A historical perspective on the discovery of neutron stars

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What is a neutron star?

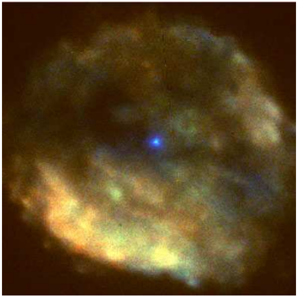
Broadly speaking a neutron star can be viewed as a **giant nucleus** with a mean density of the order of $\sim 10^{14} - 10^{15}$ g.cm^{-3}. A neutron star contains $A \sim 10^{57}$ nucleons, 90% being neutrons.

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



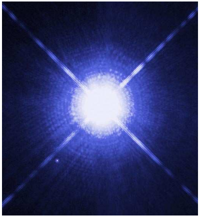
RCW 103 (from ESA)

Outline

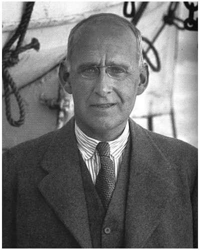
- White dwarfs and the equation of state of dense matter
- 30 years of speculations about neutron stars
- Discovery of pulsars
- Many faces of neutron stars

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/discovery of superconductivity by H. K. Onnes

1913 Bohr model of atoms

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

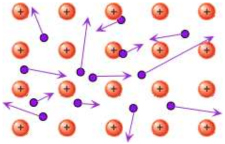
1919 Eddington's expedition to test GR predictions

1923 de Brogli hypothesis of matter waves

1925 Pauli exclusion principle

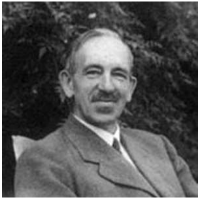
1926 Schroedinger equation, Fermi-Dirac statistics

Degenerate matter in white dwarfs



The central density in white dwarfs was found to be much higher than that in ordinary matter. At such densities atoms are fully ionized and **all electrons are free**.

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



Only four months after Dirac published his paper about the statistics of fermions, R.H. Fowler realized that this is the **electron degeneracy pressure** which resists the gravitational collapse.
MNRAS 87, 114 (1926).

Equation of state of degenerate electrons

At the high densities found in white dwarfs more massive than the sun, Wilhem Anderson pointed out that electrons must be **relativistic**.
Z. Phys. 56, 851 (1929).

The full equation of state of a degenerate electron gas (with Coulomb corrections!) had been actually derived by Yakov I. Frenkel in 1928. But Frenkel's pioneer work was largely unknown.
Yakovlev, Phys. Uspekhi 37, 609 (1994)

Edmund C. Stoner and the structure of white dwarfs

The equation of state of degenerate electrons valid for any degree of relativistic motion was independently obtained by Edmund Clifton Stoner in 1930. He is better known for his work on magnetism.

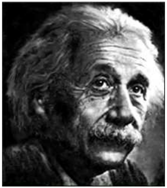
He obtained an **analytical solution** for the structure of white dwarfs using the uniform density approximation. He was also the first to predict the existence of a **maximum mass for white dwarfs** and even calculated it!

Philos. Mag. 9, 944 (1930).

Nauenberg, J. Hist. Astron. 39, 297 (2008).

Relativistic softening of dense matter

Due to the Pauli exclusion principle, each electron has a **finite speed** which increases with increasing density.



However **special relativity** tells us that the electron speed cannot exceed the speed of light. This entails a **softening** of the electron pressure at high densities.

$\Rightarrow$ Degenerate electron matter (hence white dwarfs) cannot sustain an arbitrarily high mass. Stoner found

$$M_{\max} = \frac{3}{16\pi}\left(\frac{5hc}{2G}\right)^{3/2}\frac{1}{(m_p\mu_e)^2}$$

Stoner, Philos. Mag. 9, 944 (1930).

Maximum mass of white dwarfs

The maximum mass was independently derived by Landau using the same kind of reasoning as Stoner.
Phys. Z. Sowjetunion 1, 285 (1932).

