PULSARS AND NEUTRON STARS: AN INTRODUCTION TO OBSERVATIONS AND CURRENT MODELS

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Exotic Nuclei: New Challenges, May 7-18, 2007

OUTLINE

Introduction

NEUTRON STARS OR COMPACT STARS?

A star made of neutrons… is the main idea.

BUT

it is not the only feature:

- strong gravitational field
- electro-magnetic field
- transition to the surface and/or accretion of matter from the interstellar medium (see also lecture by N. Sandulescu)
- many possibilities for nuclear matter: protons, electrons, muons, pions, *s* quarks, hyperons, …

⇒self-gravitating object at nuclear density (not only neutrons)

THE CONCEPT

In 1932, British scientist James Chadwick discovers the existence of neutrons.

The legend says that, the very same evening, Lev Landau discusses about the possibility of dense stars made only of neutrons.

SOME ORDERS OF MAGNITUDE...

- density = nuclear density $\rho_{\text{nuc}} \simeq 1.66 \times 10^{17}$ kg / m^3,
- let us take a mass $M \simeq 1M_\odot = 2 \times 10^{30}$ kg,
- the radius should be $R \simeq \sqrt[3]{\frac{3M}{4\pi\rho_{\text{nuc}}}} \simeq 14$ km,
- and the surface gravity $\sim 10^{11}$ m /s^2 (about 10^9 times that of the Sun).

DISCOVERY OF PULSARS

In 1967, at Cambridge University Antony Hewish lead an observational survey of extra-galactic radio-sources.

In august, his student Jocelyn Bell detects important signal fluctuations, which are observed to be periodic with a period of 1.337 s.

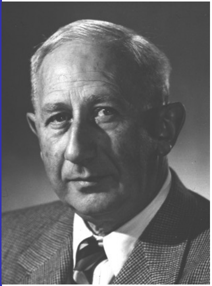
⇒pulsar or *Pulsating Source of Radio* (PSR)

PULSARS ARE NEUTRON STARS

Originally, the sources were associated with pulsations of neutron stars or white dwarfs after thinking of little green men: the first pulsar has been called LGM before PSR B1919+21...

Thomas Gold, in 1968 identifies pulsars with rotating magnetized neutron stars and predicts a slight increase of their period due to energy loss.
⇒with the discovery of the Crab pulsar (PSR B0531+21) with a period of 33 ms, white dwarfs are ruled out...

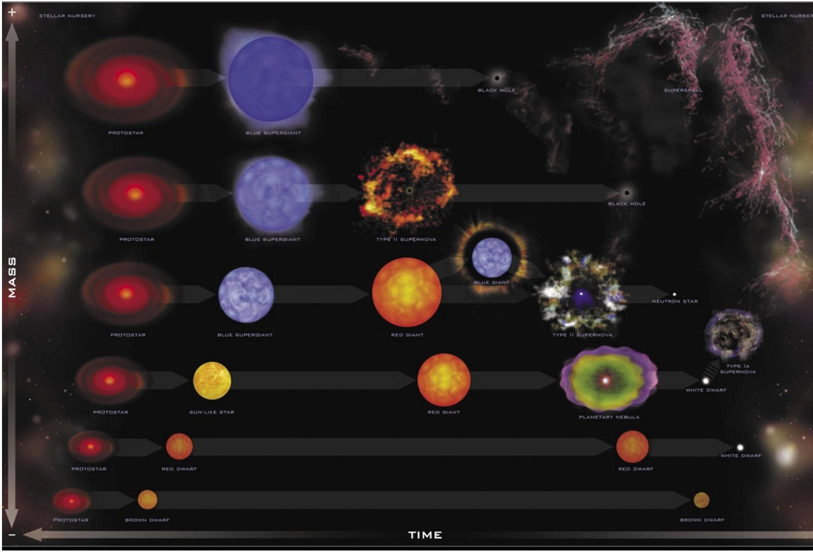
HOW ARE THEY FORMED?



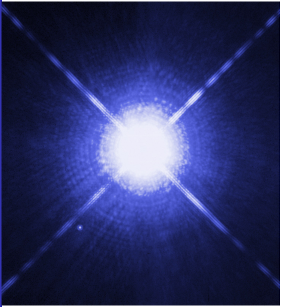
In 1934, the astronomers Walter Baade and Fritz Zwicky make the hypothesis that *supernovæ* could represent the transition between main sequence (normal) stars and neutron stars.

- reasonable explanation for the source of energy of *supernovæ*
- in accordance with the discovery of Crab pulsar(*supernovæ* observed in 1054).

