Nature of bright flares in supergiant fast X-ray transients

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Based on 2014MNRAS.442.2325
arXiv:1405.5707

Zeldovich-100, PNS-2014,
Sankt-Petersburg

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 $L_0 \sim 10^{33\text{-}34}$ erg/s
- Sporadic outburst sand flares up to ~1000 L_0

HMXRB classes: a summary

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

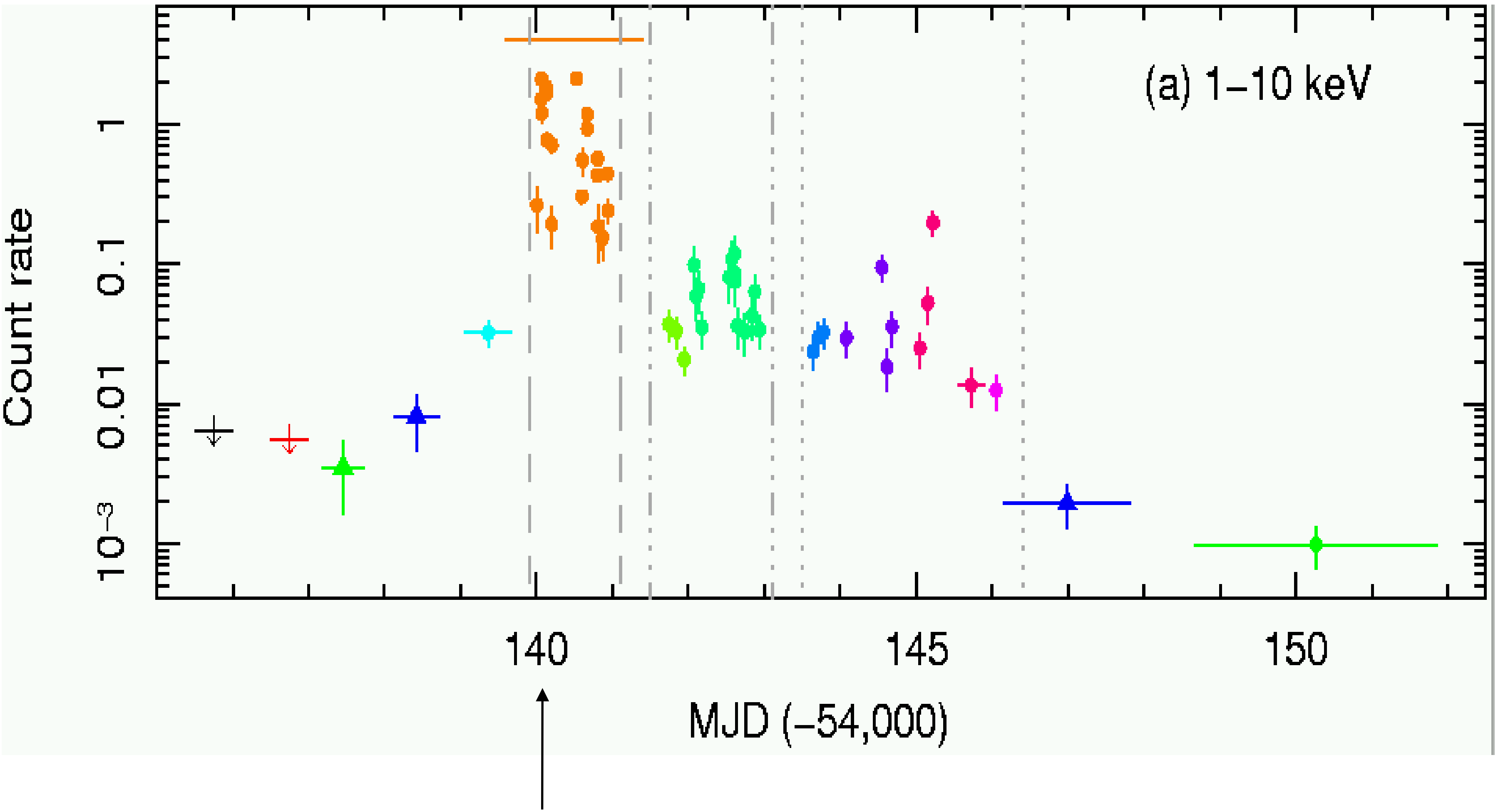
Be/X-ray binaries
typically Transient X-ray sources
with Be companions

a growing number of members
have been discovered
with INTEGRAL

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

(from L. SIdoli’s talk)

