Radio Observations and Theory of pulsars and X-ray binaries

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1. Rudiments on pulsars
2. Binary pulsars and their evolution
3. Pulsar timing concepts
4. Pulsars timing as a tool for fundamental physics
5. Prospects with SKA
6. The enigma of the Fast Radio Bursts (FRBs)
Books

- Manchester & Taylor 1977 “Pulsars”
- Lyne & Smith 2005 “Pulsar Astronomy”
- Lorimer & Kramer 2005 “Handbook of Pulsar Astronomy”
- AA.VV. 2009 “Physics of relativistic objects in compact binaries: from birth to coalescence”, Springer

Review Articles

- Stairs 2003: Testing General Relativity with pulsar timing
- Will, 2006: The confrontation btw General Relativity and experiment
- Lorimer 2008: Binary and millisecond pulsars
- Kramer & Stairs 2008: The double pulsar
- Camilo & Rasio 2005: Pulsars in Globular Cluster
- Hessels, Possenti et al 2015: Pulsars in Globular Cluster with the SKA
- Watts et al. 2015: Probing the neutron star interior and the Equation of State of cold dense matter with the SKA
- Shao et al. 2015: Testing gravity with Pulsars in the SKA era
- Tauris et al. 2015: Understanding the neutron star population with the SKA
1. Rudiments on Pulsars
After 10-200 Myr from the birth, the star assumes an onion structure.

\[ 8 \, M_{\text{sun}} \lesssim M_{\text{initial}} \lesssim 19-25 \, M_{\text{sun}} \]
The nucleus of Iron 56 has the highest binding energy
What can halt the collapse of the core?
(1932) Discovery of the neutron

Sir James Chadwick (1891-1974)

Lev Davidovich Landau (1908-1968)

(1932) ...proposes the existence of the NEUTRON STARS
... shown that the pressure due to a NEUTRON DEGENERATE GAS can STOP THE COLLAPSE of the core and

MUST EXIST A **MAXIMUM MASS** for the NEUTRON STARS

Landau reasoning (1932) leads to

\[ M_{\text{max}} \approx M_{\text{chandrasekhar}} \]

a more formal demonstration of the necessity of the existence of a maximum mass for non rotating neutron stars is from Rhoades & Ruffini (1974). Under the hypotheses:

i) \( \frac{dP}{d\rho} > 0 \) (condition of microscopic stability for avoiding matter to collapse)

ii) \( \frac{dP}{d\rho} < c^2 \) (causality compliant: sound velocity cannot overcome light velocity)

iii) The equation of state of matter is known up to density \( \rho_o = 4.6 \times 10^{14} \text{ g/cm}^3 \)

\[ M_{\text{max}} \approx 3.2 \, M_\odot \left( 4.6 \times 10^{14} \text{ g/cm}^3 / \rho_o \right)^{1/2} \]

For uniformly rotating neutron stars the upper limit is [Friedman & Ipser 1987]

\[ M_{\text{max}} \approx 6.1 \, M_\odot \left( 2 \times 10^{14} \text{ g/cm}^3 / \rho_o \right)^{1/2} \]
(1934) ... Proposed the hypothesis that the SUPERNova explosions represent the transformational event joining the Ordinary Stars with the Neutron Stars

- Collapse of the nucleus
- Ejection of the external layers
- Supernova remnant and neutroni star
(1967) ... Jocelyn Bell and Antony Hewish discover celestial objects emitting regularly repeating pulsations in the radio band. They are named PULSARs by a British journalist.
(1968) ...the confirmation of the predictions of Landau and Zwicky

The supernova of A.D. 1054... how it appears 960 yr later

a RADIO PULSAR discovered in the nebula
What is a Radio Pulsar

A **PULSAR** is a rapidly **rotating** and highly magnetized **neutron star**, emitting a pulsed radio signal as a consequence of a **light-house effect**.
The Parkes radio telescope (in Australia) where about half of the so far known $\approx 2400$ pulsars have been discovered.