STELLAR EVOLUTION



WHITE DWARFS

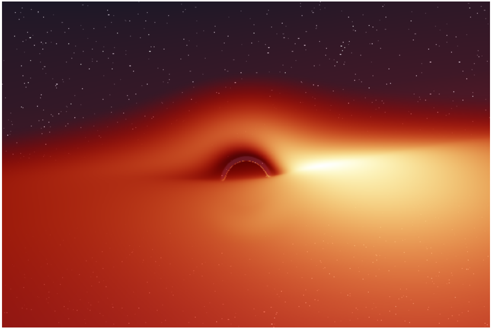


- white dwarfs have been observed as very hot (white) and very small (dwarf) stars;
- *e.g.* Sirius B has been observed with $T_{\text{eff}} = 24000K$ and $R \sim 5000$ km;
- the density is therefore $\rho \sim 10^9$ kg/m^3.

- gravity is balanced by degeneracy pressure of the electrons,
- if the mass is lower than some critical value, called *Chandrasekhar mass* $\sim 1.5 M_\odot$.
- If they do not accrete matter, white dwarfs cool down and become fainter and fainter.

BLACK HOLES

- a black hole is a region of space-time causally disconnected from asymptotic observers.
- the (geometric) boundary is called event horizon.



- inside the horizon, no light ray can reach any outside observer (black);
- what falls inside the horizon is definitely lost (hole) ...

Neutron star models

PHYSICAL INGREDIENTS

First one builds equilibrium models:

- assume that nuclear matter is a fluid;
- assume chemical equilibrium;
- give the gravitational law (self-gravitating body);
- write the hydrostatic equilibrium;
- give a law for the pressure as a function of nuclear matter density (temperature?) ⇒equation of state (EOS).

The EOS specifies the nuclear matter properties and, in particular the strength of the strong interaction between particles, which is to equilibrate gravity.

COMPACTNESS

THE NEED FOR RELATIVISTIC GRAVITY

Let us compare the escape velocity v_e from a self-gravitating body to the speed of light c:

$$\frac{1}{2}mv_e^2 = \frac{GMm}{R} \text{ and } \frac{v_e^2}{c^2} = \frac{2GM}{Rc^2} = \Xi$$

Ξ is called the compactness parameter of the body, and also measures the ratio between the gravitational potential energy and the mass energy. It value is

- 10^{-6} for our Sun,
- 10^{-3} for a white dwarf,
- 0.4 for a neutron star and
- 1 for a black hole

⇒it gives the influence of relativistic effects on the gravitational force: one needs general relativity (GR) to describe neutron stars!

TOLMAN-OPPENHEIMER-VOLKOV SYSTEM

To describe the gravitational field in GR, one needs the metric $g_{\alpha\beta}$ (static and spherically symmetric):

$$\mathrm{d}s^2 = g_{\alpha\beta}\mathrm{d}x^\alpha \mathrm{d}x^\beta = -N^2c^2\mathrm{d}t^2 + A^2\mathrm{d}r^2 + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\varphi^2\right)$$

The matter is assumed to be a perfect fluid and is given by its stress-energy tensor $T^{\alpha\beta}$:

$$T^{\alpha\beta} = \left(\rho + \frac{p}{c^2}\right)u^\alpha u^\beta + pg^{\alpha\beta}.$$

Defining $m(r)$ and $\Phi(r)$ from $A = \left(1 - \frac{2Gm}{rc^2}\right)^{-1}$ and $N = \exp\left(\Phi/c^2\right)$, Einstein and hydrostatic equations write:

$$\begin{aligned}
\frac{\mathrm{d}m}{\mathrm{d}r} &= 4\pi r^2\rho \\
\frac{\mathrm{d}\Phi}{\mathrm{d}r} &= \left(1 - \frac{2Gm}{rc^2}\right)^{-1}\left(\frac{Gm}{r^2} + 4\pi G\frac{p}{c^2}r\right) \\
\frac{\mathrm{d}p}{\mathrm{d}r} &= -\left(\rho + \frac{p}{c^2}\right)\frac{\mathrm{d}\Phi}{\mathrm{d}r}
\end{aligned}$$

SIMPLE EQUATIONS OF STATE: POLYTROPES

In order to integrate the TOV system, one must specify an EOS:

- soon after their birth in *supernovæ*, neutron stars cool down below their Fermi temperature;
- temperature effects can be neglected and nuclear reactions are at equilibrium;
- cold catalyzed matter at the endpoint of thermonuclear evolution.

$\Rightarrow$all state variables are functions of only one parameter, chosen to be *e.g.* the baryonic density n.

Defining the adiabatic index $\Gamma(n) = \frac{n}{p}\frac{\mathrm{d}p}{\mathrm{d}n}$, a family of simple EOSs, called polytropic EOSs, is obtained by assuming $\Gamma = \mathrm{const}$.

NUMERICAL RESULTS

The TOV system is integrated specifying (in addition to the EOS):

- a value of the central density (to vary the resulting mass);
- regularity conditions at $r = 0$;

Thus, the system can be integrated until $p = 0$ at the surface ($r = R$), where it is matched with vacuum spherical static solution (Birkhoff's theorem).

