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Probing neutron star physics using accreting neutron stars

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Abstract. We give an obervational overview of the accreting neutron stars systems as probes of neutron star physics. In particular we focus on the results obtained from the periodic timing of accreting millisecond X-ray pulsars in outburst and from the measurement of X-ray spectra of accreting neutron stars during quiescence. In the first part of this overview we show that the X-ray pulses are contaminated by a large amount of noise of uncertain origin, and that all these neutron stars do not show evidence of spin variations during the outburst. We present also some recent developments on the presence of intermittency in three accreting millisecond X-ray pulsars and investigate the reason why only a small number of accreting neutron stars show X-ray pulsations and why none of these pulsars shows sub-millisecond spin periods. In the second part of the overview we introduce the observational technique that allows the study of neutron star cooling in accreting systems as probes of neutron star internal composition and equation of state. We explain the phenomenon of the deep crustal heating and present some recent developments on several quasi persistent X-ray sources where a cooling neutron star has been observed.

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Probing the neutron star physics with accreting neutron stars (part 1)

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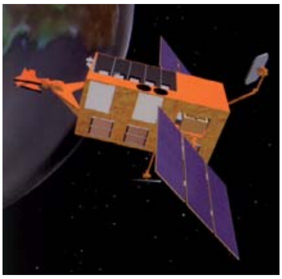
Lecture 1: outline

- Some refreshment on X-ray binaries
- Measure of the spin period (part 1)
- Measure of the spin torque of the NS
- Measure of the spin period (part 2)
- Why only 10 LMXB pulsate ?
- Do submillisecond pulsars exist ?
- Measure of the mass

How to probe the NS physics with NS LMXBs ?

1. X-ray spectra (cooling, cyclotron resonance, etc…)
2. Coherent timing (pulse profile shape, torques, timing noise, mass, glitches)
3. Thermonuclear bursts
4. Aperiodic variability (oscillation modes, QPOs)

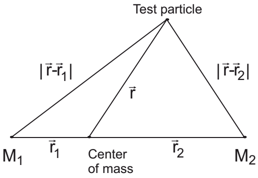
Use of three wonderful satellites: Chandra, XMM-Newton, RXTE, Suzaku, Swift

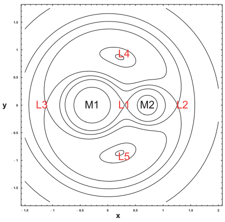


X-ray binaries: the Roche potential

Any gas flow between two stars is governed by the Euler equation (conservation of momentum for each gas element):

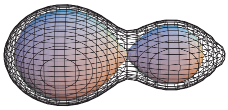
$$\rho\frac{\partial\vec{v}}{\partial t}+\rho\vec{v}\cdot\nabla\vec{v}=-\nabla P+\vec{f}$$





In the co-rotating reference frame of a binary it becomes:

$$\rho\frac{\partial\vec{v}}{\partial t}+\rho(\vec{v}\cdot\nabla)\vec{v}=-\nabla P-2\omega\times\vec{v}-\rho\nabla\phi_R$$



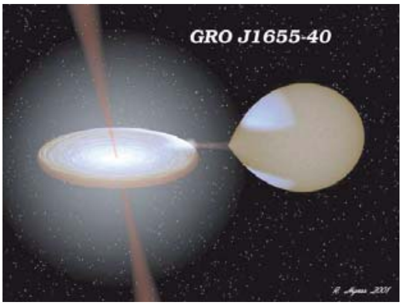
Convection of momentum through the fluid by velocity gradients

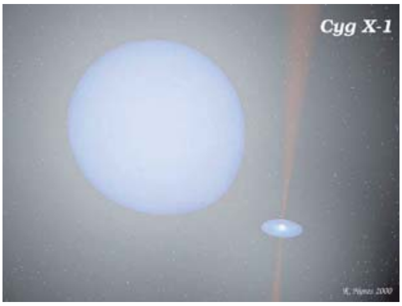
Coriolis force

Gravitational +centrifugal potential

$$\phi_R=-\frac{GM_1}{|\vec{r}-\vec{r}_1|}-\frac{GM_2}{|\vec{r}-\vec{r}_2|}-\frac{1}{2}\left(\vec{\Omega}_B\times\vec{r}\right)^2$$

The family of NS X-ray binaries

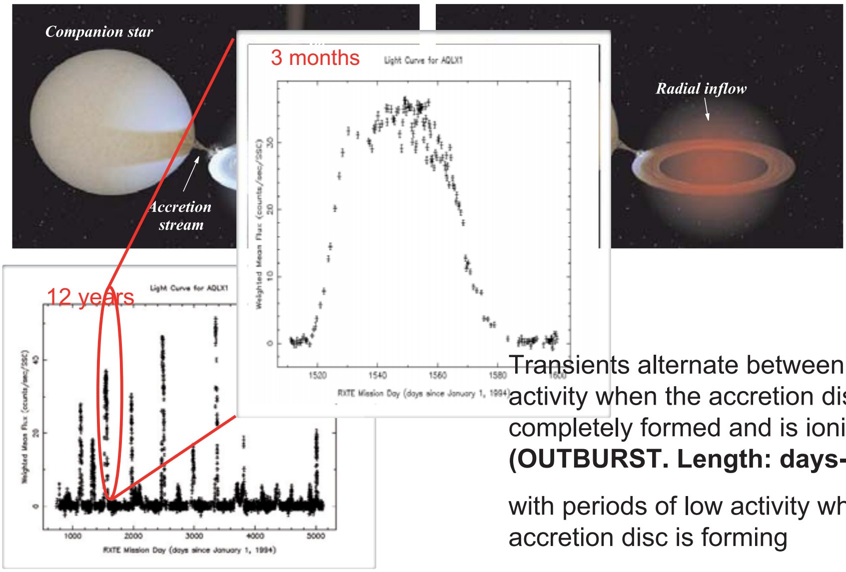




Low mass X-ray binaries
- Roche lobe overflow
- low mass companions
- old NSs
- accretion driven by an accretion disc

High mass X-ray binaries
- Wind fed accretion
- high mass companions
- young NSs
- a disc not always can form

Transient LMXBs

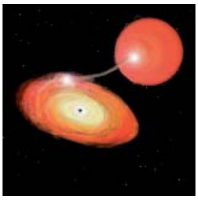


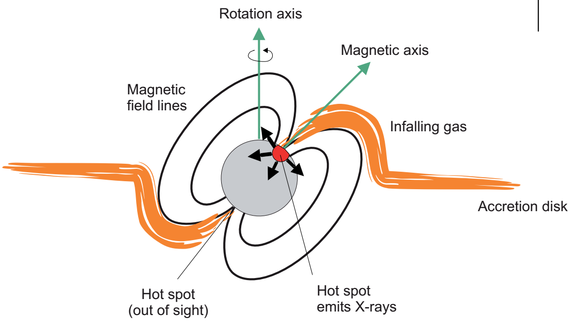
Transients alternate between periods of activity when the accretion disc is completely formed and is ionized **(OUTBURST. Length: days-months)**

with periods of low activity when the accretion disc is forming

(QUIESCENCE. Length: months-years)

Low mass X-ray binaries





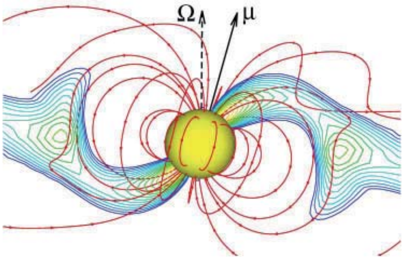
Conservation of angular momentum and viscosity leads to the formation of an accretion disc. The gas flows in the inner part of the primary Roche lobe till the following condition holds:

$$P_{mag} = \frac{B^2}{8\pi} >> (P_{gas}, P_{ram})$$

The gas then flows along the B filed lines and hits the NS surface

$$L_{Edd} \approx 1.3 \times 10^{38} \left(\frac{M}{M_{Sun}} \right) erg/s$$

Accreting millisecond pulsars



$$R_A = \left(\frac{2\mu^2 G^2 M_{NS}^2}{\dot{M}_c} \right) \propto M_{NS}^{1/7} R^{-2/7} L^{-2/7} \mu^{4/7}$$

$$R_{co} = \left(\frac{G M_{NS}}{\omega^2} \right)^{1/3} \approx 2.8 \times 10^3 M_{NS}^{1/3} P_s^{1/2} Km$$