Final lightcurve from Swift / XRT observations of ***IGR J11215-5952***



9th February 2007

Romano et al. 2007

Bright flares in SFXT

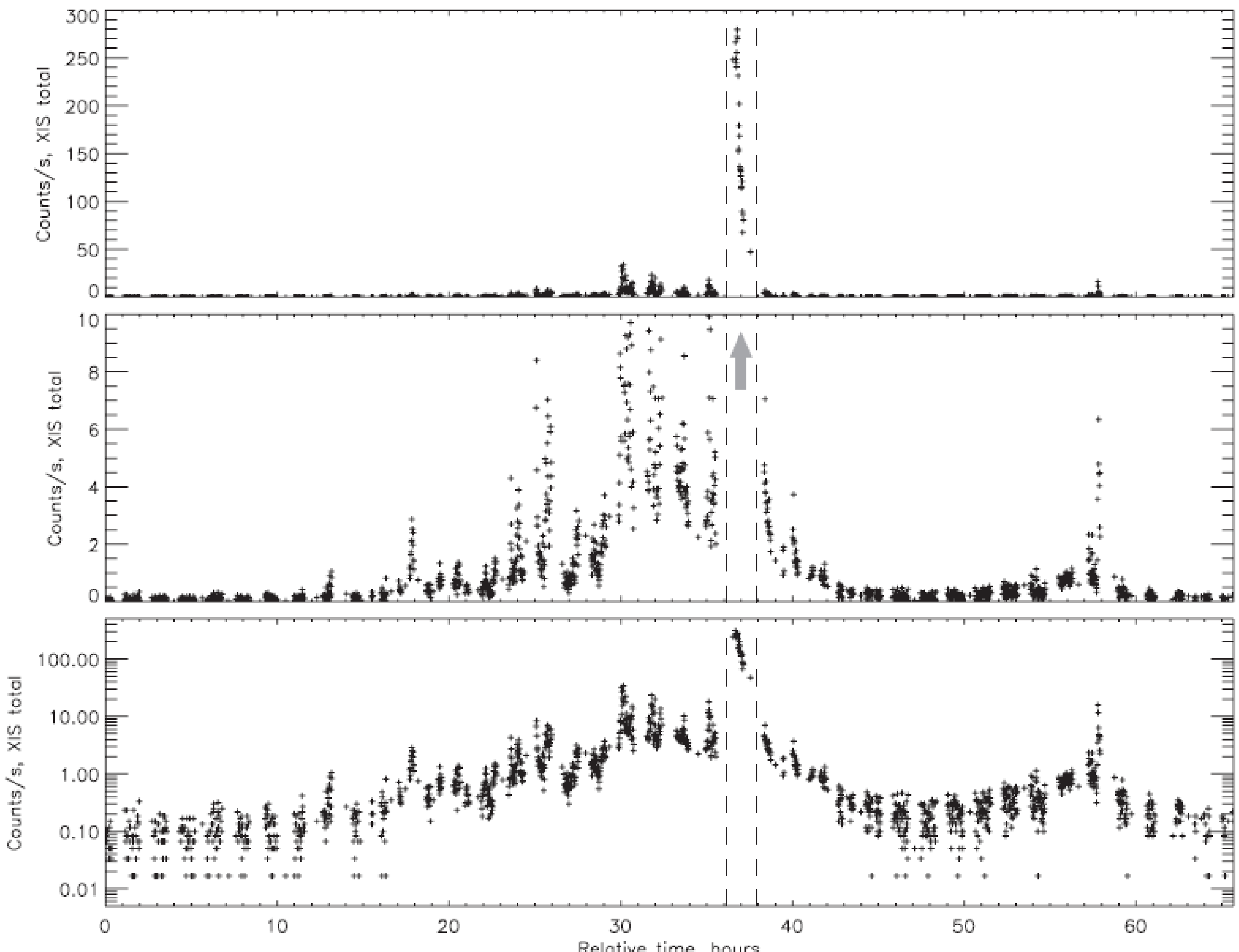


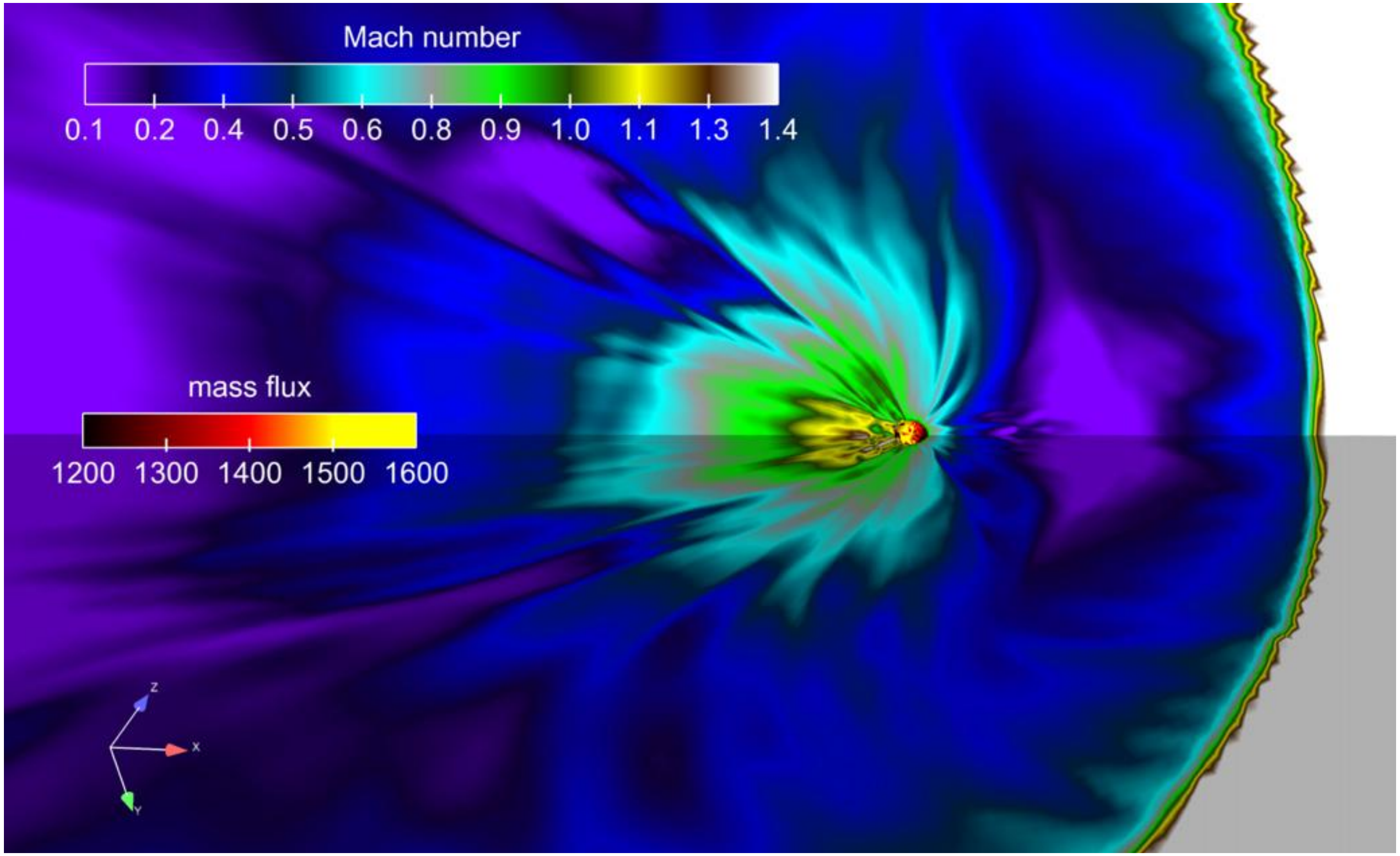
Figure 1. Light curves of the entire observation relative to MJD 54544.52698. Note the logarithmic scale in the bottom plot. The vertical dashed lines define the time period for the analysis shown in Figure 5, and the arrow in the center panel shows where the major outburst goes off scale.

