General introduction to neutron stars

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What is a neutron star?

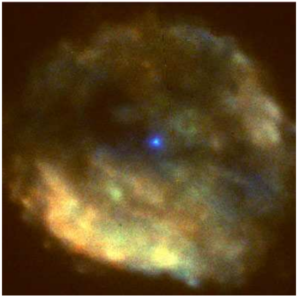
Broadly speaking a neutron star can be viewed as a **giant nucleus** with a mean density of the order of $\sim 10^{14} - 10^{15}$ g.cm^{-3}. A neutron star contains $A \sim 10^{57}$ nucleons, 90% being neutrons.

Nuclear liquid drop picture

Using the liquid drop model, we can obtain a good estimate of the typical mass and radius of a neutron star

$M \sim Am \sim 1 - 2M_{\odot}$

$R \sim r_0 A^{1/3} \sim 10$ km



RCW 103 (from ESA)

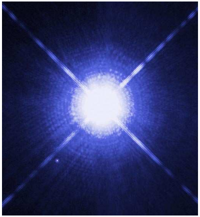
Outline

- Brief history of neutron stars
- Pulsars and other faces of neutron stars
- Formation of neutron stars
- Observational constraints on the structure of neutron stars

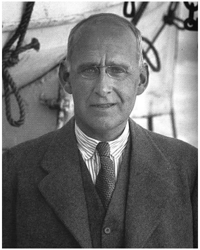
Brief history of neutron stars

Chronology

The history of neutron stars began in the 1930s. At this time a few **white dwarfs** were known. In 1915, Walter Adams spectral observations of Sirius B had revealed that white dwarfs are very compact stars.



Sirius B



Sir Arthur Eddington

In the 1920s, Arthur Eddington developed the theory of stellar structures. Later astrophysicists started to speculate about the ultimate fate of stars using the newly developed quantum theory.

Time line of physics from 1900 to 1930s

1900 Planck quantum hypothesis

1905 Einstein's theory of Special Relativity, photoelectric effect

1911 discovery of the atomic nucleus by Rutherford

1913 Bohr model of atoms

1915 Einstein's theory of General Relativity, Schwarzschild solution describing the gravitational field outside a spherical massive object

1919 Eddington's expedition to test GR predictions

1923 de Brogli hypothesis of matter waves

1925 Pauli exclusion principle

1926 Schroedinger equation, Fermi-Dirac statistics

1928 Dirac equation

First ideas about neutron stars

In February-March 1931, Landau, Bohr and Rosenfeld discussed the possible existence of compact stars as dense as atomic nuclei. Landau published a paper in January 1932.

In February 1932, the neutron (which was predicted by Rutherford in 1920) was discovered by James Chadwick. He was awarded the Nobel prize in 1935.

Talk of D. G. Yakovlev from Ioffe Institute in St Perterburg
`http://www.ift.uni.wroc.pl/~karp44/talks/yakovlev.pdf`

Baade and Zwicky prediction

In December 1933, during a meeting of the American Physical Society at Stanford, Baade and Zwicky predicted the existence of neutron stars as **supernova remnants**

William Baade and Fritz Zwicky

nova is about twenty days and its absolute brightness at maximum may be as high as $M_{\mathrm{vis}} = -14^{M}$. The visible radiation L_ν of a supernova is about 10^8 times the radiation of our sun, that is, $L_\nu = 3.78 \times 10^{41}$ ergs/sec. Calculations indicate that the total radiation, visible and invisible, is of the order $L_\tau = 10^7 L_\nu = 3.78 \times 10^{48}$ ergs/sec. The supernova therefore emits during its life a total energy $E_\tau \geq 10^5 L_\tau = 3.78 \times 10^{53}$ ergs. If supernovae initially are quite ordinary stars of mass $M < 10^{34}$ g, E_τ / c^2 is of the same order as M itself. In the *supernova* process *mass in bulk is annihilated.* In addition the hypothesis suggests itself that *cosmic rays are produced by supernovae.* Assuming that in every nebula one supernova occurs every thousand years, the intensity of the cosmic rays to be observed on the earth should be of the order $\sigma = 2 \times 10^{-3}$ erg/cm² sec. The observational values are about $\sigma = 3 \times 10^{-3}$ erg/cm² sec. (Millikan, Regener). With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

Phys. Rev. 45 (1934), 138

Relativistic equations of stellar equilibrium

Chandrasekhar

In 1930, Subrahmanyan Chandrasekhar applied Einstein's theory of Special Relativity to the stellar structure when he was only 20, and developed the theory of white dwarfs (he was awarded the Nobel prize in 1983).

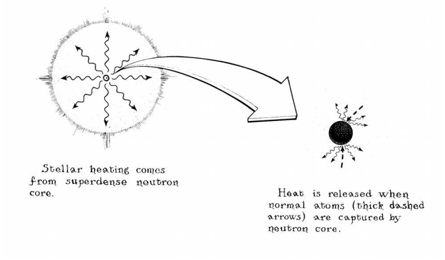
With John von Neumann, they obtained in 1934 the equations describing static spherical stars in Einstein's theory of General Relativity but they didn't publish their work.

John von Neumann

Baym, IOP Conf. Series 64 (1982),45

Neutron core

In 1937, Gamow and Landau proposed independently that a possible stellar energy source could be the accretion of matter onto a dense **neutron core**.



picture from K.S. Thorne

George Gamow and Lev Landau

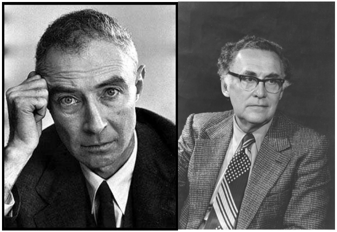
But very soon it was shown that stars are powered by thermonuclear reactions (as suggested in the 20s by Eddington and others). The interest in neutron stars then faded away.

Global structure of neutron stars

Richard Tolman

In 1939, Richard Tolman, Robert Oppenheimer and his student George Volkoff ("TOV") reobtained independently the equations describing static spherical stars in General Relativity

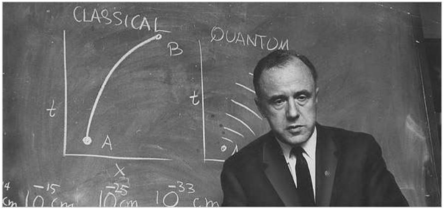
Oppenheimer and Volkoff solved these equations and calculated numerically the structure of non-rotating neutron stars. But their work was mostly ignored by astrophysicists and neutron stars were forgotten.



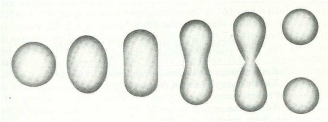
Robert Oppenheimer and George Volkoff

Theoretical developments after the Second World War

The first realistic EoS of dense matter was constructed in the 50s by John Wheeler and his collaborators (in 1939 he elaborated a liquid drop model of fission with Bohr).



Wheeler, Ann. Rev.Astr.Astrophys. 4 (1966), 393.



fission of a liquid drop

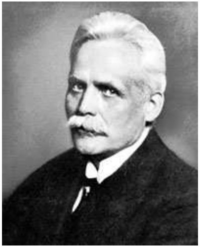
Formed in supernova explosions, neutron stars were thus expected to be "hot". In the 60s, theoretical efforts focused on modeling the cooling of neutron stars motivated by the hope of detecting their thermal emission.

X-ray observations

First cooling calculations predicted surface temperatures $T \sim 10^6$ K for neutron stars $\sim 10^3$ year old.
e.g. Chiu and Salpeter, PRL12(1964),413.

Using the Stefan-Boltzmann law, it was found that the luminosity of a neutron star is comparable to that of the Sun
$L = 4\pi R^2 \sigma T^4 \sim 10^{33}\,\mathrm{erg.s}^{-1} \sim L_\odot$

But according to Wien's law $\lambda \simeq 29$ angstroms, a neutron star emits mainly in X-rays.



Wilhelm Wien (1864-1928)

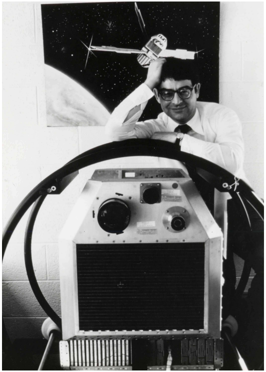
So neutron stars were not expected to be seen from Earth because X-rays cannot penetrate the atmosphere.

X-ray observations

X-ray observations in space started in the 60’s with pioneer experiments by Riccardo Giacconi (Nobel Prize 2002).

Several X-ray sources were discovered but their nature remain elusive.

The activity was also focused on supernova remnant and a natural target was the Crab nebula.



Giacconi with Uhuru satellite, 1970

"Guest stars"

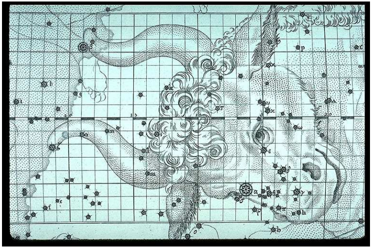
Chinese astronomers observed a very bright star in the constellation of Taurus on July 4, 1054. It was also recorded by Japonese and Arab astronomers. The "guest star" remained visible in daytime for 23 days and disappeared from the night sky after two years.

photo by Ron Lussier

Native Americans (Anasazi) might have also observed this event as suggested by the interpretation of a petroglyph in Chaco Canyon.

Rediscovery in the XVIIIth century

The "guest star" was rediscovered in Europe by the British astronomer John Bevis in 1731.



Uranographia, J. Bevis (1750)

Charles Messier

The associated nebula became the first object of the Messier catalog in 1958.

Crab nebula

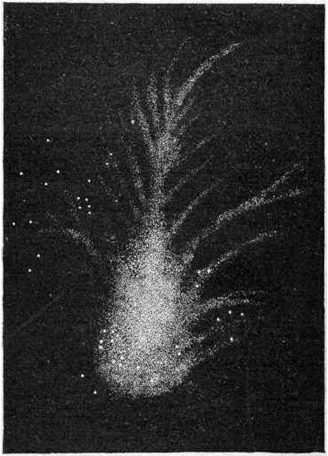
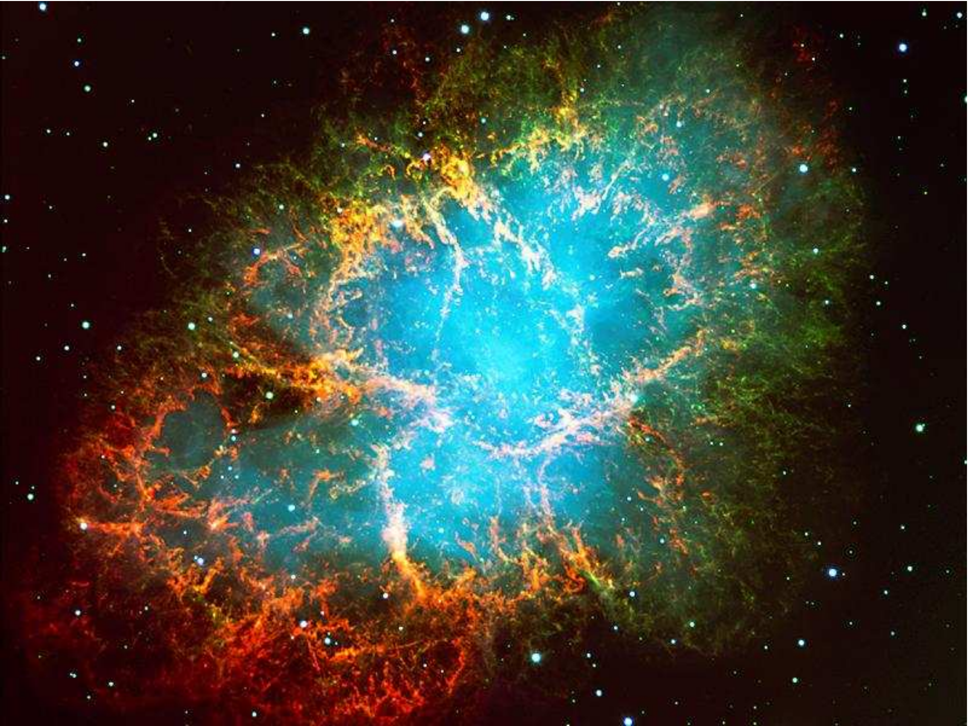


Fig. 438.

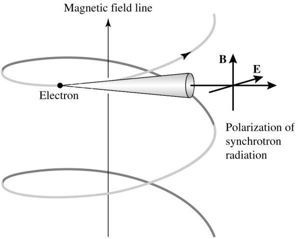
The Messier object M1 was named the "Crab nebula" by William Parson, Lord Rosse in 1844 owing to its filamentary structure .



Early observations of the Crab nebula and first speculations

Already in 1942, Baade and Minkowski found that the central region of the Crab nebula contains an unusual star. Later a strong polarized radio emission was detected.

In 1953, Shklovski interpreted this as being due to **synchrotron radiation** by relativistic electrons spiraling along a strong magnetic field.



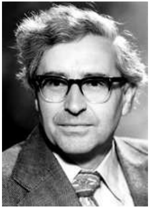
From Carroll and Ostlie

Subsequent theoretical efforts were focused on understanding the origin of the energy powering the Crab nebula.

Search for a neutron star in the Crab nebula

The Crab nebula was observed during a lunar occultation on 7 July 1964. The size of the X-ray source was estimated as 1 light-year$\sim 10^{13}$ km (size of the nebula 11 ly). This was much larger than the typical size of a neutron star (10-20 km).

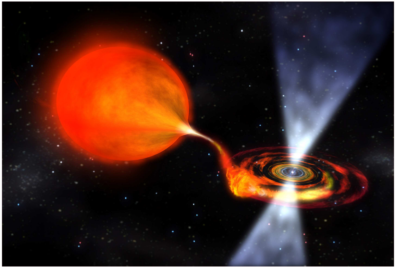
In 1965 Anthony Hewish and his student found a scintillating radio source and speculated that it "might be the remains of the original star which had exploded".



In 1967, Franco Pacini showed that a rapidly rotating neutron star with a strong dipole magnetic field could power the Crab nebula and could explain Hewish observations.

Compact X-ray sources

In 1967, Iosif Shklovsky correctly proposed that Scorpius X-1 (found in 1962) is a neutron star accreting matter from a normal star. But its work attracted little attention among astrophysicists.



Iosif Shklovsky

By 1968, about 20 compact X-ray sources were known.

