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Corbet Diagram (again)

1. Corbet R H D. Be/neutron star binaries—A relationship between orbital period and neutron star spin period. 1984
2. Corbet R. Be/neutron star binaries—Orbital and spin periods. 1985
3. Corbet R H D. The three types of high-mass X-ray pulsator. 1986
P-P(dot) Diagram

http://hera.ph1.uni-koeln.de/~heintzma/U1/IV_Pulsar.htm
Recycled Pulsars:
The first discovered millisecond pulsar is **PSR B 1937+21** (Backer, Kulkarni, Heiles, Davies & Goss 1982). After its discovery millisecond pulsars explained as the result of accretion in LMXBs by two groups independently (Alpar, Cheng, Ruderman & Shaham 1982; Radhakrishnan & Srinivasan 1982). In order to lead LMXB evolution to millisecond equilibrium rotation rates, magnetic fields must be \( \sim 10^8 - 10^9 \) G and spin-down rate of the millisecond radio pulsar would be \( \sim 10^{-19} \) s s\(^{-1}\) which is inferred by both two groups.[1]

This spin period was nearly minimum value that can be attainable by a Neutron Star! Also their magnetic fields were lower nearly 3 orders of magnitude than most known pulsars!

It is understood that this spin period is gained by spin-up, so they are also called recycled pulsars. (short spin period and older objects, no SNR observed)

**PSR B 1937+21** has no companion but **PSR B 1953+29** found in a binary and **PSR B 1957+20** is also found in a binary but its binary was in vaporization state. So it's thought that MSPs lost their companions in some way (they are
MSPs and Their History

probably vaporized by strong radiation)
These short periods require large mass transfer which is ~0.1 solar mass, at
Eddington accretion rate this would takes ~10^7 .Mass transfer phase duration
in most of the massive binaries (HMXBs) this time would be much less.

Accreting Millisecond Pulsars (AMSPs):[2]
The discovery of a 401 Hz coherent signal from the X-ray transient SAX J1808.4–3658 (Wijnands & van der Klis 1998) confirmed that old neutron stars in
LMXBs are rapidly rotating objects, spun-up by the accretion of angular
momentum from matter in-falling through a disc. Sources showing a coherent
signal with a period of few ms are called accreting millisecond pulsars (AMSP);
they are all relatively faint X-ray transients attaining peak X-ray luminosities of a
few × 10^36 erg s−1, with outbursts lasting up to a few months.

the fastest known accretion-powered pulsar", arXiv:1006.1303v2,(2011)
Properties of MSPs

- Spin periods are lower than 10ms
- Magnetic fields are lower than $10^9$ G (which is derived from measured spin-down rate)
- B field vs. period
  - Below death-line: switch off
  - Spin-up line: min. spin
  - Hubble-line: spin down age

http://astronomy.swin.edu.au/cms/astro/cosmos/m/Millisecond+Pulsar
Properties of MSPs

- General statistics: galactic disk, 90% in binaries; globular clusters, 50% in binaries
- Their companions have mass lower than 0.3 solar mass
- Very old objects: no SNR and also in PSR 1853+09 case its WD companion is at least $10^9$ yr old (surface temp. suggestion) and we know that NS is formed before WD so MSP must be older than $10^9$ yr.
- Radio emission properties: steeper radio spectra than ordinary pulsars.
  Polarization characteristics are difficult to interpret.
  (Polarization data helps us to infer the geometry of magnetic field wrt rotation axis)
  They have simple pulse profiles in Galactic Clusters and complex, multi-component profiles in Galactic Disks.
Spin-up of Neutron Stars

ANDREA POSSENTI The role of pulsars' timing in GW presentation at VESF SCHOOL on GRAVITATIONAL WAVES
Spin-down of MSP

A newly born fast spinning pulsar
dehly line

$10^7$ $10^9$ $10^{11}$ $10^{13}$

$0.001$ $0.01$ $0.1$ $1.$ $10.$

$1000$ yr

Hubble time

ANDREA POSSENTI The role of pulsars’ timing in GW presentation at VESF SCHOOL on GRAVITATIONAL WAVES
MSP evolution

