Millisecond pulsars: on their own, with a friend, or even two

Jason Hessels

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Outline

MSP = Millisecond Pulsar

- MSPs in the context of other pulsars
- Timing MSPs
- MSPs across the EM spectrum
- Pulsar triple system
- “Spiders” (black widows & redbacks)
MSPs in the context of other pulsars
MSP Formation

Young pulsars

Magnetars

Normal pulsars

Double neutron star

Millisecond pulsars

See talks by:
- van Leeuwen
- Berezina

See talks after coffee break:
- Lorimer & Kramer

(there’s no ‘normal’ when it comes to pulsars)
**MSP Formation**

1. LMXB (some IMXB)
2. Radio (some also g-ray)

Alpar, Cheng, Ruderman & Shaham 1982

Rhadakrishnan & Srinivasan 1982
MSP Formation

Afternoon spoiler: this simple picture is getting complicated!
Explosion in Discovery Rate

New MSPs mostly from huge area surveys using Arecibo, GBT and Parkes.

Looking for new PTA pulsars and new exotics

More Galactic MSPs than in GCs for the first time in a decade!

103 total in 4 years

43 Fermi targeted
27 HTRU (Parkes)
17 PALFA (Arecibo)
16 Drift/CC (GBT)

OUT OF DATE!
MSP Population

> 80% in binary; orbital eccentricity normally very small

(this is the “Binaries” session after all)

- Lots of eccentric systems recently found in GCs.

Eccentricity still easily measurable

Freire (http://www.naic.edu/~pfreire/GCpsr.html)
Connecting populations

Some evidence that the tMSPs are faster spinners

Papitto et al. 2014
The MSP Menagerie

See talk by Tauris

- Helium white dwarf.
- Carbon-oxygen white dwarf.
- Jupiter-mass companion (e.g. the “diamond planet”).
- Bloated, post-main-sequence, *(non)*-degenerate companion (0.01 - 0.4 MSun).
- Solar-mass main sequence star (e.g. J1903+0327).
- Earth-mass planetary companions (e.g. B1257+12).
- Hierarchical triple systems (e.g. J0337+1715).
- Highly eccentric systems in GCs (e.g. J0514-4002 in NGC1851, e = 0.9!).
- MSPs in relativistic systems good for gravity tests.

The list is likely to continue increasing in diversity (MSP-MSP?; MSP-BH?; sub-MSP?)
Timing MSPs
“Pulsar Timing”

Using pulsars as precision clocks

Record pulses

Average many pulses together

Measure the “times of arrival”

54255.1231254524233
54255.2643443523453
54255.3123524545899
54255.3513745623467
54255.4418456543355
54255.5001234234688
What can this teach us

Model is complete?

Position is wrong

Residual (ms)

Pulsar spinning down faster than in model

Account for each pulse; over years!

Lorimer & Kramer

Position is changing with time
PSR J1012+5307:
\[ P = 0.005255749014115410 \pm 0.000000000000000015 \text{s} \]

> 100 billion pulses in the last 15 years, and not a single rotation missed
Shapiro Delay

Demorest et al. 2010
Ultra-dense matter
See talk yesterday by Watts
Neutron star equation-of-state

Demorest, Pennucci, Ransom, Roberts & Hessels 2010,
Nature, 467, 1081

Hessels et al. 2006,
Science, 311, 1901

2MSun Pulsar
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Science, 311, 1901
QCD phase diagram

温度 $T$ [MeV]

早期宇宙

夸克-胶子等离子体

LHC

RHIC

临界点？

强子

超导体？

净夸克数密度
MSPs across the EM spectrum
Gamma-selected radio MSPs

Ray et al. 2012

>60 as of the latest count!

Is gamma-ray emission dominated by pulsations?
(Almost) radio quiet MSPs

PSR J1311-3440, see also J2339-0533 (Romani et al.)

Discovery of “black widow” system through its optical companion
(Almost) radio quiet MSPs

Discovery of MSP first through its gamma-ray pulsations.

Radio follow-up finds an almost undetectable radio pulsar.
LOFAR Millisecond Pulsars

The premier low-frequency sample

~50 MSPs detected

Kondratiev et al. 2015
LOFAR Millisecond Pulsars

Kondratiev et al. 2015

Profile evolution related to compact magnetospheres?
Horizontal bars indicate scattering time, $\tau$, as inferred from the diffractive bandwidth, $\Delta \nu_d$.