Fortuitous discovery of pulsars

In 1965, Jocelyn Bell started a PhD under the supervision of Anthony Hewish at the Cavendish Laboratory in Cambridge. Her research was about scintillation of radio sources.

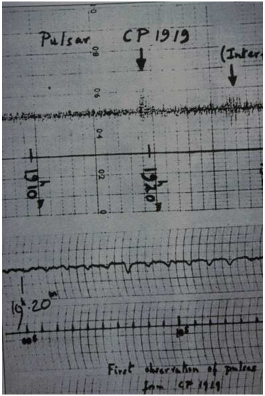
They constructed a 3.7m radiotelescope with a very good temporal resolution. The telescope (which consisted of an array of 2048 dipole antenna) was completed in July 1967.

Jocelyn Bell in 1966

Fortuitous discovery of pulsars

In August 1967, Jocelyn Bell discovered a pulsating radio source with a period of about 1 second.

The source was later found to be extremely regular. In December its period was accurately measured : 1.3373012 seconds. For joking this source was refered as "LGM" (Little Green Men). Now it is known as PSR B1919+21. By Februray 1968 when the results were published, three other sources had been found.



These new pulsating stars were dubbed "pulsars" by a journalist of the Daily Telegraph. Anthony Hewish was awarded the Nobel Prize in 1974.

Nature of pulsars

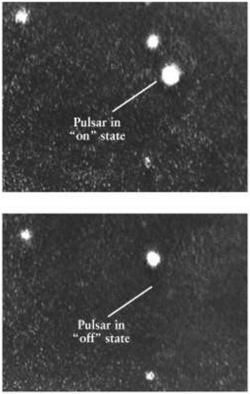
Astrophysicists speculated that pulsars might be **vibrating compact stars** (other less convincing explanations were also proposed).

- White dwarfs were excluded by the discovery of pulsars with very short periods < 1 second (periods of a vibrating or rotating self-gravitating star scales as $\sim 1/\sqrt{G\rho}$)
- Vibrating neutron stars (as suggested by Bell and Hewish) were excluded by pulsar-timing data which showed that **pulsar periods are slighly increasing with time**.

Unmasking pulsars

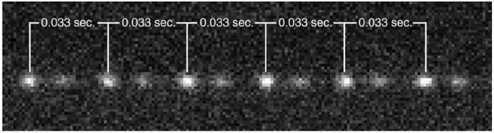
The other possibility was that pulsars are strongly magnetised rotating neutrons stars.
Pacini and Gold (1968)

Crab pulsar

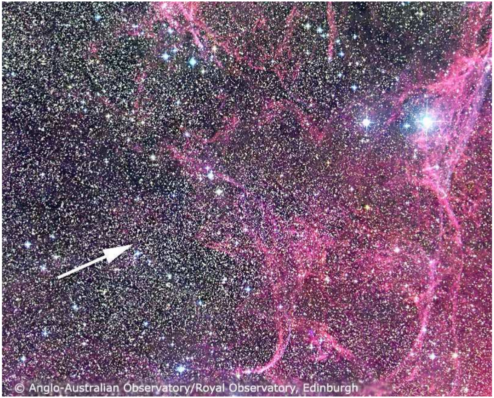


b.

A pulsar (PSR B0531+21) was eventually found in the Crab nebula in 1968 by astronomers of Green Bank observatory. Its period is only 33 milliseconds!



Vela pulsar



In the same year, astronomers from the Sydney University discovered another pulsar in a supernova remnant with a period of 89 ms : the Vela pulsar (PSR B0833-45).

The discovery of the Crab and Vela pulsars definitevely established the nature of pulsars and confirmed the predictions of Baade and Zwicky 35 years earlier that neutron stars are the compact remnants of supernova explosions.

Pulsars and other faces of neutron stars

Pulsar properties

Since 1967, $\sim$ 2000 pulsars have been discovered.
`http://www.atnf.csiro.au/research/pulsar/psrcat/`

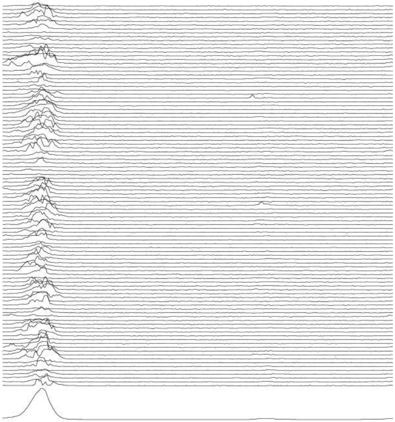
- Their period P ranges from 1.396 ms for PSR J1748$-$2446ad up to 8.5 s for PSR J2144$-$3933.
- Their period increases gradually with time at a rate given by

$$10^{-20} \lesssim \dot{P} \equiv \frac{\mathrm{d}P}{\mathrm{d}t} \lesssim 10^{-12}$$

  Note that for the best atomic clocks $\dot{P} \gtrsim 10^{-16}$ (this corresponds to a delay of 1 second every 300 millions years).
- Each pulsar has a specific pulse profile.

Pulsar fingerprint

Individual pulses vary dramatically. But the average over 100 or more pulses is remarkably stable and is specific to the pulsar.

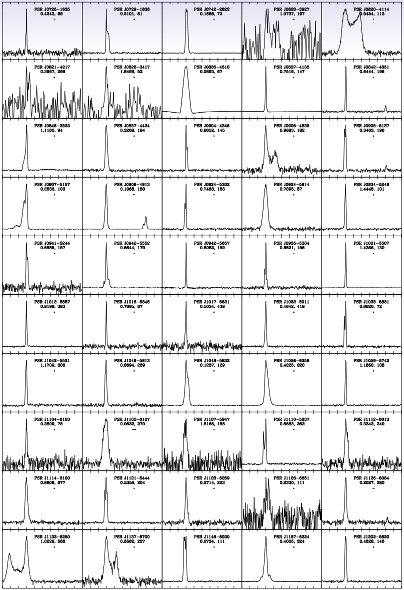


100 single pulses from the 253-ms pulsar PSR B0950+08 and pulse profile averaged over 5 minutes ($\sim$ 1200 pulses)

Ingrid H. Stairs, Living Rev. Relativity 6, (2003), 5

`http://www.livingreviews.org/lrr-2003-5`

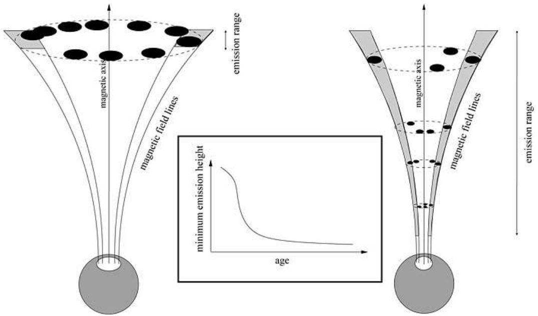
Various examples of integrated pulse profiles for different pulsars
Hobbs et al. (2004)



Online European database of pulse profiles:
`http://www.jb.man.ac.uk/~pulsar/Resources/epn/`

Pulse shape model

The observed pulse shapes are explained by two different models : the core and cone model and the patchy beam model. Observations tend to support an hybrid model



From Karastergiou and Johnston

The emission regions become more randomly distributed as the pulsar evolves.

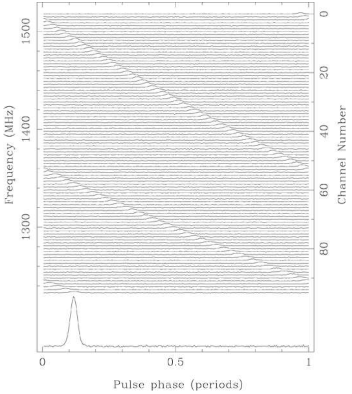
Pulse dispersion

Pulses emitted at lower frequencies arrive later than those emitted at higher frequencies due to electrons in the interstellar medium. This can be used to infer pulsar distances.

The time delay t (in ms) for a pulse of frequency ν (in Ghz) is given by $t \simeq 4.15\mathrm{DM}/\nu^2$

DM is the dispersion measure (in cm^{-3}pc)

$$DM = \int_0^d n_e \mathrm{d}l$$



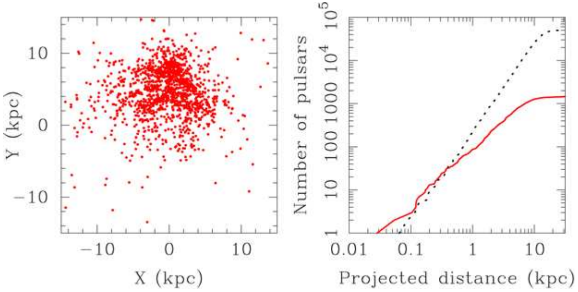
from A. Lyne

Lorimer, Living Rev. Relativity 11, (2008), 8.

`http://livingreviews.org/lrr-2008-8/`

Pulsar distribution

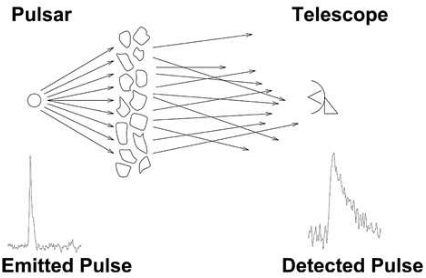
Most pulsars have been found nearby in our own galaxy due to selection effects (we observe only the brightest ones!). The solid line shows the number of observed pulsar while the dotted line shows the expected number of pulsars.

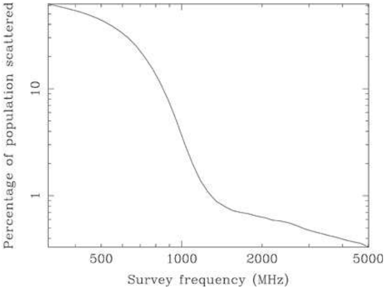


Lorimer, Living Rev. Relativity 11, (2008), 8.
`http://livingreviews.org/lrr-2008-8/`

Selection effects

The radiation beam from very rapidly rotating pulsars is strongly scattered by electron density irregularities in the interstellar medium.



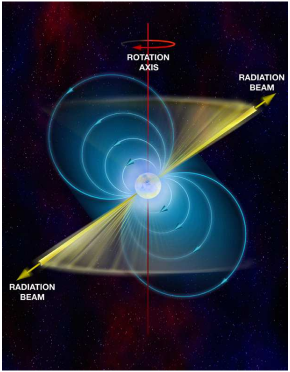


Short-period pulsars are therefore more difficult to detect.

Lorimer, Living Rev. Relativity 11, (2008), 8.
`http://livingreviews.org/lrr-2008-8/`

Origin of pulses

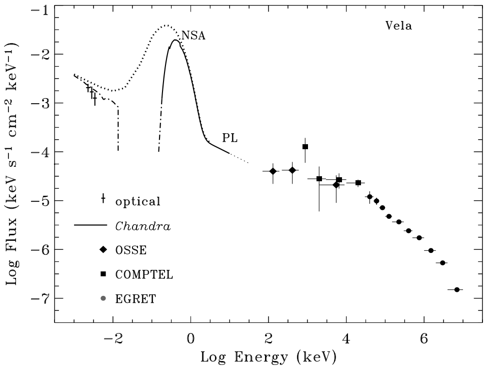
Pulsars are magnetized rotating neutron stars emitting a highly focused beam of electromagnetic radiation oriented long the magnetic axis. The misalignment between the magnetic axis and the spin axis leads to a **lighthouse effect** : from Earth we see radio pulses.



Electromagnetic spectrum of neutron stars

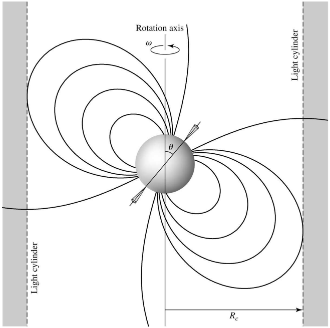
Some pulsars emit not only in radio but also at other wavelengths.

Examle: Vela pulsar



Schematic pulsar emission mechanism

From Maxwell-Faraday's law of induction, the rotating magnetic field induces a **huge electric field** at the surface of the star.



From Carroll and Ostlie

Charged particles are ejected and accelerated to relativistic speeds forming a **magnetosphere**. Electrons emit very energetic γ rays which are converted into electron-positron pairs, producing more radiations and leading to a **cascade of pair-production**.

Goldreich & Julian, ApJ157(1969),869.

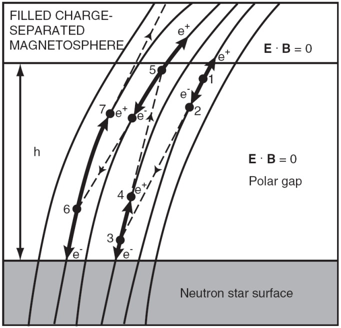
When particles reach the light cylinder $R_c = cP/2\pi$, they leave the star producing a **pulsar wind**. This can be seen in X-rays.

Magnetospheric emission models

Polar cap model

Explains the radio emission.

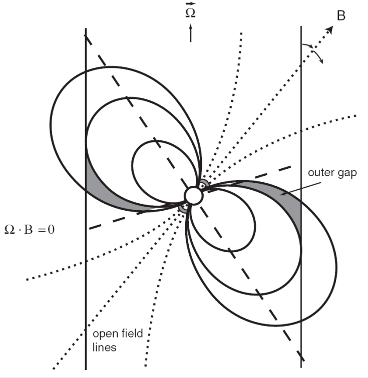
Ruderman and Sutherland



Outer gap model

Explains the intense γ emission of crab and Vela pulsars.

