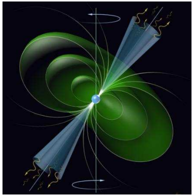
Astrophysics of Neutron Stars : Introduction

Sushan Konar



Astronomy from Archival Data

An IAU-OAD Project

2020

Archival data may be thought of as any sort of information, previously collected by others, amenable to systematic study.

Introduction :

1. The Discovery
2. The Extreme Physics
3. The Radio Pulsar
4. Timing & Null

The Discovery

The Concept : 1930s

- February 1931 : Landau completes work on maximum mass of white dwarf.

$$M_{\mathrm{max}} = \frac{3.1}{m^2} \left(\frac{\hbar c}{G} \right)^{\frac{3}{2}}$$

Predicts existence of ‘giant atomic nuclei’-like stars.

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- 15-16 December 1933 : Walter Baade & Fritz Zwicky at the APS meeting say -

  ".. supernovae represent the transition from ordinary stars into neutron stars, which in their final stages consist of closely packed neutrons. Such a star may possess a very small radius and an extremely high density.. the 'gravitational packing' energy in a cold neutron star may .. far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such."

- 15 January 1934 : The abstract of their talk is published.

[Note : $E^{\rm SNII}_{\rm obs.} \sim 10^{51}$ *erg* $<<$ $E^{\rm NS}_{\rm bind.}(\sim 10^{53}$ *erg*), neutrino factor was unknown]

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2. & 3. Baade W., Zwicky F., Proc. National Acad. Sci., 20, 254 & 259 (1934)

3. Baade W., Zwicky F. Phys. Rev. 46 76 (1934)

Chandrasekhar S., ApJ, 74, 81 (1931)

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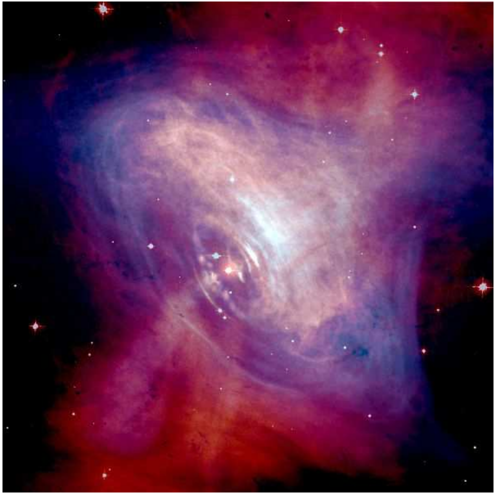
The Discovery : 1960s

- 1965 : Antony Hewish & Samuel Okoye observe *"..an unusual source of high radio brightness temperature in the Crab Nebula."*.

  Crab pulsar was detected in 1968.

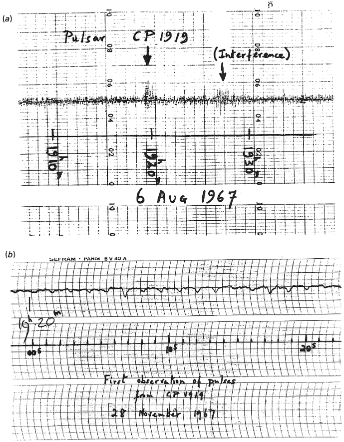


Credit : Optical - NASA/HST/ASU/J. Hester et al., X-Ray - NASA/CXC/ASU/J. Hester et al.

The Discovery : 1960s

- 1967 : Jocelyn Bell & Antony Hewish detect regular radio pulses from CP1919 (PSR J1921+2153).

  P = 1.33 s, keeping sidereal time
  First detection of a radio pulsar.



Hewish A., Bell S. J., Pilkington J. D. H., Scott P. F., Collins R. A., Nature 217 709 (1968)

The Discovery : 1960s

- 1971 : Giacconi et al. discover 4.8 s X-ray pulsations in Cen X-3.

  First detection of an X-ray pulsar.
  Cen X-3 is a high-mass X-ray binary.

X-Ray Pulsar Cen X-3

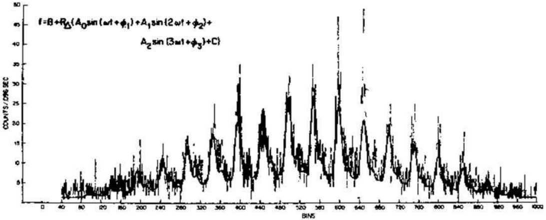


Figure 5. X–ray pulsations of Cen X–3. From Giacconi, 1974.

Pulses occur at intervals of 4.84 seconds

Giacconi, R. et al., ApJ, 167, L67 (1971)

The Interpretation : 1960s

- 1964 : Lodewijk Woltjer, from magnetic flux conservation, estimates $B_{\rm NS} \sim 10^{14} - 10^{16}$ G.
- 1967, 1968 : Franco Pacini indicates likelihood of strong radiation from rotating magnetised neutron stars, which may power supernova remnants (Crab Nebula).
- 1968, 1969 : Thomas Gold develops a similar model to explain radiation from CP1919.
- 1969 : Radhakrishnan & Cook; Gunn & Ostriker; Goldreich & Julian - radio pulsar model.