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 etire shell on free-fall time
- Reason: sporadically magnetized stellar wind

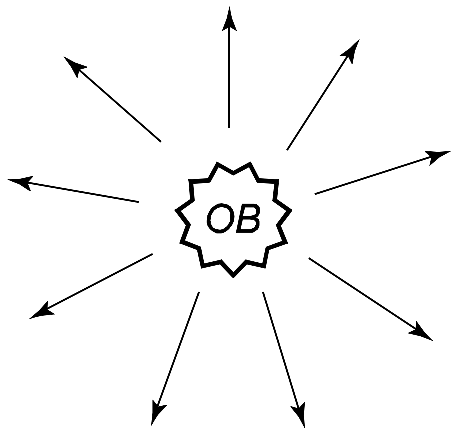
Wind-fed accretors

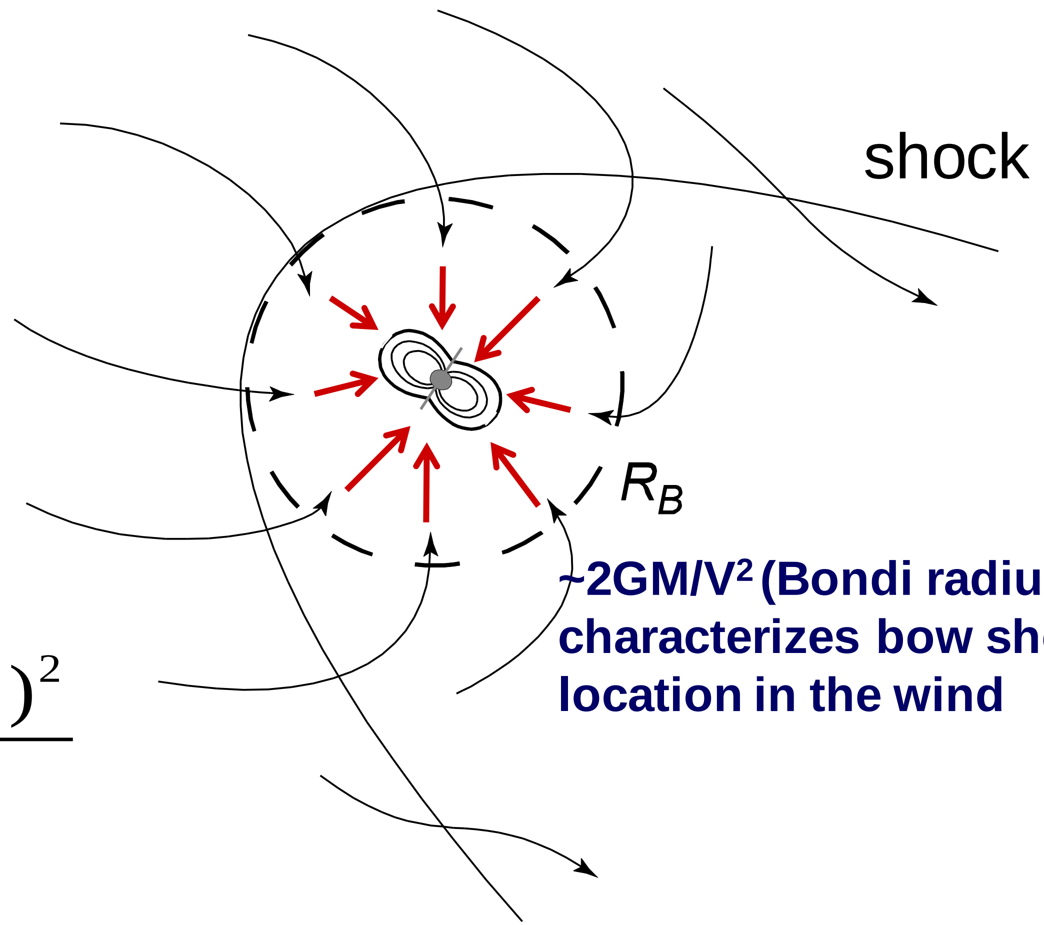
- **Matter is captured from (generally inhomogeneous) stellar wind.**