Recent MSP Evolution Model


http://www.youtube.com/watch?v=us2qmzh85Bs

## Statistics & Studied Objects

<table>
<thead>
<tr>
<th>AMSPs</th>
<th>Spin Periods</th>
<th>Orbital Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAX J1808.4 -3658</td>
<td>(401 Hz)</td>
<td>2 hr</td>
</tr>
<tr>
<td>XTE J1751 -305</td>
<td>(435 Hz)</td>
<td>42 min</td>
</tr>
<tr>
<td>XTE J0929 -314</td>
<td>(185 Hz)</td>
<td>44 min</td>
</tr>
<tr>
<td>XTE J1807 -294</td>
<td>(191 Hz)</td>
<td>40 min</td>
</tr>
<tr>
<td>XTE J1814 -338</td>
<td>(314 Hz)</td>
<td>4.3 hr</td>
</tr>
<tr>
<td>IGR J00291 +5934</td>
<td>(599 Hz) (f!)</td>
<td>2.45 hr</td>
</tr>
<tr>
<td>IGR J17498 -2921</td>
<td>(401 Hz)</td>
<td>3.8 hr</td>
</tr>
<tr>
<td>Swift J1756.9–2508</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swift J1749.4-2807</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGR J17480-2446</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Intermittent AMSPs

<table>
<thead>
<tr>
<th>AMSPs</th>
<th>Spin Periods</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aql X-1</td>
<td>(550.27 Hz)</td>
<td>(only for 150s) (Casella '07)</td>
</tr>
<tr>
<td>SAX J1748.9 -2021</td>
<td>(442.36 Hz)</td>
<td>(Hundreds of seconds) (Altamirano '07)</td>
</tr>
<tr>
<td>HETE J1900 -2455</td>
<td>(?)</td>
<td>(only first two months)</td>
</tr>
</tbody>
</table>

### Rotation Powered MSPs

- In Galactic Plane ~ 70
- In Globular Clusters ~ 150
Importance of Globular Clusters for MSPs

Two main reasons why MSPs in Globular Clusters (GCs):

1) High stellar density of GCs allows formation of binary star systems through capture in close encounters. This results in a larger density of X-ray binary sources, which in turn generates a relatively larger amount of MSPs.

2) GCs are easy targets for surveys, while surveys for non-globular MSPs require vastly larger amounts of observing time due to the inherently larger sky coverage.

Millisecond Oscillations

X-ray oscillations with msec periods:

- **Accretion-powered oscillations**: Frequency of these oscillations are at spin period of the MSP. There are 7 sources. Frequencies ranges from 185 Hz to 599 Hz. Channeling accretion flow requires magnetic field strength higher than $10^7$ G. Pulses have sinusoidal waveforms and amplitudes of the pulses indicate that magnetic field must be lower than $10^{10}$ G.

- **Nuclear-powered burst oscillations**: Frequency of these oscillations are very close to spin period of the MSP. Their pulses also have sinusoidal waveforms. X-ray spectra and properties of oscillations indicate that magnetic field strength must be lower than $10^7$ G. Thermonuclear bursts also indicate that it must be lower than $10^{10}$ G.

- **kHz QPOs**: Frequency of these oscillations have ranges from 100 Hz to 1300 Hz. QPOs originates from the closure of accretion gas to the surface. It is possible because of low magnetic field, which does not cause the gas to fall into the magnetic poles as in accretion-powered oscillations.
Accretion-powered oscillations

The XMM-Newton images of the field containing SAX J1808.4–3658 during its 2000 outburst (left panel; Wijnands 2003) and when the source was in quiescence (in 2001; right panel; see Campana et al. 2002).
Accretion-powered oscillations

Light curve of the two outbursts exhibited by J00291 during 2008, as observed by the PCU2 of the PCA aboard RXTE.

Evolution of the pulse phase delays (in μs) during the August 2008 outburst
Accretion-powered oscillations

The RXTE PCA light curve of the 2008 outbursts from IGR J00291+5934.
Accretion-powered oscillations

Examples of power spectra for each of the six currently known millisecond X-ray pulsars showing the pulsar spikes.
Accretion-powered oscillations

The RXTE/PCA (Wijnands et al. 2001) and the optical (I band) light curves (Wachter et al. 2000) of SAX J1808.4–3658 as observed during its 2000 outburst.
Accretion-powered oscillations

The RXTE/PCA light curves of five of the six accretion-driven millisecond X-ray pulsars.
kHz QPOs