Density profile

Gravitational potential

GLOBAL QUANTITIES

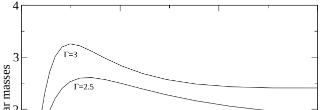
In GR, one must be cautious when defining global quantities:

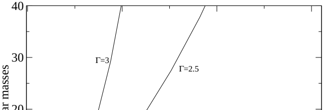
- the gravitational mass can be defined for an isolated system, and here as $M_g = \displaystyle\int_0^R 4\pi r^2 \rho(r)\mathrm{d}r = m(R)$.
- the baryon mass is given by the number of baryons contained in the star $M_b = m_b \displaystyle\int_0^R 4\pi r^2 A(r) n(r)\mathrm{d}r$.
- the gravitational redshift is the frequency relative redshift undergone by a signal emitted at the surface of the star and measured by a distant observer

$$z = \left(1 - \frac{2GM}{Rc^2}\right)^{-1/2} - 1 = (1 - 2\Xi)^{-1/2} - 1.$$

Maximal mass

Contrary to white dwarfs, where $\Gamma \to 4/3$ near maximal mass, neutron star models exhibit a maximal mass as a general relativistic effect: more mass ⇒more pressure to equilibrate ⇒more gravity ⇒more mass ...





ROTATING MODELS: MORE COMPLICATIONS

Next step: take into account rotation; two possibilities

- Analytically perturb spherical models;
- Numerically compute full models in axisymmetry.

Assumption of circularity (no meridional convective currents), ⇒four gravitational potentials, depending on (r, θ). Two more differences with spherical models:

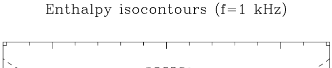
- need to specify the rotation law as $\Omega = f(r \sin\theta)$, $f =$ const being rigid rotation;
- no more Birkhoff's theorem: the gravitational potentials must be integrated up to spatial infinity, where space-time is asymptotically flat.

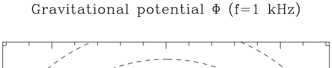
With $H = \log\left(\frac{e+p}{n m_b c^2}\right)$ the pseudo-enthalpy, the fluid equilibrium reads (γ is the fluid Lorentz factor):

$$H + \Phi - \log\gamma = \text{const.}$$

ROTATING MODELS: NUMERICAL INTEGRATION

System of four coupled non-linear Poisson-like equations, with non-compact sources ⇒use of computer techniques

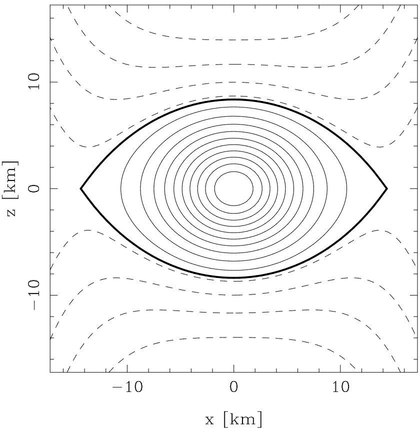

Enthalpy isocontours (f=1 kHz)


Gravitational potential Φ (f=1 kHz)

ROTATING MODELS: KEPLER LIMIT

In the case of rigid rotation, the angular frequency is physically limited by the mass shedding limit.

Enthalpy isocontours Keplerian frequency



Also called Kepler limit, here $\Omega_K \simeq 1100 Hz$.

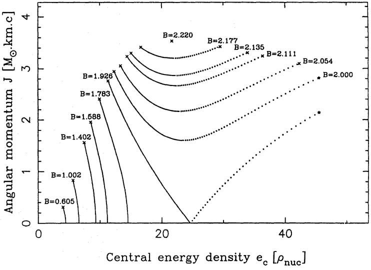
For each EOS one can define an absolute maximal rotational frequency.

SUPERMASSIVE SEQUENCES

For a given number of baryons, the effect of rotation is to:

- increase the radius of the star,
- decrease its central density,
- increase the gravitational mass.

The maximal mass associated to a given EOS is even more increased from the existence of supermassive sequences: rotating solutions that cannot exist in spherical symmetry.



SUPERFLUIDITY AND THE TWO-FLUIDS MODEL

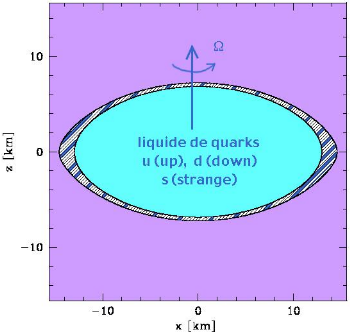
Trying to improve the model...

