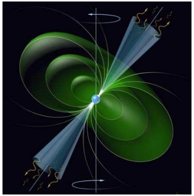
Astrophysics of Neutron Stars : The Exotica

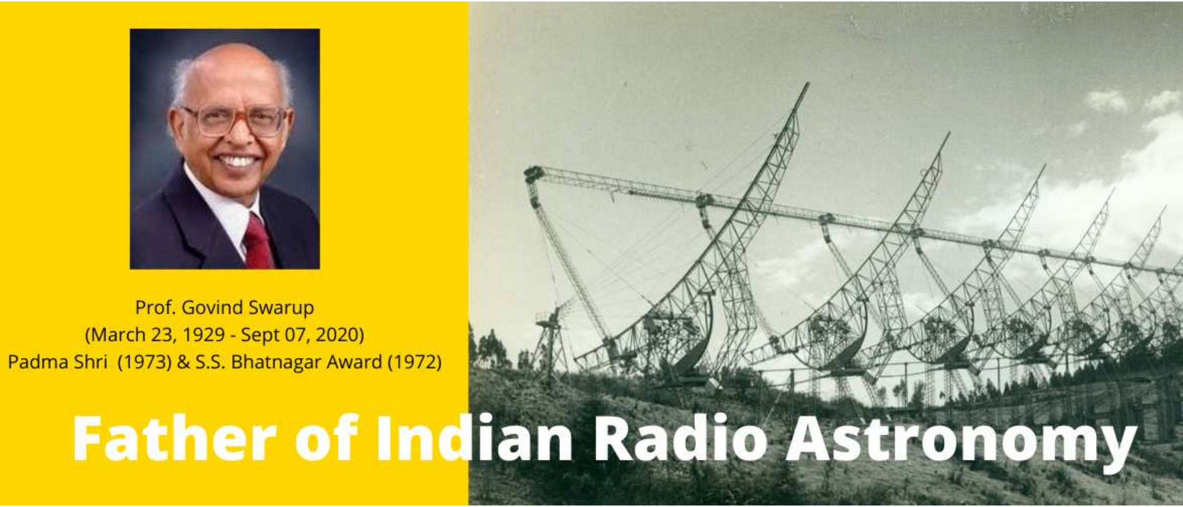
Sushan Konar



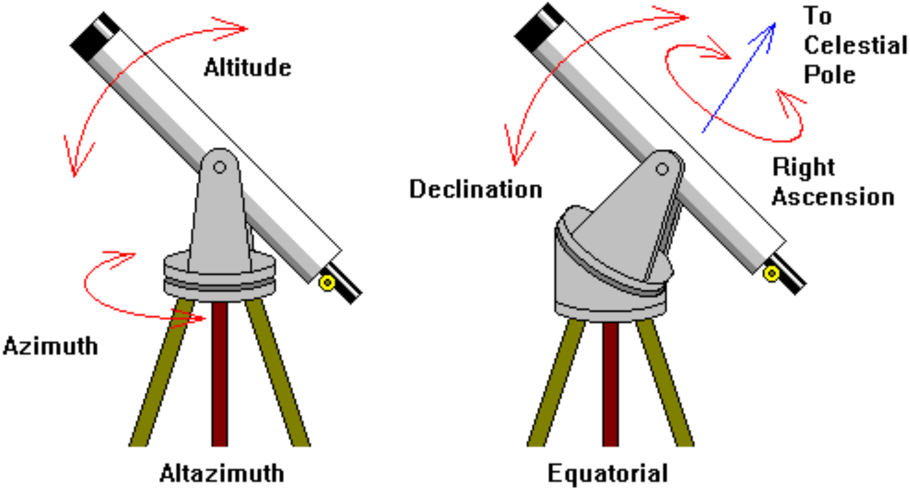
Astronomy from Archival Data

An IAU-OAD Project

2020


Prof. Govind Swarup
(March 23, 1929 - Sept 07, 2020)
Padma Shri (1973) & S.S. Bhatnagar Award (1972)
Father of Indian Radio Astronomy