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

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

has a minimum for $R = 0$ (hence the star collapses) if $M \equiv Am_p > M_{\rm max}$

$$\Rightarrow M_{\rm max} \sim \left(\frac{\hbar c}{G}\right)^{3/2} \left(\frac{1}{\mu_e m_p}\right)^2$$

Maximum mass of white dwarfs

The exact value of the white-dwarf maximum mass was calculated by Subrahmanyan Chandrasekhar by numerically integrating the equations of hydrostatic equilibrium

$$M_{\rm max} \simeq 2.018 \frac{\sqrt{6}}{8\pi} \left(\frac{hc}{G} \right)^{3/2} \frac{1}{(m_p \mu_e)^2}$$

This mass is 20% smaller than that found by Stoner.
MNRAS 91, 456 (1931).

Chandrasekhar calculated the structure of white dwarfs, five years after Stoner.

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 discussed it in his paper published 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 $M_{\text{vis}} = -14^M$. 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).

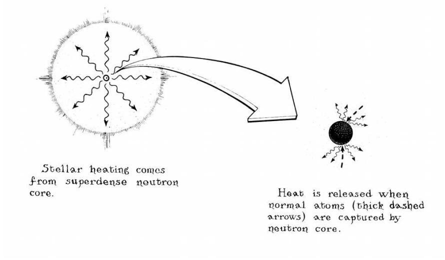
With John von Neumann, they obtained in 1934 the equations describing static spherical stars in Einstein's theory of General Relativity but they didn't publish their work.

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.

Connection between white dwarfs and neutron stars

Baade and Zwicky were apparently unaware of the work about the maximum mass of white dwarfs. This is Gamow who first made the connection in 1939 (*Phys. Rev.55, 718*). At a conference in Paris in 1939, Chandrasekhar also pointed out

> *"If the degenerate core attain sufficiently high densities, the protons and electrons will combine to form neutrons. This would cause a sudden diminution of pressure resulting in the collapse of the star to a neutron core."*

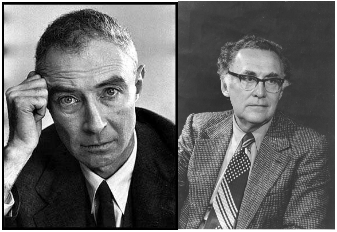
A neutron star should thus have a mass close to the Chandrasekhar limit, i.e. $M \sim 1.4 M_{\odot}$**.**

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.



Robert Oppenheimer and George Volkoff

Hydrostatic equilibrium of relativistic stars

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

Oppenheimer and Volkoff found $M_{\rm max} \simeq 0.7 M_\odot$ by considering a degenerate gas of free neutrons.

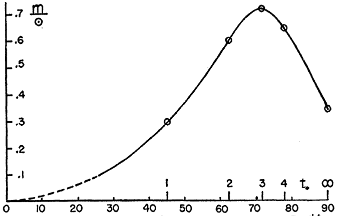
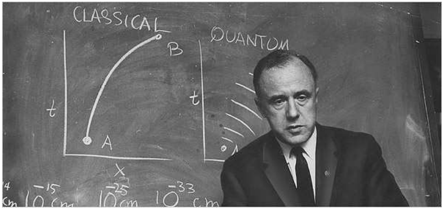


FIG. I.

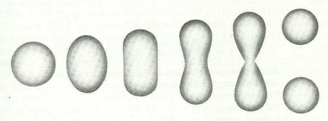
Since this is smaller than the maximum mass of supernova cores, they concluded that neutron stars could not exist.

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

For the crust, a **semi-empirical mass formula** was used together with the EoS of degenerate electrons. In the core, matter was assumed to be a mixture of three **ideal Fermi gases** (neutron, proton and electrons).

Discovery of superfluidity

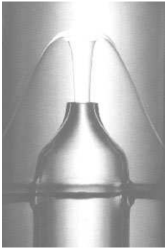
During the 1930s, it was found by several groups that below $T_\lambda = 2.17$ K, helium does not behave like an ordinary liquid.

"*by analogy with superconductors, the helium below the λ-point enters a special state which might be called* ***superfluid****.*"
Kapitza, Nature 141, 74 (1938).

"*the observed type of flow most certainly cannot be treated as laminar or even as ordinary turbulent flow.*"
Allen and Misener, Nature 141, 75 (1938).

About the history of superfluidity:
Balibar, J. Low Temp. Phys. 146, 441 (2007).

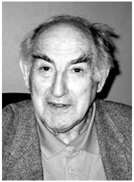
Two-fluid model



J.F. Allen and H. Jones, discovered the **fountain effect**: when heat is supplied on one side of a porous plug, the pressure of superfluid helium increases so much that it produces a liquid jet.
Allen and Jones, Nature 141, 243 (1938).

