Accreting neutron stars

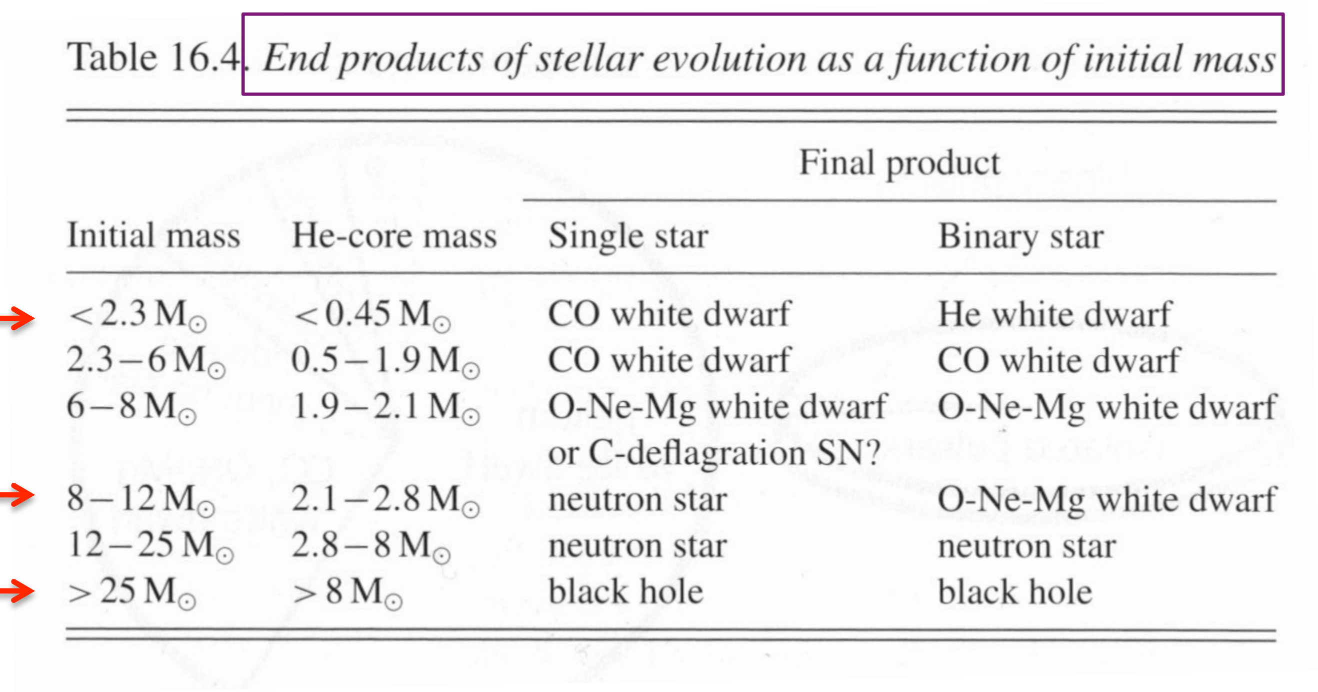


Table 16.4. *End products of stellar evolution as a function of initial mass*

		Final product	
Initial mass	He-core mass	Single star	Binary star
$< 2.3\,M_\odot$	$< 0.45\,M_\odot$	CO white dwarf	He white dwarf
$2.3 - 6\,M_\odot$	$0.5 - 1.9\,M_\odot$	CO white dwarf	CO white dwarf
$6 - 8\,M_\odot$	$1.9 - 2.1\,M_\odot$	O-Ne-Mg white dwarf or C-deflagration SN?	O-Ne-Mg white dwarf
$8 - 12\,M_\odot$	$2.1 - 2.8\,M_\odot$	neutron star	O-Ne-Mg white dwarf
$12 - 25\,M_\odot$	$2.8 - 8\,M_\odot$	neutron star	neutron star
$> 25\,M_\odot$	$> 8\,M_\odot$	black hole	black hole

wd

ns

bh

Isolated vs. accreting NS

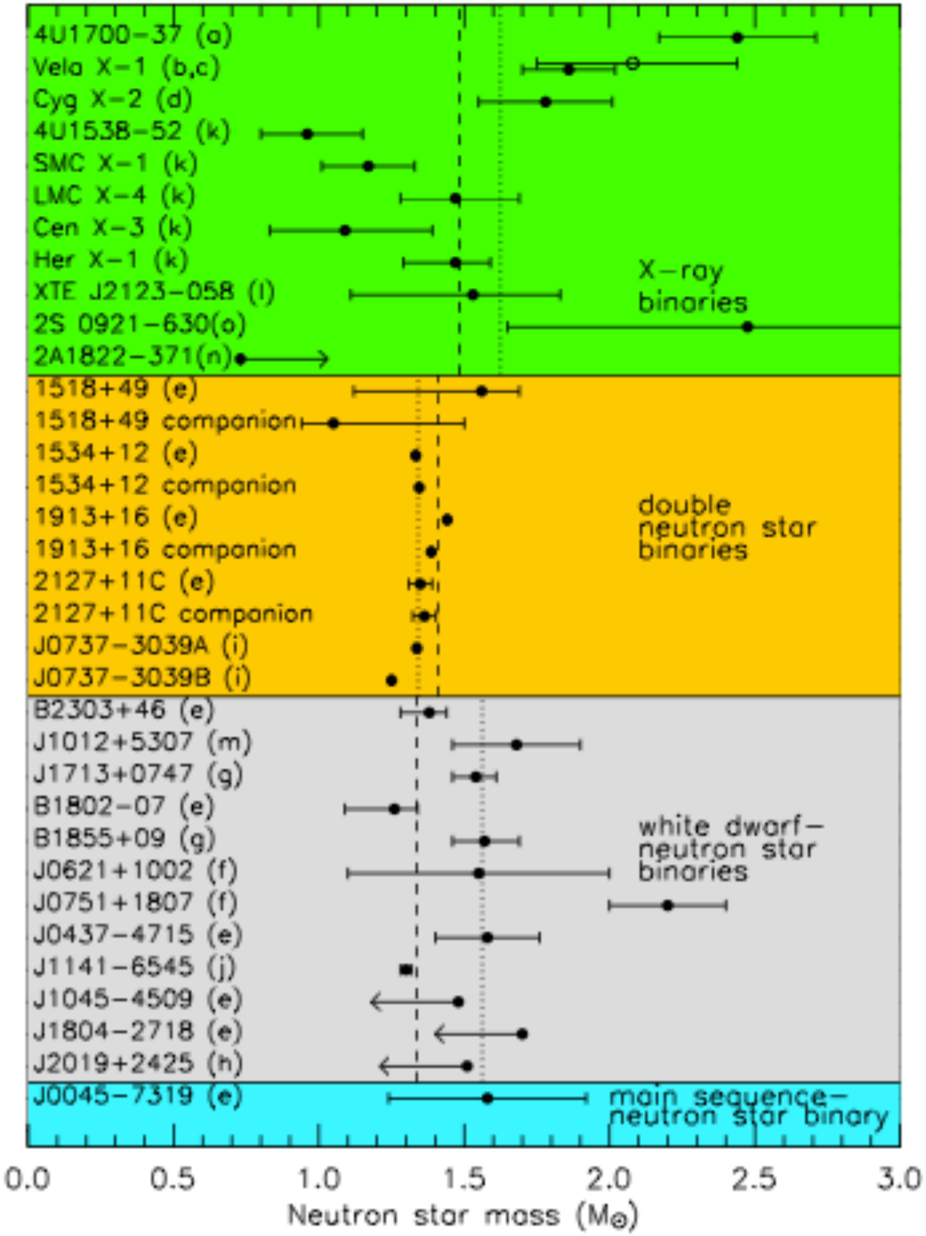
In *isolated NS*, energy is supplied by the spin energy, magnetic field decay, thermal energy or accretion from the interstellar medium.

In *accreting NS*, accretion from a companion is powering the source output
➔ **X-ray binary system**

Physics is the same but the energy supply is different

Uhuru '70: 1/3 of the 339 sources of the IVth catalog were NS in binary systems
X-ray luminosities of the order of 10^{34}-10^{38} erg/s

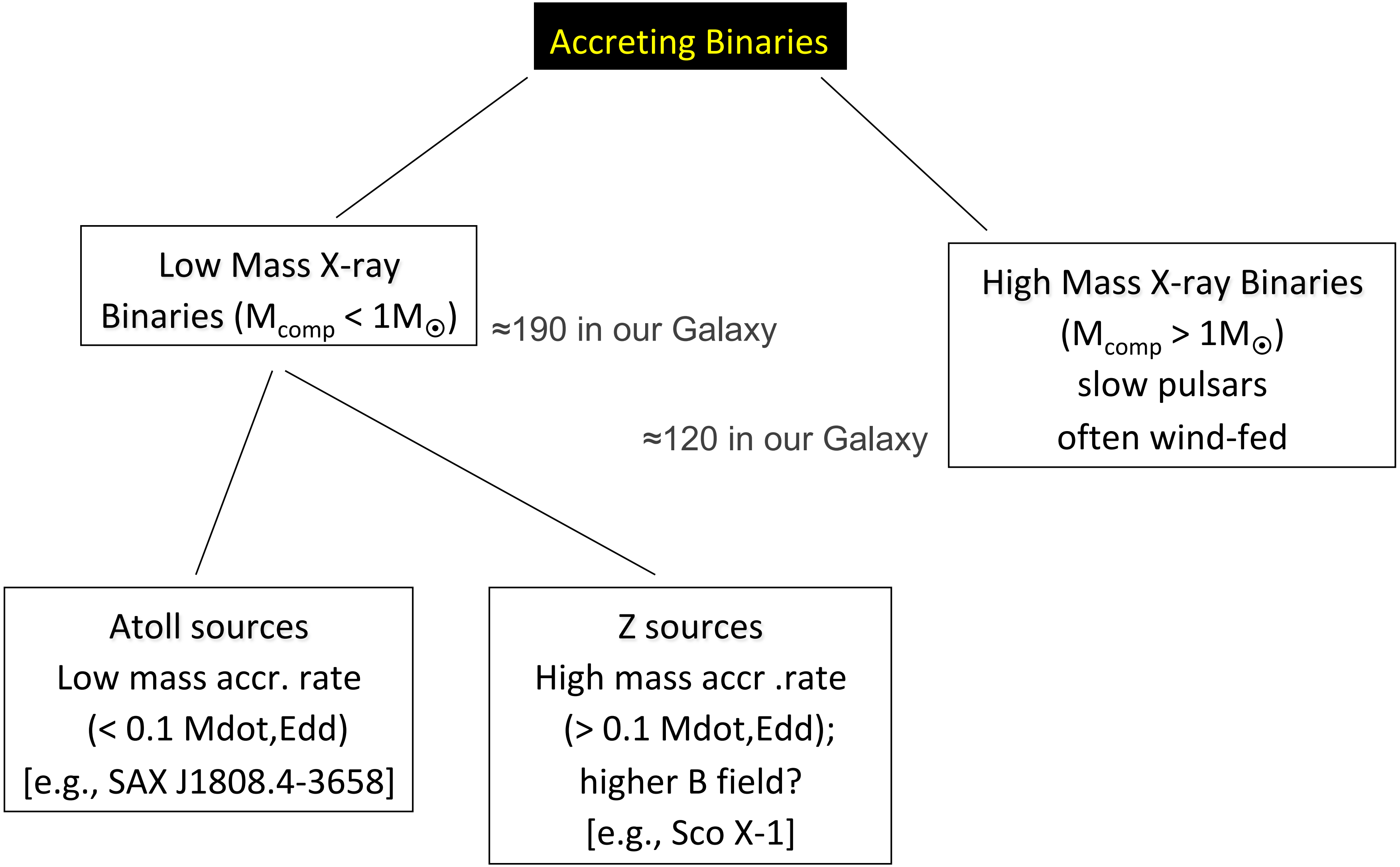
Observed NS mass distribution



NS clustered around ≈1.4 $M_\odot$

Compilation by Lattimer & Prakash 2005

First-order taxonomy of X-ray binaries



Accreting Binaries

Low Mass X-ray Binaries ($M_{comp} < 1M_\odot$)

≈190 in our Galaxy

High Mass X-ray Binaries
($M_{comp} > 1M_\odot$)
slow pulsars
often wind-fed

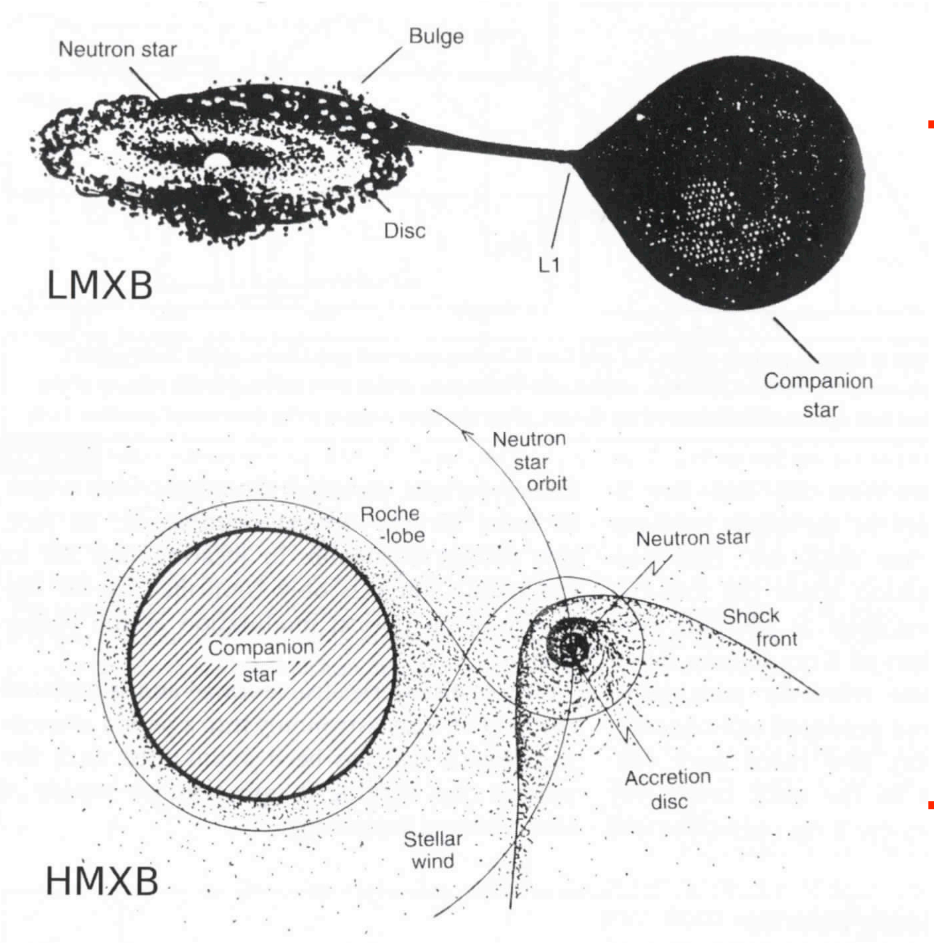
≈120 in our Galaxy

Atoll sources
Low mass accr. rate
(< 0.1 Mdot,Edd)
[e.g., SAX J1808.4-3658]

Z sources
High mass accr .rate
(> 0.1 Mdot,Edd);
higher B field?
[e.g., Sco X-1]

LMXB

HMXB



disc

stellar wind

Second-order taxonomy of X-ray binaries

Transients: episodes of X-ray emission, sometimes recurrant

Eclipsing X-ray binaries: usually among HMXBs

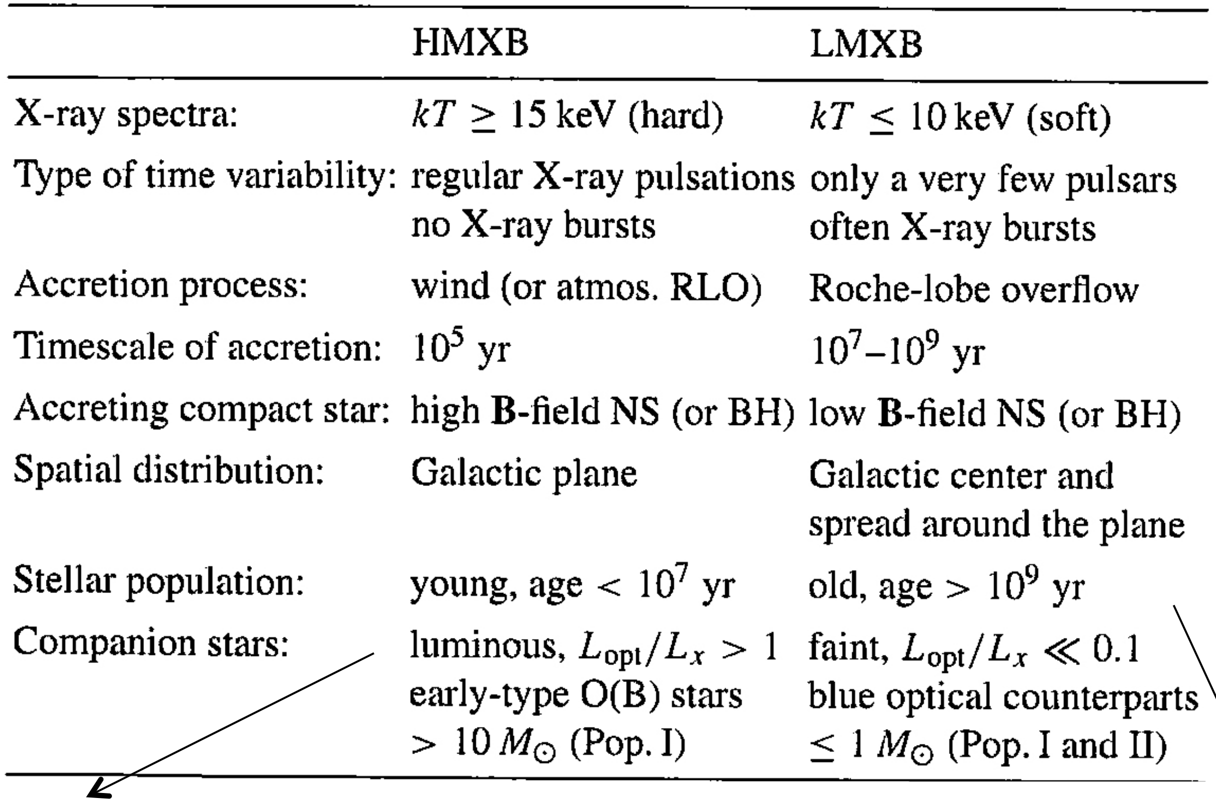
X-ray binary pulsars: X-rays are modulated by the spin of the NS

Bursters: sources showing repeated short (minutes) duration bursts of X-ray emission. They are all LMXBs with weakly magnetized NS [Type I and Type II bursts – see next]

QPO sources: sources showing quasi-periodic oscillations (broad peak in the power spectral density – PSD – obtained in a Fourier analysis of the timing data)

The QPO sources are all LMXBs

Classes depending mainly on the mass of the companion star (different mass transfer) and on the magnetic field of the NS



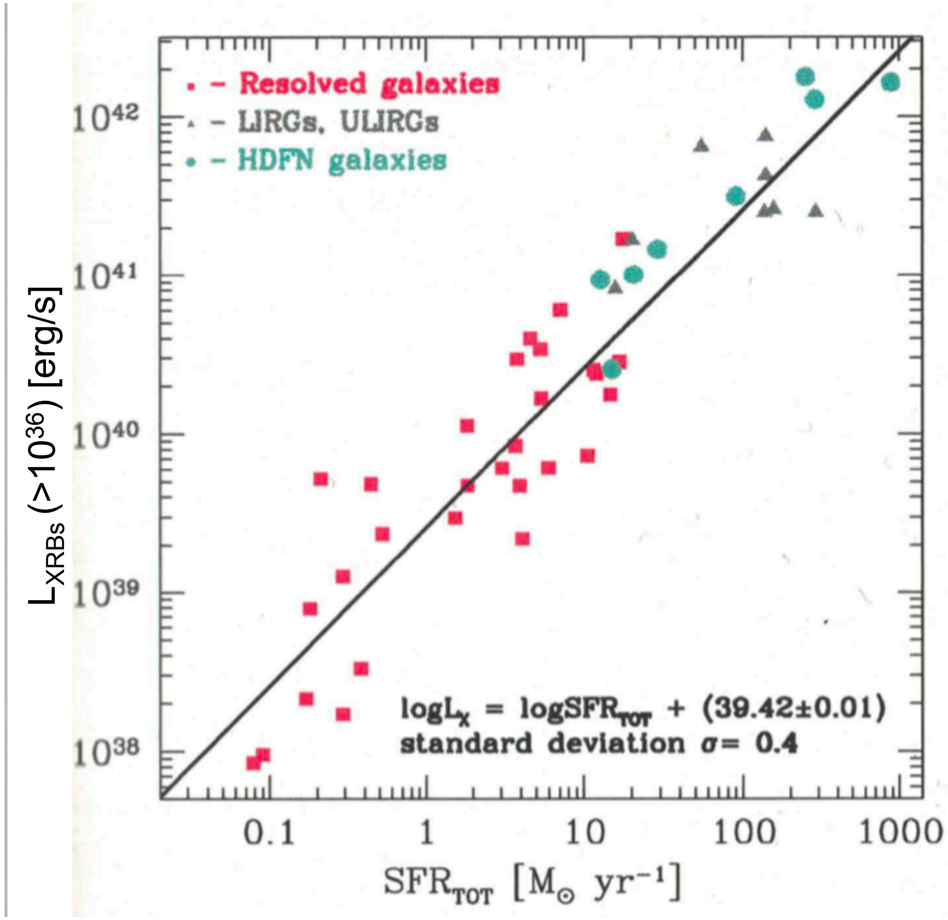
	HMXB	LMXB
X-ray spectra:	$kT \geq 15$ keV (hard)	$kT \leq 10$ keV (soft)
Type of time variability:	regular X-ray pulsations no X-ray bursts	only a very few pulsars often X-ray bursts
Accretion process:	wind (or atmos. RLO)	Roche-lobe overflow
Timescale of accretion:	10^5 yr	10^7–10^9 yr
Accreting compact star:	high **B**-field NS (or BH)	low **B**-field NS (or BH)
Spatial distribution:	Galactic plane	Galactic center and spread around the plane
Stellar population:	young, age $< 10^7$ yr	old, age $> 10^9$ yr
Companion stars:	luminous, $L_{\rm opt}/L_x > 1$ early-type O(B) stars $> 10\,M_\odot$ (Pop. I)	faint, $L_{\rm opt}/L_x \ll 0.1$ blue optical counterparts $\leq 1\,M_\odot$ (Pop. I and II)

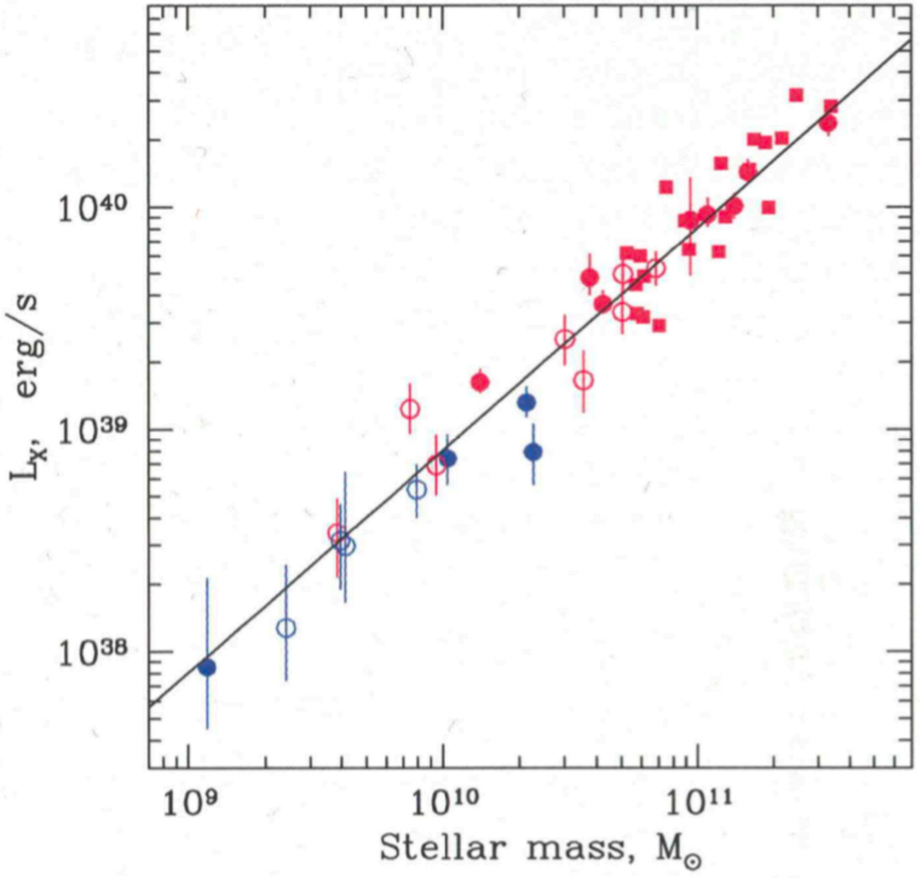
Mostly along the Galactic plane (young stellar pop.)