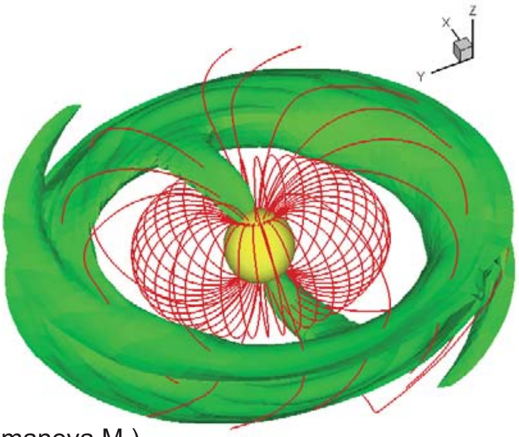
$R_A < R_{co}$ → Accretion is possible. Plasma follows the field line of the NS magnetic field

$R_A > R_{co}$ →

- Strong propeller:Accretion is prevented. Plasma is stopped by the centrifugal barrier of the magnetic field
- Weak propeller:Accretion is reduced by the centrifugal barrier but still can take place

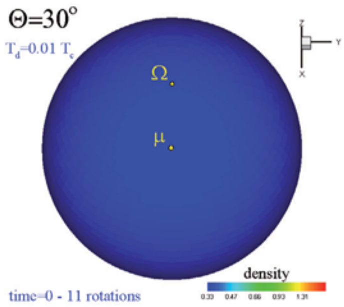
The funnel stream

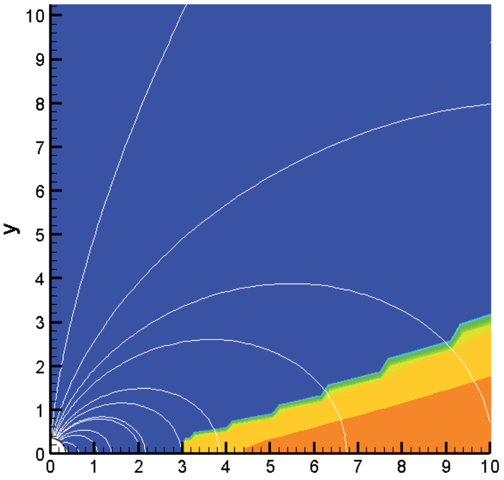
The green surface is a constant density surface, and red lines are sample magnetic field lines. Funnel streams hit the surface of the star at approximately the same position at all times, creating quasi-stationary hot spots.



Animation from the Cornell group (Romanova M.)
http://www.astro.cornell.edu/us-russia/propeller.htm

Accreting millisecond pulsars

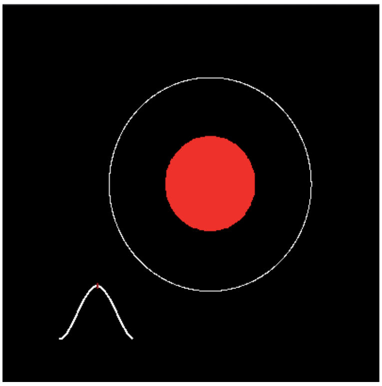




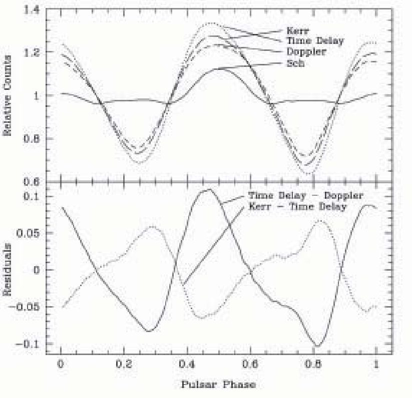
The "hot spot" created during accretion can move around the NS surface and is not completely locked to the poles.

Animation from the Cornell group (Romanova M.)
http://www.astro.cornell.edu/us-russia/propeller.htm

How to create a sinusoidal profile



GR and SR effects are important here !

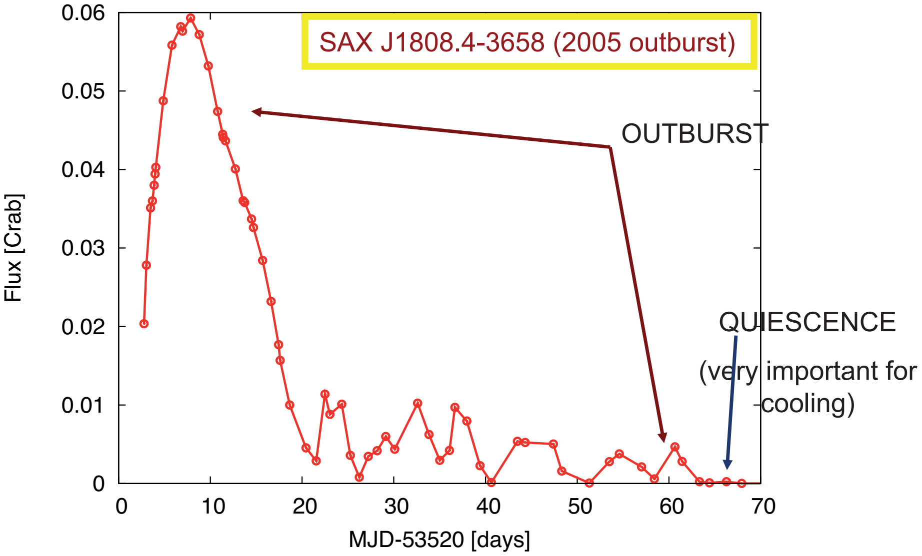


Animation from F. Ozel:

http://www.physics.arizona.edu/~fozel/

The measure of the spin period (part 1)

Observations: the lightcurves



OUTBURST

QUIESCENCE

(very important for cooling)

SAX J1808.4-3658

A clear spike emerges in the PDS of the lightcurve.

The spike is at the spin frequency of the neutron star.

Folding the data (to increase the S/N) at the spin frequency creates the average pulse profile

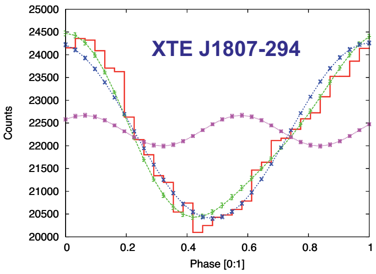
The AMXPs family

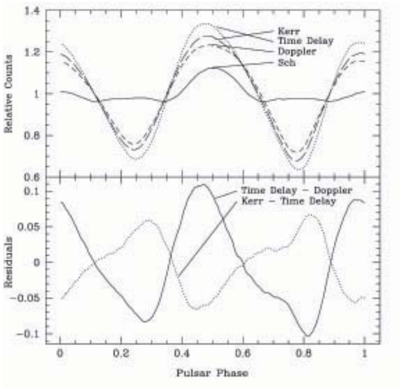
Name	Spin frequency [Hz]	Orbital Period [hr]	Reference
SAX J1808.4-3658	401	2.1	Wijnands & van der Klis (1998) Chakrabarty & Morgan (1998)
XTE J1751-305	435	0.70	Markwardt et al. 2002
XTE J0929-314	185	0.73	Galloway et al. 2002
XTE J1807-294	190	0.67	Markwardt et al. 2003
XTE J1814-334	314	4	Markwardt et al. 2003
IGR J00291+5934	599	2.5	Galloway et al. 2005
SWIFT J1756.9-2508	180	0.90	Markwardt et al. 2007

