X-ray Properties of High Mass X-ray Binaries

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Garching

- Spin period evolution (accretion physics)
- X-ray spectra (structure of stellar winds)

High Energy View of Accreting Objects:

AGN and X-ray Binaries

Agios Nikolaos, Crete, Greece, October 5-14, 2010

High Mass X-ray Binaries (HMXBs)

Early type star + accreting compact object

HMXBs

BH / NS → **Supergiant Systems**

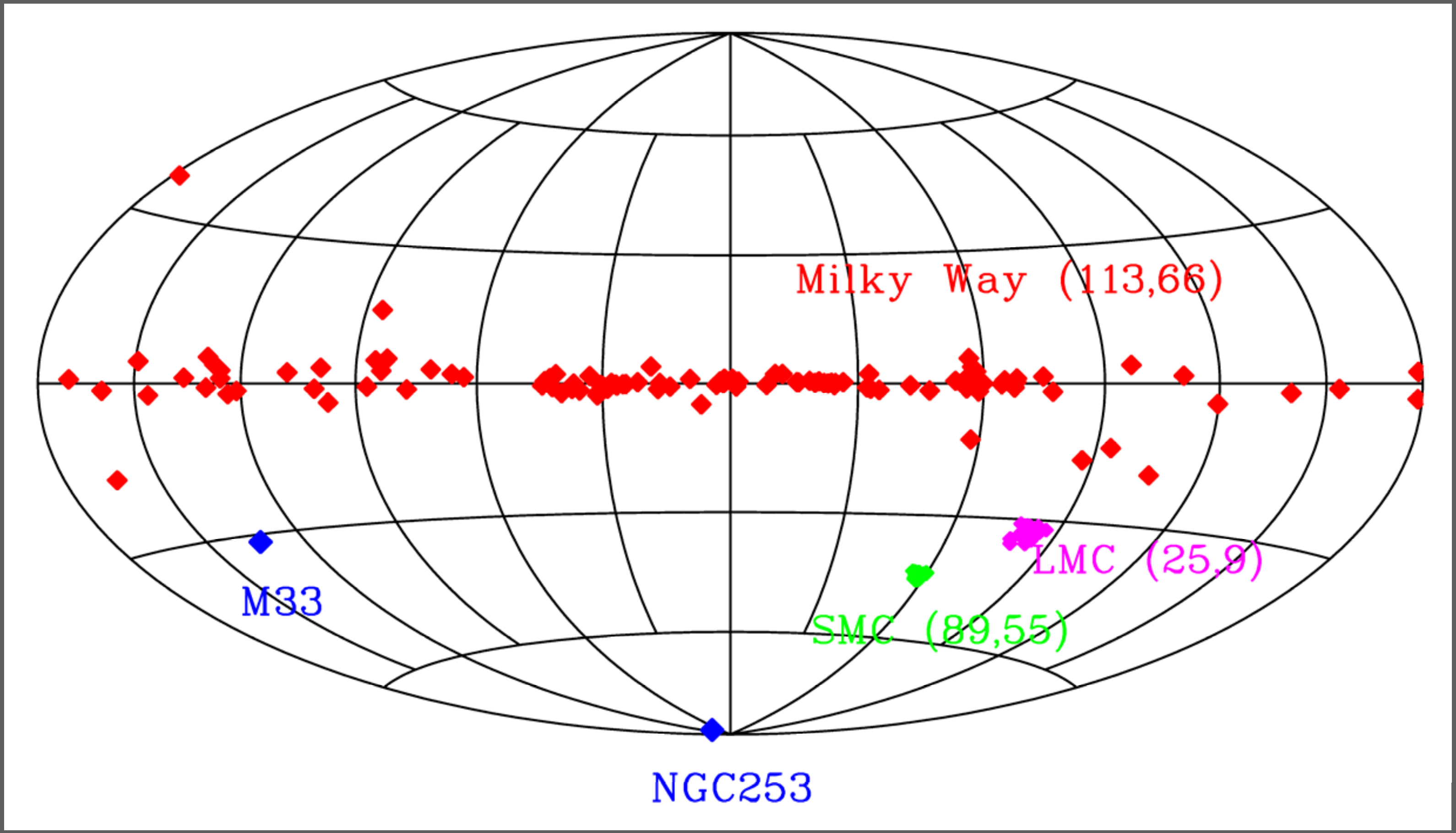
NS / WD* → **Be/X-ray Binaries** 10^{33}-10^{38} erg/s

Supergiant Systems → **Roche-lobe Overflow** 10^{38} erg/s

Supergiant Systems → **Wind Accretion** 10^{36} erg/s

*WDs should dominate according to population synthesis models
but no clear case (low-L_x systems → de Oliveira et al. 2006; SSS+Be → Kahabka et al. 2006)

HMXBs in the Milky Way and nearby galaxies



227 HMXBs and candidates 130 pulsars

MW: Liu et al. 2006
SMC: Haberl & Pietsch 2004; Coe et al 2004 + new discoveries
LMC: Negueruela & Coe 2002; Shtykovskiy & Gilfanov 2004 + new discoveries

HMXBs in the Milky Way

HMXBs

113 **(66 pulsars)**

Supergiant Systems — **20**

Be/X-ray Binaries — **52**

Roche-lobe Overflow — **1**

Wind Accretion — **18**

Exotic Systems:
Cyg X-1 (focussed wind)
Cyg X-3 (Wolf-Rayet)
LS 5039 (micro-quasar)
SS 433 (micro-quasar)

HMXBs in the Small Magellanic Cloud (MW)

HMXBs

89
113

(55 pulsars)

Supergiant Systems

1
20

Be/X-ray Binaries

78
52

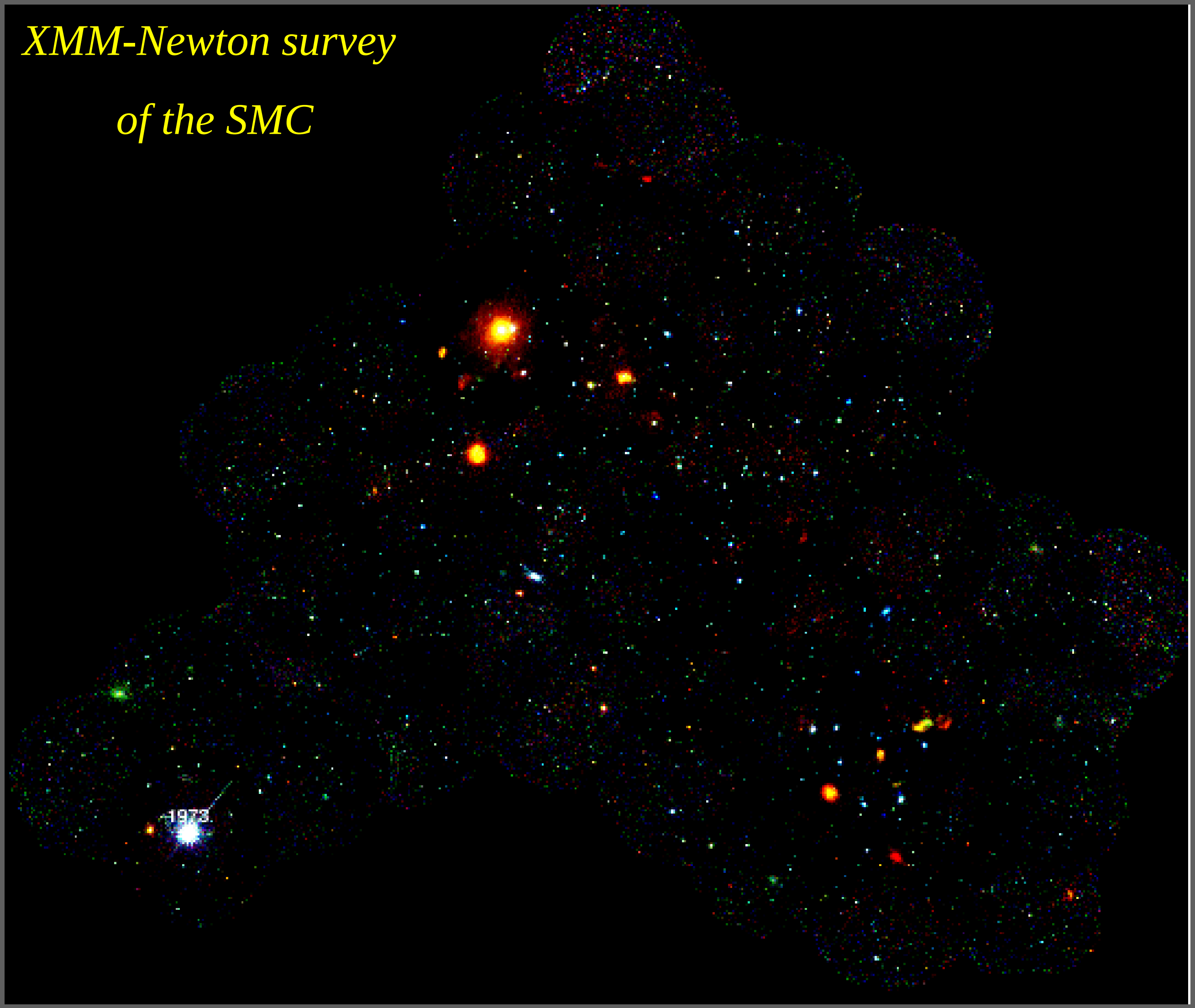
Roche-lobe Overflow

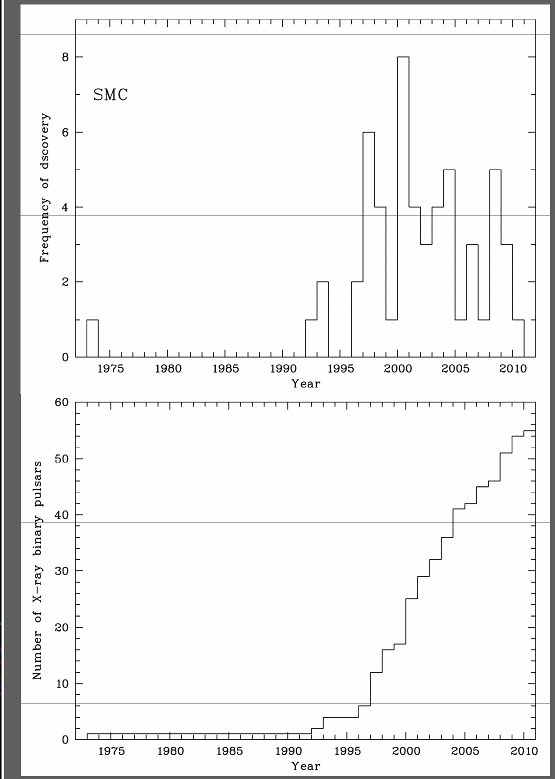
1
1

Wind Accretion

0
18

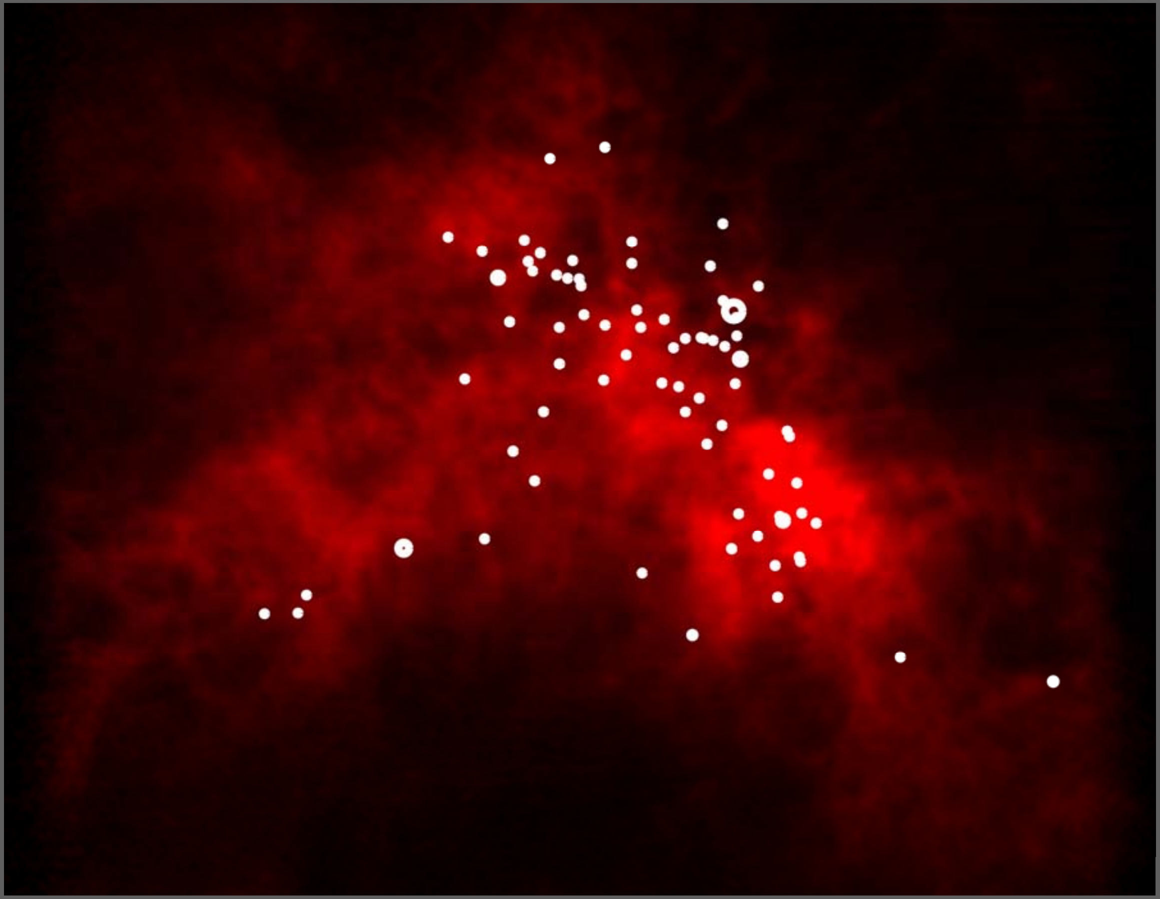
... and steadily increasing





55 pulsars
50 with good positions

Distribution in the SMC

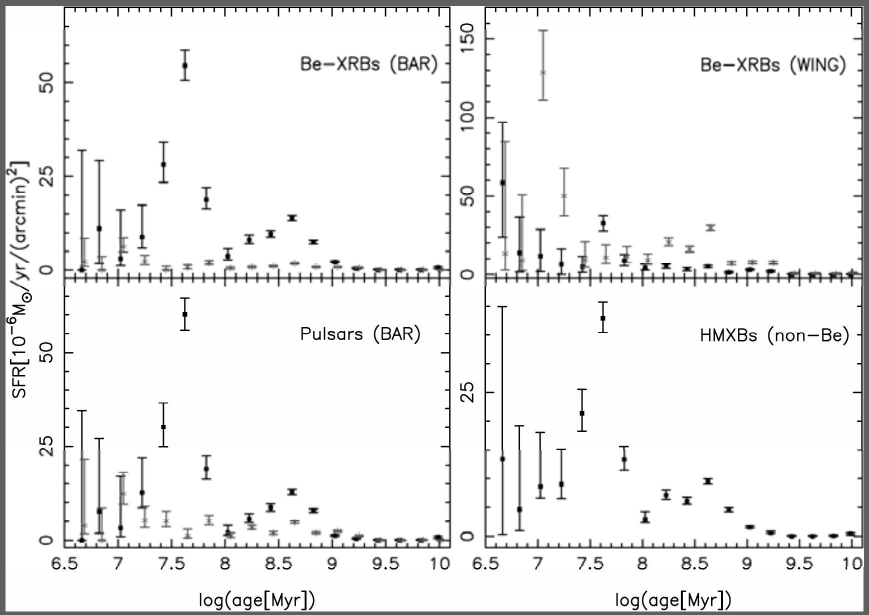


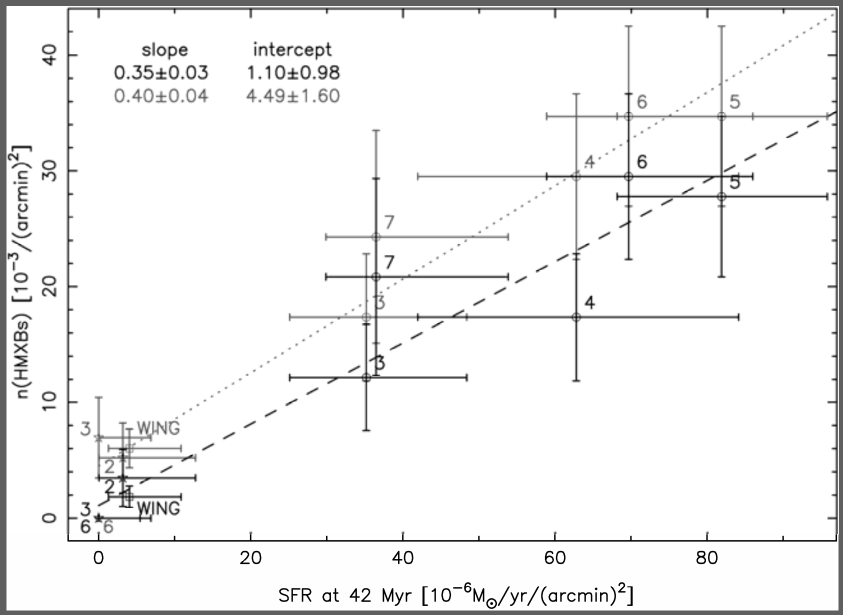
HI map

Stanimirovic et al. (1999)

