Neutron Stars: Observations

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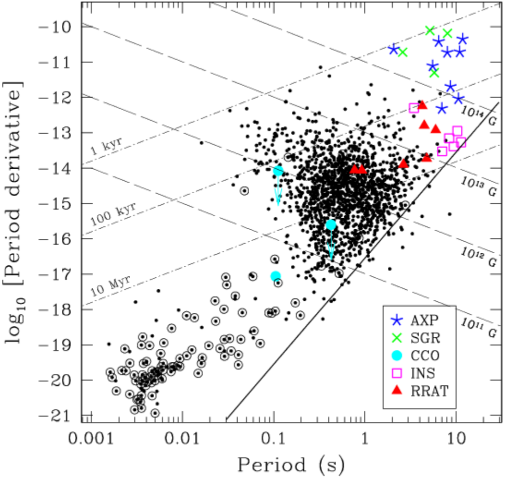
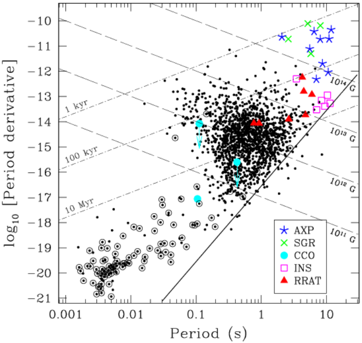
Neutron star observations: overview

- From the observational point of view, neutron stars come in many different forms:
  - Pulsars (including millisecond pulsars)
  - Anomalous X-ray pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs)
  - X-ray binaries, including high-mass and low-mass X-ray binaries (HMXBs and LMXBs)
  - Central Compact Objects
  - Gravitars?
- Radiate in many different bands: radio, optical, X-ray/gamma-ray, gravitational waves . . .
- How best to make sense of this wealth of information?

The P–$\dot{P}$ diagram

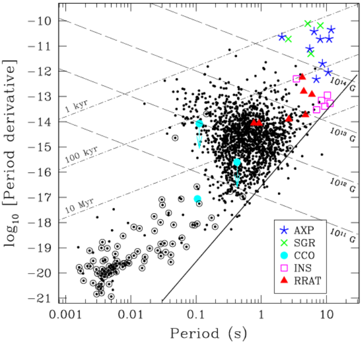


The compact object zoo: pulsars

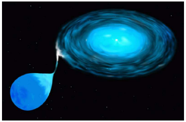


The Crab nebula (HST)

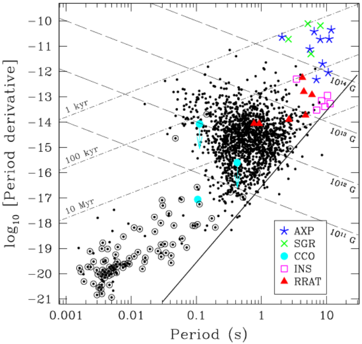
The compact object zoo: millisecond pulsars/LMXBs

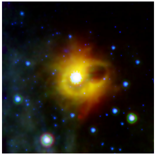


Artist's impression of an LMXB!



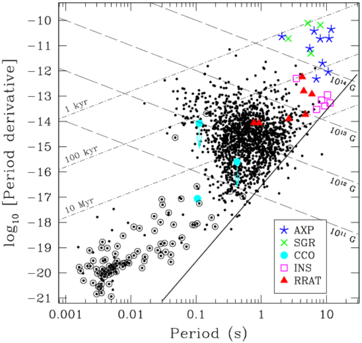
The compact object zoo: AXPs/SGRs

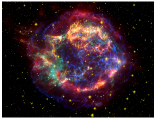




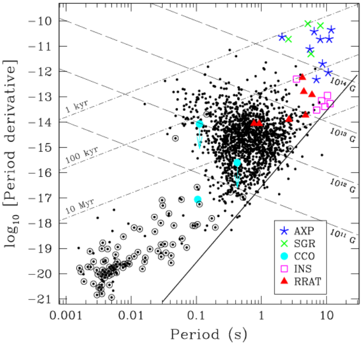
Ring surrounding SGR 1900+14 (Spitzer Space Telescope)

The compact object zoo: Central Compact Objects




Cas A nebula (Spitzer Space Telescope)

The compact object zoo: gravitars?