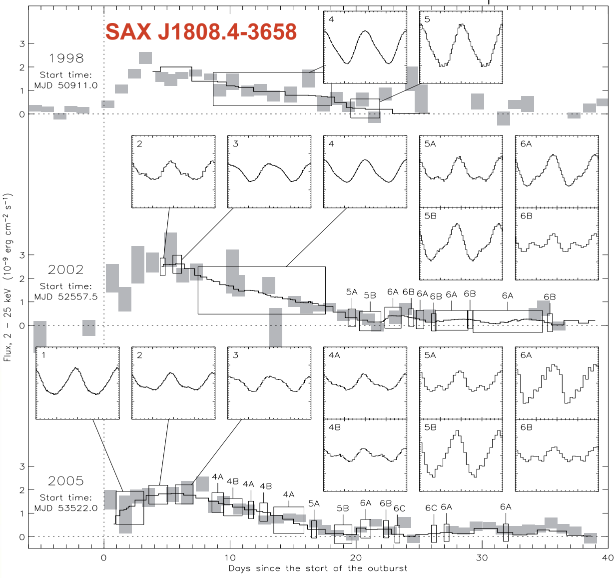
Measured spin torques

Name	Spin frequency [Hz]	Spin torque [1E-13 Hz s]	Reference
SAX J1808.4-3658	401	4.4(0.83) -0.76(0.23) <|0.25|	Burderi et al.(2006) Hartman et al.(2008)
XTE J1751-305	435	3.7(1.0)	Papitto et al. (2008)
XTE J0929-314	185	-0.92(0.40)	Galloway et al. (2002)
XTE J1807-294	190	0.25(0.10)	Riggio et al. (2008) Patruno et al. (2008)
XTE J1814-334	314	-0.67(0.07)	Papitto et al. (2007) Watts, Patruno & van der Klis (2008)
IGR J00291+5934	599	8.4(0.6) 8.5(1.1)	Falanga et al. (2005) Burderi et al. (2007)
SWIFT J1756.9-2508	180	XX	

Pulse profiles

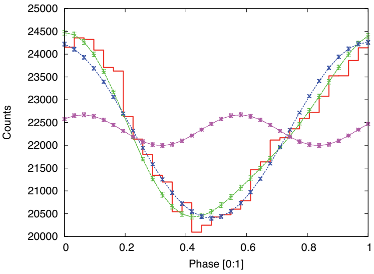






The Harmonic decomposition

- Assume uncorrelated noise in the pulse TOA uncertainities (least-squares algorithm)
- Decompose the pulse profiles in their sinusoidal components: $y = A\sin(\omega t+\phi_1)+B\sin(2\omega t+\phi_2)+C$

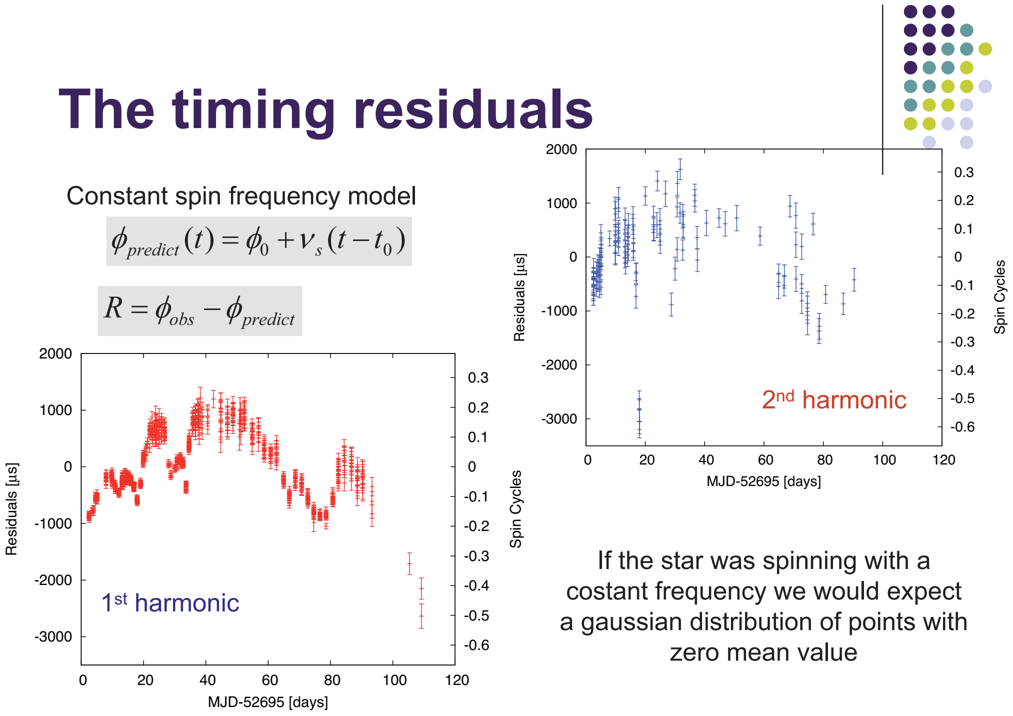


1st harmonic $\nu = \nu_{spin}$

2nd harmonic $\nu = 2\nu_{spin}$

Fit the phases with a polynomial expansion

$$\phi = \phi_0 + \nu(t-t_0) + \frac{1}{2}\dot{\nu}(t-t_0)^2 + \ldots$$



The timing residuals

Constant spin frequency model

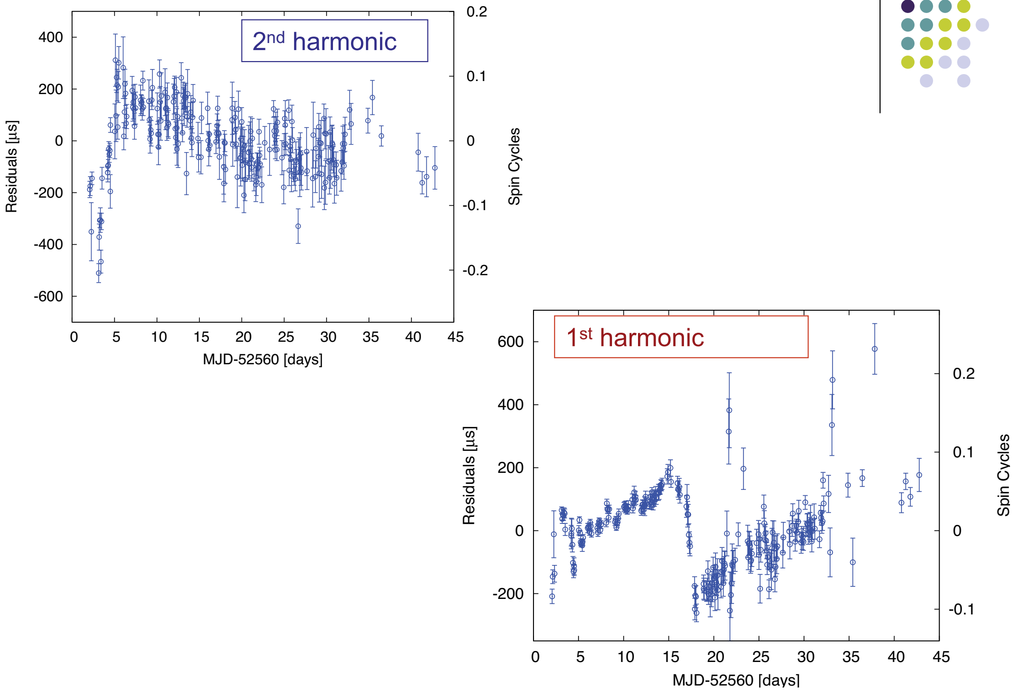
$$\phi_{predict}(t)=\phi_0+\nu_s(t-t_0)$$

$$R=\phi_{obs}-\phi_{predict}$$

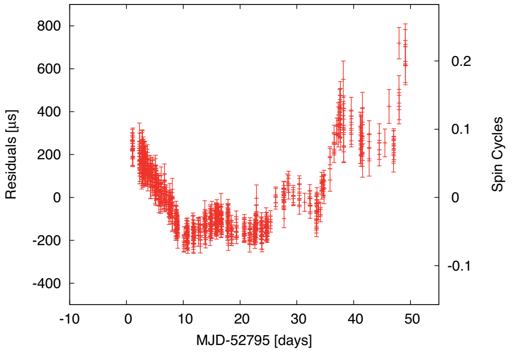
If the star was spinning with a costant frequency we would expect a gaussian distribution of points with zero mean value

The measure of the spin torque

SAX J1808.4-3658: do we really observe a spin torque ?