Equatorial Mount



Ooty Radio Telescope

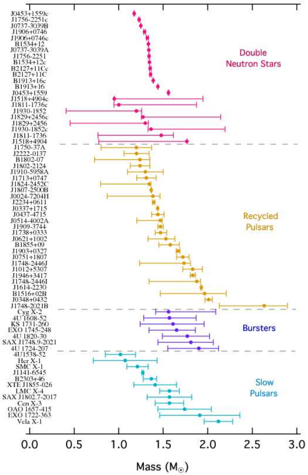
Giant Meterwave Radio Telescope

The Exotica :

1. The Interior
2. The Superfluidity
3. The Glitch

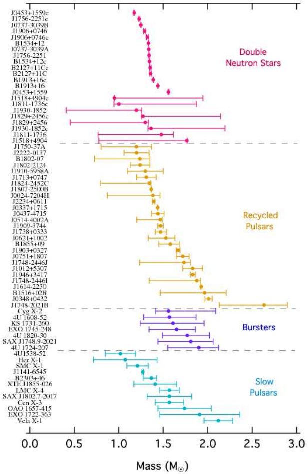
The Interior

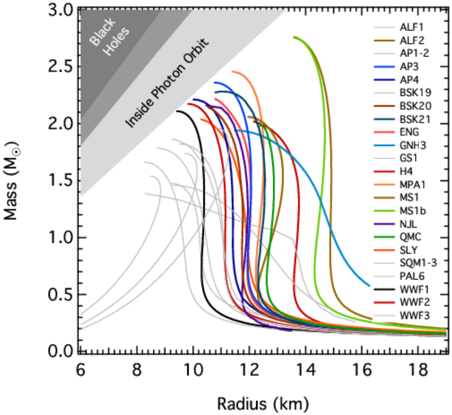
Physics of Dense Matter



Ozel F. et al., Ann.Rev.Astron.Astrophys., 54, 401 (2016)

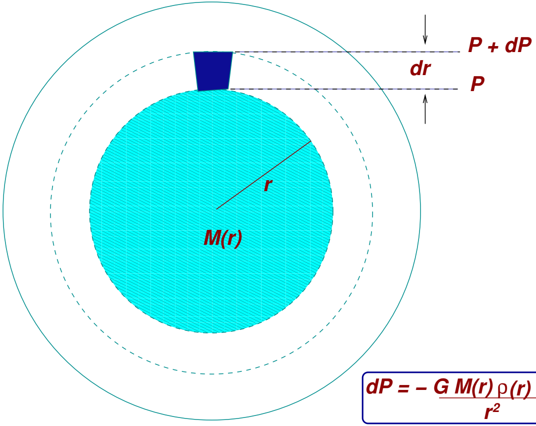
Physics of Dense Matter





Ozel F. et al., Ann.Rev.Astron.Astrophys., 54, 401 (2016)

Stellar Equilibrium



$$dP = -\frac{G\,M(r)\,\rho(r)\,dr}{r^2}$$

Stellar Structure

Equations governing stellar structure :

1. $\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$: hydrostatic pressure balance
2. $\frac{dL}{dr} = 4\pi r^2 \rho[\epsilon_n(r) - \epsilon_\nu]$: energy generation
3. $\frac{dT}{dr} = -\frac{3}{4ac}\frac{k\rho}{t^3}\frac{L(r)}{4\pi r^2}$: energy transport
4. $P = P(\rho, T)$: equation of state
5. $\frac{dM}{dr} = 4\pi r^2 \rho$: mass-radius relation

Stellar Structure : Compact Objects

Equations governing *compact* stellar structure :

1. $\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$: hydrostatic pressure balance
2. $P = P(\rho)$: equation of state
3. $\frac{dM}{dr} = 4\pi r^2 \rho$: mass-radius relation

No energy generation.

No energy transport.

No temperature.