Not seen electromagnetically!

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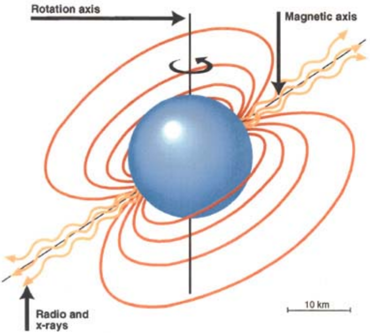
Radio pulsars: basic model

- First discovered by Hewish & Bell 1967.
- Understood as neutron stars spinning down under action of an electromagnetic torque.



Radio pulsars: spin-down

- Simplest model for spin-down torque is a power law:

$$I\dot{\Omega} = f(\chi, B)\Omega^n$$

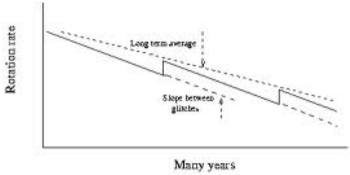
  with $f \sim B^2 \sin^2 \chi$, $n = 3$ for magnetic dipole in a vacuum.
- Can test this if *second times derivative* of Ω can be measured:

$$n_{\rm obs} = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2}$$

- Actual observed 'clean' values of $n_{\rm obs}$ all *less* than three.
- Suggested theoretical explanations include
  - Emission mechanisms other than vacuum dipole, involving particle accelerations in magnetosphere.
  - Time evolution in χ, B or even the 'effective' value of I.

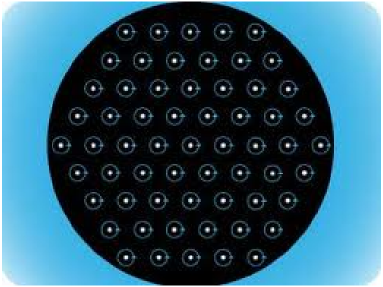
Radio pulsars: glitches

- Most of the time pulsar spin frequencies gradually decrease
- Occasionally some younger pulsars under-go sudden spin-ups
- $\sim$ 1% of spin-down reversed in glitches
- Taken as evidence that about 1% of moment of inertia decoupled from smooth spin-down.



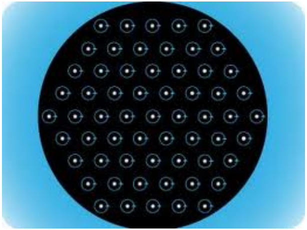
Basics: Superfluid neutron stars

- Can model star as a mixture of
  1. Superfluid neutrons
  2. Charged particles (protons & electrons)
- The superfluid neutrons rotate by forming an array of vortices:

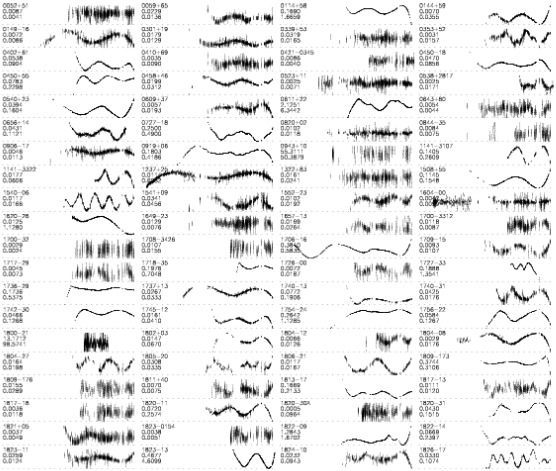


Radio pulsars: glitches

- Area density of vortices determine rotation rate.
- For smooth spin-down, vortices migrate outwards at a rate $\propto \dot{\Omega}$, to allow for smoothly decreasing area density.
- *Pinning model*: some of the superfluid vortices are rigidly attached to the solid phase, preventing them from undergoing smooth spindown.
- When a sufficiently large angular velocity lag has built up catastrophic unpinning occurs, corotation is established, spinning up the charged part of the star.