Cheng, Ho and Ruderman



X-ray astronomy of neutron stars

Several X-ray satellites have been launched since the 1960s.
By now the best observatories are

Chandra (NASA)

XMM Newton (ESA)

X-ray astronomy of neutron stars

Several X-ray satellites have been launched since the 1960s.
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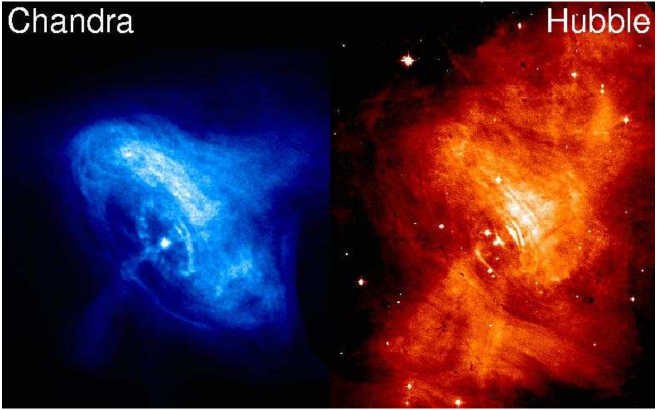
Chandra (NASA)

XMM Newton (ESA)

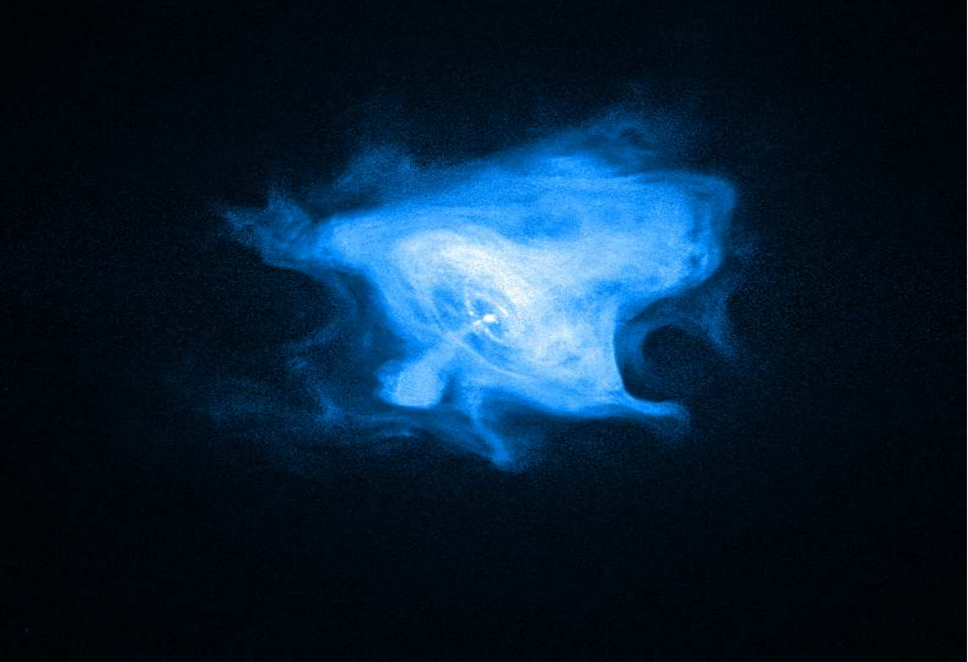
⇒ discovery of new objects and new phenomena (X-ray binaries, X-ray pulsars, X-ray bursts, QPOs, soft X-ray transients, anomalous X-ray pulsars, etc.)

X-ray observations of the Crab pulsar

X-ray observations can reveal new features that cannot be seen in optical range

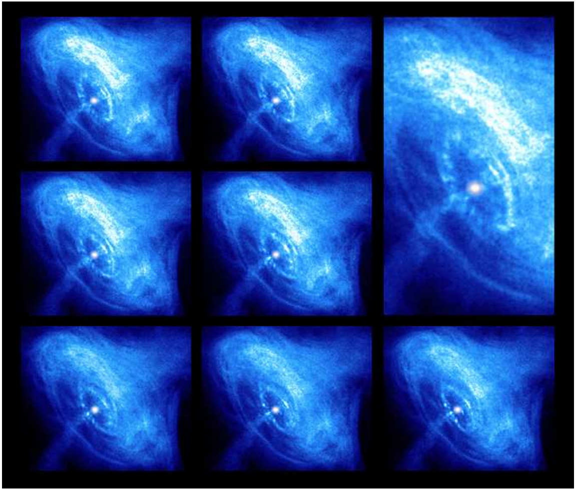


Crab pulsar wind nebula seen by Chandra



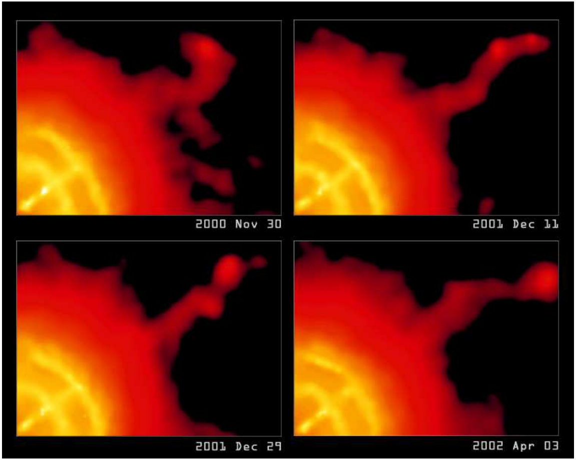
X-ray observations of the Crab pulsar

X-ray observations of the Crab pulsar by Chandra show jet like structures of high energy particles.



X-ray observations of the Vela pulsar

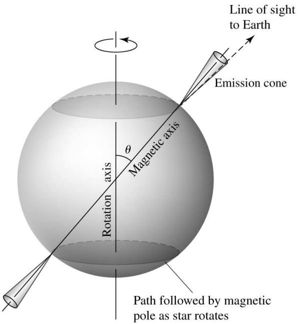
X-ray observations of the Vela pulsar by Chandra.



PSR B1509-58 seen by Chandra

Basic pulsar model

The standard model consists of a rotating neutron star with a **strong dipole magnetic field**



From Carroll and Ostlie

The loss of energy due to electromagnetic dipole radiation (in cgs units) is given by

$$\dot{E} \equiv \frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{8\pi^4 B^2 R^6 \sin^2\theta}{3c^3 P^4} \leq 0$$

B is the field strength at the magnetic pole, R is the radius of the star and P its spin period.

Pulsar magnetic field and characteristic age

As the neutron star spins down, it loses kinetic energy at a rate given by $\dot{E}_{\rm kin} = I\Omega\dot{\Omega}$. Assuming that this is entirely due to magnetic dipole radiation, we can infer the magnetic field strength

$$P\dot{P} = \frac{8\pi^2 B^2 R^6 \sin^2\theta}{3c^3 I} \Rightarrow B = \frac{\sqrt{6c^3 I P\dot{P}}}{2\pi R^3 \sin\theta}$$

If the initial period at birth is infinitively short and that B and I remain constant, we can further obtain the **characteristic age** τ of the pulsar

$$\int_0^P P\mathrm{d}P = P\dot{P}\int_0^\tau \mathrm{d}t \Rightarrow \tau = \frac{P}{2\dot{P}}$$

Pulsar ages

For the Crab pulsar, $P = 0.0331$ s and $\dot{P} = 4.23 \times 10^{-13}$, we find $\tau \simeq 1.2 \times 10^3$ years. This is in reasonable agreement with the known age of the supernova (1054 AD).

The validity of the rotating magnetic dipole model can be better tested by measuring higher order time derivatives of the pulsar angular frequency Ω.

Braking index

$$n \equiv -\frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$

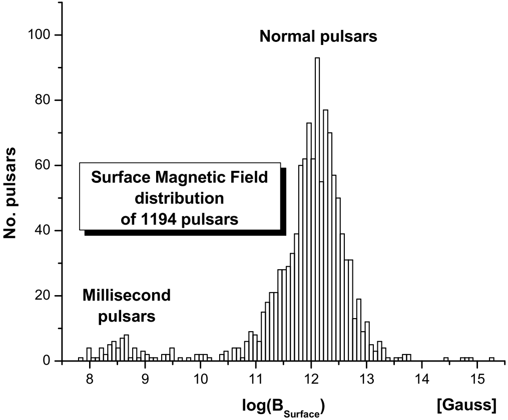
The dipole model predicts $n = 3$.

PSR B1509−58	2.84
Crab	2.5
Vela	1.4

The spin-down can be caused by other mechanisms (e.g. pulsar wind, gravitational wave emission, etc.)

Pulsar magnetic fields

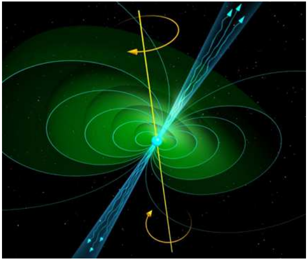
Most pulsars have a surface magnetic field of order $B \sim 10^{12}$ G.



Seiradakis and Wielebinski, Astron.Astrophys.Rev.12(2004), 239.

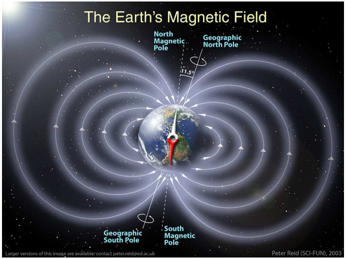
Comparison with other magnetic systems

Pulsars $B \sim 10^{12}$ G



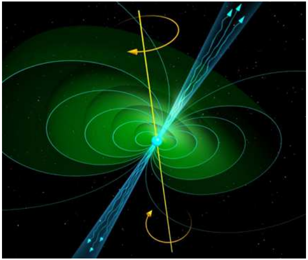
VS

Earth $B \simeq 0.3 - 0.6$ G



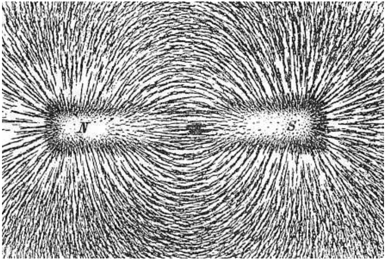
Comparison with other magnetic systems

Pulsars $B \sim 10^{12}$ G



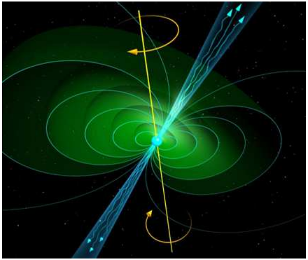
VS

magnet $B \sim 10^3 - 10^4$ G



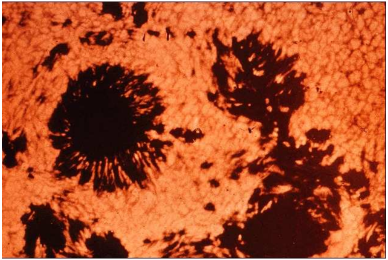
Comparison with other magnetic systems

Pulsars $B \sim 10^{12}$ G



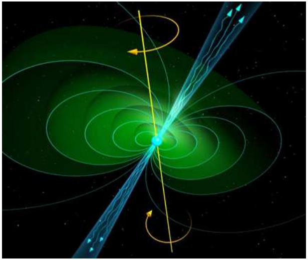
VS

Sun spot $B \sim 10^5$ G



Comparison with other magnetic systems

Pulsars $B \sim 10^{12}$ G



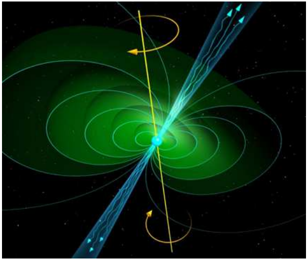
VS

lab $B \simeq 4.5 \times 10^5$ G

strongest continuous field (Florida State University, USA)

Comparison with other magnetic systems

Pulsars $B \sim 10^{12}$ G



VS

lab $B \simeq 2.8 \times 10^7$ G

strongest pulsed field
(VNIIEF, Sarov, Russia)

Why is the magnetic field so high?

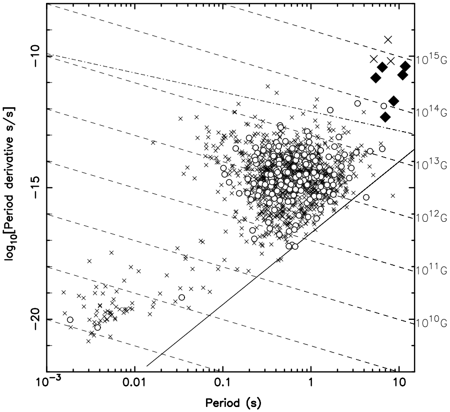
If we assume that the **magnetic flux** $\Phi = B 4\pi R^2$ is conserved during the gravitational collapse of the degenerate iron core eventually leading to a proto-neutron star, we have

$$\Phi_i = \Phi_f \Rightarrow B_f = B_i \left(\frac{R_i}{R_f}\right)^2$$

White dwarfs with magnetic fields as high as 10^9 G have been found. Taking $B_i \sim 10^9$ G and $R_i/R_f \sim 10^3$, we find $B_f \sim 10^{14}$ G. Neutron stars are born with huge magnetic fields!

Neutron star magnetic fields

Most pulsars have a surface magnetic field of order $B \sim 10^{12}$ G.

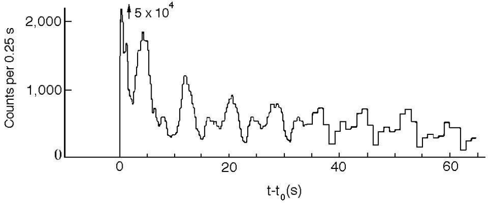


A few neutron stars have a much stronger magnetic field of order $B \sim 10^{14} - 10^{15}$ G (the internal field could be even higher!). These stars belong to a different class of neutron stars called **magnetars**.

Hobbs et al, MNRAS 333 (2004), L7.

The March 5, 1979 event

The theory of magnetars was proposed in 1992 by Robert Duncan, Christopher Thompson and Bohdan Paczynski to explain Soft Gamma Repeaters (SGR). SGRs are repeated sources of X and γ ray bursts. The first such object called SGR 0525$-$66 was discovered in 1979.

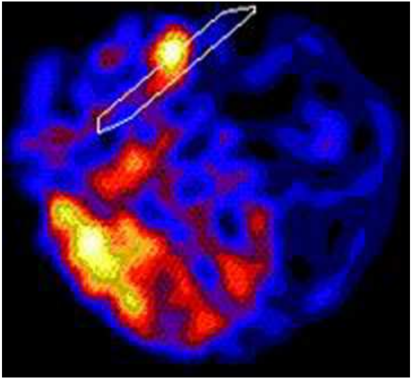


A very intense gamma-ray burst was detected on March 5, 1979 by two Soviet satellites Venera 11 and Venera 12.

The burst lasted about 3 minutes and showed a periodic modulation of 8s.

Mazets et al., Nature 282 (1979), 587.

The March 5, 1979 event



ROSAT

The source was later found to lie inside a supernova remnant in the Large Magellanic Cloud (N49) thus suggesting that it might be a young isolated neutron star.But it was difficult at that time to explain the origin of the bursts.

Other burst sources have been found. 8 SGRs (4 confirmed, 4 candidates) are currently known.