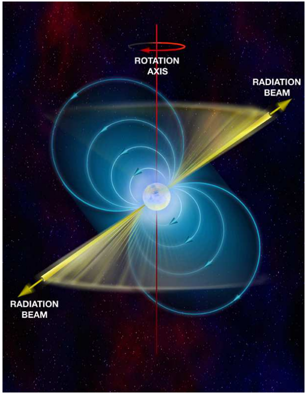


Figure Credit : Bill Saxton, NRAO/AUI/NSF

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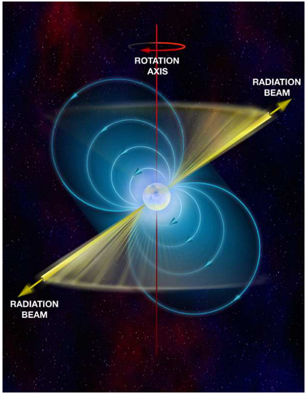

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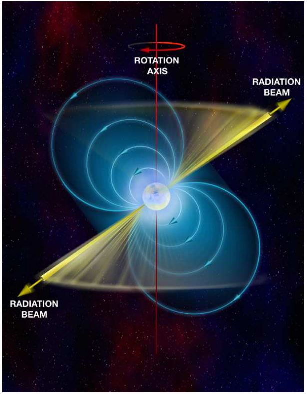

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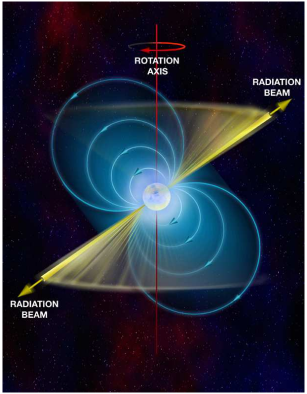

The Extreme Physics

The End States

- Failed Stars : $M < 80\, M_{\rm Jupiter}$ ($M_{\rm Jupiter} \simeq 0.001\ {\rm M}_{\odot}$)
  - Giant Planets - $M < 13\, M_{\rm Jupiter}$, no fusion
  - Brown Dwarfs - $13\, M_{\rm Jupiter} < M < 80\, M_{\rm Jupiter}$, D^2 fusion
- Stellar Remnants - Compact Stars
  - White Dwarfs
  - **Neutron Stars**
  - Black Holes

Gravity Defied I - IV, **Resonance, March - June, 2017***, Sushan Konar*

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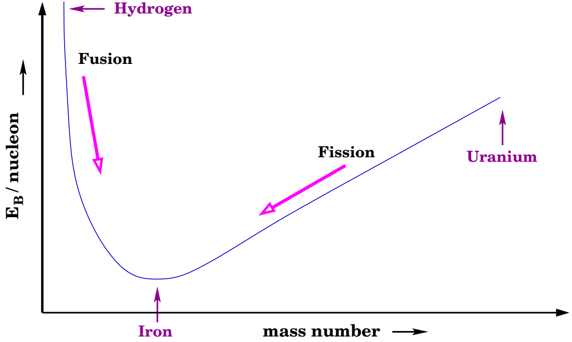
The Active Phase



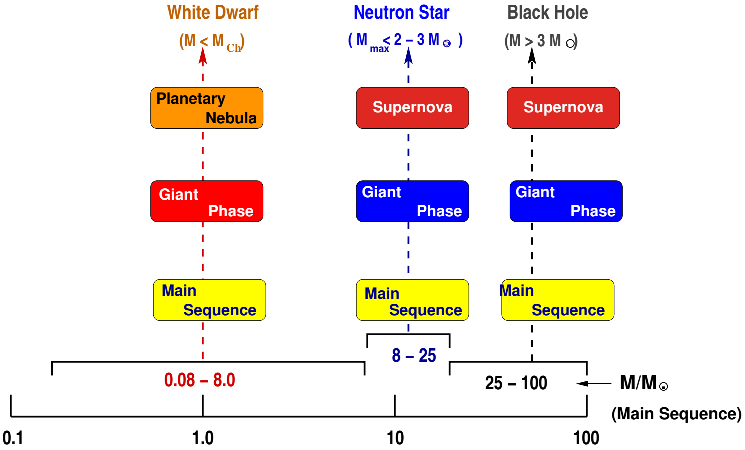
Fusion Chain -
$H^1 \rightarrow He^4 \rightarrow Be^8 \rightarrow C^{12} .. \rightarrow Fe^{56}$

No 'exothermic' fusion beyond Fe^{56}.
(Fe^{56} - minimum binding energy/nucleon)

No radiative pressure support beyond iron peak elements.

Figure credit : Sushan Konar

Stellar Remnants



Extreme Physics

Dimensions :

- $M \sim 1 - 3\,\mathrm{M}_\odot \quad (\mathrm{M}_\odot \sim 2 \times 10^{33}$ gm)

  $M \simeq 2.14\,\mathrm{M}_\odot$, *Cromatie H. T. et al., Nature Astronomy, 2019*
- $R \sim 10 - 15$ Km

Compact Structure : Consequences

- Binding Energy : $E_B \simeq \frac{GM^2}{R} \sim 10^{53}$ erg
- GR Effects : Schwarzschild factor - $\frac{2GM}{Rc^2} \sim 0.3$

Extreme Physics

Dimensions :

- $M \sim 1 - 3\ \mathrm{M}_\odot \quad (\mathrm{M}_\odot \sim 2 \times 10^{33}$ gm)
- $R \sim 10 - 15$ Km

Compact Structure : Consequences

- Fast Rotation : $P_{\rm spin}^{\rm min} = 2\pi \left(\frac{r^3}{GM}\right)^{\frac{1}{2}}$ ($P < P^{\rm min}$ would make the object disintegrate)

  $P_{\rm spin}^{\rm min} \sim 5 \times 10^{-4}$ for a neutron star.