To spin or not to spin ?



AMXP	Noise level
SAX J1808.4-3658	High
XTE J1751-305	Low
XTE J0929-314	Very low
XTE J1807-294	Very high
XTE J1814-334	High
IGR J00291+5934	Low
SWIFT J1756.9-2508	XX

Basically all the AMXPs show “timing noise” at some degree.

What is the origin of this ‘noise’ ?

Noise is does not mean “measurement noise” (boring) but some unknown origin of the phenomenon. Can be hiding the best part of the physics there !

The origin of “timing noise”

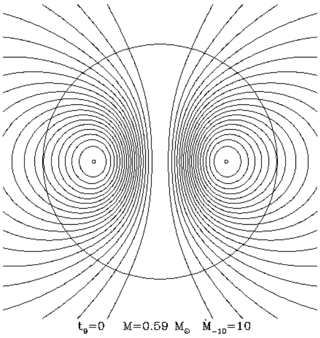
Timing noise might be the most important and interesting part of the NS physics. It’s not just a ‘measurement noise’ !!!

1. Transfer of angular momentum
2. Superfluidity
3. Magnetic field
4. Accretion process and disc-magnetosphere interaction

It is observed in: radio pulsar (young), magnetars, HMXBs, LMXBs (both AMXPs and slowly rotating)

Why the number of pulsating LMXBs is so small ?

Why not all the NS-LMXBs pulsate ?



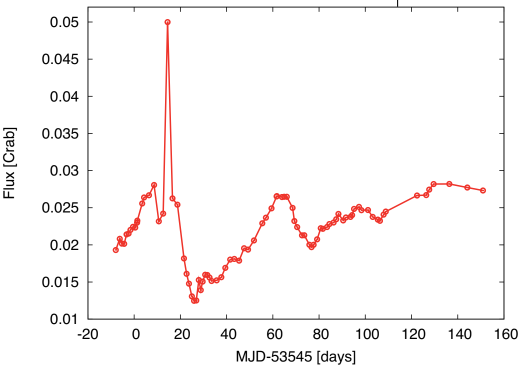
The freshly accreted diamagnetic material destroys the external B field.

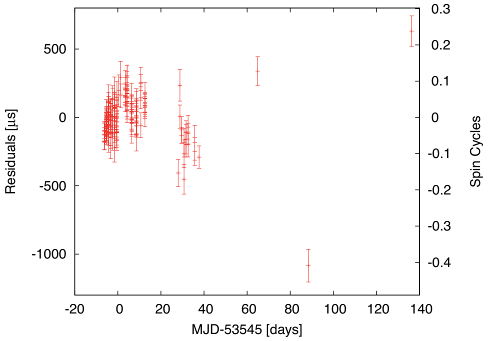
The Ohmic diffusion on the contrary tries to magnetize the accreted material.

(Animation: Andrew Cumming)

Intermittent pulsar 1: HETE J1900+2455

This source was behaving like a normal AMXPs, then the pulsations disappeared after ~2 months.

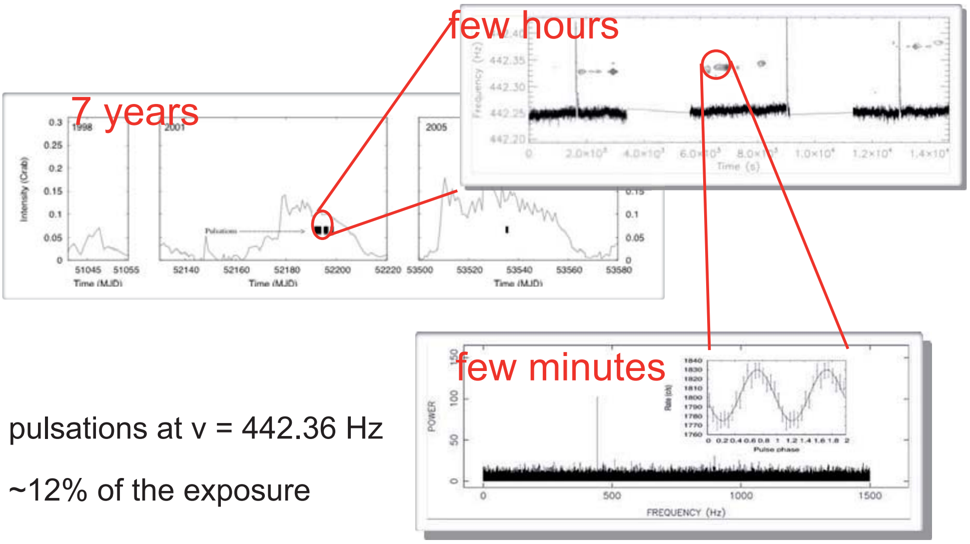




Pulsation at ~377 Hz

Pulsations in ~10% of the exposure

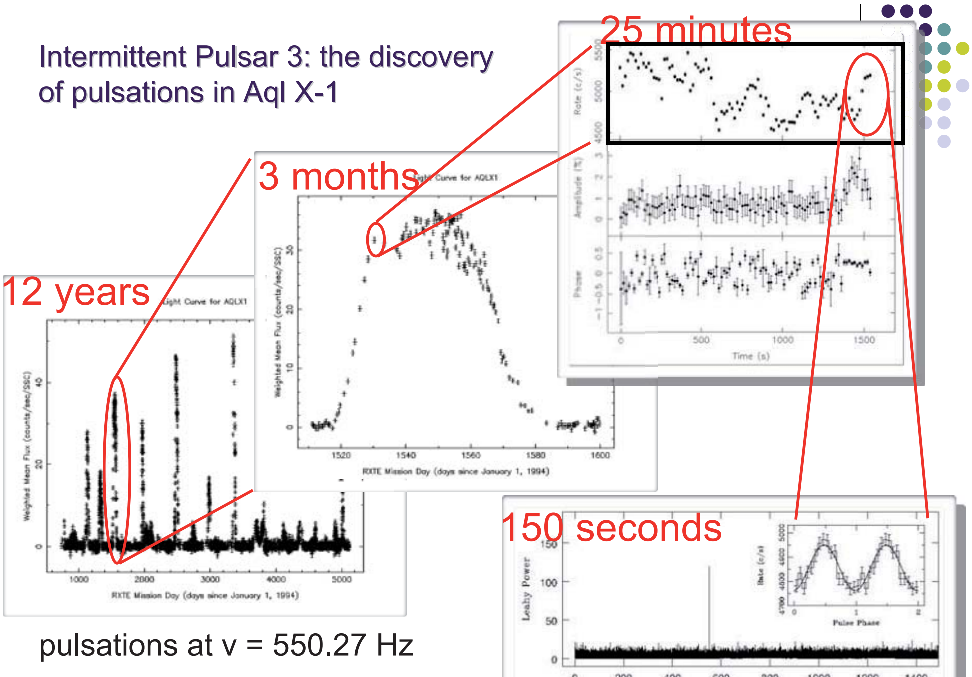
Intermittent pulsar 2: SAX J1748.9-2021



pulsations at v = 442.36 Hz

~12% of the exposure

Intermittent Pulsar 3: the discovery of pulsations in Aql X-1

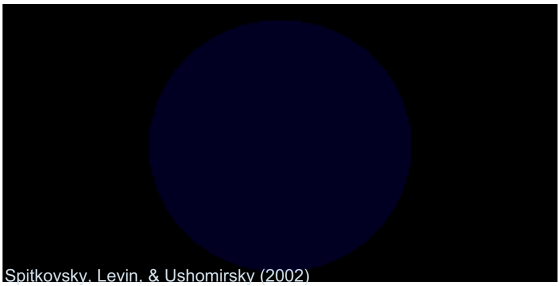


pulsations at v = 550.27 Hz

detected in 0.01% of the exposure

The measure of the spin (part 2)