Galaxy center and Galactic bulge + globular clusters

HMXB vs. LMXB

- **Companion**: Be or OB supergiant *vs.* A star or later
- **Mass transfer**: winds *vs.* Roche lobe overflow
- **Orbital period**: long *vs.* hr/days





N_{HMXB}, $L_{X,\ HMXBs} \propto$ SFR

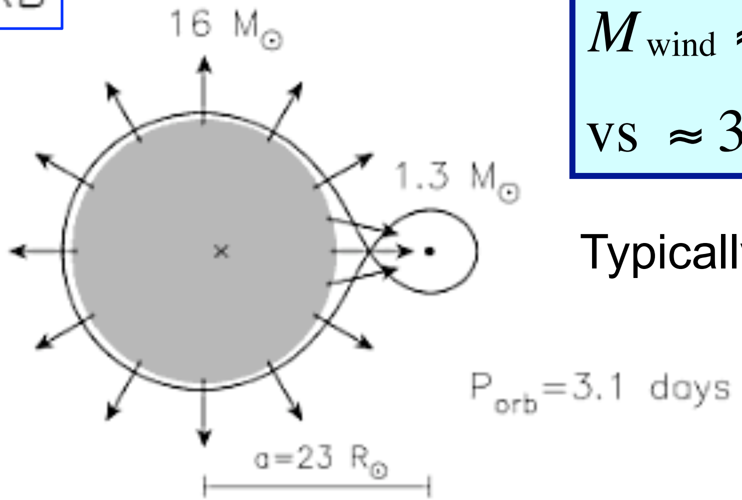
$L_{\mathrm{X,HMXB}} \approx\ 2.5 \times 10^{39} \times\ SFR\ (M_{\mathrm{Sun}}/\mathrm{yr})$

N_{LMXB}, $L_{X,\ LMXBs} \propto M_{star}$

$L_{\mathrm{X,LMXB}} \approx\ 1.0 \times 10^{39} M_{\mathrm{star}}/(10^{10} M_{\mathrm{sun}})$

Review for ISSI Space Sciences Series by Gilfanov & Merloni, 2014 (and references therein)

HMXB

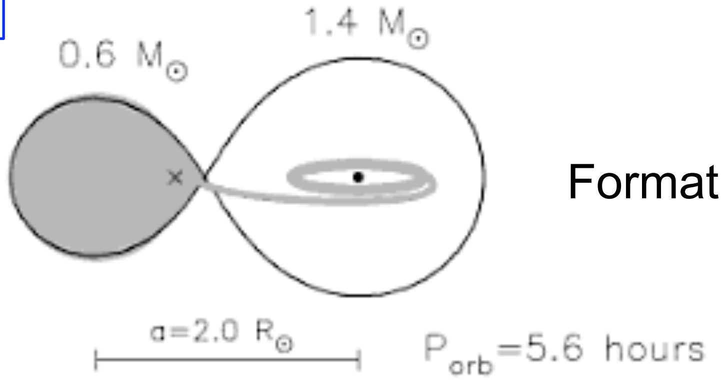


$$\dot{M}_{\rm wind} \approx 10^{-6} - 10^{-4}\ \mathrm{M}_{\rm sun}/yr$$

$$\text{vs} \approx 3\times 10^{-14}\,\mathrm{M}_{\rm sun}/yr\ (\text{Sun})$$

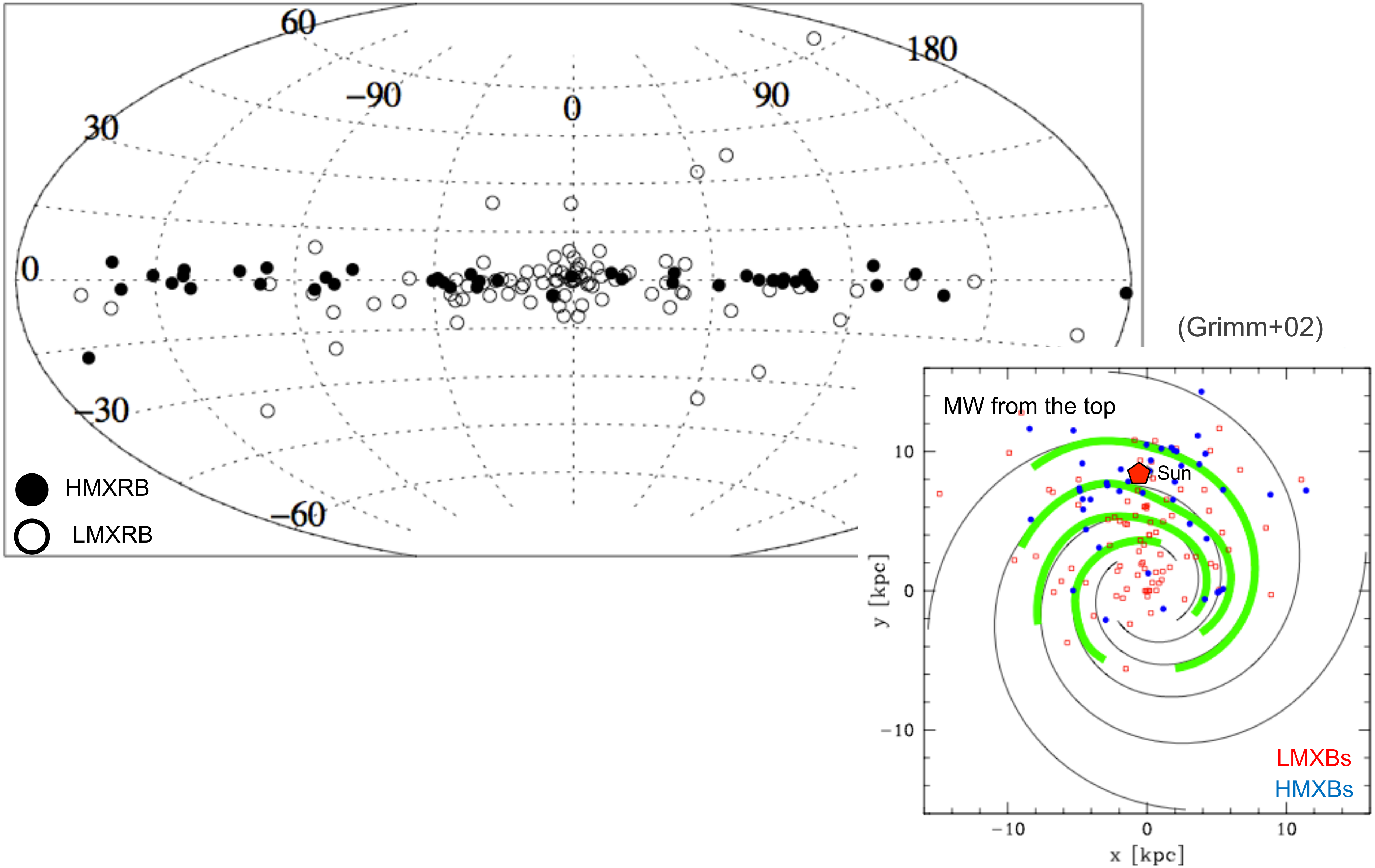
Typically, no accretion disk

LMXB



Formation of an accretion disk

Location of binary populations in the MW



(Grimm+02)

How does the magnetic field influence accretion?

$B > 10^{12}$ G

The material is funneled along the B lines down to the polar region of the NS where X-ray emitting hot spots (T up to 10^8 K) form

Pulsar phenomenon if the magnetic axis is inclined wrt. the rotational axis (50% of these have cyclotron lines) ➔ accretion-powered X-ray pulsars (≈160 so far, MW + nearby galaxies)

$B < 10^9$ G

Accretion can happen over a larger part of the NS surface, till nuclear burning flash occurs, producing an X-ray burst

X-ray activity

✧ Mass transfer rate from the donor

✧ Magnetic field of the compact star

✧ X-ray heating of the accretion disc by the “accretion luminosity”

The interplay between these three quantities explains why <u>in general</u>:

- BHs mostly in transient LMXBs
- NSs in persistent LMXBs
- Pulsars mostly in HMXBs

Recently, ms-PSRs in transient LMXBs

Accretion physics

Radiation from accreting NS mostly in X-rays: surface of the NS + accretion disc

Mostly thermal emission: bremsstrahlung + blackbody ($T>10^7$ K), but also power-law from Comptonization by hot thermal electrons (evident in the low/hard state)

High magnetic fields: cyclotron resonant scattering lines, sometimes variable throughout the phase (*pulse-phase spectroscopy* technique)

Protons falling onto the surface of NS: $v \approx 0.4c$ ➔ $E_{kin} \approx 200$ MeV

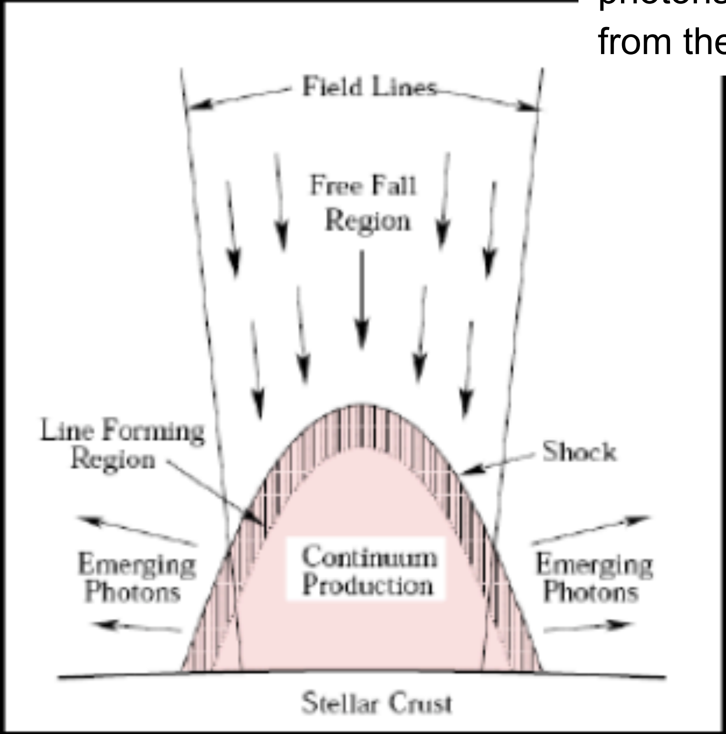
$$L_{acc} \approx \eta \frac{GM\dot{m}}{R} \approx 10^{37}\,\dot{m}_{17}\left(\frac{M}{M_{sun}}\right)\left(\frac{R}{10\ \mathrm{km}}\right)^{-1}\ \mathrm{erg/s}$$

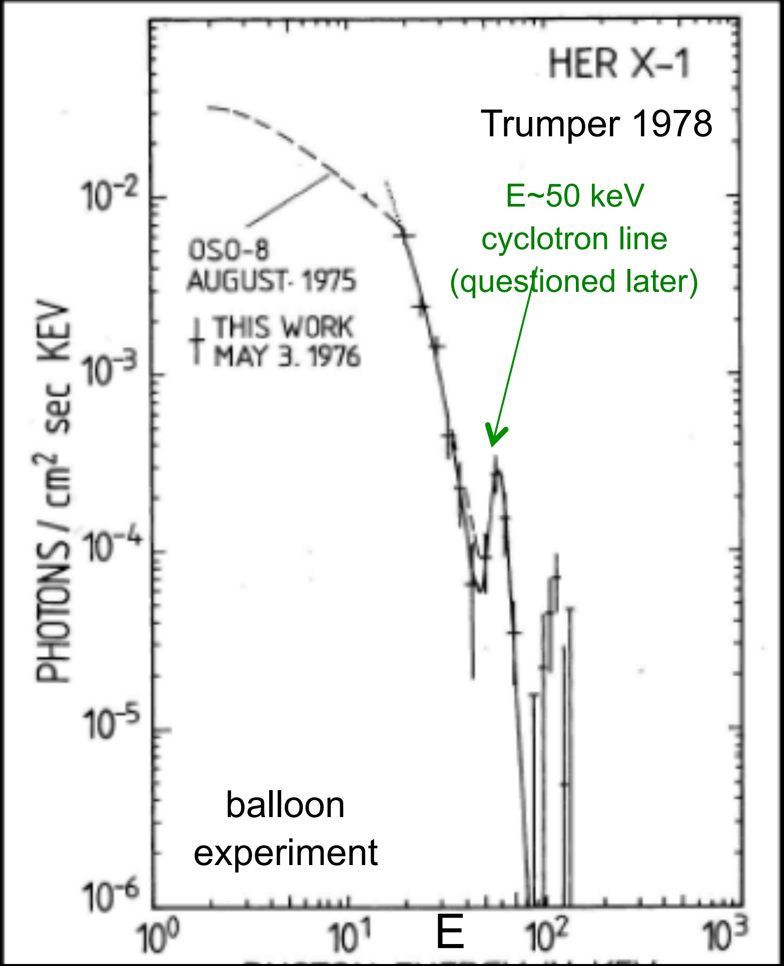
mdot= accreted mass/time
η=energy conversion factor
m_{17}=mass accretion rate in units of 10^{17} g/s

Angular momentum dissipated through the accretion disc
Low B: accretion disc possibly close to the surface of the NS
High B: truncated accretion disc ➔ the magnetic field “guides” the material towards the polar regions of the NS ➔ possible spin-up/slow-down of the NS

Cyclotron Lines

Resonant scattering of photons trying to escape from the accretion flow





Trumper 1978

E~50 keV cyclotron line (questioned later)

balloon experiment

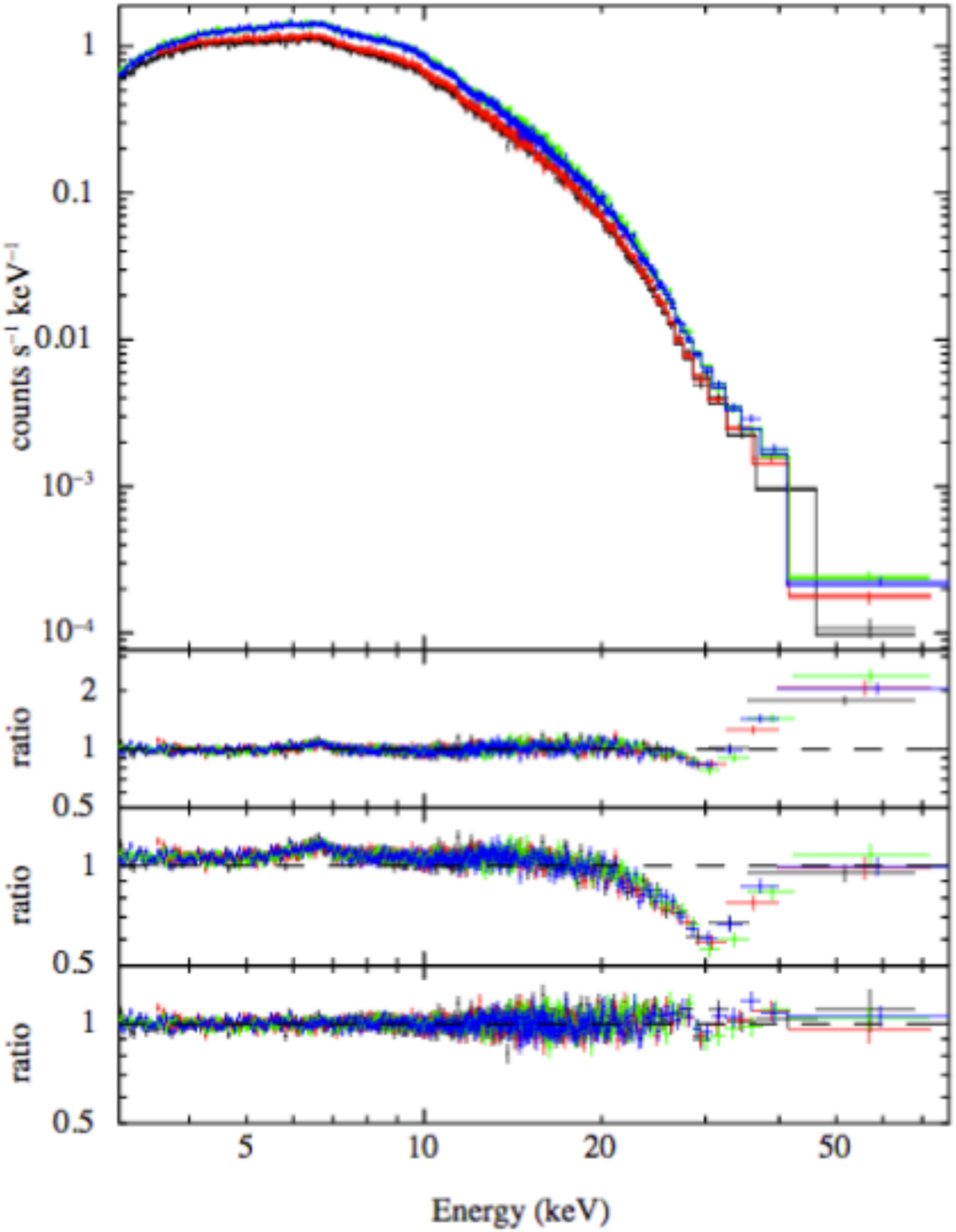
$$E_{cyc} \simeq \hbar\omega_B = \hbar\frac{eB}{m_e}$$

$$E_{\rm cyc} \approx 11.6\ \frac{B}{10^{12}\ G}\ \frac{1}{(1+z_{\rm gr})}\ \mathrm{keV}$$

Cyclotron lines: lines in magnetized accreting NS, due to resonant scattering processes with electrons. Photons undergo resonant scattering with the electrons, trapped in the dense plasma, absorbed and quasi instantly re-emitted. Those photons may escape once their energy has changed sufficiently from the resonant Landau energies.

Be binary
NuSTAR spectra
B=2×10^{14} G

One of the few lines observed in systems at $L_X > 10^{38}$ erg/s



Tendulkar+14

High-mass X-ray Binaries (HMXBs)

HMXB: main properties

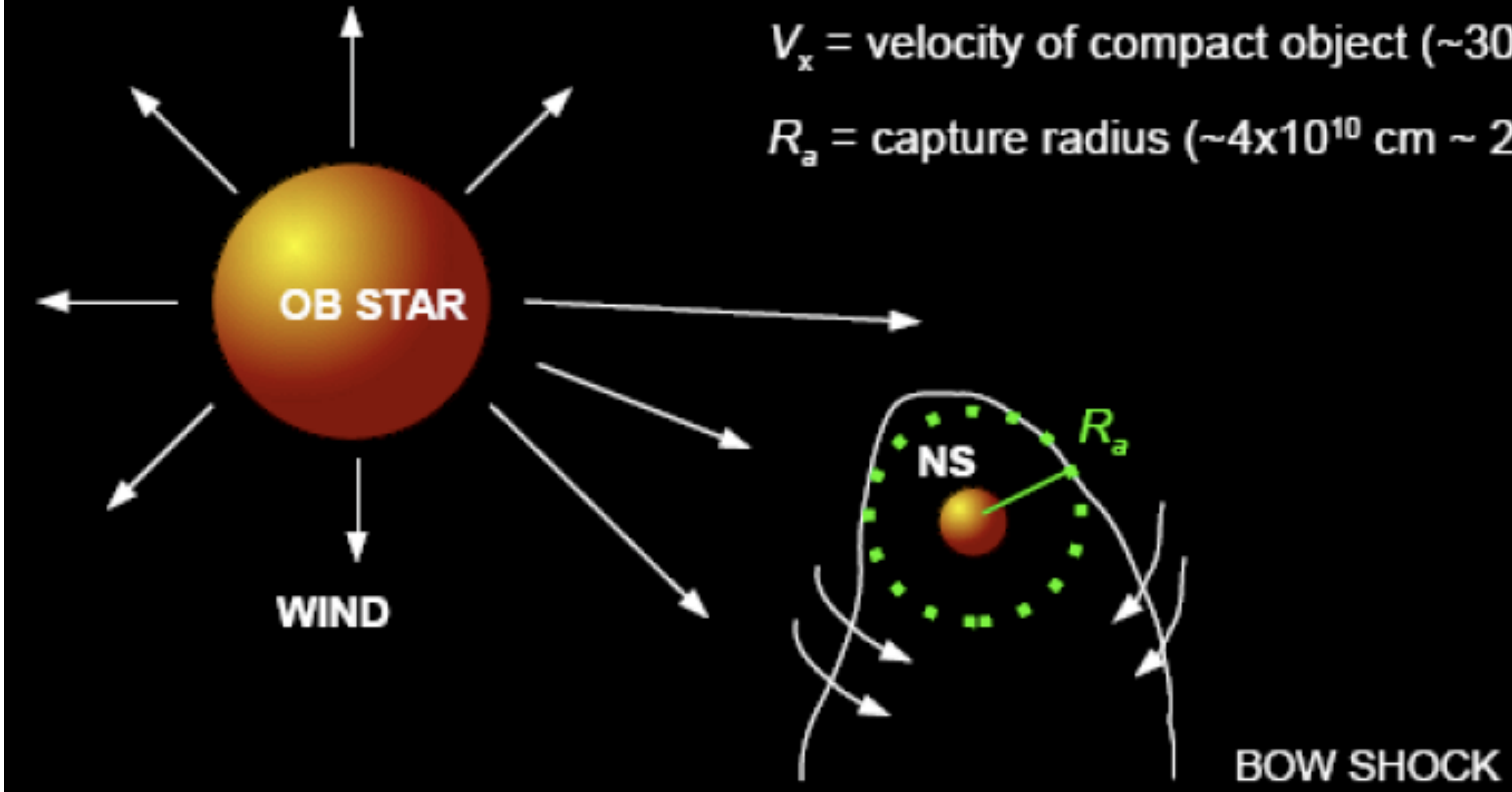
- ✓ OB supergiant: $M \geq 15\ M_{\odot}$, Be stars: $M \geq 5\ M_{\odot}$
- ✓ Accretion via an accretion disc (Be stars) or wind (OB stars)
- ✓ Mdot$\approx 10^{-5}\ M_{\odot}$/yr
- ✓ $L_x/L_{opt} \approx 1$
- ✓ ≈50% of the NS in HMXBs are highly magnetized – pulsars
- ✓ $kT \geq 15$ keV typically, hard X-ray emission
- ✓ P=4.8 hr – 187 days
- ✓ ≈4% of HMXBs have a BH as compact object

Accretion Radius: Ra

V_w = wind velocity (~1000 Km s^{-1})

V_x = velocity of compact object (~300 Km s^{-1})

R_a = capture radius (~4x10^{10} cm ~ 2-3 R_*)

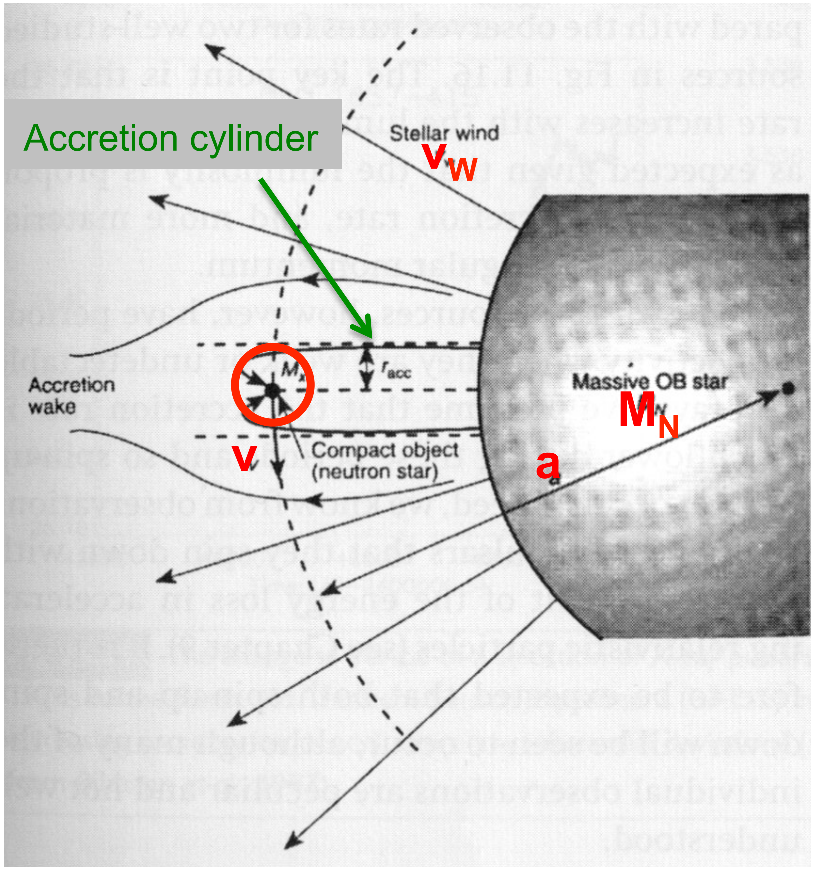


$$R_a = \frac{2\,GM_X}{V_X^2 + V_W^2} \sim \frac{2\,GM_X}{V_W^2} \sim 4\times10^{10}\ cm$$

a limited fraction of the wind as "captured"

$$\boxed{\dot{M}_{capt} / \dot{M}_w \sim 10^{-5}}$$

Accretion through the wind: Bondi-Hoyle accretion



Matter (mass=m) passing within r_{acc} (“capture” radius) from the compact object is accreted if its E_{kin}<U (potential energy) in the vicinity of the compact source (mass=M_X)

$$\boxed{\frac{1}{2}m\mathrm{v}_{\mathrm{rel}}^2 = \frac{GM_X m}{r_{\mathrm{acc}}} \longrightarrow r_{\mathrm{acc}} = \frac{2GM_X}{\mathrm{v}_{\mathrm{rel}}^2}}$$

where

$$\boxed{\mathrm{v}_{\mathrm{rel}} = \sqrt{\mathrm{v}^2 + \mathrm{v}_{\mathrm{wind}}^2}}$$

and

$$\boxed{\mathrm{v}^2 = \frac{GM_N}{a}}$$

M_N=mass of the “normal” star; a=radius of the orbit, v=velocity of the compact object

$$\boxed{\dot{M} = \pi \mathrm{r}_{\mathrm{acc}}^2 \mathrm{v}_{\mathrm{rel}} \rho}$$

