FORMATION OF MILLISECOND PULSARS AND DOUBLE NEUTRON STARS

Thomas Tauris
Argelander-Institut für Astronomie - Universität Bonn
Max-Planck-Institut für Radioastronomie
• Overview of the MSP population
• Formation scenarios of MSP subclasses
• Probing Stellar Evolution using MSPs
• The recycling phase and accretion physics
• Formation of double neutron star systems
The NS population

100,000,000 NSs in Milky Way

tip of the iceberg:
- strong B-fields
- rapid spin
- accreting
- hot (newborn)
The MSP population – companion stars

~200 binary MSPs

AXMSPs 20

tMSPs 3+1

Spiders 39
- redbacks
- black widows
- planets

CO/ONeMg WDs 25

He WDs 95

The MSP population - companion stars

Texas Symp. - Geneva 2015

Thomas Tauris - Bonn Uni. / MPIfR
The MSP population - The P-P_{\dot{p}} diagram

Tauris, Kaspi, Breton, Deller, et al. (2015)

- 2016 pulsars in total – Apr. 2014
- 169 pulsars in binaries
- 55 pulsars in SN remnants
- 29 magnetars/CCOs/XDINS
- 19 RRATs

Spin period, $P$ (sec)

Texas Symp. - Geneva 2015  Thomas Tauris - Bonn Uni. / MPIfR
Tauris (2011)

- Redbacks
- Black widows
- Planets

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

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

PG 1159

ONeMg WD

Sun

SSS

MSP

Low-mass He WD
Sub-stellar dwarf
Single MSP

He WD

CO WD (He WD)

CO WD

CO WD

ONeMg WD

He WD (CO WD)

Case A

Case B

Early Case B

Case C (CE)

LMXB

IMXB

AIC

Redbacks
Black widows
Planets
The MSP population - The standard formation scenario

- Rapid spin: \( P < 50 \, \text{ms} \)
- Small period derivative: \( \dot{P} < 10^{-17} \, \text{s}^{-1} \)

**Ingredients needed for recycling:**

- Increase of spin ang. mom.
- Decrease of period derivative

**Solution:**

- Accretion of mass

\[
N = \dot{J}_* \equiv \frac{d}{dt}(I\Omega_*) = \dot{M}_* \sqrt{GM*} r_A \xi
\]

\[
\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) - \frac{c^2}{4\pi} \nabla \times \left( \frac{1}{\sigma} \times \nabla \times \vec{B} \right)
\]

\[
B = \sqrt{\frac{3c^3 I_{NS}}{8\pi^2 R_{NS}^6}} P \dot{P}
\]

Lamb, Pethick & Pines (1973)
Ghosh & Lamb (1979, 1992)

Geppert & Urpin (1994); Konar & Bhattacharya (1997)

**Magnetic-dipole model**
The MSP population - The Spiders

Black widows
Redbacks

$\log(M_2/M_\odot)$

$N$

J2051-0827
B1957+20
J1023+0038

$P_{\text{orb}} (d)$

GWR dominates
MSP turn-on

"It’s simply a matter of beaming and geometry…"
• 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 ‘Huntsman’ spider: 1FGL J1417.7-4407 (Strader et al. 2015)

Camilo et al. (2016):
\[ P_{\text{orb}} = 5.4 \text{ days} \]
\[ M_2 = 0.33 \pm 0.03 \, M_{\text{sun}} \quad (M_{\text{NS}} = 1.77 - 2.13 \, M_{\text{sun}}) \]
\[ P = 2.66 \, \text{ms} \]

Discovery of the first Red-Bump Spider?

Their existence was predicted theoretically in 1999....

Red-bump MSPs decouple from RLO because of a chemical discontinuity. (Tauris & Savonije 1999, see also D’Antona et al. 2006). Only for \( P_{\text{orb}} > 3 \) days.
3FGL J1417.5-4402

The first Red-Bump Spider?

Tauris & Savonije (1999)

3FGL J1417.5-4402 (Camilo et al. 2016):

- $P_{\text{orb}} = 5.4$ days
- $M_2 = 0.33 \pm 0.03 \, M_{\odot}$

0.32 $M_{\odot}$
The MSP population - The eccentric MSPs

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

**Eccentric MSPs:**  
PSR J2234+06  
PSR J1946+3417  
PSR J1950+2414  
PSR J0955-6150  
PSR J1618-3921  

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

**Circularization by tidal forces:**  
Phinney (1992)  
Phinney & Kulkarni (1994)
The MSP population - The eccentric MSPs

Do eccentric MSPs have a triple origin? ......difficult

Puzzles:
1) Why always near end of RLO? (so orbit doesn't circularize again)
2) Why is ecc. always ~0.1?
3) Why do all systems have $P_{\text{orb}}=20–30$ days?
Probing Stellar Evolution using MSPs
PSR J0337+1715, a remarkable Galactic triple millisecond pulsar

Discovered by Ransom, Stairs, Archibald, Hessels,... Ransom et al. (2014), Nature 505, 520
Stellar Forensics

Tracing the evolution backwards

see also Sabach & Soker (2015)

- Applying constraints from knowledge of stellar evolution and mass transfer (RLO).
- Simulations of the dynamical effects of the supernova explosion.
- At all stages ensuring that the triple remains dynamically stable on a long timescale.