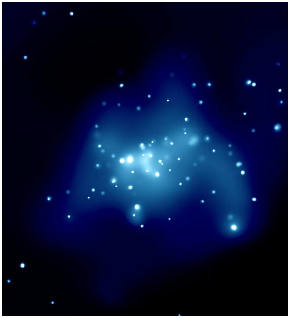
`http://www.physics.mcgill.ca/~pulsar/magnetar/main.html`

Anomalous X-ray pulsars

Anomalous X-ray pulsars (AXP) are isolated sources of pulsed X-rays which have much in common with SGRs.

Their periods range from 2 to 12s and their spin-down rate $\dot{P} \sim 10^{-11}$. They have characteristic magnetic fields $B \sim 10^{14}$ G. Some of them are bursters.

SGRs and AXP are thought to belong to the same class of neutron stars: magnetars.

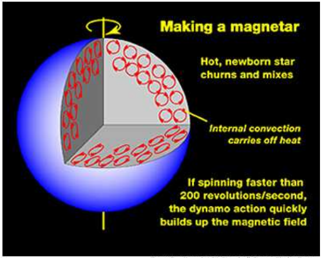


CXO J164710.2-455216 (Chandra)

10 AXPs (9 confirmed, 1 candidate) are currently known.

`http://www.physics.mcgill.ca/~pulsar/magnetar/main.html`

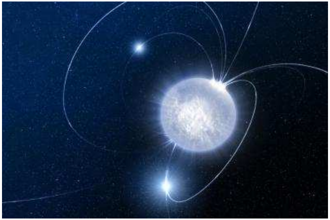
Theory of magnetars



Dave Dooling, NASA Marshall Space Flight Center

The interior of a neutron star is an almost perfect electrical conductor. Duncan and Thompson showed that strong magnetic fields $\sim 10^{16}$ G can be generated via **dynamo effects** in hot newly-born neutron stars.

Huge amount of magnetic energy can be occasionally released thus producing γ-ray bursts.

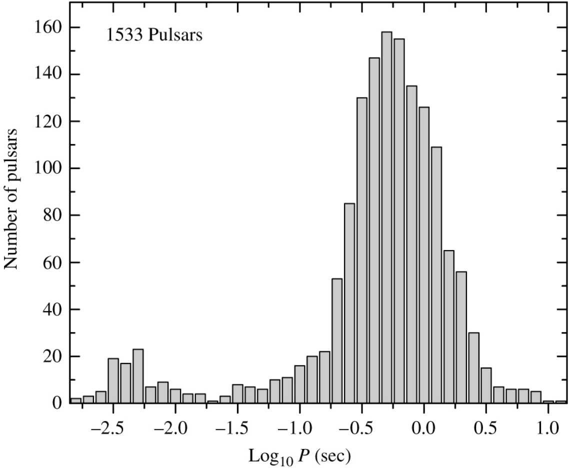


Robert Duncan webpage:

`http://solomon.as.utexas.edu/~duncan/magnetar.html`

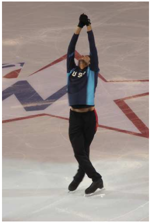
Pulsar spin periods

The distribution of pulsar spin-periods shows two peaks corresponding to two different classes of pulsars.



Why are pulsars spinning so fast?

If we assume that the angular momentum $J = I\Omega$ and the mass is conserved during the gravitational collapse of the degenerate iron core, the situation is similar to a spinning ice skater.



Taking the initial stellar core (i) and the final neutron star (f) as spheres with a moment of inertia $I = (2/5)MR^2$, we have

$$J_i = J_f \Rightarrow P_f = P_i \left(\frac{R_f}{R_i}\right)^2$$

Taking $P_i \sim 10^3$ seconds and $R_f/R_i \sim 10^{-2}$, this leads to $P_f \sim 10^{-3}$ seconds. Newly-born neutron stars are spinning very fast!

Discovery of millisecond pulsars

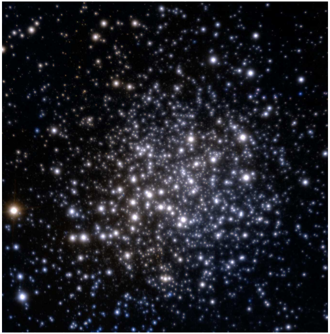
The first millisecond pulsar was found in 1982 at Arecibo by Backer's team. Today $\sim$ 200 millisecond pulsars are known. The fastest one PSR J1748$-$2446ad discovered in 2005, has a period of only 1.396 ms!

Millisecond pulsars are characterised by

$1.4 \leq P \leq 30$ ms

$\dot{P} \leq 10^{-19}$

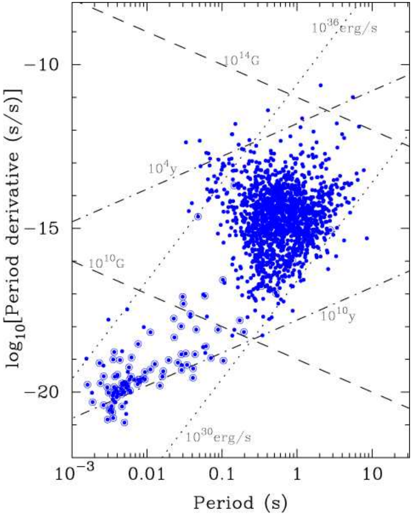
Most of them belong to a binary system and are found in globular clusters.



Globular cluster Terzan 5 (ESO)

Millisecond pulsars in the $P - \dot{P}$ diagram

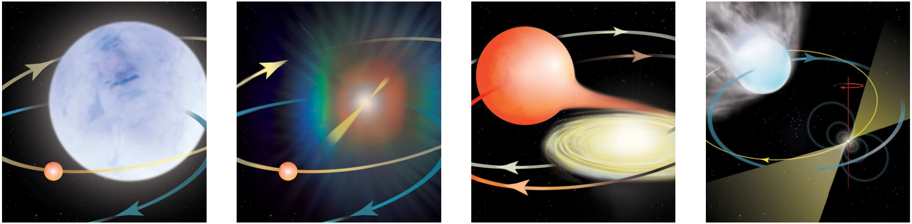
In the standard scenario of neutron star formation from supernova explosions, the fastest pulsars are the youngest



Millisecond pulsars (open circles) are **very old neutron stars** and have a lower magnetic field than ordinary pulsars. The fastest ones are not associated with any supernova remnant.

Formation of millisecond pulsars

1. A supergiant star and a Sun-like star orbit each other in a binary system.
2. The massive star explodes in a supernova, leaving behind a neutron star.
3. After billions of years, the lower-mass star evolves into a red giant, and transfers mass and angular momentum to the neutron star.
4. Once accretion ends, the neutron star is spinning very rapidly and emerges as a millisecond radio pulsar.



From Bill Saxton, NRAO

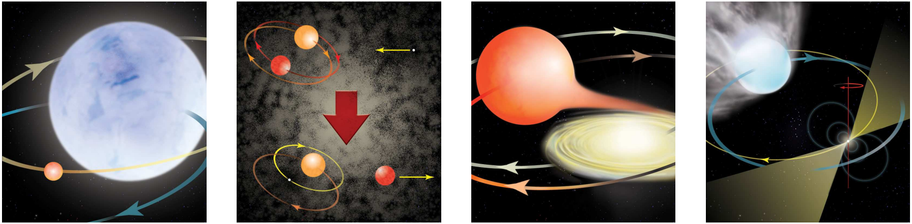
Formation of millisecond pulsars in globular clusters

1. A supergiant star and a Sun-like star orbit each other in a binary system.

2. The lowest mass star is ejected from the binary and is replaced by an ancient neutron star

3. After billions of years, the lower-mass star evolves into a red giant, and transfers mass and angular momentum to the neutron star.

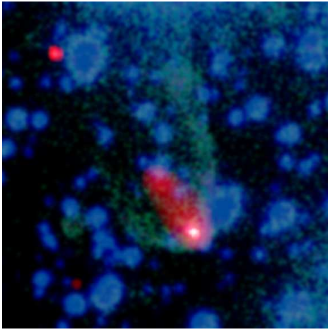
4. Once accretion ends, the neutron star is spinning very rapidly and emerges as a millisecond radio pulsar.



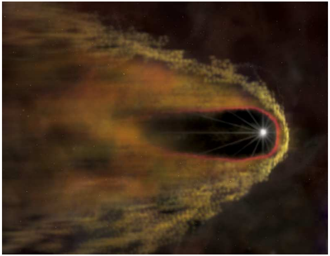
From Bill Saxton, NRAO

Black widow pulsars

A fraction of millisecond pulsars are not in a binary system.



Black widow pulsar (Chandra)



artistic view (M.Weiss)

The intense relativistic wind of some recycled pulsar may have actually destroyed their companion star, as observed in PSR B1957+20.

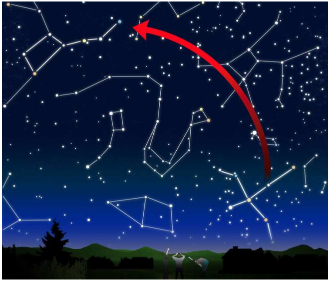
Pulsars and supernova remnants

A very small number of pulsars have been found in a supernova remnant (SNR).

- SNR could contain a neutron star which is not seen as a pulsar because the radiation beam does not intersect the line of sight (CCO).
- Pulsars can live much longer than the SNR where they are formed (pulsar lifetime $\sim 10^8$ yr or more, SNR lifetime $\sim 10^5$ yr).
- Somes pulsars have been observed to move with a very high velocity (up to $\sim$ 1500 km/s in Puppis A).

Pulsar kick

Pulsar kicks are thought to arise from asymmetries during supernova explosions. PSR B1508+55 is one of the fastest pulsars. Radio telescope observations (VLBA) show that it is moving at a speed of $\sim$ 1100 km/s.



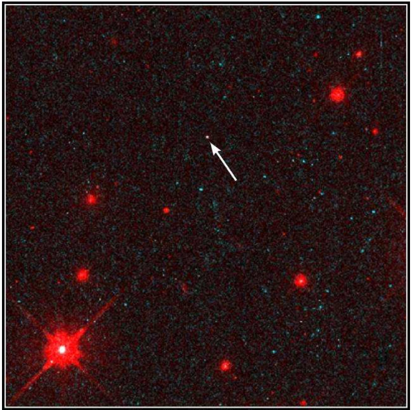
from Bill Saxton

PSR B1508+55 is probably born 2.5 million years ago in the constellation Cygnus. During this time it has moved across about a third of the night sky as seen from Earth.

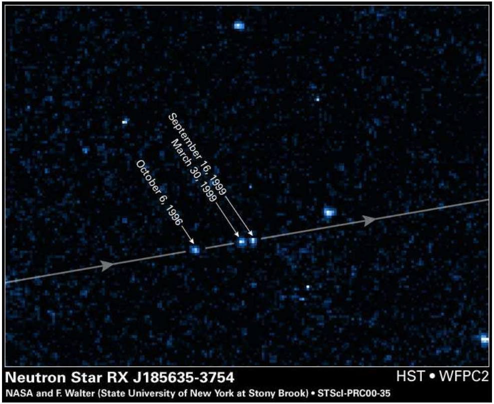
Chatterjee et al.,ApJ630(2005),L61.

An isolated neutron star seen by Hubble

The motion of neutron stars can also be followed in visible light, like for instance RX J185635−3754.

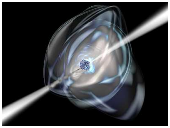

Isolated Neutron Star RX J185635-3754 HST • WFPC2
PRC97-32 • ST ScI OPO • September 25, 1997
F. Walter (State University of New York at Stony Brook) and NASA

An isolated neutron star seen by Hubble

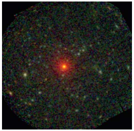


By monitoring this neutron star over several years, it has been found that the star is moving at a speed of $\sim$ 100 km/s.

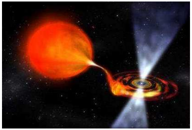
The many faces of neutron stars



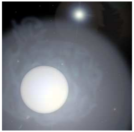
Anomalous X-ray Pulsars



dim isolated neutron stars



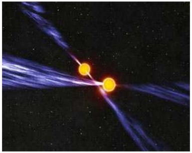
X-ray binaries



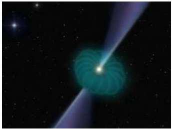
bursting pulsars

Soft Gamma Repeaters

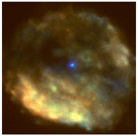
pulsars



binary pulsars



Rotating Radio Transients



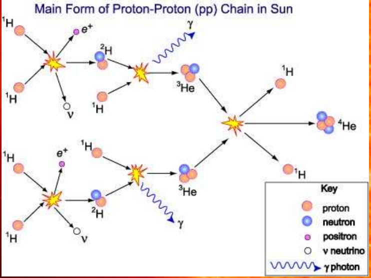
Compact Central Objects

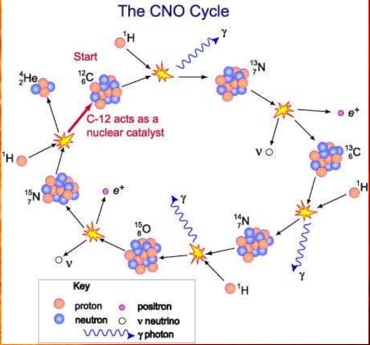
planets around pulsar

Formation of neutron stars

Stellar evolution

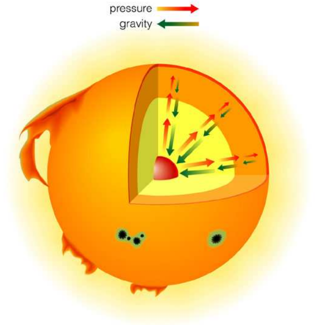
Ordinary stars are powered by **thermonuclear reactions**. During most of their lives, stars fuse hydrogen into helium in their cores via the pp chain or the CNO cycle.

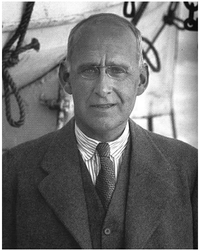




Stellar hydrostatic equilibrium

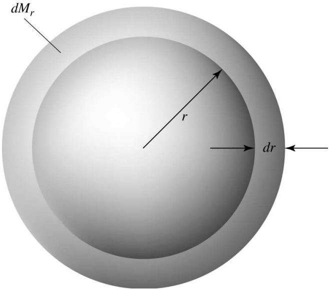
The gravitational pull is counterbalanced by the thermal gas pressure and for the most massive stars by the radiation pressure.