  $P_{\rm spin}^{\rm min} \sim 1.5$ hours for Earth.

  $P_{\rm spin} = 1.396 \times 10^{-3}$ *s for PSR J1748-2446ad; Hessels J. W. T. et al.,Science, 311, 1901 (2006)*

Extreme Physics

Dimensions :

- $M \sim 1 - 3\ \mathrm{M}_{\odot} \quad (\mathrm{M}_{\odot} \sim 2 \times 10^{33}$ gm)
- $R \sim 10 - 15$ Km

Compact Structure : Consequences

- Strong Magnetic Field : $P^{\mathrm{G}}_{\mathrm{central}}\ (\frac{Gm^2}{R^4}) \gtrsim P^{\mathrm{EM}}\ (\frac{B^2}{8\pi})$

  $B_{\mathrm{max}} \sim 10^{18}$ G for a neutron star.

  $B_{\mathrm{s}} \sim 2.06 \times 10^{15}$ *G for PSR J1808-2024; Mereghetti, S. et al., ApJ, 628, 938 (2005)*

Magnetic Field of Astrophysical Objects

	mass $\mathrm{M}_\odot$	**radius** **cm**	$\mathbf{B}^{\mathrm{surface}}_{\mathrm{ovserved}}$ **G**	$\mathbf{B}^{\mathrm{central}}_{\mathrm{max}}$ **G**
Earth	10^{-6}	6×10^{8}	$\lesssim 1$	10^{7}
Jupiter	10^{-3}	7×10^{9}	~ 10	10^{7}
Brown Dwarf	$0.01 - 0.8$	10^{10}	$1 - 10^{3}$	$10^{7} - 10^{8}$
Sun	**1.0**	10^{11}	$\sim$ **few**	10^{8}
White Dwarf	$\simeq$ **1.4**	10^{9}	$10^{3} - 10^{9}$	10^{12}
Neutron Star	**1.0 - 3.0**	10^{6}	$10^{8} - 10^{15}$	10^{18}

Extreme Physics

Dimensions :

- $M \sim 1 - 3\ \mathrm{M}_\odot \quad (\mathrm{M}_\odot \sim 2 \times 10^{33}$ gm)
- $R \sim 10 - 15$ Km
- $\rho_{\mathrm{av.}} \sim 10^{14} - 10^{15}\ \mathrm{g\,cm^{-3}} \quad (\rho_{\mathrm{nuc}} \sim 2.3 \times 10^{14}\ \mathrm{g\,cm^{-3}})$

High Density : Consequences

- Degenerate Material : $T_{\mathrm{F}}\ (E_{\mathrm{F}} = k_{\mathrm{B}}\, T_{\mathrm{F}}) \;>>\; T_{\mathrm{NS}}$

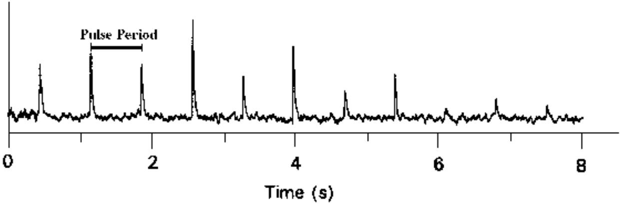
  electrons - degenerate, relativistic

  protons - degenerate, non-relativistic

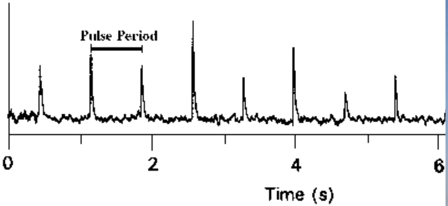
  neutrons - degenerate, non-relativistic
- A high density, zero temperature system.