Thermonuclear explosions, a.k.a. Type I X-ray busrts


Spitkovsky, Levin, & Ushomirsky (2002)

$$\begin{aligned}\alpha &\equiv \frac{\int L_{\rm accr}dt}{E_{\rm burst}} \approx \frac{GM/R}{E_{\rm nuc}}\\ &\approx \frac{200\ \text{MeV per nucleon}}{(1-5)\ \text{MeV per nucleon}}\end{aligned}$$

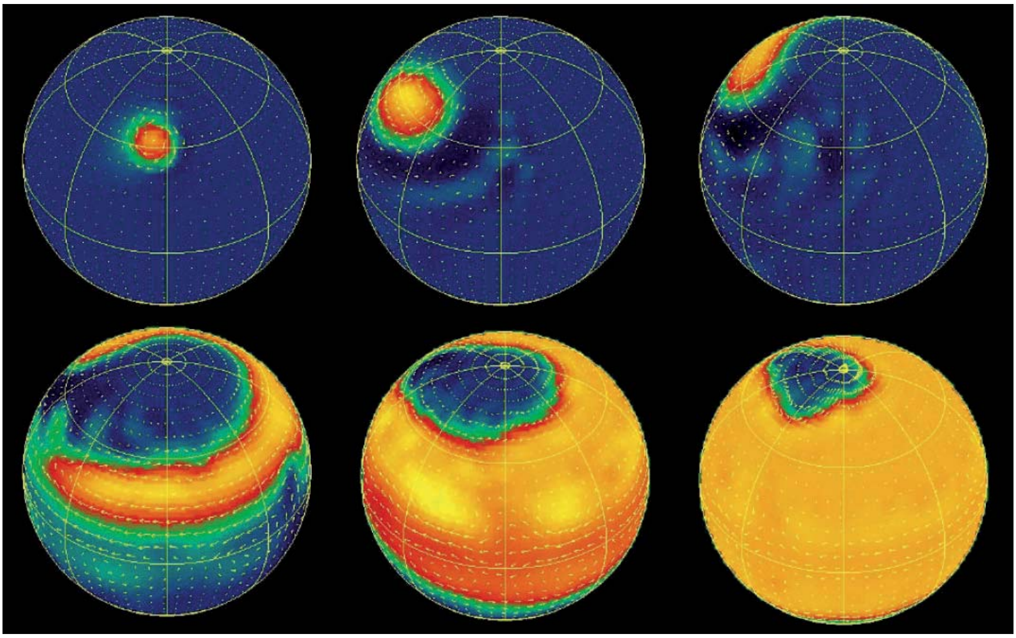
Q~5 Mev/barion Qacc~200 Mev/barion

Burst→ very rapid unstable nuclear reaction of the accreted material

It takes many hours to accumulate an thermally unstable pile of fuel

But only ~10-100 seconds to burn it !

So the burst is triggered in one specific position on the surface (otherwise you need identical triggering conditions to better than 1 part over 1000 for the local themal instability to occur simultaneously on the whole surface)

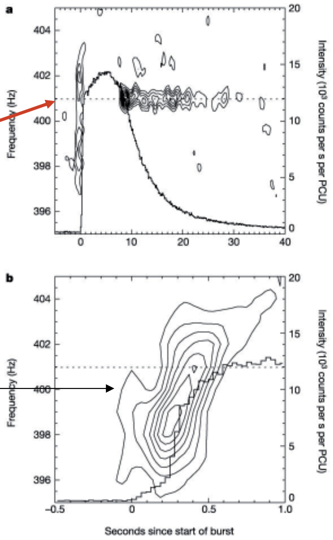


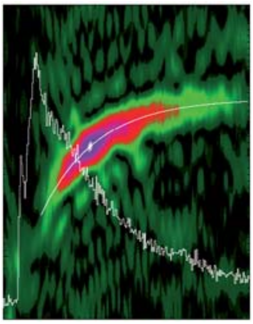
Spreading of the burning flame   Spitkovsky, Levin, & Ushomirsky (2002)

Burst oscillations: nuclear powered pulsars

SAX J1808.4-3658 confirms that the asymptotic frequency of burst oscillations is the spin frequency of the NS

$$\nu_{burst} = \nu_s \approx 401 Hz$$





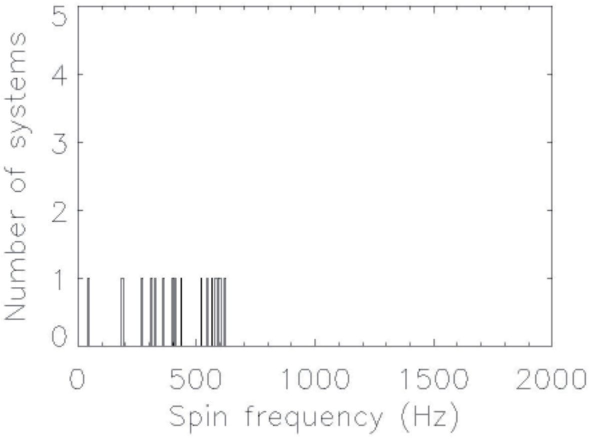
Slow drift

Rapid drift

Do submillisecond pulsar exist ?

What is the spin distribution of NS in LMXBs ?

Nuclear powered pulsars + Accretion powered pulsars have a spin drop off at ~730 Hz



RXTE has no problem to detect a ~2 kHz oscillation. So why we don' t observe submillisecond pulsars ?

Do submillisecond pulsar exist ?

1. Steady disc accretion onto a magnetized neutron star will lead to an equilibrium period if:

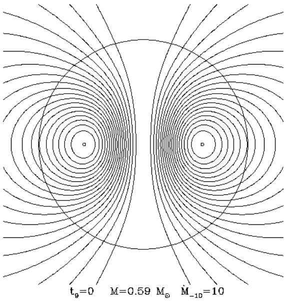
$$R_A = \left(\frac{2\mu^2 G^2 M_{NS}^2}{\dot{M}_c} \right) \propto M_{NS}^{1/7} R^{-2/7} \dot{M}^{-2/7} \mu^{4/7}$$

$$R_{co} = \left(\frac{GM_{NS}}{\omega^2} \right)^{1/3} \approx 2.8 \times 10^3 M_{NS}^{1/3} P_s^{1/2} Km$$

$$\boxed{R_A \sim R_{co}} \longrightarrow \boxed{P_{eq} = 1s \left(\frac{B}{10^{12} G} \right)^{6/7} \left(\frac{\dot{M}}{10^{-9} M_{Sun} yr^{-1}} \right)^{-3/7}}$$

However B here is an ***effective*** field ! It's not necessarily the B field of the NS !

Something more on the spin equlibrium



Remember what we have said a few slides before: the external effective B field can be zero, i.e. can be screened by the diamagnetic freshly accreted material.

$$\boxed{P_{eq} = 1s \left(\frac{B_{\to 0}}{10^{12} G} \right)^{6/7} \left(\frac{\dot{M}}{10^{-9} M_{Sun} yr^{-1}} \right)^{-3/7} \to 0}$$

Therefore in this scenario, no limit on the equilibrium frequency exists.

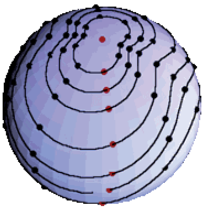
So we do we observe $\nu_{s,\max} = 716 Hz$?