- PSR B0329+54: period of $0.714$ s
- PSR B0833-45: period of $0.089$ s
- PSR B1937+21: period of $0.0016$ s
**The rotating magnetized NS in vacuum**

\[ \mu = \frac{1}{2} B_p R^3 \]

is the magnetic moment

\[ R = \text{NS radius} \]

\[ B_p = \text{polar magn. field} \]

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**Assuming that the rotational energy loss**

\[ L_{sd} = \frac{d}{dt} (E_{rot}) = \frac{d}{dt} (I\Omega^2/2) = I \Omega \dot{\Omega} \]

matches the emitted power (derived from the basic electrodynamics Larmour formula):

\[ L_{dipole} = \left[ \frac{2}{3} c^3 \right] | \vec{\mu} |^2 \]

one can infer...
Derived parameters: age & magnetic field

- Actual age of pulsar is function of initial period and braking index $n = (\frac{\nu}{\nu_0})\frac{\dot{P}}{P}$ (assumed constant)

- For $P_0 << P$, $n = 3$, have “characteristic age”

- If true age known, one can compute initial period

- From braking equation, one can derive $B_0$ at NS equator with $R = NS$ radius. Value at pole is $2B_0$

- Typically assumed $R = 10$ km, $l = 10^{45}$ gm cm$^2$, $n = 3$

(from Manchester & Taylor)
Radio pulsar basic parameters

Radio pulsars are powered by **rotational energy**

The observation of the spin period $P$ and of its derivative $\dot{P}$ allows one to give an estimate of various physical quantities:

- **Spin-down age:** $\tau_c = 1.6 \cdot 10^6 \frac{P}{P_{-14}} \text{ yr}$
- **Spin-down power:** $L_{\text{sd}} = 3.9 \cdot 10^{32} P^3 P_{-14}^3 \text{ erg/s}$
- **Surface magnetic field:** $B_{\text{surf}} = 3.2 \cdot 10^{12} \left[ \frac{P}{P_{-14}} \right]^{3/2} \text{ Gauss}$

...and allows one to place a pulsar on the basic $P$ vs $P$ [or $P$ vs $B_{\text{surf}}$] diagram...
The $B_s$ vs $P$ diagram

A pulsar is put on it once both $P$ and $dP/dt$ are measured, from which

$$B_s = 3.2 \cdot 10^{19} [P \dot{P}]^{\frac{1}{2}} \text{ G}$$

ATNF Pulsar Catalogue
Pulsar Energetics

Spin-down Luminosity:

\[ L_{sd} = \dot{E}_{sd} = -I\Omega\dot{\Omega} = 4\pi^2 I \dot{P} P^{-3}, \text{ where } \Omega = 2\pi / P \]

For a “normal” pulsar, \( I \sim 10^{45} \text{ g cm}^2 \), \( P \sim 1 \text{ s} \), \( \dot{P} \sim 10^{-15} \), \( L_{sd} \sim 10^{32} \text{ erg s}^{-1} \).

For an MSP, \( P \sim 3 \text{ ms} \), \( \dot{P} \sim 10^{-20} \), \( L_{sd} \sim 10^{34} \text{ erg s}^{-1} \).

(from Manchester & Taylor)

Radio Luminosity:

\[ L_{rad} = S \ 4\pi d^2 \ \Delta\nu \]

For \( S \sim 10 \text{ mJy} = 10^{-28} \text{ W m}^{-2} \text{ Hz}^{-1} = 10^{-25} \text{ erg cm}^{-2} \text{ Hz}^{-1} \)
\( d = 1 \text{ kpc} = 3 \times 10^{21} \text{ cm} \), \( \Delta\nu = 10^9 \text{ Hz} \), \( L_{rad} \sim 10^{28} \text{ erg s}^{-1} << L_{sd} \)

(from Manchester & Taylor)
Radio emission is a coherent process

- Source power is very large, but source area is very small
- Specific intensity is very large
- Pulse timescale gives limit on source size \( \sim c \Delta t \)
- Brightness temperature: equivalent black-body temperature in Rayleigh-Jeans limit

\[
I_\nu = \frac{2\nu^2 k T_B}{c^2} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}
\]

For pulse timescale \( \Delta t = 1 \mu s \), source area \( A \sim (c \Delta t)^2 = 10^9 \text{ cm}^2 \) and \( L_{rad} = 10^{29} \text{ erg s}^{-1} \):

\[
I = 10^{20} \text{ erg s}^{-1} \text{ cm}^{-2} (= 10^7 \text{ MW cm}^{-2}!!)
\]

For solid angle \( \sim 1 \text{ sr} \), \( \nu = 10^9 \text{ Hz} \): \( T_B \sim 10^{30} \text{ K} (!!) \)

Radio emission must be from a COHERENT process!
The total energy budget for the Crab

Given the following parameters at 2008 for the Crab Pulsar:

\[ P = 33.5965 \text{ msec} \]
\[ \frac{dP}{dt} = 4.2 \times 10^{-13} \text{ sec/sec} \]

\[ E_{\text{rot}} = 0.5 I \Omega^2 = 3 \times 10^{49} \text{ erg} \]
\[ L_{\text{sd}} = \frac{d}{dt} (E_{\text{rot}}) = \frac{d}{dt} (0.5 I \Omega^2) = 4.6 \times 10^{38} \text{ erg/sec} \]

Whereas, observing the total luminosity \( L_{\text{total}} \) released from the whole Crab Nebula:

\[ L_{\text{total}} = L_{\text{psr}} + L_{\text{snr}} = L_{\text{e.m.}} + L_{\text{kin_sn}} \approx 5 \times 10^{38} \text{ erg/sec} \]

Radio pulsars belong to the category of the rotation powered neutron stars.
Wide band emission and efficiency of conversion of spin down luminosity in Rotation Powered Neutron Stars
Rotating neutron-star model: magnetospheric gaps

Various proposed regions of particle acceleration

Inner (polar cap) gap

Outer gaps

$W \cdot B = 0$

Cheng et al. (1986); Romani (2000)

Harding (2002)
Basic picture of pulsar electrodynamics

- For a typical pulsar, $P = 1$ s, $P = 10^{-15}$ s/s, $B_s \sim 10^{12}$ G
- Typical electric field at the stellar surface $E_s \sim W R B_s / c \sim 10^9$ V/cm
- $e^\pm$ reach ultra-relativistic energies in $< 1$ mm
- $e^\pm$ emit g-ray photons by curvature radiation. These have energy $>> 1$ MeV and hence decay into $e^\pm$ pairs in strong B field
- These in turn are accelerated to ultra-relativistic energies and in turn pair-produce, leading to a cascade of $e^+/e^-$ pairs
- Relativistic pair-plasma flows out along ‘open’ field lines
- These flows lead to generation of radiation beams at high energy via synchrotron and/or inverse Compton processes
- Additional coherent processes in the magnetosphere of (as yet) unassessed nature lead to the generation of radio beam(s)
Mean pulse shapes

Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Lorimer & Kramer (2005)
• Pulsar spectra are typically steep
  \[ \text{Flux} \sim \nu^{-\alpha} \quad \langle \alpha \rangle \sim 1.7 \]
  \[ 0.0 < \alpha < 3.5 \]
• A turnover is typically at \( \nu \sim 100\text{-}200 \text{ MHz} \)
  but there are exceptions

MPIfR (2000)
Frequency Dependence of Mean Pulse Profile

- Pulse width generally increases with decreasing frequency.
- Consistent with ‘magnetic-pole’ model for pulse emission.
- Lower frequencies are emitted at higher altitudes.

Manchester et al. (2005)

Phillips & Wolsczcan (1992)
In the subsample of pulsar with $P > 100$ ms, there appears a tendency to present smaller beam widths for longer spin periods: $W_{10\%} \sim 5.4^\circ / P(s)^{0.5}$
A stable pulse profile builds up only after summing many (typically 100-1000) pulses.
Radio Beam structure

Core + multiple cones structure
Rankin (1990, 1995)

Patchy structure
Manchester & Lyne (1988)
The many flavours of the Neutron Stars

≈ 2400 Radio pulsars *(powered by rotational energy)*

≈ 20 Rotating Radio Transients *(powered by rotational energy?)*

26 Magnetars *(powered by magnetic energy)*

7 X-ray Dim Isolated NS *(powered by thermal energy?)*

≈ 10 Central Compact Objects in SNR *(powered by thermal energy?)*

≈ few 100s Accreting NS in binaries *(powered by accretion energy)*
The many flavours of the Neutron Stars

http://www.atnf.csiro.au/people/pulsar/psrcat
The many flavours of the Neutron Stars

The $P$ vs $P$ diagram
The many flavours of the Neutron Stars

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The $P$ vs $P$ diagram

ATNF Pulsar Catalogue + [Tauris et al 2015]
The current pulsar demography

≈10 % of known pulsars are in **binaries**