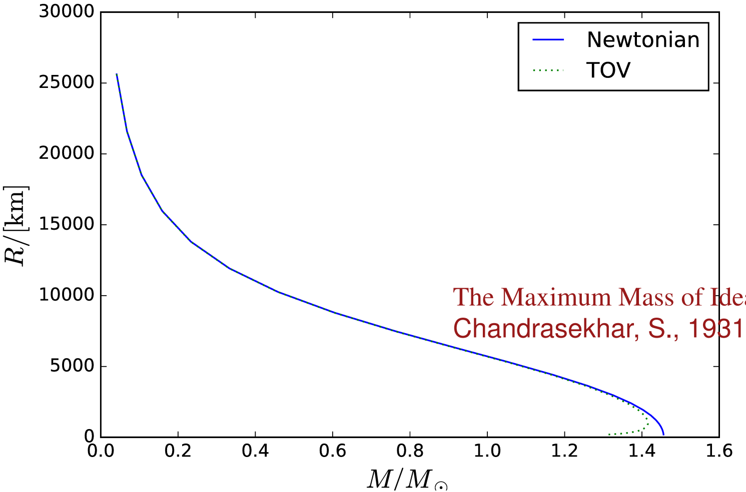
White Dwarf

Giant Single Crystal in the Sky

- $M \sim 0.5 - 1.4\ \mathrm{M}_\odot$
- $R \sim 10^4$ km
- $\rho \sim 10^9\ \mathrm{g\,cm^{-3}}$
- $B \lesssim 10^9$ Gauss ($B \sim$ Gauss for Earth)

A crystalline solid of heavy atoms (upto Fe^{56}) immersed in a sea of Fermi-degenerate electrons.

White Dwarf : Chandrasekhar Mass



The Maximum Mass of Ideal White Dwarfs
Chandrasekhar, S., 1931, MNRAS, 91, 456

Stellar Structure : GR Effects

Equations governing *compact* stellar structure :

1. $\frac{dP}{dr} = -\frac{G(M(r)+4\pi r^3 P(r)/c^2)(\rho(r)+P(r)/c^2)}{r^2\left(1-\frac{2GM(r)}{r^2c^2}\right)}$
   Tolman-Oppenheimer-Volkoff (TOV) Equation
2. $P = P(\rho)$: equation of state
3. $\frac{dM}{dr} = 4\pi r^2 \rho$: mass-radius relation

No energy generation.

No energy transport.

No temperature.

Equation of State

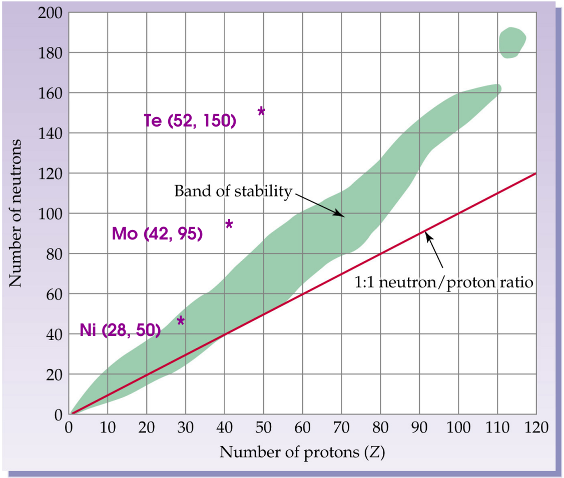
Active Stars : nuclear fusion : $P_{\mathrm{Gr}} = P_{\mathrm{gas}} + P_{\mathrm{rad}}$

Dead Stars : no energy generation : $P \sim P_{\mathrm{Fermi\ degeneracy}} + P_{\mathrm{other}}$

- White Dwarf :
  degenerate electrons + ionic crystal
  $\rho \sim 10^6 - 10^9\ \mathrm{g\,cm^{-3}}$ $\rightarrow$ relativistic electrons : $P_{\mathrm{gas}} \sim \rho^{4/3}$
- Neutron Star :
  degenerate neutrons + degenerate protons, electrons
  high density : nuclei dissolves, $p + e \rightarrow n + \bar{\nu}$
  $\rho_{\mathrm{av.}} \sim \rho_{\mathrm{nuc}}$ $\rightarrow$ non-relativistic neutrons : $P_{\mathrm{gas}} \sim \rho^{5/3}$, $P_{\mathrm{nuclearinteractions}}$

The Neutron-Proton Ratio

- *neutron-rich elements in the crust of a neutron star*



Credit : Sushan Konar, 2017, Resonance

State of Matter

Crust : Metallic

- Outer Crust : $\rho \leq \rho_{\mathrm{drip}}$

degenerate electrons + neutron-rich nuclei

- Inner Crust : $\rho_{\mathrm{drip}} \leq \rho \leq \rho_{\mathrm{nuc}}$

deg. electrons + superfluid neutrons + neutron-rich nuclei

Core : Superfluid

- Outer Core - deg. electrons + sf neutrons + superconducting protons
- Inner Core - ? exotic phases ?