The lack of submillisecond pulsars

1. The magnetic screening model is wrong and we don’t see pulsations for another reason (e.g., intermittency)
2. The EOS forbids the spin frequency to grow above ~700 Hz (no reasonable model can really predict that low spin frequencies)
3. The pulsar spin is blocked by another intrinsic mechanism. The best candidate is the emission of gravitational waves.

Example 1: GWs driven by r-mode instabilities can carry away substantial angular momentum

Example 2: accretion-induced crustal quadrupole moment



Open questions for theorists (and not)

1. What is the origin of timing noise ? Can it tell us something about the interior ?
2. Why not all LMXBs pulsate ? Is possible to have an external effective B field that behaves ‘intermittently’ ?
3. Why there are no submillisecond pulsars ? Is it due to GW emission or it’s a consequence of a strong B field in all the NS ?

Reading

- Romanova et al. 2008 (arXiv0803.2865R)
- Long, Romanova, Lovelace 2008
- Patruno et al. 2008
- Casella et al. 2008
- Galloway et al. 2006
- Altamirano et al. 2008
- Cumming et al. 2001
- Hartman et al. 2008
- Wijnands & van der Klis 1998
- Chakrabarty D. 2004 (http://arxiv.org/abs/astro-ph/0408004)
- Wijnands 2006 (http://staff.science.uva.nl/~rudy/admxp/index.html)
- Lamb et al. 2008
- Watts, Patruno & van der Klis 2008
- http://www.astro.uva.nl/xray/amxp/program.html

Probing the neutron star physics with accreting neutron stars (part 2)

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How to probe the NS physics with NS LMXBs ?

- X-ray spectra (cooling, cyclotron resonance, etc…)
- Coherent timing (pulse profile shape, torques, timing noise, glitches)
- Thermonuclear bursts
- Aperiodic variability (oscillation modes, QPOs)

Use of three wonderful satellites: Chandra, XMM-Newton, RXTE

Outburst vs. quiescence

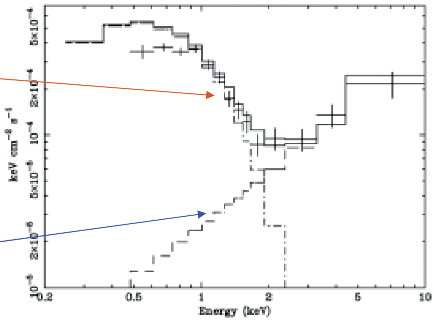
- During an outburst we observe:
  1. disc + NS surface emission
  2. the outburst luminosity is given by $\dot{M}_{outb}$
  3. the quiescent luminosity is given by $\dot{M}_{q}$
  4. the average mass transfer rate is therefore: $\langle \dot{M} \rangle = \frac{\dot{M}_{outb} \cdot t_{outb} + \dot{M}_{q} \cdot t_{q}}{t_{q} + t_{outb}}$

So we need to measure four observables (assuming L and Mdot are related) to determine the average mass transfer rate

Typical outburst X-ray luminosity: ~1e36 – 1e37 erg/s

Typical quiescent X-ray luminosity: ~1e33 erg/s

The quiescent emission



Transiently accreting NSs **in quiescence** have usually soft BB-like X-ray spectra

The harder part is usually fitted with with a power law of photon index 1-2

INTERPRETATION:

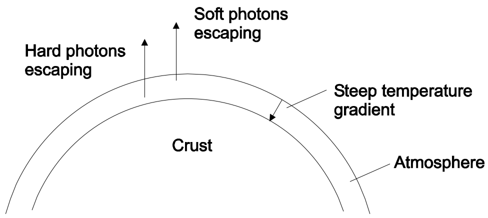
Black body-like component comes from the heat released from the NS surface

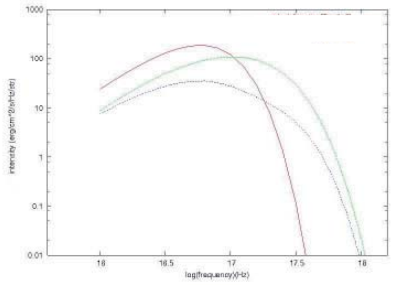
Power law component is of unknown origin and remains unexplained (continued accretion, shock from a pulsar wind, others)

How to fit a quiescent spectrum ? BB vs. NSA models

The spectrum of a NS is not a pure BB for two reasons:

2. There is an atmosphere with a chemical composition, a magnetic field.
3. The free free absorption (absorption of a photon by the free electron in the Coulomb field of a ion) is proportional to ν^{-3}





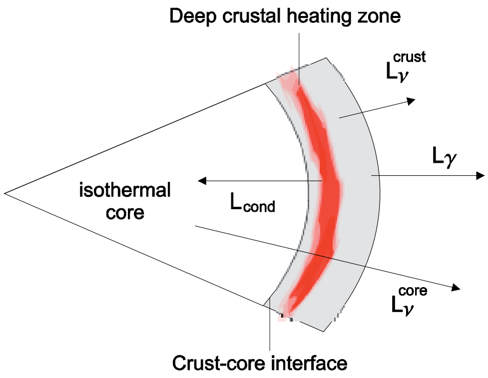
Heating and cooling of NSs

Incandescent luminosity:

$$L_i \approx fQ_{nuc}\left(\frac{1}{t_r}\int \dot{M}dt\right) \equiv fQ_{nuc}\left\langle \dot{M}\right\rangle$$

$$Q_{nuc} \approx 1-1.5MeV/m_p$$

The accreted material sinks to a depth of ~900 m and then burns via pycnonuclear reactions and beta captures



The crust-core coupling

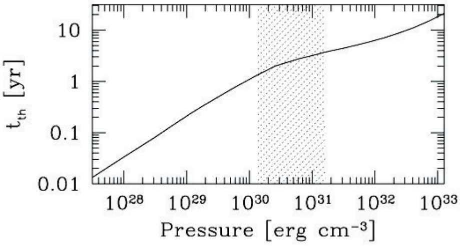
- A fraction f or heat flows into the core
- A fraction 1-f flows into the crust

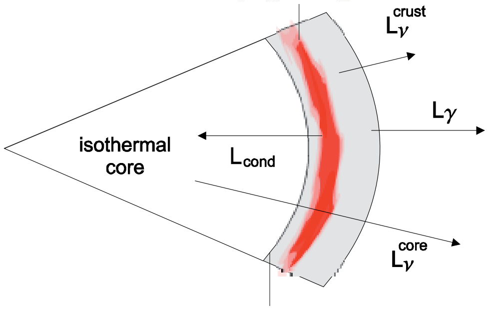
The core has high thermal conductivity and heat capacity → temperature is almost unchanged

The crust has high thermal conductivity and low heat capacity → temperature significantly incresed by the heat flow

$$\frac{L_o t_o}{L_i t_r} = \frac{GM/R}{fQ_{nucl}} \approx \frac{200}{f}$$

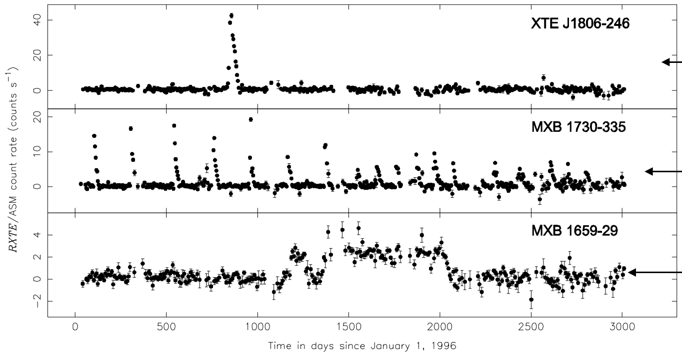
$$t_{th} = \frac{1}{4}\left[\int_0^P \left(\frac{c_P}{K\rho}\right)^{1/2} \frac{dP}{g}\right]$$





