various telescopes.

Scientists were able to determine the masses of the two stars and show that this type of event could be the origin of powerful short gamma-ray bursts.



This image shows how
a nearby neutron star
looks like from Earth, in visible light.

Quiz

1. Neutron stars are:
   a. collapsed cores of massive stars
   b. a kind of black holes
   c. remnants of galaxies

2. What is the typical mass of a neutron star?
   a. between 8 and 25 solar masses
   b. more than 100 millions of solar masses
   c. between 1 and 3 solar masses

3. Neutron stars are observed
   a. in all electromagnetic wavelengths
   b. only in X-rays and visible light
   c. only in gamma rays
   d. only in radio

4. The surface temperature of neutron stars is typically
   a. greater than 100 million degrees
   b. a few million degrees
   c. similar to that of the Sun

Answers: a c a b

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This booklet was written in 2024 by Paweł Haensel, Leszek J. Zdunik from Nicolaus Copernicus Astronomical Center (Poland) and Michał Bejger from INFN Ferrara (Italy) and Nicolaus Copernicus Astronomical Center (Poland). It was revised by Stan Kurtz (UNAM, Mexico) and Grażyna Stasińska (Paris Observatory).

Cover image: Artist's view of a neutron star. Credit: Casey Reed, Penn State University.

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