Medicina

1st MCCT-SKADS Training School

28 September 2007

Pulsars and Collapsed Objects

ANDREA POSSENTI

INAF - Osservatorio di Cagliari
Outline

The absolute beginners - Discovery of the first pulsar (1967)

Unveiling the mystery - Discovery of a pulsar associated with the Crab Nebula (1968)

Fun for two - Discovery of the binary pulsar PSR B1913+16 (1974)

Please put the pulsar in the recycle bin - Discovery of the millisecond pulsar PSR B1937+21 (1982)

Spinning in the crowds - Discovery of the first millisecond pulsar PSR B1821+24A in a globular cluster (1987)

Not only stellar mates - Discovery of the first planet pulsar PSR B1257+12 (1992)

Fun from two - Discovery of the first double pulsar PSR J0737-3039A/B (2003)

Fun for everyone - The present and future of radio pulsar science (from 2007 on...)

Basic References

Books

- Manchester & Taylor 1977 “Pulsars”
- Lyne & Smith 2005 “Pulsar Astronomy”
- Lorimer & Kramer 2005 “Handbook of Pulsar Astronomy”

Review Articles

- Rickett 1990, ARAA - Scintillation
- Science, April 2004 - Neutron Stars, Isolated Pulsars, Binary Pulsars
- Living Reviews articles: (http://relativity.livingreviews.org/Articles)
  - Stairs 2003: General Relativity and pulsar timing
  - Lorimer 2005: Binary and millisecond pulsars
  - Will, 2006: General Relativity theory and experiment
  - Cordes et al.: Pulsars as tools
  - Kramer et al.: Strong-field tests of General Relativity
The absolute beginners: discovery of pulsars (1967)

Anthony Hewish  Jocelyn Bell

periodic pulses!

P = 1.33 sec
dt = 25 ms

White Dwarfs oscillation?
White Dwarfs rotation?
Neutron Star rotation?
Unveiling the mystery: discovery of a pulsar associated with the Crab Nebula (1968)

A period of $P = 33$ ms, increasing by 36 ns/day
Neutron stars do exist...

- Formed in Type II supernova explosion - core collapse of red giant when the mass exceeds "Chandrasekhar Mass"
- Diameter 20 - 30 km  Mass ~ 1.4 Msun

(Lattimer & Prakash 2004)
...and neutron stars/pulsars are born in supernova explosion!

- Energy release $\sim 3GM^2/5R \sim 3 \times 10^{53}$ erg $\sim 0.1$ Mc$^2$
- En. Kinetic of SNR $\sim 10^{51}$ erg; 99% of grav energy in $v$ and anti-$v$
- Asymmetry in neutrino ejection gives kick to NS
- Measured pulsar proper motions: $<V_{2D}> = 211$ km s$^{-1}$
- $<V_{3D}> = 4<V_{2D}>/\pi = 2<V_{1D}>$ for isotropic velocities

~ 30 young pulsars associated with a SNR

(PSR B2224+65)

(Guitar Nebula)

(PSR B2224+65)

(Guitar Nebula)

(Hobbs et al. 2005)

(Cordes et al. 2003)
Radiopulsars are rapidly rotating and highly magnetized neutron stars anisotropically emitting radiowaves.
Radio emission mechanism is poorly known yet, but certainly a coherent process!

- Source power is very large, but source area is very small
- Specific intensity is very large
- Pulse timescale gives limit on source size \( \sim c\Delta t \)

\[
I_\nu = \frac{2\nu^2 kT_B}{c^2} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}
\]

For pulse timescale \( \Delta t = 1\mu s \), source area \( A \sim (c\Delta t)^2 = 10^9 \text{ cm}^2 \) and \( L_{rad} = 10^{29} \text{ erg s}^{-1} \):

\[
I = 10^{20} \text{ erg s}^{-1} \text{ cm}^{-2} (= 10^7 \text{ MW cm}^{-2}!!)
\]

For solid angle \( \sim 1 \text{ sr} \), \( \nu = 10^9 \text{ Hz} \): \( T_B \sim 10^{30} \text{ K} (!!) \)

(Manchester & Taylor 77)
The rotational energy pays the energy bill

Spin-down Luminosity: (Manchester & Taylor 77)

\[ L_{sd} = \dot{E}_{sd} = -I \dot{\Omega} \dot{\omega} = 4\pi^2 I \dot{P} P^{-3}, \text{ where } \Omega = \frac{2\pi}{P} \]

For a “normal” pulsar, \( I \sim 10^{45} \text{ g cm}^2, P \sim 1 \text{ s}, \dot{P} \sim 10^{-15}, L_{sd} \sim 10^{32} \text{ erg s}^{-1}. \)

For an MSP, \( P \sim 3 \text{ ms}, \dot{P} \sim 10^{-20}, L_{sd} \sim 10^{34} \text{ erg s}^{-1}. \)

Radio Luminosity:

\[ L_{\text{rad}} = S \, 4\pi d^2 \, \Delta \nu \]

For \( S \sim 10 \text{ mJy} = 10^{-28} \text{ W m}^{-2} \text{ Hz}^{-1} = 10^{-25} \text{ erg cm}^{-2} \text{ Hz}^{-1} \)
\( d = 1 \text{ kpc} = 3 \times 10^{21} \text{ cm}, \Delta \nu = 10^9 \text{ Hz}, L_{\text{rad}} \sim 10^{29} \text{ erg s}^{-1} < < L_{sd} \)

Assuming magneto-dipole braking in vacuum:

\[ L_{\text{dipole}} \sim B^2_{\text{surf}} \Omega^4 \]

and by equating \( L_{\text{dipole}} = L_{sd} \) one can get
pulsar Ages and Magnetic fields

Magnetic dipole energy loss

Observed $P$ and $\dot{P}$

$B_{\text{surf}} \propto (\dot{P} P)^{1/2}$

$\tau_c = \frac{1}{2} \frac{P}{\dot{P}}$
The observed $P$ and $\dot{P}$ translates in the fundamental $P$ vs $\dot{P}$ diagram

Galactic disk pulsars

ATNF Pulsar Catalogue
(www.atnf.csiro.au/research/pulsar/psrcat)
... since 1967 until 27 September 2007 ... 1765 PULSARS!