Crust-core interface

The quasi persistent transients



~1 month outburst. Long recurrence time

~1 month outburst

Short recurrence time

Very long outburst ~2.5 yr. Recurrence time unknown

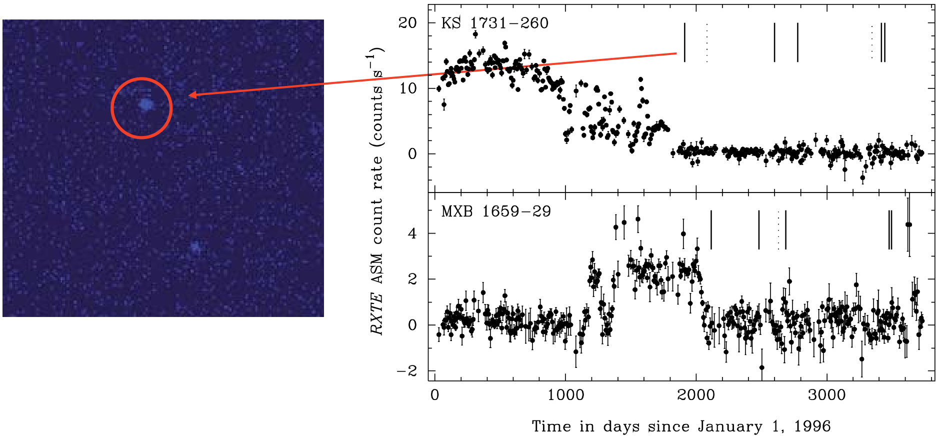
Two transient LMXBs show very long outbursts with length of the order of ~1-10 yr. This means that the quiescent luminosity is very high with respect to the normal transients with outburst length of ~1 month

Deep crustal heating can thus break the core-crust coupling and make the crust much hotter than the core

How many quasi persistent transients do we know ?

Source name	Status
EXO 0748-676	Detected in outburst since February 1985
GS 1826-238	Detected in outburst since September 1988
XTE J1759-220	Detected in outburst since February 2001
4U 2129+47	Quiescent since 1983 after at least 11 years in outburst
X 1732-304	Quiescent since 1999 after at least 12 years in outburst
KS 1731-260	Turned off in February 2001 after an outburst of ~12.5 years
MXB 1659-29	Turned off in Spetember 2001 after an outburst of ~2.5 years

KS 1731-260

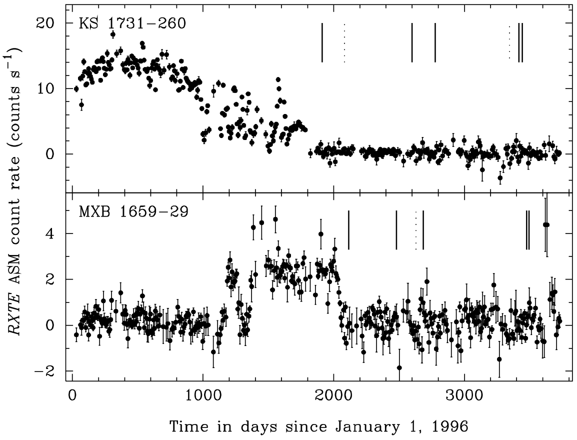


In quiescence all the LMXBs are very faint ! Luminosities of ~1e32-1e33 erg/s

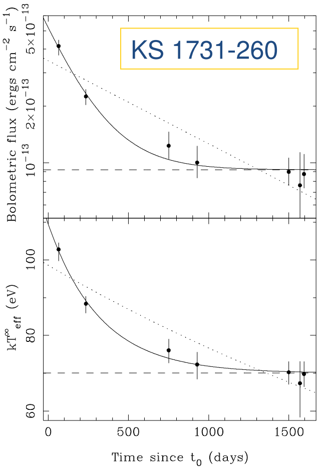
MXB 1659-29

Very recent new Chandra observation on 2008 Apr. 27

The total quiescent monitoring now extends up to 6.6 yrs



Power law vs. exponential decay: the situation ‘till early 2008

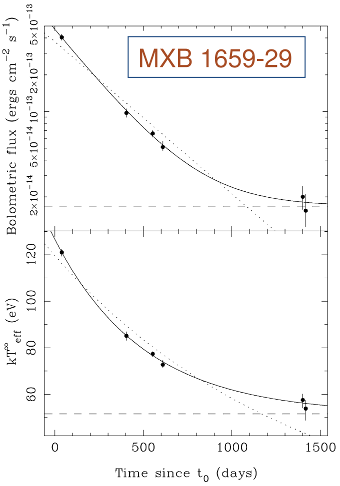


$y(t) = a \exp[-(t-t0)/b] + c$

a = normalization constant

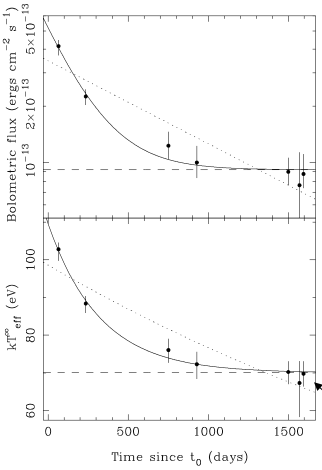
b = e-folding time

c = constant offset (set by the core temperature)



Flux and Temperature well fitted by an exponential decay plus a constant offset (set by the core temperature)

The thermal relaxation timescale and the surface temperature



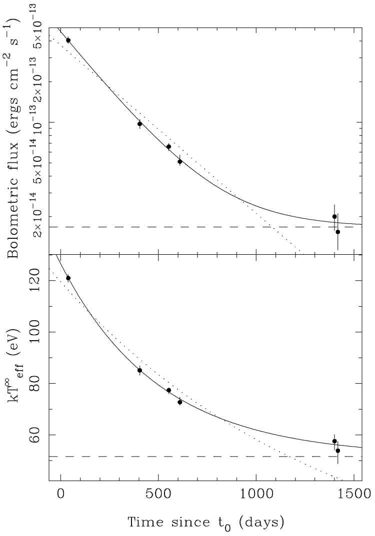
In KS 1731 we have not reached the equilibrium between the core and the crust yet.

The constant flux level indicates a ~70(2) eV surface temperature and an e-folding timescale of 325(101)

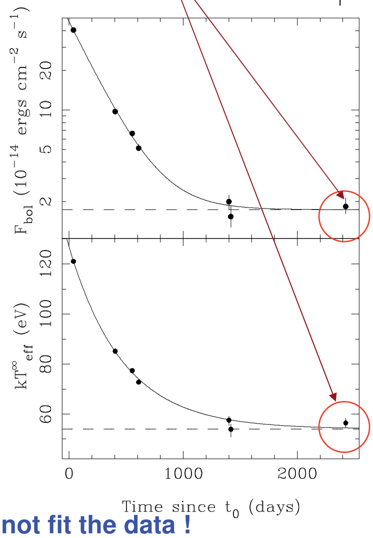
Some residual slope is still possible

The new observation of MXB 1659-29

Before April 2008



After April 2008



Power law model does not fit the data !

New constraints for MXB 1659

	NSA (D=10 kpc)	NSA (D=5kpc)	NSA (D=13kpc)	BB
Normalization (a, eV)	73(2)	54(1)	82(2)	176(11)
e-folding time (b, days)	472(23)	485(27)	473(24)	437(43)
Constant level (c, eV)	54(1)	45(1)	58(1)	141(3)

How model dependent is the result ?