The Radio Pulsar

Radio Pulsar

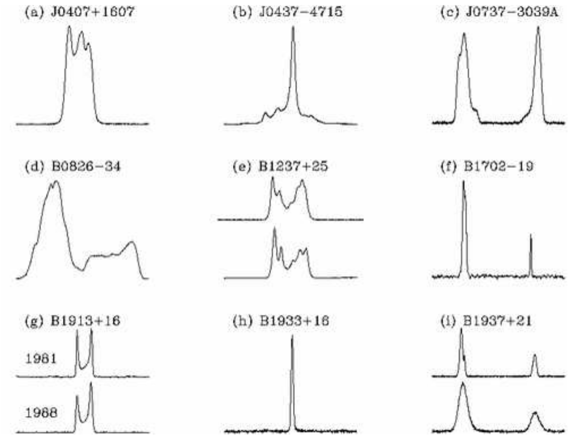


Radio Pulsar



GMRT, NCRA-TIFR
Pune, India

Radio Profile



- wide variation in pulse shapes
- different shape at different energies

Image Credit : Jodrell Bank Observatory

High-Energy Profile

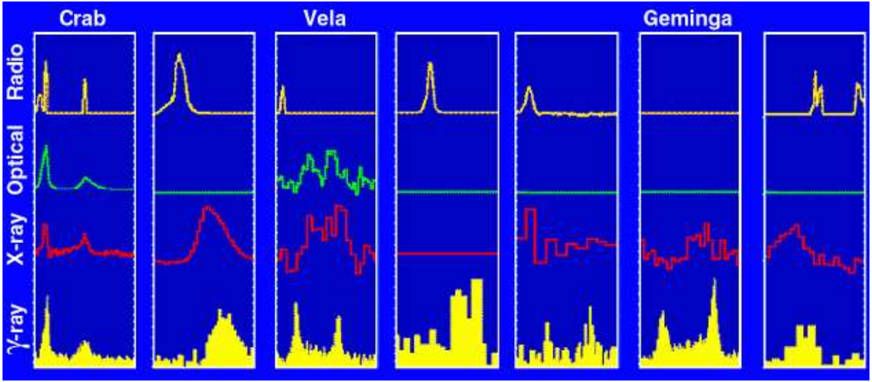


Image Credit : Jodrell Bank Observatory

Magnetosphere

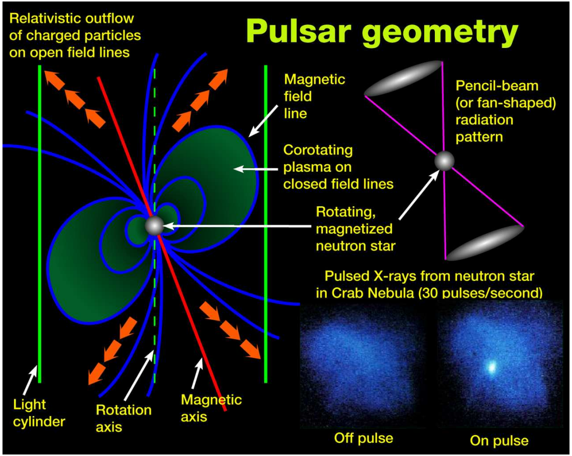


Image Credit : NASA

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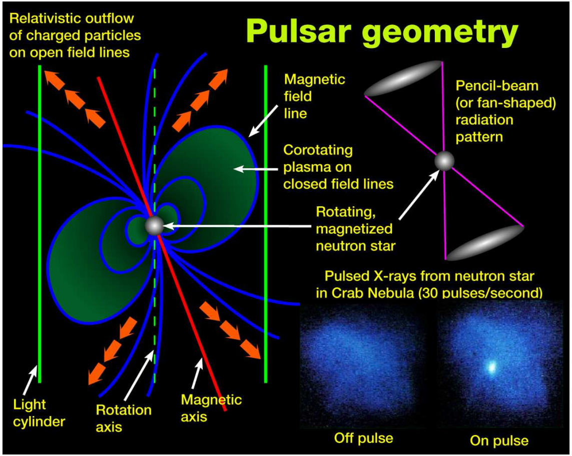


Image Credit : NASA

Magnetosphere - field dominated :

$$F_{\mathrm{G}} / F_{\mathrm{EM}} \simeq \frac{GMm_e}{r^2} \Big/ \frac{e\Omega r B}{c} \simeq 10^{-12}$$

for $B \sim 10^{12}$ G, $P_s \sim 1$ s

F_{G} - gravitational force on an electron

F_{EM} - electromagnetic force on an electron

Magnetosphere - force-free :

$$\mathbf{E} + \frac{1}{c}(\Omega \times \mathbf{v}) \times \mathbf{B} = \mathbf{0} \Rightarrow \delta n = \frac{\Omega.\mathbf{B}}{2\pi e c}$$

$\mathbf{E}$ - induced electric field

δn - net charge density

Brightness Temperature

Brightness Temperature (T_B) of an Emitting Region

$$I_\nu = B_\nu(T_B) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_\mathrm{B} T_B}} - 1}$$

ν - frequency of radiation

I_ν - specific intensity

B_ν - Planck function (blackbody radiation)

Rayleigh-Jeans Law

$I_\nu = \frac{2\nu^2}{c^2} k_\mathrm{B} T_B$ for $h\nu << k_\mathrm{B} T_B$

T_B - blackbody temperature

k_B - Boltzmann constant

Brightness Temperature

Pulsar Radiation :

$I_\nu \sim 10^4 - 10^7 \; erg.s^{-1}.cm^{-2}.Hz^{-1}.sr^{-1}$

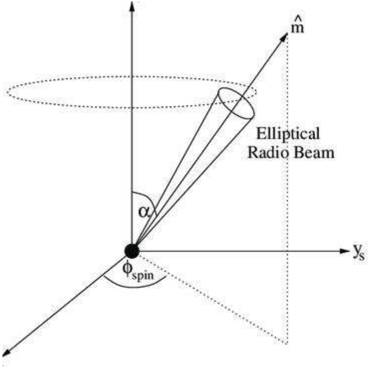
$T_b \sim 10^{23} - 10^{26} \; K$

- absurdly high blackbody temperature
- unfeasible particle energies
- radiation in higher frequency (than radio)

pulsar emission $\neq$ blackbody radiation

Dipolar Model

$$\mathbf{m} = \frac{1}{2} B_p R^3 \left(\cos\alpha\, \mathbf{e}_{||} + \sin\alpha\, \cos\Omega t\, \mathbf{e}_{\perp} + \sin\alpha\, \sin\Omega t\, \mathbf{e}'_{\perp}\right)$$
$$\Rightarrow m = \frac{1}{2} B_p R^3$$



m - stellar magnetic moment

B_p - surface dipolar field
R - stellar radius
Ω - stellar spin frequency
α - angle of inclination
$\mathbf{e}_{||}$ - unit vector parallel to rotation axis
$\mathbf{e}_{\perp}, \mathbf{e}'_{\perp}$ - unit vectors perpendicular to rotation axis