PSR 0329+54
P = 714 ms

PSR 0833-45
P = 89 ms
An immediate use of so many pulsars...

...investigating the interstellar medium
Dispersion in InterStellar Medium

Free electrons in ISM

\[ t_2 - t_1 \propto (v_2^{-2} - v_1^{-2}) \, \text{DM} \]

\[ \text{DM} = \int_0^L n_e \, dl \]
\[ \delta t_{DM} = \frac{DM}{1.2 \times 10^{-4}} \frac{\delta \nu}{\nu^3} \]

- @ 430 MHz \rightarrow 100 \mu s for DM=1 pc/cm\(^3\), \(\delta \nu=1\) MHz
- @ 1400 MHz \rightarrow 3 \mu s for DM=1 pc/cm\(^3\), \(\delta \nu=1\) MHz
Dispersion & Pulsar Distances

- For pulsars with independent distances (parallax, SNR assoc, HI absorption) one can determine mean $n_e$ along path. Typical values ~ 0.03 cm$^{-3}$

- From many such measurements can develop model for Galactic $n_e$ distribution, e.g. NE2001 model [Cordes & Lazio 2002]

- Can then use the model to determine distances to other pulsars
A model for DM in the Galaxy

[Taylor & Cordes 1993]
Smearing due to multi-path scattering

\[ \delta t_{\text{scatt}} \sim \frac{1}{v^4} \]
A model for $t_{\text{scatt}}$ in the Galaxy at 1.0 GHz

[ Taylor & Cordes 1993 ]
• Spectrum of interstellar electron density fluctuations
  • Follows Kolmogorov power-law spectrum over 12 orders of magnitude in scale size (from $10^{-4}$ AU to 100 pc)
  • Mostly based on pulsar observations

(Armstrong et al. 1995)
Faraday Rotation & Galactic Magnetic Field
Fun for two - The discovery of the binary pulsar B1913+16 (1974)

$P = 59$ ms but not a steady slow down
How one can measure with high precision the pulse period...
• Spin parameters: $v, \dot{v}, \ddot{v}, \dddot{v} \ldots$

• Astrometric parameters: position, proper motion, parallax
Pulsar Timing: Binary pulsars

- 5 Keplerian parameters:
  \[ P_{\text{orb}}, a_p, e, \omega, T_0 \]

- Mass function:
  \[
  f(m_p, m_c) = \frac{4\pi^2}{G} \frac{(a_p \sin i)^3}{P_{\text{orb}}^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}
  \]

- Estimate of companion mass if inclination known
- Minimum companion mass for \( i = 90 \) deg
From the determination of the mass function of PSR B1913+16, it appeared probable that the radiopulsar was in a binary system with a second neutron star as a companion.

First possibility of studying relativistic effects on the orbital evolution!
Pulsar Timing: relativistic pulsars

The modification in the shape of the orbit
periastron precession
The modifications in the Time Of Arrival (TOA) of the pulses

Shapiro Delay
The modifications in the Time Of Arrival (TOA) of the pulses

Gravitational redshift & time dilation

![Graph showing the modifications in TOA over orbital phase. The graph illustrates the gravitational redshift and time dilation effects with labeled key points: Early, Periastron, Apastron, Late.](image_url)
The modification of the shape of the orbits

Orbital decay
What do we learn observing these relativistic effects (PK parameters)?

\[ \dot{\omega} = 3 \left( \frac{P_b}{2\pi} \right)^{-5/3} (T_c M)^{2/3} (1 - e^2)^{-1}, \quad \text{Periastron precession} \]

\[ \gamma = e \left( \frac{P_b}{2\pi} \right)^{1/3} T_{\odot}^{2/3} M^{-4/3} m_c (m_p + 2m_c), \quad \text{Time dilation & gravitational redshift} \]

\[ \dot{P}_b = -\frac{192\pi}{5} \left( \frac{P_b}{2\pi} \right)^{-5/3} \left( 1 + \frac{73}{24} e^3 + \frac{37}{96} e^4 \right) (1 - e^3)^{-7/2} T_{\odot}^{5/3} m_p m_c M^{-1/3}, \quad \text{Orbital period decay} \]

\[ r = T_{\odot} m_c, \quad \text{Shapiro delay (amplitude)} \]

\[ s = x \left( \frac{P_b}{2\pi} \right)^{-2/3} T_{\odot}^{-1/3} M^{2/3} m_c^{-1}. \quad \text{Shapiro delay (shape)} \]

...where...

- \( e \): orbital eccentricity (observed)
- \( P_b \): orbital period (observed)
- \( x \): projected semimajor axis (observed)
- \( m_p \): pulsar mass
- \( m_c \): companion star mass
- \( M = m_p + m_c \): total system lagrangian mass

Observing the values of only 2 PK parameters once more than 2 relativistic PK parameters are known, one derives the masses of the 2 bodies and hence predicts the further PK par on the basis of a given Gravity Theory.

One can measure the pulsar and companion star masses with unrivalled precision.

A test for Gravity Theories.
The prediction of the General Relativity for $P_b$...

PSR B1913+16

Pulsar + Neutron Star

(2 PK par $\rightarrow$ masses)

The measurements done by Russell Hulse & Joe Taylor...