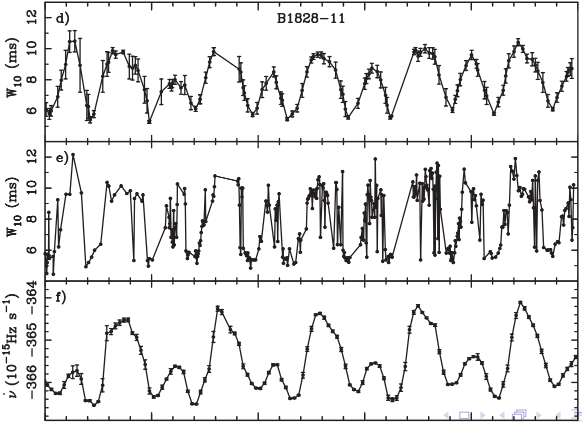
Radio pulsars: timing noise



Hobbs et al (2010)

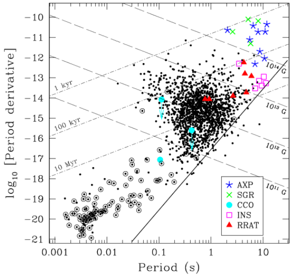
Radio pulsars: timing noise

- Some pulsars display some sort of quasi-periodiucity in their timing residuals.
- May be evidence for free precession
- But evidence is emerging for magnetosphere playing an important role in the noise process.



Millisecond pulsars and X-ray binaries

- Pulsars in binary system can accrete material from their companion star.
- During accretion phase, get an X-ray binary.
- In low-mass systems, accretion is long-lived, and accreted angular momentum spins pulsar up to millisecond periods.



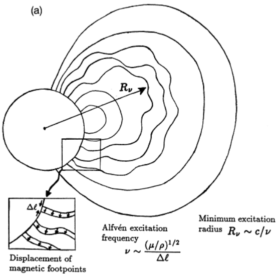
Magnetars: observations

- There exists a set of peculiar ‘pulsars’ whose luminosities far exceed their spin-down energies
- Traditionally divided into
  1. Anomalous X-ray Pulsars (AXPs)
  2. Soft Gamma-Ray Repeaters (SGRs)

  but distinction becoming blurred.
- What are they?

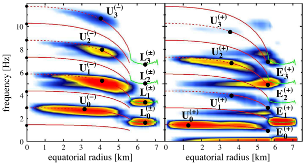
Magnetars: Thompson & Duncan model

- Thompson & Duncan developed *magnetar* model (see sketch belwo from Thompson & Duncan 1995)
- They gave several different arguments that AXPs/SGRs are ultra-magnetised neutron stars, $B \sim 10^{15}$ G.
- Energetics explained by decay of magnetic field on $\sim 10^5$ year timescale
- Magnetic field diffuses, building up strain in elastic crust. When breaking strain reach, reconfiguration of magnetic field occurs, powering a relativistic fireball.



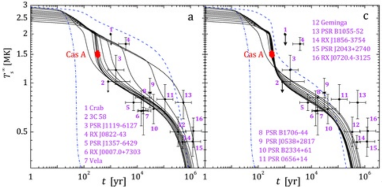
Magnetars: quasi-periodic oscillations

- Quasi-periodic oscillations have been seen in the tails of some giant SGR flares.
- First clear evidence for *neutron star oscillations*.
- Relating observed frequencies to NS structure is an active area of research.
- Much of current effort looks at magnetoelastic models, e.g. Gabler et al 2013, who confirm existence of ‘continuos spectrum’:



Central compact objects & cooling

- CCOs are ‘hot spots’ in supernovae remnants with thermal X-ray specta; presumably cooling neutron stars.
- For most stars, cooling dominated by neutrino emission from core.
- Density and state of matter determine exact reactions, e.g.
  - (m)Urca: n $\rightarrow$ p + e + $\bar{\nu}_e$ and p + e $\rightarrow$ n + ν_e
- Fast cooling can indicate presence of exotic component...
- ...or onset of superfluidity!



Shternin et al 2011

Summary

- Exist models to explain all the various observational manifestations of compact objects.
- Many aspects still not fully understood, e.g. braking indices, timing noise.
- Relationship between the different ‘species’ still a matter of debate . . .