Slow Down : Dipolar Model

Rotating Dipole → Time Variability → Radiation

Radiative Energy : $\dot{E}_{\rm rad} = -\frac{2}{3\,c^3}|\ddot{\mathbf{m}}|^2 = -\frac{1}{6\,c^3} B_p^2\, R^6\, \Omega^4\, \sin^2\alpha$

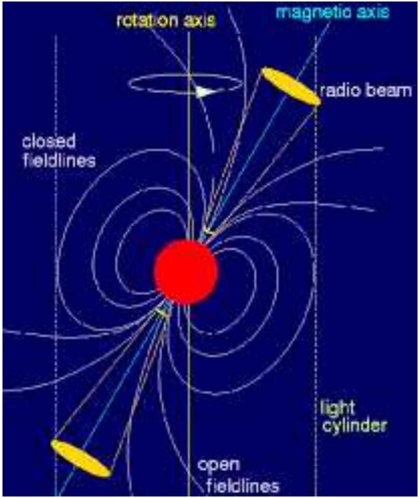
Rotational Energy : $E_{\rm rot} = \frac{1}{2} I\Omega^2 \Rightarrow \dot{E}_{\rm rot} = I\Omega\dot{\Omega}$

Dipolar Field : $E_{\rm rot} = \dot{E}_{\rm rad} \Rightarrow B_p \simeq 3.2 \times 10^{19}(P_s\dot{P}_s)^{1/2}$

Radiation slow-down : $\dot{E}_{\rm rot} < 0 \rightarrow \dot{\Omega} < 0$

Characteristic Age : $\tau_{\rm ch} = \frac{P_s}{2\dot{P}_s}$ for $P_s^\circ << P_s$ (P_s° - initial spin-period)

Radio Pulsar : The Model



Credit : Jodrell Bank Observatory

- fast rotation + strong magnetic field ⇒ strong electric field
  acceleration of charged particles → radiation
  energetic radiation → pair production
- synchrotron radiation, Compton scattering,
  (radio radiation mainly from) curvature radiation

- $P_{\rm spin} \sim 10^{-3} - 10^{1.5}$ s
- $B_{\rm surface} \sim 10^{8} - 10^{15}$ G
- $\dot{E}_{\rm rot} \propto I\Omega\dot{\Omega} \propto \Omega^4 B^2$ - dipole model

Slow-Down : Other..

Gravitational Radiation at the cost of Rotational Energy

$\dot{E}_{\rm GW} < 0 \rightarrow \dot{\Omega} < 0$

Rotating Mass Quadrupole Moment → Gravitational Radiation

$\dot{E}_{\rm GW} = I \, \Omega \, \dot{\Omega} = -\frac{32}{5} \frac{G}{c^5} I^2 \, \epsilon \Omega^6$

ϵ - ellipticity
G - gravitational constant

Characteristic Age : $\tau_{\rm ch}$ (gravitational)

Typically : $\tau_{\rm ch}(EM) << \tau_{\rm ch}(GW)$

Actual slow-down is a combination of EM and GW radiation.

Braking Index

Power Law Deceleration

$\dot{\Omega} = -(constant)\,\Omega^n \rightarrow n = -\frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2}$

n - braking index

n = 3 : magnetic dipole radiation

n < 3 : magnetic dipole radiation + alignment..

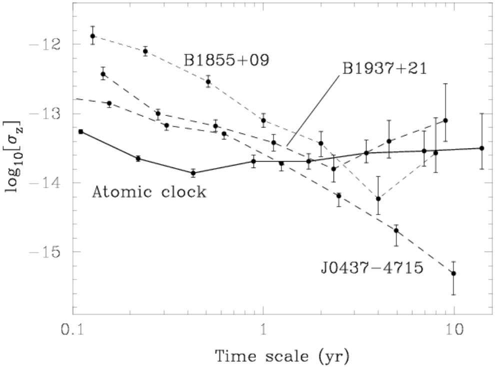
n < 3 : higher magnetic multipoles

n = 5 : gravitational radiation

n = 3.43 : Crab Pulsar (combination effects)

Timing & Null

Precision Timing

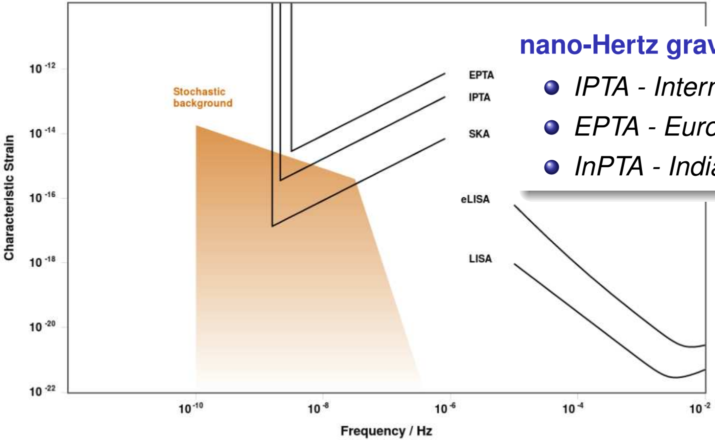


Lorimer D. R., Living Rev. Rel., 11, 8 (2008)

$\dot{P} \sim 5 \times 10^{-22} - 5 \times 10^{-10}$ s/s

The fractional stability of millisecond pulsars compared to an atomic clock. B1855+09 and B1937+21 are comparable (just slightly worse) to the atomic clock over timescales of years. J0437-4715 is inherently stable.