NOBEL Prize 1993

Taylor & Hulse

NOBEL Prize

1993

Taylor & Hulse

NOBEL Prize

1993

Taylor & Hulse

R

Russell Hulse

Joe Taylor...
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital period $P_b$ (d)</td>
<td>0.420737299122(10)</td>
</tr>
<tr>
<td>Projected semi-major axis $a$ (s)</td>
<td>3.729464(2)</td>
</tr>
<tr>
<td>Eccentricity $e$</td>
<td>0.2736775(3)</td>
</tr>
<tr>
<td>Longitude of periastron $\omega$ (deg)</td>
<td>27457679(5)</td>
</tr>
<tr>
<td>Epoch of periastron $T_0$ (MJD)</td>
<td>50260.92493075(4)</td>
</tr>
<tr>
<td>Advance of periastron $\dot{\omega}$ (deg yr$^{-1}$)</td>
<td>1.755789(9)</td>
</tr>
<tr>
<td>Gravitational redshift $\gamma$ (ms)</td>
<td>2.070(2)</td>
</tr>
<tr>
<td>Orbital period derivative $\left(\dot{P}<em>b\right)</em>{\text{obs}}$ (10$^{-12}$)</td>
<td>$-0.137(3)$</td>
</tr>
<tr>
<td>Shape of Shapiro delay $s$</td>
<td>0.975(7)</td>
</tr>
<tr>
<td>Range of Shapiro delay $r$ (\mu s)</td>
<td>6.7(1.0)</td>
</tr>
</tbody>
</table>

**PSR B1534+12**

*after a dozen yrs of observations*

non-radiative predictions of GR verified at 0.05% level
Please, put the pulsar in the recycle bin

Discovery of the millisecond pulsar
B1937+21 (1982)

\[ P = 1.557 \text{ ms} \quad [\text{Backer et al. 1982}] \]

\[ V = 0.13 \text{ c} \]

Extreme physical conditions occur in millisecond pulsars

First promise of putting constraints to the Equation of State for nuclear matter!
How to explain this new group of pulsars?
A newly born pulsar has high magnetic field and relatively short spin period.
A young pulsar evolves relatively fast and slows down.

The magnetic field of an old pulsar might eventually decay.
Died pulsars

Slow pulsars with low magnetic fields are not observable as radio sources any more
A died pulsar could be spun up and rejuvenated by an evolving binary companion.
A newly born fast spinning pulsar

Hubble time

1000 yr

A recycled pulsar
Many Millisecond Pulsars are extremely good clocks

A clock stability comparable to the best time standards!!!

\[ P = 0.0015578064924327 \pm 0.000000000000000004 \text{ sec} \]

In this pulsar, after few years of pulse timing, we can predict the time of arrival of pulses within \(1 \mu\text{s over 1 year}!\)
Spinning in the crowds - Discovery of the first millisecond pulsar PSR B1821+24A in a globular cluster (1987) [Lyne et al. 1987]

M 28 (NGC 6626 in Sagittarius)
Pulsars in Globular Clusters

... animation of 22 pulsars in 47 Tucanae
Ionized gas in 47 Tucanae

- Correlation of DM and P
- P due to acceleration in cluster potential
- Pulsars on far side of cluster have higher DM
- Gas density $\sim 0.07 \text{ cm}^{-3}$, about 100 times local density
- Total mass of gas in cluster $\sim 0.1 \, M_{\text{sun}}$

First detection of intra-cluster gas in a globular cluster! (Freire et al. 2001)
### Millisecond pulsars in other clusters

<table>
<thead>
<tr>
<th>Cluster</th>
<th>PSR Name</th>
<th>P</th>
<th>P_eclipse</th>
<th>M_c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 6266</td>
<td>PSR J1701-30</td>
<td>5.24 ms</td>
<td></td>
<td>&gt;0.19 M_{sun}</td>
<td>6.7 kpc</td>
</tr>
<tr>
<td>NGC 6397</td>
<td>PSR J1740-53</td>
<td>3.65 ms</td>
<td>1.35 d (eclipse)</td>
<td>&gt;0.18 M_{sun}</td>
<td>2.2 kpc</td>
</tr>
<tr>
<td>NGC 6544</td>
<td>PSR J1807-24</td>
<td>3.06 ms</td>
<td>0.071 d (1.7 h)</td>
<td>&gt;0.009 M_{sun} (10 M_{Jup})</td>
<td>2.5 kpc</td>
</tr>
<tr>
<td>NGC 6752</td>
<td>PSR J1910-59</td>
<td>3.27 ms</td>
<td>0.86 d</td>
<td>&gt;0.19 M_{sun}</td>
<td>3.9 kpc</td>
</tr>
</tbody>
</table>

[D’Amico et al. 2001]
Probing the central M/L in NGC 6752

5 pulsars discovered and timed @ Parkes [D’Amico et al 2000] [D’Amico et al 2002]

the negative \((dP/dt)/P\) of two MSP located in the central regions is dominated by the cluster potential well

a unusually high M/L>6-7 in the central regions of the cluster

\(~ 3400 \, M_{\text{sun}}\) of low-luminosity matter in the inner 0.076 pc

[D’Amico et al 2002 ] [Ferraro et al 2003 ]
An energetic encounter for PSR-A in NGC 6752

PSR-A is the most offset pulsar ever detected in a globular cluster and PSR-C the second most offset [D’Amico et al 2000] [D’Amico et al 2002]

both pulsars probably ejected in the halo by a dynamical encounter in the cluster core occurred less than ~ 0.7 Gyr ago [Colpi, Possenti & Gualandris 2002]

a double black-hole of mass [10-50 M_{\odot}] appears the most probable center of scattering [Sigurdsson 2003] [Colpi, Mapelli, Possenti 2004]
GBT Search of Globular Cluster Terzan 5

- 5.9h obs with 82 µs sampling
- $S_{\text{min}} \sim 15$ µJy
- 600 MHz bandwidth at 2 GHz
- 32 pulsars discovered!! 34 total in cluster
  (www.naic.edu/~pfreire/GCpsr.html)
- Two eccentric relativistic binaries; N-star \sim 1.7 \, M_\odot?

