Recycled pulsars: spins, masses and ages

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Neutron stars are beasts!
Recycled pulsars provides evidence
Overview of the MSP population

Recycled Pulsar \textit{Spins}

Recycled Pulsar \textit{Masses}

Recycled Pulsar \textit{Ages}

Formation of \textit{double neutron star systems}
The MSP population - Their Companion Stars

156 binary pulsars in the **Galactic disk** with measured $\dot{P}$ (180 in total)

See talks by:
- Guillot
- Ransom
- Possenti
- Prager
- Pallanca
- Cadelano
- Sandoval
- Mignami
- Papitto

**Graph:**
- **Period derivative, log $\dot{P}$**
- **Spin Period, $P_{\text{spin}}$ (sec)**
- **Orbits:**
  - He WD companion: 83
  - CO WD companion: 31
  - NS companion: 12
  - MS star companion: 12
  - Ultra light companion: 18
  - Globular cluster: 39
The MSP population - Formation channels

ZAMS

1-2 $M_{\text{sun}}$

CE

3-7 $M_{\text{sun}}$

SN

Case A

Case B

LMXB

IMXB

MSP

drawbacks black widows planets

low-mass He WD
sub-stellar dwarf
single MSP

He WD

CO WD
(He WD)

CO WD

CO WD
ONeMg WD

PG 1159

ONeMg WD

SSS

AIC

MSP

He WD
(CO WD)

Tauris (2011)
"It’s simply a matter of beaming and geometry..."
The MSP population - The Spiders

- **Geometric beaming** is likely to be causing the difference between Black widows and Redbacks (Chen, Chen, Tauris & Han, 2013, ApJ 775, 27)

- Redbacks do **not** evolve into black widows (two distinct populations) but see also Benvenuto et al. (2014). Other recent papers: Ablimit & Li (2014), Smedley et al. (2015).

- Do Redbacks eventually produce WDs? Probably not... (competition between evaporation and burning of hydrogen)

- **Problem:** poor understanding of magnetic braking

- **Problem:** how/when the radio MSP turns on?

- **Problem:** understanding the accretion and the mechanism of transitional MSPs

Archibald et al. (2009)
Papitto et al. (2013)
Stappers et al. (2014)
Bassa et al. (2014)

and review by Jason Hessels (2015, BONN VII. NS workshop)
The MSP population - The eccentric MSPs

**WDNS systems:**
- PSR B2303+46
- PSR J1141-6545

**Eccentric MSPs:**
- PSR J2234+06 (Deneva et al. 2013)
- PSR J1946+3417 (Barr et al. 2016)
- PSR J1950+2414 (Knispel et al. 2015)
- PSR J0955-6150 (Camilo et al. 2015)
- PSR J1618-3921 (Bailes 2010; Octau et al. 2016)

**Proposed hypothesis for eccentric MSPs:**
- Freire et al. (2011)
- Freire & Tauris (2014)
- Antoniadis (2014)
- Jiang, Li, Dey & Dey (2015)

- no mass transfer after SN
- Circularization by tidal forces

**Diagram:**
- Eccentric MSPs
- Circularization by tidal forces
- He WD companion
- CO/ONeMg WD companion
- Ultra light companion

**Graph:**
- Orbital period, \( P_{orb} \) (days)
- Eccentricity, \( \log \text{ecc} \)
Recycled Pulsar Spins - accretion physics

\[ P_{eq} = 2\pi \sqrt{\frac{r_{mag}^3 1}{GM \omega_c}} \land r_{mag} (\dot{M}, B) \land B(P, \dot{P}) \]

\[ \dot{P} = \frac{2^{1/6} G^{5/3} \dot{M} M^{5/3} P_{eq}^{4/3}}{P} (1 + \sin^2 \alpha) \cdot \varphi^{-7/2} \cdot \omega_c^{7/3} \]

spin-up line in \( PP' \) diagram

Tauris, Langer & Kramer (2012)

Important!

\[ \dot{P} \]

Spin-up valley

Classical spin-up line

e.g. Bhattacharya & van den Heuvel (1991)

disk - magnetosphere parameters:

\[ R_{mag} = \varphi R_{Alfven} \]

\[ \Omega_{NS} = \omega_c \Omega_{mag}^{Kep.} \]
All spin-up lines shown here are calculated for $\dot{M} = \dot{M}_{Edd}$

The width of each "line" is caused by $(\dot{M}, \alpha)$
Mass needed to spin up pulsar:

$$\Delta M_{eq} \approx 0.22 M_{\odot} \left(\frac{M_{NS}/M_{\odot}}{P_{eq}^{4/3}}\right)^{1/3}$$

Tauris, Langer & Kramer (2012)

MODEST 16 - Bologna
Recycled Pulsar Spins - Roche-lobe decoupling phase (RLDP)

\[ P_{eq} \propto R_{mag}^{3/2} \]

Equilibrium spin is broken

\[
N(t) = n(\omega) \left[ \dot{M}(t) \sqrt{GMr_{mag}(t)} \xi + \frac{\mu^2}{9r_{mag}^3(t)} \right] - \frac{\dot{E}_{dipole}}{\Omega(t)}
\]

Tauris (2012), Science 335, 561

MSPs lose 50% of \( E_{rot} \)
Recycled Pulsar Spins - Roche-lobe decoupling phase (RLDP)

Before RLDP

"during...?"