Archibald et al. 2014
Cyclic Spectroscopy

Example dynamic spectrum
Smoothed to ~2kHz resolution

Diffractive bandwidth vs. frequency

$$\Delta \nu_d = \frac{1}{2\pi \tau}$$

Solid line: best-fit power-law
Dotted line: power-law of -4

Probes scattering in a previously unreachable regime

Archibald et al. 2014
Pulsar triple system
A pulsar riddle

No Orbits Removed

Zoomed region above

Ransom et al. 2014
A pulsar riddle

Green Bank Telescope
Westerbork
Arecibo Observatory

No Orbits Removed (zoomed)

Modified Julian Date (MJD) – 55920

Ransom et al. 2014
PSR J0337+1715 Triple System

Outer Orbit
$P_{\text{orb}} = 327 \text{ days}$
$M_{\text{WD}} = 0.41 M_{\odot}$

Inner Orbit
$P_{\text{orb}} = 1.6 \text{ days}$
$M_{\text{PSR}} = 1.44 M_{\odot}$
$M_{\text{WD}} = 0.20 M_{\odot}$

Orbital inclinations

"Young, hot" White Dwarf
16 lt-sec
Magnified 15x

"Cool, old" White Dwarf
472 lt-sec

Center of Mass
118 lt-sec

Figure credit: Jason Hessels
A pulsar riddle

Ransom et al. 2014

Alle rode meetpunten zijn van Westerbork!
A pulsar riddle

Ransom et al. 2014
### Outer Companion Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right ascension</td>
<td>$03^h 37^m 43^s.82589(14)$</td>
</tr>
<tr>
<td>Declination</td>
<td>$17^h 15^m 14^s.828(2)$</td>
</tr>
<tr>
<td>Solar system ephemeris</td>
<td>DE405</td>
</tr>
<tr>
<td>Reference epoch</td>
<td>MJD 55920.0</td>
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### Pulsar Parameters

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<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Pulsar spin frequency</td>
<td>$365.953363096(11)$ Hz</td>
</tr>
<tr>
<td>Spin frequency derivative</td>
<td>$-2.3658(12) 	imes 10^{-11}$ Hz s$^{-1}$</td>
</tr>
</tbody>
</table>

### Keplerian Parameters

#### Outer Keplarian Parameters

- **Semimajor axis** for outer orbit: $(a \cos i)_O = 1.21752844(4)$ lt-s
- **Orbital period**: $P_{b,O} = 1.629401785(5)$ d
- **Eccentricity parameter** $(e \cos i)_O = 6.8567(2) \times 10^{-4}$
- **Eccentricity parameter** $(e \sin i)_O = 0.171(2) \times 10^{-3}$
- **Time of ascending node**: $t_{asc,O} = MJD 55920.407717436(17)$

#### Inner Keplarian Parameters

- **Semimajor axis** for inner orbit: $(a \sin i)_I = 74.67271018(8)$ lt-s
- **Orbital period**: $P_{b,I} = 3.627574117(7)$ d
- **Eccentricity parameter** $(e \cos i)_I = 3.5186279(3) \times 10^{-2}$
- **Eccentricity parameter** $(e \sin i)_I = -3.462130(11) \times 10^{-3}$
- **Time of ascending node**: $t_{asc,I} = MJD 56233.935815(7)$

### Interaction Parameters

- **Semimajor axis** projected in plane of sky: $(a \cos i)_I = 1.4900(5)$ lt-s
- **Semimajor axis** projected in plane of sky: $(a \sin i)_I = 91.42(4)$ lt-s
- **Inner companion mass over pulsar mass**: $q_I = m_{i,I}/m_p = 0.13737(4)$
- **Difference in longs. of asc. nodes**: $\delta = 2.7(6) \times 10^{-3}$

### Inferred or Derived Values

#### Pulsar Properties

- **Pulsar period**: $P = 2.73258863241(9)$ ms
- **Pulsar period derivative**: $\dot{P} = 1.7666(9) \times 10^{-20}$
- **Inferred surface dipole magnetic field**: $B = 2.2 \times 10^{9}$ G
- **Spin-down power**: $E = 3.4 \times 10^{34}$ erg s$^{-1}$
- **Characteristic age**: $\tau = 2.5 \times 10^{4}$ yr

#### Orbital Geometry

- **Pulsar semimajor axis (inner)**: $(a_I) = 1.224(4)$ lt-s
- **Eccentricity (inner)**: $e_I = 6.9178(2) \times 10^{-4}$
- **Longitude of periastron (inner)**: $\omega_I = 97.6182(19)$°
- **Pulsar semimajor axis (outer)**: $(a_O) = 118.04(3)$ lt-s
- **Eccentricity (outer)**: $e_O = 3.53561955(17) \times 10^{-2}$
- **Longitude of periastron (outer)**: $\omega_O = 95.619483(19)$°
- **Inclination of invariant plane** $i = 39.243(11)$°
- **Inclination of inner orbit** $i_I = 39.254(10)$°
- **Angle between orbital planes** $\delta = 1.20(17) \times 10^{-2}$°
- **Angle between eccentricity vectors** $\delta_e \sim \omega_O - \omega_I = -1.9987(19)$°

#### Masses

- **Pulsar mass**: $m_p = 1.4378(13)$ $M_{\odot}$
- **Inner companion mass**: $m_{i,I} = 0.19751(15)$ $M_{\odot}$
- **Outer companion mass**: $m_{i,O} = 0.4101(3)$ $M_{\odot}$
Was Einstein right?