(Ransom et al. 2005)

- PSR J1748-2446ad - fastest known pulsar!
- $P = 1.3959$ ms, $f_0 = 716.3$ Hz, $S_{2000} \sim 80$ µJy
- Binary, circular orbit, $P_b = 1.09$ d
- Eclipsed for \sim 40% of orbit
- $m_c > 0.14 \, M_\odot$

(Hessels et al. 2006)
GBT Search of Globular Cluster Terzan 5

- 5.9h obs with 82 µs sampling

Table 2. The 10 fastest spinning known radio pulsars. Data compiled from the Australia Telescope National Facility pulsar database (33).

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Spin frequency (Hz)</th>
<th>$P_b$ (days)</th>
<th>$M_{\text{2, min}}$ ($M_\odot$)</th>
<th>Eclipse fraction</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1748–2446ad</td>
<td>716.358</td>
<td>1.0944</td>
<td>0.14</td>
<td>0.4</td>
<td>Terzan 5</td>
</tr>
<tr>
<td>B1937+21</td>
<td>641.931</td>
<td>isolated</td>
<td></td>
<td></td>
<td>Galaxy</td>
</tr>
<tr>
<td>B1957+20</td>
<td>622.123</td>
<td>0.3819</td>
<td>0.021</td>
<td>0.1</td>
<td>Galaxy</td>
</tr>
<tr>
<td>J1748–2446O</td>
<td>596.435</td>
<td>0.2595</td>
<td>0.035</td>
<td>0.05</td>
<td>Terzan 5</td>
</tr>
<tr>
<td>J1748–2446P</td>
<td>578.496</td>
<td>0.3626</td>
<td>0.37</td>
<td>0.4</td>
<td>Terzan 5</td>
</tr>
<tr>
<td>J1843–1113</td>
<td>541.812</td>
<td>isolated</td>
<td></td>
<td></td>
<td>Galaxy</td>
</tr>
<tr>
<td>J0034–0534</td>
<td>532.714</td>
<td>1.5892</td>
<td>0.14</td>
<td>0</td>
<td>Galaxy</td>
</tr>
<tr>
<td>J1748–2446Y</td>
<td>488.243</td>
<td>1.17</td>
<td>0.14</td>
<td>0</td>
<td>Terzan 5</td>
</tr>
<tr>
<td>J1748–2446V</td>
<td>482.507</td>
<td>0.5036</td>
<td>0.12</td>
<td>0</td>
<td>Terzan 5</td>
</tr>
<tr>
<td>B0021–72J</td>
<td>476.048</td>
<td>0.1206</td>
<td>0.020</td>
<td>0.1</td>
<td>47 Tucanae</td>
</tr>
</tbody>
</table>

(Hessels et al. 2006)
Not only stellar mates - Discovery of the first planet pulsar PSR B1257+12 (1992)

A: 3.4 Earth masses, 66.5-day orbit

B: 2.8 Earth masses, 98.2-day orbit

C: ~ 1 Moon mass, 25.3-day orbit

[Wołczczan & Frail 1992]
High-mass MS companion:
  P medium-long, $P_b$ large, highly eccentric orbit, youngish pulsar
  4 known, e.g. B1259-63

Double neutron-star systems:
  P medium-short, $P_b \sim 1$ day, highly eccentric orbit, pulsar old
  8 + 2? known, e.g. B1913+16

Young pulsar with massive WD companion:
  P medium-long, $P_b \sim 1$ day, eccentric orbit, youngish pulsar
  2 known, e.g. J1141-6545

Pulsars with planets:
  MSP, planet orbits from months to years, circular
  2 known, e.g. B1257+12

Intermediate-Mass systems:
  P medium-short, $P_b \sim$days, circular orbit, massive WD companion, old
  pulsar 12 + 2? known, e.g. B0655+64

Low-mass systems:
  MSP, $P_b$ hours to years, circular orbit, low-mass WD, very old pulsar
  $\sim$105 known, $\sim$55 in globular clusters, e.g. J0437-4715, 47Tuc J
An intriguing zoo for studying stellar and binary evolution

- **A**: Main-sequence stars, one > 8 M☉, one low-mass (-1M☉)
  - Primary explodes as supernova
  - Result: long-period binary system with a millisecond pulsar and a low-mass white dwarf companion
  - Example: PSR J1713+0747

- **B**: Main-sequence stars, one > 8 M☉, one intermediate-mass (-5 M☉)
  - Primary explodes as supernova
  - Result: mildly recycled pulsar (spin period tens of milliseconds) in a close orbit with a massive white dwarf (-1 M☉)
  - Example: PSR J1407-5112

- **C**: Main-sequence stars, one > 7 M☉, one ~5 M☉
  - Mass transfer from the primary to the secondary
  - Result: common-envelope evolution: the NS spirals into and expels the envelope of the companion
  - Example: PSR J1411-5545

- **D**: Main-sequence stars, both > 8 M☉
  - Primary explodes as supernova
  - Result: double-neutron-star system
  - Example: PSR B1913+16
Fun from two
discovery of the first
double pulsar
J0737-3039
(2003)

[Burgay et al. 2003]
[Lyne et al. 2004]

© Saverio Ceravolo
The discovery of PSR J0737-3039A (April 2003)

[Burgay, D’Amico, Possenti et al. 2003]

Binary pulsar

• $P = 22.7\text{ ms}$

Orbital period = 2.4 hr

Eccentricity = 0.08

Orbital parameters suggest that the system is relatively massive, probably consisting of two NSs.