Millisecond pulsar mass: $1.438 \, M_\odot$
inner WD mass: $0.197 \, M_\odot$
inner WD temp: $15\,800 \, K$
inner $P_{\text{orb}}$: 1.63 days
inner ecc: 0.00069
outer WD mass: $0.410 \, M_\odot$
outer $P_{\text{orb}}$: 327 days
outer ecc: 0.035
angle between orb. planes: 0.01°

Ransom et al. (2014), Kaplan et al. (2014)
Pre-CE configuration? Hierarchical structure?

1)

2)
Stellar Evolution and MSPs - The $M_{\text{WD}} - P_{\text{orb}}$ correlation

Tauris & van den Heuvel (2014)

Tauris & Savonije (1999)
Pulsar Recycling - accretion physics

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

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

spin-up line in \( P \dot{P} \) – diagram

Tauris, Langer & Kramer (2012)

Important!

disk magnetosphere parameters:

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

\[ \Omega_{NS} = \omega_c \Omega^{Kep.}_{mag} \]

Classical spin-up line e.g. Bhattacharya & van den Heuvel (1991)
Mass needed to spin up pulsar:

\[ \Delta M_{eq} \approx 0.22 M_{\odot} \left( \frac{M}{M_{\odot}} \right)^{1/3} \frac{P^{4/3}_{\text{ms}}}{P^{4/3}} \]

Tauris, Langer & Kramer (2012)

Liponov & Postnov (1984)

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Ultra-stripped SNe – Double NS systems

- HMXB
- Common envelope
- NS + naked He star
- Case BB RLO
  - Ultra-stripping / recycling
- Ultra-stripped SN
- Recycled pulsar + Young pulsar
- NS+NS merger
  - LIGO
Ultra-striped SNe – Double NS systems

70 systems \( \text{BEC} \)

\( P_{\text{orb}, i} = 0.06–120 \text{ days} \)

\( M_{\text{He}, i} = 2.5–10 \text{ M}_{\odot} \)

- Tauris, Langer, Podsiadlowski (2015), MNRAS
## Double Neutron Star Systems

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<th>$P$ (ms)</th>
<th>$P_{\text{dot}}$ ($10^{-18}$)</th>
<th>$P_{\text{orb}}$ (d)</th>
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<th>$M_{\text{psr}} / M_{\text{comp}}$</th>
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Ultra-stripped SNe – Pre-SN cross-sections

If SN mass cut is here...

Lattimer & Yahil (1989)

Small kicks? (yes)
Suwa et al. (2015)

\[ M_{NS} \approx 1.10 - 1.80 \, M_{\odot} \]

\[ P_{\text{orb,i}} = 0.1 \, \text{days} \]
\[ M_{\text{He,i}} = 2.5 - 6.0 \, M_{\odot} \]

DNS \((P_{\text{orb}} - P_{\text{spin}})\) and \((P_{\text{orb}} - \text{ecc})\) correlations

\[ P_{\text{orb}} \uparrow \implies \Delta t_X \downarrow \implies \Delta M_{\text{NS}} \downarrow \implies P_{\text{spin}} \uparrow \]

...more complicated as such, but in general obs. data is reproduced nicely.
• Binary stellar evolution

• Population synthesis (input distributions and stellar grids)

• Galactic star formation rate (formation history of massive binaries)

• Galactic potentials (to probe location of mergers in host galaxies)

• Extrapolation to local Universe (scaling-law of galaxy number density)
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 ....and other puzzling MSP systems (3FGL 1417.5...)
  - But also well-constrained behaviour...
    - The ($M_{WD}$, $P_{ORB}$) – 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 formed via an ultra-striped SN
  - Ultra-striped SNe often (but not always) lead to small kicks
  - ($P_{orb}$,$P_{spin}$) and ($P_{orb}$,ecc) - correlations in DNS systems

- LIGO/VIRGO merger rates
  - DNS: 1-10 Myr$^{-1}$ MWGal$^{-1}$ → Detection of 1 week$^{-1}$ (~ factor 100)