Following the suggestion of Fritz London that superfluidity is related to **Bose-Einstein condensation**, Laszlo Tisza showed that there should exist **two velocity fields**. This model was further developed by Landau.
Tisza, Nature 141, 913 (1938).
Landau, Phys. Rev. 60, 356 (1941).

Theory of superconductivity

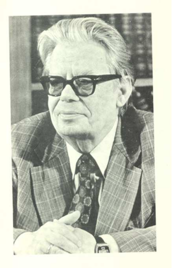


In 1950, Ginzurg and Landau developed a **phenomenological** theory of superconductivity.

A **microscopic** theory of superconductivity was proposed in 1957 by Bardeen, Cooper and Schrieffer. Gorkov later shown that the GL model can be derived from the BCS theory.

Superfluidity and superconductivity in neutron stars

The BCS theory was applied to nuclei by Bohr, Mottelson, Pines and Belyaev
Phys. Rev. 110, 936 (1958).
Mat.-Fys. Medd. K. Dan. Vid. Selsk. 31 , 1 (1959).



N.N. Bogoliubov, who developed a microscopic theory of superfluidity and superconductivity, was the first to explore its application to nuclear matter.
Dokl. Ak. nauk SSSR 119, 52 (1958).

Superfluidity in neutron stars was suggested by Migdal in 1959. It was studied by Ginzburg and Kirzhnits in 1964, and by Wolff in 1966.
Ginzburg and Kirzhnits, Zh. Eksp. Teor. Fiz. 47, 2006, (1964).
Wolff, Astrophys. J. 145, 834 (1966).

Are electrons in neutron stars superconducting?

The critical temperature of a uniform non-relativistic electron gas is given by ($T_{\rm pi}$ is the plasma temperature)

$$T_{\rm ce} = T_{\rm pi}\exp\left(-8\hbar v_{\rm Fe}/\pi e^2\right) \Rightarrow T_{\rm ce} \propto \exp(-\zeta(\rho/\rho_{\rm ord})^{1/3})$$

with $\rho_{\rm ord} = m_{\rm u}/(4\pi a_0^3/3)$. At densities above $\sim 10^6$ g.cm^{-3}, electrons become relativistic $v_{\rm Fe} \sim c$ so that ($\alpha = e^2/\hbar c \simeq 1/137$)

$$T_{\rm ce} = T_{\rm pi}\exp\left(-8/\pi\alpha\right) \sim 0$$

Ginzburg, J. Stat. Phys. 1(1969),3.

Electrons in neutron stars are not superconducting.

Nuclear forces and maximum mass of neutron stars

In 1959, Cameron constructed neutron-star models using the **Skyrme equation of state** for high-density matter. He found that:

- nuclear forces considerably **stiffen the EoS**
- the maximum mass of neutron stars $M_{\rm max} \simeq 2M_\odot$ is much higher than that found by Oppenheimer and Volkoff
- neutron stars can thus be formed as proposed by Baade and Zwicky
- neutron star cores may contain various nuclear species such as hyperons.

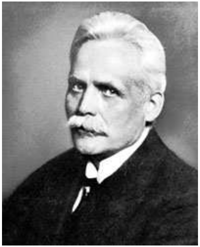
Formed in supernova explosions, neutron stars were thus expected to be "hot". In the 60s, theoretical efforts focused on modeling the cooling of neutron stars motivated by the hope of detecting their thermal emission.

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)

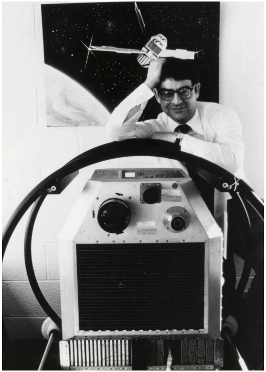
So neutron stars were not expected to be seen from Earth because X-rays cannot penetrate the atmosphere.

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 remained elusive.

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

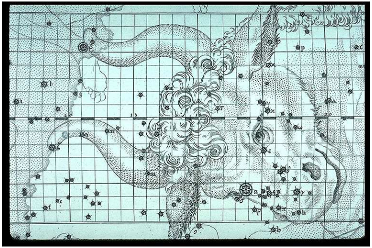


Giacconi with Uhuru satellite, 1970

Riccardo Giacconi and Piero Rosati (2008)
`http://www.scholarpedia.org/article/Cosmic_X-ray_sources`

Crab nebula

The Crab nebula was first observed by the British astronomer John Bevis in 1731.