Huge periastron advanced (16.88°/yr)

[From Burgy Danaico Possentid et al. 2003]
Pulsations from PSR J0737-3039B (Oct 2003)

[ Lyne, Burgay, Kramer, Possenti et al. 2004]

The first double pulsar ever known!
# Basic Parameters

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>22.7 ms</td>
<td>2.77 s</td>
</tr>
<tr>
<td>$\dot{P}$</td>
<td>$1.7 \times 10^{-18}$</td>
<td>$0.88 \times 10^{-15}$</td>
</tr>
<tr>
<td>SpinDown age</td>
<td>210 Myr</td>
<td>50 Myr</td>
</tr>
<tr>
<td>$B_{\text{surf}}$</td>
<td>$6 \times 10^9$ G</td>
<td>$1.6 \times 10^{12}$ G</td>
</tr>
<tr>
<td>$R_{\text{LC}}$</td>
<td>1,080 km</td>
<td>$1.32 \times 10^5$ km</td>
</tr>
<tr>
<td>$B_{\text{LC}}$</td>
<td>$5 \times 10^3$ G</td>
<td>0.7 G</td>
</tr>
<tr>
<td>$\dot{E}_{\text{rotational}}$</td>
<td>$6 \times 10^{33}$ erg s$^{-1}$</td>
<td>$1.6 \times 10^{30}$ erg s$^{-1}$</td>
</tr>
<tr>
<td>Mean Orbit Velocity</td>
<td>301 km s$^{-1}$</td>
<td>323 km s$^{-1}$</td>
</tr>
</tbody>
</table>
The basic parameters Period, SpinDown age and $B_{\text{surf}}$ fit with the evolutionary path to the double pulsar systems suggested since long ago [van den Heuvel & deLoore 1975]
Mass-mass diagram for J0737-3039A&B
Mass-mass diagram for J0737-3039A&B

Mass function A

© Kramer - JBO
Mass-mass diagram for J0737-3039A&B
Kepler's 3\textsuperscript{rd} law

To 1PN order, relative separation given by:

$$ a_R = \left( \frac{G_{AB} M_{tot}}{n^2} \right)^{1/3} \left[ 1 - \frac{1}{6} (5\varepsilon + 3 - 2\nu) \left( \frac{G_{AB} M_{tot} n}{c^3} \right)^{2/3} \right] $$

$$ n = \left( \frac{2\pi}{P_b} \right), \quad \nu = m_A m_B / M_{tot}^2, \quad \varepsilon = 2\gamma + 1, \quad G_{AB} = G_{AB} \text{(strong field)} $$

...so that for "any" theory of gravity to 1PN order:

$$ R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B} \text{ Ratio is independent of strong (self-)field effects!} $$

Different to other PK parameters, which all depend on strong-field modified "constants" like $G_{AB}$ which differs from $G_{\text{Newton}}$ depending on strong-field effects in theory!
Mass-mass diagram for J0737-3039A&B
Mass-mass diagram for J0737-3039A&B

Periastron advance

GR! Theory dependent!
Mass-mass diagram for J0737-3039A&B

Grav. Redshift + 2nd order Doppler

GR! Theory dependent!
Shapiro delay in PSR-A arrival times

[ Lyne, Burgay, Kramer, Possenti et al. 2004]

\[
(\Delta t)_{\text{Shap}} = \frac{R_s}{c} \ln \left( \frac{1 + e \cos \phi}{1 - \sin i \sin \psi} \right)
\]
Mass-mass diagram for J0737-3039A&B

Mass A (M_⊙)

Mass B (M_⊙)

- Shapiro s
- GR!
- Theory dependent!
Mass-mass diagram for J0737-3039A&B

Shapiro r

GR! Theory dependent!
Mass-mass diagram for J0737-3039A&B
Mass-mass diagram for J0737-3039 @ Feb 2004
Mass—mass diagram for J0737-3039 @ Jun 2007

\[ M_B = 1.249(1)M_{\odot} \]

\[ M_A = 1.338(1)M_{\odot} \]

Observed shape of Shapiro delay in agreement with GR at 0.05% level

4 independent tests of GR!

at June 2007
What will be feasible to measure: Geodetic Precession

Precession periods only ~70 years [Burgay et al. 2003]

~ 4 time shorter than in any other double neutron star: much easier to be detected, thence imposing strong constraints to the geometry of the pulsar beam
What will be feasible to measure: Aberration

Aberration affects pulse profiles and influences the Time of Arrivals of the pulses.

\[ \Delta_A = A\{\sin[\omega + A_e(u)] + e \sin \omega\} + B\{\cos[\omega + A_e(u)] + e \cos \omega\} \]

[ Damour & Deruelle 1986 ]

Unfortunately the related PK parameters (A & B) are usually absorbed in Roemer delays.

Measuring masses, orbital semi-major axes and eccentricities of two sources in the same binary we should be able to disentangle the aberration contribution!
What could be feasible to measure: Neutron Star Structure

Total periastron advance to 2PN level: [Damour & Schaefer 1988]

\[ k^{tot} = \frac{3\beta_0^2}{1-e_T} \left[ 1 + f_0\beta_0^2 - g_s^A \beta_0^A \beta_0^B - g_s^B \beta_0^B \right] \]

1PN 2PN Spin A Spin B

Equation-of-State for the nuclear matter!!

A 10% accuracy on I would exclude most EoS [Lattimer & Schutz 2004] [Morrison et al. 2004]

\[ \beta_S = \frac{2\pi c}{G P_p m^2} \]
The unique occurrence of strong interactions between the energetic flux from A and the magnetosphere of B (1st evidence)

The signal of PSR A displays eclipses for ~20 s at superior conjunction...

... and the nature of the occulting medium is dependent on the rotational phase of B

Superior conjunction

[Breton et al. 2007]
The unique occurrence of strong interactions between the energetic flux from A and the magnetosphere of B (2nd evidence)

The intensity and pulse profile of B strongly vary along the orbit ...

... and during a portion of the phases of high brightness, the radio emission from B matches the ~ 44 Hz electromagnetic pulses arriving from A

[McLaughlin et al. 2004]
High brightness phases of B are changing! Possibility of removing degeneracy between different models checking their predictions about evolution in a human-scale time!