Sir Arthur Eddington
(1882-1944)

Hydrostatic equilibrium equations



$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm(r)\rho(r)}{r^2}$$

$$m(r) = 4\pi \int_0^r \xi^2 \rho(\xi) \mathrm{d}\xi$$

Boundary conditions:
$P(0) = P_0$, $m(0) = 0$
$P(R) = 0$, $m(R) = M$.

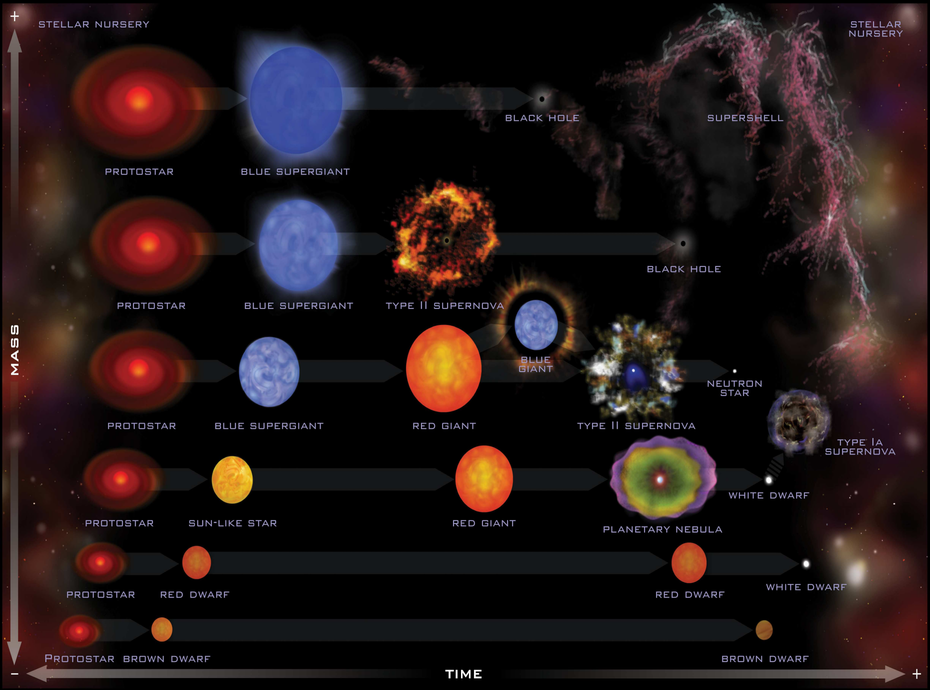
In ordinary stars the pressure is provided by

the thermal gas pressure

$$P = \rho k_\mathrm{B} T$$

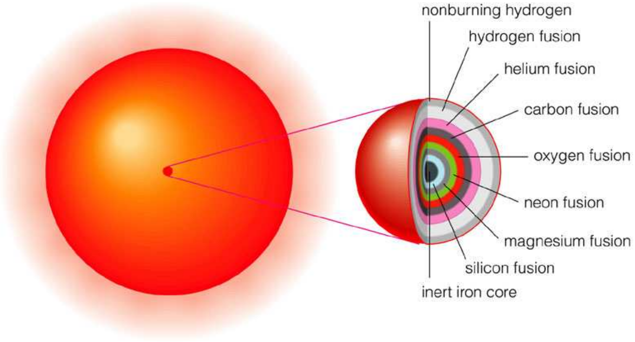
the radiation pressure

$$P = \frac{4}{3}\frac{\sigma T^4}{c}$$


STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
MASS
TIME
+
−
+
−

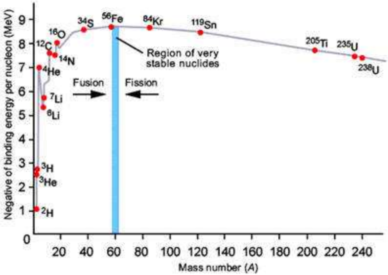
Stellar nucleosynthesis

In stars with a mass $M \gtrsim 8 - 10 M_{\odot}$, fusion reactions proceed beyond hydrogen burning and yield heavier and heavier elements (C, N, O... up to Si and Fe) leading to an onion-like structure



End of stellar nucleosynthesis

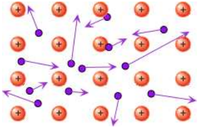
The stellar nucleosynthesis stops when nuclei in the iron region are produced because they are the most stable elements



The iron core becomes inert and can no longer sustain the gravitational pressure

$\Rightarrow$ the iron core collapses, crushing matter to higher and higher densities.

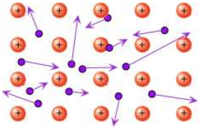
Degenerate matter



When the density reaches $\sim 10^4$ g/cm^3 the atoms become fully ionized and the free electrons form a degenerate Fermi gas.

However electrons are fermions and due to the Pauli exclusion principle (1925), they cannot occupy the same quantum state.

Degenerate matter



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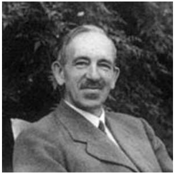
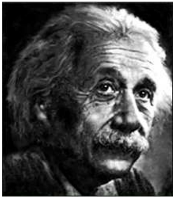


$\Rightarrow$ this leads to an **electron degeneracy pressure** $P_e(\rho)$ which resists the gravitational collapse

R.H. Fowler (1926)

Relativistic softening of dense matter

Quantum degeneracy means that electrons have a finite velocity even at $T = 0$.



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Relativistic softening of dense matter

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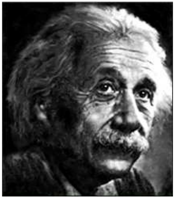

When $\rho \gtrsim 10^6$ g/cm^3, electrons become relativistic and **special relativity** tells us that the electron velocity cannot exceed the speed of light.

$\Rightarrow$ Electrons cannot sustain an arbitrarily high mass

Maximum mass of supernova cores

Assuming the core is made of ultra-relativistic electrons, the total energy $E_{\rm kin} + E_{\rm pot}$ with

$$E_{\rm kin} \sim AY_e\varepsilon_F \sim \hbar c(AY_e)^{4/3}/R, \qquad E_{\rm pot} \sim -GA^2m_p^2/R$$

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Chandrasekhar mass limit

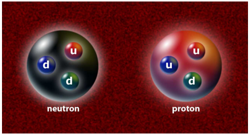
$$\Rightarrow M_{\rm Chand} \sim \left(\frac{\hbar c}{G}\right)^{3/2}\left(\frac{Y_e}{m_p}\right)^2$$

For iron core, $M_{\rm Chand} \simeq 1.44 M_\odot$


Scanned at the American Institute of Physics

Neutronization of matter

The neutron mass is slightly higher than the proton one $\Rightarrow$ the neutron in vacuum is unstable.



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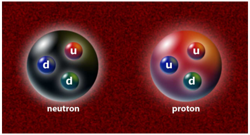


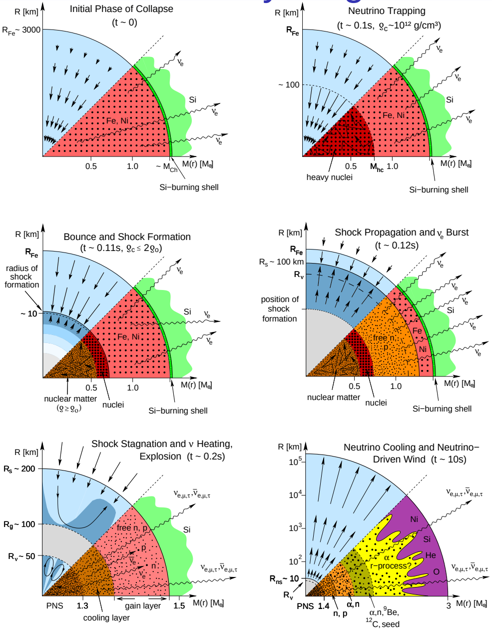
However in dense matter, neutrons become stable when the electron chemical potential exceeds the neutron-proton mass energy difference

$$\mu_e \sim \hbar c k_e > (m_n - m_p)c^2 \simeq 1.29 \text{ MeV}$$

Since $k_e = (3\pi^2 n_e)^{1/3}$, this occurs at densities

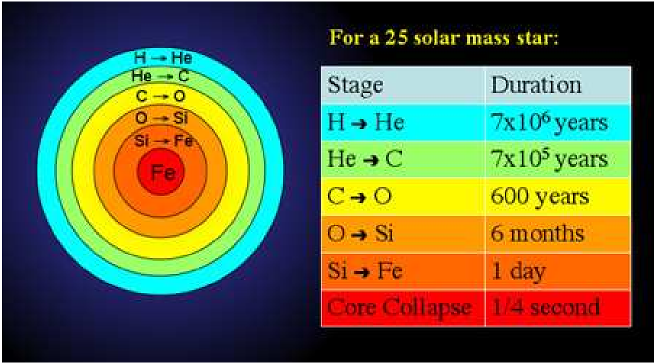
$$\rho \gtrsim \frac{A}{Z}\frac{m_p}{3\pi^2}\left(\frac{\Delta m c^2}{\hbar c}\right)^3 \sim 10^7 \text{ g/cm}^3$$

Evolutionary stages of stellar core collapse



Janka et al., Phys.Rep.442(2007),38.

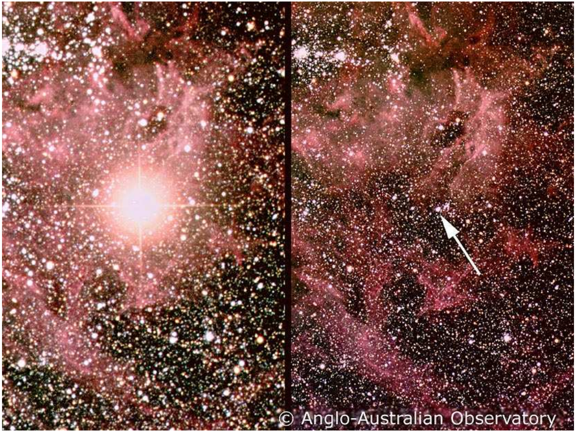
Time scales of stellar evolution



Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

SN1987A

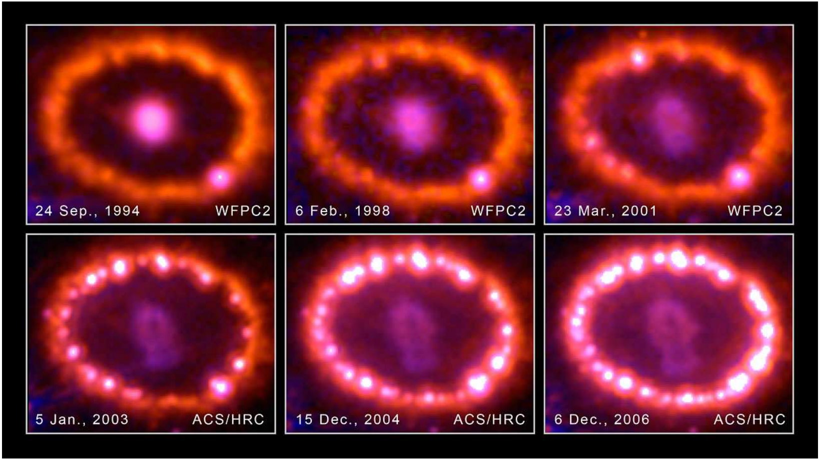
Supernova explosion observed in February 1987 in the large Magellanic cloud



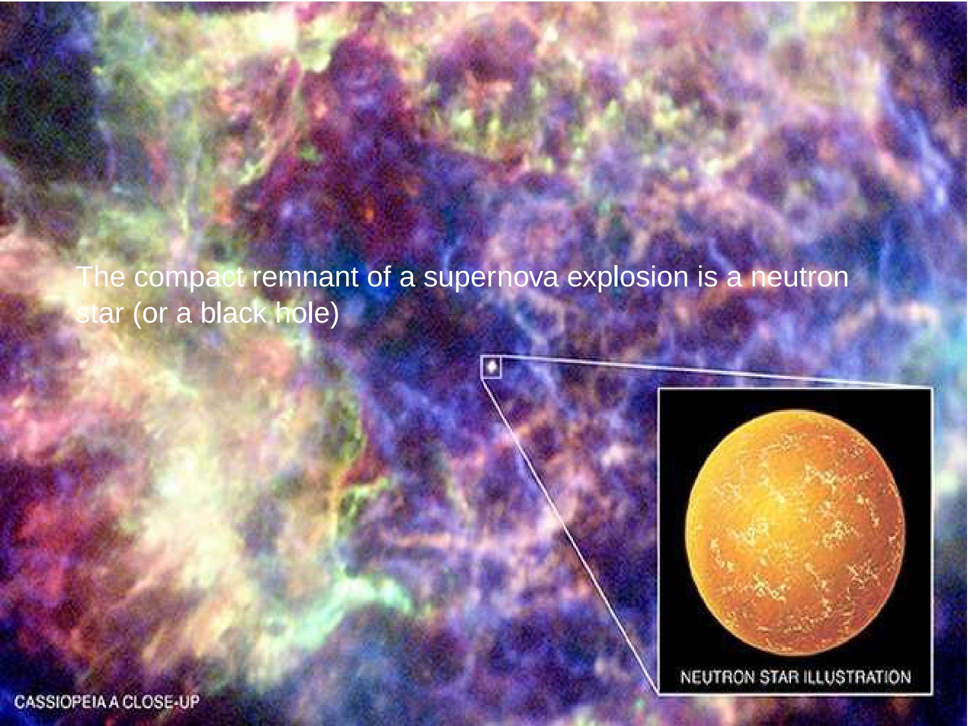
Right panel: before the explosion, Left panel: 10 days after

SN1987A

A time sequence of Hubble images showing the collision of the expanding supernova remnant with a ring of dense material ejected by the progenitor star 20000 years before the supernova.