77 HMXBs with good position
51 known pulse period
26 properties of Be/X-ray binary - unknown pulse period

HMXBs and Star Formation History





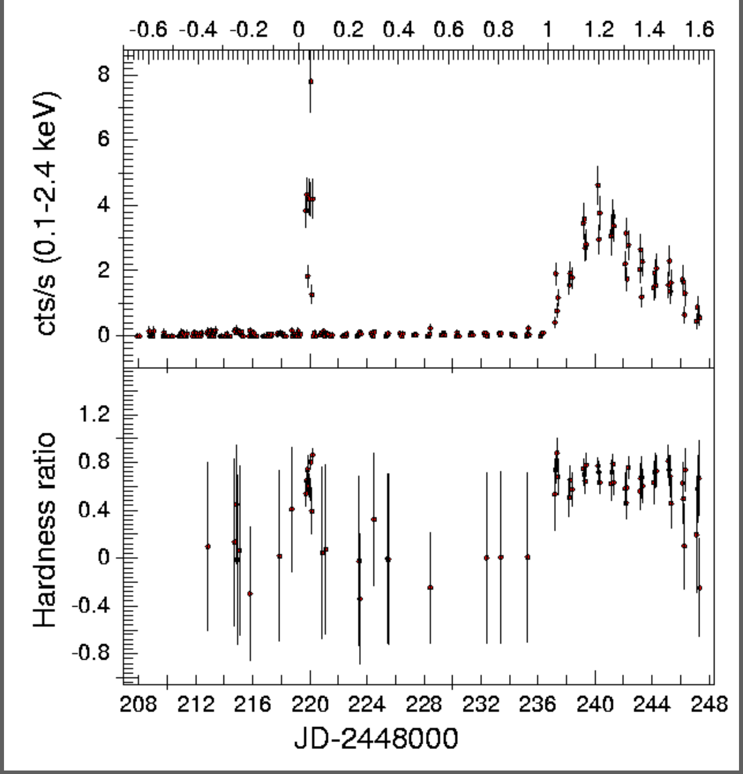
- **HMXBs in regions with star formation bursts 25-60 Myrs ago**
- **number of HMXBs correlates with SFR at 42 Myr**

Antoniou et al. 2010 - See talk

Transient Be/X-ray binaries

- Short (a few days) X-ray outbursts ($L_x \sim 10^{36-37}$ erg s^{-1}) separated by the orbital period generally (not always) occurring near the periastron passage of the NS (type I)
- Giant X-ray outbursts ($L_x > 10^{37}$ erg s^{-1}) lasting several weeks (type II)

  Be disc loss
- Periods of quiescence with $L_x \sim 10^{33}$ erg s^{-1}

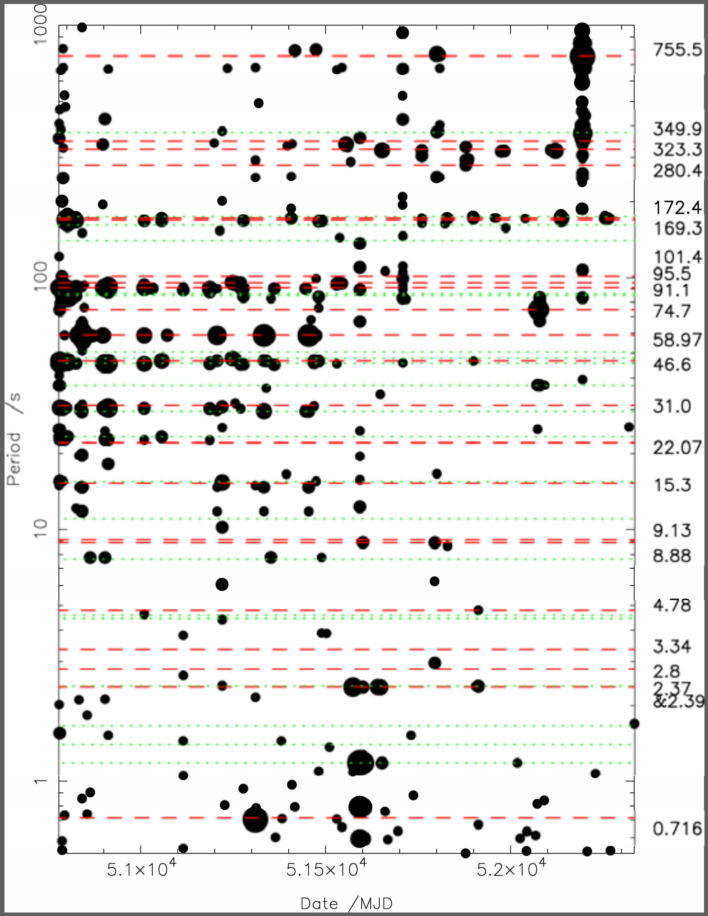


A 0538-66 in ROSAT survey

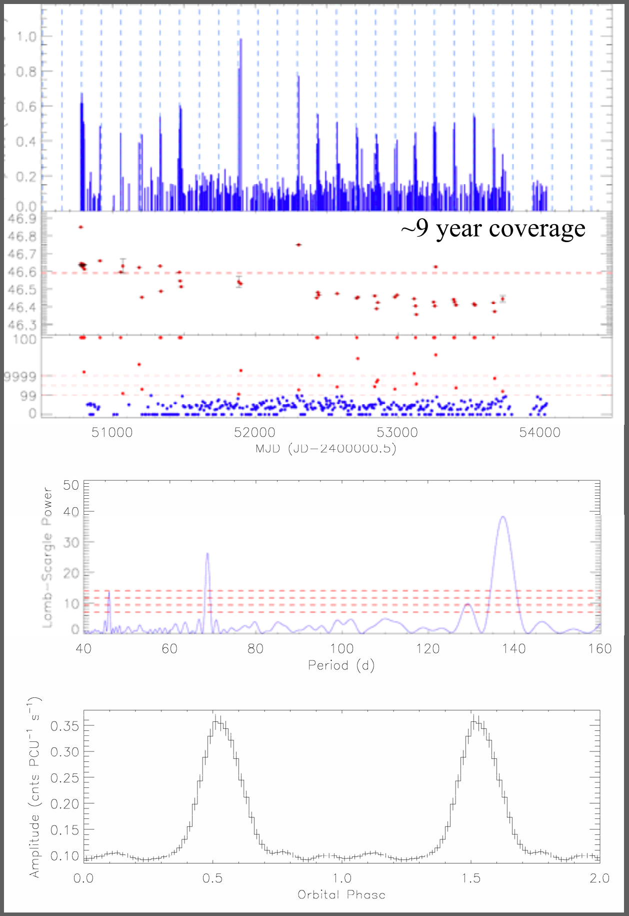
(Mavromatakis & Haberl 1993)

Orbital periods – X-rays

- Orbital parameters from X-ray timing (Doppler modulation of spin period)
  Milky Way, RXTE monitoring of SMC pulsars → Poster by Townsend et al.
- Long term monitoring of outburst behaviour (X-ray and optical)