[Burgay, Possenti et al. 2005]
Spin-Powered Pulsars: A Census

- Number of known pulsars: 1765
- Number of millisecond pulsars: 170
- Number of binary pulsars: 131
- Number of pulsars in globular clusters: 129
- Number of extragalactic pulsars: 20

Data from ATNF Pulsar Catalogue, V1.25 (www.atnf.csiro.au/research/pulsar/psrcat; Manchester et al. 2005)
Why searching more pulsars?

✓ Pulsars are excellent clocks, leading to many interesting experiments in astrophysics and fundamental physics: gravity theories, nuclear matter, plasma physics.

✓ Pulsars are excellent probes of the interstellar medium and are widely distributed in the Galaxy.

✓ A few especially interesting objects with unique properties will probably be found in a large-scale survey.

✓ Leads to a better understanding of the Galactic distribution and birthrate of pulsars, of binary and stellar evolution, of their relationship to other objects such as supernova remnants, and of the emission physics.
The sensitivity formula

\[ S_{\text{min}} \sim \frac{T_{\text{sys}} + T_{\text{sky}}}{G \sqrt{N_p \Delta v \Delta t}} \sqrt{\frac{W_e}{P - W_e}} \]

- \( T_{\text{sys}} \) = system noise temperature
- \( T_{\text{sky}} \) = sky temperature
- \( G \) = antenna gain
- \( N_p \) = number of polarizations
- \( \Delta v \) = total bandwidth
- \( \Delta t \) = total integration time
- \( P \) = pulsar period
- \( W_e \) = effective pulse width
- \( W_e = W^2 + \delta t^2 + \delta t_{\text{DM}}^2 + \delta t_{\text{scatt}}^2 \)
- \( \delta t \) = sampling time
- \( \delta t_{\text{DM}} \) = dispersion smearing
- \( \delta t_{\text{scatt}} \) = scattering smearing
\[ S_{\text{min}} \sim \frac{T_{\text{sys}} + T_{\text{sky}}}{G \sqrt{N_p \Delta v \Delta t}} \sqrt{\frac{W_e}{P - W_e}} \]

\[ W_e = W^2 + \delta t_{\text{samp}}^2 + \delta t_{\text{DM}}^2 + \delta t_{\text{scatt}}^2 \]

\[ G \rightarrow \text{large aperture} \]

\[ T_{\text{sky}} \sim v^{-2.7} \text{ (r.a. \& dec)} \iff S_{\text{psr}} \sim v^{-1.7} \]

\[ \delta t_{\text{DM}} = \frac{\Delta t_{\text{DM}}}{1.2 \times 10^{-4}} \frac{\Delta v}{v^3} \]

\[ \delta t_{\text{scatt}} \sim \frac{1}{v^4} \]

\[ \delta t_{\text{samp}} \rightarrow 0 \]
Better use high $\nu$ 

$\delta t_{DM} \sim \nu^{-3}$

$\delta t_{scatt} \sim \nu^{-4}$

$T_{sky} \sim \nu^{-2.7}$

Narrow beam \(\sim\) Ok

In order to find many pulsars we have to search large volumes

Deep surveys in the disk
In order to find many pulsars we have to search large volumes.

Better use low $\nu$

Large telescope beam!

$S_{\text{psr}} \sim \nu^{-1.7}$

Away from the Galactic plane:

Low DM

Scattering negligible

$T_{\text{sky}} \sim 30 \text{ K}$
Standard search technique

Radio frequency

DM$_k$

FFT

Power spectrum

Fluctuation frequency

Integrated pulse profile

Pulse phase

Folding

time

- Standard search technique
- Radio frequency
- DM$_k$
- FFT
- Power spectrum
- Fluctuation frequency
If the code picked up the correct apparent pulse repetition period $P$
If the code picked up a slightly wrong apparent pulse repetition period $P$
If the apparent pulse repetition period $P$ is not changing too quickly along the observation, the code can still pick $P$.

Knowing exactly how $P$ changes, one can easily recover the pulse profile.
But if the Doppler acceleration is too high, the signal is not picked up in the fluctuation spectrum!
But if the Doppler acceleration is too high, the signal is not picked up in the fluctuation spectrum!

No pulsar suspect!
One way to take into account Doppler is to resample the time series according to a trial acceleration.

\[ \text{Nr of FFTs} = N_{DM} \times N_{acc} \]
Coherent (linear) acceleration search

[ Camilo et al 2000 ]
Segmented FFT procedure helps
Segmented vs standard search

9 ms pulsar

[ Faulkner, PhD Thesis 2004 ]
Dynamic spectrum search

[ Chandler, PhD Thesis 2004 ]
Phase modulation search

\[ \frac{(r - r_{\text{spin}})}{r_{\text{orb}}} \]

\[ \Phi_{\text{orb}} = 41.3 \pm 4 \text{ radians} \]

\[ \sim |u_{-\Phi_{\text{orb}}}(\Phi_{\text{orb}})|^2 \]

\[ \sim |\Phi_{\text{orb}}(\Phi_{\text{orb}})|^2 \]

\[ \sim 2r_{\text{orb}}\Phi_{\text{orb}} \text{ bins} \]

\[ f_{\text{spin}} \]

\[ \text{Power / Coherent Power} \]

[ Ransom et al 2001 ]
Phase modulation VS segmented search

9 ms pulsar

[Faulkner, PhD Thesis 2004]
The choice of the observing parameters of the survey (wide or deep) and the amount of computational capabilities result in a different sampling of evolutionary stage of pulsars and hence of the $P$-$\dot{P}$ diagram.
The Parkes multibeam surveys

Parkes 64 m radiotelescope

Multibeam receiver

System parameters:

- 13 beams
- $T_{\text{sys}} \sim 25$ K
- $\Delta \nu \sim 288$ MHz @ 1.4GHz
- $\delta \nu = 13 \times 96 \times 3$ MHz
- $\delta \nu = 512 \times 0.5$ MHz
The Parkes multibeam surveys