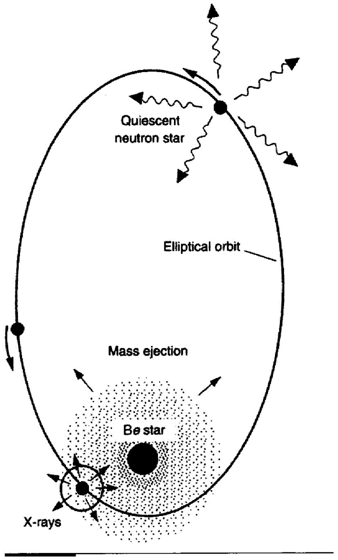
Mass accretion inside the acc. cylinder

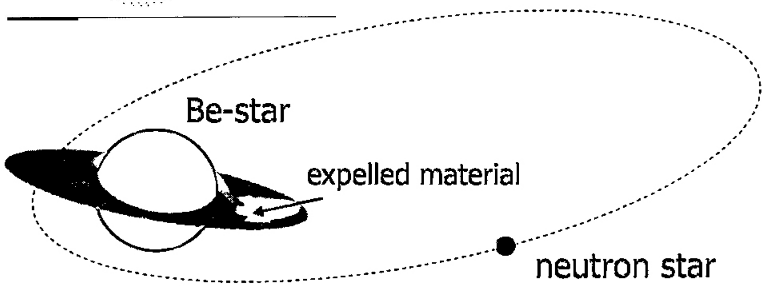
$$\boxed{\rho = \dot{M}_{\mathrm{wind}} \big/ 4\pi a^2 \mathrm{v}_{\mathrm{wind}}}$$

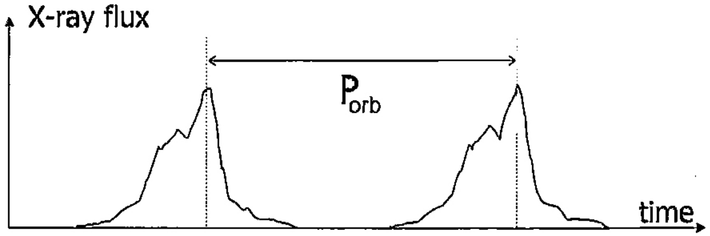
Assumption of uniform wind

$$\boxed{\frac{\dot{M}}{\dot{M}_{\mathrm{wind}}} = \left(\frac{M_X}{M_N}\right) \frac{(\mathrm{v}/\mathrm{v}_{\mathrm{wind}})^4}{[1+(\mathrm{v}/\mathrm{v}_{\mathrm{wind}})^2]^{3/2}} \approx 10^{-5} - 10^{-3}}$$

Be system (in the HMXB class)







Be star: rapidly rotating B star with Balmer lines in emission plus strong stellar wind and high mass loss rate (sometimes referred to as "active hot stars")

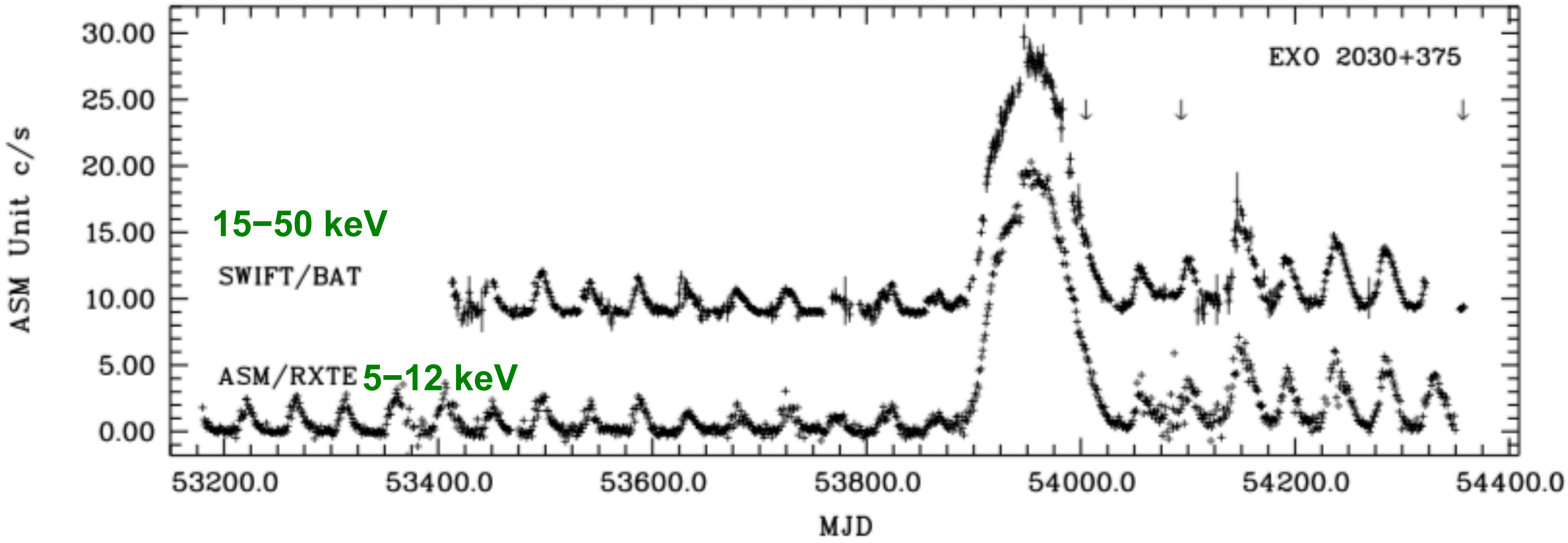
$M \approx 8-20\ M_\odot$

the NS moves in an eccentric orbit around the Be star which is not filling its Roche lobe.

Near the periastron passage, the NS accretes circumstellar matter, ejected from the rotating Be star, resulting in an X-ray burst lasting several days

Highly variable (not persistent) X-ray emission

P=46.02 days



Baykal et al. (2008)

Discovery of HMHBs

Triangular response of “old” collimators

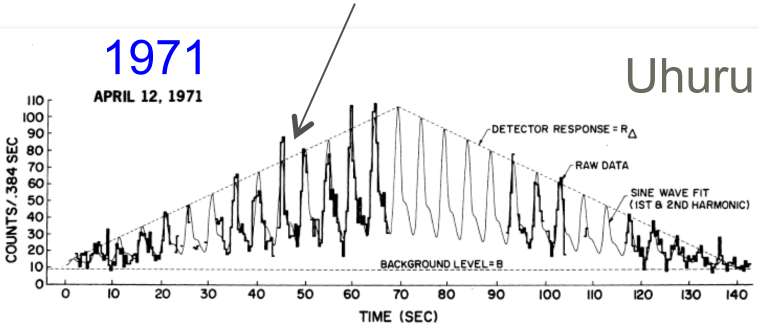


Fig. 2.—Histogram shows counts accumulated in 0.384-s intervals in the 2–6-keV energy range as a function of time on 1971 April 12. Missing portions of the data are due to quick-look transmission dropout. The spacecraft spin rate during this observation was about 0°.07 s^{-1}. The sinusoidal function fit to the data is shown as the continuous curve and is given analytically by the function $f = B + R_\Delta[A_0 \sin(\omega t + \phi_1) + A_1 \sin(2\omega t + \phi_2) + A_2 \sin(3\omega t + \phi_3) + C]$.

- Cen X-3 (Giacconi et al., 1971) *4.8 sec pulses*
- Binary nature (Schreier et al. 1972)

- Beppo*SAX*, *RXTE*, *Chandra*, XMM-*Newton*

~ a few hundred known

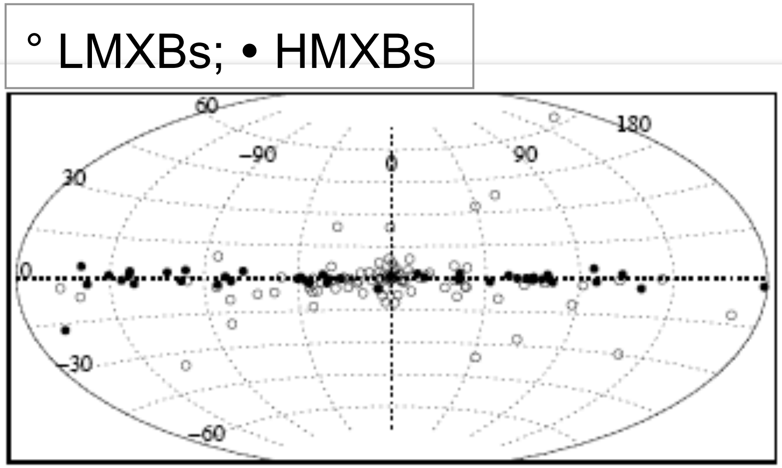
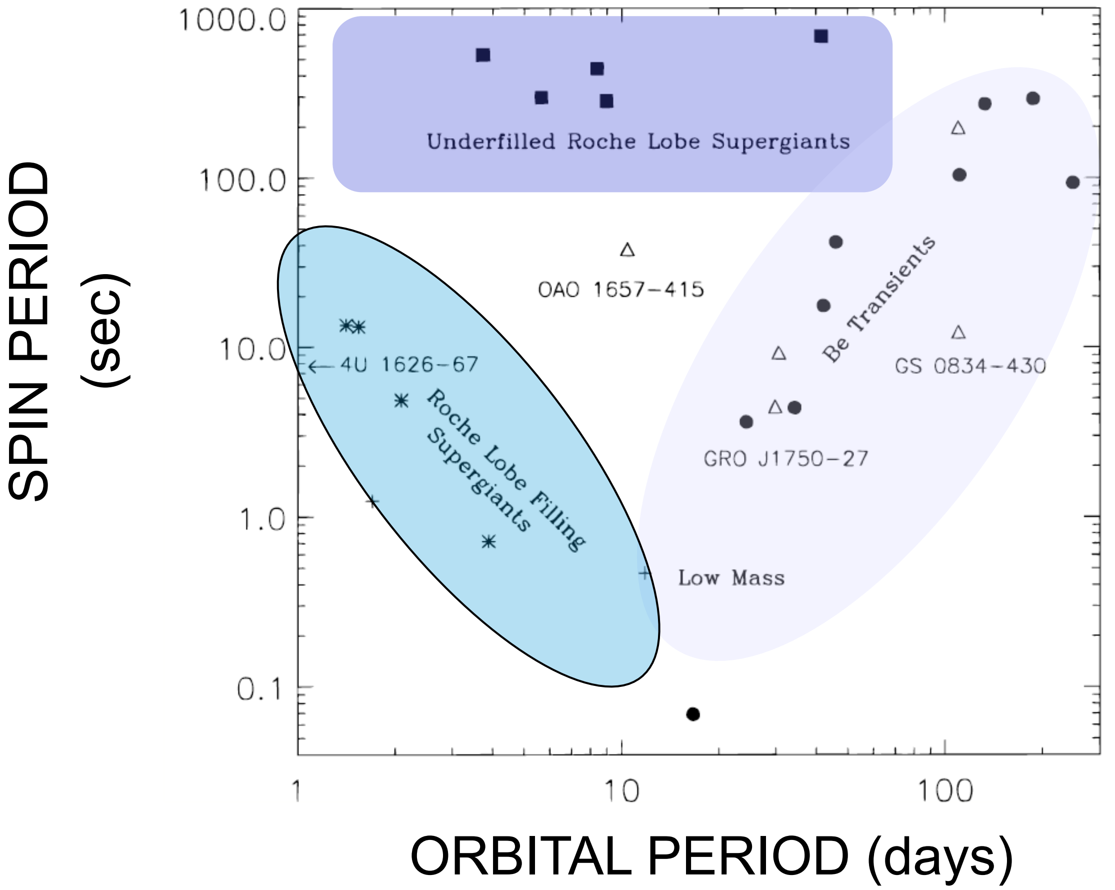


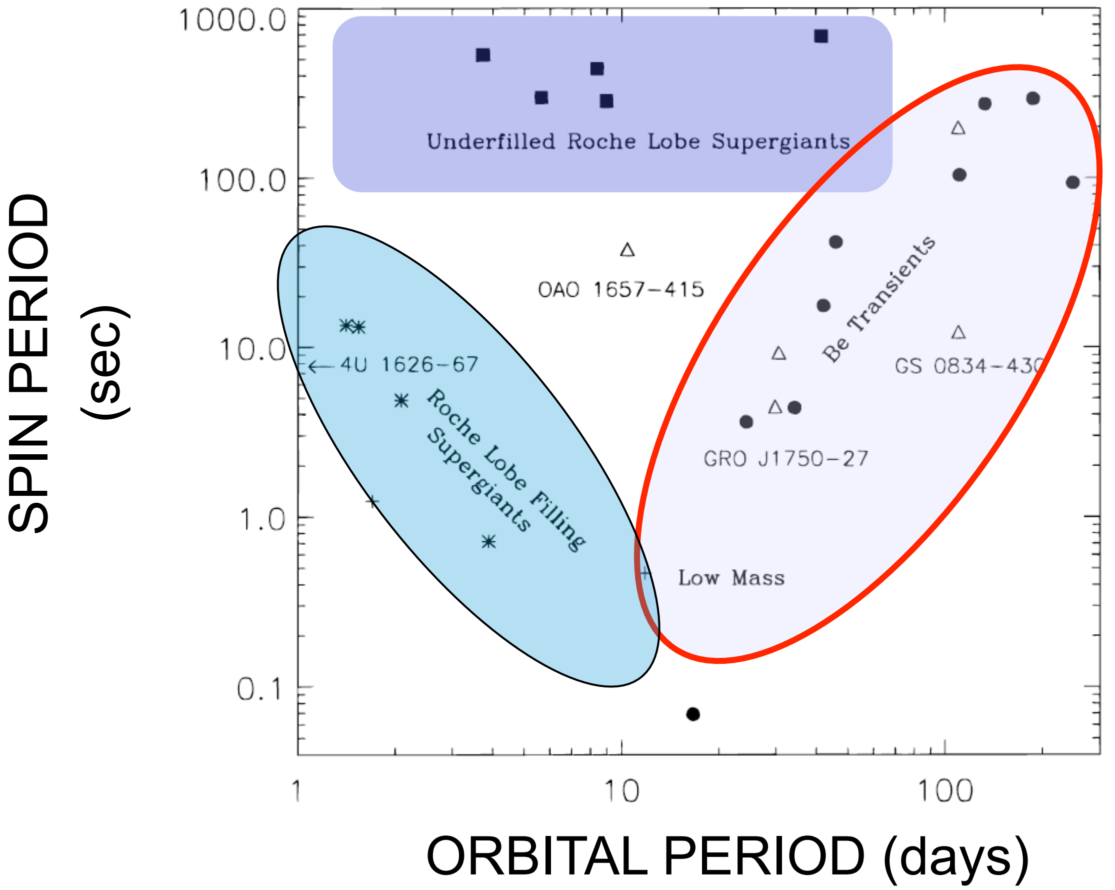
Fig. 1.1. Distribution of Low-Mass X-ray Binaries (open symbols) and High-Mass X-ray Binaries (filled symbols) in galactic coordinates (Grimm, Gilfanov & Sunyaev 2002).

The zoo of HMXBs



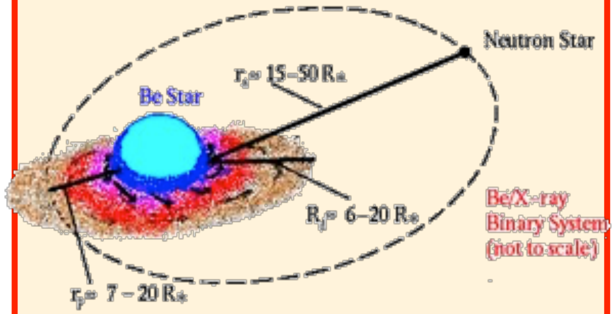
Bildsten et al. 1997

The zoo of HMXBs



Bildsten et al. 1997

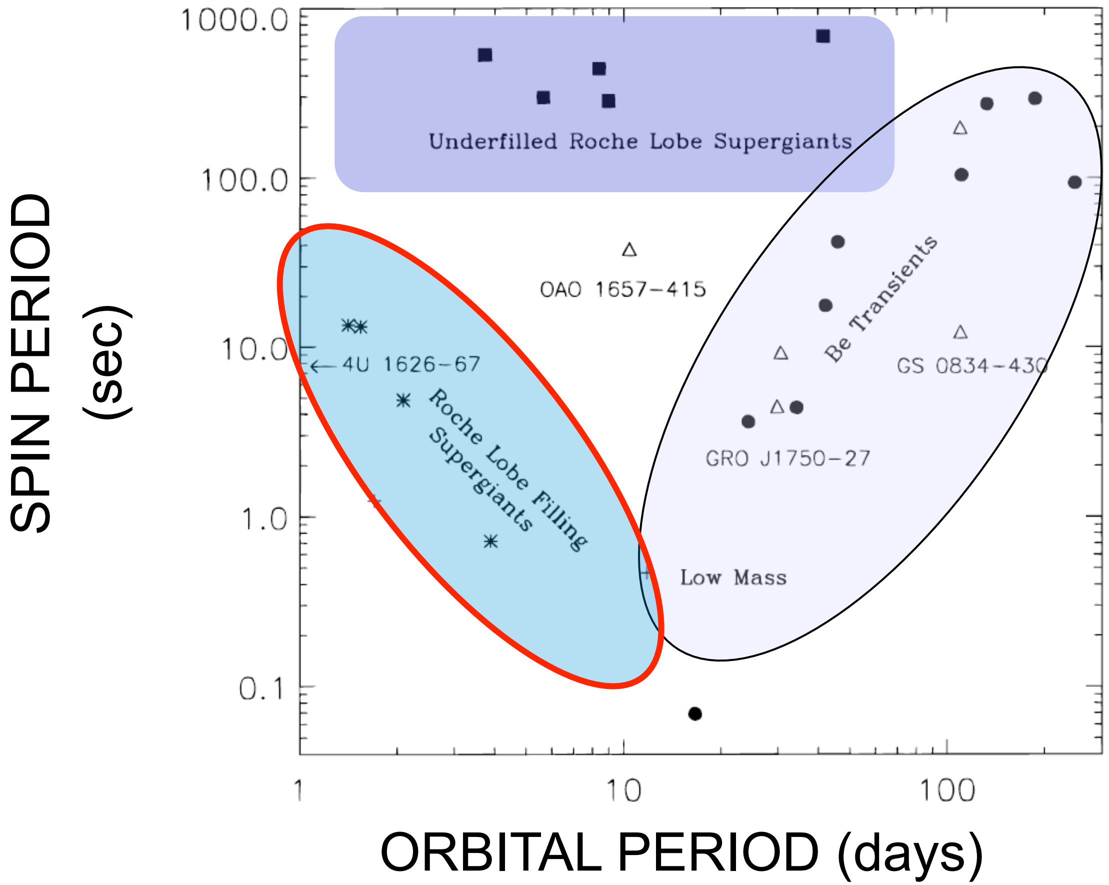
Be Transients



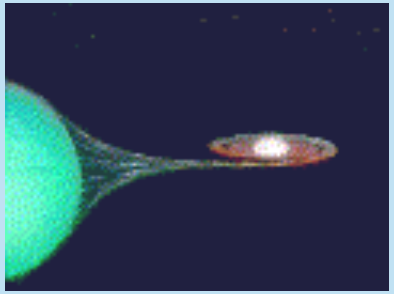
Activity at periastron

The zoo of HMXBs

Bildsten et al. 1997

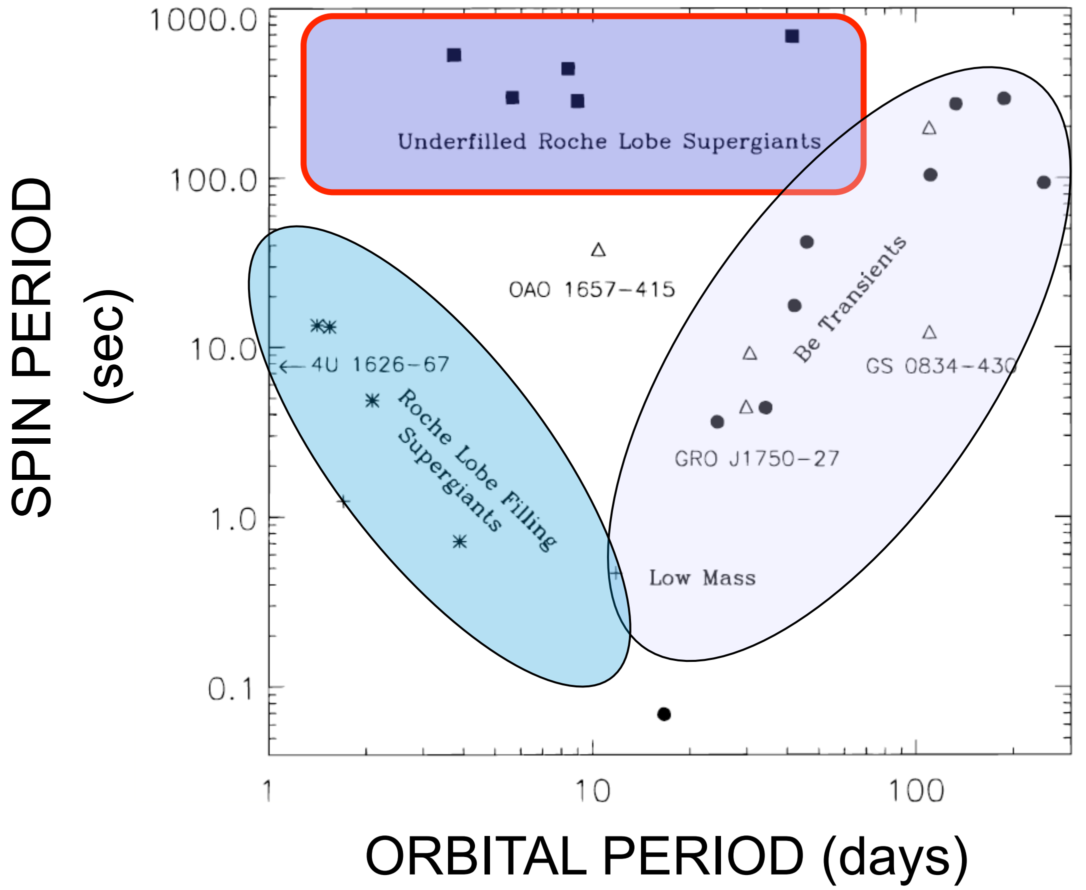


Persistent Disk-fed Systems



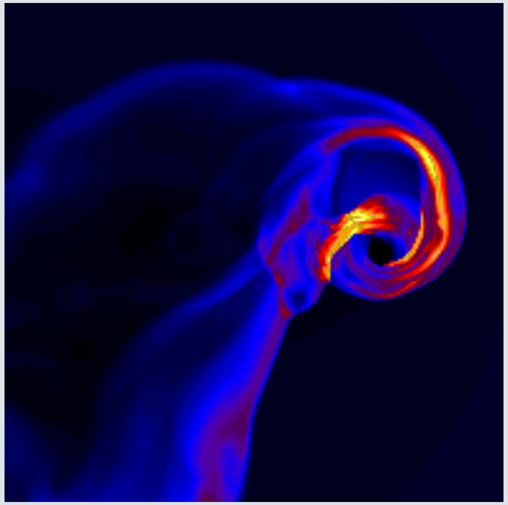
$L_X \geq 10^{37}$ erg/s

The zoo of HMXBs



Bildsten et al. 1997

Persistent Wind-fed Systems



$L_X \approx 10^{35-37}$ erg/s

X-ray pulsars: Spin periods

Definitions

Co-rotation radius: distance at which the NS rotational velocity equals the Keplerian velocity of the accretion flow

$$r_{co} = \left(\frac{G\, M_X}{\Omega_S^2} \right)^{1/3}$$

Magnetospheric radius: radius at which the ram pressure of a spherically symmetric inflow is equal to the magnetic pressure

$$\frac{B^2(r)}{8\pi} = \rho(r) \mathrm{v}_{\mathrm{in}}^2(r)$$

Spin-down/spin-up of the NS linked to the interaction between the accretion flow and the magnetic field of the NS in a boundary layer

Period at equilibrium

$$r_{co} = r_m \longrightarrow P_{eq} \propto M_X^{-2/7} L_{37}^{-3/7} R_6^{15/7} B^{6/7}$$

At equilibrium: no angular momentum is transferred

M_X=mass of the NS

L_{37}=Lx/10^{37} erg/s

R_6=radius of the NS in units of 10^6 cm; B=mag field

$$r_m < r_{co} \longrightarrow spin - up$$
$$r_m > r_{co} \longrightarrow spin - down$$

The extension of the magnetosphere (e.g., related to a decrease of the accretion rate) prevents from further accretion ➔ accretion (“centrifugal”) barrier=*propeller effect*

$$\boxed{r_m < r_{co} \rightarrow spin - up}$$

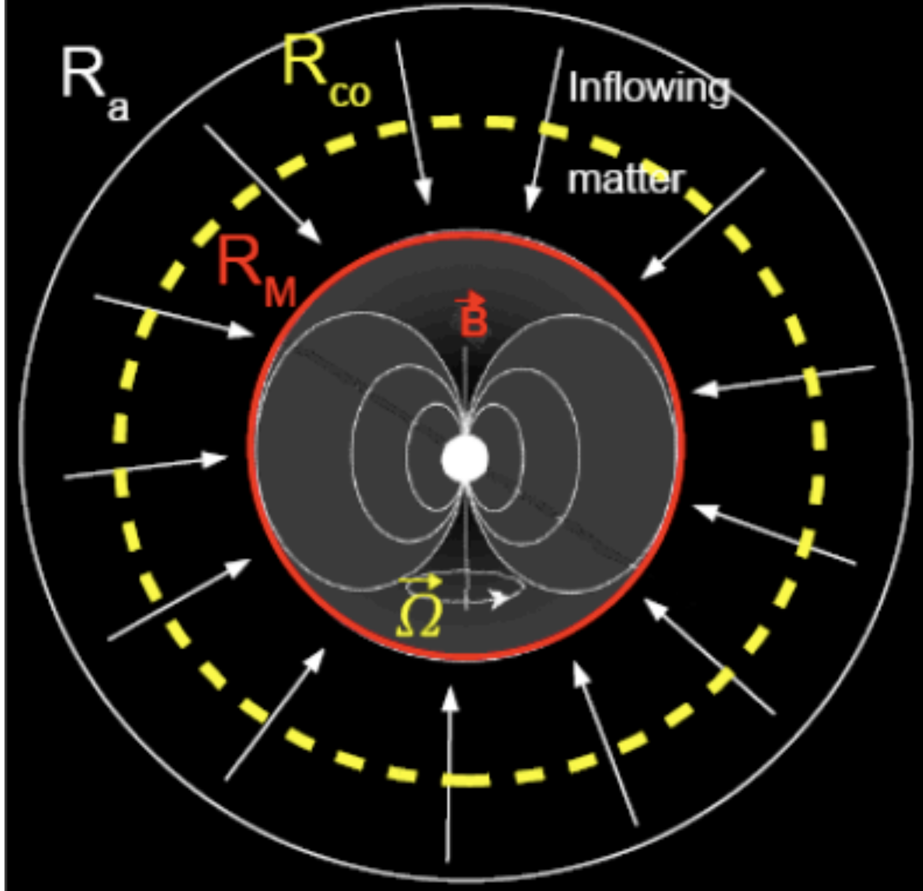
In this case, the specific angular momentum of the accreted matter is larger than that of the star, which will be spun up by the accreting flow

$$\boxed{r_m > r_{co} \rightarrow spin - down}$$

In this case, the specific angular momentum of the accreted matter is smaller than that of the star, which will be slowed down by the accreting flow (*propeller effect*)

In magnetic neutron star, at a given radius (depending on the strength of the magnetic field), the accreted matter becomes solidly linked to the magnetic field lines that are co-rotating with the neutron star

Characteristics radii



Magnetospheric Radius: r_m

$$P_{mag}(r)=\frac{B^2(r)}{8\pi}=P_{ram}(r)=\rho(r)v_{in}^2(r)$$

$$\dot{M}_{acc}=4\pi r^2\rho(r)v_{in}^2$$

$$r_m=\left(\frac{1}{2}\xi\right)^{1/2}\mu^{4/7}(2GM_X)^{1/7}\dot{M}_{acc}^{-2/7}$$

$$r_m=2.9\times10^8\mu_{30}^{4/7}m^{1/7}R_6^{-2/7}L_{37}^{-2/7}\,cm$$

Corotation Radius: r_{co}

$$r_{co}=\left(\frac{GM_X}{\Omega_s^2}\right)^{1/3}=1.5\times10^8 m^{1/3}P_s^{2/3}\,cm$$

Different relative position of these radii -> Different regimes

(Illarionov & Sunyaev 1975, Stella, White & Rosner 1986)

Higher accretion Mdot means that the magnetosphere is compressed by the increased pressure of the accreting flow ➔ the magnetospheric radius decreases and the correspondant Keplerian frequency increases

Magnetospheric radius
from balance

$$\boxed{\frac{B^2(r)}{8\pi} = \rho(r)\mathrm{v}_{\mathrm{in}}^2(r)}$$

$$\boxed{B_0 r_0^3 = B_M r_m^3 \rightarrow B_M = B = B_0 r_0^3 / r_m^3}$$

B_0=surface magnetic field
r_0=radius of the NS
r_m=magnetospheric radius

$$\boxed{\mathrm{v}_{\mathrm{in}}(r) = \mathrm{v}_{\mathrm{ff}} = \sqrt{\frac{2GM_X}{r_m}}}$$

V_{ff}= free-fall velocity

$$\boxed{\begin{aligned} &\dot{M}_{acc} = 4\pi r_m^2 \rho(r)\mathrm{v}_{\mathrm{in}}(r) \rightarrow \rho(r)\,\mathrm{v}_{\mathrm{in}}^2 = \frac{\dot{M}_{acc}\,\mathrm{v}_{\mathrm{in}}}{4\pi r_m^2} = \\ &= \frac{\dot{M}_{acc}(2GM_X/r_m)^{1/2}}{4\pi r_m^2} = \frac{\dot{M}_{acc}(2GM_X)^{1/2}}{4\pi} r_m^{-5/2} \end{aligned}}$$

Continuity equation

$$\rho(r)\ \mathrm{v}_{\mathrm{in}}^2 = \frac{\dot{M}_{acc}(2GM_X)^{1/2}}{4\pi}\, r_m^{-5/2}$$

$$\frac{B^2}{8\pi} = \frac{(B_0 r_0^3)^2}{8\pi}\,\frac{1}{r_m^6}$$

$$\Longrightarrow \frac{(B_0 r_0^3)^2}{8\pi}\,\frac{1}{r_m^6} = \frac{\dot{M}_{acc}(2GM_X)^{1/2}}{4\pi}\, r_m^{-5/2}$$

$$\rightarrow r_m \propto \left(\frac{B_0^2 R_0^6}{M_X^{1/2}\,\dot{M}_{acc}}\right)^{2/7} = B_0^{4/7} R_0^{12/7} M_X^{-1/7}\,\dot{M}_{acc}^{-2/7}$$

$$L_X = \frac{GM_X\,\dot{M}}{R_0} \rightarrow \dot{M}^{-2/7} = \left(\frac{L_X R_0}{GM_X}\right)^{-2/7}$$

$$\Longrightarrow r_m \propto B_0^{4/7} R_0^{10/7} M_X^{1/7} L_X^{-2/7}$$

Co-rotation radius:

distance at which the NS rotation velocity matches the Keplerian one: $E_{centr}=E_{grav}$

$$\Omega^2 R = \frac{GM}{R^2} \rightarrow R^3 = r_{co}^3 = \frac{GM}{\Omega^2} \rightarrow r_{co} = \left(\frac{GM}{\Omega^2}\right)^{1/3}$$

$$\Omega = \frac{2\pi}{P} \quad \Rightarrow \quad r_{co} \propto M_X^{1/3} P^{2/3}$$

$$r_m = r_{co} \rightarrow B_0^{4/7} R_0^{10/7} M_X^{1/7} L_X^{-2/7} = M_X^{1/3} P^{2/3}$$

$$\rightarrow P_{eq} \propto (B_0^{4/7} R_0^{10/7} M_X^{1/7} L_X^{-2/7} M_X^{-1/3})^{3/2} \propto M_X^{-2/7} L_X^{-3/7}$$

Period at
the equilibrium

Low-mass X-ray Binaries (LMXBs)

LMXB: main properties

✓ A to M stars, typically $M \lesssim 2\ M_\odot$

✓ Mass transfer through Roche lobe overflow, feeding an optically thick accretion disc (AD), mostly emitting in the X-ray band

✓ $L_x/L_{opt} \approx 100$-1000, except for the ADC (AD corona, ≈20), hiding the X-ray source

✓ Heating of the companion is important

✓ Less likely to observe eclipses, often dips (l.o.s. intercepted by the accr. stream)

✓ Mdot$\approx 10^{-8 \div -10}\ M_\odot$/yr

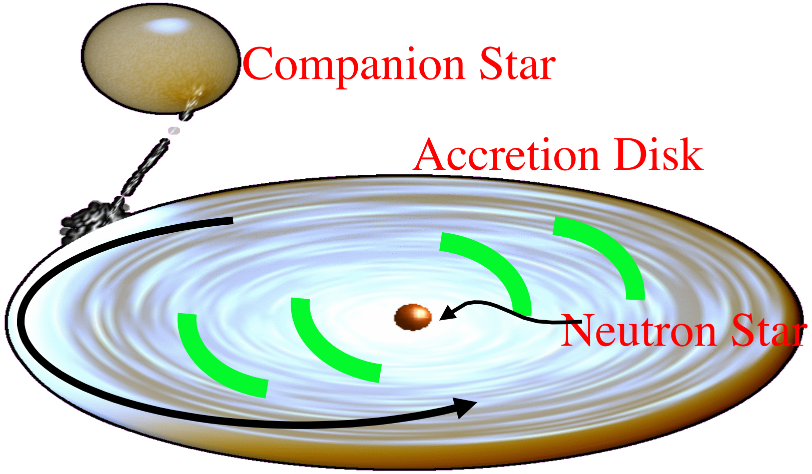
✓ P≈0.19 hr – 17 days

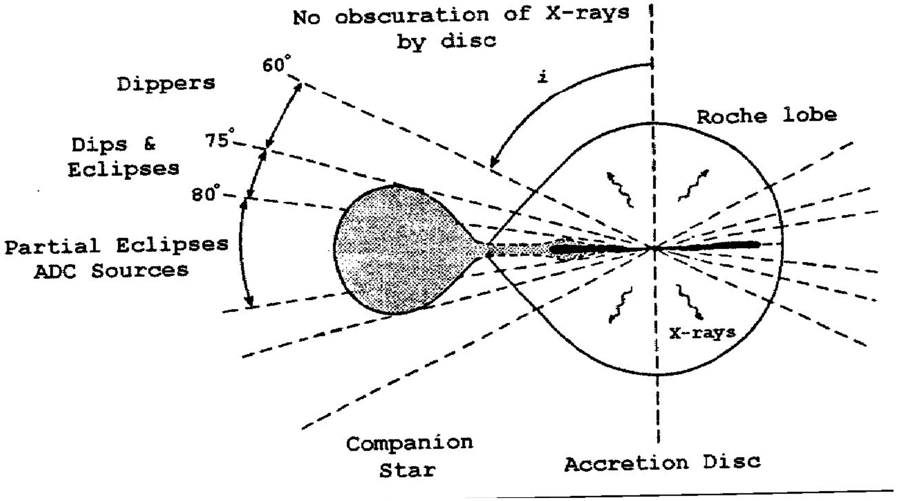
✓ ≈20% BH candidates

✓ NS in LMXBs weakly magnetized ($B \lesssim 10^{10}$ G) ➔ not PSR, rather bursters and QPOs

✓½ LMXBs are transients, soft + hard components

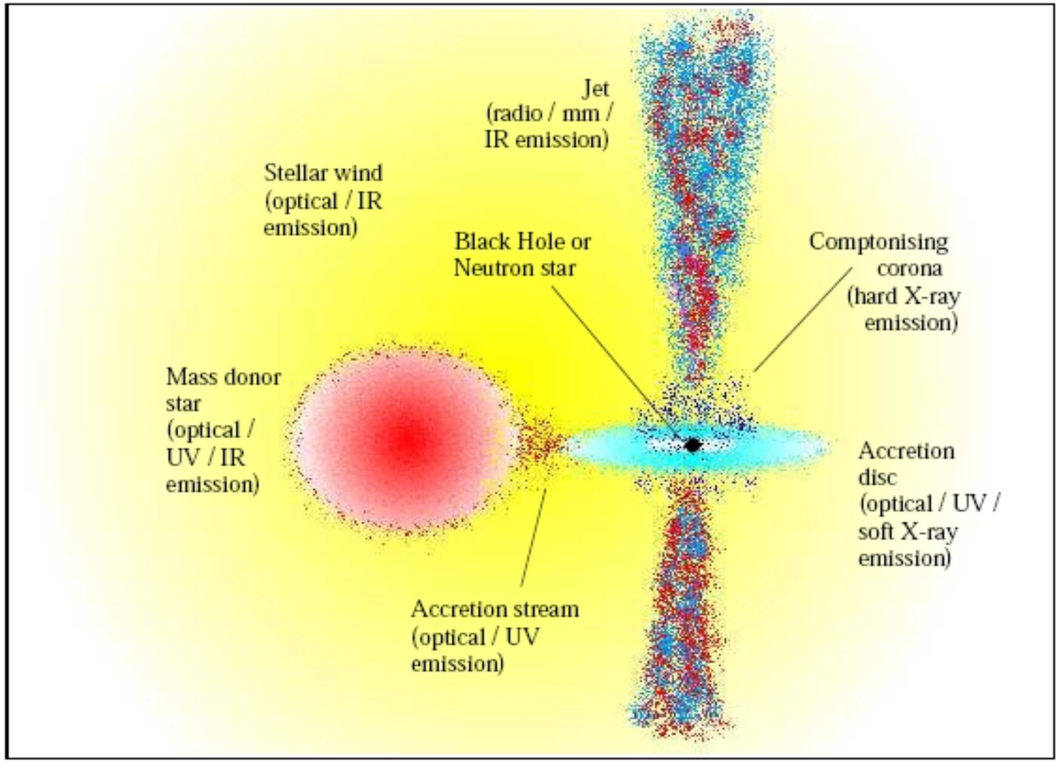
Low-mass X-ray binaries (LMXBs)





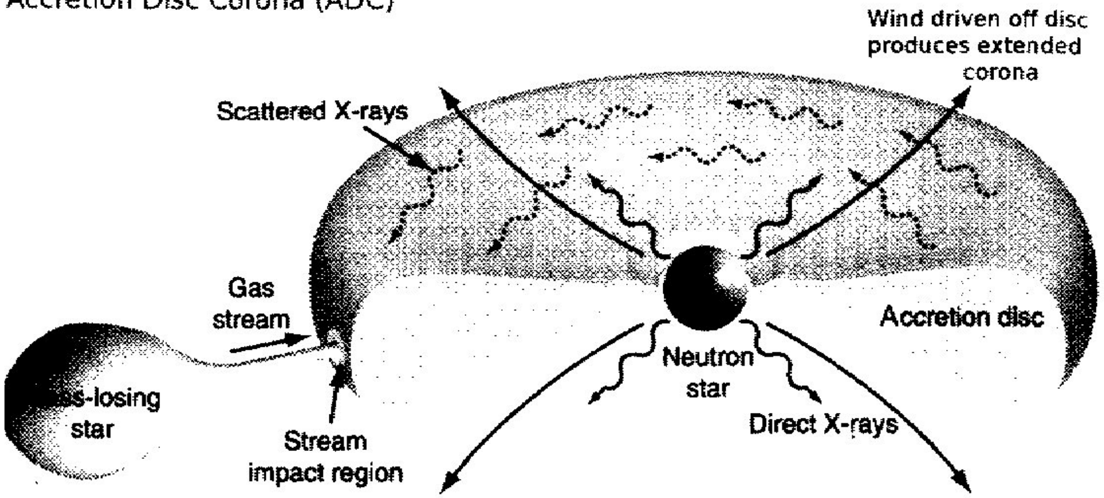
Possible obscuration from the companion star:
Dips and Eclipses (observed in X-rays)
Dips from the edge of the accretion disk where the gas stream from the companions star hits the disk

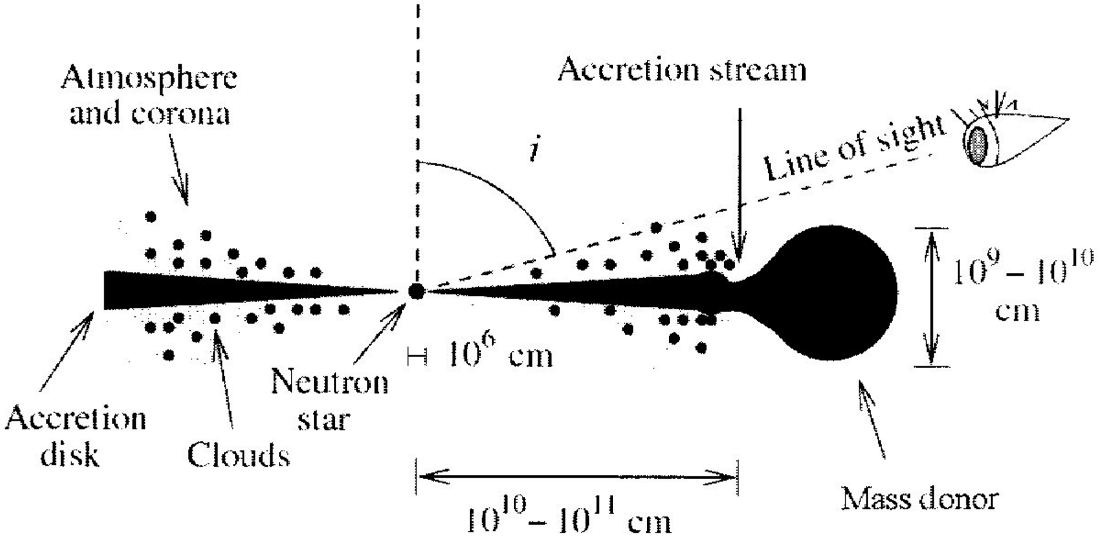
LMXBs: emission processes



- Accretion disc → black body (thermal)
- Corona → Comptonization
- Reflection → reflected emission by the accretion disk
- Jet? → non-thermal emission (synchrotron emission)

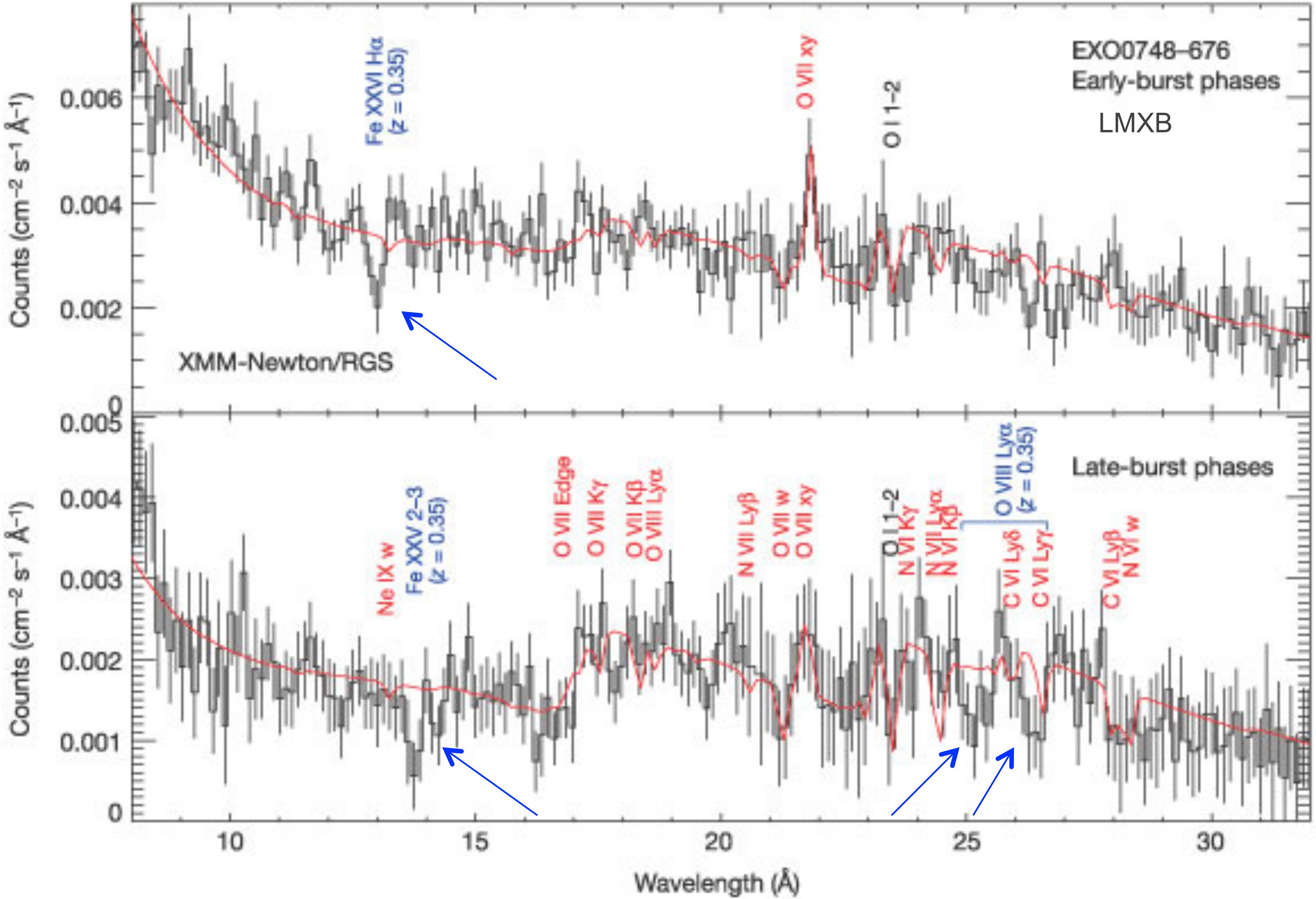
Accretion Disc Corona (ADC)





Cottam et al. (2002, Nature)

Strong gravitational redshifts



Gravitational redshift of spectral lines of a NS during a burst - photosphere lines

$$1+z_{gr} = \left(1-\frac{2GM}{c^{2}R}\right)^{-1/2}$$

LMXB as weakly magnetized systems

✓ $B \approx 10^{8-10}$ Gauss, A to M stars, typically $M \leq 2\ M_{\odot}$

✓ Atoll vs. Z sources: classification based on a color diagram (CD)

Atoll sources

- $L_x < 10^{37}$ erg/s typically
- Low-frequency QPOs
- Low mass accr. rate ($< 0.1\ M_{dot,\ Edd}$)

Z sources

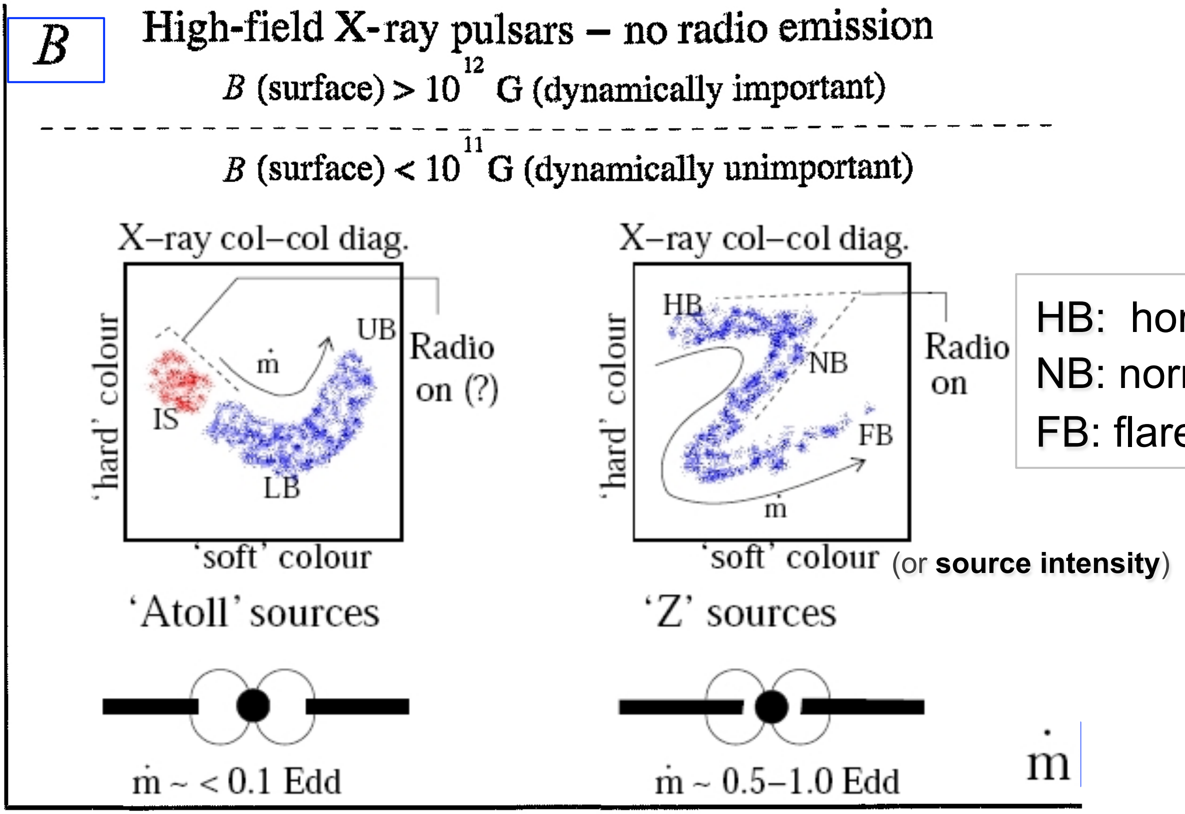
- $L_x > 10^{37}$ erg/s typically
- They often show QPOs
- Slightly higher B (10^{9-10} G)
- Higher accretion rate
- Longer P
- All seem to have jets

Atoll vs. Z sources (LMXBs)

IS: island state
LB: lower banana
UB: upper banana

Soft color=
(3−5 keV)/(1−3 keV)

Hard color=
(6.5−18 keV)/(5−6.5 keV)



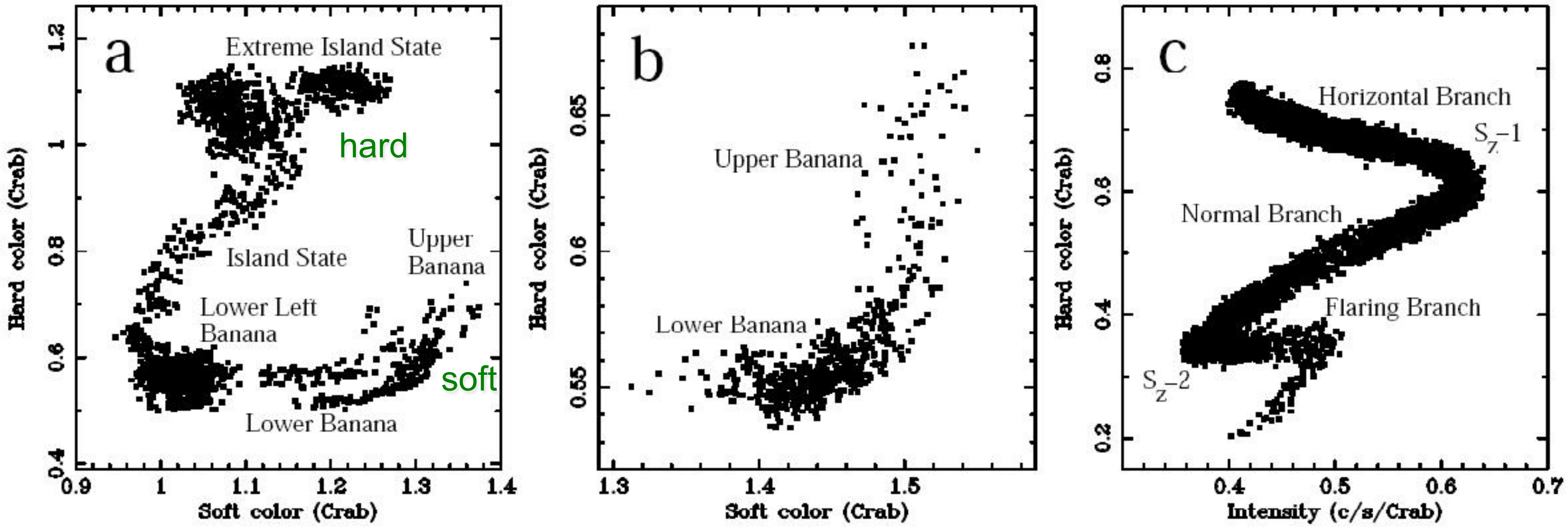
HB: horizontal branch
NB: normal branch
FB: flare branch

X-ray color changes related to changes in the accretion rate, affecting the source X-ray luminosity and variability

Insights into the color-color diagrams

twin kHz-QPOs in LLB
IS isolated because of duration
and observational windowing

kHz-QPOs and HBOs occur in HB and upper NB

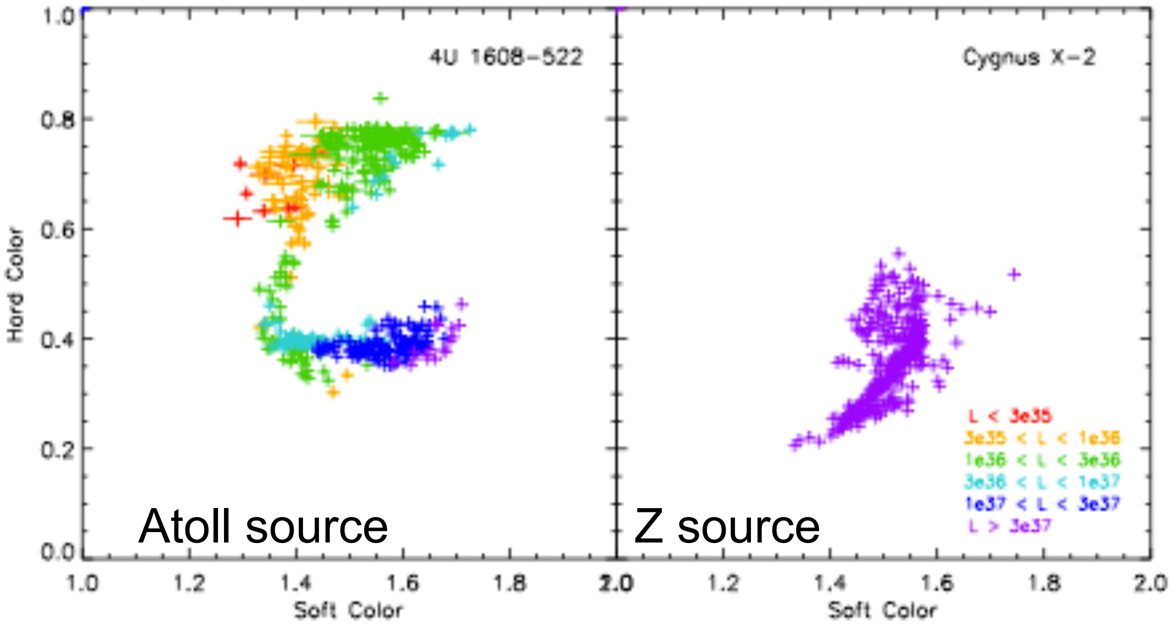


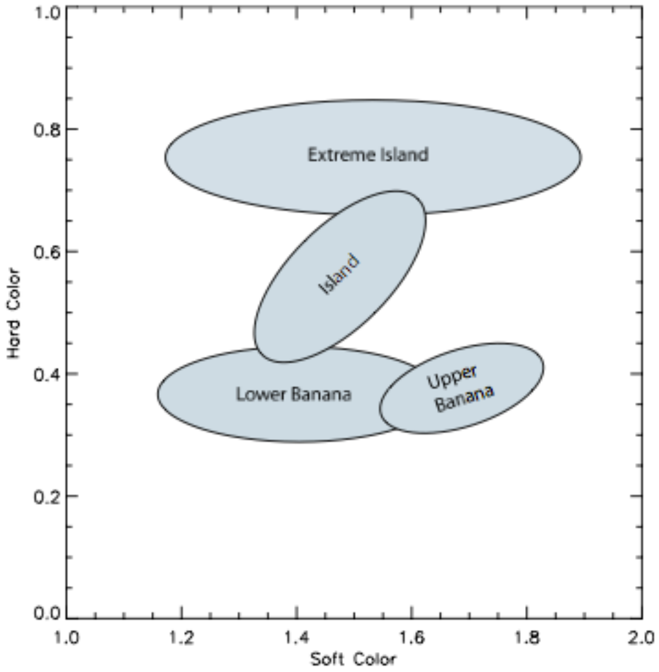
L/L_{Edd} ≈0.01

≈0.1 L/L_{Edd}

Van der Klis (2006)

Soft color=(3-5 keV)/(1-3 keV)
Hard color=(6.5-18 keV)/(5-6.5 keV)





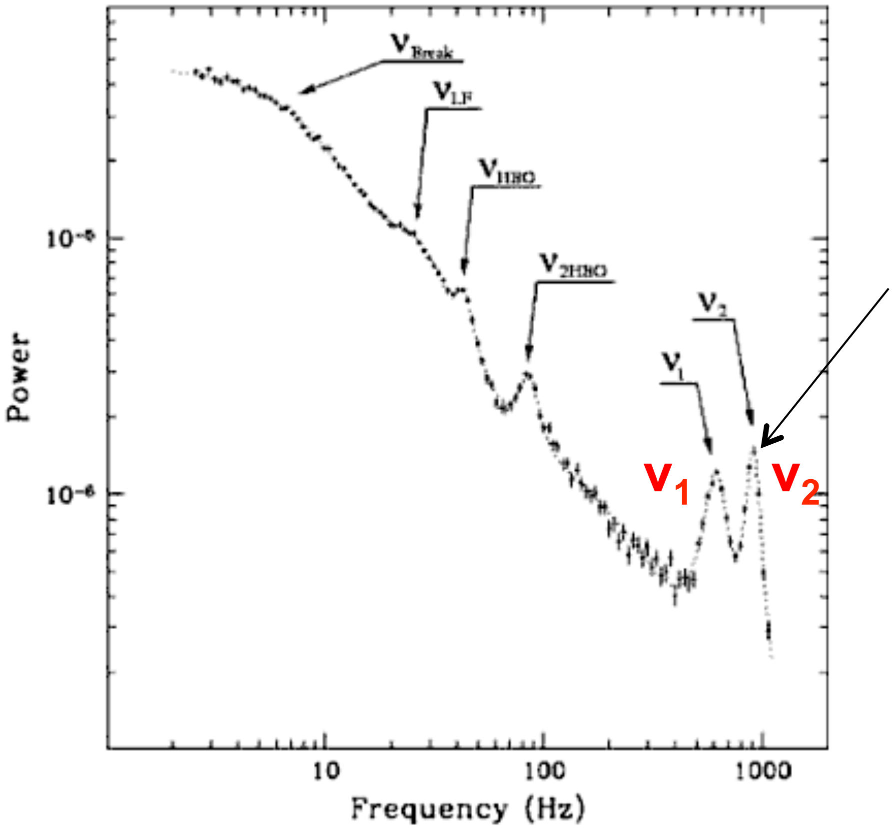
The same source passes through different “states” according to its accretion rate

Not easy to distinguish sometimes…

Quasi periodic oscillations (QPOs)

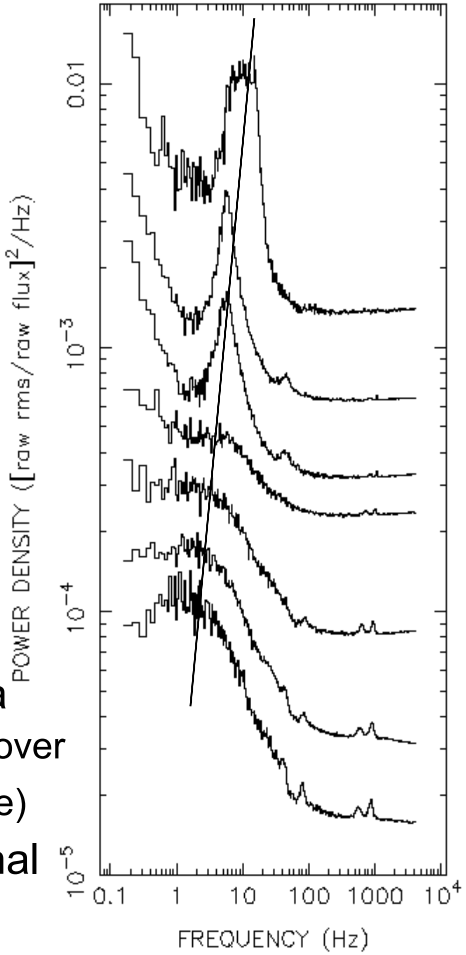
Quasi periodic oscillations: observations (I)

Frequency of the peaks increases with the accretion rate (i.e., X-ray flux).
If two peaks are present, their separation stays nearly constant



kHz QPOs

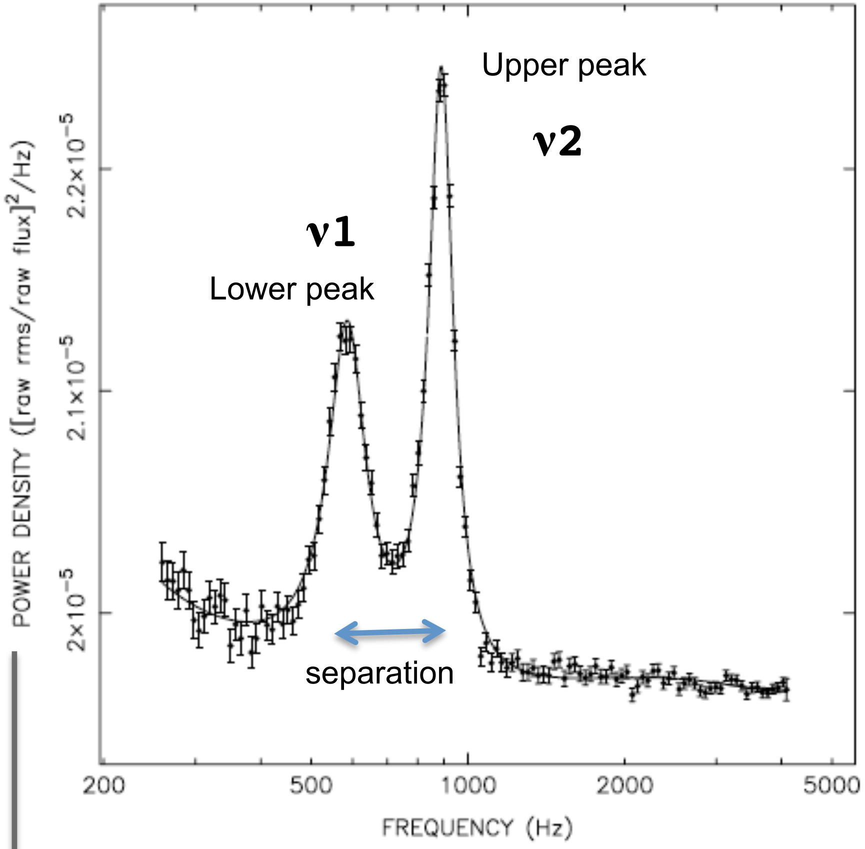
QPOs: peaks in the Fourier variability power density spectra
(which describes how the power of a signal or time series is distributed over the different frequencies, i.e., at which frequencies variations are large)
kHz QPOs: correspond to frequencies close to few gravitational radii



Sco X-1
Van der Klis

Quasi periodic oscillations: observations (II)

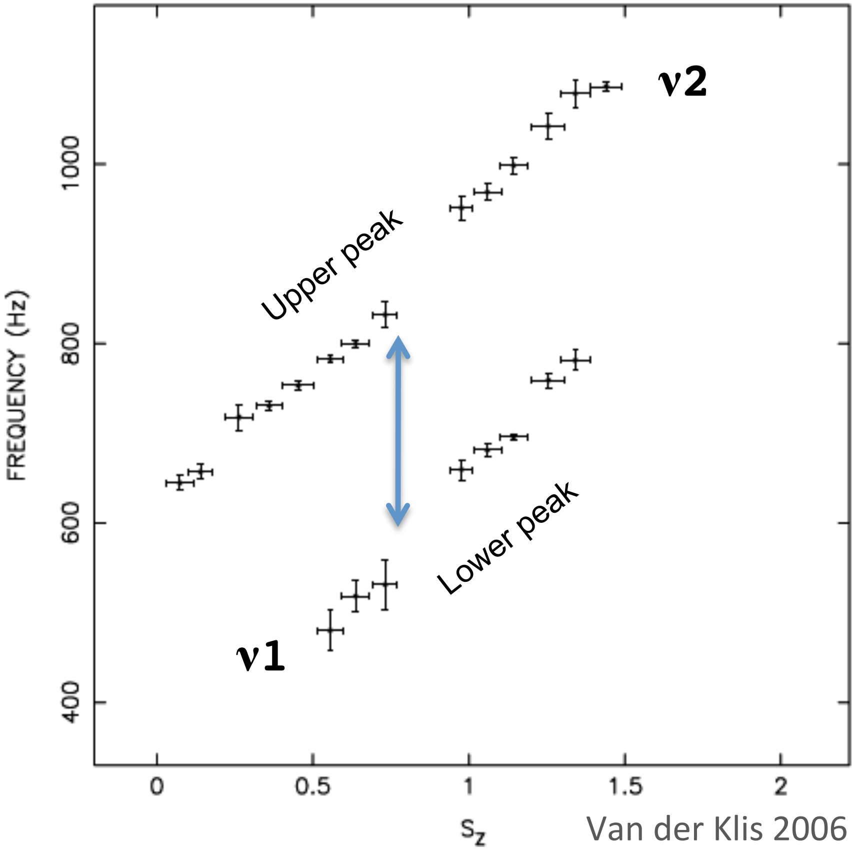
Power Spectrum



Frequency

Power mostly at particular frequencies

Flux



Van der Klis 2006

~accretion rate

Separation ≠ constant may be explained by clumps approaching to the NS

Quasi periodic oscillations: some theory (I)

$$\boxed{\upsilon_{orb} \approx 1200 \text{ Hz } (r_{orb}/15 \text{ km})^{-3/2} m_{1.4}^{1/2}}$$

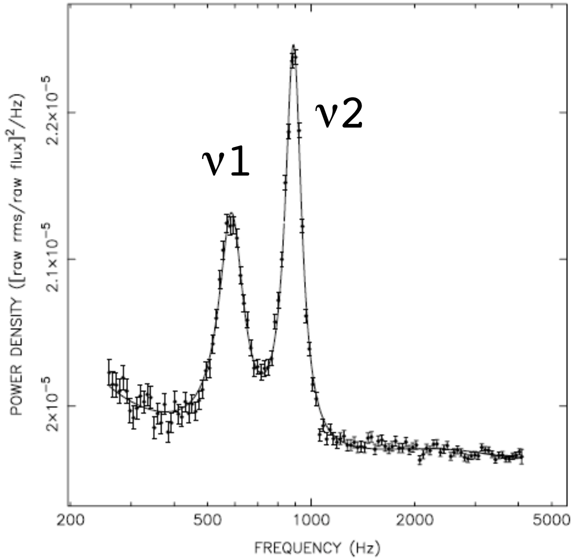
Orbital frequency around a NS: Keplerian frequency at the inner edge of the disc in most models

$m_{1.4}$=NS mass in units of 1.4 $M_\odot$

$$\boxed{R_{ISCO} = 3R_S = 6R_G = 6GM/c^2 \approx 12.5 \; m_{1.4} \text{ km}}$$

Maximum frequency corresponding to **I**nnermost **S**table **C**ircular **O**rbit (ISCO)

$$\Rightarrow \boxed{\upsilon_{ISCO} = 1580 \text{ Hz}/m_{1.4}}$$



Spin-orbit beat-frequency model (II)

$$\nu_2 = \nu_{orb}$$

$$\nu_1 = \nu_{beat}$$

ν_2: frequency of Keplerian rotation of material at the inner edge of the accretion disk

$$\nu_1 = \nu_{beat} = \nu_2 - \nu_{spin}$$

ν_{spin}: spin frequency of the NS

ν_{beat} is the frequency at which a given particle orbiting in the disc overtakes a given point on the spinning star

Expected (and often observed) that the spin frequency is constant (≈300 Hz)

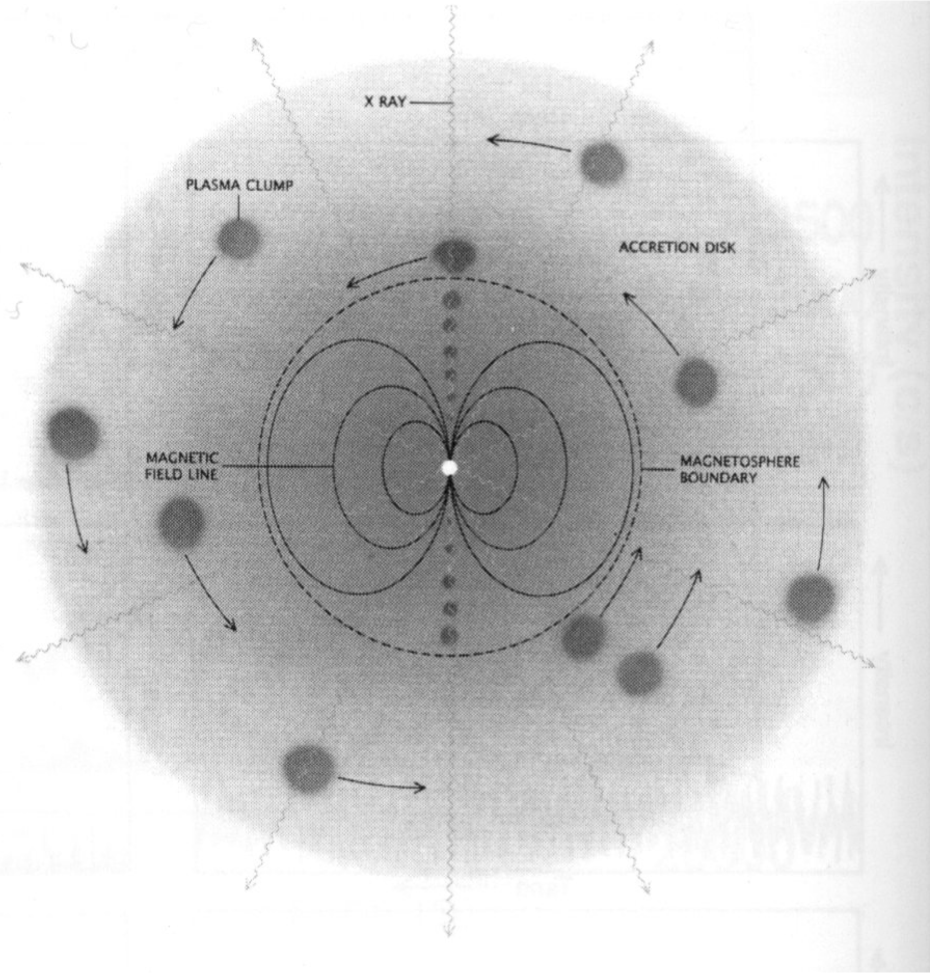
Sometimes: $\Delta\nu=\nu_{spin}/2$

Sonic-point beat-frequency model: the preferred orbital radius is identified with the inner edge of the accretion disc

Underlying idea: “clumps” of material can enter the magnetosphere preferentially at certain points (e.g., near the magnetic poles) ➔ favourable situation when the *beat frequency* ranges between the frequency of Kepler rotation and that of the NS (spin)

Spin-orbit beat-frequency model (III)

Basic principle of most of the current models explaining QPOs: plasma motion in a strong-field region, with the disk being the most plausible “cause”

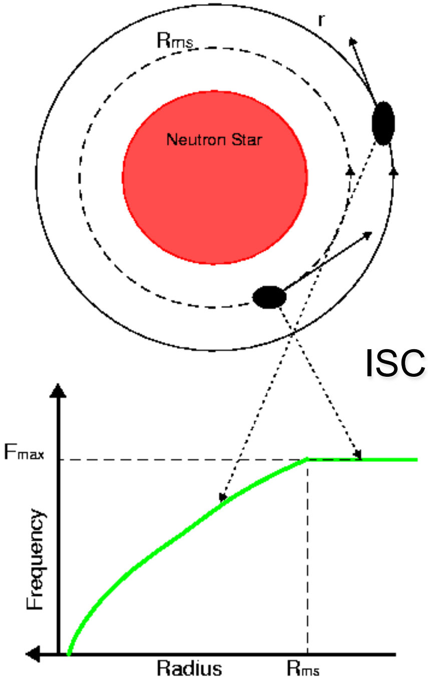


Clumps of matter (plasma) falling onto the compact object at a preferred frequency ν_{beat}

Accretion of plasma clumps when a clump is over the pole of the NS. This occurs at a frequency which is the difference between the orbital period of the inner disc and the NS’ spin frequency

Hints of kHz-QPO models (IV)

- Beat-frequency model (Strohmayer et al. 1996; Miller et al. 1998)
- Resonance model (Abramowicz et al. 2003)
- Relativistic precession model (Stella & Vietri 1999)
- Alfven wave oscillation model (Zhang 2004; Li & Zhang 2005)



ISCO saturation

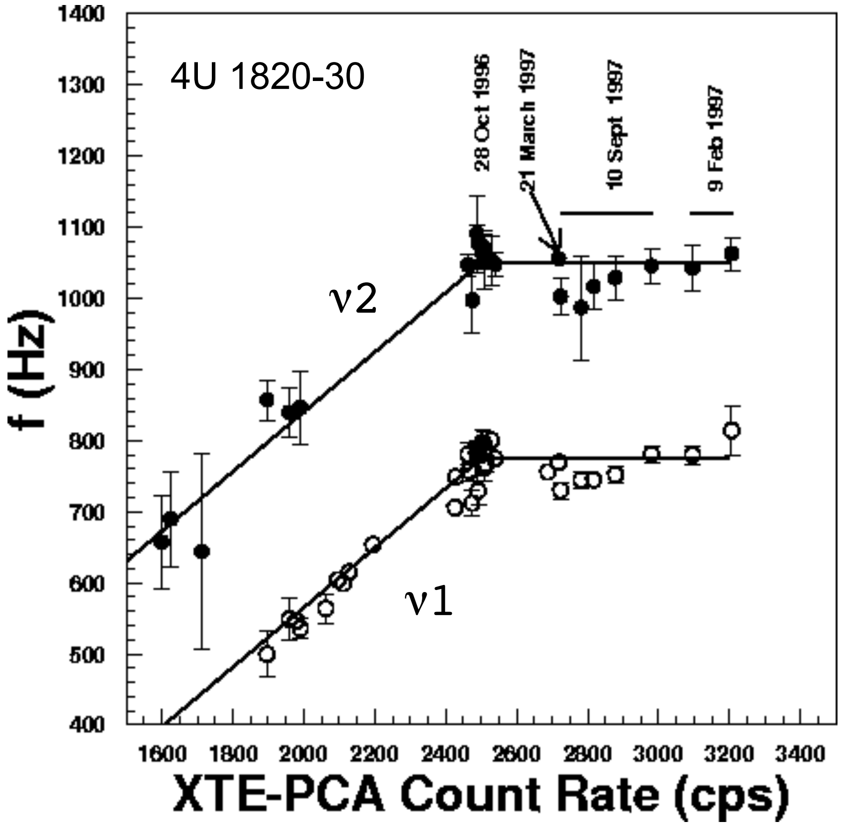
Einstein's General Relativity: Perihelion precession

$v_2 = v_{kepler}$ at some point of the disc

$v_1 = v_{precession} = v_2 [1 – (1 – 3Rs/r)^{1/2}]$

$\Delta v = v_2 - v_1$ is not constant

Saturation of frequency of kHz-QPOs? (V)



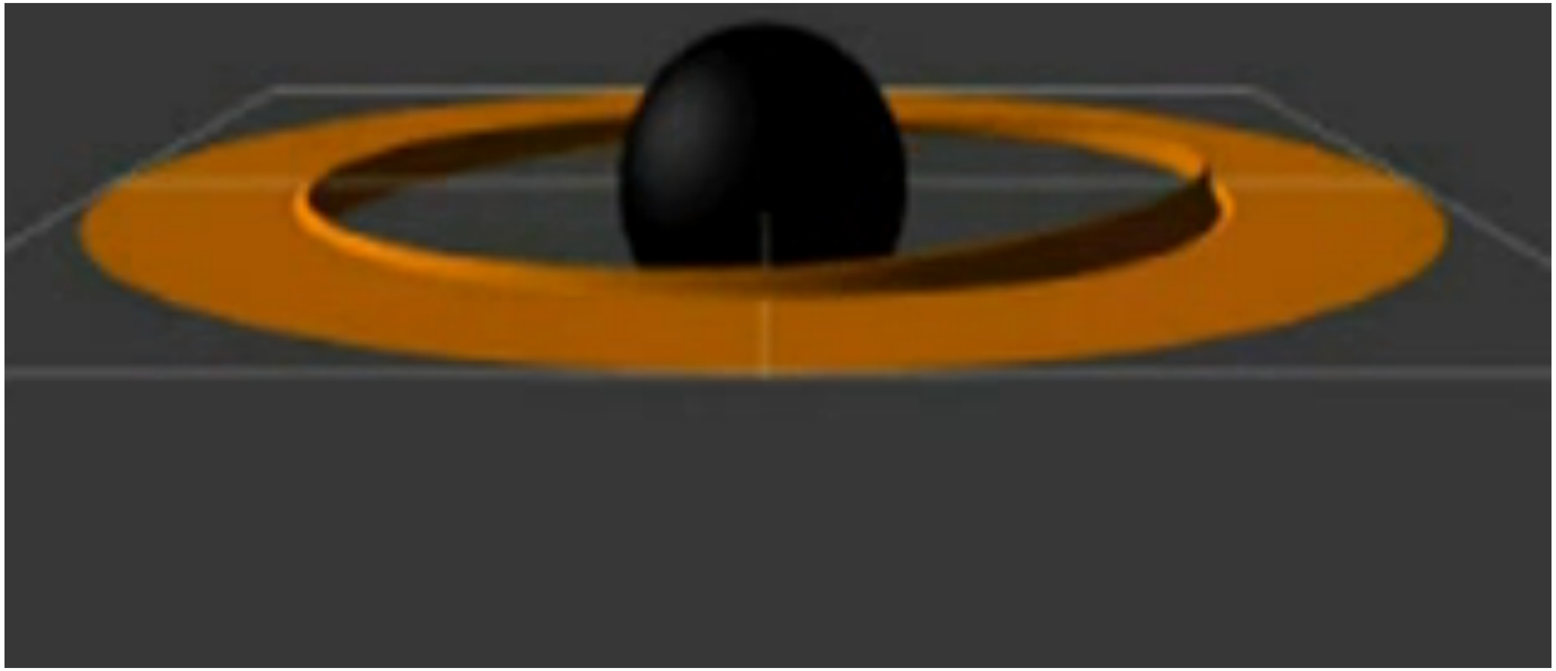
Zhang et al. 1998; Van der Klis et al. 2000

Anything to do with the "limit"
of the NS surface?
Marginally stable orbit?
Probably yes

Low-frequency QPO: ν_{HBO}

Less-clear origin: Lense-Thirring precession of the inner disc around the rotational axis of the NS? Strong-gravity effect

Theory (1918) predicts that the orbital plane of a test particle in a non-equatorial orbit precesses around the body' symmetry axis



Evolution of HMXBs and LMXBs

In external galaxies, their integrated X-ray emission is used as a proxy of star-formation and mass assembly histories of the galaxies (but the presence of the AGN – if any – should be taken under control)

HMXB evolution

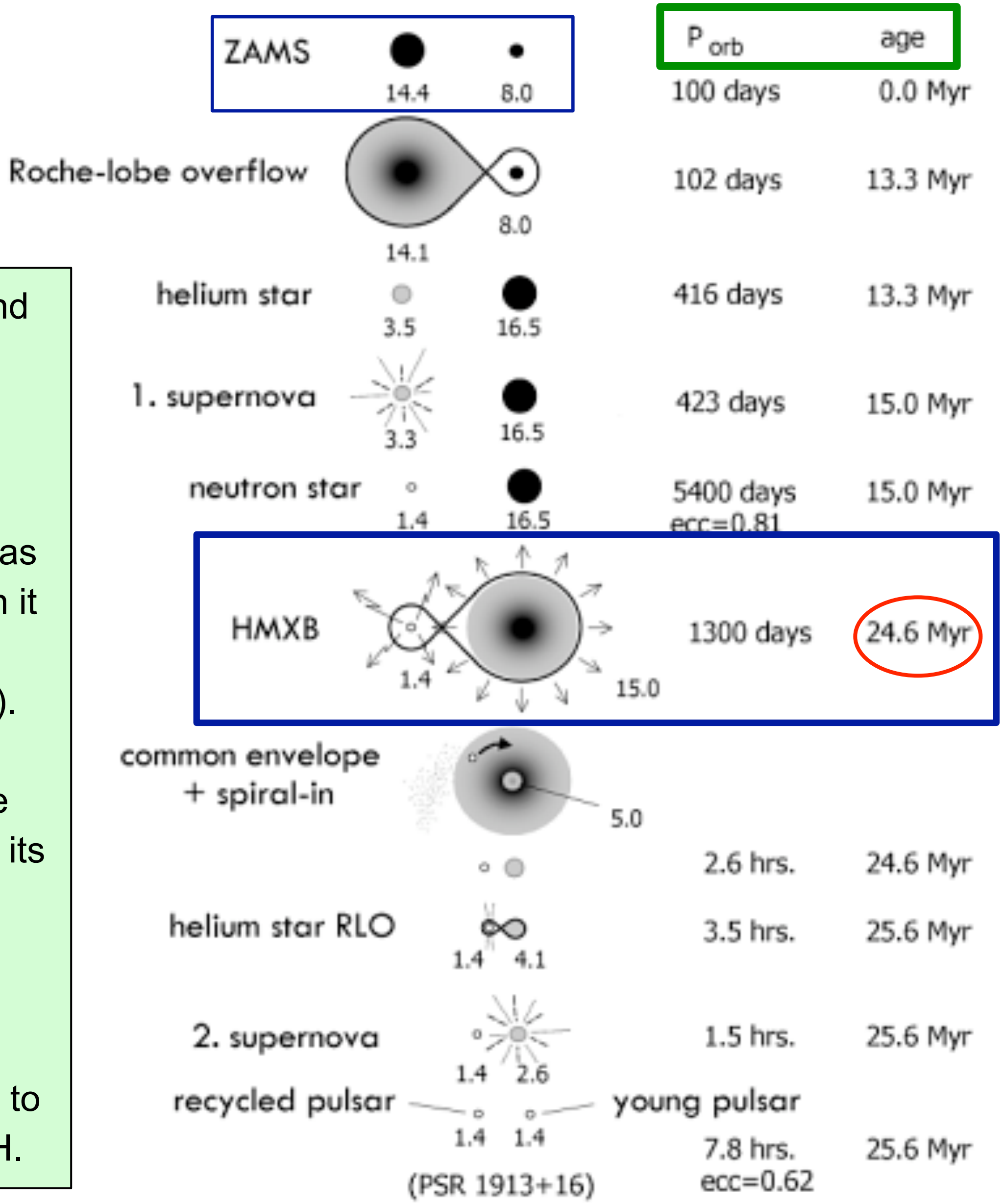
The more massive star reaches the end of its life first, exploding as a SN and leaving a NS or a BH.

The explosion can disrupt the binary system, but if the star that exploded was less massive than its companion when it exploded, the system may survive (maybe leaving a more eccentric orbit).

The companion star then comes to the end of its life and forms a giant, losing its outer layers onto the compact object.

➔ HMXB phase

Eventually, the companion star comes to the end of its life, leaving a NS or a BH.



Integrated emission from **HMXBs** as a **star-formation rate indicator** in external galaxies

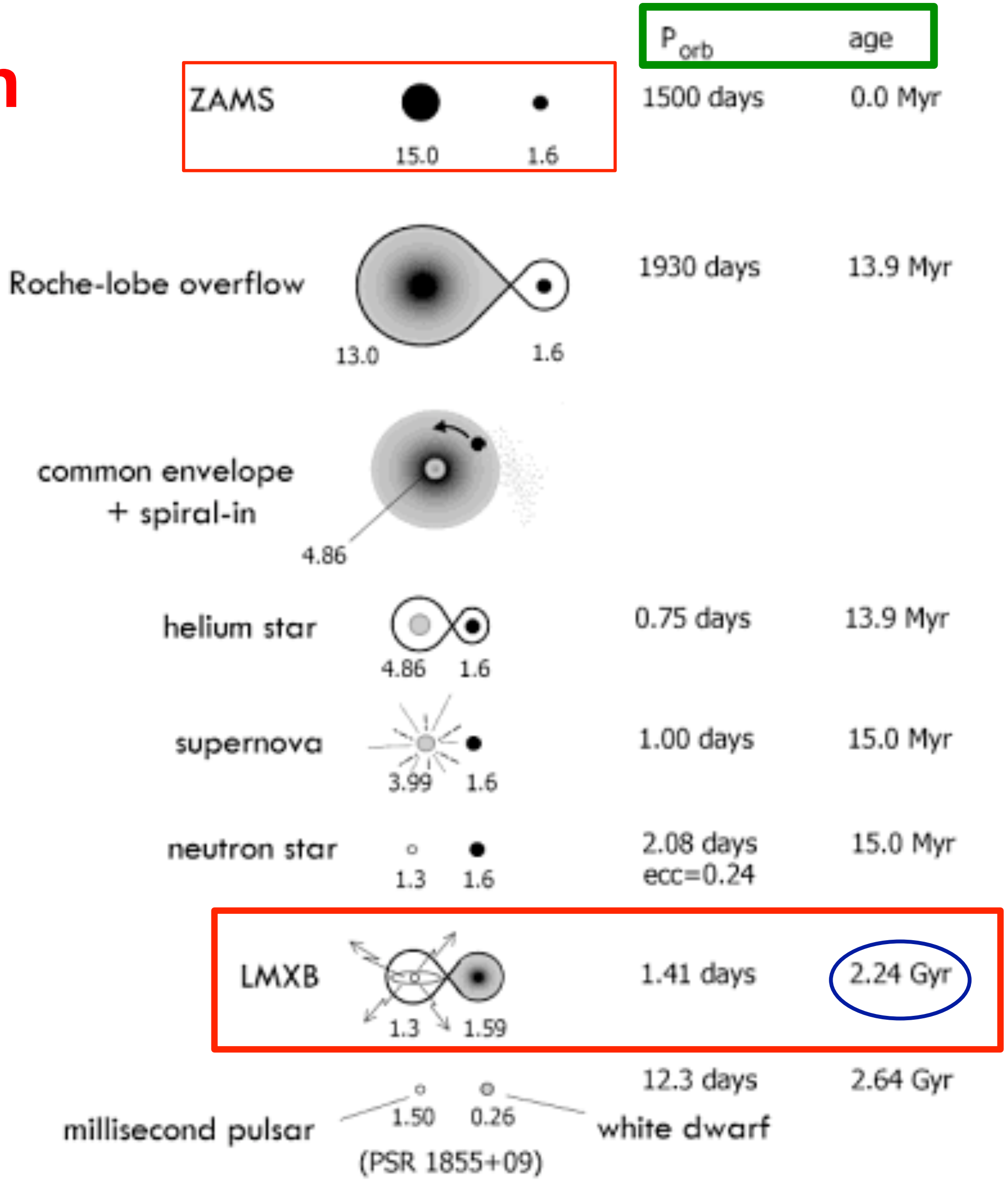
LMXB evolution

Capture is a viable explanation for the formation of these systems (e.g., in globular clusters).

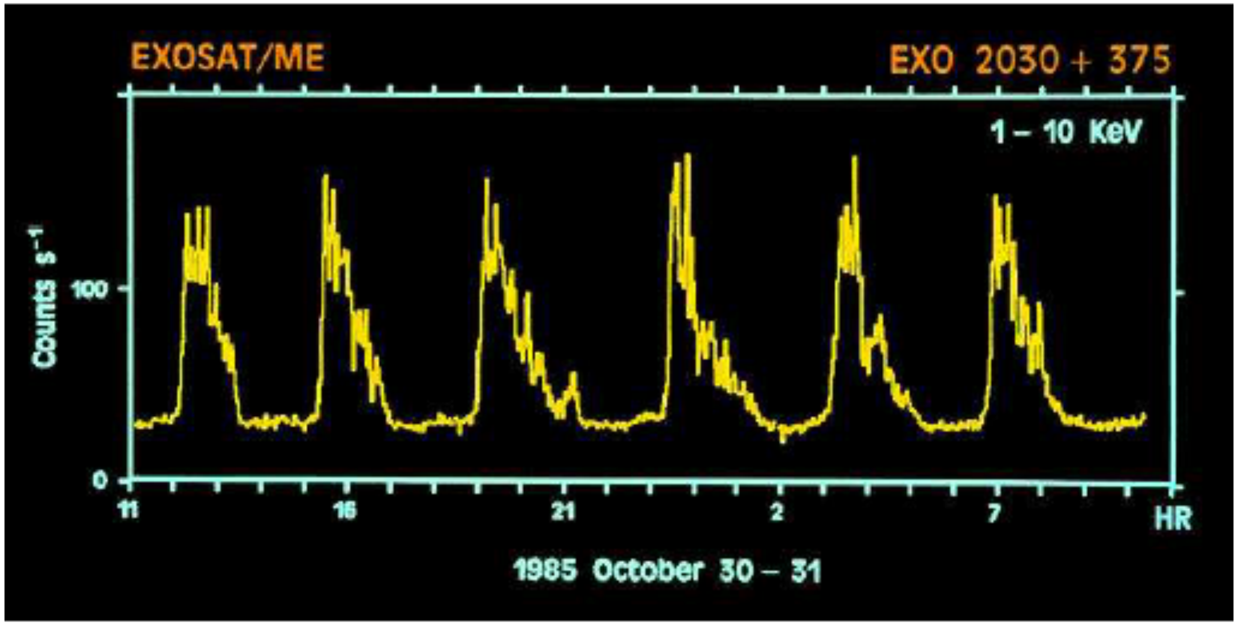
Mass transfer via Roche lobe overflow, till a SN event occurs (leaving a NS or a BH).

➔ LMXB phase

A ms-PSR may be produced due to the spin-up from accreted material.



X-ray bursters

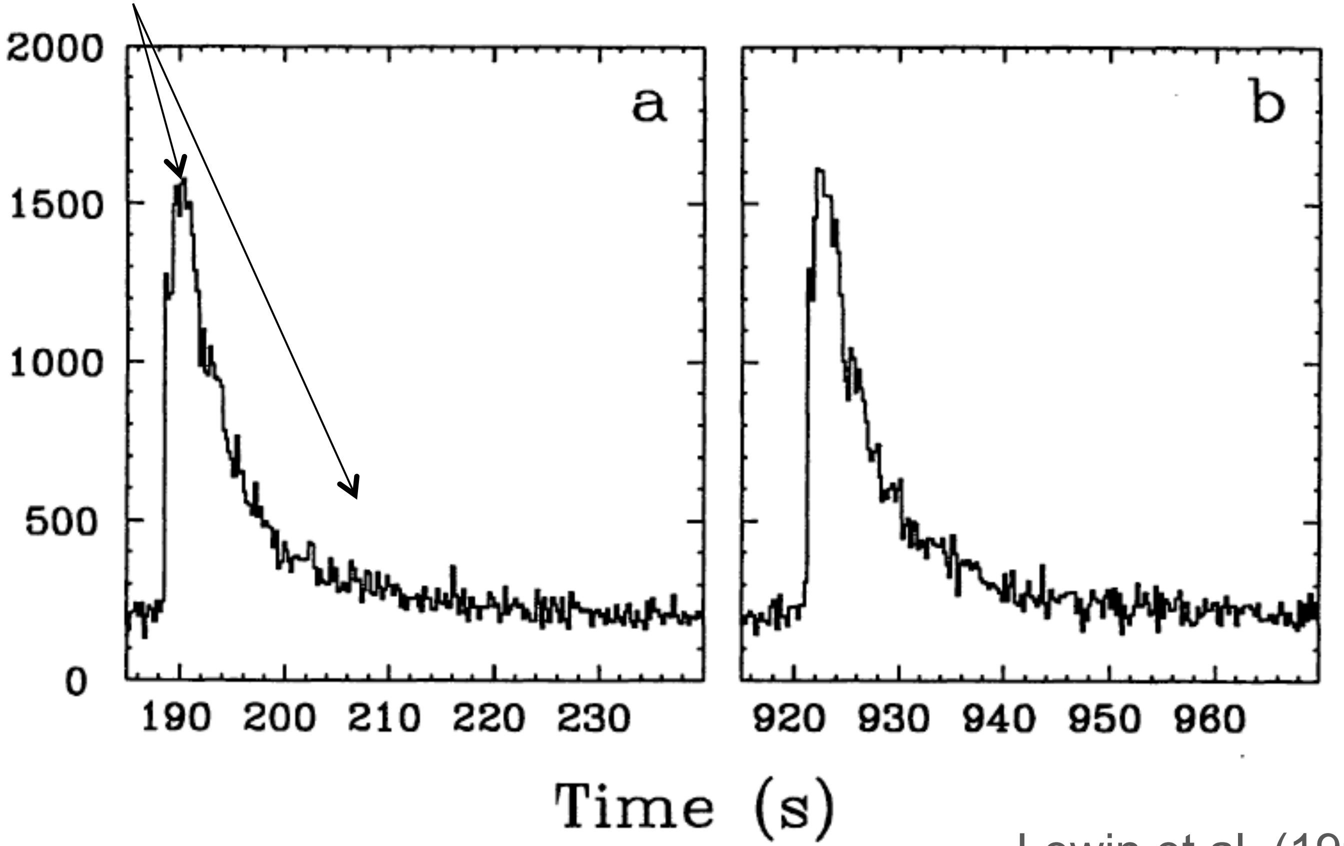


X-ray bursts from EXO 2030+375 as seen with *EXOSAT*

➔ Interpretation: Thermonuclear explosions on NS surface

Fast rise,
exponential decay

EXOSAT lightcurves



Lewin et al. (1993)

Bursters: main properties (I)

✓ Associated to low-B NS: matter almost directly to the NS surface

✓ A surface (hence, a NS) is required to have a **thermonuclear flash** (H fusing into He, then burning in an explosion event), emitting via blackbody emission

✓ Compression rate depending on Mdot/A_{accr}, where A_{accr} is the area covered by the accreted material=$4\pi R^2$ ➔dP≈10^{22-23} erg/cm^3 ➔CNO

✓ Fast rise of X-ray emission (≈ a few seconds) + exponential decay (10-100 sec). In super-bursts, the bursts is prolungated, with E≈10^{42} erg (thermonuclear flashes from fuel layers at a greater depth?)

Bursters: main properties (II)

✓ Time between bursts ≈ 1hr − few hrs

✓ Total energy ≈10^{39-40} erg

✓ Flux(steady)/Flux(burst) ≈ 100 (20−300) ≈ E(grav)/E(nuclear)

[integrating over duration time]

$$\boxed{\frac{E_{acc}}{E_{nuc}} = \frac{\eta m_p c^2}{0.007 m_p c^2} \approx \frac{0.1}{0.007}}$$

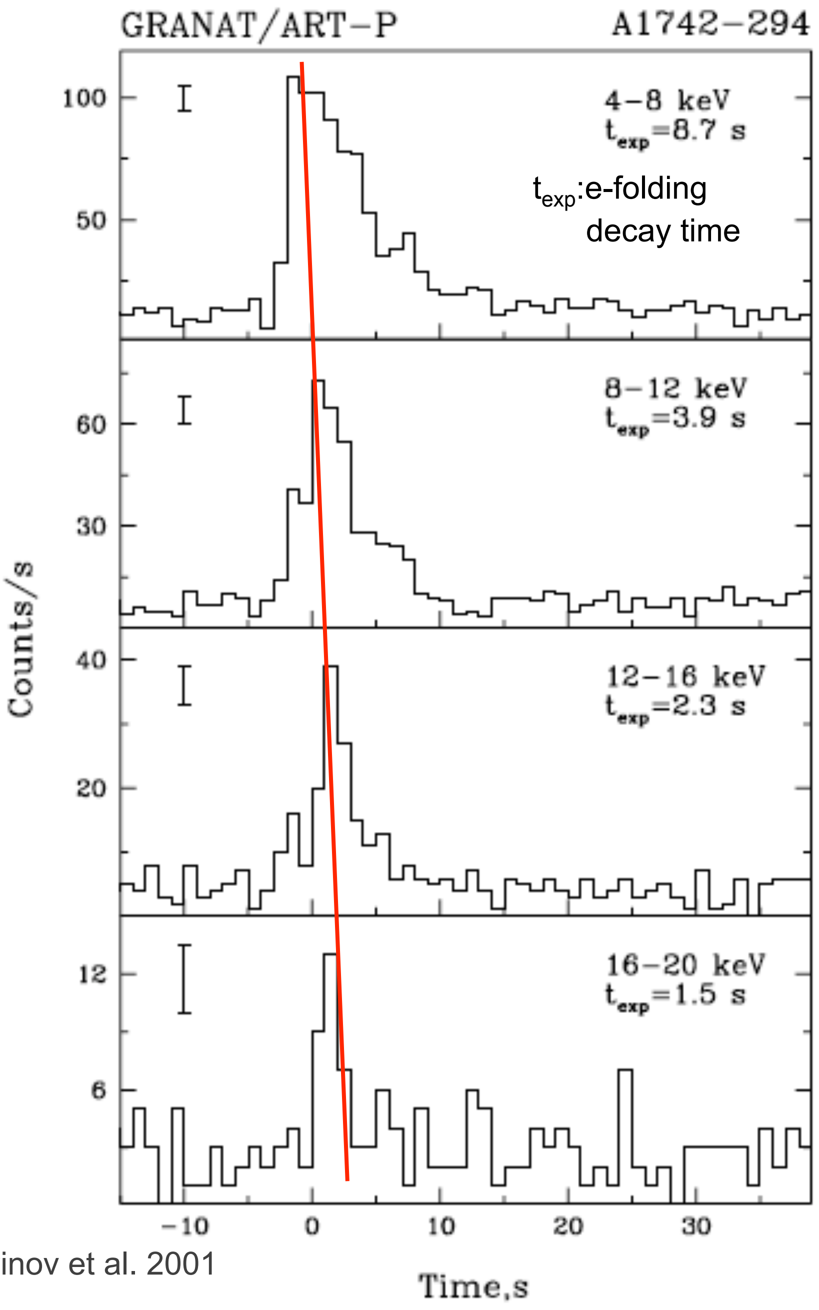
Not all the nuclear energy is emitted as BB radiation

✓ For increasing time intervals between bursts, more matter is accumulated ➔ strength correlated with the time interval to the previous burst

✓ Strong bursts in early phase linked to expanding atmosphere (photospheric radius expansion, *PRE,* phase, where Eddington limit is reached and radiation pressure is high)

Type I burst

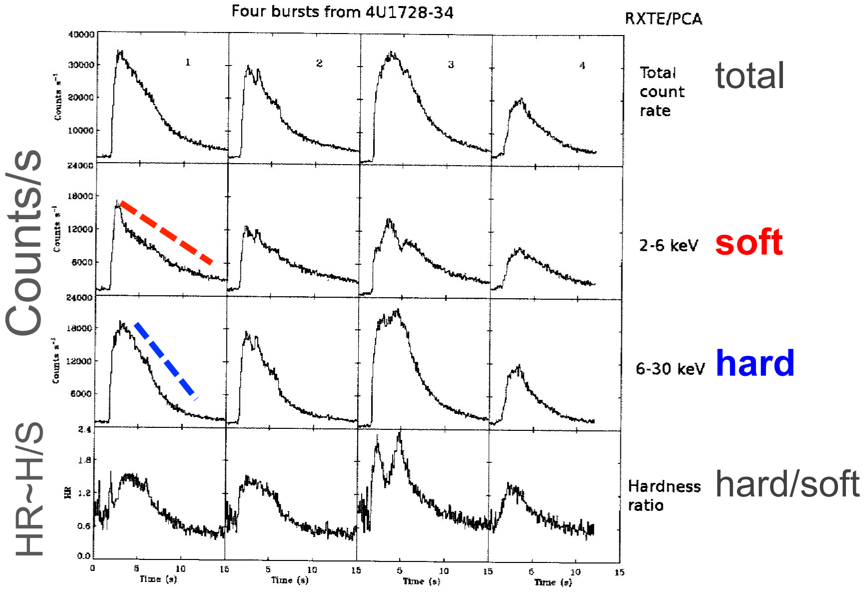
Photon energy increases from top to bottom



Lutovinov et al. 2001

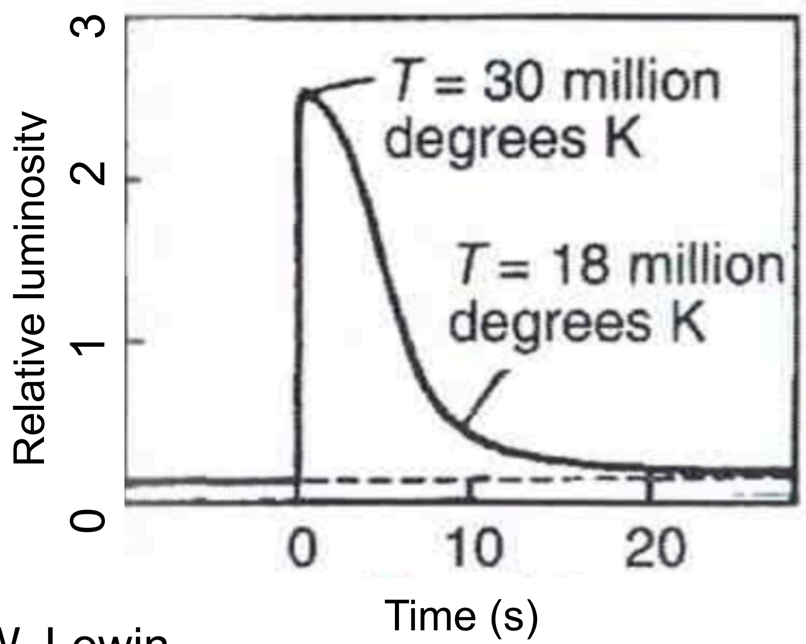
The peak flux in the hard (16-20 keV) band is reached later than in the softer bands (burst rise time ≈5 sec vs. ≈1-2 sec)

There is a softening of the spectrum during the exponential decay



At lower energies, the burst persists for much longer (more pronounced tail) – see t_{exp} in the figure on the left

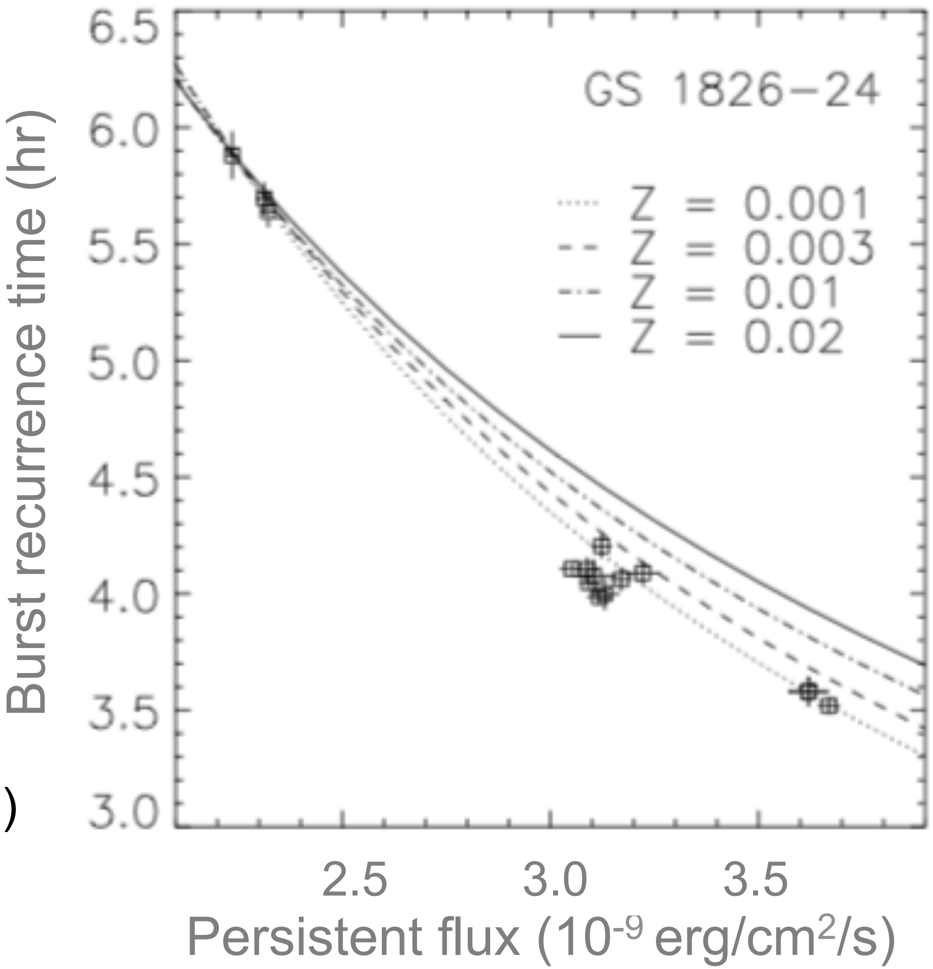
Theoretical behaviour of an X-ray burst



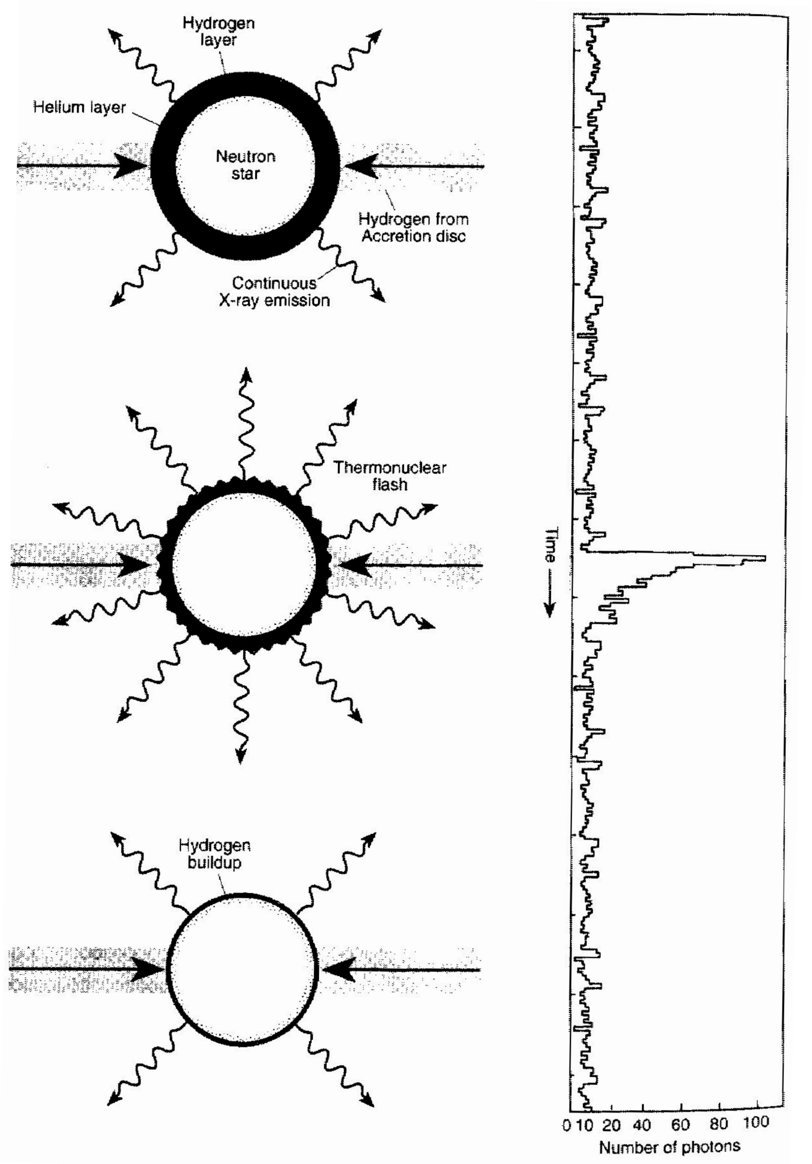
W. Lewin

Rapid raise, peak temperature,
and subsequent cooling

Observations



Galloway et al. (2004)

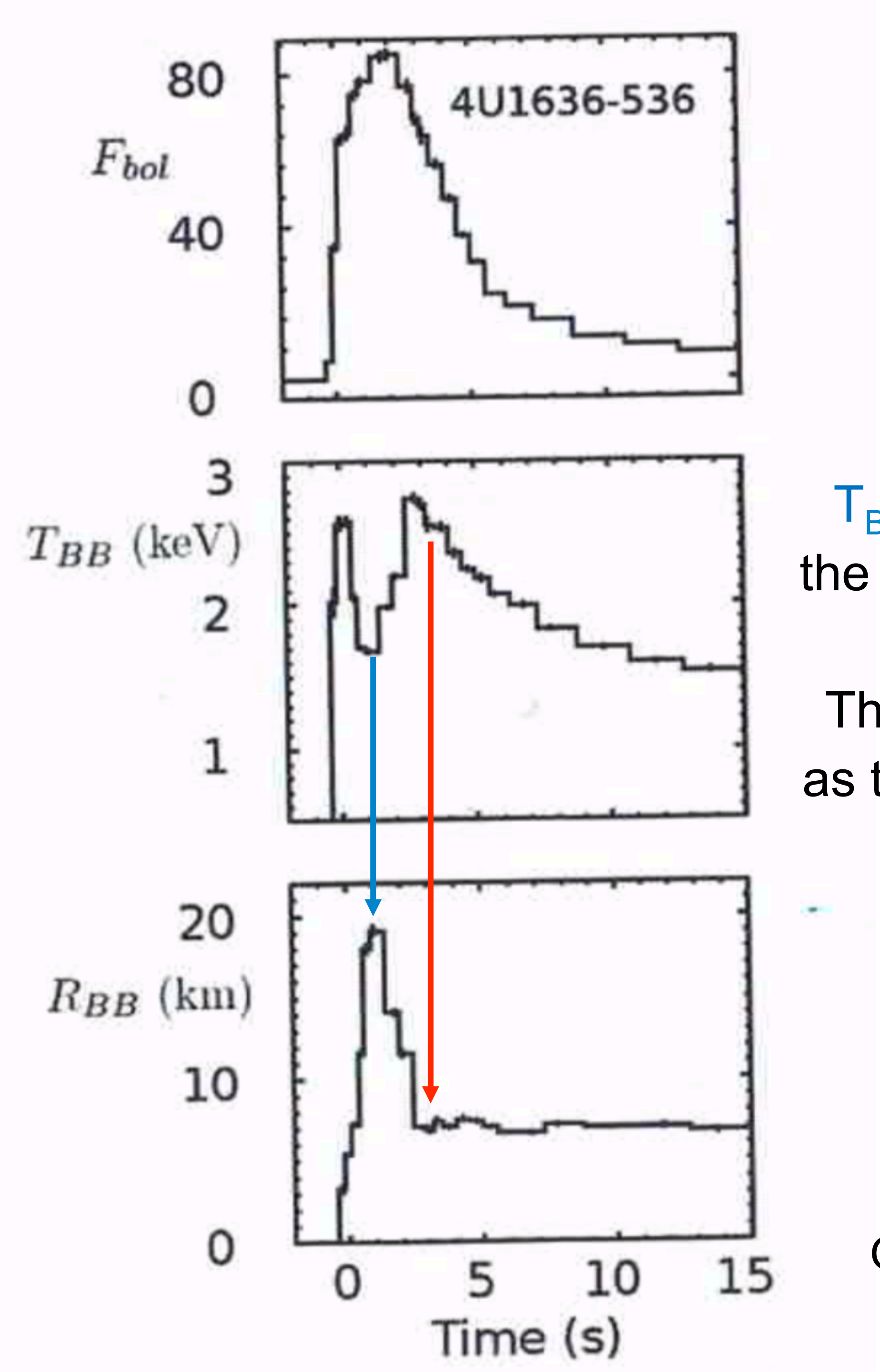


H is gathered from the companion star → steady burning into He, in an underlying layer → at critical T and ρ, thermonuclear flash of He into C (often exceeding the Eddington luminosity; photosperic radius expansion, *PRE*, bursts in these cases). Temperature drops as the radius expansion occurs and then recovers as the material quickly falls back to the NS surface

- Recurrence: few hrs−day
- $t_{burst} \approx 0.5-5$ sec+decay 10−100 sec
- $E_X \approx 10^{39}$ erg$\approx E_\odot$ in a week

The "cycle" restarts

Ignition density and temperature reached in hrs-days. Burning typically occurs at a depth of ≈10m and column density of $\approx 10^8$ g/cm^2

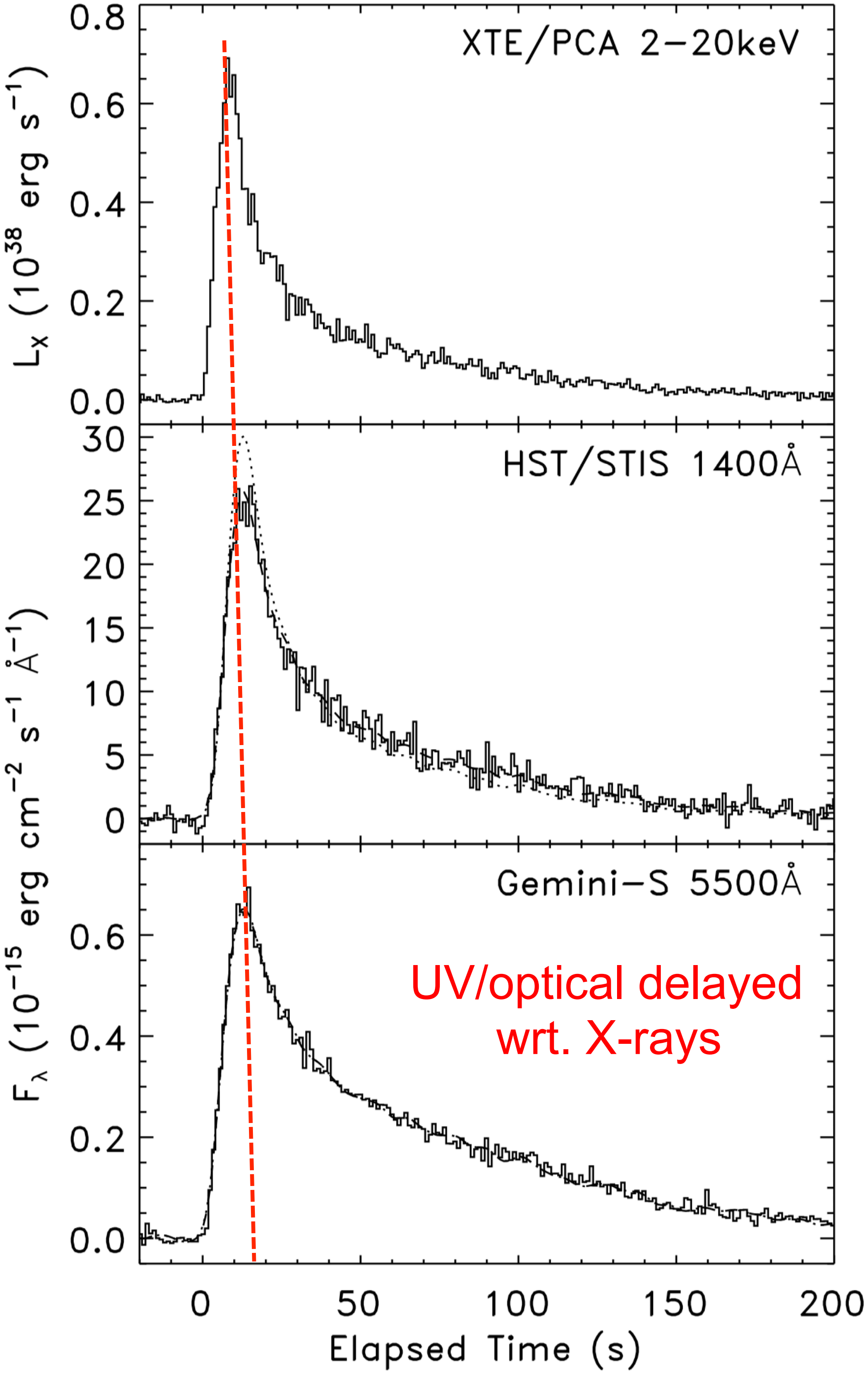


Photospheric Radius Expansion (PRE)

T_{BB} falls during the expansion of the photosphere (larger R_{BB} value).

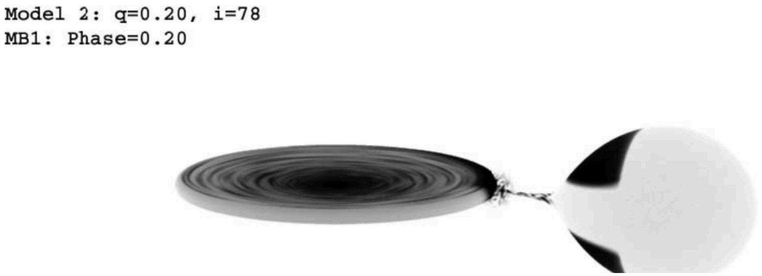
The temperature recovers (rises) as the material quickly falls back to the NS surface

4U1636-536
Galloway et al. (2003)

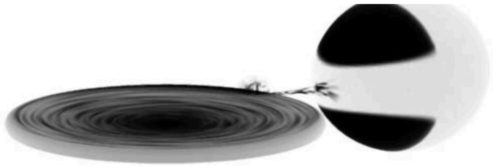


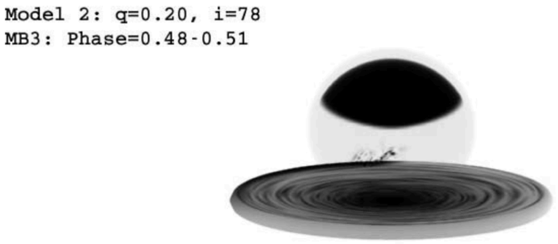
UV/optical delayed wrt. X-rays

Model



The X-rays from the burst can irradiate the surface of the accretion disc and the non-shadowed areas of the inner face of the donor star (shown as dark shading)





Several-second (~4−6) delay between X-ray and optical/UV peaks → time taken from the burst to heat the disc, which then re-radiates this energy as optical burst → observations over an entire cycle would help to establish the system geometry

Hynes et al. (2006)

Bursters: classification

(“relaxation oscillator”)

Type I Bursters: thermonuclear fusion on the surface of a NS

Type II Bursters: in addition to Type I, in the so-called Rapid Bursters: intermittent accretion because of disc instabilities

Accretion disc instabilities brings to a temporary enhancement of the accretion rate

Magnetosphere acts as a gate that the surrounding material has to pass through

When in one burst the reservoir (AD? magnetosphere?) was emptied to a high degree, it will take a longer time to replenish it again, while, if partially emptied, it will need a shorter time to the next burst

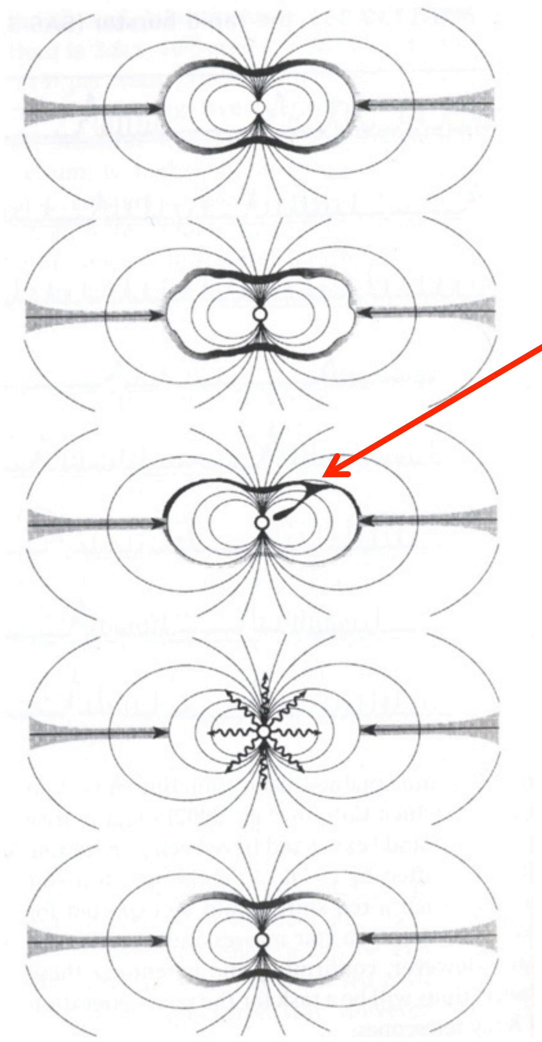
- ✓ Rapid bursters: Δt between bursts$\approx$7 sec (<1 hr)
- ✓ No softening during decays
- ✓ Often coupled with Type I events
- ✓ F_{int}(Type II)~120×F_{int}(Type I) if RB is burst-active

Type II bursters

due to instabilities, it is possible to partially empty the reservoir of material falling down to the surface of the NS ➔ correlation between E and time interval to the next burst

➔ need to replenish the reservoir (BUT triggering mechanism not totally clear)

Magnetospheric gate model for the Rapid Bursters



(from W. Lewin)

Material accreting from the disc is held back by the NS magnetosphere. When sufficient material has built up outside the gate, the magnetosphere can no longer hold it, and it ruptures, therefore allowing it to fall onto the NS, producing a **Type II burst**. When the material is gone, the gate re-forms and the process restarts.

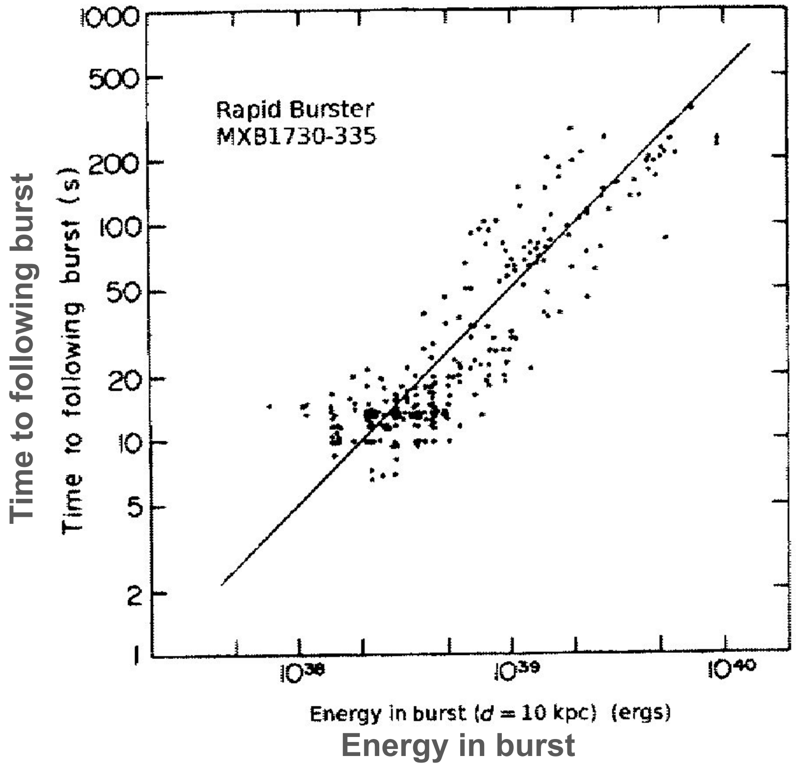
If it were not for the magnetosphere, this would appear as steady accretion.

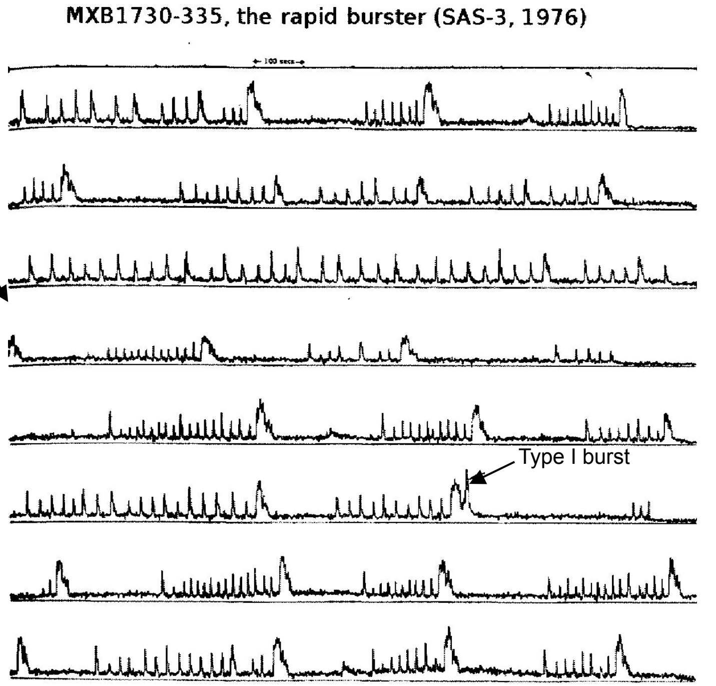
This material produces a thermonuclear flash.

Type II burst:

- The smallest bursts are very close together
- The big bursts are always followed by a long gap

- $\Delta t \approx$ sec−hr variability
- $t_{burst} \approx$ sec−min
- $E_X \approx (1\times10^{38}-7\times10^{40})$ erg





each panel=24 min

Rapid bursters: more energetic bursts require more time for the material to be accumulated (longer period of steady X-ray flux). Dependence on the rate at which matter is accreted. The *temperature* is nearly *constant* during the burst.

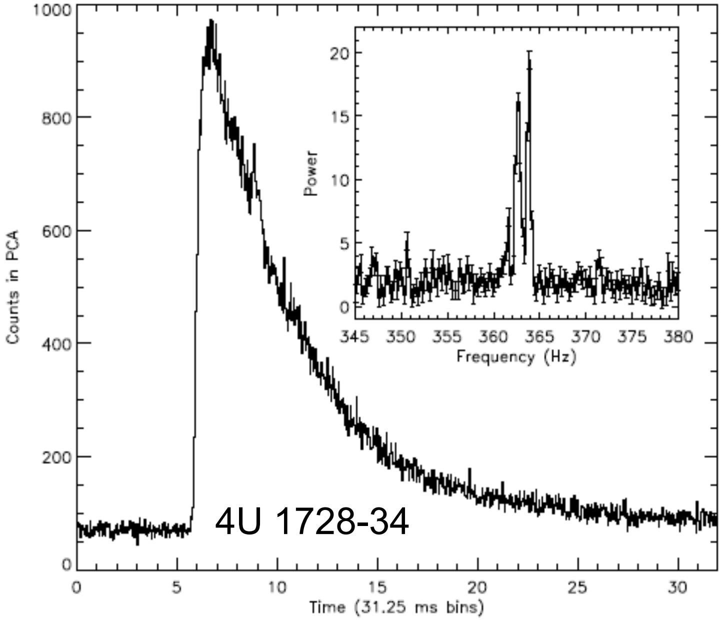
Steady burning (fusion energy) would be overwhelmed by the gravitational energy emission (≈a few MeV vs. ≈200 MeV) ➔ actually, we see such emission as bursts

Burst oscillations (I)

✓ Not all the fuel is burned up in each burst and not all of the NS surface is involved

✓ Magnetic field + patchy burning may lead to anisotropic emission during X-ray bursts, related to the rotation

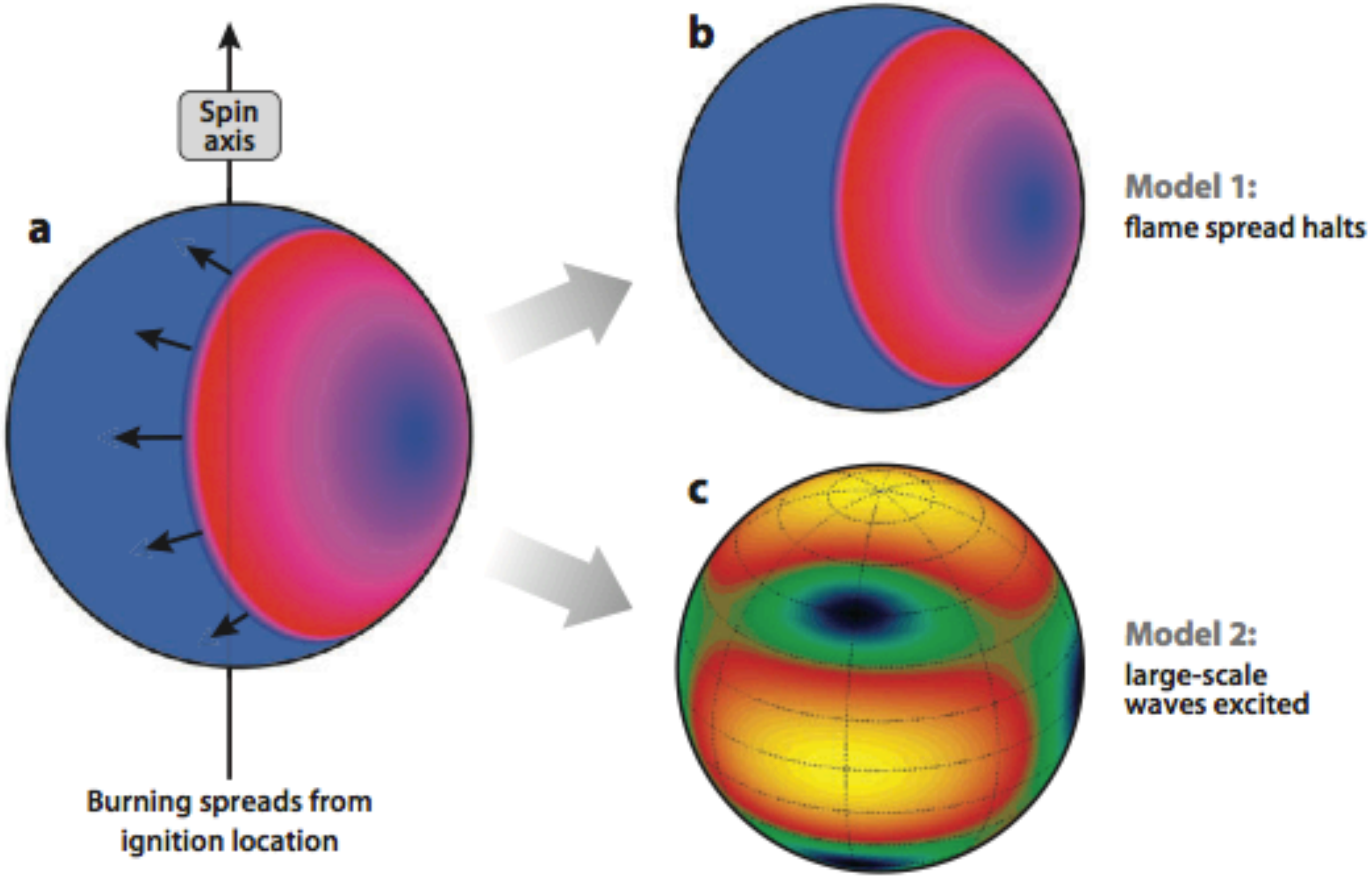
➔ Hot spots over the surface or in an atmospheric layer (spin modulation)



In Type 1 bursts

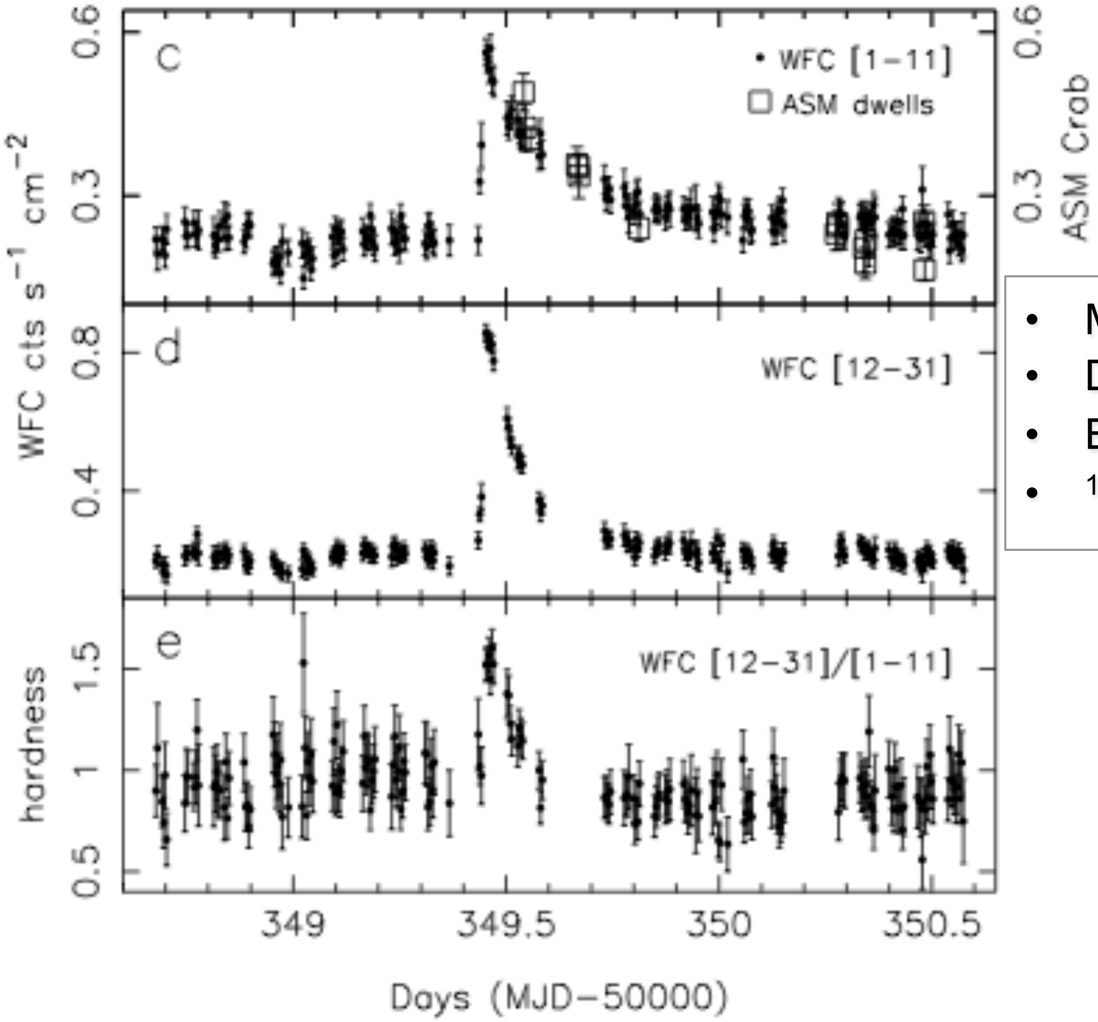
Strohmayer et al. (1996)

Burst oscillations (II)



Watts, ARAA 2012

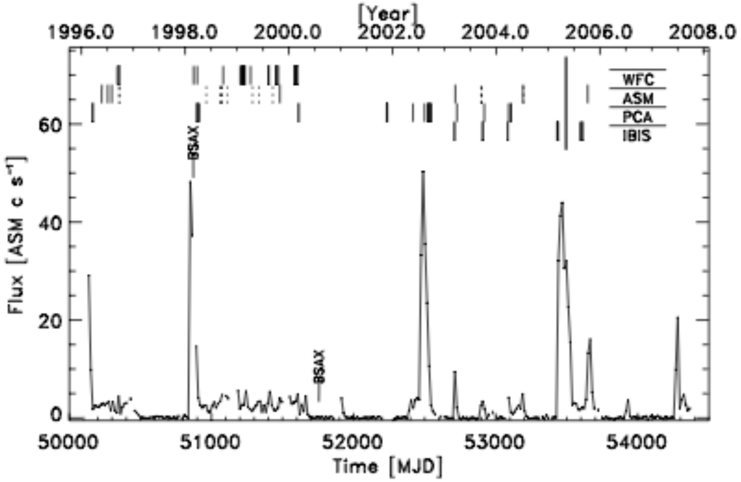
Superbursts



Kuulkers+02: KS1731-260

Thermonuclear flashes
from deeper layers (hence,
larger volume of material?)

- Much larger recurrence time – yrs
- Decay time: ≈1-3 hours
- E≈10^{42} erg
- $^{12}C+^{12}C$ reaction? Unstable C burning?



Way to possibly estimate the radius of a NS in a burst

$$L = 4\pi R^{2}\sigma_{SB}T^{4} \rightarrow R_{OBS} = \sqrt{\frac{L}{4\pi\sigma_{SB}T^{4}_{OBS}}} \xrightarrow{L=F_{OBS}\times 4\pi d^{2}} R_{OBS} = \frac{d}{T^{2}_{obs}}\sqrt{F_{obs}/\sigma_{SB}}$$

Stefan's law

Effects that need to be taken into account

1. **Electron Compton scattering** in the NS atmosphere: shifts the BB to higher energies and slightly changes its shape ➔ diluted BB

$$T_{color} = T_{BB} \times f_{col}$$

f_{col}=color factor

2. The **surface gravitational redshift** shifts the temperature towards a lower value

$$T_{obs} = T_{BB} / (1 + z_{gr})$$

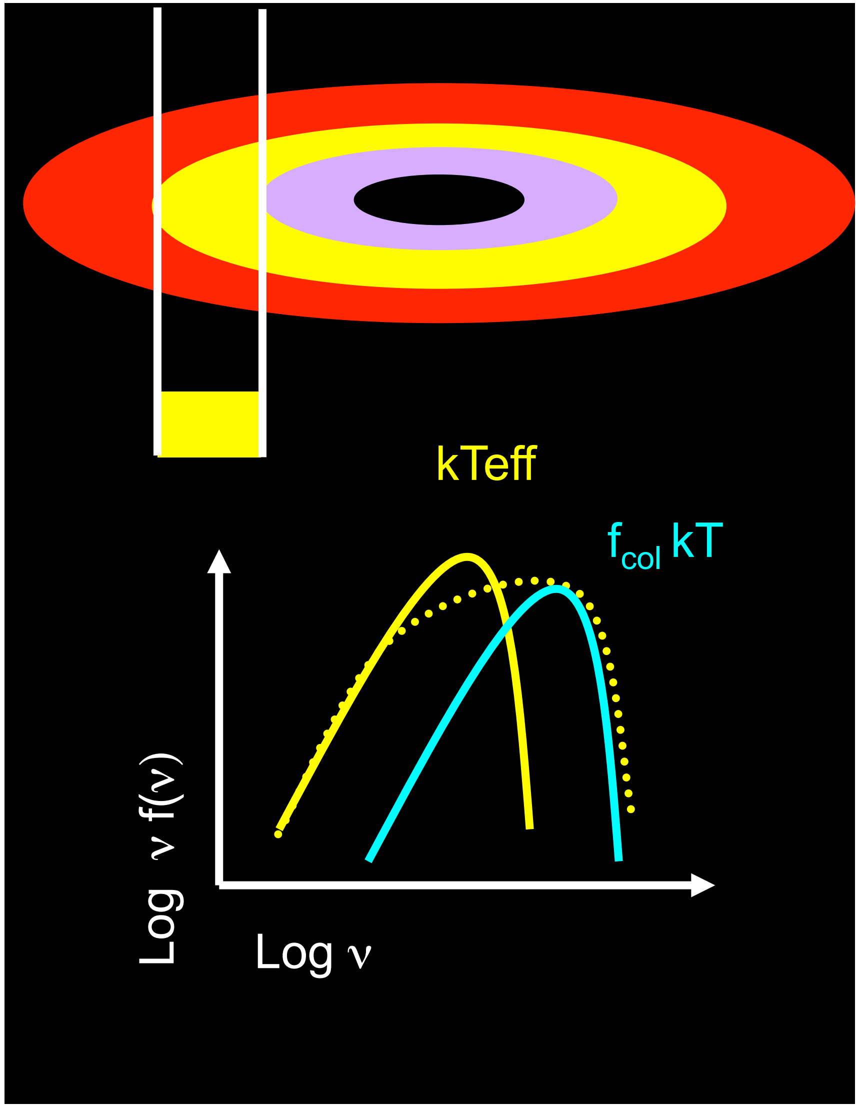
$$T_{obs} = T_{BB} \times f_{col} / (1 + z_{gr})$$

Way to estimate R_{NS} (R_{obs}) via observations and assumptions

Reading: thin-shell instability, Schwarzshild & Harm 1965

Effect 1: f_{col}

- Surely even disc spectra are not this simple
- Disc annuli not blackbody – too hot, so little true opacity. Compton scattering important
- Modified blackbody (Shakura & Sunyaev 1973)
- Described by color temperature f_{col}
- And relativistic smearing effects on the spectra at each radius

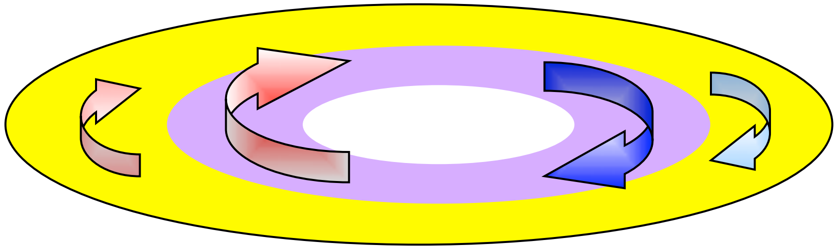


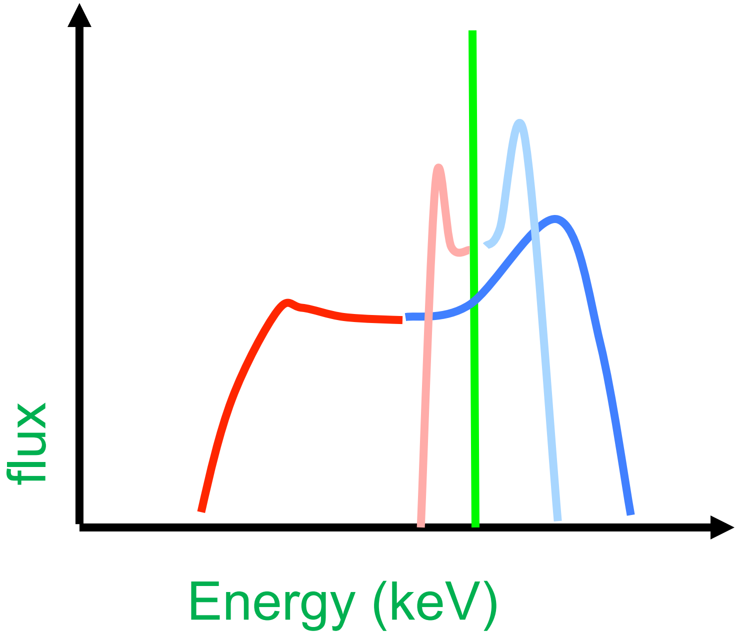
(Credits: C. Done)

Effect 2: relativistic effects

- Relativistic effects (special and general) affect all emission (Cunningham 1975)
- Emission from the side of the disc coming towards us is blueshifted and boosted by Doppler effects, while opposite side is redshifted and suppressed.
- Also time dilation and gravitational redshift
- Broadens the spectrum at a given radius wrt. a “narrow” blackbody
- Similar effects on the iron Kα line

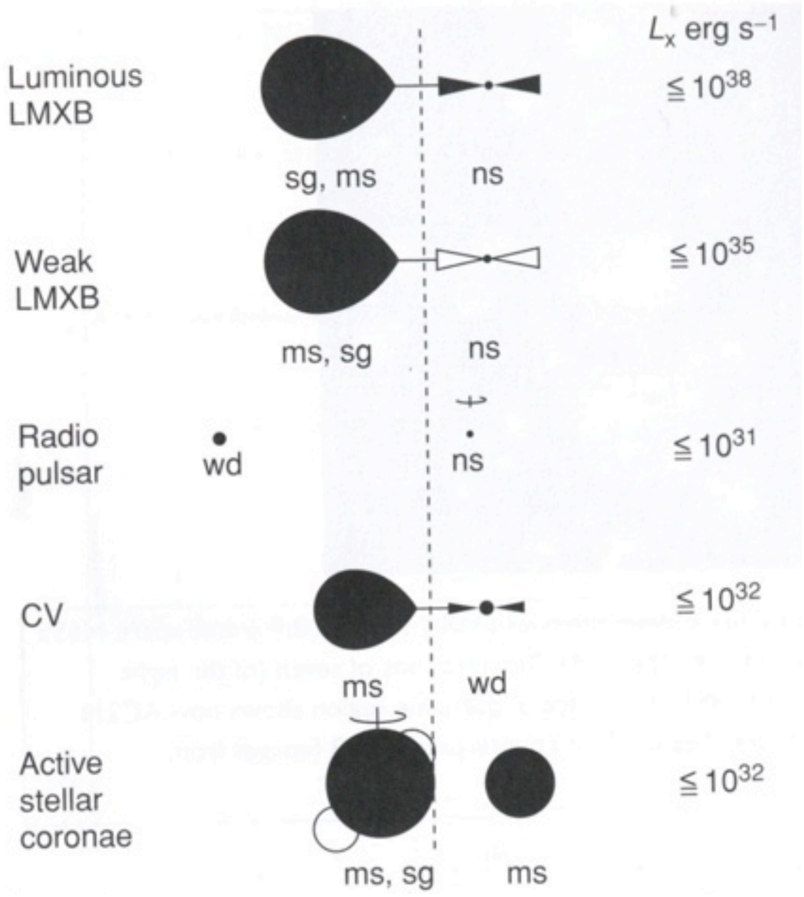
(Credits: C. Done)





Fabian et al. 1989

Compact objects in globular clusters



(Adapted from Verbunt & Lewin 2006)

Luminous LMXB

Quiescent LMXB

Binary radio PSR

NS

CV

WD

Stars with active coronae

stars