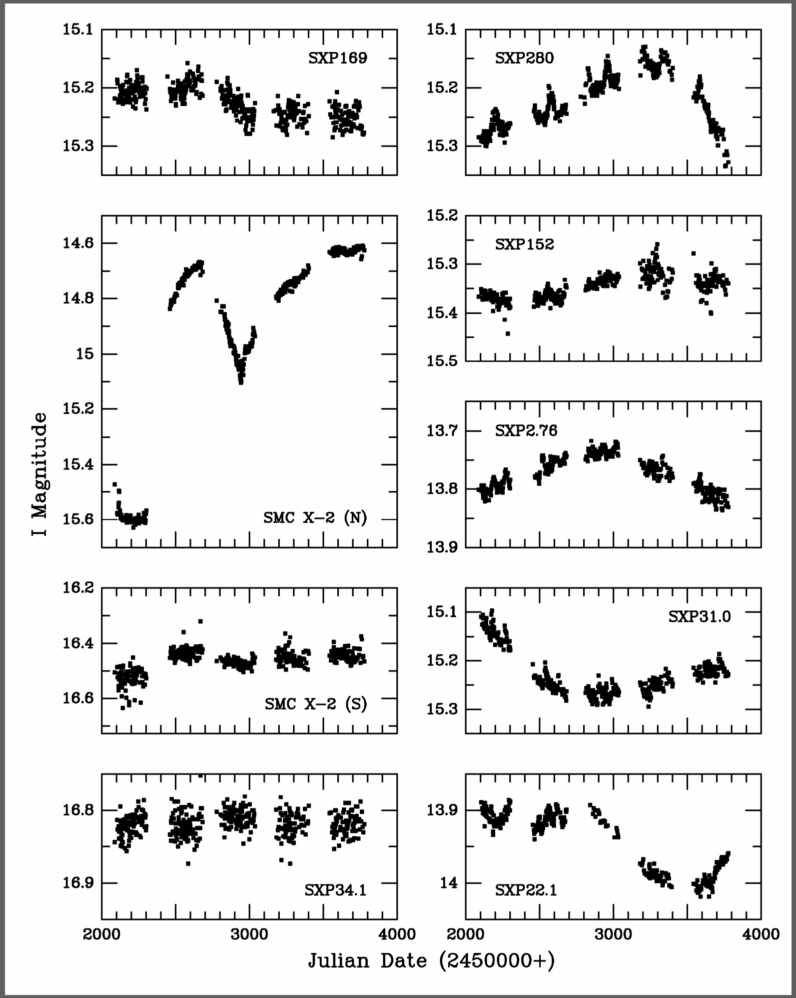
Laycock et al. 2005

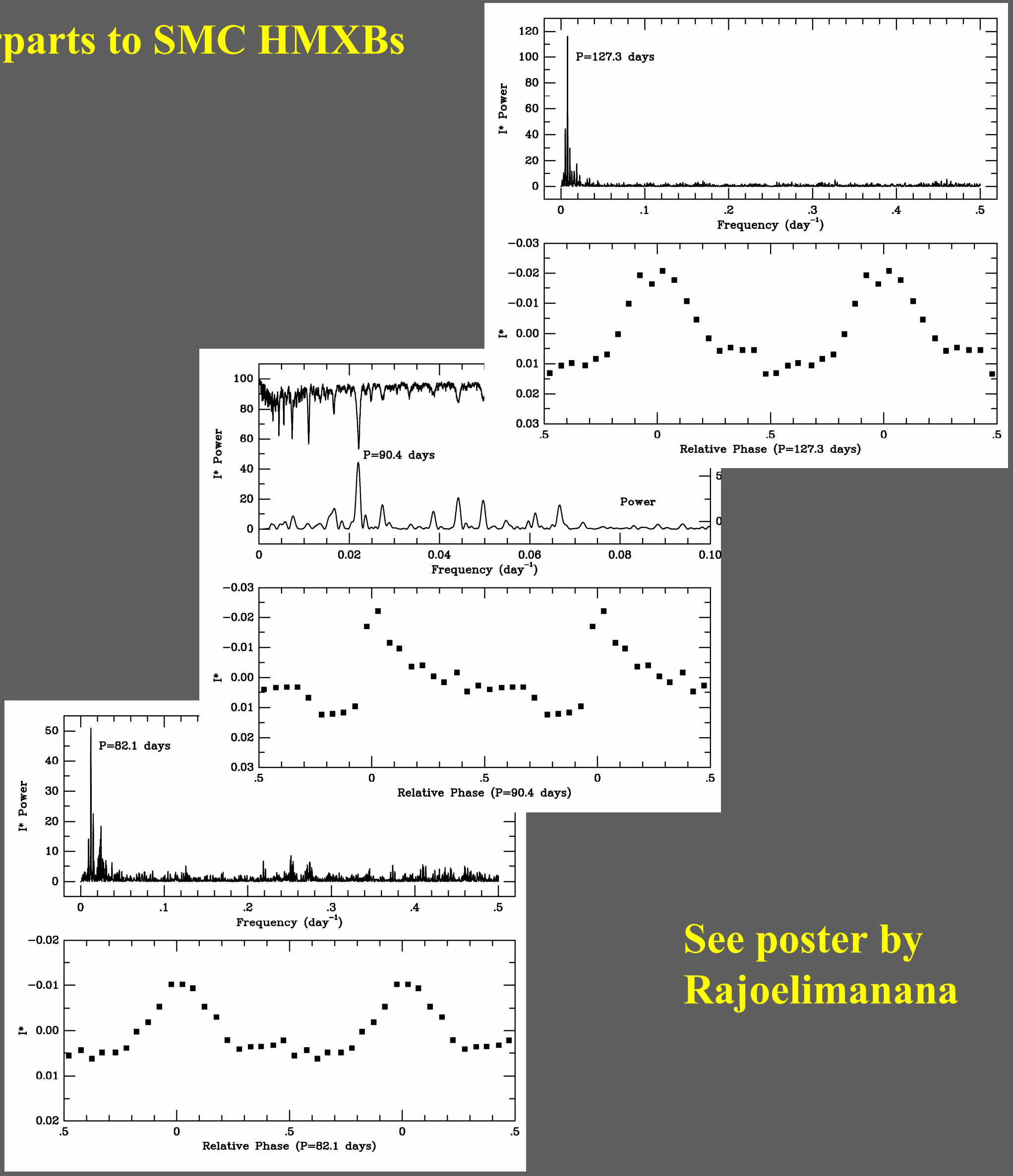


Galache et al. 2008

Orbital periods – optical

MACHO / OGLE monitoring of Be counterparts to SMC HMXBs

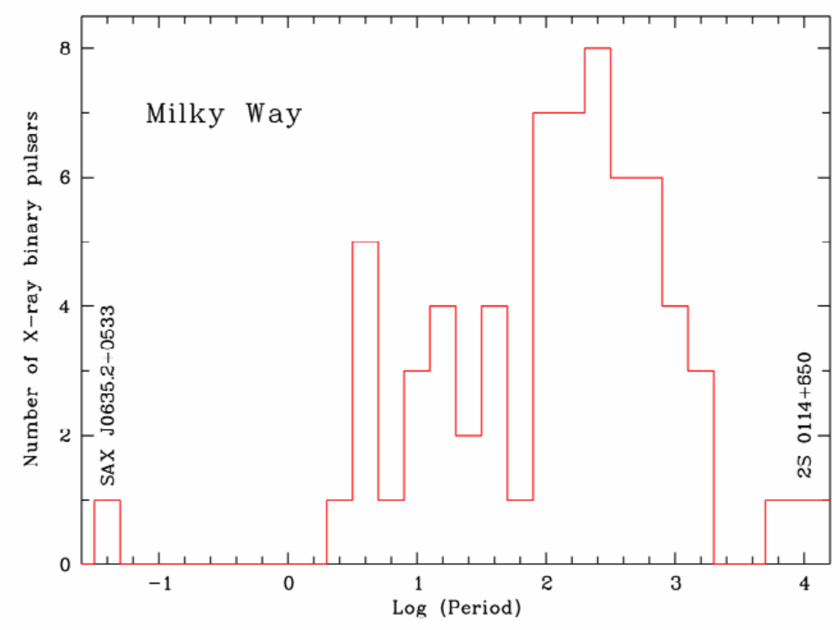


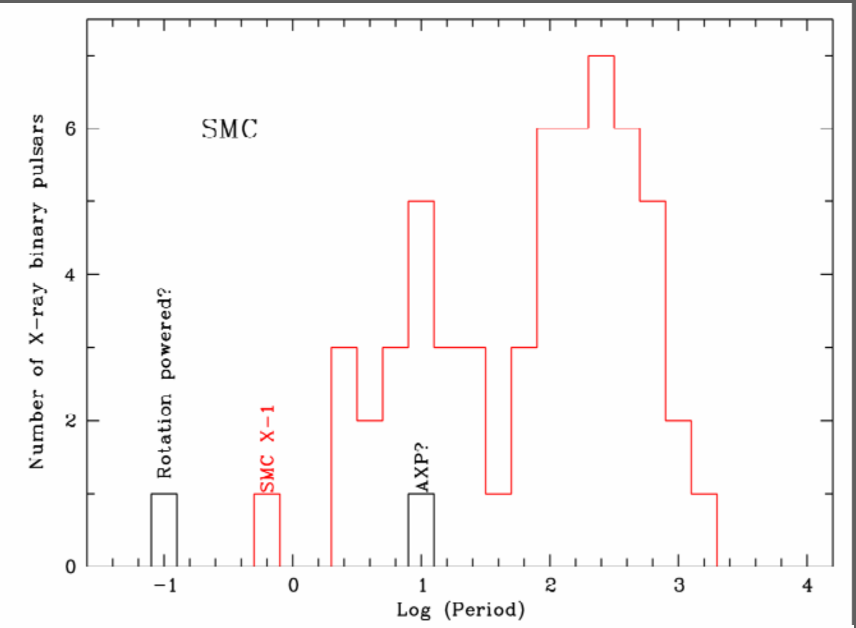


Schmidtke et al. 2006 (OGLE-III)

See poster by Rajoelimanana

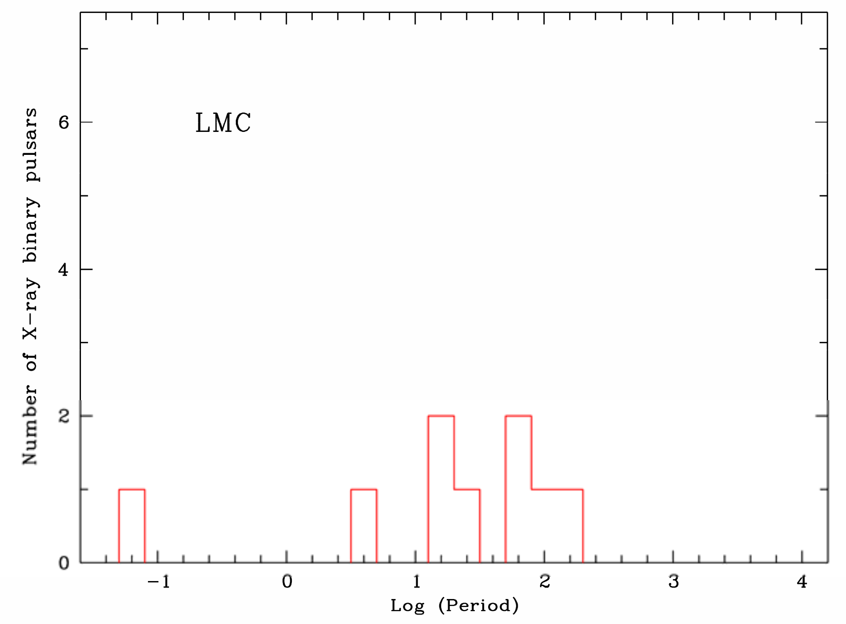
Spin periods



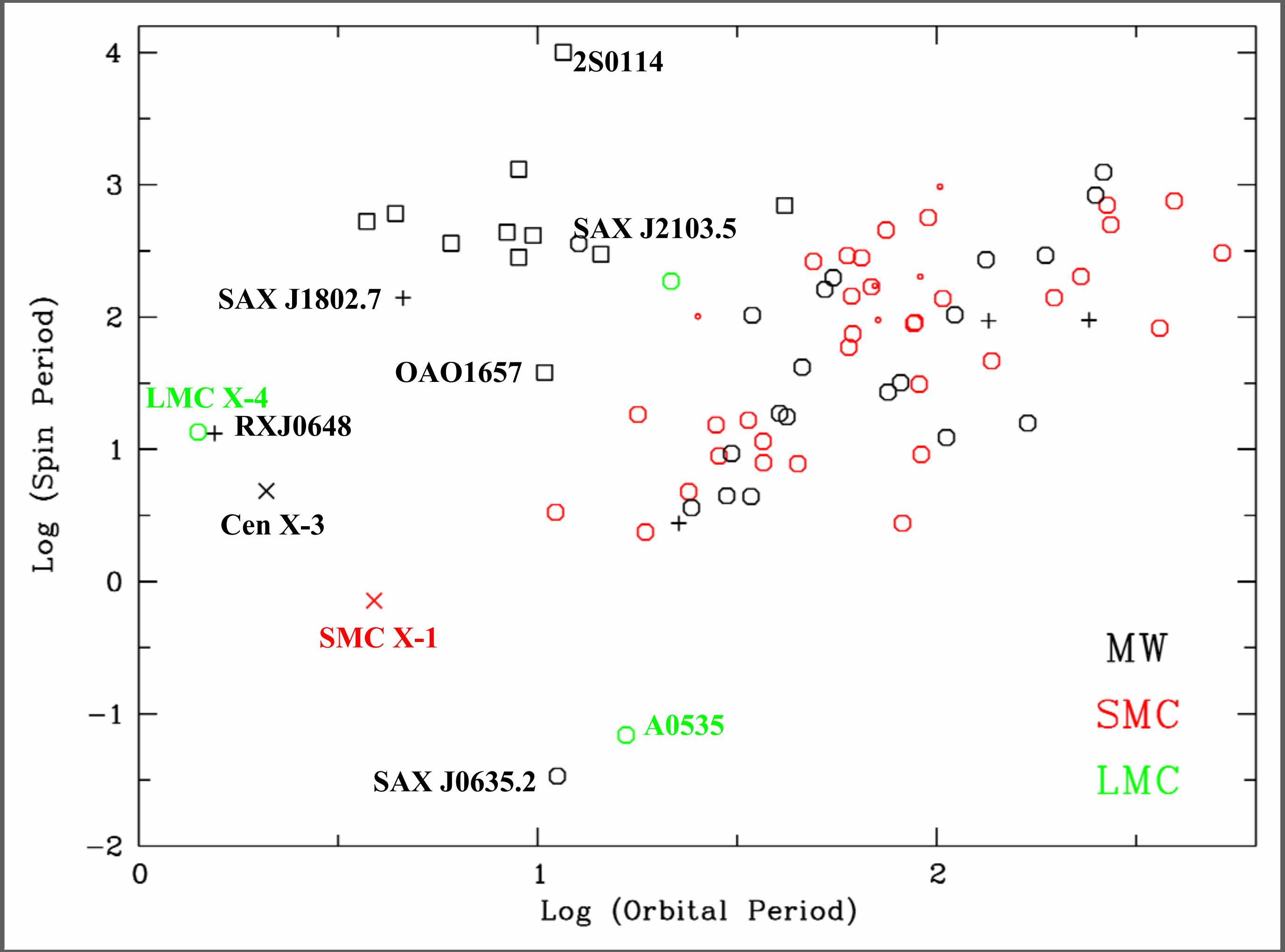


MW: 113 HMXBs + candidates
66 pulsars
SMC: 89 HMXBs + candidates
55 pulsars
LMC: 25 HMXBs + candidates
9 pulsars

- **Peak between 100 s and 1000 s**
- **Bimodal structure in the spin distribution?**
  → talk by Malcolm Coe



Orbital period – spin period: observations



Updated version of the P_{orb} – P_{spin} diagram (Corbet et al. 1986)

Spin Period Evolution

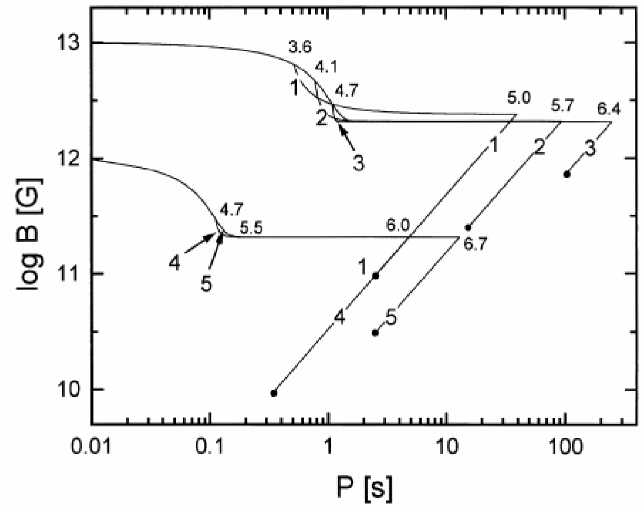


Figure 1. The B–P tracks of a neutron star during the main-sequence evolution of the companion: $\tau_{ms} = 10^7$ yr, $V_w = 10^7$ cm s^{-1}, $\rho_0 = 10^{13}$ g cm^{-3}, $Q = 0.01$, $\zeta = 0.1$. In the case of a strong initial magnetic field ($B_0 = 10^{13}$ G), tracks are calculated for $\dot{M} = 10^{-10}$ (curve 1), 10^{-11} (2) and 10^{-12} $M_\odot$ yr^{-1} (3); in the case of a weak field ($B_0 = 10^{12}$ G) for $\dot{M} = 10^{-10}$ (4) and 10^{-11} (5). Numbers near the tracks indicate the logarithm of the phase transition time. Filled circles mark the ends of tracks.

Model	B_0 [G]	$\dot{M}$ [$M_\odot$/y]
1	10^{13}	10^{-10}
2	10^{13}	10^{-11}
3	10^{13}	10^{-12}
4	10^{12}	10^{-10}
5	10^{12}	10^{-11}

- **quasi-isolated**

  magnetic dipole braking

- **propellor phase**

  magnetospheric radius > corotation radius

  efficient braking

  critical spin period depends on

  - spin period
  - mass loss (magnetic pressure = ram pressure)

- **wind accretion**

- **Roche-lobe overflow**

Urpin et al. 1998

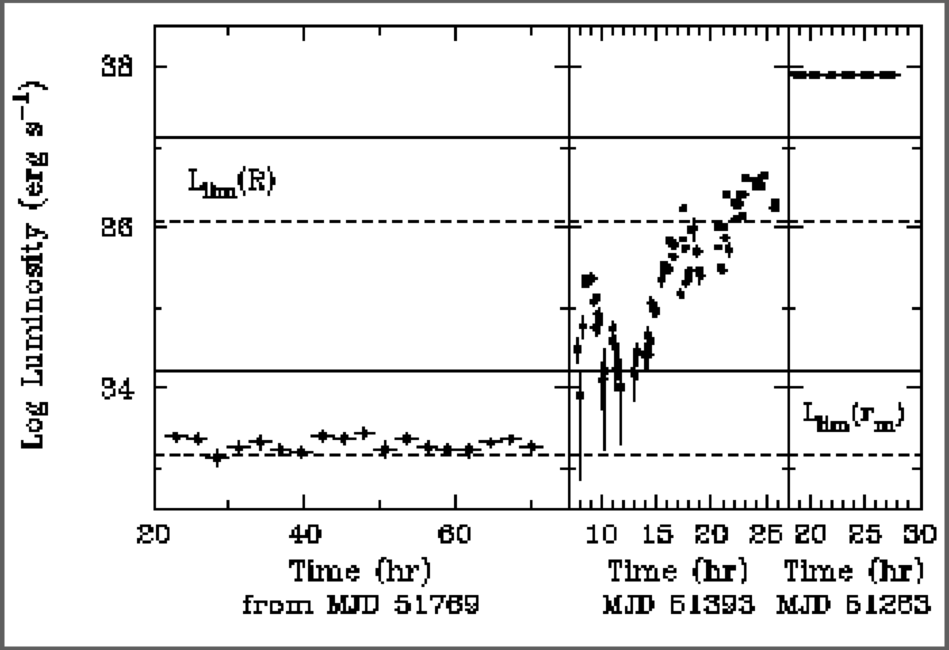
Transition to centrifugally inhibited regime

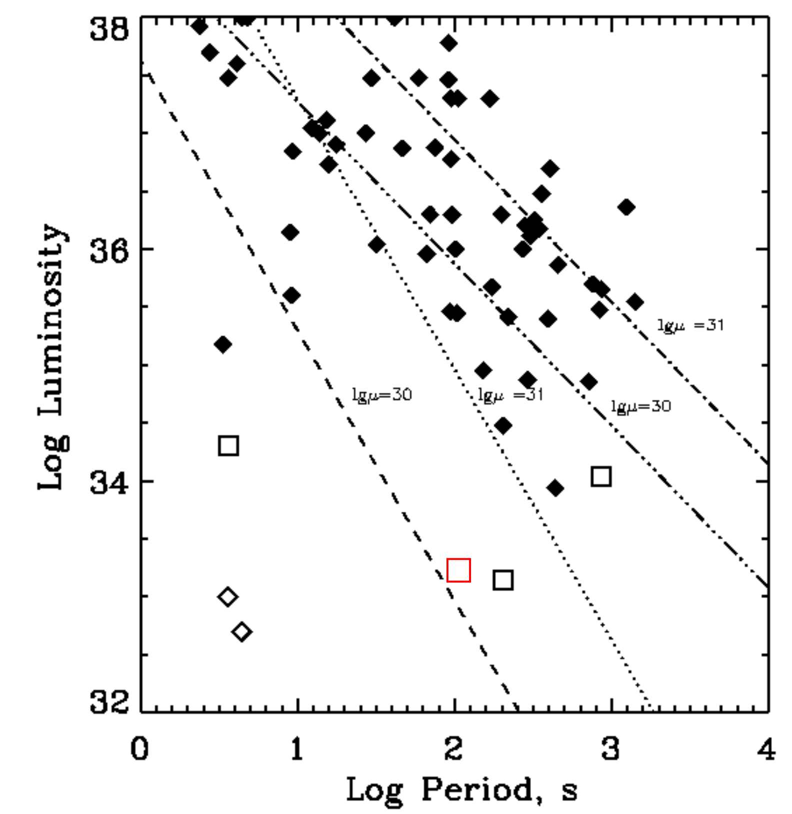
4U 0115+63 (Campana et al. 2001)

- low variability during quiescence and outburst
- quiescent level 2 x 10^{33} erg s^{-1}
- large variability in transition from low to high state (factor 250 in 15 hrs)

  difficult to explain with direct accretion

- transition from propeller to accretion regime?