Rotation : vortices in neutron superfluid
Magnetic Field : superconducting fluxoids and/or crustal currents

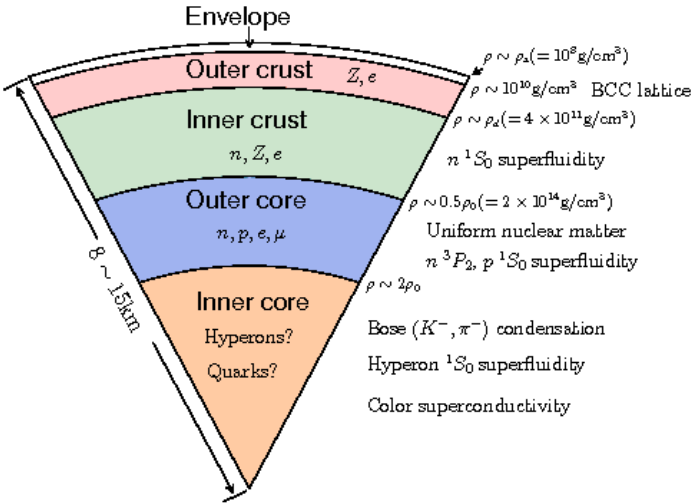
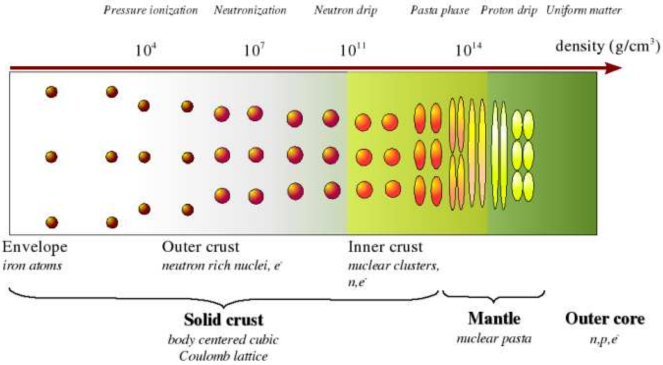


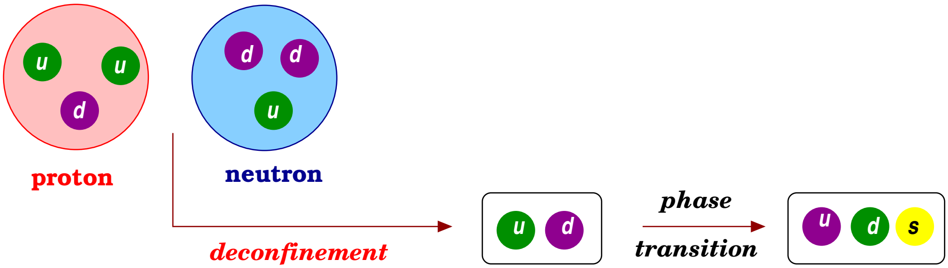
Figure credit : Lim, Y. et al. Int.J.Mod.Phys. E26 (2017)

Nuclear Pasta

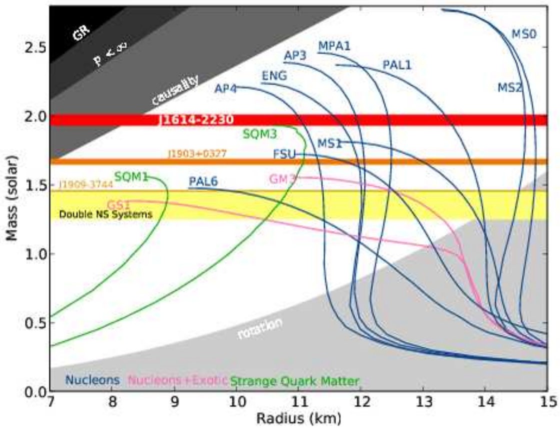


Chamel N., Haensel P., Living Reviews in Relativity, 11 (2008)

Strange Star?