1. e-folding timescales are consistent with each other with any model assumed
2. Shape of the cooling curve independent from the distance
3. Core temperature can be inferred from the relaxed surface emission, by integrating the thermal structure of the crust.
4. Core temperature: 3.5x10^7 K (kT ~ 7 keV) deep He layer overlying a pure Fe layer)

8.3x10^7 K (kT ~ 3 keV) shallow He layer overlying a layer of heavy
. rp-process ashes

Modified URCA predicts:

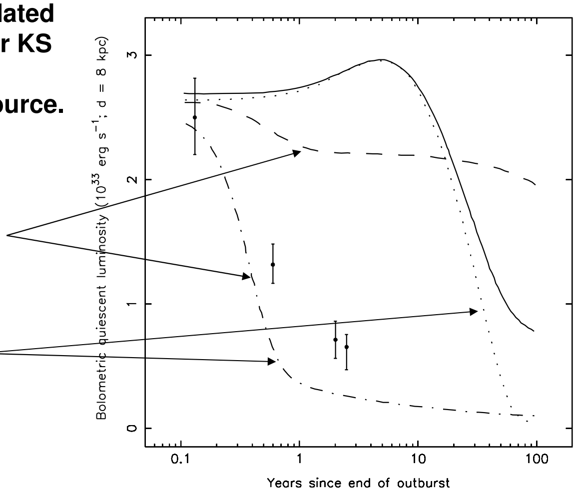
$$2\times10^{29}\, erg/s < L_\nu < 2\times10^{32}\, erg/s$$

Incandescent luminosity observed (for D=10kpc) ~ $L_i \approx 6\times10^{33}$

Therefore even in the most optimistic case there is a factor 30 in difference between what predicted by the minimal cooling paradigm and the observed luminosity

1. Enhanced neutrino & high thermal conductivity of the crust ?

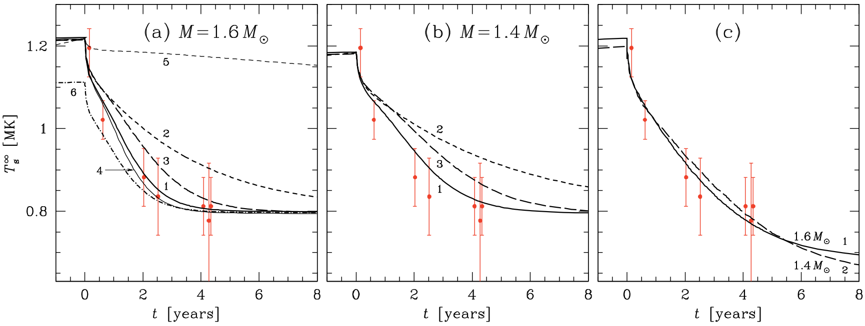
Rutledge et al. 2002 calculated detailed cooling curves for KS 1731-260 using the mass accretion history of the source.



High crust thermal conductivity

Enhanced cooling

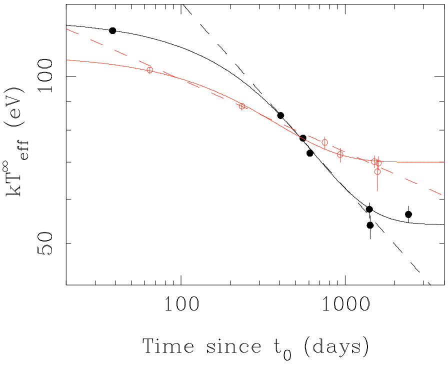
Enhanced neutrino & high thermal conductivity of the crust ?



With the current observation we can't confirm (yet ?) that KS 1731-260 requires enhanced cooling emission. It can be fit with a power law model or an exponential decay equally well. The only requirement is an high thermal conductivity of the crust

Beta capture can produce nuclei in excited states → deexcitation can generate extra heat → no enhanced cooling required

Exponential vs. power law



Power law model definitely ruled out for MXB 1659, but still possible for KS 1731

MXB 1659 more massive than KS 1731 ?

Red curve → KS 1731-260

Black curve → MXB 1659-29

SAX J1808.4-3658

Outbursts last for ~1 month

Recurrence time quite well known: ~2.5 yr (observed outbursts in the 1996, 1998, 2000, 2002, 2005)

Low magnetic field: B~1e8 G Distance of approx. 2.5 -- 3.5 kpc

Very low luminosity in quiescence: ~5e31 erg/s

Known mass transfer rate: Mdot~1e-10 Msun/yr

ONE OF THE BEST KNOWN LMXBs !

-Pulsations

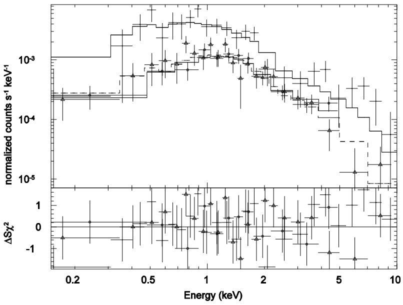
-- Thermonuclear bursts

-- Bursts oscillations

-- Twin kHz QPOs

-- Fast cooling

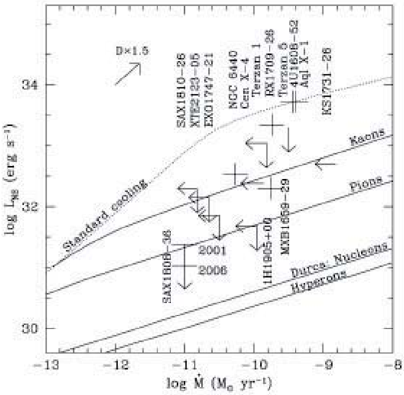
-- Multiple outbursts



Minimal cooling paradigm

Note: the problem here is different ! We're not trying to measure the surface temperature evolution with time, we are trying to observe the

minimum luminosity of the source for a given mass transfer rate



Quasi persistent sources (KS 1731, MXB 1659) are HOT, and emit a HIGH flux in the early stages of quiescence

$$L_{bol} \approx 10^{33} erg/s$$

How fast does it cool ?

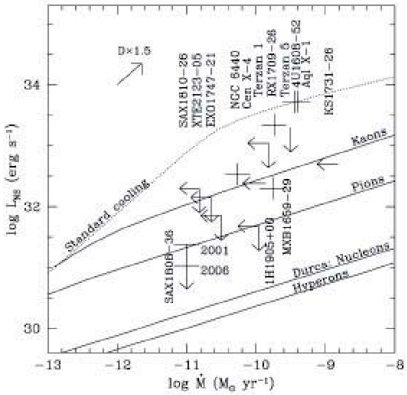
Normal transients (SAX J1808.4) can be COLD and emit a LOW flux during quiescence

$$L_{bol} \approx 5\times 10^{31} erg/s$$

How cold is it ?

Minimal cooling paradigm

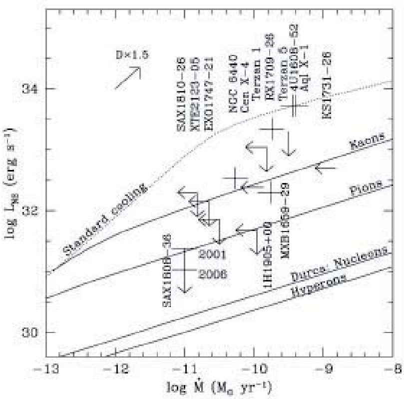
Epoch	NH (1e22 cm^-2)	kT (eV)	L (erg/s)
2001	0.13	<42	2.4e31
2006	0.13	<35	1.2e31
2001 & 2006	0.13	<34	1.1e31
2001 & 2006	0.15(4)	<61	1.0e31



Sources of error

- Distance D=3.5(1) kpc → 6% uncertainity
- Mass and radius → 3% (M=1.4 R=10 Km to M=2.0 R=12 Km)
- Mass transfer rate assumed to be the observed one

Assuming 50% uncertainty in mass transfer rate and distance still requires enhanced cooling for SAX J1808. Observations need to be highly biased from an unknown source of error to move SAX J1808 from the enhanced cooling region



Why the thermal component is not residual accretion ?

- Accretion shows variability on short timescale while we see a smooth exponential decay

Therefore the surface emission is quite robust

- If residuals accretion takes place, we expect variation on the observed quiescent luminosity from cycle to cycle

Major sources of uncertainity:

2. Distance (and therefore the X-ray Luminosity)
3. Recurrence time (and therefore the AVERAGE mass transfer rate)

Reading

- Yakovlev & Pethick
- Page, Geppert & Weber
- Cackett et al.
- Chackett et al.
- Brown & Bildsten
- Rutledge et al.
- Heinke et al.
- More references will appear later…check on the website