2 systems in propeller state:

(different X-ray spectrum, no pulsations)

4U 0115+63: 3.6 s / (0.8–2) x 10^{33} erg s^{-1}
V 0332+53: 4.4 s / ~5 x 10^{32} erg s^{-1}
(Campana et al. 2002)

Critical period for propeller – accretor transition
magnetospheric radius = corotation radius
$P_A = 2^{5/14} \pi (G/M)^{-5/7} (\mu^2/\dot{M})^{3/7}$
(Popov & Raguzova 2004)

3A 0535+262: 104 s

(1.5–4) x 10^{33} erg s^{-1} by RXTE and BeppoSAX

pulsations detected during one observation, powerlaw spectrum

B = 10^{13} G → magnetospheric radius > corotation radius

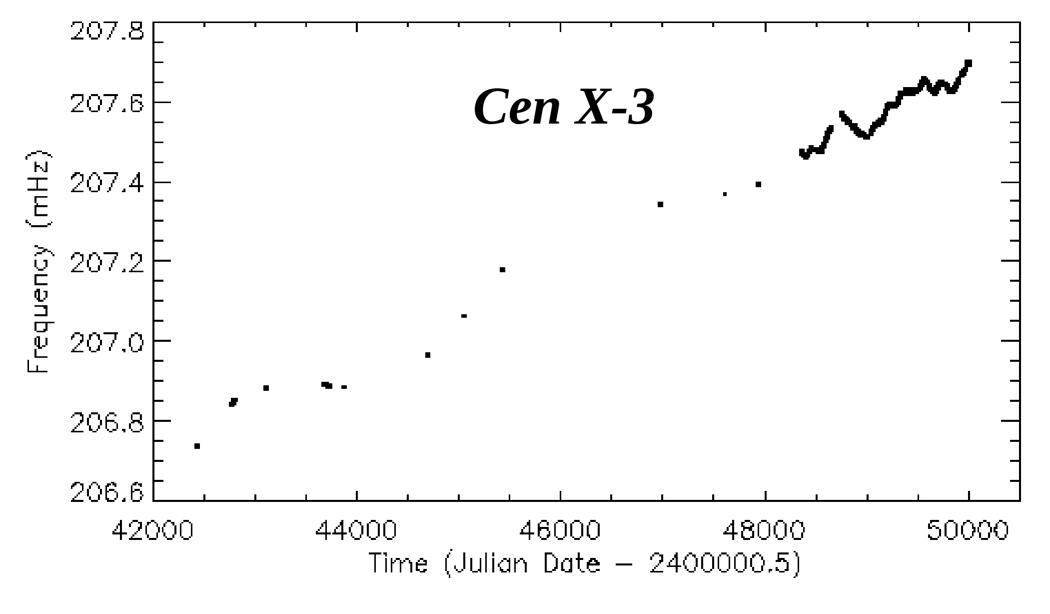
still very low level accretion? **(Mukherjee & Paul 2004)**

Roche-lobe filling supergiant systems

Persistent and bright ($L_x \sim 10^{38}$ erg s^{-1})

matter flow via an accretion disc

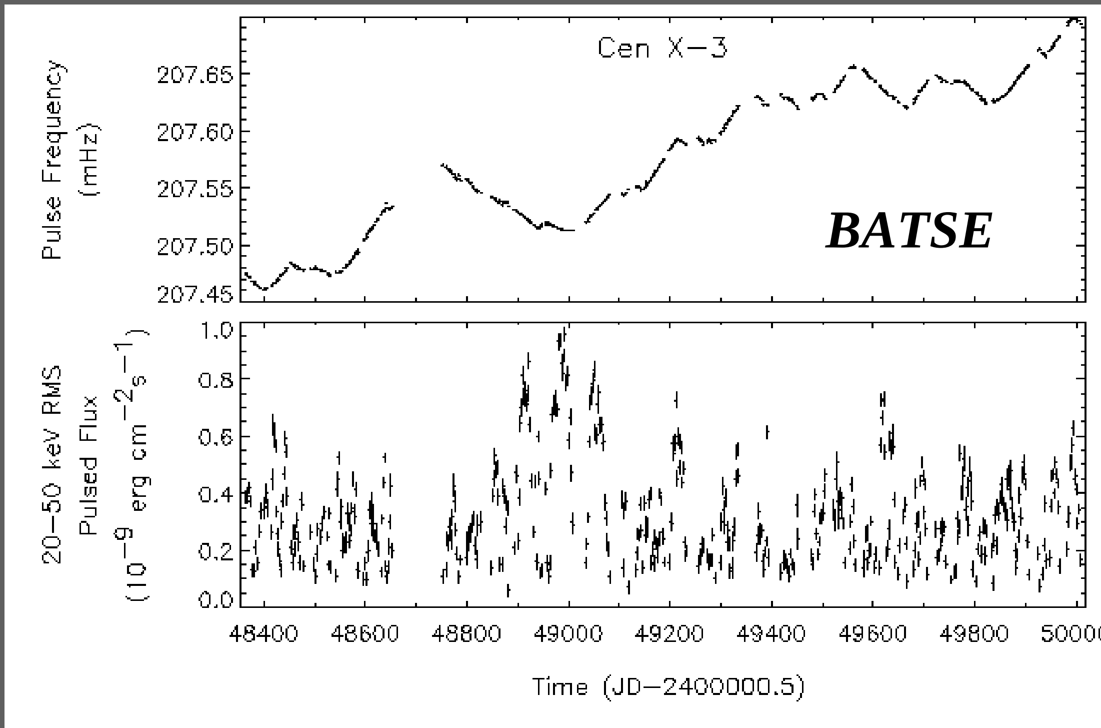
long-term spin up

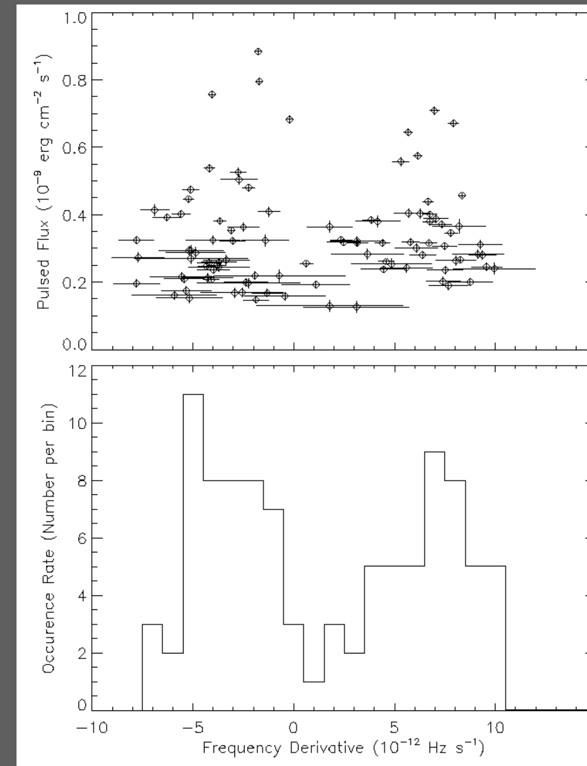


- **Secular spin-up 8 x 10^{-13} Hz s^{-1}**
- **Factor of ~5 slower than predicted**
- **Phases of spin-down**

(Bildsten et al. 1997)

Cen X-3





10-100 day intervals with transitions between steady spin-up and spin-down at predicted rates with net spin-up on long terms

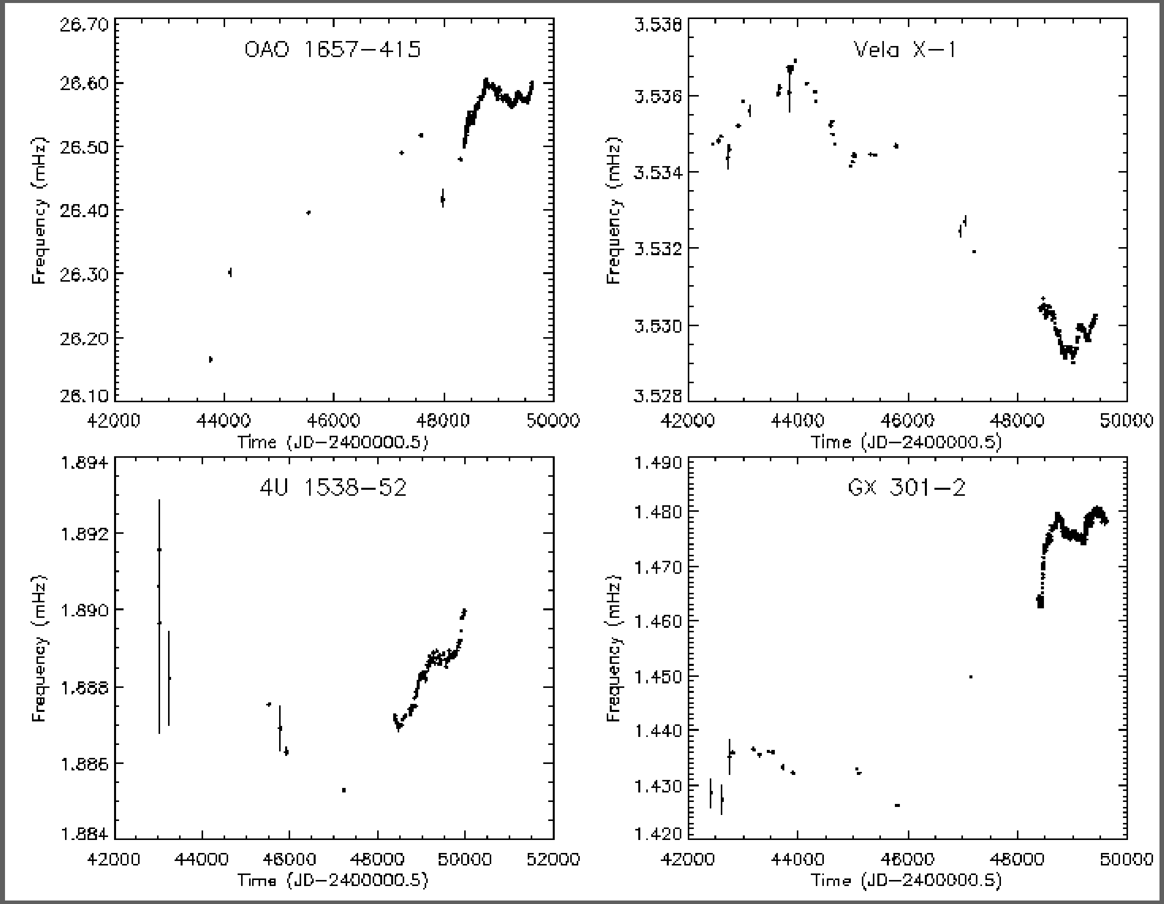
models with angular momentum transport outwards while accretion is going on

magnetic interaction disk/star (Bildsten et al. 1997)

Wind accreting supergiant systems

Persistent - often eclipsing - $L_x \sim 10^{35\text{-}37}$ erg s^{-1}

accretion from strong stellar wind of supergiant



random walk in frequency

(Bildsten et al. 1997)

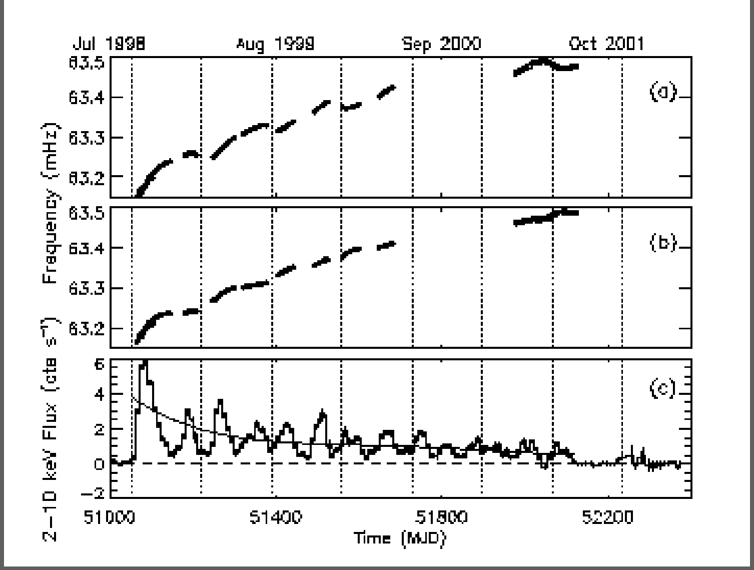
Be/X-ray binaries: Spin-up during outbursts