See talk by Kramer this morning
Strong Equivalence Principle
“Spiders”
(black widows & redbacks)
MSP “Spiders”

So named because these pulsars are ‘devouring’ (ablating) their companions

Black widows:
\[< 0.1M_{\text{Sun}} \] (semi) degenerate companion

Redbacks:
\[ \approx 0.2M_{\text{Sun}} \] non-degenerate companion

See talks by Papitto, Ferrigno, Wadiasingh

Blame Mallory Roberts

‘Black Widow’ and ‘Redback’ Pulsar Binaries
# Black Widows vs. Redbacks

## Black widows
- $M_{\text{comp}} < 0.1\, M_{\odot}$
- $\sim 10\%$ eclipse fraction
- Less Roche-lobe filling?
- Less $T_0$ wander?
- $\delta(T_0) \sim 1-10\, \text{s}$

## Redbacks
- $M_{\text{comp}} > 0.1\, M_{\odot}$
- $\sim 50\%$ eclipse fraction
- Completely Roche-lobe filling?
- More $T_0$ wander?
- $\delta(T_0) \sim 10-100\, \text{s}$

Seems like we may have more types of eclipsing radio MSPs as well: ones earlier in the recycling process?
An Explosion of Spiders

Does not include all the (strange) systems in GCs
MSP Population

Orbits

Freire (http://www.naic.edu/~pfreire/GCpsr.html)

Orbits

Planets

DNSs

LMBPs

GRBIns

Eclipsers

10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1 10

f (M_\odot)

10^{-4} 10^{-3} 0.01 0.1 1 10

P_B (days)

GCs: 18 BWs, 12 RBs
Field: 17 BWs, 8 RBs
Comparable numbers and properties!

4 orders of mag in PB
8 orders of mag in f(M)
Porb vs. Comp. Mass

Adapted from Podsiadlowski et al. 2001

What are the evolutionary links, if any?

Ultra-compact X-ray binaries

Black Widows

Redbacks

See talk by Thomas Tauris
Porb vs. Comp. Mass

Pulsars with $P < 8$ms

- Black Widows
- Redbacks
- Accreting MSPs

Roberts
Eclipsing MSPs
Westerbork data

J0023+0923
J1810+1744
J2129-0429
J2215+5135

Orbital Phase
Rotational Phase

Eclipse Delay
“Mini” Eclipse
Eclipse Delay

Hessels
MSP Eclipses

Rotational Phase: 0 - 1.69ms
Orbital Phase: 0 - 4.8hr

Millisecond Pulsar J1023+0038
Observed for a full orbit at 92cm with WSRT

Zoom of “mini eclipses” and eclipse delays

Cumulative Pulse Profile
~10 million pulses summed

Eclipse Ingress

Eclipse Egress

Pulsar in the main eclipse
~50% of the orbit at 92cm

Artist’s Impression: Bill Saxton (NRAO)
PSR J1023+0038

Pspin = 1.7ms
Porb = 0.20d
Mcomp = 0.13MSun

See talks by Amruta Jaodand and Kyle Parfrey

Archibald et al. 2015
**Radio Pulsar State**

- Observed radio/gamma-ray pulsar.
- Likely radio eclipses.
- Lots of orbital timing noise.
- Modulation of X-rays at orbital period (shock).

**Disk State**

- No visible radio pulsar (off?).
- Increased optical, X-ray, and gamma-ray brightness.
- Double peaked optical emission lines.
- Flat-spectrum radio continuum source (jet?).
- No X-ray orbital modulation.
- X-ray dropouts and flares.
“Normal MSPs” vs. Spiders

- Gravity tests
- EOS constraints

- Accretion physics
- Pulsar wind
- Particle acceleration
- Shocks
- MSP formation and evolution
- EOS constraints?
- ...

...
Conclusions

• As the number of known MSPs increases, so do the number of scientific applications.
• The diversity of MSP systems is providing great puzzles in stellar evolution.
• Multi-wavelength observations are crucial for getting the most out of radio MSPs.
• ...and I didn’t even talk about the *Fermi* Galactic bulge GeV excess.