- Neutrons are predicted to be superfluid;
- Other constituents are locked together by viscosity and magnetic field;⇒another fluid
- Both fluids are coupled by the strong nuclear force...

⇒need for two-fluid framework, with non-dissipative coupling via entrainment and the nuclear “symmetry energy”.

STRANGE QUARK STARS

Deconfined beta-stable (u,d,s) quark matter has been proposed as the absolute ground state of matter at zero temperature.
⇒some "neutron stars" could be "strange quark stars"…
… more compact, rotating faster, they have been invoked several times to explain anomalous observations.

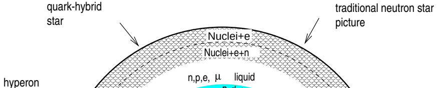


⇒many numerical models to predict their exact properties.

CONSIDERED MODELS FOR NUCLEAR MATTER

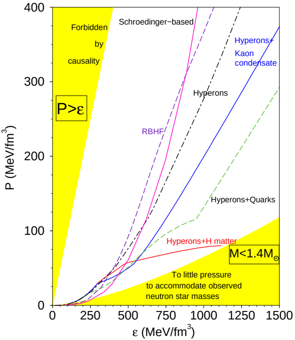
Beside the “standard model” $(n, p, e$ and $\mu)$ and the “strange quark star” picture, many possibilities have been considered for the inner core:

- pion condensate,
- hyperons,
- kaon condensate,
- quark condensate (color superconductivity?)



Some popular equations of state

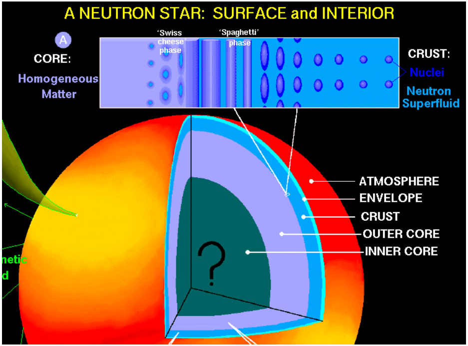
EOS represents the major uncertainty when building models of neutron stars.⇒use of different EOSs present in the literature to compare all models to observations.



- polytropic EOSs,
- incompressible (constant density matter) or causal limit EOSs
- $(n, p, e$ and $\mu)$ described by Skyrme potential (*e.g.* Skyrme Lyon 4 as in Douchin & Haensel 2001);
- MIT bag model for (u, d, s) quark matter.

⇒very different conditions from laboratory experiments (high N/Z, low temperature, ...).

STRUCTURE AND TRANSITION TO THE SURFACE

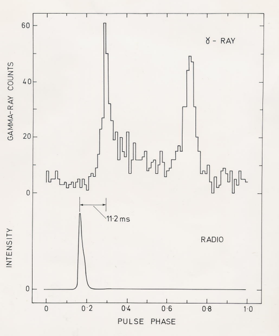


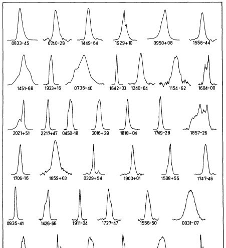
The very interior is poorly known, but from the center, there must be a transition to
neutron-rich fluid ⇒neutrons dripping out of nuclei
⇒crystal-like structure of nuclei for the outer crust.

Observations and constraints

PULSATING SOURCES IN RADIO AND X-RAYS

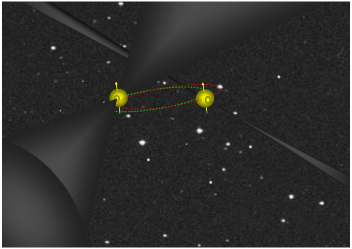
Pulsars emit pulses in radio or X-rays, sometimes both (*e.g.* Vela):





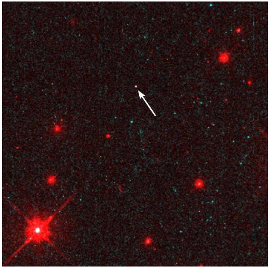
BINARY PULSARS

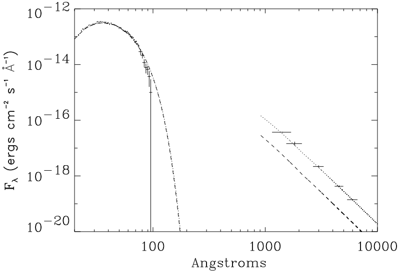
In 1974 R.A. Hulse and J.H. Taylor discovered first binary pulsar PSR B1913+16. Others have been discovered since then, including a double pulsar (both neutron stars are active and emit in our direction)
⇒precise timing of binary pulsars have provided numerous valuable and very accurate observations