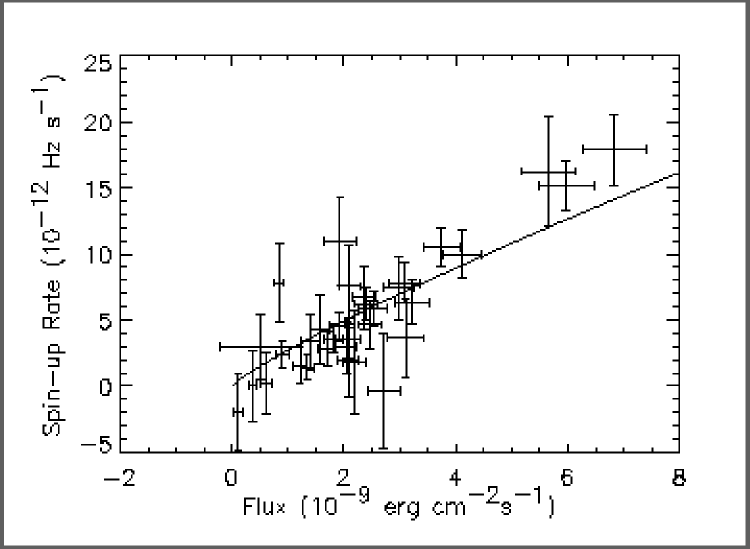
Type I outbursts

typical spin-up rates <5 x 10^{-12} Hz s^{-1}

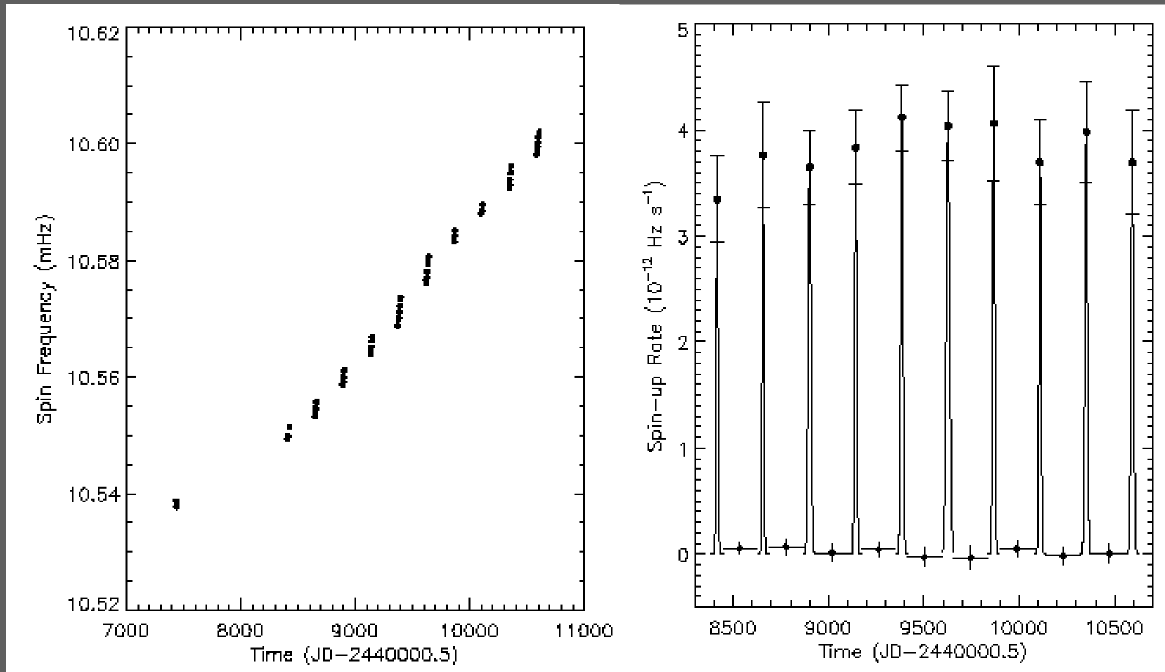
Type II outbursts

typical spin-up rates >8 x 10^{-12} Hz s^{-1} **(e.g. Bildsten et al. 1997)**

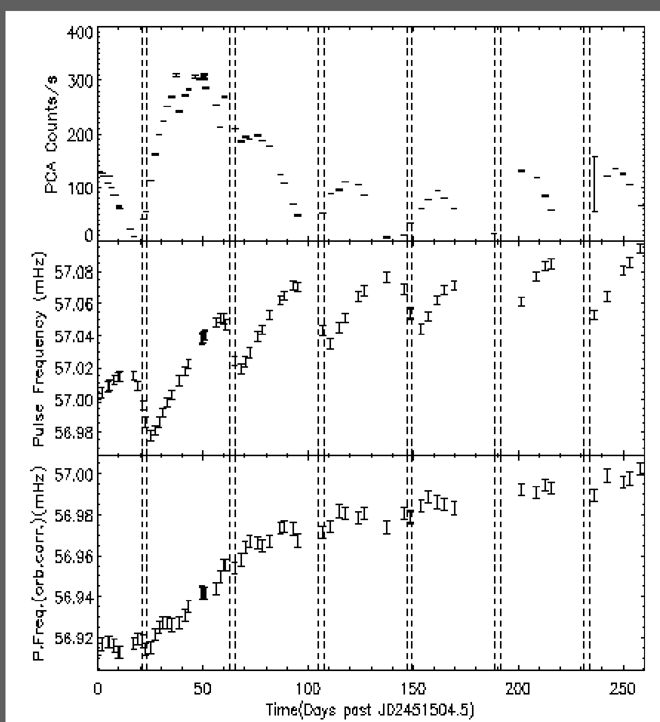


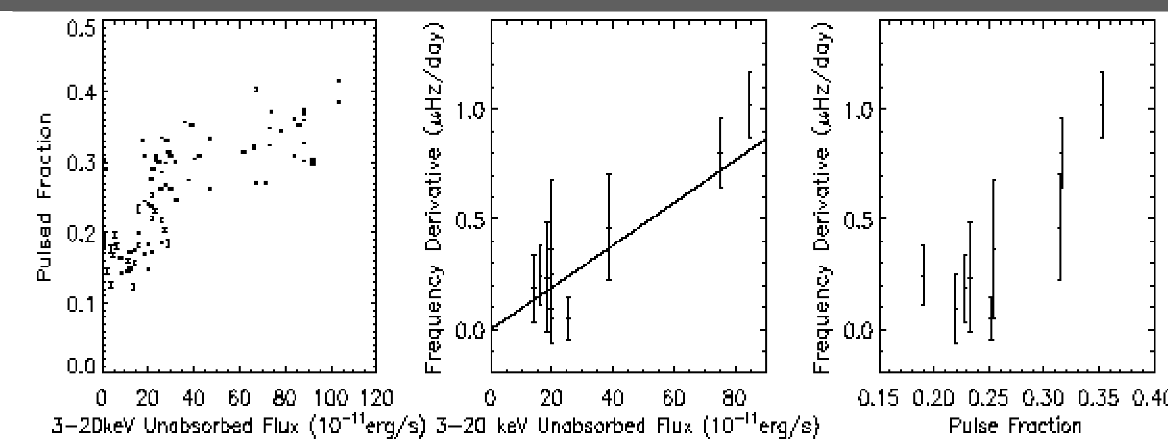


XTE J1946+274 = GRO J1944+26 (Wilson et al. 2003)



GS 1843-02 = 2S 1845-024
(Finger et al. 1999)



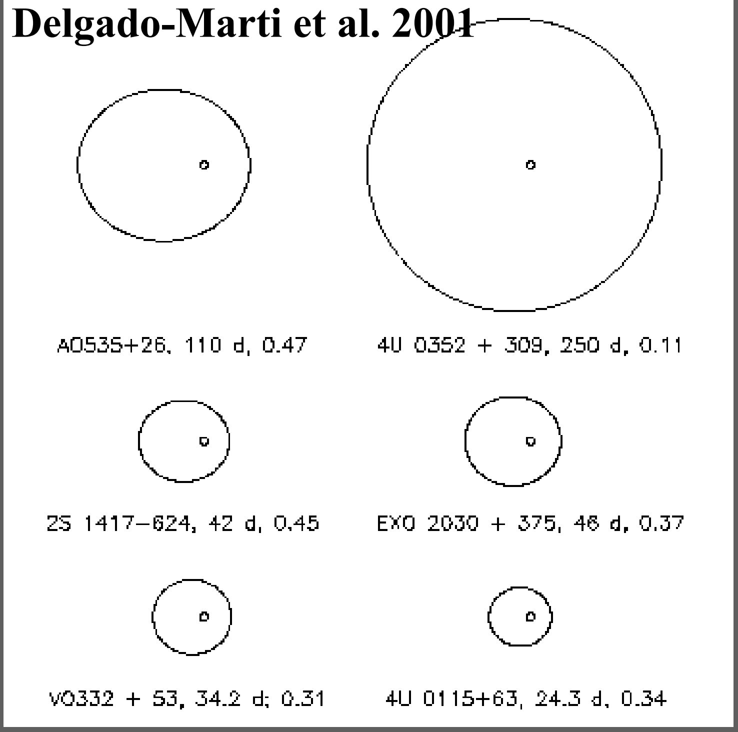


2S 1417-62
(Inam et al. 2004)

Persistent Be/X-ray binaries

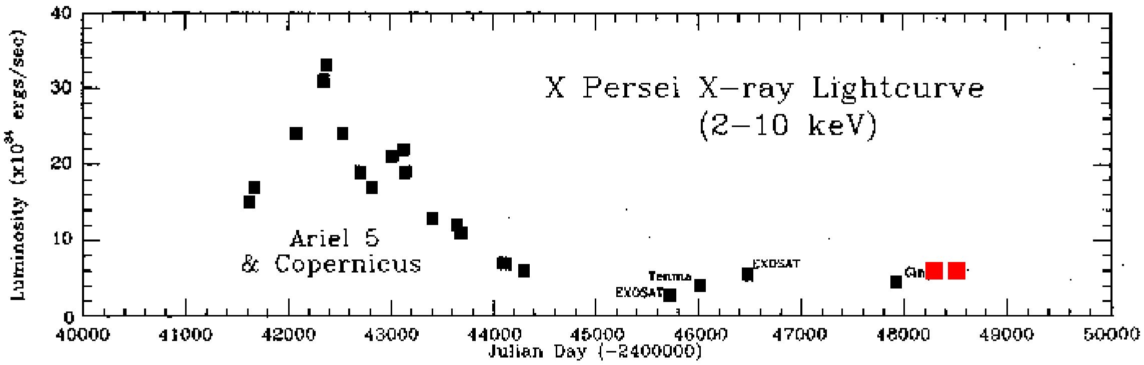
- moderate luminosity of 10^{34-35} erg s^{-1}
- relatively small long-term variability
- long pulse periods (large orbit, low eccentricity)
- absent or weak Fe K_{α} emission line @ 6.4 keV
- no dependence of the X-ray spectrum on intensity

X Persei	835 s
RX J0146.9+6121	1400 s
RX J1037.5–5647	862 s
RX J0440.9+4431	203 s
1SAX J1452.8-5949	437 s
AX J1749.2-2725	220 s
AX J1700-4157	715 s

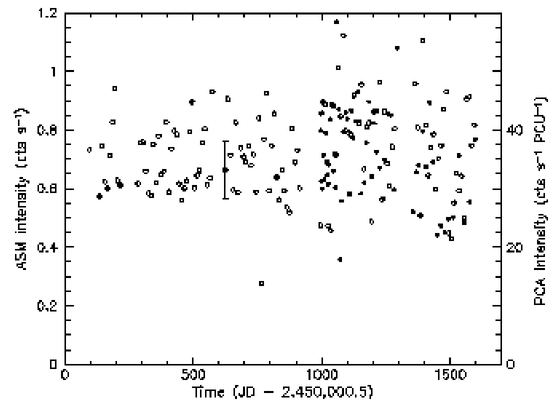


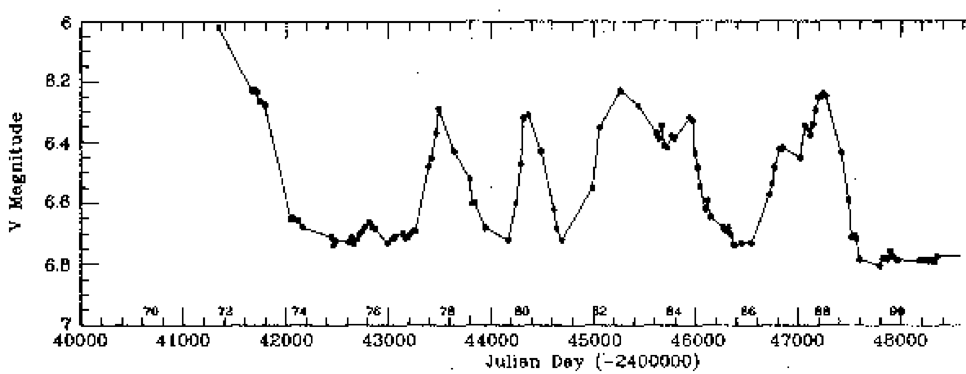
Delgado-Marti et al. 2001

1971 1993

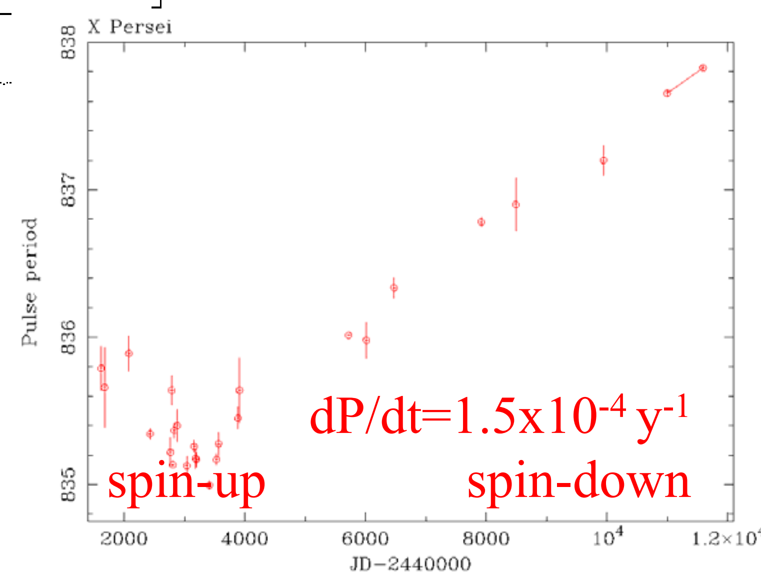


(Delgado-Marti et al. 2001)

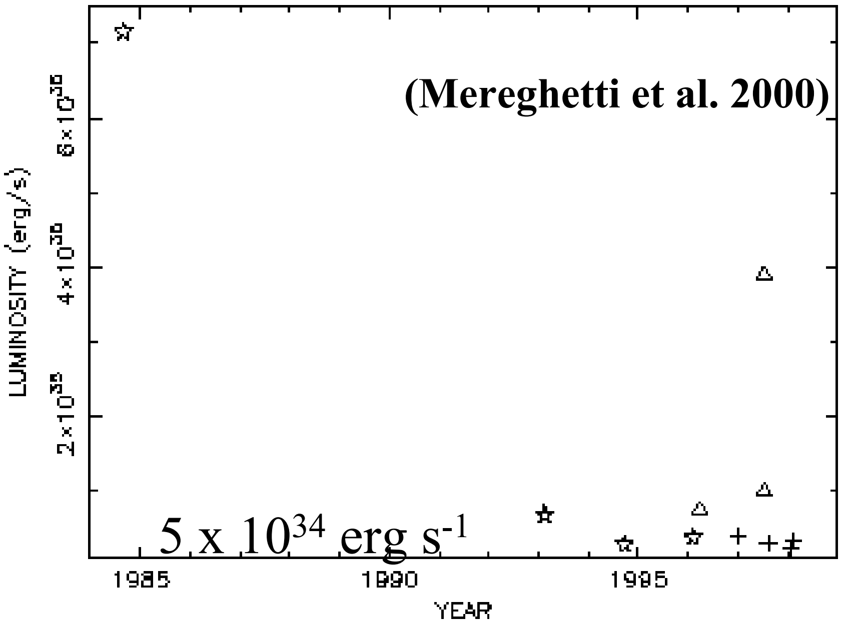




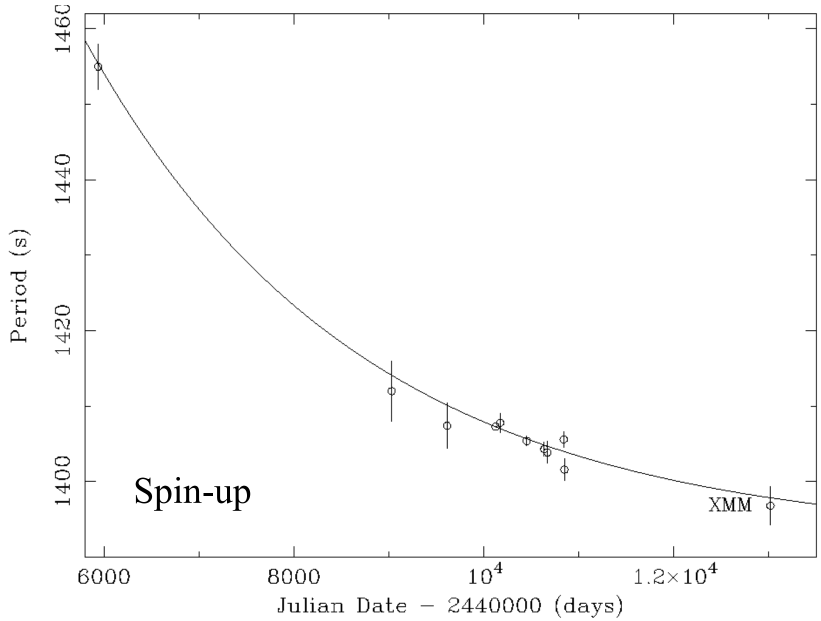
(Roche et al. 1993)