Uranographia, J. Bevis (1750)

Charles Messier

And in 1758 by Charles Messier. The Crab nebula became the first object of the Messier catalog published in 1774.

Crab nebula

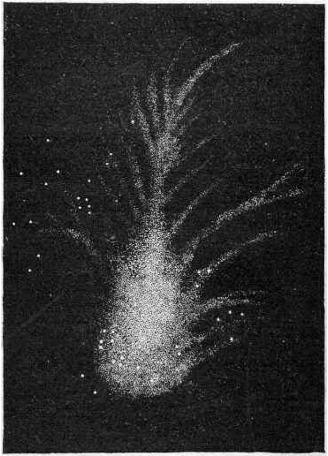


Fig. 438.

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

The "guest star" in Taurus

During the 1920s and 1930s, the Crabe nebula was identified as the remnant of a supernova that exploded on July 4, 1054.

A bright star was observed by Chinese, Japonese and Arab astronomers. The "star" remained visible in daytime for 23 days and disappeared from the night sky after two years.

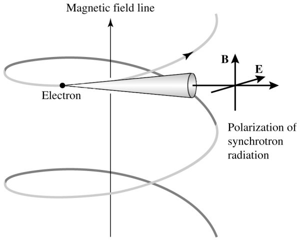
photo by Ron Lussier

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

First speculations about the Crab nebula

Already in 1942, Baade and Minkowski found that the central region of the Crab nebula contains an unusual star.

A radio emission was detected in 1949. In 1953, Shklovsky predicted that this is due to **synchrotron radiation** by relativistic electrons spiraling along a strong magnetic field. Later the polarition of radio emission was confirmed.



From Carroll and Ostlie

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

Neutron star magnetic fields

In 1964, Lodewijk Woltjer (who did his PhD with Jan Oort on the Crab nebula) argued that neutron stars could have very strong magnetic fields. This was also independently shown by Ginzurg.

If we assume that the **magnetic flux** $\Phi = B4\pi R^2$ is conserved during the gravitational collapse of massive stars eventually giving birth to a neutron star, we have

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

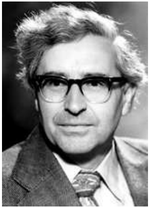
This implies neutron-star magnetic fields up to $B_f \sim 10^{16}$ G.

Woltjer, Astrophys. J. 140,1309 (1964).
Ginzburg, Sov. Phys.Doklady 9, 329 (1964).

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).

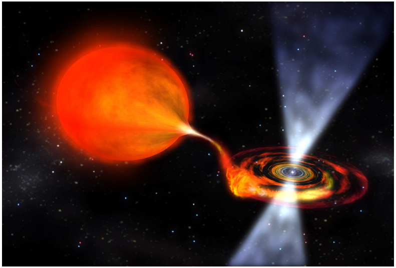
In 1965 Anthony Hewish and his student found a **scintillating radio source** and speculated that it "might be the remains of the original star which had exploded". *Nature 207, 59 (1965).*



In 1967, Franco Pacini (who was a young postdoc at Cornell) showed that a **rapidly rotating neutron star with a strong dipole magnetic field** could power the Crab nebula.

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 (*ApJ 148, L1*). But his 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.

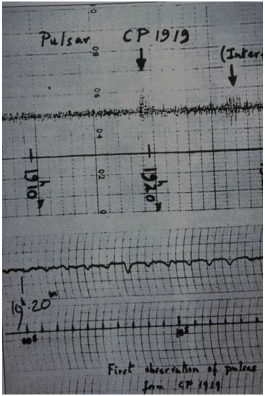
They constructed a 3.7m radiotelescope with a very good temporal resolution. The telescope (which consisted of an array of 2048 dipole antenna) was completed in July 1967.

Jocelyn Bell in 1966

Fortuituous 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**.

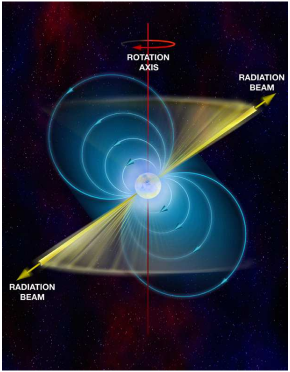
Unmasking pulsars

The other possibility was that pulsars are strongly magnetised rotating neutrons stars as proposed by Timothy Gold (and earlier by Pacini).