Parkes 64 m radiotelescope

- 13 beams
- $T_{\text{sys}} \approx 25 \degree \text{K}$
- $\Delta \nu \approx 288 \text{MHz} @ 1.4 \text{GHz}$
- $\delta \nu = 13 \times 96 \times 3 \text{MHz}$
- $\delta \nu = 512 \times 0.5 \text{MHz}$

- $\delta v = 512 \times 0.5 \text{ MHz}$
PM Group: Jodrell Bank, ATNF, Cagliari, Columbia, McGill, ...
PH Group: Cagliari, Jodrell Bank, ATNF, Columbia, ...
Swin Group: Swinburne, Caltech

SW Survey (Swinburne Group)
PM Survey (PM Group)
PH Survey (PH Group)
Field pulsars only (N=1275)

A growing number of millisecond pulsars:

Since reprocessing started: new MSPs > 10

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>12 32 17.840(5)</td>
<td>-6 51 03.73(4)</td>
<td>88.28±0.02(3)</td>
<td>8.16(2) × 10$^{-19}$</td>
<td>5126.00(1)</td>
<td>1.86327241(8)</td>
<td>1.35485217(2)</td>
<td>0.0001(18)</td>
<td>239.4(5)</td>
<td>0.3</td>
<td>11.0</td>
<td>11.0</td>
<td>38.0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>14 35 20.756(4)</td>
<td>-6 51 06.58(6)</td>
<td>9.3349 ± 0.02(8)</td>
<td>2.45(4) × 10$^{-19}$</td>
<td>5126.00(1)</td>
<td>1.86327241(8)</td>
<td>1.35485217(2)</td>
<td>0.0001(18)</td>
<td>239.4(5)</td>
<td>0.3</td>
<td>11.0</td>
<td>11.0</td>
<td>38.0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>14 54 10.908(2)</td>
<td>-6 51 06.58(6)</td>
<td>45.24 ± 0.02(9)</td>
<td>8.17(6) × 10$^{-19}$</td>
<td>5126.00(1)</td>
<td>1.86327241(8)</td>
<td>1.35485217(2)</td>
<td>0.0001(18)</td>
<td>239.4(5)</td>
<td>0.3</td>
<td>11.0</td>
<td>11.0</td>
<td>38.0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>18 10 58.988(2)</td>
<td>-6 51 06.58(6)</td>
<td>5126.00(1)</td>
<td>1.51(7) × 10$^{-19}$</td>
<td>5126.00(1)</td>
<td>1.86327241(8)</td>
<td>1.35485217(2)</td>
<td>0.0001(18)</td>
<td>239.4(5)</td>
<td>0.3</td>
<td>11.0</td>
<td>11.0</td>
<td>38.0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>19 04 31.382(4)</td>
<td>-6 51 06.58(6)</td>
<td>5126.00(1)</td>
<td>1.31(3) × 10$^{-19}$</td>
<td>5126.00(1)</td>
<td>1.86327241(8)</td>
<td>1.35485217(2)</td>
<td>0.0001(18)</td>
<td>239.4(5)</td>
<td>0.3</td>
<td>11.0</td>
<td>11.0</td>
<td>38.0</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Pulsars with Magnetar Fields

- Manchester, et al. 2001
- Lorimer, et al. 2004
- Faukner, et al. 2006
40 new young pulsars ($\tau \lesssim 100$ kyr)

Now we know 26 "Vela-like" ($E > 10^{36}$ erg s$^{-1}$)

<table>
<thead>
<tr>
<th>PSR</th>
<th>$P$ (ms)</th>
<th>$\Lambda_c$, $\tau_c$ (kyr)</th>
<th>$E$ ($10^{36}$ erg s$^{-1}$)</th>
<th>Ref</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0833−45</td>
<td>89.3</td>
<td>11</td>
<td>6.9</td>
<td>1 G, E</td>
<td></td>
</tr>
<tr>
<td>J0555−4644</td>
<td>64.7</td>
<td>141</td>
<td>1.1</td>
<td>III</td>
<td></td>
</tr>
<tr>
<td>J0940−5228</td>
<td>87.5</td>
<td>42</td>
<td>1.9</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>J1016−5857</td>
<td>107.4</td>
<td>21</td>
<td>2.6</td>
<td>2 G, E</td>
<td></td>
</tr>
<tr>
<td>J1046−58</td>
<td>123.7</td>
<td>20</td>
<td>2.0</td>
<td>3, 4 G, E</td>
<td></td>
</tr>
<tr>
<td>J1105−6107</td>
<td>63.2</td>
<td>63</td>
<td>2.5</td>
<td>5 G, E</td>
<td></td>
</tr>
<tr>
<td>J1112−6103</td>
<td>65.0</td>
<td>33</td>
<td>4.5</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>J1301−6305</td>
<td>184.5</td>
<td>11</td>
<td>1.7</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>J1345−6437</td>
<td>213.3</td>
<td>13</td>
<td>10.0</td>
<td>III, 8 E</td>
<td></td>
</tr>
<tr>
<td>J1450−6048</td>
<td>68.2</td>
<td>13</td>
<td>3.0</td>
<td>5 G, E</td>
<td></td>
</tr>
<tr>
<td>J1542−5625</td>
<td>78.2</td>
<td>32</td>
<td>3.2</td>
<td>III</td>
<td></td>
</tr>
<tr>
<td>J1541−5910</td>
<td>84.2</td>
<td>97</td>
<td>0.9</td>
<td>III</td>
<td></td>
</tr>
<tr>
<td>J1706−44</td>
<td>132.3</td>
<td>18</td>
<td>4.4</td>
<td>3 G, E</td>
<td></td>
</tr>
<tr>
<td>J1718−3825</td>
<td>74.7</td>
<td>90</td>
<td>1.3</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>J1727−33</td>
<td>139.4</td>
<td>26</td>
<td>1.2</td>
<td>3 G</td>
<td></td>
</tr>
<tr>
<td>J1747−2958</td>
<td>98.8</td>
<td>26</td>
<td>2.5</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>J1757−24</td>
<td>124.9</td>
<td>16</td>
<td>2.6</td>
<td>7 G</td>
<td></td>
</tr>
<tr>
<td>J1800−21</td>
<td>133.6</td>
<td>16</td>
<td>2.2</td>
<td>10 G</td>
<td></td>
</tr>
<tr>
<td>J1809−1917</td>
<td>82.7</td>
<td>51</td>
<td>1.8</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>J1823−13</td>
<td>105.3</td>
<td>21</td>
<td>2.9</td>
<td>10 G, E</td>
<td></td>
</tr>
<tr>
<td>J1828−1301</td>
<td>72.1</td>
<td>77</td>
<td>1.6</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>J1837−0604</td>
<td>96.3</td>
<td>34</td>
<td>2.0</td>
<td>II, 8</td>
<td></td>
</tr>
<tr>
<td>J1913+1011</td>
<td>35.9</td>
<td>169</td>
<td>2.9</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>J1951+32</td>
<td>39.5</td>
<td>107</td>
<td>3.7</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>J2021+3651</td>
<td>103.7</td>
<td>17</td>
<td>3.4</td>
<td>12 E</td>
<td></td>
</tr>
<tr>
<td>J2229+6114</td>
<td>51.6</td>
<td>11</td>
<td>22.0</td>
<td>13 E</td>
<td></td>
</tr>
</tbody>
</table>