X Persei



RX J0146.9+6121

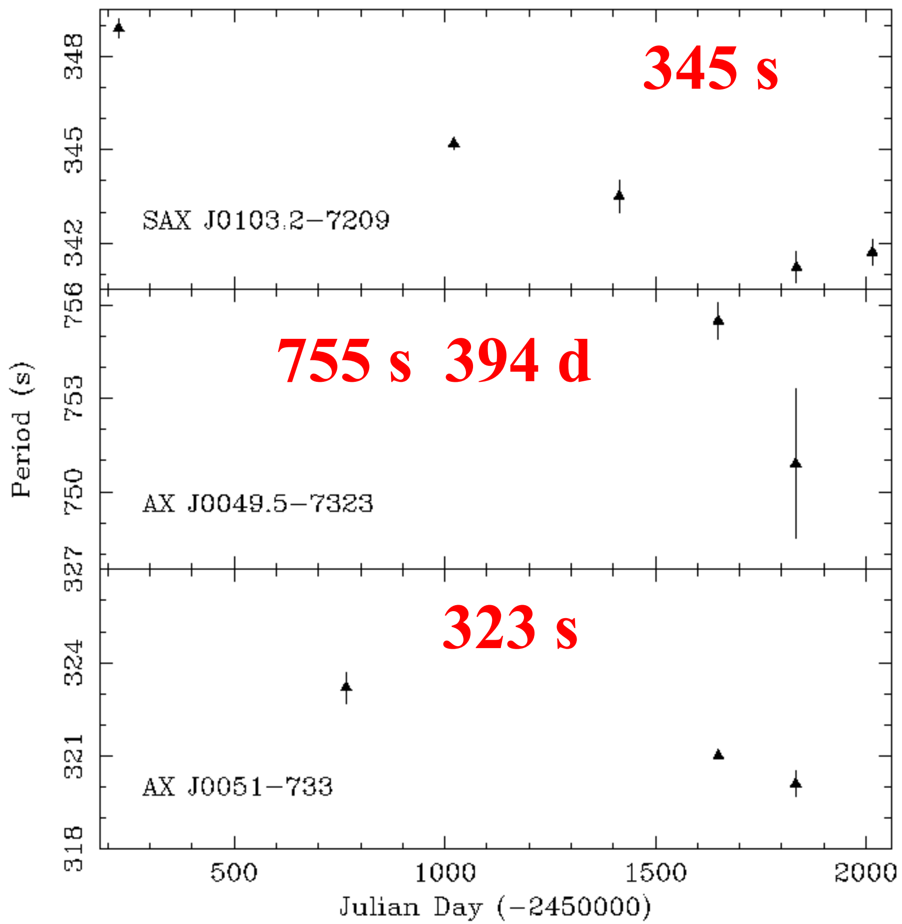


XMM-Newton observation
2004-01-15
L_x = 4.4 x 10^{33} erg s^{-1}

→ **Equillibrium period ?**

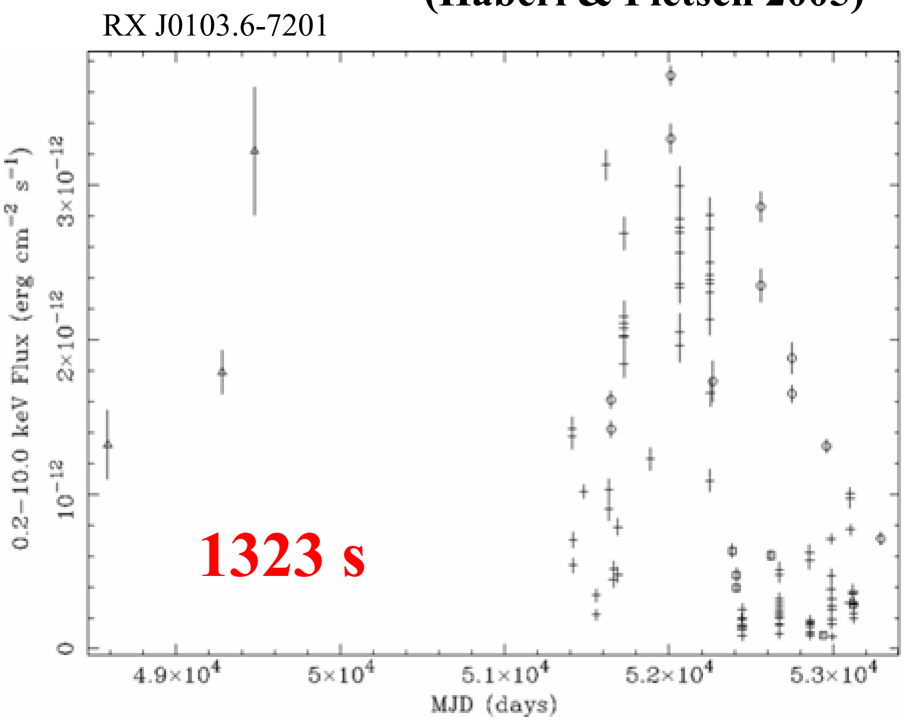
Others

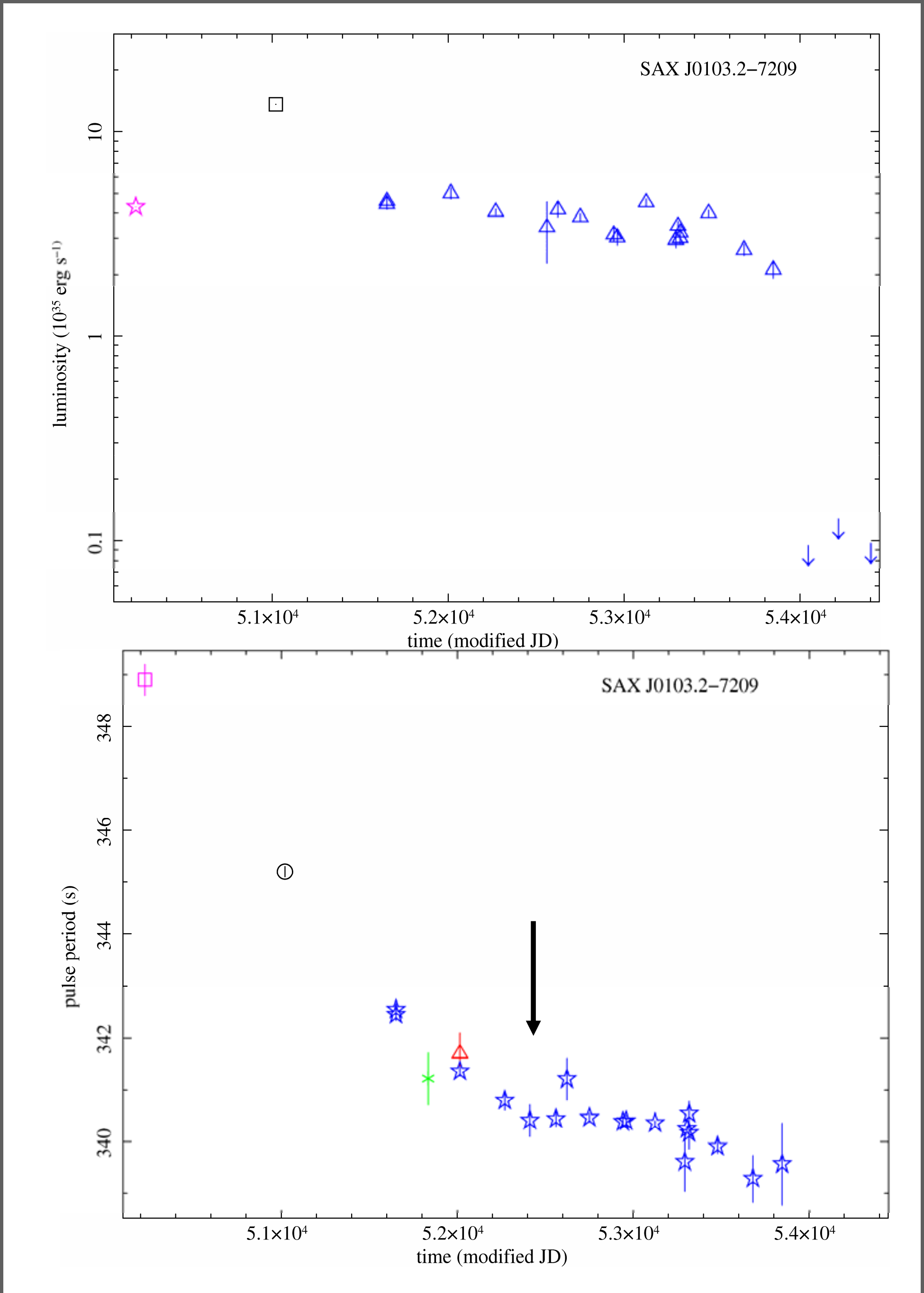
(Haberl & Pietsch 2004)



Long-period pulsars in the SMC

(Haberl & Pietsch 2005)





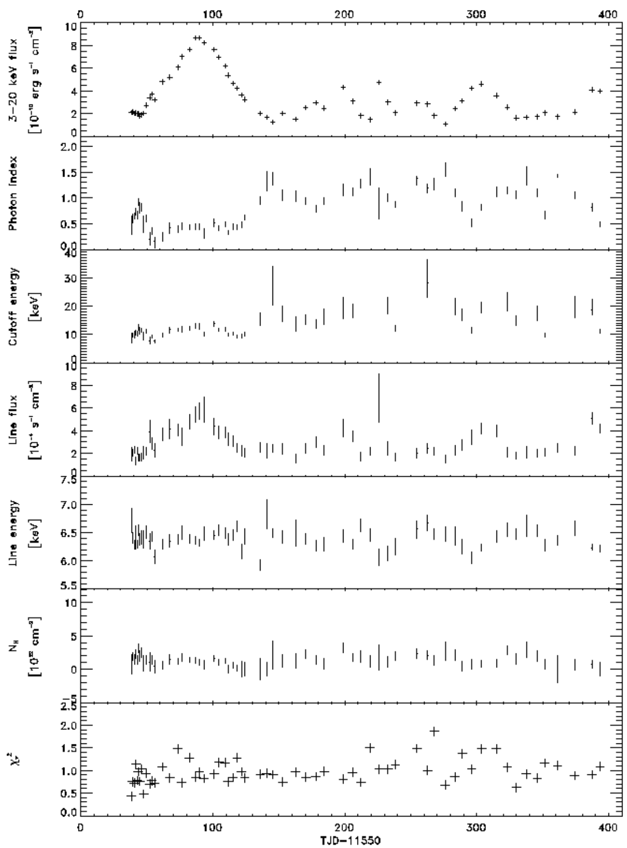
SAX J0103.2-7209
345 s

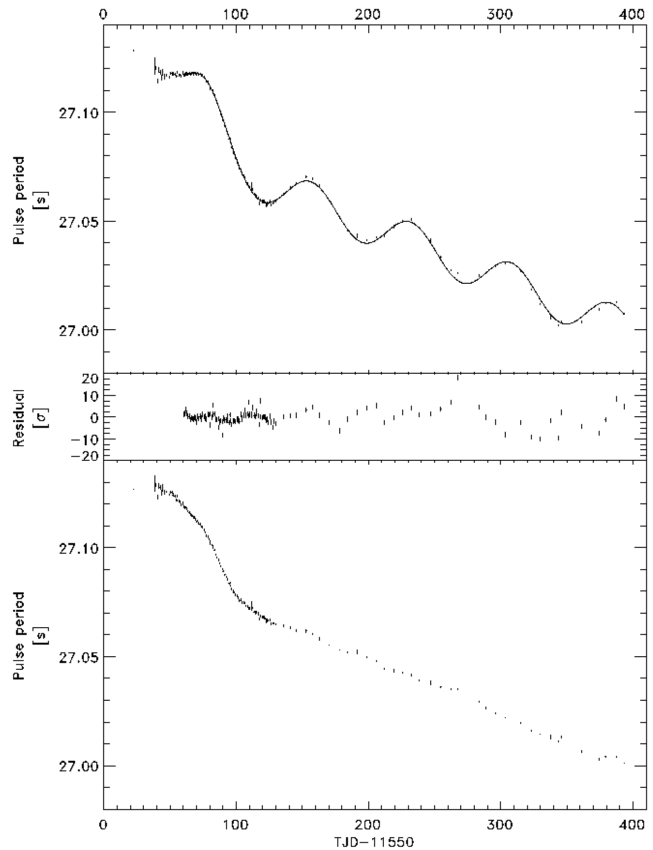
Eger & Haberl 2008

- **Luminosity ~4x10^{35} erg s^{-1}**
- **Linear pulsar spin-up abruptly ceased after May 2002 but no change in luminosity**
  - **reversal in disc torque ?**
  - **pulsar reached equillibrium period ?**

But ...

