High Mass X-ray Binaries hosting a neutron star: a review

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High Mass X-ray Binary

The majority of the HMXB population hosts a neutron star instead of a BH

O or B-type Star

$M_{\text{opt}} > 10M_\odot$

Accreting magnetized NS
B $\sim 10^{12}$ G

X-ray pulsar
Two types of HMXBs depending on the massive companion

- **O or B-type supergiant**
  - They loose mass through a **strong** (spherically symmetric) **wind**
  - → stellar wind capture by the NS
  - → **SgHMXBs** (persistent or transient → Supergiant Fast X-ray Transients, **SFXTs**)

- **Be star**  main sequence B stars with Balmer lines in emission
  - Rapidly rotating, they loose mass mainly from the **equatorial** region, through a circumstellar **decretion keplerian disc** (coplanar or misaligned with the orbit). Also a polar wind is present.
  - The mechanism for the Be disc formation is unclear (rotation is insufficient)
  - → accretion from the Be disc
  - → **Be/XRBs** (mostly X-ray transients)
Corbet diagram before INTEGRAL (before October 2002)

sgHMXB
- O, B supergiants
- Porb: 1-15d
- Quasi circular orbits
- Persistent (L_x \sim 10^{36} \text{ erg/s})

Be-HMXB
- Be stars with circumstellar discs
- Porb: > 10 days to months
- Elliptical orbits
- Transients (L_x \sim 10^{36} - 10^{38} \text{ erg/s})

Wind-fed persistent sgHMXBs

“B-emission stars and X-ray sources”
Maraschi, Treves, van den Heuvel 1976

Corbet diagram for Galactic HMXBs
Wind accretion
Sg HMXBs

Wind velocity (beta-law):

\[ v_w(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta \]
Wind accretion
Sg HMXBs

Wind velocity (beta-law):

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0.8 – 1.2
Wind accretion
Sg HMXBs

Wind velocity (beta-law): $v_w(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta$

Terminal velocity ~ 1000 – 2000 km/s

Wind velocity $v(r)$ vs. radial distance $r/\R_0$
Wind accretion
Sg HMXBs

Wind velocity (beta-law):

\[ v_w(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta \]

Bondi radius \( R_{acc} \):

\[ R_{acc} = \frac{2GM_{NS}}{v_{rel}^2(a)} \]

Mass loss rate from the OB star \( \dot{M}_w \sim 10^{-6} M_\odot/yr \)
Wind accretion
Sg HMXBs

Wind velocity (beta-law):

$$v_w(r) = v_\infty \left(1 - \frac{R_\ast}{r}\right)^\beta$$

Bondi radius $R_{acc}$:

$$R_{acc} = \frac{2GM_{NS}}{v_{rel}^2(a)}$$

(a = orbital separation)

Accretion luminosity:

$$L_X \propto \frac{\rho_w(a)}{v_{rel}^3(a)} \propto \frac{\dot{M}_w}{v_w^4(a)}$$

$L_x \sim 10^{35} - 10^{36}$ erg/s

Mass loss rate from the OB star

$$\dot{M}_w \sim 10^{-6} \, M_\odot/yr$$
Effect of the binary eccentricity on the calculated X-ray light curves

Calculated assuming spherically symmetric supergiant wind (with beta = 0.5), and two orbital periods, 20 and 70 days

Raguzova & Lipunov 1998
The rotation period, the magnetic field strength and the pressure of the wind determine whether or not accretion onto the NS is possible.

In case of direct accretion:

If matter outside the magnetosphere can cool down efficiently, all matter captured within $R_{acc}$ will accrete.

**magnetospheric radius ($R_M$)**

$$R_M \approx 2 \times 10^{10} a_{10}^{4/7} \dot{M}_{-6}^{-2/7} \nu_8^{-8/7} \mu_{33}^{4/7} \text{ cm}.$$  

**corotation radius ($R_{co}$)**

$$R_{co} = 1.7 \times 10^{10} P_{s/3}^{2/3} \text{ cm}.$$  

**accretion (Bondi) radius ($R_{acc}$)**

$$R_{acc} = 2GM_{NS}/\nu_w^2 = 3.7 \times 10^{10} \nu_8^{-2} \text{ cm}.$$
Transitions between different regimes depending on changes of the relative positions of the three radii.

(given a NS with its B-field & Pspin, transitions depend on wind density & velocity at the NS orbit)

Direct accretion

Racc < Rco < RM

Rco < RM < Racc

RM < Rco < Racc

Bozzo, Stella & Falanga 2008
Clumpy winds complicate the picture

In principle, HMXBs can probe wind clumpiness (density and velocity wind structure)
- X-ray variability traces the mass inflow rate
- absorbing column density variations due to massive clumps passing in front of the NS

Credits: ESA C. Carreau/Nazé et al.
Clumpy winds
complicate the picture

In principle (in absence of any mediating mechanism), HMXBs can probe wind clumpiness (density and velocity wind structure at the NS separation) by means of:

- X-ray flux variability tracing the mass inflow rate

- Absorbing column density variations:
  they can be due to massive clumps passing in front of the NS

Credits: ESA  Bozzo et al. 2011
Structures in the stellar wind produced by the interaction with the accretor

Formation of a gas stream as the binary separation is decreased in HMXBs

Stellar wind clumps are likely disrupted by the accretion wake, while other bubbles appear to form behind the shock
Sg HMXB simulations

Wind **density distribution** in a Sg HMXB hosting a **neutron star** with different **masses**

![Density distribution plots](image)

- **M<sub>NS</sub> = 1.5 solar masses**
- **M<sub>NS</sub> = 2 solar masses**

**Figure 1.** Density distribution (in gr cm<sup>-3</sup>; color bar) on the orbital plane after ~ 3 orbits. The wind terminal velocity is \( v_\infty \approx 500 \text{ km s}^{-1} \) and the mass-loss rate is \( \dot{M}_w \approx 10^{-6} \text{ } M_\odot \text{ yr}^{-1} \). The mass of the neutron star scales from 1.5 (left) to 2.0 \( M_\odot \) (right). The color version of this figure is available on-line.

Manousakis et al. 2013
Sg HMXB simulations

Eclipsing system

\( M_x = 1.5 \, M_\odot \) (short–long)
\( M_x = 1.6 \, M_\odot \) (dotted dashed)
\( M_x = 1.7 \, M_\odot \) (long dashed)
\( M_x = 1.8 \, M_\odot \) (short dashed)
\( M_x = 1.9 \, M_\odot \) (dotted)
\( M_x = 2.0 \, M_\odot \) (solid)

Increasing NS mass

Manousakis et al. 2013
Corbet diagram before INTEGRAL (October 2002)

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Be/X-ray transients

“B-emission stars and X-ray sources”
Maraschi, Treves & van den Heuvel 1976

Be star decretion keplerian disc

Be-star

expelled material

neutron star

X-ray flux

$P_{\text{orb}}$

time

Type I outburst

Most of the accretion takes place during periastron passages

Tauris & van den Heuvel 2006
Be XRBs: two outburst types

Type I outbursts: Periodic on $P_{\text{orb}}$

Type II outbursts: No recurrence time
Associated with catastrophic perturbation of the Be disc

Reig 2011
The viscous decretion disc can undergo formation and dissipation episodes (Negueruela et al. 2001)
The Be disc is truncated by tidal interaction with the NS. Type II giant outbursts could be due to capture of larger (than in type I) amount of matter from a tilted and warped Be disc.
Supergiant Fast X-ray Transients

\textbf{INTTEGRAL/ISGRI}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{integral_isgri.png}
\caption{Lightcurve of the observation of XTE J1739−302, in the energy range 18 − 60 keV (IBIS/ISGRI). Arrows indicates the peaks of luminosity.}
\end{figure}

\textbf{Sguera et al. 2005}

\textbf{Negueruela et al. 2006}
After INTEGRAL
Supergiant Fast X-ray Transients

SgHMXB
- O, B supergiants
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- Quasi circular orbits
- Persistent

Be-HMXB
- Be stars
- Porb: days-months
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- Transients

**Corbet diagram for Galactic HMXB**

- **SFXTs**
  - O, B supergiants
  - Transients

**3.3 d**
**30 d**
**51 d**

**GRU** 16479-4514
**GRU** 16418-4532
**GRU** 17544-2619
**SAX** 18483-0371
**SAX** 18166-1703
**XTE** J1739-302
**RX J16465-4307**
**RX J11215-5952**
After INTEGRAL
Supergiant Fast X-ray Transients

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Corbet diagram for Galactic HMXBs

SFXTs
- O, B supergiants
- Transients

$e > 0.8$

$e \approx 0.4$

3.3 d
30 d
51 d

Porb (d)
The SFXT   IGR J17544-2619

Exceptional outburst from a SFXT near the periastron passage...BUT this occurs rarely!
This does not happen every periastron passage

Suzaku/XIS

Rampy et al. 2009

Obs duration ~ 2.7 days
P orb ~ 4.9 days

$10^{37}$ erg/s
Long-term SFXTs X-ray emission: intermediate luminosity state of $10^{33}-10^{34}$ erg/s (quiescence is at $10^{32}$ erg/s in the 1-10 keV band)

Ada will discuss INTEGRAL results on SFXTs!
Observationally

- Mostly around $10^{33} - 10^{34}$ erg/s
- Sporadic, short and bright flares ($10^{36} - 10^{37}$ ergs/s)
- Flares: minutes - hours
- Outburst: a few days
- Dynamic range up to $10^5 - 10^6$

This is only a sketch, no real data!
Wind accretion

- Bondi accretion is an approximation to calculate the time-averaged $L_x$ of classical HMXBs
- If applied to the new class of transient SgHMXBs, the Supergiant Fast X-ray Transients, it results into average $L_x \sim 100$ times higher than observed $\rightarrow$ **SFXTs are subluminous**
- The mechanism for the X-ray **flares** is unclear

**The mystery of SFXTs is twofold**

This is only a sketch, no real data!
### Observationally
- Mostly around $10^{33} - 10^{34}$ erg/sec
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- Dynamic range up to $10^5$

### Physical mechanism debated
- Peculiar wind and/or orbit (in'tZand 05, Walter+07, Sidoli+07, Negueruela+08, …)
- Particular properties of NS (gating mechanism, Grebenev+07, Bozzo+08)
- Subsonic settling accretion regime (Shakura+12, +13, +14)

This is only a sketch, no real data!
SFXTs intermittent and sporadic X-ray flares

• Are they produced by an intermittent input?
  Dense clumps in the wind $\rightarrow$ X-ray flares?
Clumpy SG winds + different orbital configurations are not enough to explain SFXTs **flares** & their **low time-averaged Lx**

Supergiant winds are clumpy
SFXTs **intermittent** and sporadic X-ray flares

• Are they produced by an **intermittent input**?
  Dense clumps in the wind → X-ray flares?

• Are the flares produced by a **gated mechanism**?
SFXTs: centrifugal or magnetic barrier?

To explain transitions between quiescence to bright flares in SFXTs in presence of variations in the supergiant wind parameters:

- either a **magnetic barrier** (magnetar with a $P_{\text{spin}}$ of ~ 1000 s)
- or a **centrifugal barrier** (neutron star with a $B \sim 10^{12}$ G and a $P_{\text{spin}}$ ~ 10 s)

\[
R_{\text{acc}} < R_{\text{co}} < R_{\text{M}} < R_{\text{M}} < R_{\text{co}} < R_{\text{acc}}
\]

Direct accretion

\[
R_{\text{M}} < R_{\text{co}} < R_{\text{acc}}
\]

\[
R_{\text{acc}} < R_{\text{M}} < R_{\text{co}}
\]

\[
R_{\text{acc}} = \text{accretion radius (Bondi)}
\]

\[
R_{\text{M}} = \text{magnetospheric radius}
\]

\[
R_{\text{co}} = \text{corotation radius}
\]

Bozzo, Stella & Falanga 2008
NuSTAR unveils the magnetic field strength in a SFXT

$B = (1.45 \pm 0.03) \times 10^{12} \ G \cdot (1 + z)$

The magnetar nature of IGRJ17544 is ruled out
Quasi spherical accretion in slow pulsars

$L_x > 4 \times 10^{36} \text{ erg/s}$

$\dot{M} \approx \rho v R_B^2 - \rho \frac{(2GM)^2}{v^3}$

$R_B = \frac{2GM}{v^2}$

$\approx 2GM/v^2$ (Bondi radius) characterizes bow shock location in the wind

Figure 1. Supersonic (Bondi-Hoyle-Littleton) accretion onto magnetized NS

$L_x < 4 \times 10^{36} \text{ erg/s}$ (usual)

Subsonic settling accretion without shock near magnetosphere

Matter subsonically settles down inside the shell with radius $\sim R_B$

Convective isomomentum shell $\omega(R) \sim 1/R^2$

Figure 2. Subsonic settling accretion onto magnetized NS

(Shakura et al. 2012)
L_x > 4 \times 10^{36} \text{ erg/s} \\

\text{Accretion Bondi-Hoyle-Littleton}

\[
\dot{M} \approx \rho v R_b^2 - \frac{\rho (2GM)^2}{v^3}
\]

\[
R_b = \frac{2GM}{v^2}
\]

L_x < 4 \times 10^{36} \text{ erg/s} \\

\text{Subsonic settling accretion without shock near magnetosphere}

\text{Matter subsonically settles down inside the shell with radius } \sim R_b

\text{Convective isomomentum shell } \omega(R) \sim 1/R^2

\textbf{Shell}

- Accretion rate controlled by plasma \textbf{cooling} (Rayleigh-Taylor instability, matter through magnetosphere: radiative cooling or Compton cooling)
- Mediates angular momentum transfer from/to magnetosphere
- Accretion can be significantly smaller than Bondi direct accretion
- Flares no more “tied” to orbit
- HMXB unified scenario

(Shakura et al. 2012; 2014)
Usual SFXTs state  
$10^{33} - 10^{34}$ erg/s

Magnetic reconnection is a proposed mechanism to allow the collapse of the Shell of captured matter above the magnetosphere onto the NS in SFXTs. SFXTs supergiant companions should display higher $B$ stellar field than in other HMXBs

(Shakura et al. 2012, 2014)
A broadband perspective on massive X-ray binaries: towards a unified picture

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