After RLDP

Papitto, Torres, Rea, Tauris (2014)

Beware:
Partly comparing apples and oranges (Tauris 2012)
Where are the sub-ms MSPs?

- Speed limit caused by GW (Bildsten 1998, Chakrabarty et al. 2003) - however, see also Patruno et al. (2012)
- RLDP (Tauris 2012)
- Observational selection effects (....no)
- Magnetospheric conditions are not satisfied (Lamb & Yu 2005)

\[ P_{eq} \approx 1.40 \text{ ms} \cdot B_8^{6/7} \left( \frac{\dot{M}}{0.1 \dot{M}_{\text{Edd}}} \right)^{-3/7} \left( \frac{M}{1.4 M_{\odot}} \right)^{-5/7} R_{13}^{18/7} \]

**Problem:**

those LMXB systems which experience the largest values of $\dot{M}$
are short lived $\rightarrow$ B high and less net accretion onto NS $\rightarrow$ no sub-ms MSP

and vice versa: those LMXB systems in which the NSs have small B-fields had a long lived
RLO $\rightarrow$ low-mass donors $\rightarrow$ small values of $\dot{M}$ $\rightarrow$ no sub-ms MSP

+ torque is small for a magnetosphere close to the NS $\rightarrow$ requires a long spin-up timescale

Tauris (2016), in prep.
Recycled Pulsar Masses – the distribution

Antoniadis, Tauris, Özel et al. (2016, to be submitted).

Mass (Solar Mass)

Likelihood

1.17 - 2.01 M☉
Recycled Pulsar Masses - indirect determination

Antoniadis, Tauris, Özel et al. (2016, to be submitted)

\[ f(M_{NS}, M_2, i) \equiv \frac{4\pi^2 (a_{NS} \sin i)^3}{GP_{orb}^2} = \frac{M_2^3 \sin^3 i}{(M_{NS} + M_2)^2} \]

from \(M_{WD}-P_{orb}\) relation
Recycled Pulsar Masses - The $M_{\text{WD}} - P_{\text{orb}}$ correlation

Tauris & van den Heuvel (2014)

Tauris & Savonije (1999)

Orbital period, $P_{\text{orb}}$ (days)

Mass of helium white dwarf, $M_{\text{WD}}$ ($M_\odot$)
Fully recycled MSPs exist with masses $\sim 1.3 \, M_{\odot}$ and $\sim 0.2 \, M_{\odot}$ helium white dwarf companions.

Accretion efficiencies $< 10$-$20\%$

Accretion disk instabilities?
Propeller effects?
Accretion disk winds?
Recycled Pulsar Ages – true ages

2 < n < 5

See also Kiziltan & Thorsett (2010)
Recycled Pulsar Ages – true ages

\[ \dot{\Omega} \propto -\Omega^n \quad (\text{deceleration law}) \]

\[ t = \frac{P}{(n - 1) P} \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right] \quad n = \text{const}. \]

\[ \tau \equiv \frac{P}{2 \dot{P}} \quad \text{Characteristic age} \]

\[ \tau \text{ is small} \rightarrow \text{recycled MSP is young} \]

\[ \tau \text{ is large} \rightarrow \text{recycled MSP can have any age} \]

Tauris, Langer & Kramer (2012)

Only WD cooling as true age indicator
Recycled Pulsar Ages – true ages

Ages from WD cooling: remember to add the proto-WD stage! (up to 2 Gyr)

- Istrate, Tauris, Langer & Antoniadis (2014)
- Istrate, Marchant, Tauris, et al. (2016, to be submitted)

[incl. element diffusion and rotational mixing]
Ultra-stripped SNe – Formation of Double NS systems

Tauris et al. (2013), ApJL
Tauris, Langer & Podsiadlowski (2015), MNRAS
Recycled Pulsar J1024-0719 - a triple system origin?

Bassa et al. (2016), arXiv:1604.00129
Kaplan et al. (2016), arXiv:1604.00131
Conclusions

• The last decade has revealed new interesting MSPs
  • The spiders, The transitional MSPs (tMSPs), The eccentric MSPs

• New MSPs keep challenging Stellar Evolution
  • The Triple MSP, PSR J1024-0719, 3FGL 1417.5.....
  But also well-constrained behaviour...
  • The \((M_{\text{WD}}, P_{\text{ORB}})\) – correlation, MSP spin periods vs companion types

• The recycling phase revisited
  • The spin-up line should be replaced with a ‘spin-up valley’
  • Characteristic ages of MSPs are pretty useless as age estimators

• Formation of double neutron star (DNS) systems
  • All DNS systems which merge formed via an ultra-striped SN
  • Ultra-striped SNe often (but not always) lead to small kicks
  • \((P_{\text{orb}}, P_{\text{spin}})\) and \((P_{\text{orb}}, \text{ecc})\) - correlations in DNS systems

THANK YOU!