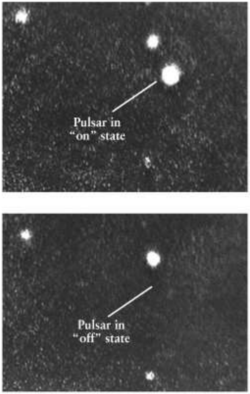
Gold, Nature 218, 731 (1968).

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.

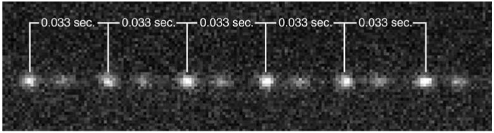


Crab pulsar

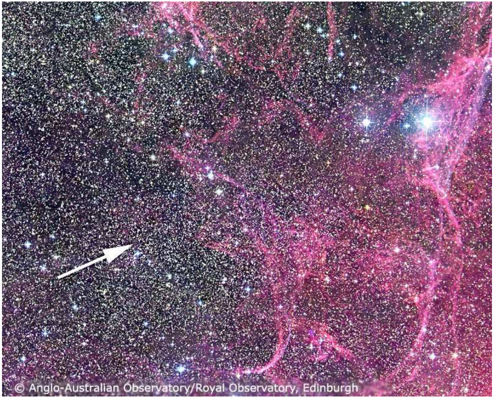


b.

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.

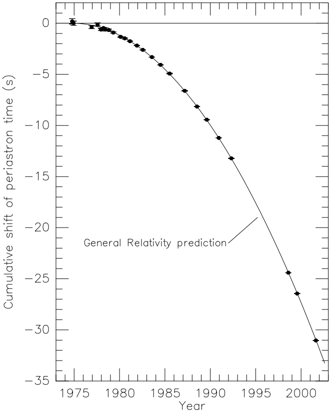
Pulsars and supernova remnants

Actually 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).

Discovery of the binary pulsar PSR 1913+16

In 1974, R.A. Hulse and J.H. Taylor discovered a pulsar in a binary system (Nobel Prize in 1993). Their observations were used to **prove the existence of gravitational waves** predicted by Einstein's theory of general relativity.



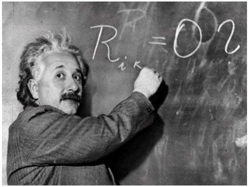
According to general relativity, a binary star system should emit gravitational waves. The loss of orbital energy leads to a decrease in orbital period. The observed orbital decay is in excellement agreement with theoretical predictions.

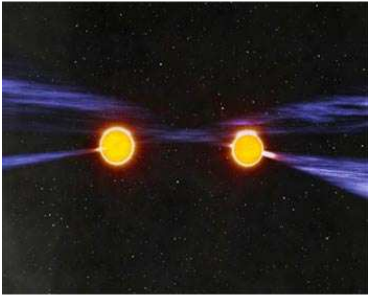
Weisberg and Taylor, astro-ph/0407149

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**.

Discovery of millisecond pulsars

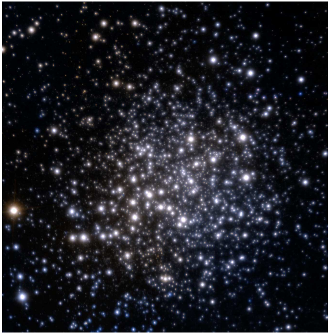
The first millisecond pulsar was found in 1982 at Arecibo by Backer's team. Today $\sim$ 200 millisecond pulsars are known. The fastest one PSR J1748$-$2446ad discovered in 2005, has a period of only 1.396 ms!

Millisecond pulsars are characterised by

$1.4 \leq P \leq 30$ ms

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

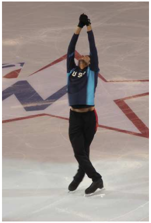
Most of them belong to a binary system and are found in globular clusters.



Globular cluster Terzan 5 (ESO)

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.



