Neutron Stars -
Extraordinary Cosmic Laboratories

Dr. Vanessa Graber
Institute of Space Sciences (IEC), Spain

JULY 5TH, 3:30pm (CEST)
THE UNIVERSE AS A LABORATORY

Image credit: NASA

Combine observations, mathematical calculations and computer simulations to learn about the Universe.
Neutron stars unite many extremes of physics that cannot be recreated on Earth.

WHAT are these extremes?

HOW do we know these extremes exist?

WHAT is going on in their interiors?
Neutron stars unite many extremes of physics that cannot be recreated on Earth.

WHAT are these extremes?

HOW do we know these extremes exist?

WHAT is going on in their interiors?
Neutron stars are born in supernova explosions.

Crab Nebula, 1054

Cassiopeia A, ~1670

Image credit: NASA, ESA, J. Hester, A. Loll (ASU)

Image credit: NASA, JPL-Caltech, STScI, CXC, SAO
Neutron stars have a mass comparable to the Sun but the size of a city.
Neutron stars mainly consist of neutrons and are the densest object we know of.

Densities up to $10^{15}$ g/cm$^3$ = 1,000,000,000,000,000 g/cm$^3$
Neutron stars are very fast and stable rotators. They can rotate up to \(~700\) times per second.
Neutron stars are the strongest magnets in the Universe.

Field strengths of $\sim10^{12}$ Gauss = 2,000,000,000,000,000 x Earth’s magnetic field

Image credit: ESO, L. Calçada
Neutron stars unite many extremes of physics that cannot be recreated on Earth.

WHAT are these extremes?

WHAT is going on in their interiors?

HOW do we know these extremes exist?
Neutron stars emit light in different parts of the electromagnetic spectrum.
OBSERVING NEUTRON STARS

They were first observed in the radio band in 1967 by Jocelyn Bell Burnell.

Neutron stars emit radiation like a lighthouse - they pulse.
The first source had a period of ~1.3 seconds and was nicknamed LGM-1, which stands for ‘Little Green Man’.
700 neutron stars have been observed as radio pulsars.

We time pulsars to measure the period and its derivative.

Obtain age and magnetic field strength estimate.
If the pulsar is in a binary, the arrival time of the pulses is altered as the two stars orbit around each other.

High precision measurements allow us to extract the neutron star mass.

Image credit: B. Saxton, NRAO, AUI, NSF
OBSERVING NEUTRON STARS

Neutron stars emit light in different parts of the electromagnetic spectrum.
OBSERVING NEUTRON STARS

With temperatures of $\sim 10^7 \, ^\circ\text{C} = 10,000,000 \, ^\circ\text{C}$, they emit thermal black-body radiation in the X-rays.

Using X-ray observatories, we can learn about their temperatures and radii.
Neutron stars unite many extremes of physics that cannot be recreated on Earth.

WHAT are these extremes?

HOW do we know these extremes exist?

WHAT is going on in their interiors?
Neutron star conditions are so extreme that the equation of state of matter is unknown.
Neutron star conditions are so extreme that the equation of state of matter is unknown.

How squishy are neutron stars?

Image credit: N. Wex
Like the Earth, neutron stars are composed of distinct layers.

- Atmosphere (hydrogen, helium, carbon)
- Outer crust (ions, electrons)
- Inner crust (neutrons, ions, electrons)
- Outer core (neutrons, protons, electrons)
- Inner core (?????)
Like the Earth, neutron stars are composed of distinct layers.
Neutrons, protons and electrons are fermions - elementary particles with spin 1/2.

Fermions have to obey the Pauli exclusion principle.
Neutrons, protons and electrons are fermions - elementary particles with spin 1/2.

Fermions have to obey the Pauli exclusion principle.

Neutrons resist compression, which prevents neutron stars from collapsing.

Fermions have spin 1/2, 3/2, 5/2, ...
Neutron stars are cold enough to contain new quantum phases of matter.

Neutrons (protons) can form pairs and undergo phase transitions into superfluid (superconducting) states.
Superfluids are fluids that flow without viscosity.

Superconductors have zero electrical resistivity and try to expel their magnetic field.

Their existence is a direct result of quantum mechanics.

Neutron stars are the largest superfluids and superconductors in the Universe.
Superfluids cannot rotate like classical fluids. They have to form vortices, which can be envisaged as tiny, rapidly rotating tornadoes.

Image credit: NOAA Photo Library
SUPERFLUID VORTICES

Each vortex carries a unit of circulation, adding up to mimic classical rotation.

Neutron star interiors contain \( \sim 10^5 = 100,000 \) vortices per square centimetre.
Each vortex carries a unit of circulation, adding up to mimic classical rotation.

Neutron star interiors contain $\sim 10^5 = 100,000$ vortices per square centimetre.

Image credit: Peter Engels, JILA
PULSAR GLITCHES

Over a long time, the neutron star loses energy and will rotate slower and slower.

Sudden glitches interrupt the regular spin-down of pulsars.
Sudden glitches interrupt the regular spin-down of pulsars.
To illustrate the concept: what happens when a rotating cooked / raw egg is stopped?

Transfer of angular momentum!
Sudden spin-ups (glitches) interrupt the regular spin-down of pulsars.

Glitches are a manifestation of quantum mechanics.
Sudden spin-ups (glitches) interrupt the regular spin-down of pulsars. 

Studying glitches is one way to learn about the properties of matter.

Glitches are a manifestation of quantum mechanics.
Because neutron stars unite many extremes of physics that cannot be recreated on Earth, they are ...  

GREAT COSMIC LABORATORIES!!  

THANKS FOR LISTENING.