EoS : Mass-Radius Relation



$M \simeq 2.14\,\mathrm{M}_\odot$
(heaviest neutron star so far)

- *Cromartie H. T. et al., Nature Astronomy, 439 (2019)*

Figure credit : Demorest P. et al., Nature, 467, 1081 (2010)

The Superfluidity

State of Matter

- Fermi Temperature : $T_{\mathrm{F}} \simeq 10^{12}$ K
- NS Temperature : $T_{\mathrm{NS}} \simeq 10^{6}$ Kd
- *"BCS-like" pairing of neutrons and protons (1950)*
- Superfluid Transition Temperature : $T_{\mathrm{C}} \simeq 10^{11}$ K

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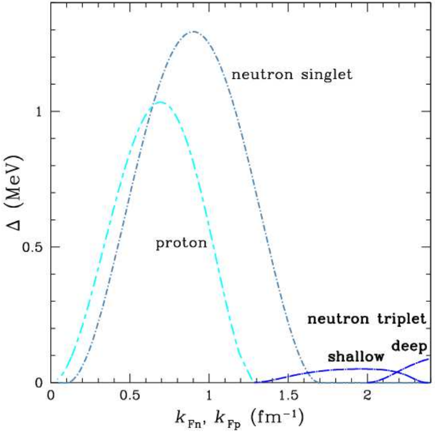
Pairing Energies



Ho, W. C.G. et al. PoS ConfinementX, 260 (2012)

Δ - specise-wise pairing energy

k_F - Fermi wave-number

Critical Temperatures

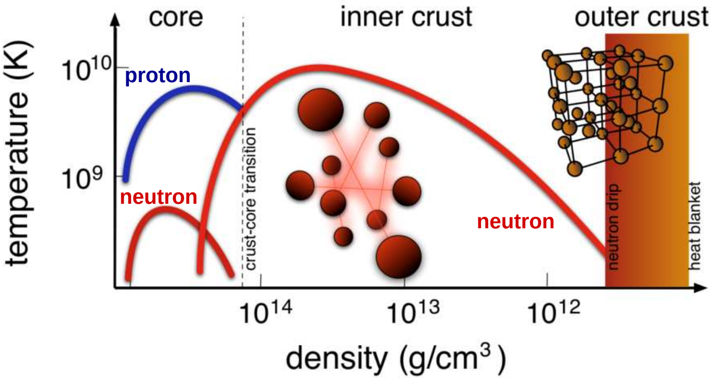
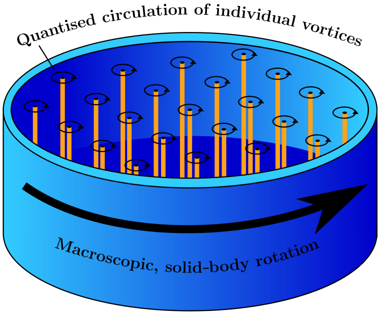


Figure credit : Graber, V. et al., Int.J.Mod.Phys., D26, 08, 1730015 (2017)

Neutron Supefluidity



- *rotation by creation of vortices*
- quantum of circulation : $I_n = h/2m_n \sim 2 \times 10^{-3}\ cm^2.s^{-1}$
- number of rotational vortices : $2\pi R^2 \Omega_{\rm NS}/I_n \sim 2 \times 10^{16}(P/s)^{-1}$

Figure credit : Graber, V. et al., Int.J.Mod.Phys., D26, 08, 1730015 (2017)

Proton Superconductivity

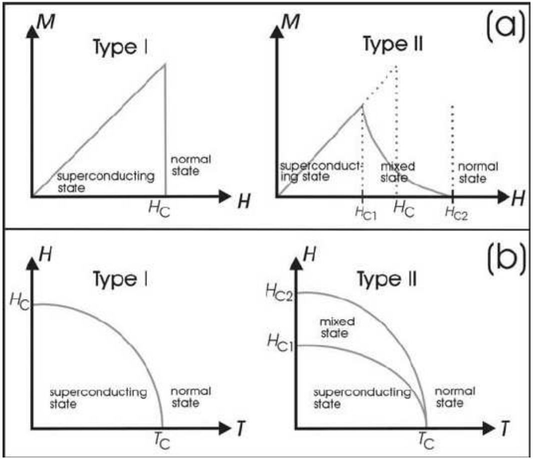


Figure Credits : Iman Santoso

superconductor magnetisation

- Type-I - Meissner effect for $H < H_c$
- Type-II - flux penetration for $H_{c1} < H < H_{c2}$