Gravitational Physics : Pulsar Timing Array

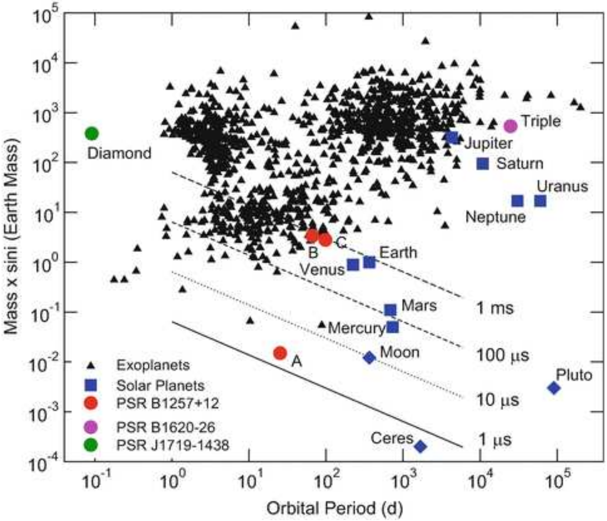


nano-Hertz gravitational wave detection

- *IPTA - International Pulsar Timing Array*
- *EPTA - European Pulsar Timing Array*
- *InPTA - Indian Pulsar Timing Array : GMRT, ORT*

Figure : http://gwplotter.com/

Extrasolar Planet Detection



- timing precision → planet detection
- 1992 : first extra-solar planet (B1257+12)
- planet formation conditions?

Kramer M., Handbook of Exoplanets, 1 (2017)

Time of Arrival

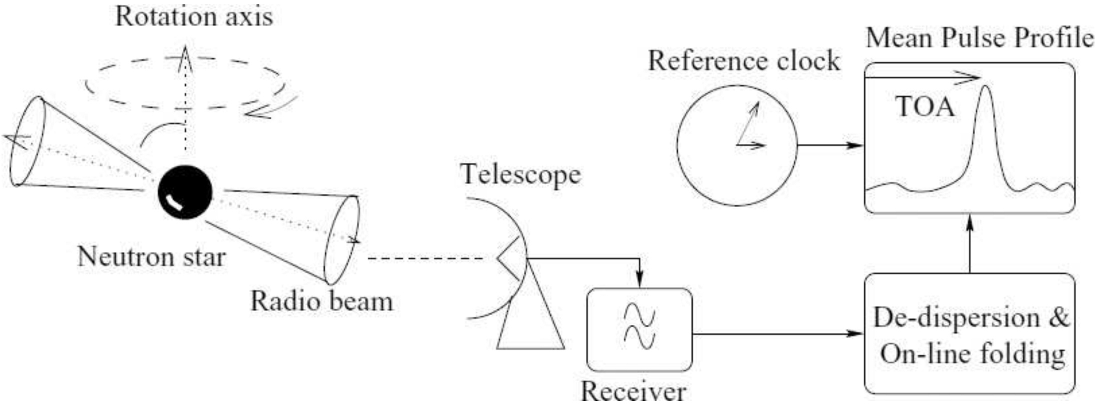
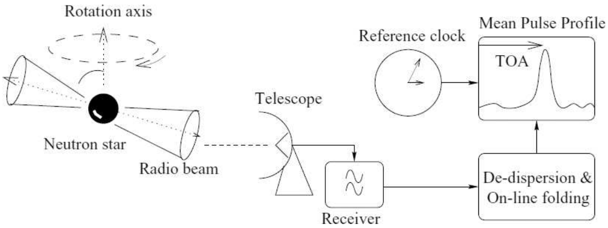


Figure Credit : Lorimer D.R., Living Reviews in Relativity, 11, 8 (2008)

Time of Arrival



TOA : time of arrival

refers to a fiducial point on profile

delay with respect to a template profile

$$\mathcal{P}(t) = a + b\mathcal{T}(t - \tau) + \mathcal{N}(t)$$

- $P(t)$ - observed profile
- $T(t)$ - template profile
- $N(t)$ - noise
- τ - time shift

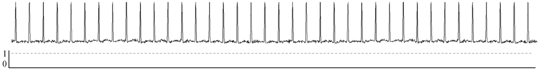
Isolated Pulsars

Time Delay

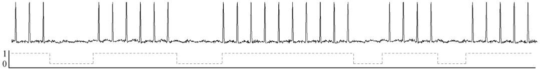
$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} - \Delta/f^2 + \Delta_{R_\odot} + \Delta_{S_\odot} + \Delta_{E_\odot}$$

- t_{SSB} - solar system barycentric delay
- t_{topo} - topocentric delay
- t_{corr} - clock corrections
- Δ/f^2 - correction for dispersion measure
- $\Delta_{R_\odot}$ - Romer delay (light-travel time from telescope to SSB)
- $\Delta_{S_\odot}$ - Shapiro delay (correction for spacetime curvature)
- $\Delta_{E_\odot}$ - Einstein delay (gravitational redshift + time dilation)

