Nature of bright flares in supergiant fast X-ray transients

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SFXT: a phenomenon

• SFXT= Supergiant Fast X-ray Transients
• New class of high-mass X-ray binaries (HMXBs), heavily obscured in soft X-rays. Mostly discovered by INTEGRAL in hard X-rays (Sunyaev et al. 2003a,b; Grebenev et al. 2003, 2004; Lutovinov et al.2004; Molkov et al. 2004)
• Quiescent state $L_0 \sim 10^{33-34}$ erg/s
• Sporadic outburst sand flares up to $\sim 1000$ $L_0$
Persistent wind fed accreting X-ray pulsars with supergiant companions

“typical” HMXRBs, Vela X-1 like

A new class ->
Supergiant Fast X-ray Transients with supergiant companions transient emission, with short duration outbursts, typically few hours, less than Be/XRBs outbursts

highly absorbed HMXRBs discovered with INTEGRAL

Bright persistent disk-fed massive X-ray binaries (Cen X-3 like) in close orbits

Be/X-ray binaries typically Transient X-ray sources with Be companions

a growing number of members have been discovered with INTEGRAL

(from L. Sldoli’s talk)
Final lightcurve from Swift / XRT observations of \textit{IGR J11215-5952}
Figure 1. Light curves of the entire observation relative to MJD 54544.52698. Note the logarithmic scale in the bottom plot. The vertical dashed lines define the time period for the analysis shown in Figure 5, and the arrow in the center panel shows where the major outburst goes off scale.
SWXT bright flares: a model

- Non-stationary accretion from stellar wind
- Settling accretion mode onto magnetized NS ➔ hot shell around the magnetosphere
- In stable regime: accretion is controlled by plasma cooling (radiative if $L<10^{35}$ erg/s, or Compton if $L>10^{35}$ erg/s)
- Bright flare= instability of the entire shell on free-fall time
- Reason: sporadically magnetized stellar wind
Wind-fed accretors

- Matter is captured from (generally inhomogeneous) stellar wind.

3D, $\Gamma=5/3$, Blondin & Raymer 2012
Accretion Bondi-Hoyle-Littleton

\[ t_{cool} \ll t_{freefall} \]

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

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

\(-2GM/v^2\) (Bondi radius) characterizes bow shock location in the wind.
Bondi (supersonic) accretion regime

- If plasma cooling time $\ll$ free fall time
- Free fall with velocity $u_r = u_{ff}$
- Shock close to magnetosphere ($h_s \ll R_A$)
- $R_A$ is Alfvén radius determined from ram and magnetic pressure balance
- Plasma rapidly cools and enters magnetosphere due to Rayleigh-Taylor instability (Arons, Lea’76)
- Plasma carries angular momentum $j \sim \dot{M} \Omega_{\text{binary}} R_B^2$ (Illarionov, Sunyaev’75)
- Happens at high X-ray luminosities $L_x > 4 \times 10^{36} \text{ erg/s}$
Subsonic settling accretion without shock near magnetosphere

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

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

$t_{cool} \gg t_{freefall}$

$\dot{M} \sim \dot{M}_{Bondi} \left( \frac{t_{ff}}{t_{cool}} \right)^{1/3}$

Shakura et al. 2012

PNS-2014/Sankt-Petersbutg
Settling subsonic accretion regime

- If plasma cooling time $\gg$ free fall time
- Settling with velocity $u_r = f(u)u_{ff}$, $f(u) < 1$, determined by plasma cooling rate (Compton cooling, radiative cooling)

$$f(u) \approx \left(\frac{t_{ff}}{t_{cool}}\right)^{1/3}$$

- Happens for moderate X-ray luminosities $L_x < 4 \times 10^{36}$ erg/s (Shakura et al. 2012)
Vertical structure

• Hydrostatic equilibrium

\[- \frac{1}{\rho} \frac{dP}{dR} - \frac{GM}{R^2} = 0\]

Adiabatic solution:

\[\frac{\mathcal{R}T}{\mu_m} = \frac{\gamma - 1}{\gamma} \frac{GM}{R}\]

\[\gamma = \frac{5}{3} \quad \rho(R) = \rho(R_A) \left(\frac{R_A}{R}\right)^{3/2}\]
Alfven surface: from gas pressure balance
(cf. in supersonic accretion – from dynamic pressure balance!)

- Gas pressure balance

\[ P_g = \frac{\rho gRT}{\mu_m} = P_m = \frac{B(R_A)^2}{8\pi} \]

- Change density from mass continuity

\[ \rho(R_A) = \frac{\dot{M}}{4\pi u_R(R_A)R_A^2} \]

Settling accretion:

\[ f(u) = \frac{u_R}{\sqrt{2GM/R}} < 1 \]

\[ R_A = \left[ \frac{4\gamma}{\gamma - 1} f(u)K_2 \frac{\mu^2}{\dot{M}\sqrt{2GM}} \right]^{2/7} \]

\[ K_2 \approx 7.6, \ f(u) \approx 0.1 \]

(Arons & Lea, 1976)

model
Plasma entering magnetosphere

- **Critical temperature:**

\[ \mathcal{R} T_{cr} = \frac{\cos \chi \, \mu_m G M}{2\kappa R_A \, R_A} \]

\[ \kappa = 1/(\text{curvature radius}) \]

Stable : \( T > T_{cr} \)

Unstable : \( T < T_{cr} \)

- **Effective gravity:**

\[ g_{eff} = \frac{G M}{R_A^2} \cos \chi \left(1 - \frac{T}{T_{cr}}\right) \]

(Elsner, Lamb’77)

Stability of magnetosphere increases when it becomes more curved (concave)
Two cooling regimes

- Compton cooling time:

\[ t_C = \frac{3}{2\mu_m} \frac{\pi R_A^2 m_e c^2}{\sigma_T L_x} \approx 10.6[s] R_9 M_{16}^{-1} \]

\[ \frac{dT}{dt} = -\frac{T - T_x}{t_C} \]

At given \( L_x \) cooling occurs at \( R<R_x \). At higher radii – Compton heating takes place.

Radiative cooling time

\[ t_{rad} \approx 300 s \left( \frac{R_A}{10^9 \text{ cm}} \right) \left( \frac{L_x}{10^{36} \text{ erg/s}} \right)^{-1} \left( \frac{f(u)}{0.1} \right), \quad \frac{dT}{dt} \sim \sqrt{T} \]
Plasma entry rate

\[
< u > \approx \left( \frac{t_{\text{ff}}}{t_{\text{cool}}} \right)^{1/3} \sqrt{\frac{2GM}{R_A}} = \left( \frac{t_{\text{ff}}}{t_{\text{cool}}} \right)^{1/3} u_{\text{ff}}
\]

\[
R_{A,C} \approx 10^9 \text{ cm } \dot{M}_{16}^{-2/11} \mu_{30}^{6/11}
\]

\[
R_{A,\text{rad}} \approx 10^9 \text{ cm } \dot{M}_{16}^{-6/27} \mu_{30}^{16/27}
\]

\[
f(u)_C = \frac{< u >_c}{u_{\text{ff}}} \sim 0.22 \dot{M}_{16}^{4/11} \mu_{30}^{-1/11}
\]

\[
f(u)_{\text{rad}} = \frac{< u >_{\text{rad}}}{u_{\text{ff}}} \sim 0.1 \dot{M}_{16}^{6/27} \mu_{30}^{2/27}
\]
Application to real sources

Example light curves of Vela X−1, 4U 1907+09 and GX 301−2 (HEASARCH archive data).

- Observed as sudden drops in X-ray luminosity with a duration of a few 100-1000 s
- Most studied in: Vela X-1, 4U1907+09, GX 301-2, etc.

Shakura N et al. MNRAS 2013;428:670-677
Vela X-1 off state (Doroshenko et al. 2011)

Suzaku XIS data

High state, $L_x \sim 3 \times 10^{36}$

Low state: spectrum is softer $L_x \sim 3 \times 10^{35}$

Most important: At off-state, phase of hard X-ray pulse changes by 90 degrees
cusp is almost stable
Pulse profiles of Vela X-1 as observed by Suzaku (in normalized counts from Doroshenko et al. 2011) at normal luminosity levels (four upper panels) and in an ‘off’ state (four lower panels).

- **High state:** Pulse maximum in the hardest channels is shifted by ~90 deg relative to low state.

- **Low state:** Pencil-beam at $E>E_{\text{cyc}}$, vacuum polarization effects at $E_{\text{vac}}<E<E_{\text{cyc}}$, absorption dominates scattering below $E_{\text{vac}}$.

Shakura N et al. MNRAS 2013;428:670-677
Back to SFXT
SFXT IGR J11215, $P^* = 187$ s

Sidoli et al. 2007
Bright flares in SFXT (INTEGRAL, 17-50 keV)
\[ \Delta E_{38} = (3.3 \pm 1.0)L_{34}^{0.77 \pm 0.13} \]

\[ \Delta M \approx \frac{2}{3} \frac{\dot{M}_a}{f(u)} t_{ff}(R_B) \quad \Delta M_{\text{rad}} \approx 8 \times 10^{17} [g] L_{34}^{7/9} v_8^{-3} \mu_{30}^{-2/27} \]

\[ \Delta E = 0.1 \Delta M c^2 \quad v_8 \approx 0.62 \]
Role of stellar wind magnetic field

Solar wind: Tangent magnetic field \(\rightarrow\) smaller solar wind velocity by a factor of 2 (Milovanov & Zeleny 2006)
Magnetized winds from O-B stars

- ~10% of hot O-B stars are known to have magnetic fields up to a few kG (Braithwaite 2013)

<table>
<thead>
<tr>
<th>Table 1. Summary of current knowledge of magnetic fields in early-type stars.</th>
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<tr>
<td>Magnetic subset &amp; Chemical peculiarities (Ap/Bp) &amp; Fossil field</td>
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<tr>
<td>( \lesssim 10% ) &amp; Fossil field</td>
</tr>
<tr>
<td>Rest of population &amp; Subgauss fields detected in two stars, probably present in all stars? &amp; No direct detections</td>
</tr>
<tr>
<td>&amp; Failed fossil field &amp; Indications of magnetic activity</td>
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<td>&amp; &amp; Subsurface convection dynamo</td>
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How to produce an outburst?

- Observed amplitude of outbursts up to 1000 times as the quiescent value ($\sim 10^{34} - 10^{35}$ erg/s) = low state (radiative plasma cooling)

- At low state:

\[
L_{x,\text{low}} \simeq 5 \times 10^{35} \left[ \frac{\text{erg}}{\text{s}} \right] f(u)_{\text{rad}} \left( \frac{M}{10 M_\odot} \right)^{2.76-2/3} \left( \frac{v_\infty}{1000 \text{km/s}} \right)^{-1} \left( \frac{v_{w,\text{NS}}}{500 \text{km/s}} \right)^{-4} \left( \frac{P}{10^4} \right)^{-4/3},
\]

\[
f(u)_{\text{rad}} = \frac{<u>_{\text{rad}}}{u_{ff}} \sim 0.1 L_{36}^{2/9} \mu_{30}^{2/27} \sim 0.036 L_{34}^{2/9} \mu_{30}^{2/27},
\]

- Magnetized wind $\Rightarrow$ Decrease wind velocity (factor 2) $\Rightarrow$
  increase in Bondi accretion rate + reconnection $\Rightarrow$ $f(u)=1$ $\Rightarrow$

\[
L_{x,\text{outburst}} \simeq 2^5 \times 10 \times L_{x,\text{low}} \sim (300 - 1000) L_{x,\text{low}}
\]
Plasma without magnetic field entries magnetosphere due to RT instability

Plasma with magnetic field opens magnetospheric boundary by magnetic reconnection

26.06.2013
Difference between SFXT and steady HMXB

- Lower mean accretion rate through the magnetosphere during the settling accretion (factor $f(u)<<1$)
- Time for reconnection: $t_{\text{rec}} \sim R/v_{\text{rec}} < t_{\text{inst}} \sim t_{\text{ff}}/f(u)$
- $f(u) < v_{\text{rec}}/v_{\text{ff}} \sim \text{reconnection efficiency}<<1$
- At high accretion rates ($f(u)\sim1$) no time for reconnection to occur
Conclusions

• At < $4 \times 10^{36}$ erg/s wind-fed pulsars can be at subsonic settling accretion $\Rightarrow$ accretion rate onto NS is determined by the ability of plasma to enter magnetosphere.

• Two states of plasma entrance the magnetosphere depending on cooling mechanism:
  
  \( L > 3 \times 10^{35} \) erg/s Compton cooling dominates in the equatorial region of magnetosphere $\Rightarrow$ HIGH state
  
  \( L < 3 \times 10^{35} \) erg/s radiative cooling dominates in the equatorial region of magnetosphere $\Rightarrow$ LOW state.
  
  Transition from high to low state is accompanied by $\sim 90$ degree phase shift of hard pulse maximum

• Settling accretion can be realized at low (quiescent) states of SFXTs. SFXT outbursts can be triggered by magnetic field in stellar winds of O-B supergiants (low velocity + Bondi accretion in outbursts)
References


Thank you for your attention