Proton Superconductivity

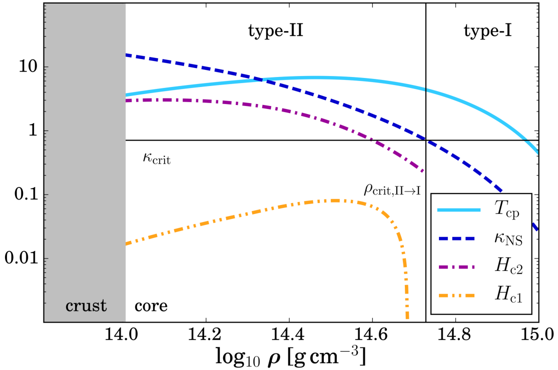


Figure credit : Graber, V. et al., Int.J.Mod.Phys., D26, 08, 1730015 (2017)

density-dependence

- $T_{\rm cp}$ - transition temperature (10^9 K)
- H_{c1}, H_{c2} - critical fields (10^{16} G)
- $\phi = hc/2e = 2 \times 10^{-7}$ G.cm^2 - flux quantum
- number of flux quanta rotational vortices : $BR^2/\phi \sim 10^{31}(B/10^{12}\ G)^{-1}$

EoS : Cooling Curves

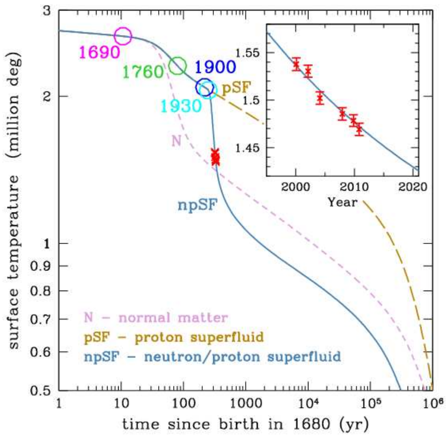
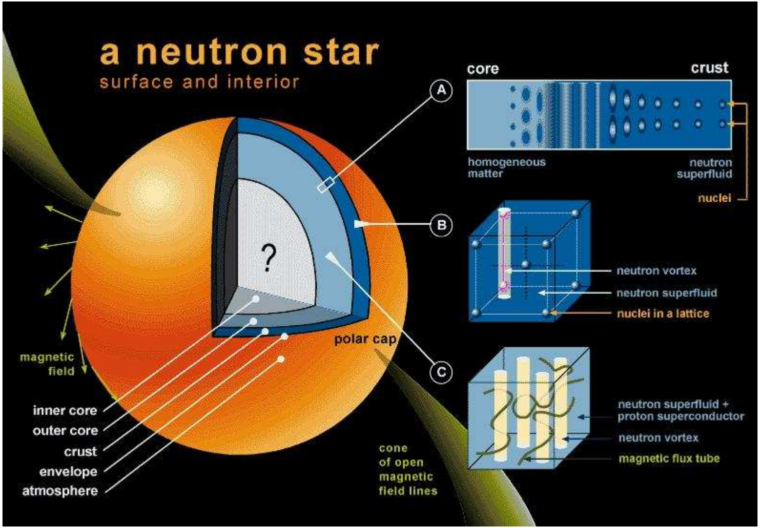


Figure credit : Ho, W. C.G. et al. PoS ConfinementX, 260 (2012)

Inter-pinned Superfluids



The Glitch

Vela Pulsar

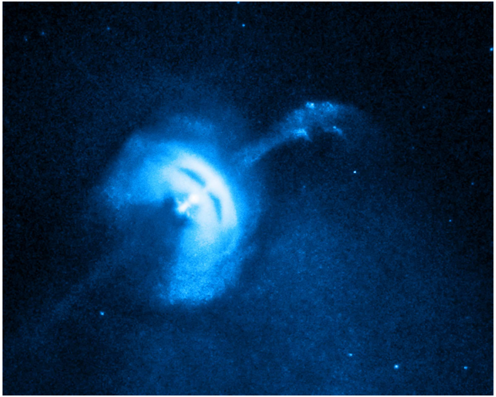


Image credit : NASA

In October 1968, astronomers from the Sydney University discovered a pulsar with a period of 89 ms in the Vela constellation. The Crab pulsar was found the next month by astronomers from the Green Bank observatory.