THERMAL EMISSION

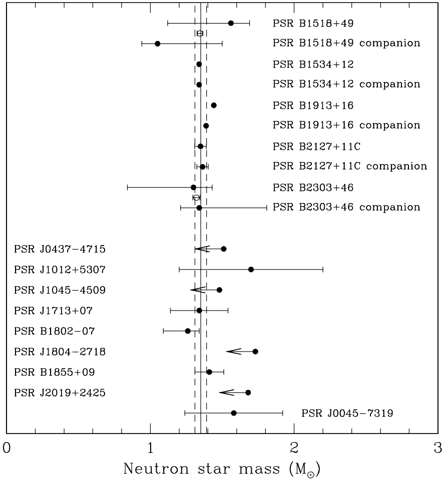
- in 1996, an isolated neutron star has been discovered in optics and X-rays;
- it shows no pulsar emission, only a surface thermal one, at $T \sim 10^5 K$;
- called RX J185635-3754, it is situated at a distance of 120 pc from us (parallax measure by HST).





claimed to be a strange star for a while...

MEASURE OF MASSES



All measured neutron star masses have been obtained from binary systems:

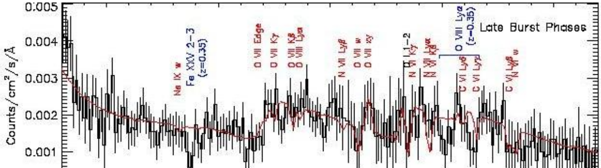
- X-ray binaries (accreting neutron star);
- binary pulsars.

In the last case, the measures are very precise.

$\Rightarrow$a realistic EOS must be able to give a maximal mass higher than $\sim 1.6 M_\odot$.

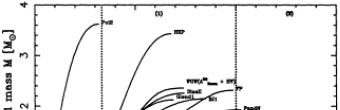
COMPACTNESS

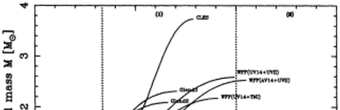
- Contrary to main sequence (normal) stars and white dwarfs, very few neutron stars radiate as black bodies...
- Strong magnetic field make atmosphere models complicated. ⇒radii are not known!



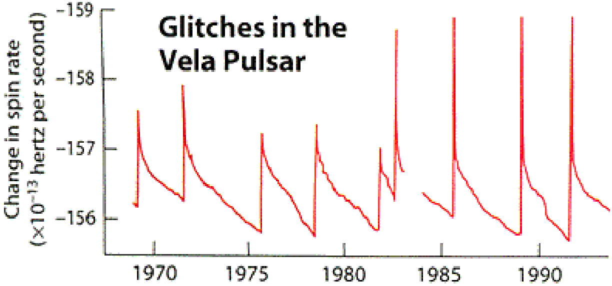
ROTATION PERIODS

- Rotation periods are easily deduced from pulse periods and range from $P = 1.56$ ms to $P = 8.5$ s.
- There has been a claim that a sub-millisecond ($P = 0.5$ ms) has been detected in the Large Magellanic Cloud, inside the SN1987a supernova, but withdrawn





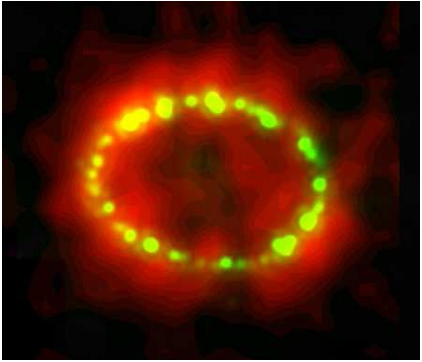
GLITCHES



Some pulsars exhibit sudden changes in the rotation period: instead of regularly slowing down, it shows rapid speed-up.
⇒within the two-fluid framework:

- the outer crust (+fluid) is slowed down, not the inner fluid;
- until the stress (or interaction) between both becomes larger than some threshold.
- can turn into a “starquake”.

NEUTRINOS



One of the major astrophysical events of last century was the observation of the supernova SN1987a in the Large Magellanic Cloud and the detection of a dozen of neutrinos ν_e.

These are an evidence of neutronization of matter through inverse β-reaction:

$$p + e^- \rightarrow n + \nu_e$$

which is a confirmation of the scenario proposed by Baade and Zwicky 50 years earlier.

note: no pulsar has been ever found in the supernova remnant.

SLOWING DOWN OF PULSARS

In 1969, the variation of the period of the Crab pulsar is measured giving

$$\dot{P} = 36 \text{ ns } / \text{ day.}$$

Since $\dot{P} > 0$, the pulsar is slowing down, as predicted by Gold's model.

When estimating the age of a pulsar one can derive the simple formula

$$T \sim \frac{1}{2}\frac{P}{\dot{P}}.$$

If applied to the Crab (observed in 1054), one gets $T \sim 1250$ years.