3D, Γ=5/3, Blondin & Raymer 2012

Accretion Bondi-Hoyle-Littleton





$$t_{cool} << t_{freefall}$$

~2GM/V² (Bondi radius) characterizes bow shock location in the wind

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

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

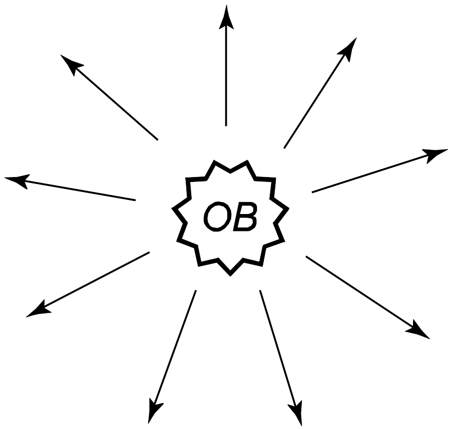
Bondi (supersonic) accretion regime

- If plasma cooling time << free fall time
- Free fall with velocity $u_r = u_{ff}$
- Shock close to magnetosphere ($h_s \ll R_A$)
- R_A is Alfven 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 $j \sim \dot{M}\Omega_{binary}R_B^2$

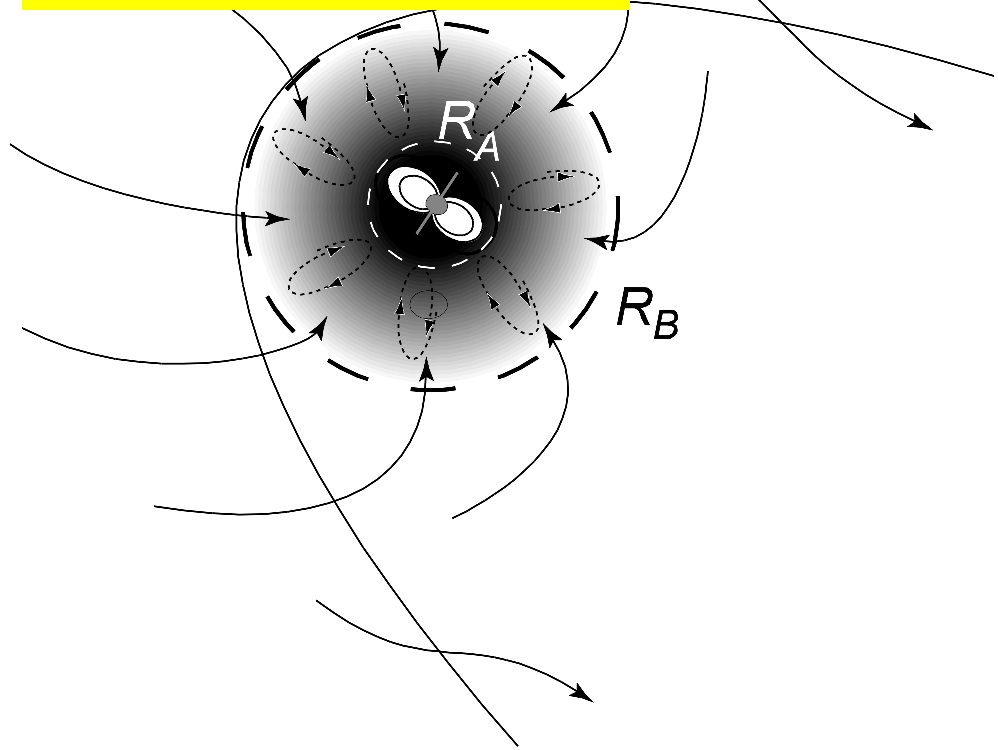
  (Illarionov, Sunyaev'75)
- Happens at high X-ray luminosities $L_x > 4 \times 10^{36}$ erg/s