The Glitch

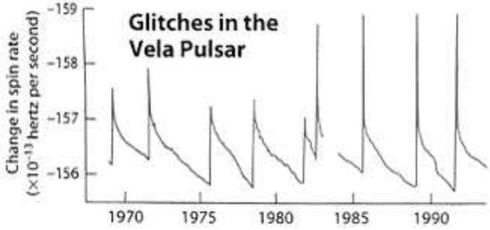


Image credit : Chamel N., 2013

First Glitches

Between February 24 and March 3 1969, Vela was found to pulse more rapidly than before!

The rotational frequency had increased by $\delta\Omega/\Omega \simeq 2 \times 10^{-6}$.

The increase in the spin-down rate was $\Delta\dot{\Omega}/\dot{\Omega} \simeq 7 \times 10^{-3}$.

A smaller glitch was also observed in the Crab pulsar in September 1969.

$$(\delta\Omega/\Omega)^{\text{vela}}_{\text{typical}} \sim 10^{-6}, \qquad (\delta\Omega/\Omega)^{\text{crab}}_{\text{typical}} \sim 10^{-9}$$

The Glitch

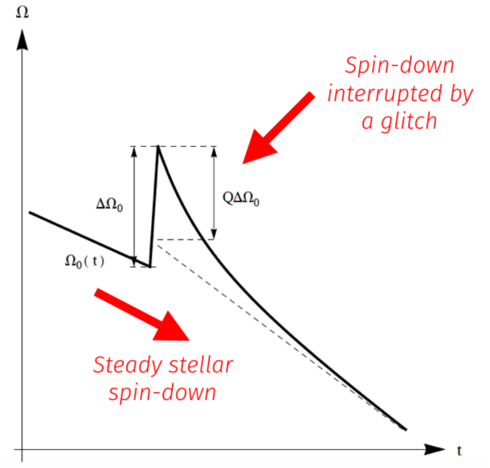


Image credit : Lisa Drummond

The Glitch

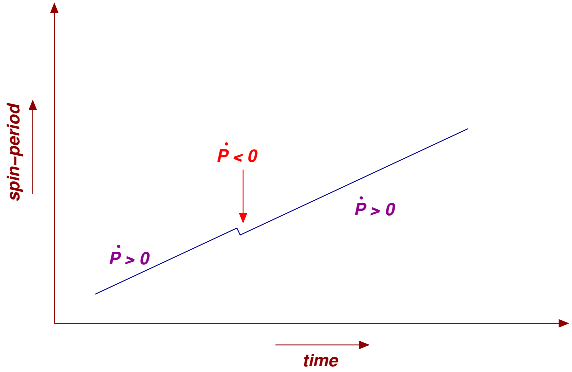


Image credit : Sushan Konar

- sudden decrease in P $(10^{-12} \leq \delta\nu/\nu \leq 10^{-4})$
- followed by a relaxation towards unperturbed P

Statististics of Glitch

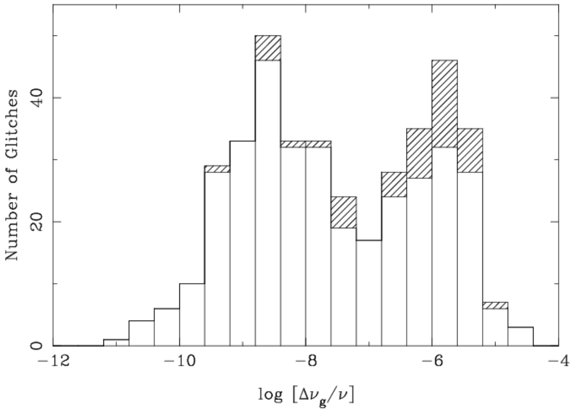


Figure credit : Yu M. et al., MNRAS, 429, 688 (2013)