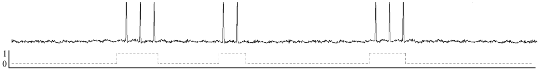
Nulling Pulsars



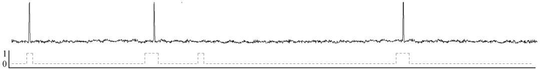
Radio Pulsar



Nulling Pulsar

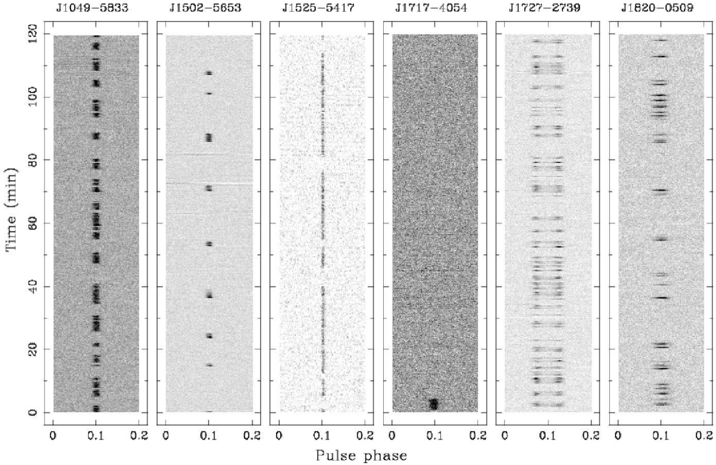


Extreme Nulling



RRAT

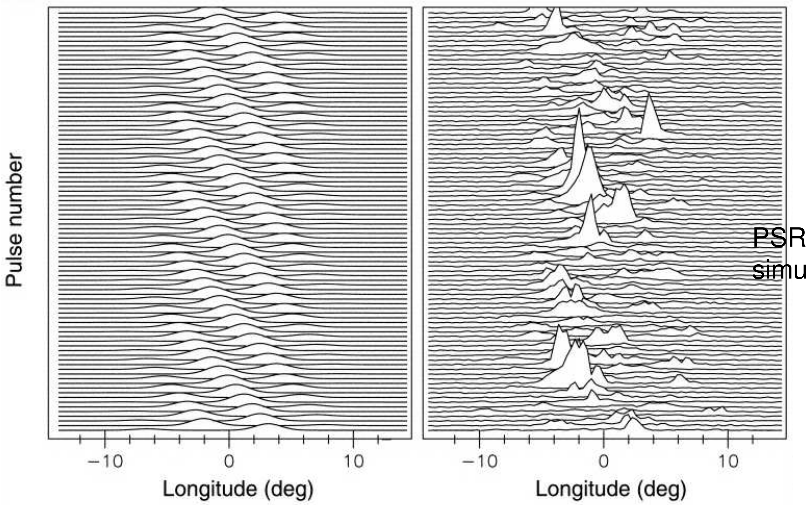
Nulling Behaviour



varied nulling patterns

Figure credit : Wang N., Manchester R. N., Johnston S., MNRAS, 377, 1383 (2007)

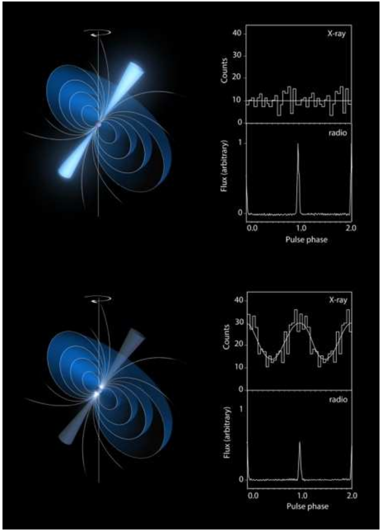
Drifting Subpulses



PSR B0943+10
simulated and observed behaviour

Figure credit : Deshpande, A. A., Rankin, J. M., ApJ, 524, 1008 (1999)

Mode Changing



PSR B0943+10 - radio & X-ray brightness switched
Hermsen W. et al., Science, 339, 436 (2013)

Image credit : ESA/ATG medialab; ESA/XMM-Newton; ASTRON/LOFAR

Nulling Behaviour

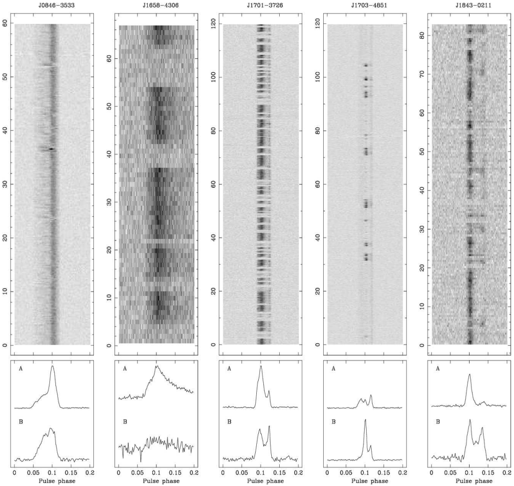


Figure credit : Wang N., Manchester R. N., Johnston S., MNRAS, 377, 1383 (2007)