The compact remnant of a supernova explosion is a neutron star (or a black hole)



Compactness criterion

The compactness of an object of mass M and radius R can be estimated from the dimensionless parameter

$$\Xi \equiv \frac{2GM}{Rc^2}$$

PSR J1846-0258 (Chandra)

Earth	10^{-10}
Sun	10^{-6}
White dwarf	$10^{-4} - 10^{-3}$
Neutron star	$\sim \mathbf{0.2 - 0.4}$
stellar black hole	1

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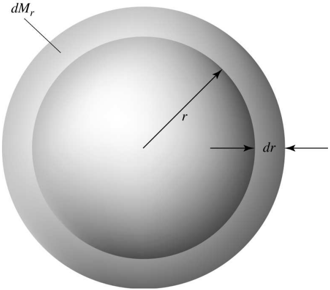
$\Rightarrow$ Neutron stars have to be described using Einstein's theory of General Relativity

Non-relativistic stars

Hydrostatic equilibrium equations in Newtonian theory:

$$\begin{aligned}\frac{\mathrm{d}P}{\mathrm{d}r} &= -\frac{GM(r)\rho(r)}{r^2}\\ M(r) &= 4\pi\int_0^r \xi^2\rho(\xi)\mathrm{d}\xi\\ \rho(r) &= n_\mathrm{b}(r)m_\mathrm{b}\end{aligned}$$



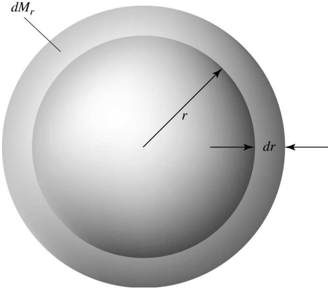
Boundary conditions:
$P(0) = P_0$, $M(0) = 0$
$P(R) = 0$, $M(R) = M_\mathrm{b} = Am_\mathrm{b}$.

M_b is called the **baryon mass**.

Relativistic stars

Hydrostatic equilibrium equations in General Relativity:

$$
\begin{aligned}
\frac{dP}{dr} &= -\frac{G\rho M(r)}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{c^2 r}\right)^{-1} \\
M(r) &= 4\pi\int_0^r \xi^2\rho(\xi)\mathrm{d}\xi \\
\rho(r) &= \varepsilon(r)/c^2
\end{aligned}
$$



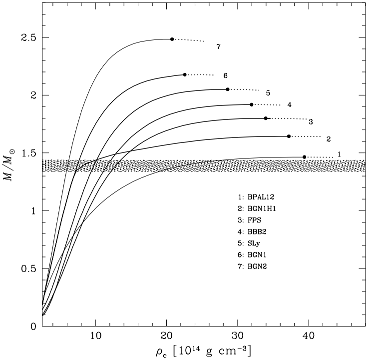
Boundary conditions:
$P(0)=P_0$, $M(0)=0$
$P(R)=0$, $M(R)=M<Am_{\mathrm{b}}$

M is called the **gravitational mass**.

Maximum mass of neutron stars

For a given equation of state (EoS) $P(\rho)$ there exists a maximum mass, which arises from both Special Relativity and General Relativity.

From Haensel



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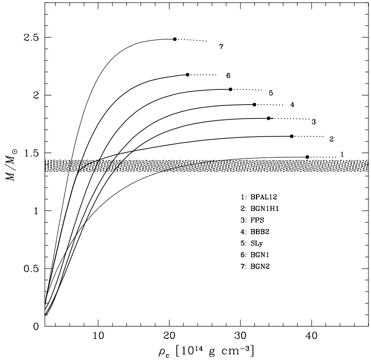

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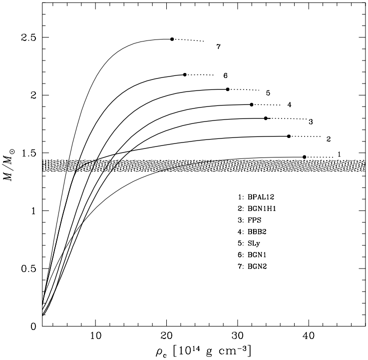
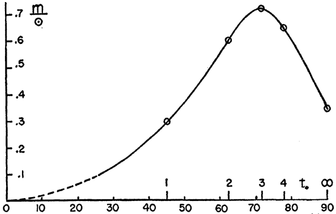


- Special Relativity softens the EoS: at high ρ, $P(\rho) \propto \rho^{4/3}$ instead of $\rho^{5/3}$.
- General Relativity increases the gravitational pull

Maximum mass of neutron stars

in 1939, Oppenheimer and Volkoff found $M_{\mathrm{max}} \simeq 0.7 M_{\odot}$ by considering a **non-interacting** gas of degenerate neutrons.



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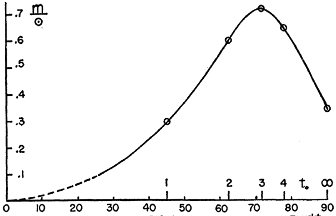

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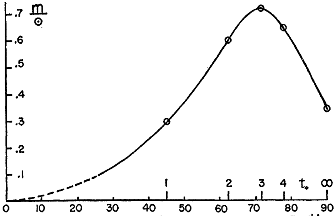

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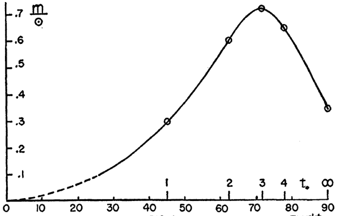

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- nucleon-nucleon interactions are very strong!

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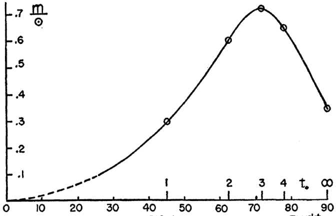

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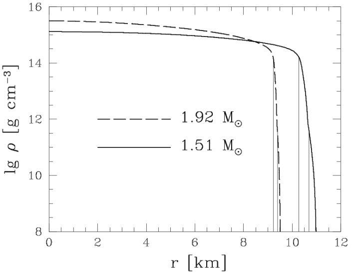
But in 1959, Cameron considered a more realistic equation of state and found $M_{\mathrm{max}} \simeq 2 M_{\odot} > M_{\mathrm{Chand}}$

- nucleon-nucleon interactions are very strong!
- neutron stars can be formed as proposed by Baade and Zwicky

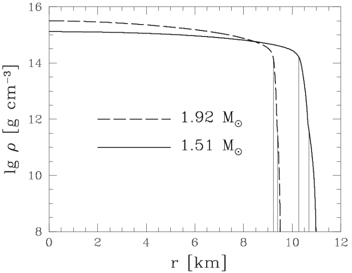
Incompressible star



For realistic EoS, the density varies very little in the stellar interior except for the crustal layers.

From Haensel

Incompressible star



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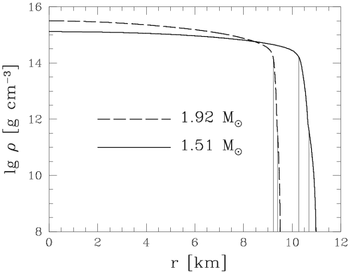

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Let us consider a fluid star with a constant density $\rho_{\rm inc}$. In this (unphysical) case, Einstein's equations can be solved analytically (Schwartzschild, 1916). The maximum mass is

$$M_{\rm max}^{\rm inc} \simeq 5.09 M_\odot \left(\frac{5 \times 10^{14}\ {\rm gcm}^{-3}}{\rho_{\rm inc}} \right)^{1/2}$$

Note that for an incompressible Newtonian star, the mass can be arbitrarily high.

Upper bound on the maximum mass

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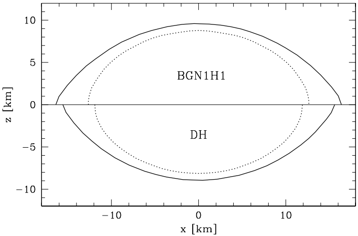
$$\frac{\mathrm{d}P}{\mathrm{d}\rho} > 0.$$

If the EoS is known up to ρ_{u}, this implies

$$M_{\mathrm{max}}^{\mathrm{CL}} \simeq 3.0 M_{\odot} \left(\frac{5 \times 10^{14}\,\mathrm{g cm^{-3}}}{\rho_{\mathrm{u}}} \right)^{1/2}$$

Maximum mass and rotation

In GR, all forms of energy contribute to the gravitational mass.



In particular, this implies that **rotating stars have larger masses than static stars** due to centrifugal energy.

Haensel et al, New Astr. Rev. 51 (2008),785.

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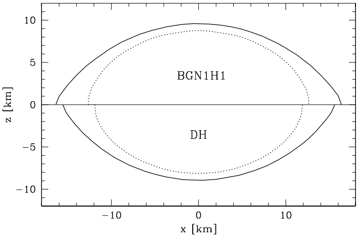

Haensel et al, New Astr. Rev. 51 (2008),785.

In particular, this implies that **rotating stars have larger masses than static stars** due to centrifugal energy.

The maximum possible mass is thus increased

$$M_{\max}^{\mathrm{CL,rot}} = 3.89 M_{\odot} \left(\frac{5 \times 10^{14}\,\mathrm{g cm^{-3}}}{\rho_{\mathrm{u}}} \right)^{1/2}$$

Constraints on the mass and radius

The radius of a neutron star with a given mass M cannot be arbitrarily small.

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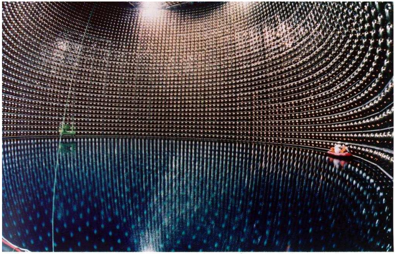
- Causality constraint (sound speed is smaller than the speed of light):

$$R > 2.9\frac{GM}{c^2}$$

Observational constraints

Neutrino outburst from SN1987A

Before visible observation of the supernova explosion SN1987A, $\sim$ 20 electron antineutrinos were detected within $\sim$ 10 seconds by neutrino detectors on Earth.



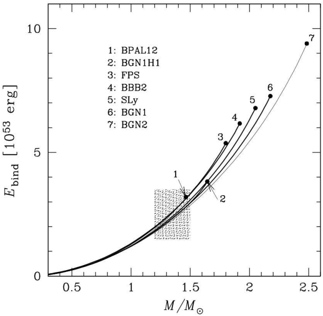
Neutrino events from SN1987A

Kamiokande II	11
IMB	8
Baksan	5 (?)

The total energy of the neutrino outburst was estimated as $E_\nu \simeq 3 \times 10^{53}$ erg.

Binding energy of neutron stars and SN1987A

The theory of type II supernovae predicts that 99% of the energy released during a type II supernova explosion is in the form of neutrinos and antineutrinos.



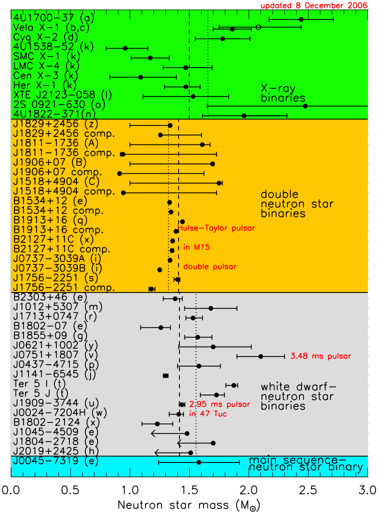
Haensel, Potekhin, Yakovlev (2007).

The total energy release $\simeq E_\nu$ corresponds to the difference between the energy of the collapsing core and that of the newly-born neutron star

$$E_{\rm bind} = (A_{\rm b} m_{\rm b} - M)c^2$$

All EoS agree with observations of SN1987A thus confirming gravitational collapse scenario.

Neutron star mass measurements

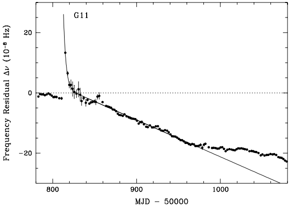


Lattimer and Prakash, Phys. Rep. 442(2007),109.

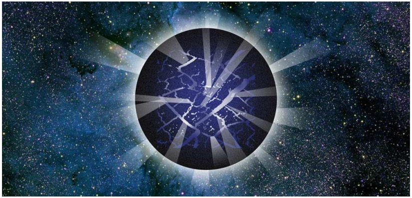
Pulsar glitches

Sometimes P may suddenly decrease. The variations are tiny but observable.

$$\frac{\Delta\Omega}{\Omega} \sim 10^{-9} - 10^{-5}$$



Example of a glitch in the Crab pulsar



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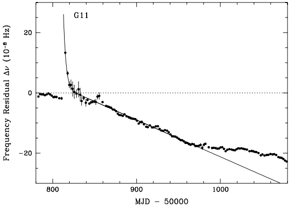

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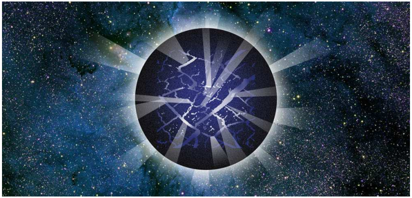

$\Rightarrow$ **Small pulsar glitches** are interpreted as **starquakes** thus providing a direct proof for the existence of a solid **crust**

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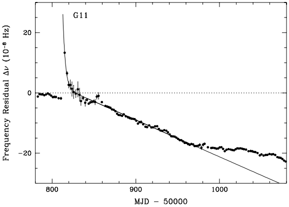
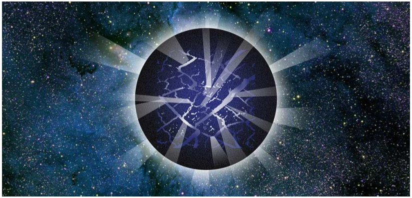


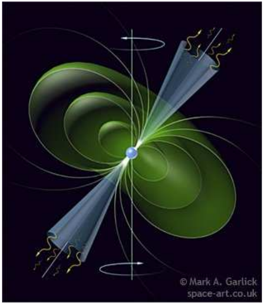
Example of a glitch in the Crab pulsar



⇒ **Small pulsar glitches** are interpreted as **starquakes** thus providing a direct proof for the existence of a solid **crust**

⇒ **Large glitches** and the observed **long relaxation times** bring strong evidence of **superfluidity** inside neutron stars

Pulsar dynamics



Unlike superfluid neutrons, electrically charged particles are essentially locked together by the interior magnetic field on very long timescales of the order of the age of the star
Easson, ApJ 233(1979), 711.

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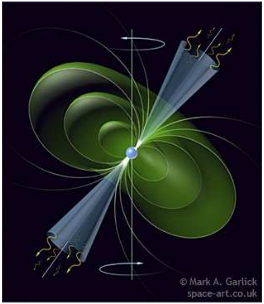


Unlike superfluid neutrons, electrically charged particles are essentially locked together by the interior magnetic field on very long timescales of the order of the age of the star
Easson, ApJ 233(1979), 711.