NEUTRON STARS AS SOURCES OF GRAVITATIONAL WAVES

Using a linearized version of Einstein equations describing the gravitational field from the matter-energy distribution:
The gravitational luminosity is

$$L \sim \frac{G}{c^5} s^2 \omega^6 M^2 R^4$$

(s being a factor related to non-sphericity of the matter distribution);changing the formula to

$$L \sim \frac{c^5}{G} s^2 \left(\frac{2GM}{Rc^2} \right)^2 \left(\frac{v}{c} \right)^6$$

allows to see that good sources are

- non-spherical (and dynamically changing);
- compact ($\Xi \sim 1$);
- in relativistic motion.

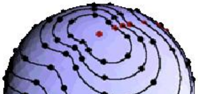
⇒with the exception of first point, neutron stars are good potential sources...

ASTEROSISMOLOGY

To be efficient emitters, it is not enough to be flattened by rotation: they must have a variation in time of their quadrupole moment: *e.g.* deformation not symmetric / rotation axis.

Off-axis deformations can come from

- magnetic field;
- crust (1 mm high mountains);
- oscillations (vibrations) of the fluid.

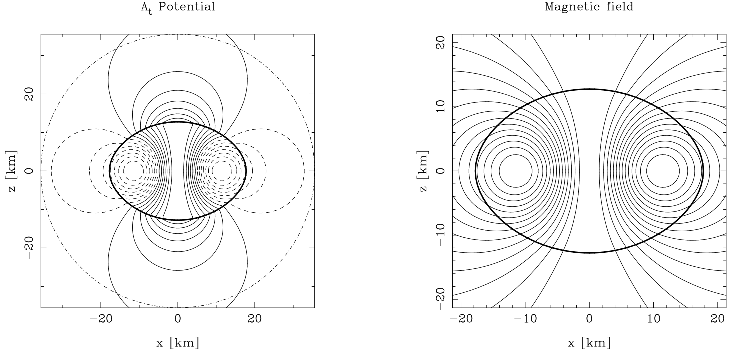


Many modes, but most promising could be r-modes (Rossby waves) driven unstable by

Magnetic field
and
pulsar models

MAGNETIZED NEUTRON STARS: NUMERICAL MODELS

Magnetic field is important in the emission of pulsars
⇒magnetized rotating models: aligned magnetic and rotation axis.

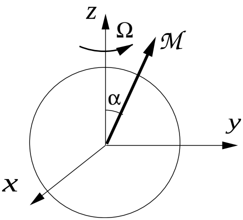


In the system giving rotating models, one adds:

- two Poisson-like equations for the electro-magnetic potential (Maxwell equations)
- a magnetic potential in the equilibrium equation ("Bernoulli equation").

ROTATING DIPOLE MODEL

To emit electro-magnetic waves, magnetic axis must not be aligned with the rotation one ⇒oblique dipole (simplest analytic) model .



Accelerated dipole ⇒radiation of its rotational energy $E = \frac{1}{2} I \Omega^2$:

$$\dot{E} = -\frac{2\pi}{3c^2\mu_0}\Omega^4 R^6 B_p^2 \sin^2\alpha$$

⇒Deduce polar magnetic field B_p from observations of $\dot{P}$, assuming the star is a sphere.

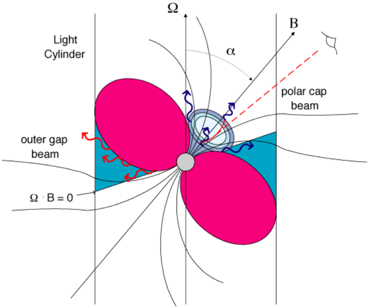
For the Crab pulsar $B_p \sin\alpha \simeq 5.3 \times 10^8$ T.

Emission mechanism

Open problem: the precise emission mechanism for pulsars. Two main mechanisms are now proposed:

- The polar cap model: the emission region is near the magnetic pole, where the magnetic field is very strong, so pairs are created

$$\gamma + \vec{B} \rightarrow e^+ + e^- + \vec{B}.$$



- The outer gap model: the emission region is at the limit of closed magnetic field lines.

BRAKING INDEX AND ORDERS OF MAGNITUDE

- If isolated rotating neutron stars are strong sources of gravitational radiation, then a part of pulsar slow-down should be due to this mechanism too. In general

$$\dot{\Omega} = -K\Omega^n,$$

where n is the braking index ($n = 3$ for electro-magnetic waves and $n = 5$ for gravitational waves).
- Observations (few and noisy) indicate $n \lesssim 3$ ⇒electro-magnetic radiation seem to be at the origin of the pulsar slow-down.
- Usual pulsars have $B_p \sim 10^{8-9}$ T, ⇒depending on the exact current distribution inside the star, the magnetic deformation is rather small: in numerical models