Nulling Behaviour

- null - abrupt cessation of pulsed emission
- association with drifting of subpulses
- association with mode changes
- association with switching emission frequencies
- association with change in $\dot{P}_s$

Population Characteristics

- $\sim$ 200 nulling pulsars
- $0.5s \lesssim P_s \lesssim 10.0s$
- 10^{11} G $\lesssim B_s \lesssim 10^{13}$ G
- 10^6 Yr $\lesssim \tau_{\rm ch} \lesssim 10^8$ Yr
- 10 pc.cm$^{-3} \lesssim DM \lesssim 10^3$ pc.cm^{-3}

Nulling Pulsars II

Characterising Parameters

- nulling fraction (NF) $\lesssim$ 95%
- null length (NL) [not much data]
- neither NL or NF is an unique marker

NP Classes (NL)

- classical nuller - a few pulses
- intermediate nuller - up-to a few hours
- intermittent pulsar - even years
- RRAT - characterised by single pulse emission

Radio Pulsar : Age

- $P-$ current pulsar period
- P_0- initial pulsar period
- $\dot{P}-$ current period derivative
- $B-$ current dipolar magnetic field
- τ_p- current pulsar age

$$\begin{aligned} B &= a(P\dot{P})^{1/2} \Rightarrow \\ \tau_p &= \frac{1}{2}a^2(P^2 - P_0^2)B^{-2} \\ &\simeq \frac{1}{2}a^2 P^2 B^{-2} \simeq \ (P_0 << P) \end{aligned} \tag{1}$$

$\tau_c = \left(\frac{\mathrm{P}}{2\dot{P}}\right)$, constant B justified over radio pulsar lifetime ($\sim 10^6$ year).

Radio Pulsar : Life Expectancy

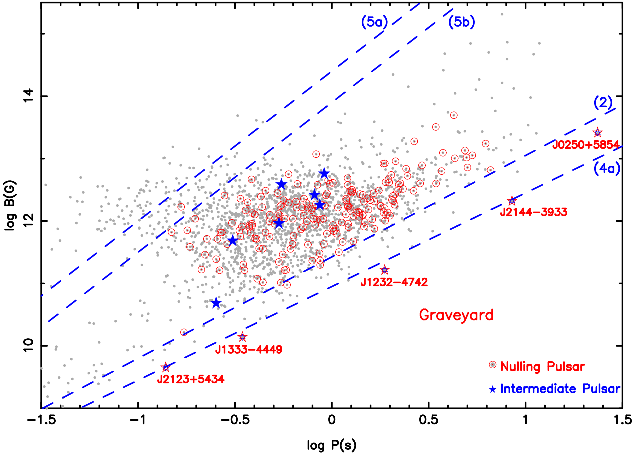
$$\begin{aligned}
\log\ B &= a_1(\log\ P + \log\ \dot{P}), \quad \text{dipolar field} \\
\tau_p &= a_3 P^2 B^{-2}, \quad \text{current age}
\end{aligned}$$

$$\begin{aligned}
\log\ B &= a_2 \log\ P + b_2 \log\ \dot{P}, \quad \text{death-line} \\
\tau_t &= a_4 P_D^2 B^{-2}, \quad \text{age at death} \\
P_D &= f(B), \quad \text{period at death}
\end{aligned}$$

$$\epsilon_{\rm proximity} = \frac{\tau_t - \tau_p}{\tau_t}, \quad \text{death-line proximity parameter}$$

Nulling not correlated with $\epsilon_{\rm proximity}$.

Nulling Pulsars : Death-line



- **2** - very curved field
- **4a** - twisted, strong high multipole field
- **5a, 5b** - central/shifted dipole

Figure credit : Konar S., Deka U., JApA, 40, 42 (2019)

***** GMRT Project ongoing***

The Resources

Resource I : Suggested Reading

- *Can Stars Find Peace?*
G. Srinivasan

- *Pulsars*
R. N. Manchester and J. H. Taylor

- *Pulsar Astronomy*
A. Lyne and F. Graham-Smith

- *Handbook of Pulsar Astronomy*
D. R. Lorimer and M. Kramer

- *Stellar Remnants : Saas-Fee Advanced Course 25*
S. D. Kawaler, I. Novikov and G. Srinivasan

- *Black Holes, White Dwarfs and Neutron Stars*
S. L. Shapiro and S. A. Teukolsky

Resource II : Database

- *Pulsars(ATNF) :*
http://www.atnf.csiro.au/research/pulsar/psrcat/

- *Globular Cluster Pulsars (Paulo Freire) :*
http://www.naic.edu/∼pfreire/GCpsr.html

- *Galactic Millisecond Pulsars :*
http://astro.phys.wvu.edu/GalacticMSPs/

- *AXPs, SGRs, Magnetars (McGill) :*
http://www.physics.mcgill.ca/ pulsar/magnetar/main.html

- *X-Ray Pulsars (Remeis-Sternwarte) :*
https://www.sternwarte.uni-erlangen.de/wiki/index.php/List-of-accreting-X-ray-pulsars

- *Glitching Pulsars (Jodrell Bank) :*
http://www.jodrellbank.manchester.ac.uk/research/research-groups/pulsars-and-time-domain-astrophysics/glitches-pulsars/

- *Gamma-Ray Pulsars (LAT) :*
https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars