Recent achievements about wind-fed High mass X-ray binaries

The New High Energy Sky after a Decade of Discoveries
INTEGRAL workshop 2015

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Outline

• Wind-fed (neutron star) High Mass X-ray Binaries: short introduction

• The INTEGRAL contribution
  - The zoo of HMXBs after 13 yrs of INTEGRAL
  - The X-ray variability of HMXBs: toward a unified picture of massive star winds
  - Long term monitoring of wind-fed HMXBs

• The future ahead
Wind-fed HMXBs: a short introduction

**Neutron star** + O-B supergiant or hypergiant
- Circular or elongated orbits
- Orbital periods few to tens of days
- Young systems (few to tens of $10^6$ yrs)
- Highly magnetized NS expected ($B > 10^{11-12}$ G)
- Spin Periods $>100$ s up to $>>1000$ s

Typical **stellar wind** parameters:
- $V_\infty \sim 500$-3000 km/s
- $M_W \sim 10^{-6}$-$10^{-5} \, M_\odot /$yr $\sim 10^{19} - 10^{20}$ g/s
Wind-fed HMXBs: a short introduction

The classical wind accretion scenario:

\[ \dot{M}_w \sim 4\pi \rho r^2 V_w \quad \text{Spherically symmetric wind} \]

\[ R_a \sim \frac{2GM_{\text{NS}}}{V_W^2} \sim 10^{10} \text{cm} \quad \text{Accretion radius} \]

\[ \frac{\dot{M}_{\text{capt}}}{\dot{M}_w} \sim \frac{R_a^2}{r^2} \sim 10^{-4} \quad \text{Wind accretion efficiency} \]

\[ L_{\text{acc}} \sim \frac{GM_{\text{NS}} \dot{M}_{\text{capt}}}{R_{\text{NS}}} \sim 10^{35-37} \text{ erg/s Accretion luminosity} \]

Typical variability timescale \( R_a / V_W \sim 100 - 1000 \text{ s} \)
Wind-fed HMXBs: a short introduction

- Soft thermal photons from the NS up-scattered to energies \( \sim 100 \) keV
- Hot accreting material \( \rightarrow \) Comptonization
- Absorption due to material local to the source
- Emission lines due to fluorescence of X-rays onto NS surrounding medium or from highly ionized ions
- “Soft excesses”
- Cyclotron lines

- Bright emitters > 10 keV \( (5 \times 10^{34} \text{ erg/s}) \)
- Highly absorbed \( (>>10^{22} \text{ cm}^{-2}) \) in the soft energy range \( (0.5-10 \text{ keV}) \)

IGR J16418-4848 (Walter+ 2003)
The INTEGRAL contribution

- Tripled the number of known wind-fed HMXBs
- Probed the variability time scales (~ks) to unveil previously unknown behaviors (obscuration, flares)
- Monitored all known HMXBs for 13 yrs (deep exposures along the Galactic plane)
The INTEGRAL contribution

• 24 Persistent wind-fed HMXBs
  - Classical Systems
  - 6 Highly obscured systems: \( N_H \gg 10^{22} \text{ cm}^{-2} \)

• 10 Supergiant Fast X-ray Transients (see L. Sidoli talk)
  - Not an homogeneous class of sources

• 2 Black-hole systems (not considered in this review)
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Classical Systems

“Persistent” sources:
• Display the expected averaged X-ray luminosity mostly dependent on the orbital period

\[
\frac{\dot{M}_{\text{capt}}}{\dot{M}_W} \sim \frac{R_a^2}{r^2} \sim 10^{-4}
\]

\[
L_{\text{acc}} \sim \frac{G M_{\text{NS}} \dot{M}_{\text{capt}}}{R_{\text{NS}}} \sim 10^{35-37}\ \text{erg/s}
\]

• Display a limited X-ray luminosity variability of ~10-100 on time scales of 100-1000 s and sometimes “off-states”
  - Structured winds
  - Hydrodynamic effects
Structured Winds

$P_{\text{orb}} \sim 8.9 \text{ d}$
$P_{\text{spin}} \sim 283 \text{ s}$
$e = 0.09$
$B0.5lB$

**Clumpy Wind Accretion** (Sako+ 2003)

$$
\dot{M}_{\text{capt}} \propto \dot{M}_W \sim 4\pi r^2 V_W
$$

$$
L_{\text{acc}} \sim \frac{G M_{\text{NS}} \dot{M}_{\text{capt}}}{R_{\text{NS}}}
$$

$$
\Delta \rho \sim 10$
$$
\Delta V_W \sim 2-3
$$

$\Delta L_X \sim 10-100$

Accretion of clump $\rightarrow$ X-ray flare
No clump $\rightarrow$ off-state

Averaged $L_X \sim 4 \times 10^{36} \text{ erg/s}$
Flux variations $\sim 20-50$ on time scales of 100-1000 s
(see also Martinez-Nunez+ 2014)
Structured Winds

\( P_{\text{orb}} \sim 8.9 \text{ d} \)
\( P_{\text{spin}} \sim 283 \text{ s} \)
\( e = 0.09 \)
\( B0.5lb \)

Clumpy Wind Accretion:

\( \dot{M}_{\text{capt}} \propto \dot{M}_w \sim 4\pi pr^2V_w \)

\( L_{\text{acc}} \sim \frac{GM_{\text{NS}}\dot{M}_{\text{capt}}}{R_{\text{NS}}} \)

\( \Delta \rho \sim 10 \)
\( \Delta V_w \sim 2-3 \)
\( \Delta L_X \sim 10-100 \)

(Sako+ 2003)

Accretion from a clumpy wind produces log-normal distributions of the source X-ray luminosity, in agreement with observations (Fuerst+ 2010)
Structured Winds

- Predicted theoretically since ~1980: instabilities of radiatively driven winds (Lucy & White 1980)
- Observational features in Opt./UV spectra: «outward moving inhomogeneities» (Eversberg 1998)

Hydrodynamical simulations:

1D: very massive clumps ($\Delta \rho \sim 10^4$)
2D: instabilities prevent large clumps

(Feldmeier+ 1997; Oskinova+ 2012; Dessart+ 2002, 2005)

Quantitative spectroscopy:

*Ad hoc* clumps distributions + radiative transport to simulate Opt./UV spectra

(Surlan+ 2013)

$\Delta \rho \sim 10$

$\Delta V_W \sim 2-3$

Long observations of wind-fed HMXBs → the NS probes *in situ* the structure of the stellar wind
Hydrodynamic Effects

Hydrodynamic simulations wind-fed NS in a supergiant HMXB:
- Gravitational focusing
- Coriolis force (circular orbit)
- X-ray photoionization feedback
- Smooth & symmetric stellar wind

$P_{\text{orb}} \sim 8.9 \text{ d}$
$P_{\text{spin}} \sim 283 \text{ s}$
$e = 0.09$
$B0.5Ib$

- Simulated lightcurve
- Log-normal distribution of the flares
- Model is sensible to different NS masses: can weight NSs

(see R. Walter talk)
The INTEGRAL contribution

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Highly Obscured Systems

“Persistent” sources:
- Display the expected *averaged* X-ray luminosity mostly dependent on the orbital period but they have exceptionally high absorption column densities local to the sources
  \[
  \dot{M}_W \sim 4\pi \rho r^2 V_W \quad \rightarrow \text{Low velocity wind}
  \]
- Display a limited X-ray luminosity *variability* of $\sim 10-100$ on time scales of 100-1000 s and sometimes “off-states”
  - Structured winds
  - Hydrodynamic effects
How to slow down the Supergiant wind

- X-ray feedback on the stellar wind: photoionization and cut-off of the radiative acceleration

Vela X-1: emission lines from H- and He-like ions by photoionization + fluorescent emission lines from several elements in lower charge states.

Highly ionized ions: between NS and supergiant

Fluorescent lines: stellar wind, reflection off the stellar photosphere, and the accretion wake.
How to slow down the Supergiant wind

- X-ray feedback on the stellar wind: photoionization and cut-off of the radiative acceleration

\[
\zeta = \frac{L_X}{nR^2}
\]

(Kallman et al. 2004)

Slow wind in the highly obscured IGR J17252–3616

Radiative force cut-off ionization parameter \( \zeta > 100 \)

Other recent works have been investigating the wind structure as a function of \( \zeta \)

(Krtička+ 2012, 2015)
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Supergiant Fast X-ray Transients

“Transient” sources:
- Short flares lasting few $\times$ 1000 s
- Quiescent level is much lower than the luminosity expected according to the standard wind accretion scenario
- Few to hundred days orbital periods
- Very little known about spin periods
- X-ray spectra strongly reminiscent of accreting NSs
  - Extreme massive clumps in the stellar winds?
  - Inhibition of accretion?

(Sguera+ 2005)
Supergiant Fast X-ray Transients

Vela X-1 (classical SgXBs prototype)
Orbital period 8.9 days
Average luminosity $4 \times 10^{36} \text{ erg/s}$
Luminosity variations $\sim 20-50$

![Graph showing Vela X-1 data](Suzaku/XIS; 0.5-12 keV; Odaka 2013)

IGRJ17544-2619 (SFXT prototype)
Orbital period 4.9 days
Average luminosity: $4 \times 10^{34} \text{ erg/s}$
Luminosity variations $\sim 10^6$

![Graph showing IGRJ17544-2619 data](Suzaku/XIS; 0.5-12 keV; Rampy 2009)
Extremely Clumpy Stellar Winds

Theory and observations of massive stars suggest:

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\[ \hat{M}_{\text{capt}} \propto \hat{M}_W \propto \rho V_W^{-4} \]

\[ \Delta L_X \sim 10^4-10^5 \]

\[ \Delta \rho > 1000 \]

15 h observation of IGRJ18410-0535

Estimated clump size:

\[ R_{cl} \approx 8 \times 10^{11} \text{ cm} \]

\[ M_{cl} \approx 1.4 \times 10^{22} \text{ g} \]

60% Supergiant star radius
Extremely Clumpy Stellar Winds

- A brand new field: hydrodynamic simulations of the “ingestion of clumps” by NS in Supergiant HMXBs
  - Will the Clump survive the photoionization and gravitational focusing of the NS?
Extremely Clumpy Stellar Winds

• There is a general interest in the existence of very large clumps even from the community working on isolated massive stars:
  - Clumps affect the mass loss rate estimate from massive stars by large factors (>3)
  - Add uncertainties on our understanding of massive stars evolution
  - Impact on many fields of Astrophysics, including Cosmology (massive star feedback and Galaxy enrichment)

• Supergiant HMXBs offer the possibility to improve our knowledge on the massive star winds, exploiting the role of **NSs as probes of stellar wind properties**
Are CIR of O-B supergiant playing any role in the X-ray variability of Supergiant HMXB?

- Discrete Absorption Components → observations
- Present in all (observed) O-B supergiants
- Corotating Interaction Regions → theoretical model
- Azimuthal variation of wind velocity and density
- Time-scale = rotational period, days
- Collision of fast / slow winds

- Could SFXT flares be the outcomes of the NS interaction with the CIRs?
- Why no CIRs in classical systems?
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The INTEGRAL contribution

Continuous monitoring of bright HMXBs. After 13 yrs:

- Most accurate ephemeris in the literature
- Measurements of orbital period decay (in some cases)
  - Tidal interactions
  - Rapid mass transfer
- Study the long term energy dependence of the X-ray eclipse
  - Accretion wakes
  - Large and stable stellar wind structures
  - Systematic analysis still missing
- Swift/BAT and MAXI are also helping (Coley+ et al. 2015; Rodes-Roca+ 2015)
Bright Future Ahead

Future
**Future**

**INTEGRAL**: with another 10 years of data we could definitely improve further the ephemerides of many other sources and keep unveiling unpredicted behaviors of wind-fed systems (?)

**XMM-Newton NuSTAR Swift**: investigate the origin of the flaring behavior, the NS magnetic field strength and geometry → is it affecting the X-ray variability?

**Absorption & clumps**

**Astro-H**
Wind dynamics in bright sources

**Astrosat**

**eRosita**
Discover up to 240 new HMXBs (Doroshenko+ 2014)

**Einstein Probe**
Monitor fast soft X-ray transient

**LOFT-like**
Dynamics of clump ingestion and wind accretion
**Athena/X-IFU** will permit similar studies on the entire class of known HMXBs, going to limiting fluxes of 1/100 – 1/1000 lower than Vela X-1.