The power spectrum of SAX J1808.4–3658. The top panel shows the two simultaneous kHz QPOs discovered during its 2002 outburst. The bottom panel shows the enigmatic 410 Hz QPO also seen during this outburst. The figures are adapted from Wijnands et al. (2003).
Examples of the aperiodic timing features seen in the six millisecond pulsars.
Spectral Properties of AMSPs

(J00291-2004 December outburst)

Spectral parameters of the thermal Comptonization compps fit to the JEM-X/ISGRI data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H (10^{22} \text{ cm}^{-2})$</td>
<td>0.28 (f)</td>
</tr>
<tr>
<td>$kT_e$ (keV)</td>
<td>49$^{+2}_{-1}$</td>
</tr>
<tr>
<td>$kT_{\text{seed}}$ (keV)</td>
<td>1.49$^{+0.16}_{-0.32}$</td>
</tr>
<tr>
<td>$\tau_T$</td>
<td>1.12$^{+0.06}_{-0.06}$</td>
</tr>
<tr>
<td>$A_{\text{seed}}$ (km$^2$)</td>
<td>20.7$^{+12.8}_{-8.8}$</td>
</tr>
<tr>
<td>$\cos \theta$</td>
<td>0.60$^{+0.06}_{-0.06}$</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td>44/37</td>
</tr>
<tr>
<td>$L_{1-300\text{ keV}} (10^{36} \text{ erg s}^{-1})$</td>
<td>3.7</td>
</tr>
</tbody>
</table>

"Assuming a distance of 5 kpc.

The unfolded spectrum of IGR J00291+5934 fitted with an absorbed compps model. The data points correspond to the JEM-X (5–20 keV) and ISGRI (20–200 keV) spectra, respectively. The total spectrum of the model is shown by a solid curve. The lower panel presents the residuals between the data and the model.

"INTEGRAL and RXTE observations of accreting millisecond pulsar IGR J00291+5934 in outburst" M. Falanga, L. Kuiper, (2005)
The outburst evolution of the best-fit spectral parameters of the compps model. Each point, except the last, corresponds to a one day averaged spectrum; due to the lower flux level the last points are averaged over two days.
Multiwavelenght Observations of MSPs

**RXTE, XMM, Chandra telescopes**: detection of x-rays from AMSPs, timing & spectroscopy

**INTEGRAL**: detection of bursts, spectroscopy

**FERMI**: detection of gamma rays from MSP, spectroscopy

http://www.vbtube.com/vbulletin4-demo/youtube_browser.php?do=show&vidid=MSeYkLKgxfE

**PARKES, GBT, Arecibo Telescopes**: detection of radio waves from MSPs, timing, spectroscopy

**Optic**: too faint companions & hard to detect optical data.
Interesting Studies about MSPs (1)

Transformation of a Star into a Planet in a Millisecond Pulsar Binary.

M. Bailes$^{1,2,3}$, S. D. Bates$^4$, V. Bhalerao$^5$, N. D. R. Bhat$^{1,3}$, M. Burgay$^6$, S. Burke-Spolaor$^7$, N. D’Amico$^{6,9}$, S. Johnston$^7$, M. J. Keith$^7$, M. Kramer$^{8,4}$, S. R. Kulkarni$^5$, L. Levin$^{1,7}$, A. G. Lyne$^4$, S. Milia$^{9,6}$, A. Possenti$^6$, L. Spitler$^1$, B. Stappers$^4$, W. van Straten$^{1,3}$

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$^2$Department of Astronomy, University of California, Berkeley, CA, 94720, USA.
$^3$ARC Centre for All-Sky Astronomy (CAASTRO).
$^4$Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK.
$^5$Caltech Optical Observatories, California Institute of Technology, MS 249-17, Pasadena, CA 91125, USA.
$^6$INAF - Osservatorio Astronomico di Cagliari, Poggio dei Pini, 09012 Capoterra, Italy.
$^7$Australia Telescope National Facility, CSIRO Astronomy and Space Science, P.O. Box 76, Epping NSW 1710, Australia.
$^8$MPI fuer Radioastronomie, Auf dem Huegel 69, 53121 Bonn, Germany.
$^9$Dipartimento di Fisica, Università degli Studi di Cagliari.

Interesting Studies about MSPs (2)

Rotation powered MSPs are extremely precise and stable clocks! It's important to detect gravitational waves by measuring tiny changes in the pulsars' rotation caused by the passage of gravitational waves.

http://www.sciencedaily.com/releases/2010/01/100105143728.htm