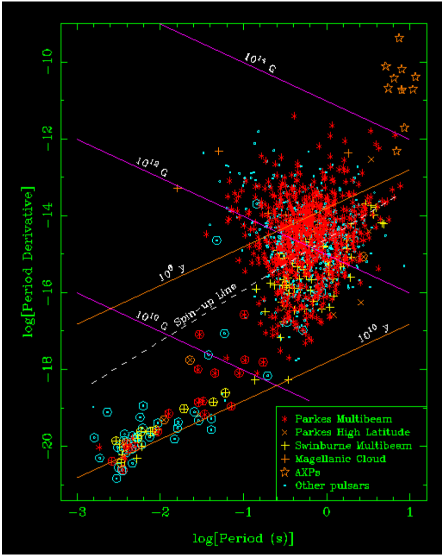
$$\frac{p_{\text{mag}}}{p_{\text{fluid}}} \sim 10^{-9}.$$

$\left(\dot{P}, P\right)$ DIAGRAM

The $\sim$ 1500 known pulsars can be displayed on a $(P, \dot{P})$ plane, with the death line below which no radio emission can be seen.

Two categories of pulsars:

- "usual" ones, with $P \sim 1$ s and $B_p \sim 10^8$ T;
- millisecond pulsars, with much lower magnetic fields.



PULSAR RECYCLING

It is difficult to imagine the formation scenario of a 1 kHz rotating neutron star

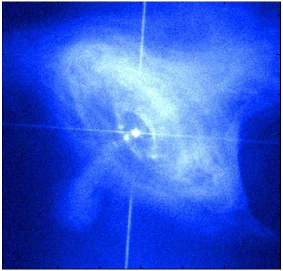
⇒millisecond pulsars must have been accelerated in some way.

As nearly all millisecond pulsars are in binary systems, it seems plausible that the acceleration has occurred by accreting matter and angular momentum from the companion.

⇒pulsar recycling.

PULSAR WIND NEBULAE

- Further out from the pulsar, a wind of relativistic particles is powered by the high-energy phenomena occurring in the pulsar magnetosphere.
- The wind is interacting with the supernova remnant and decelerated to sub-relativistic speed across a strong shock.
- These injected particles are thus radiating far from the pulsar in the pulsar wind nebula (also called “plerion”).
- The plerion can be observed at many wavelengths, but is mostly seen in X-rays. The typical plerion is the Crab

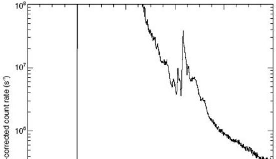


MAGNETARS

Some objects: Soft Gamma-ray Repeaters (SGR) and Anomalous X-ray Pulsars (AXP) observed in very-high energy emission, are associated with neutron stars with a very high magnetic field $B_p \sim 10^{10-12}$ T.

⇒magnetars

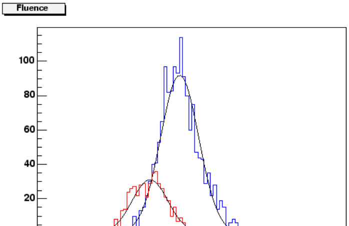
- These pulsars have high $\dot{P}$ and low P;
- they could represent as much as 10 % of all neutron stars (below death line);
- They can produce very strong bursts of X- and γ-rays, from the (glitch-like) re-arrangement of the crust, in which the magnetic field is pinned. The most striking case was the December 2004



Neutron stars as probes for modern physics

GAMMA-RAY BURSTS: OBSERVATIONS

From the 60s, military satellites have observed high-energy events producing bursts of γ-rays (GRB). Many dedicated satellites are now in operation, in conjunction with ground-based observations to catch the afterglows.



Two categories of GRBs have been observed:

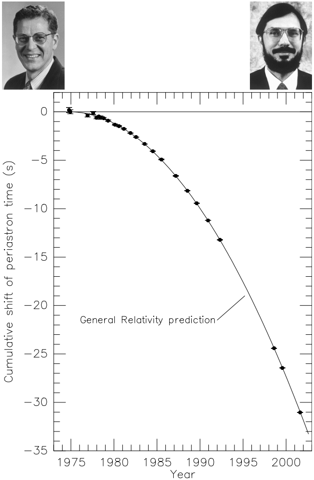
- short ones, with a duration between 0.03 s and 2 s;
- long ones from 2 s to 1000 s.

CENTRAL ENGINE FOR SHORT GAMMA-RAY BURSTS

GRBs are the most energetic events, as the *supernovæ*. The emission mechanism is rather well understood, but the central powering engine is still uncertain.
For short GRBs, the standard model requires the merger of a binary system of neutron stars.