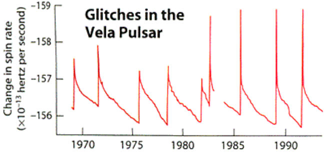
$\Rightarrow$ Pulsar interiors contain (at least) **two distinct fluids**:

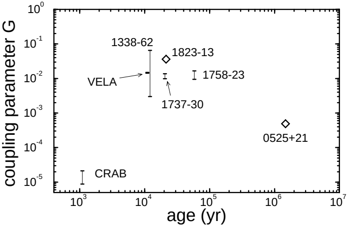
- a plasma of charged particles (nuclei in the crust, protons, leptons)
- a neutron superfluid

Baym et al, Nature 224 (1969), 673.

Glitch constraints

Large glitches like in Vela are thought to be caused by a transfer of angular momentum between the neutron superfluid and the charged particles.





$$\frac{I^{\mathrm{s}}}{I} \geq \mathcal{G}$$

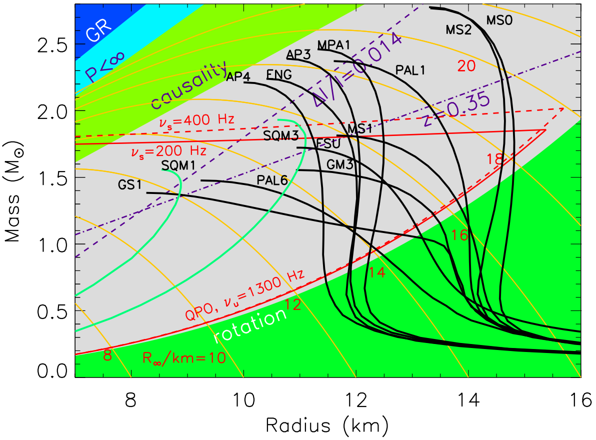
$$\mathcal{G} = \frac{\Omega}{|\dot{\Omega}_{\mathrm{av}}|}\frac{1}{\tau}\sum_i \frac{\Delta\Omega_i}{\Omega}$$

For the Vela pulsar, $R \geq 3.6 + 3.9\frac{M}{M_\odot}\ \mathrm{km}$

Link, PRL83 (1999), 3362

Carter and Chamel, MNRAS 368(2006), 796

Constraint in the mass-radius diagram



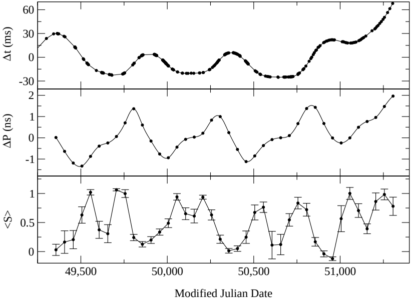
Lattimer and Prakash, Phys. Rep. 442(2007),109.

Neutron star precession

Long-term cyclical variations of order months to years have been reported in a few neutron stars: Her X-1 (accreting neutron star), the Crab pulsar, PSR 1828−11, PSR B1642−03, PSR B0959−54 and RX J0720.4−3125.

Example: Time of arrival residuals, period residuals, and shape parameter for PSR 1828−11

Stairs et al., Nature 406(2000),484.



These variations have been interpreted as the signature of **neutron star precession**.

Precession and superfluidity

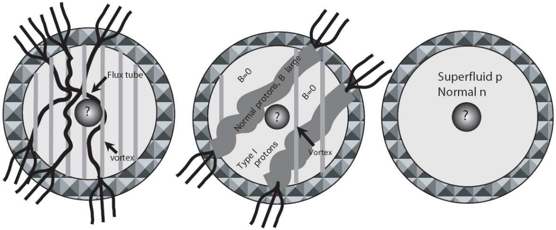
Observations of long-period precession put contraints on the superfluid properties of neutron star interiors.

For a non-superfluid star with deformation $\epsilon = \Delta I / I$,

$$P_{\text{prec}} = \frac{P}{\epsilon} \gg P$$

For a superfluid star with pinned vortices

$$P_{\text{prec}} = \frac{I}{I_{\text{pin}}} P \ll P$$



Link, Astrophys. Space Sci.308(2007),435.

What is the maximum spin rate of neutron stars?

In Newtonian gravity, the **mass shedding limit** for a uniform rigid sphere of mass M and radius R is

$$P^N_{\rm min} = 2\pi\sqrt{\frac{R^3}{GM}} \simeq 0.55 \left(\frac{M_\odot}{M}\right)^{1/2} \left(\frac{R}{10\,\rm km}\right)^{3/2} \ \rm ms$$

In General Relativity with realistic EoS,

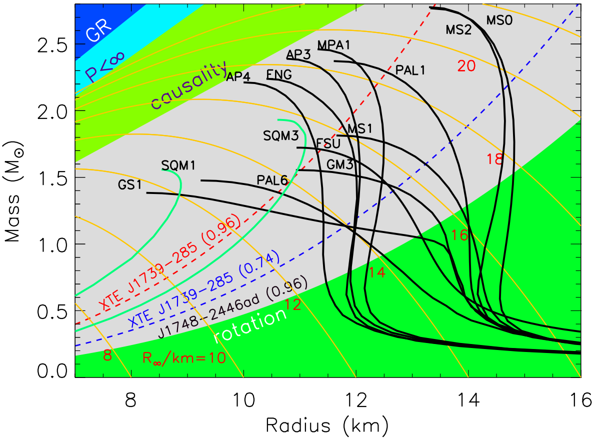
$$P_{\rm min} \simeq 0.96 \left(\frac{M_\odot}{M}\right)^{1/2} \left(\frac{R}{10\,\rm km}\right)^{3/2} \ \rm ms$$

$\Rightarrow$ constraint on the mass-radius since $P > P_{\rm min}$

What is the most rapidly rotating neutron star?

PSR J1748-2446ad $\Rightarrow$ $\mathbf{P = 1.39595482}$ **ms**
XTE J1739-285 $\Rightarrow$ $P < 1$ ms??

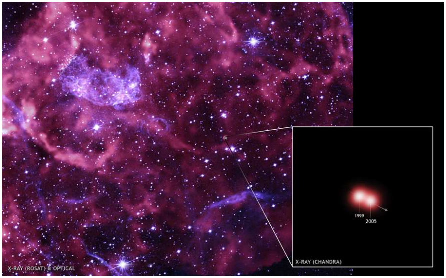
Constraint in the mass-radius diagram



Lattimer and Prakash, Phys. Rep. 442(2007),109.

Cooling of isolated neutron stars

During the first tens of seconds, the newly formed proto-neutron star with a radius of $\sim$ 50 km stays very hot with $T \sim 10^{11} - 10^{12}$ K. Within $\sim 10 - 20$ s the proto-neutron star becomes transparent to neutrinos and thus rapidly cools down by powerful neutrino emission shrinking into an ordinary neutron star.

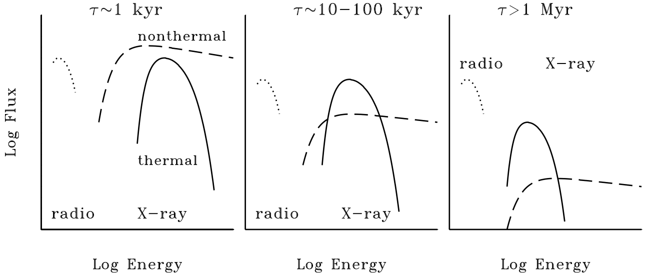


Puppis A (RX J0822-4300) from Chandra

After about $10^4 - 10^5$ years, the cooling is governed by the emission of thermal photons due to the diffusion of heat from the interior to the surface.

Thermal X-ray emission of neutron stars

The thermal X-ray emission of young neutron stars is usually hindered by the magnetospheric component. For old pulsars, the thermal radiation dominate but is too low to be detectable (except for hot polar caps).

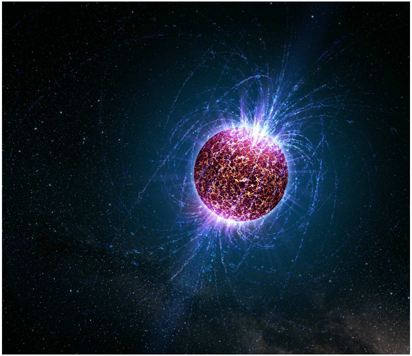


Picture from Zavlin

Thermal X-ray emission of neutron stars

The thermal X-ray emission of young neutron stars is usually hindered by the magnetospheric component. For old pulsars, the thermal radiation dominate but is too low to be detectable (except for hot polar caps).

A few isolated neutron stars with no magnetospheric activity have been found (Compact Central Objects, Dim Isolated Neutron Stars)
$\Rightarrow$ good targets!



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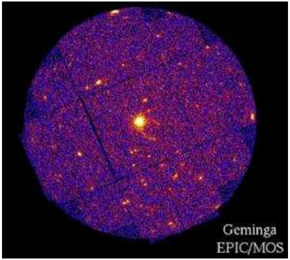
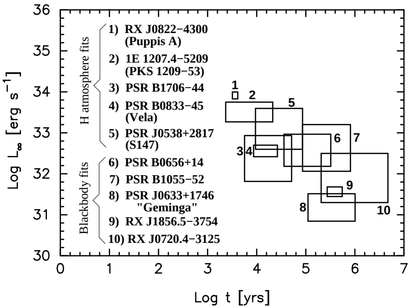




Page and Reddy, Ann.Rev.Nucl.Part.Sys. 56 (2006), 327.

`http://www.astroscu.unam.mx/neutrones/home.html`

Cooling of neutron stars

Theoretical cooling simulations yield the surface temperature vs age. The curve depends on neutron star mass, radius, composition, superfluidity, presence of magnetic field...

Cooling of neutron stars

Theoretical cooling simulations yield the surface temperature vs age. The curve depends on neutron star mass, radius, composition, superfluidity, presence of magnetic field...

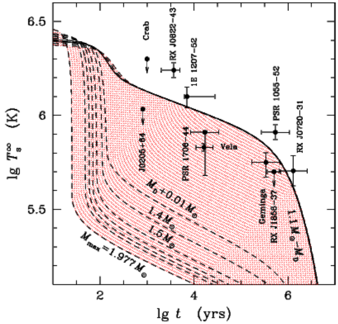
The *actual* surface temperature T_s is related to the *observed* surface temperature T_s^∞ by

$$T_s^\infty = T_s \sqrt{1 - \frac{2GM}{Rc^2}}$$

Cooling of neutron stars

Theoretical cooling simulations yield the surface temperature vs age. The curve depends on neutron star mass, radius, composition, superfluidity, presence of magnetic field...

no superfluidity

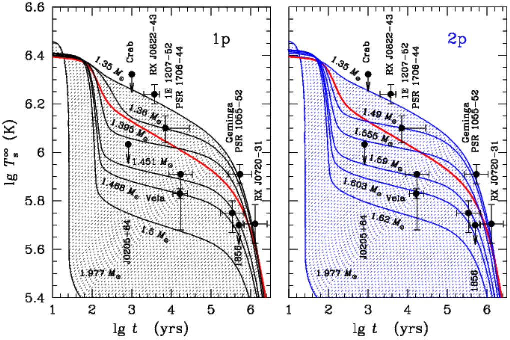


Yakovlev and Pethick, Ann.Rev.Astron.Astrophys 42 (2004), 169

Cooling of neutron stars

Theoretical cooling simulations yield the surface temperature vs age. The curve depends on neutron star mass, radius, composition, superfluidity, presence of magnetic field...

proton superfluidity

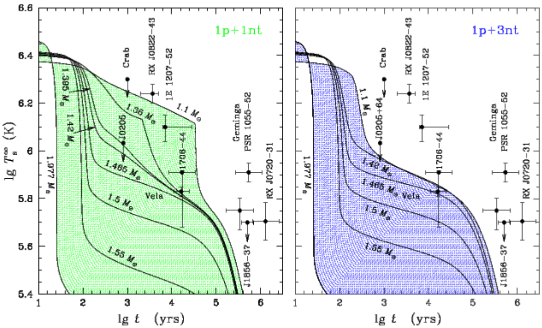


Yakovlev and Pethick, Ann.Rev.Astron.Astrophys 42 (2004), 169

Cooling of neutron stars

Theoretical cooling simulations yield the surface temperature vs age. The curve depends on neutron star mass, radius, composition, superfluidity, presence of magnetic field...

proton and neutron superfluidity in the core

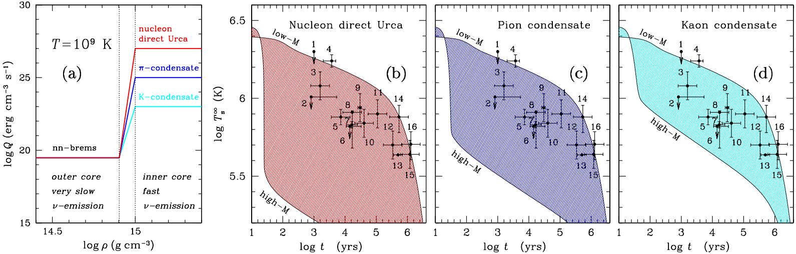


Yakovlev and Pethick, Ann.Rev.Astron.Astrophys 42 (2004), 169

Cooling of neutron stars

Theoretical cooling simulations yield the surface temperature vs age. The curve depends on neutron star mass, radius, composition, superfluidity, presence of magnetic field...

exotica



Yakovlev et al, proceedings (2007), arXiv:0710.2047

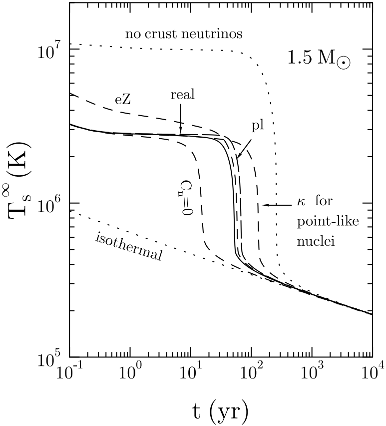
$\Rightarrow$ evidence for superfluidity in neutron stars but hard to conclude about exotic content

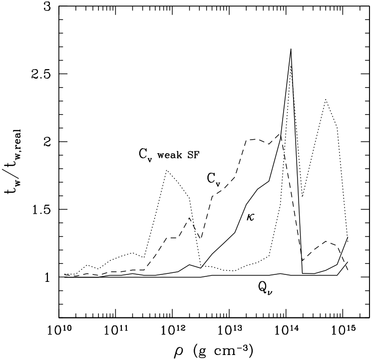
Neutron star formation and cooling

Due to its relatively low neutrino emissivity, the crust of a newly-born neutron star cools less rapidly than the core and thus stays hotter.

