Pulsar Properties: the connection between radio and high-energy pulses

- The largest pulses detected at radio wavelengths appear to be synchronised with the high-energy (x-ray) emission.
- We also see structure on the timescale of nanoseconds. This is really quite astonishing, because the speed of light is only 30 centimetres per nanosecond and for us to be able to detect structure within pulses on nanosecond timescales implies that these events are localised to something that is at most a few metres across!
Pulsar Properties: the connection between radio and high-energy pulses

- The connection between radio and high-energy pulses may also be related to the micro structure in normal pulses.
- The Pulsar emission and in particular the micro pulses are highly polarised, up to 100% elliptically polarised and often greater than 10% circular polarisation.
- The characteristic S-like swing of polarisation PA (position angle) implies that this is an aspect of the viewing geometry.

Pulsar Properties

- Pulsars are weak, steep spectrum radio sources with $\alpha \approx -1.7$, and median luminosity of around 3 mJy/kpc$^2$.
- The numbers known are approximately:
  - Radio: $\sim 2500$
  - Optical: $\sim 6$
  - X-ray: $\sim 100$
  - Gamma-ray: $> 200$

The Life of Pulsars

Pulsar periods increase with time. The slowing down implies they are losing energy. We can estimate the energy loss rate as follows:

$$ E_{\text{rot}} = \frac{1}{2} I \omega^2 $$

$$ \Rightarrow \frac{dE_{\text{rot}}}{dt} = I \omega \frac{d\omega}{dt} $$

$\omega$ from $P$, $\dot{\omega}$ from $\dot{P}$

For the Crab pulsar

$$ P = 3.33 \times 10^{-2} \, s $$

$$ \dot{P} = 4.23 \times 10^{-13} \, s^{-1} $$

Assume $M=1.4 \, M_\odot$

$$ \Rightarrow R = 1.2 \times 10^4 \, m $$

$$ \Rightarrow I = 1.4 \times 10^{38} \, \text{kg m}^2 $$

Energy losses $\Rightarrow$ Power $= 6 \times 10^{31} \, W$
The Life of Pulsars

- Pulsar periods when pulsar was formed:
  - J0537-6910: <14 ms
  - B0531+21: 19 ms
  - B1951+32: 27 ms
  - B0540-69: 30 ms
  - J0205+6449: 60 ms
  - J1811-1925: 62 ms
  - J1124-5916: 90 ms
  - B0538+2817: 139 ms

- As pulsars age they move to the right on this diagram until they reach the graveyard zone, where they are unable to sustain pulses (because the rotation energy and magnetic fields are declining).
- The pulses turn off for periods of seconds up to hours, and some are seen more “off” than “on”.
- Eventually they will vanish from sight.

Graphic from Michael Kramer, Jodrell Bank.
The Life of Pulsars

- When initially formed, pulsars are "born" with small rotation periods, on the order of 1 to 10 milliseconds, and large slow down rates, $P$-dot, on the order of $10^{-12}$ seconds per second.
- They then evolve initially along lines of constant slow down rate.
- Eventually, their slow down rate decreases but their magnetic field also weakens, making their radio emission less powerful. When they are too faint to be detected, we say they have crossed the pulsar "death line" and have become invisible.
- It is believed that future millisecond pulsars enter the "graveyard" as members of binary systems. As the companion evolves, mass and angular momentum are transferred from the companion to the pulsar, spinning it up.
- Once "spun-up", the pulsar is "born again" as a millisecond pulsar.
- The only problem with this picture is that it would predict that all millisecond pulsars are members of binary systems. But they aren't.... However, one of them, PSR 1957+20, nicknamed the "Black Widow" appears to be evaporating its companion away. So perhaps all single millisecond pulsars are "black widows".
Pulsars: Proper Motion

• When the pulsar is formed, the supernova explosion is not necessarily symmetric and therefore the pulsar may be left with a significant velocity relative to the centre of the supernovae remnant.

• For example, in J0538+2816 (S147), the proper motion tells us that the age of the supernova is approximately 30,000 years. Red cross is the SNR centre. Blue cross is the current pulsar position.

• Similar measurements can be made at x-ray energies, and this has been done for the supernova remnant Puppis-A. The pulsar is called the cosmic cannon ball.

Pulsars and Supernovae Remnants

• This ROSAT x-ray image of the central part of the supernova remnant Puppis-A shows a bright point source with an x-ray luminosity more than 2000 times brighter than its optical luminosity (indicating it may well be a hot neutron star) about 6.1 arc minutes away from the centre of the supernova.

• The supernova remnant is about 3700 years old (measured from its expansion velocity) indicating that it is moving at ~1500 km s⁻¹ relative to the centre of the remnant (from which it presumably originated).

Oppenheimer & Volkov predicted that the mass of a neutron star would be approximately 1.4 solar masses. This is based on quantum mechanical calculations, and an exact value depends on the equation of state that is used to describe the relationship between the internal pressure and density of a neutron star as a function of mass.

The equation of state is not well known for the high densities in neutron stars. By looking at binary pulsars we can measure the mass of a number of neutron stars.

These observations show that the average mass is approximately 1.35 solar masses, very close to the above theoretical prediction.
Masses measured from pulsar timing. Vertical dashed (dotted) lines indicate category error-weighted (unweighted) averages.

Pulsars: Internal Structure

- Models of the internal structure of a pulsar are highly dependent on the equation of state used in the model.
- Pulsar timing observations suggest that we have the following structure:
  - The overall diameter of a neutron star is probably about 20 kilometres (12 miles)
  - The outer atmosphere is a superhot plasma.
  - The outer crust has a structure that we get some information about from star quakes. This is a crystal lattice approximately 200 metres thick.
  - There is an inner crust (here also we get information from star quakes) which is also crystal lattice approximately one kilometre thick.
  - Then we have the outer core which is an atomic particle fluid with the density from $10^{14} - 10^{17}$ kg m$^{-3}$.
  - And then finally we have an inner core which is a solid chunk of subatomic particles.
Pulsars: Timing Information

• It is possible to measure the period of a pulsar with astonishing accuracy. The period of B1937+21 is $P = 0.0015578064924327 \pm 0.0000000000000004$ s.
• It is a very complicated business to measure the arrival time of pulses with this sort of accuracy.
• Measurements have to be transformed to the barycentre of the solar system. The measurements have to take into account the relative position and motions of the pulsar, the telescope and the earth.
• They have to bear in mind that the pulsar is spinning down and therefore the exact instant at which the observation is made is critical. The timing measurements may be further complicated if the pulsar is part of a binary system.
• There are likely to be relativistic effects and in young pulsars we see what are known as star quakes.

• From the timing information we can derive position, proper motion and parallax as well as lots of other details about the way these objects behave.
• These plots show a range of residuals found after the main slow-down is removed from the data.