Subsonic settling accretion without shock near magnetosphere

Matter subsonically settles down inside the the shell with radius ~R_B



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



$$t_{cool} >> t_{freefall}$$

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

Shakura et al. 2012

Settling subsonic accretion regime

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

$$\dot{M} = 4\pi R_A^2 \rho(R_A) f(u) \sqrt{\frac{2GM}{R_A}}$$

R_A is Alfven radius from gas and magnetic pressure balance

- **$f(u) \approx (t_{ff}/t_{cool})^{1/3}$**
- **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:
$$\frac{\Re T}{\mu_m}=\frac{\gamma-1}{\gamma}\frac{GM}{R}$$

$$\gamma = 5/3 \qquad \rho(R)=\rho(R_A)\left(\frac{R_A}{R}\right)^{3/2}$$

Alfven surface: from gas pressure balance (cf. in supersonic accretion – from dynamic pressure balance!)

- Gas pressure balance

$$P_g = \frac{\rho \Re T}{\mu_m} = P_m = \frac{B(R_A)^2}{8\pi}$$

- Change density from mass continuity

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

Settling accretion:

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

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

K_2~7.6 , f(u)~0.1 (Arons & Lea, 1976) model

Plasma entering magnetosphere

- **Critical temperature:**

$$\Re T_{cr} = \frac{\cos\chi}{2\kappa R_A}\frac{\mu_m GM}{R_A}$$

$$\kappa = 1/(curvature\,radius)$$

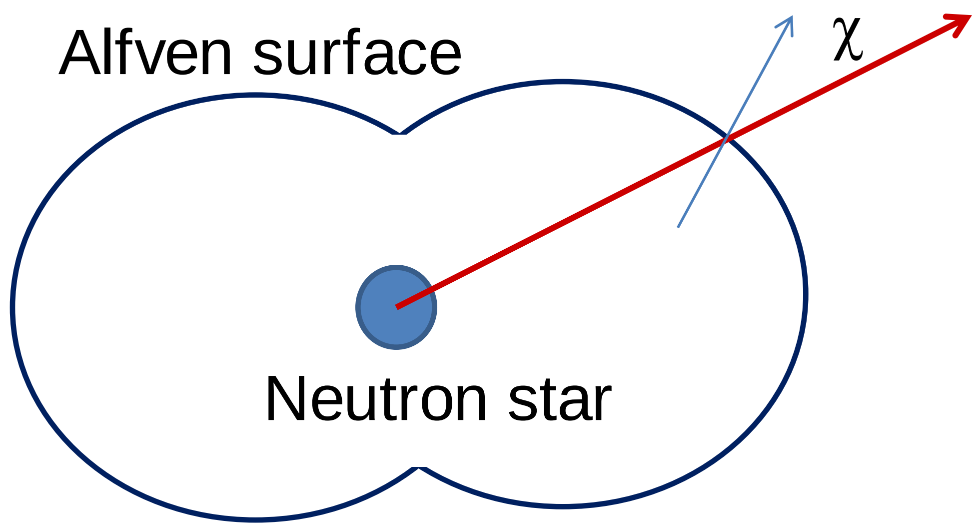
Stable : $T > T_{cr}$

Unstable : $T < T_{cr}$

- **Effective gravity:**

$$g_{eff} = \frac{GM}{R_A^2}\cos\chi\left(1 - \frac{T}{T_{cr}}\right)$$

(Elsner, Lamb'77)



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

Two cooling regimes

- Compton cooling time:

$$t_C = \frac{3}{2\mu_m}\frac{\pi R_A^2 m_e c^2}{\sigma_T L_x} \approx 10.6[\mathrm{s}] R_9^2 \dot{M}_{16}^{-1} \qquad \frac{dT}{dt} = -\frac{T - T_x}{t_C}$$

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

Radiative cooling time

$$t_{rad} \approx 300s \left(\frac{R_A}{10^9 cm}\right)\left(\frac{L_x}{10^{36} erg/s}\right)^{-1}\left(\frac{f(u)}{0.1}\right), \qquad \frac{dT}{dt} \sim \sqrt{T}$$