- The result of this collapse leads to the formation of a black hole surrounded by a hot torus emitting neutrinos.
- These could in turn deposit energy at the base of a relativistic jet,

BINARY PULSARS IN GENERAL RELATIVITY



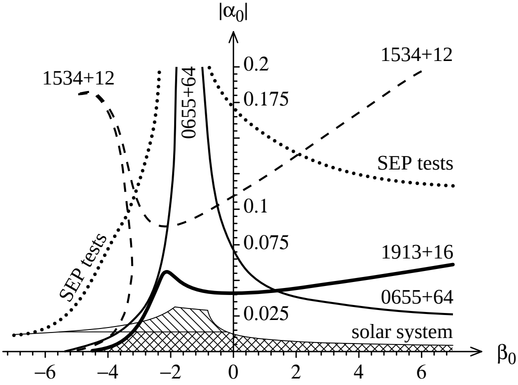
Binary pulsars have been timed in an extreme accurate way, starting with PSR 1913+16, by Russel Hulse and Joseph Taylor.
This precise timing allowed for a comparison with General Relativity prediction of

- the periastron shift,
- the angular momentum loss due to emission of gravitational waves.

Excellent agreement and check of General Relativity ⇒Nobel Price in 1993

TENSOR-SCALAR THEORIES OF GENERAL RELATIVITY

Other binary pulsars have been discovered and precisely timed. They have allowed for a comparison of general relativity with "more general" theories: tensor-scalar theories of gravity.



They are parameterized by two numbers (α_0, β_0); $\alpha_0 = 0$ and $\beta_0 = 0$ correspond to general relativity.

DETECTORS OF GRAVITATIONAL WAVES

LIGO: USA, LOUISIANA

LIGO: USA, WASHINGTON

VIRGO: FRANCE/ITALY (PISA)

the arms of these Michelson-type LASERS are 3 km (VIRGO) and 4 km (LIGO) long ... with almost perfect vacuum. ⇒they have just been built and are starting to acquire data.

ASTROPHYSICAL SOURCES OF GRAVITATIONAL WAVES

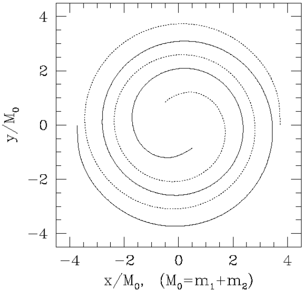
NEUTRON STARS AND BLACK HOLES

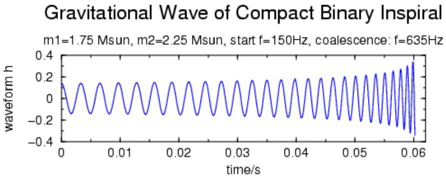
Many of astrophysical sources of high-frequency (10 → 1000 Hz) gravitational radiation imply neutron stars:

- at the very moment of their birth, *supernovæ* produce a fair amount of gravitational waves, although not very efficient (almost spherically symmetric);
- soon after that, proto-neutron stars can undergo growth of unstable oscillations, inducing deformations and a strong gravitational wave burst ;
- isolated rotating neutron stars: slightly deformed they emit gravitational waves. Not very efficient, but this mechanism is regular and the radiation can be integrated over a long period to increase the signal-to-noise ratio;
- binary systems of neutron stars or neutron star/black hole are losing angular momentum due to the emission of gravitational waves. They end up in a violent coalescence with a large amount of waves.

ASTROPHYSICAL SOURCES OF GRAVITATIONAL WAVES

BINARY NEUTRON STARS





- Binary neutron stars and/or black holes are the best candidates to be detected by ground-based interferometric detectors of gravitational waves;
- fitting the quasi-periodic signal before the merger, one could recover the direction and the masses.
- the end of the signal is then sensitive to the radius of the neutron star and it might be possible (although difficult) to extract it/them from the signal.

PULSARS AS ULTRA-STABLE CLOCKS

Binary pulsars can give very precise measures of strong-field gravitational field.
⇒isolated pulsars have been proposed as ultra-stable clocks.

If their physical properties are well understood, the long-term stability of pulsars as clocks is better than human-made atomic clocks.

One can see pulsars as precise clocks situated all over the universe and sending time signals to us...

⇒In particular, very low-frequency gravitational waves ($10^{-7} \rightarrow 10^{-4}$ Hz), it has been suggested that an extensive study and timing of pulsars could bring detections.

INFORMATIONS ABOUT NUCLEAR MATTER

When building models of neutron stars and/or pulsar emission, the highest level of uncertainty comes from the EOS.
⇒Could observations of neutron stars give any indication on the EOS of cold matter at nuclear density?

- a high mass or rotation rate can exclude some EOSs
- glitches can tell us about superfluidity
- a real thermal spectrum of a neutron star, together with its distance, could give the radius...
- high signal-to-noise ratio detection of gravitational waves from a binary neutron star could give masses and radii.

★ HOLY GRAIL ★

Get some points in the mass-radius diagram of neutron stars