Pulsars with Magnetar Fields

The total score: a real boom of pulsar discoveries!

<table>
<thead>
<tr>
<th>Parkes discoveries</th>
<th>Radio pulsars in the Catalog: ~ 1765</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parkes PM</strong></td>
<td>131 Binaries</td>
</tr>
<tr>
<td>= 725</td>
<td></td>
</tr>
<tr>
<td><strong>Parkes Swin</strong></td>
<td>170 Millisecond (P&lt;25ms)</td>
</tr>
<tr>
<td>= 69+25</td>
<td></td>
</tr>
<tr>
<td><strong>Parkes PH</strong></td>
<td>26 Vela-like</td>
</tr>
<tr>
<td>= 18</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>8 Double Neutron star binaries</td>
</tr>
<tr>
<td>= 837</td>
<td>1 Double pulsar</td>
</tr>
<tr>
<td><strong>Parkes GC search</strong></td>
<td>129 in 24 Globular Clusters</td>
</tr>
<tr>
<td>= 12</td>
<td></td>
</tr>
<tr>
<td><strong>Parkes 47 Tuc search</strong></td>
<td></td>
</tr>
<tr>
<td>= 22</td>
<td></td>
</tr>
</tbody>
</table>
Arecibo Alfa Survey at 1.4 GHz
~ 300-500 discoveries in 3-5 yrs?

Parkes Perseus Arm Survey at 1.4 GHz
15-30 discoveries?

GBT Pilot Surveys at 350 MHz 30-50 discoveries

GBT Drift Scan Survey at 350 MHz > 100 discoveries?

GMRT Survey at 610 MHz 5-10 discoveries?

GBT Surveys of Globular Clusters at 2.1 GHz > 100 discoveries?

Parkes Galactic MSP Survey at 1.4 GHz 50-100 MSP discoveries?
Fun for everyone: Pulsar Astrophysics with the SKA (from 200x)

General science case covers lots of topics [Cordes et al. 2004]

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- Extreme Dense Matter Physics
- Multi-wavelength studies
- Exotic systems
- Gravitational physics (SKA KSP)

Strong-field tests of gravity using pulsar & black holes identified as one of five SKA Key Science Projects
Galactic Census with the SKA

[ Kramer et al. 2004 ]

- Discovery of almost every pulsars in Galaxy: in total ~ 10000-20000 pulsars
- ~ 1000 millisecond pulsars
- more and more Double-Pulsar Systems
Galactic Census with the SKA

[ Kramer et al. 2004 ]

Timing of discovered binary and millisecond pulsars to very high precision:

- “Find them!”
- “Time them!”
- “VLBI them!”

Not just a continuation of what has been done before
Complete new quality of science possible!
Cosmological Gravitational Wave Background

• Pulsars discovered in Galactic Census also provide network of arms of a huge cosmic gravitational wave detector

• Perturbation in space-time can be detected in timing residuals

• Sensitivity: dimensionless strain

\[ h_c(f) \sim \frac{\sigma_{\text{TOA}}}{T} \]
Cosmological Gravitational Wave Background

With such an array of pulsars, Pulsar timing can detect a stochastic gravitational wave background

Sources:

- Inflation
- String cosmology
- Cosmic strings
- Phase transitions

...and also:

- Merging massive BH binaries in early galaxy evolution

\[ h_0^2 \Omega_{GW}(f) \sim \text{const.} \]

\[ h_0^2 \Omega_{GW}(f) \propto f^{2/3} \]
Cosmological Gravitational Wave Background

[ Kramer et al. 2004 ]

**PTA limit:**

\[ h_0^2 \Omega_{GW}(f) \sim \sigma_{TOA}^2 f^4 \]

Further by correlation:

\[ \frac{1}{\sqrt{N_{PSR}}} \]

**Improvement:** 10^4!

**Spectral range:** nHz

only accessible with SKA!

complementary to

LISA, LIGO & CMB
The last not prohibited dream: a pulsar orbiting a Black Hole (200?)

- Astrophysical black holes are expected to rotate
- BH have spin and quadrupole moment
- Both can be measured by high precision pulsar timing via relativistic and classical spin-orbit coupling

- Not easy! It is not possible today!
- Requires SKA sensitivity!

Test Cosmic Censorship Conjecture & No-Hair Theorem!

[ Wex & Kopeikin 1999 ]

[ Kramer et al. 2004 ]
Happy hunting, folks !!!