Plasma entry rate

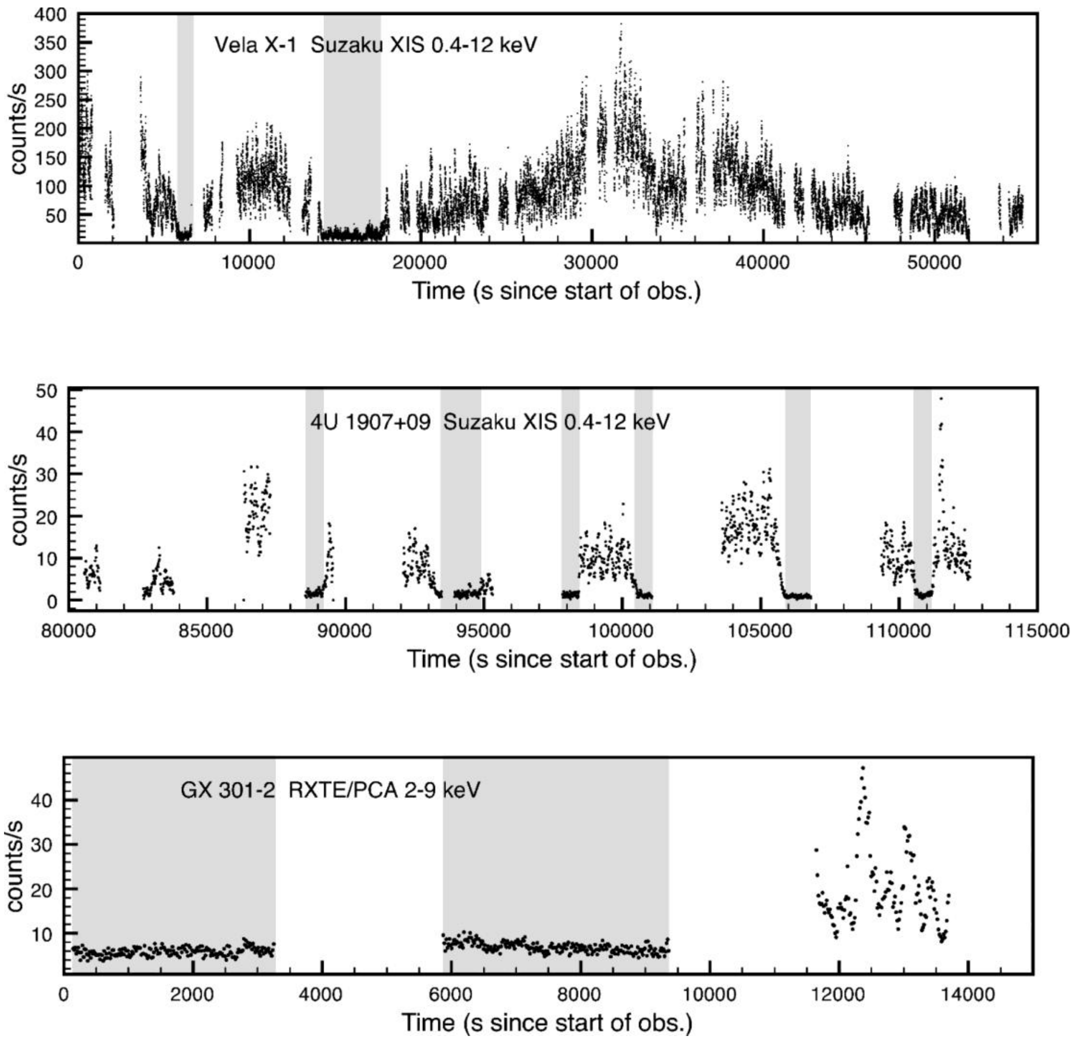
$$< u > \approx \left(\frac{t_{ff}}{t_{cool}} \right)^{1/3} \sqrt{\frac{2GM}{R_A}} = \left(\frac{t_{ff}}{t_{cool}} \right)^{1/3} u_{ff}$$

$$R_{A,C} \approx 10^9 cm \ \ \dot{M}_{16}^{-2/11} \mu_{30}^{6/11} \qquad f(u)_C = \frac{< u >_c}{u_{ff}} \sim 0.22 \dot{M}_{16}^{4/11} \mu_{30}^{-1/11}$$

$$R_{A,rad} \approx 10^9 cm \ \ \dot{M}_{16}^{-6/27} \mu_{30}^{16/27} \qquad f(u)_{rad} = \frac{< u >_{rad}}{u_{ff}} \sim 0.1 \dot{M}_{16}^{6/27} \mu_{30}^{2/27}$$