The time it takes for the star to become isothermal is very sensitive to the crust physics

Thermal relaxation of neutron star crusts





$$t_W \simeq (\Delta R)^2 \left[1 - \frac{2GM}{R}\right]^{-3/2} \frac{C_{\rm tot}}{\kappa}$$

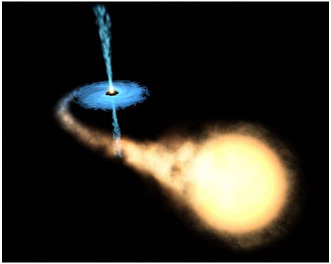
Gnedin et al., MNRAS 324 (2001), p725.

Fortin et al., arXiv:0910.5488

X-ray binaries

Neutron stars in X-ray binaries may be heated as a result of the accretion of matter from the companion star.

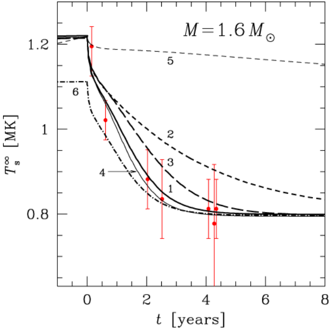
The accretion of matter onto the surface of the neutron star triggers thermonuclear fusion reactions which can become explosive, giving rise to X-ray bursts.



In **soft X-ray transients**, accretion outbursts are followed by **long period of quiescence** during which the accretion rate is much lower. In some cases, the period of accretion can last long enough for the crust to be heated out of equilibrium with the core.

Thermal relaxation of soft X-ray transients

The thermal relaxation during the quiescent state has been recently monitored for KS 1731−260 and for MXB 1659−29 after an accretion episode of 12.5 and 2.5 years respectively. This puts constraints on the properties of neutron star crusts.



Curve 2 : pure crystalline crust without neutron superfluidity
Curve 5 : amorphous crust with neutron superfluidity

Shternin et al., Mon. Not. R. Astron. Soc.382(2007), L43.
Brown and Cumming, ApJ698 (2009), 1020.

Neutron star atmospheres

The interpretation of the thermal X-ray spectrum requires modelling radiation transfer in the neutron star atmosphere.
http://www.ioffe.ru/astro/Stars/

- Atmosphere model fits yield estimate of the **radiation radius**

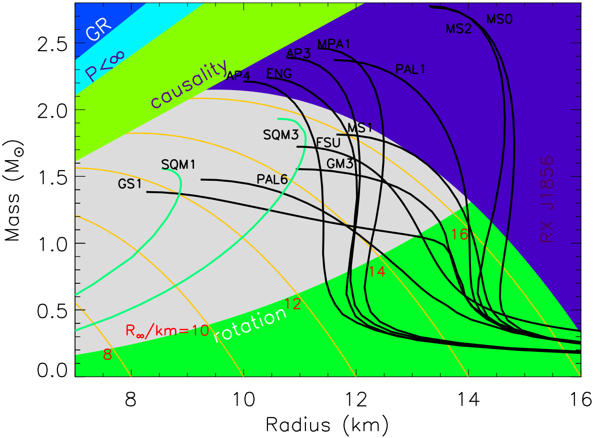
$$R_\infty = R\sqrt{1-\frac{2GM}{Rc^2}}^{-1}$$

- Identification of spectral lines provide the **gravitational redshift**

$$z \equiv \frac{\lambda_\infty - \lambda_0}{\lambda_0} = \sqrt{1-\frac{2GM}{Rc^2}}^{-1} - 1$$

Constraint in the mass-radius diagram

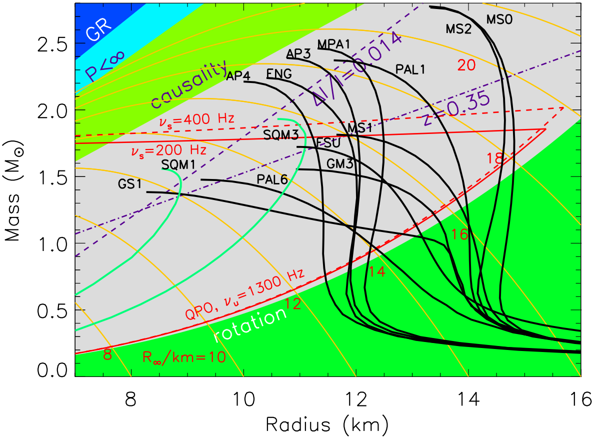
Constraints from atmosphere model fits of RX J1856−3754 thermal spectrum.



Lattimer and Prakash, Phys. Rep. 442(2007),109.

Constraint in the mass-radius diagram

Fe XXV and XXVI spectral lines have been identified in EXO 0748−676 implying $z \simeq 0.35$ (but controversial issue).



Lattimer and Prakash, Phys. Rep. 442(2007),109.

The intriguing case of RX J1856.5-3754

X-ray observations of RX J1856.5-3754 by Chandra

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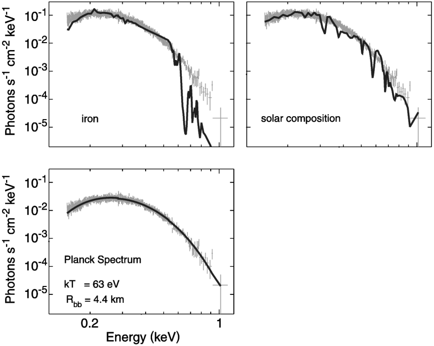

Fig. 3: The Chandra LETG X-ray spectrum of RX J1856 fitted with (non-magnetic) photospheric models assuming pure iron and solar composition. The best fit is obtained with a Planck spectrum (Burwitz et al. 2003).

Trumper (2005), astro-ph/0502457

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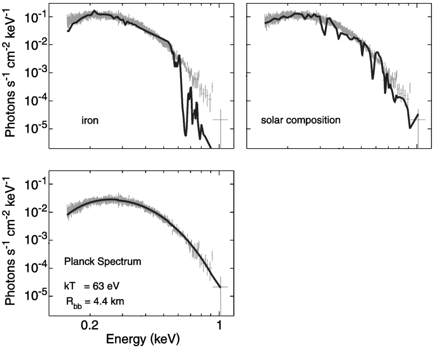


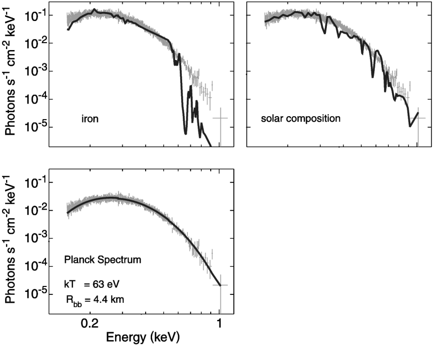
Trumper (2005), astro-ph/0502457

Fig. 3: The Chandra LETG X-ray spectrum of RX J1856 fitted with (non-magnetic) photospheric models assuming pure iron and solar composition. The best fit is obtained with a Planck spectrum (Burwitz et al. 2003).

The best fit is obtained for a pure black body spectrum (no spectral lines!)

The intriguing case of RX J1856.5-3754

X-ray observations of RX J1856.5-3754 by Chandra



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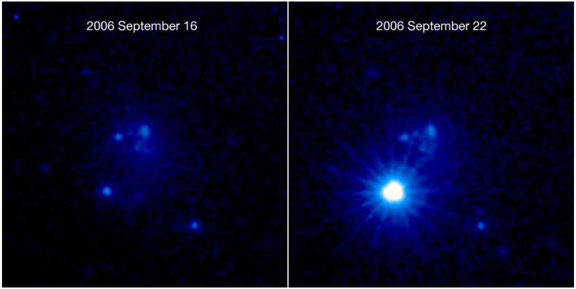
Trumper (2005), astro-ph/0502457

$\Rightarrow$ condensed magnetic surface? bare quark stars?

Soft-Gamma repeaters

Some isolated neutron stars are sources of very energetic X- and gamma ray bursts. These objects called Soft-Gamma Repeaters are thought to be neutron stars with superstrong magnetic fields $\sim 10^{14} - 10^{15}$ G: **magnetars**.

Example: CXOU J164710.2-455216



Magnetars

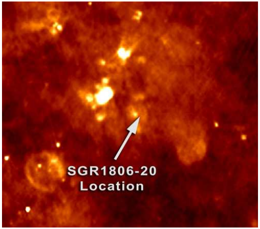
Recently QPOs have been discovered in the X-ray flux of giant flares from SGR.

- SGR 1806–20 (27 December 2004)
  18, 26, 29, 92.5, 150, 626.5, 1837 Hz

  Israel et al., ApJ 628 (2005),53

  Watts et al., ApJ 637 (2006),117

  Strohmayer et al., ApJ 653 (2006),593

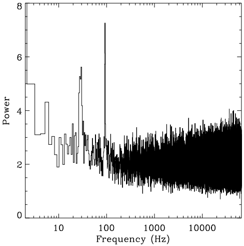


- SGR 1900+14 (27 August 1998)
  28, 54, 84 and 155 Hz

  Strohmayer et al., ApJ 632 (2005),111

- SGR 0526–66 (5 March 1979)
  43.5 Hz

  Barat et al., A&A 126 (1983),400.



Asteroseismology of magnetars

QPOs are interpreted as seismic vibrations following magnetic crustquakes. The frequencies of the modes depend on the structure of the star.

Asteroseisomology of magnetars

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$$f_{n=0,\ell=2} \simeq 2\pi v_t \sqrt{\frac{1 - 2GM/Rc^2}{R r_{\mathrm{cc}}}}$$

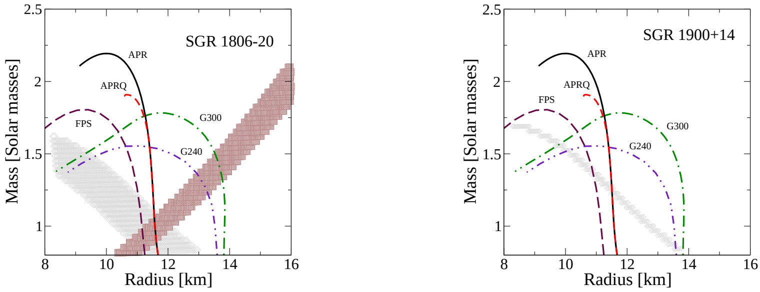
$$f_{n=0,\ell} \simeq f_{n=0,\ell=2} \sqrt{(\ell - 1)(\ell + 2)}$$

$$f_{n>0} \simeq \left(1 - \frac{2GM}{Rc^2}\right) \frac{2\pi^2 n v_r}{\Delta R}$$

Asteroseisomology of magnetars

QPOs are interpreted as seismic vibrations following magnetic crustquakes. The frequencies of the modes depend on the structure of the star.

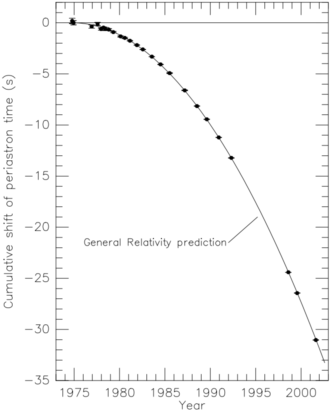
$\Rightarrow$ constraint on the mass and radius



Samuelsson and Andersson, MNRAS 374 (2007), 256

Binary pulsar PSR 1913+16

The existence of gravitational waves (predicted by General Relativity), has been indirectly confirmed by observations of the binary pulsar PSR 1913+16 discovered by Hulse and Taylor in 1974 (Nobel Prize in 1993).



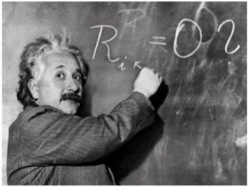
According to general relativity, a binary star system should emit gravitational waves. The loss of orbital energy leads to a decrease in orbital period. The observed orbital decay is in excellement agreement with theoretical predictions.

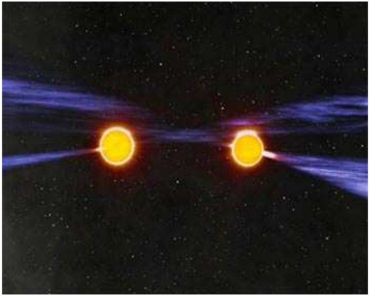
Weisberg and Taylor, astro-ph/0407149

Binary pulsars as a probe of fundamental physics

Neutron stars are the most compact stars in the Universe.

General Relativistic effects can thus be very pronounced. The pulsar's periastron in PSR 1913+16 advances every day by the same amount as Mercury's perihelion advances in a century!





PSR J0737−3039 is a binary system discovered in 2003 and consisting of two observed radio pulsars. This system provides a **laboratory for testing various effects predicted by General Relativity**.

Gravitational wave astronomy

Direct observations of gravitational waves are now becoming possible.

LIGO (USA)

VIRGO (France, Italy)

TAMA300 (Japan)

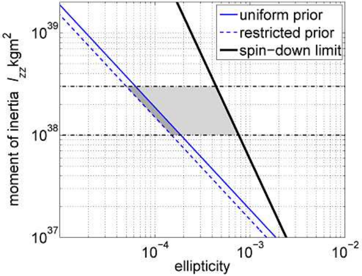
GEO600 (Germany, UK)

LIGO constraint on the Crab pulsar spin-down

A neutron star with nonaxial deformations, rigidly rotating with the angular frequency Ω, radiates gravitational waves.

The star thus loses energy at a rate given by
$$\dot{E} = -\frac{32}{5}\frac{G}{c^5} I^2 \epsilon^2 \Omega^6$$

ϵ is a dimensionless parameter characterizing deformations (the size of mountains is $\sim \epsilon R$). It can be constrained by *direct* observations with gravitational-wave detectors



LIGO, ApJ683(2008),L45.

Conclusion

- Baade and Zwicky predicted in the 1930s that neutron stars are born in supernova explosions. Neutron stars were thus expected to be seen in X-rays. But observations remained unconclusive until pulsars were discovered in 1967.
- Many other faces of neutron stars have been found: SGR, AXP, CCO, XDIN, RRAT, etc.
- Observations of various phenomena (pulsar glitches, pulsar precession, thermal X-ray emission, soft γ-ray bursts, etc.) can give us some information about the interior of neutron stars.

$\Rightarrow$ Lecture about EoS and superfluid properties of neutron stars by J. Margueron.