The transient XTE J1543–568

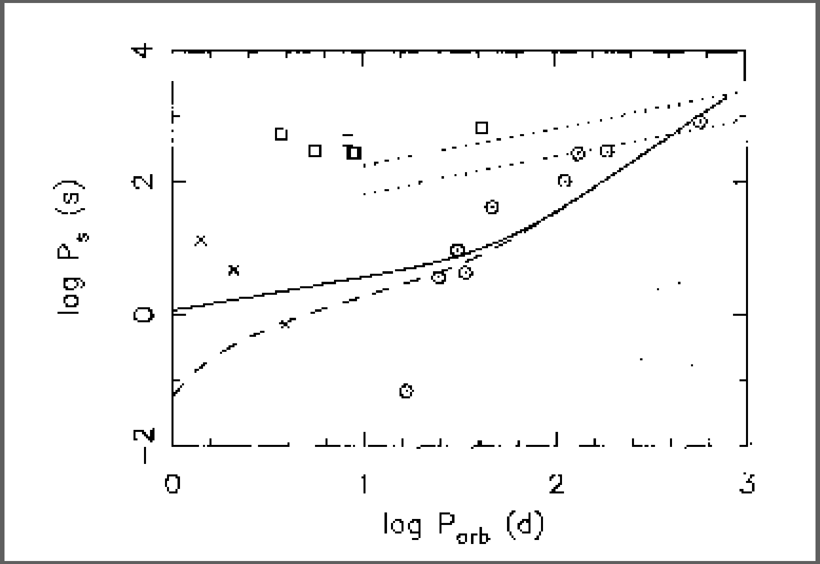




Porb = 75.56 ± 0.25 days
e < 0.03
(in ‘t Zand et al. 2001)

similarly:
KS 1947+300
Porb = 40.415 ± 0.010 days
e = 0.033 ± 0.013
(Galloway et al. 2004)

Orbital period – spin period: theory



Porb – Pspin diagram (Corbet et al. 1986)

Critical (equilibrium) spin period

Wind-fed SG-HMXBs:

- wind-driven accretion torques not sufficient
  to spin-up NS
- equilibrium spin period of main-sequence phase

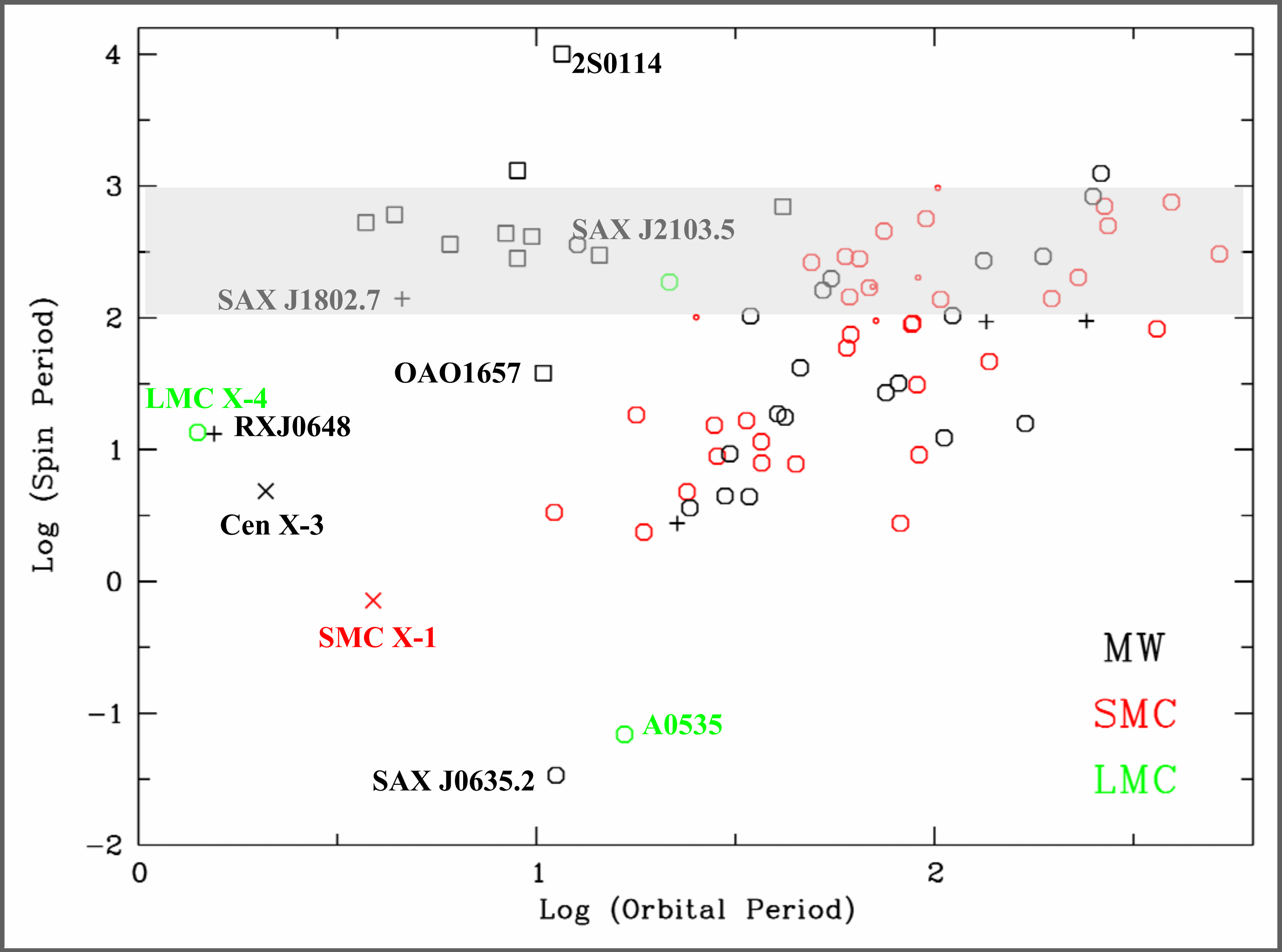
Be/X-ray binaries:

- between equilibrium line for slow equatorial wind
  and the line for fast polar wind
  (selection effect for active systems)
- wide systems (>100 d) as in SG systems

Waters & van Kerkwijk (1989)

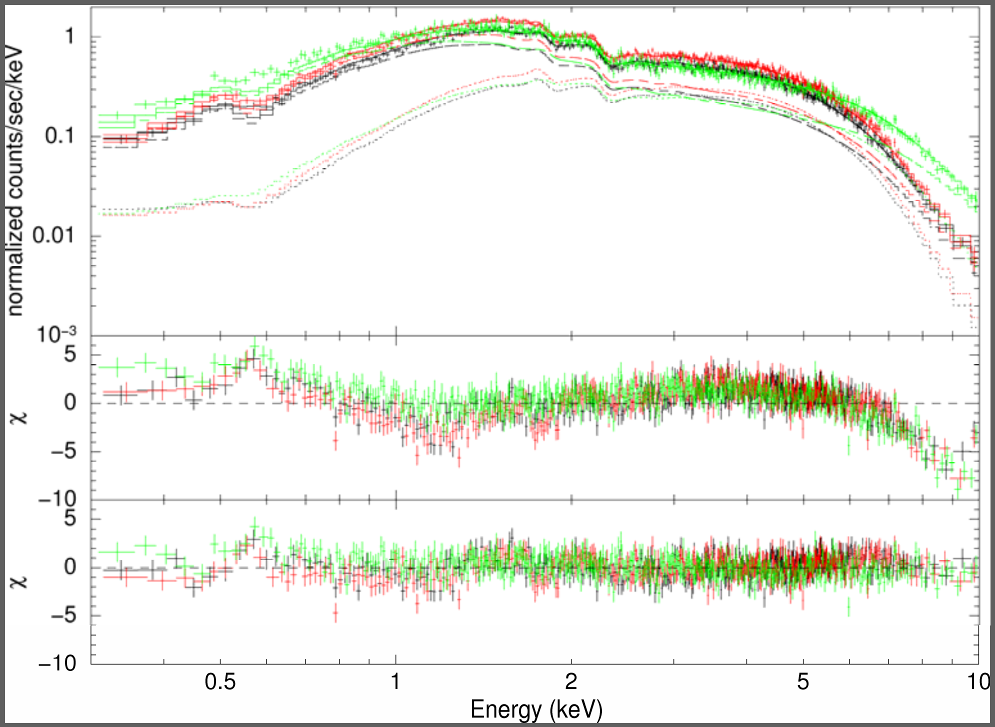
Li & van den Heuvel (1996)

Orbital period – spin period: observations



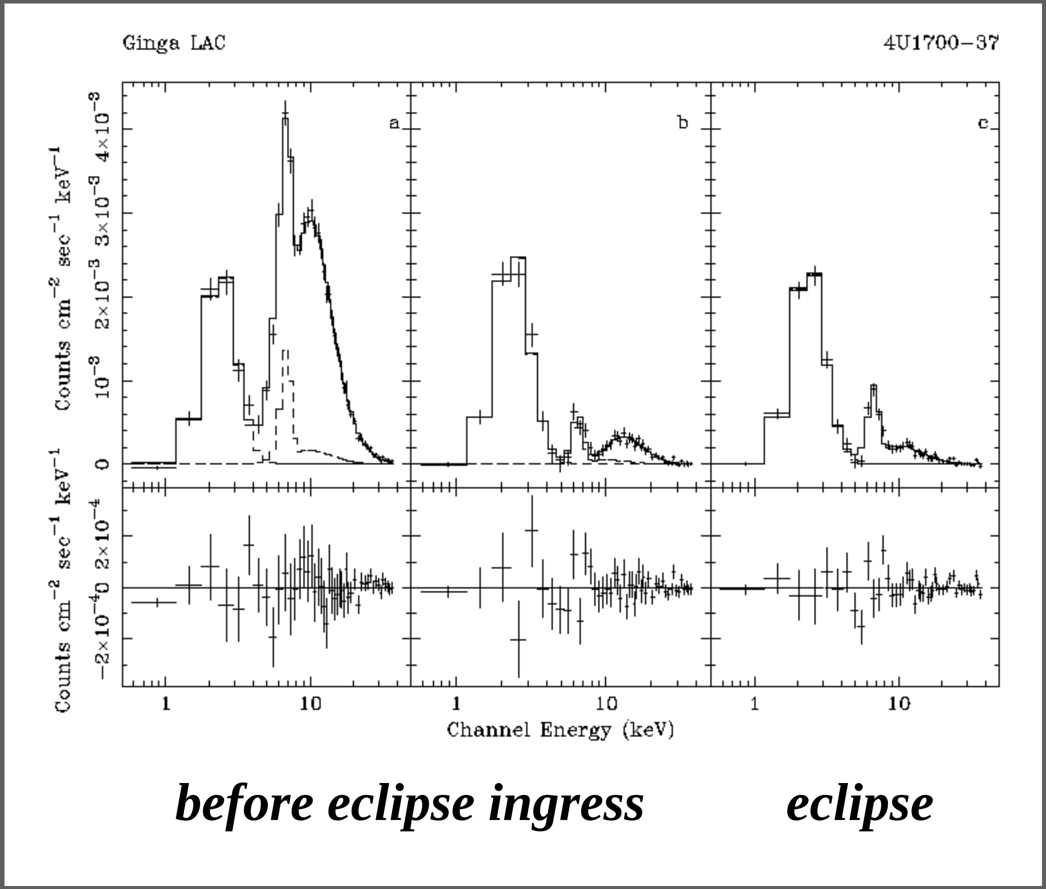
Updated version of the $P_{orb} – P_{spin}$ diagram (Corbet et al. 1986)

The X-ray spectra of HMXBs



X Persei (Be/X-ray binary)
La Palombara & Mereghetti 2007

- Direct emission from the NS:
  power-law (with high-E cutoff)
  photon index ~ 0.9-1.0 (0.1-10 keV)
- Reprocessing in wind:
  optically thin emission
  emission lines
  scattering on free electrons
- Reprocessing at inner edge of accretion disk:
  optically thick emission



Reprocessing in strong wind driven by the UV radiation of the O supergiant

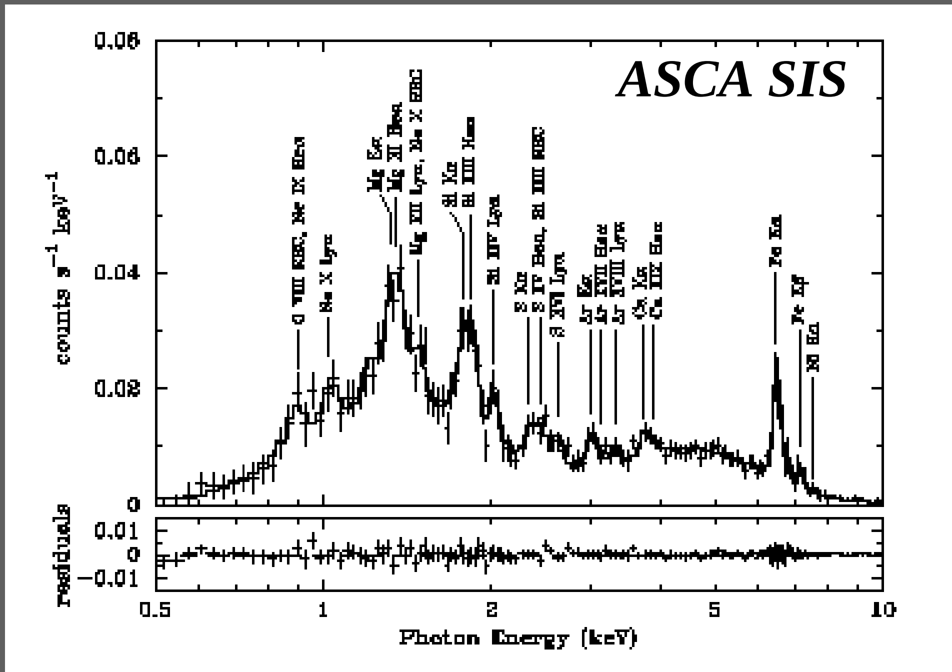
- Fe K lines

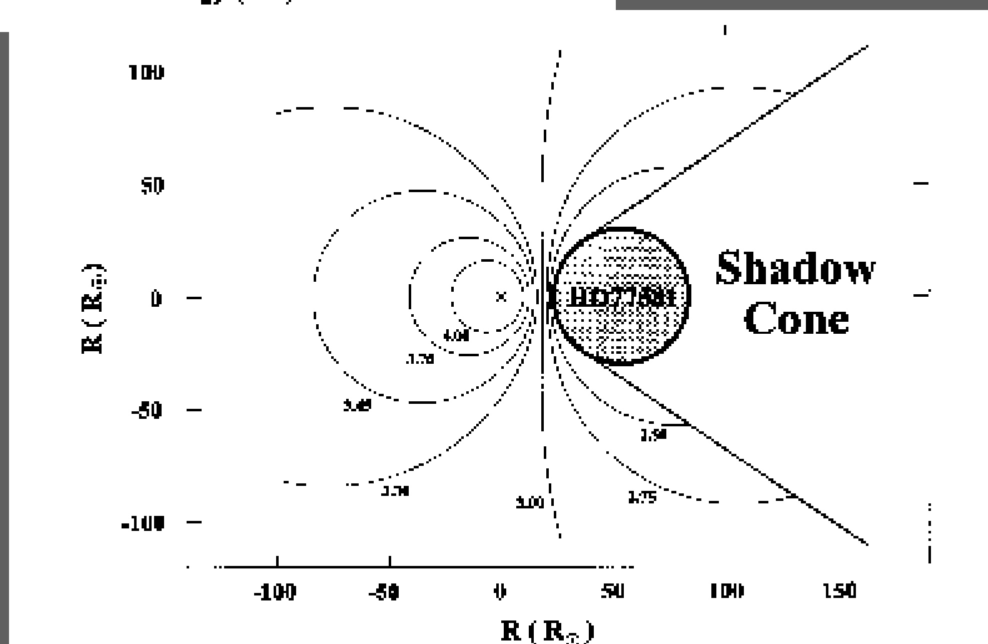
- soft component

clearly seen during eclipse

4U1700-37 (supergiant system)