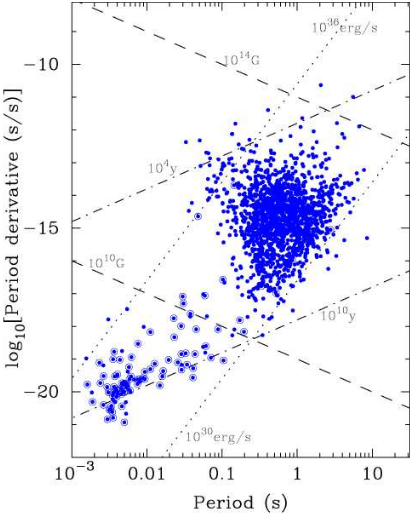
Taking the initial stellar core (i) and the final neutron star (f) as spheres with a moment of inertia $I = (2/5)MR^2$, we have

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

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!

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

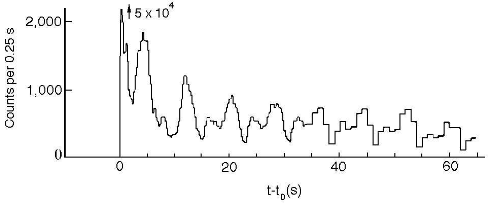
In the standard scenario of neutron star formation from supernova explosions, the fastest pulsars are the youngest



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.

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.

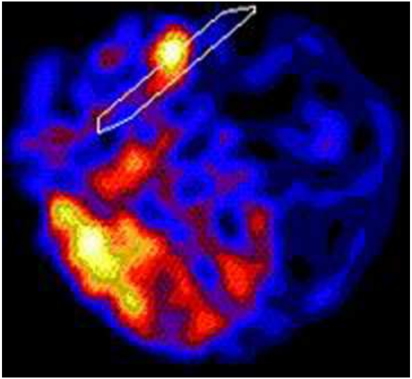


A very intense gamma-ray burst was detected on March 5, 1979 by two Soviet satellites Venera 11 and Venera 12.

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.

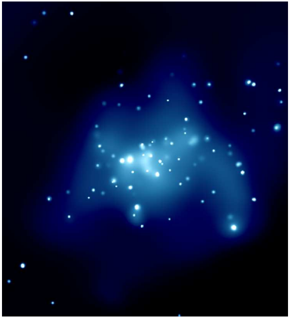
`http://www.physics.mcgill.ca/~pulsar/magnetar/main.html`

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.

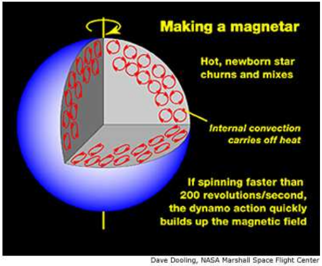


CXO J164710.2-455216 (Chandra)

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

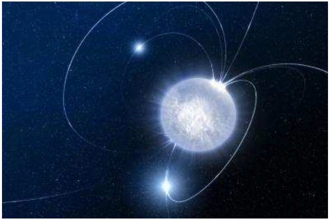
`http://www.physics.mcgill.ca/~pulsar/magnetar/main.html`

Theory of magnetars



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`

Neutron stars: 50 years of discoveries

1962 Accreting neutron star Sco X-1

1967 Pulsar PSR 1919$+$21

1974 Binary pulsar PSR 1913$+$16

1979 Magnetar SGR 0525$-$66

1982 Millisecond pulsar PSR B1937$+$21

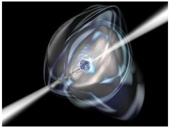
1992 Planetary system around PSR B1257$+$12

2003 Double pulsars PSR J0737$-$3039

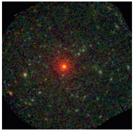
2005 Fastest pulsar PSR J1748$-$2446ad

2006 Discovery of RRATs (Rotating Radio Transients)

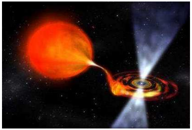
The many faces of neutron stars



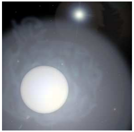
Anomalous X-ray Pulsars



dim isolated neutron stars



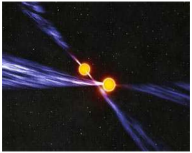
X-ray binaries



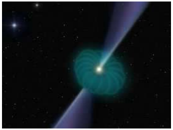
bursting pulsars

Soft Gamma Repeaters

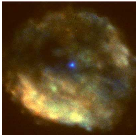
pulsars



binary pulsars



Rotating Radio Transients



Compact Central Objects

planets around pulsar