Haberl et al. 1992





(1) recombination lines and

radiative recombination continuum

from photo-ionized gas

(2) fluorescent K-shell lines

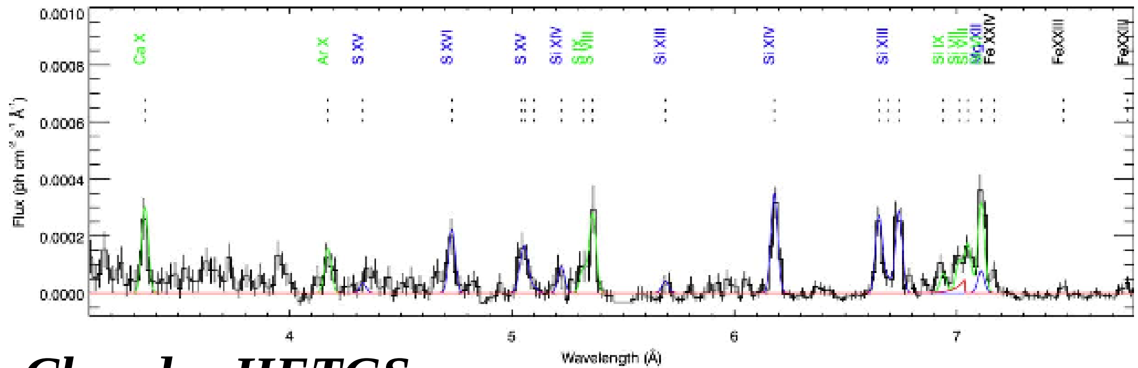
from (nearly) neutral matter

(3) non-thermal continuum

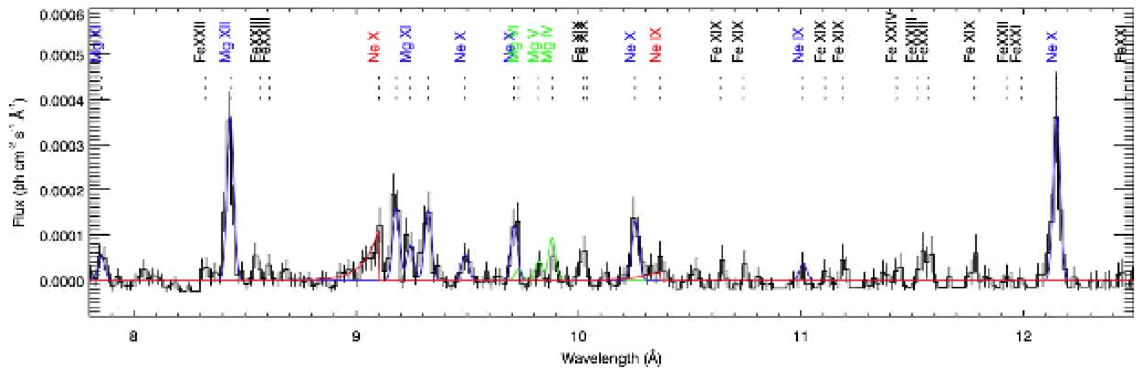
scattered by free electrons

(Sako et al. 1999)

Vela X-1 (SG system)



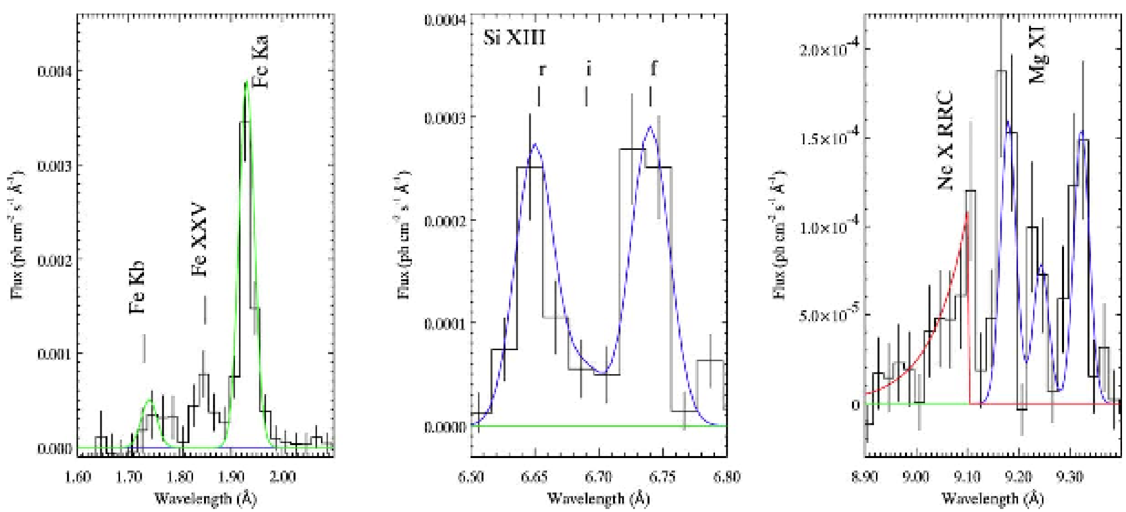
Chandra HETGS



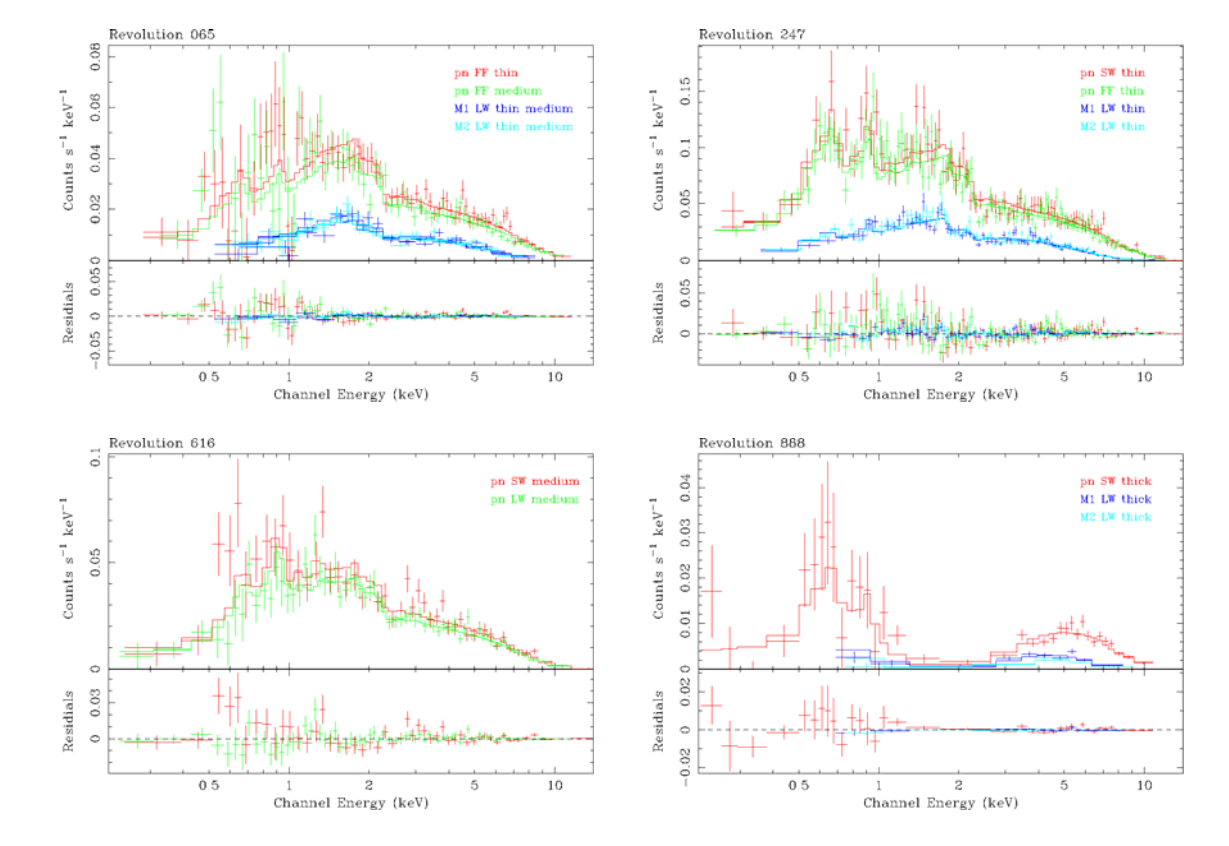
Schulz et al. 2002

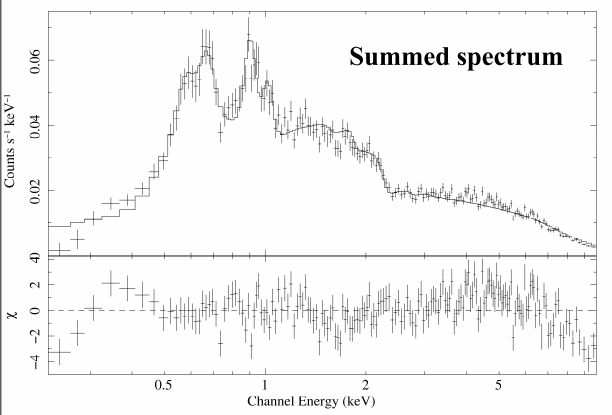
Vela X-1

Fluorescent lines from clumped wind



Soft components in X-ray spectra of Be/XRBs

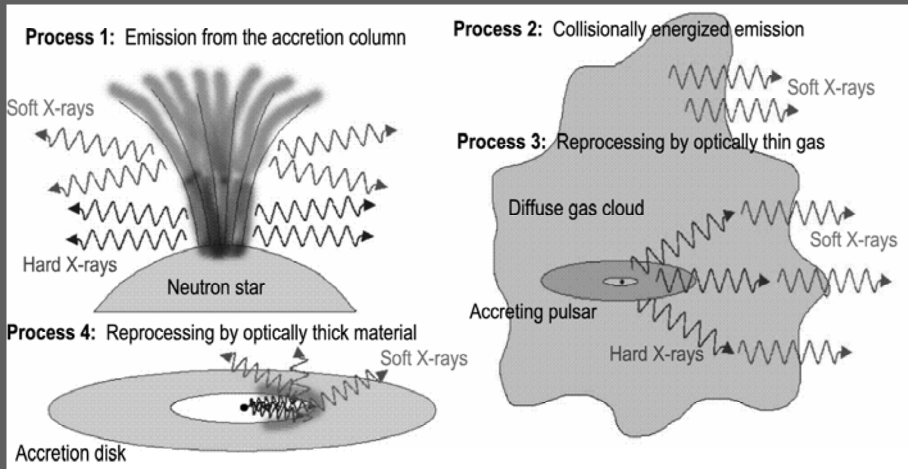




RX J0103.6-7201 (B0 III-Ve in SMC)

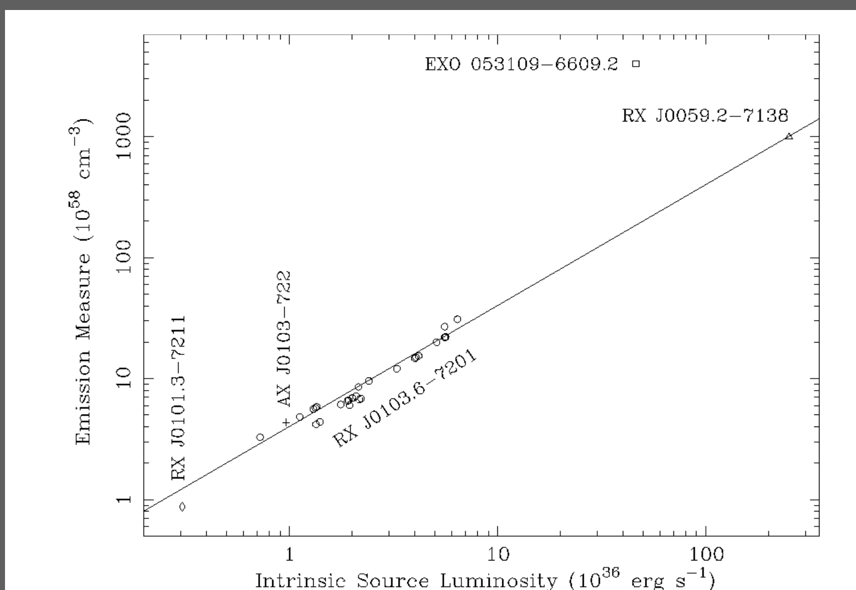
1323 s **Eger & Haberl 2008**

A near-eclipse?



Hickox et al. (2004):

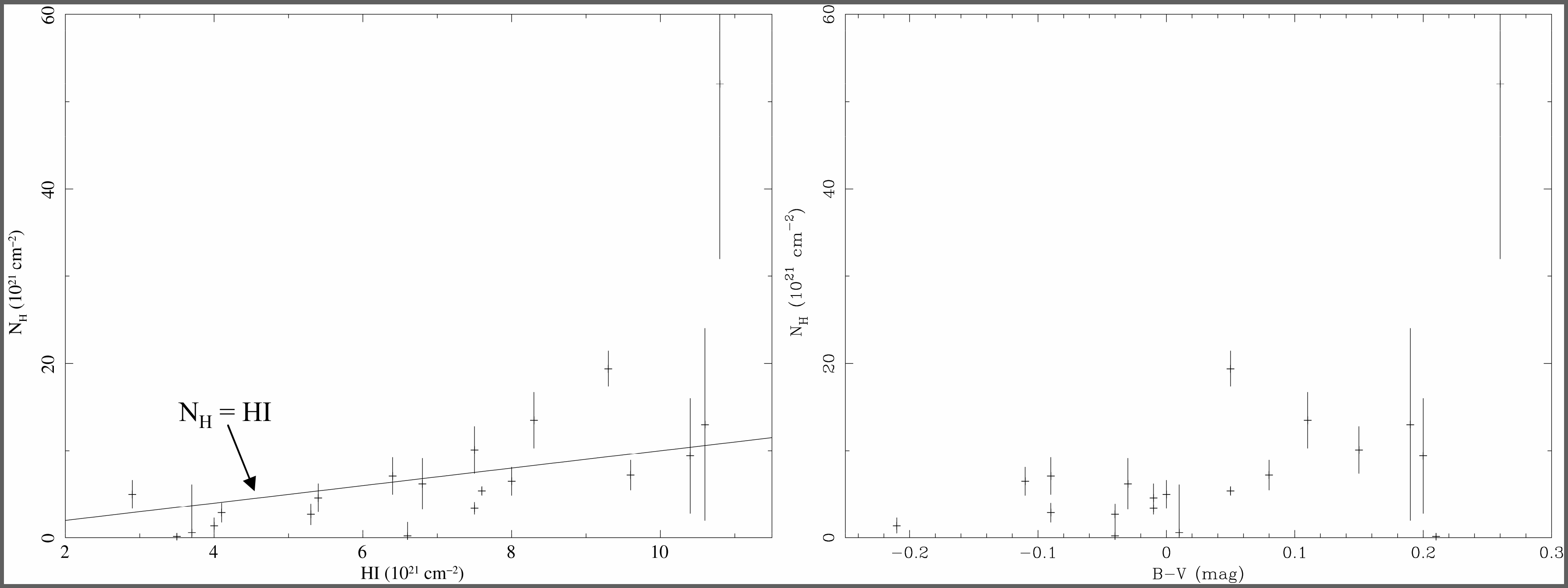
- $L_x > 10^{38}$ erg s^{-1}:
  Inner region of accretion disk
- Lower luminosities:
  Diffuse gas in system



Haberl & Pietsch (2005):

- Correlation of low-energy and power-law component intensities
- One single process?

X-ray absorption



Haberl et al. (2008): Be/XRBs in the SMC

General increase of nH with total SMC column density

A significant fraction of the X-ray absorption arises in ISM

Summary

Large samples of HMXBs are available (~100)

- Milky Way: Physics of individual systems
  - (High-resolution spectroscopy, timing)
  - Accretion process
  - Wind structure
- SMC: Statistical studies
  - observations of many systems simultaneously at similar distance
  - global properties
  - population studies

We understand the global picture but not all the details.

- Monitoring with RXTE (timing)
- High-sensitivity imaging instruments Chandra, XMM-Newton (spectroscopy)