Application to real sources

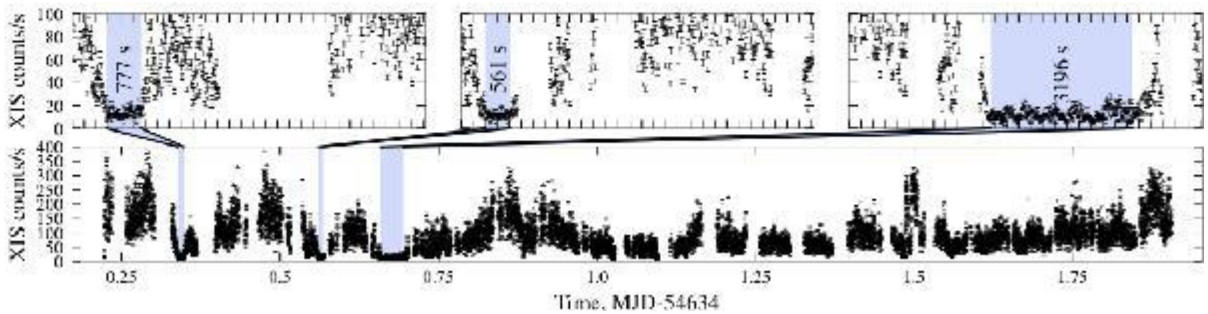
Example light curves of Vela X−1, 4U 1907+09 and GX 301−2 (HEASARCH archive data).



- 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.

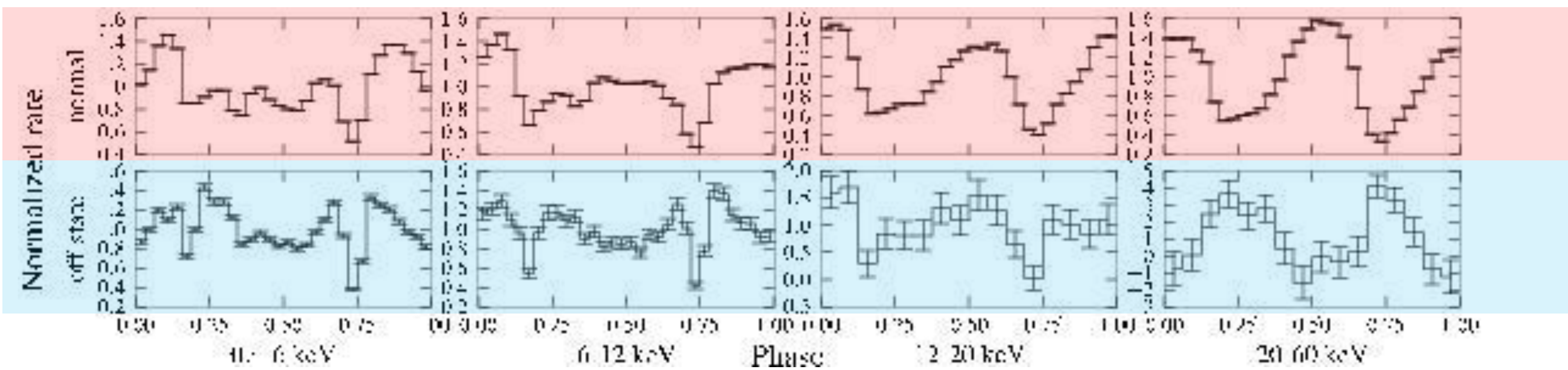
Shakura N et al. MNRAS 2013;428:670-677

Vela X-1 off state (Doroshenko et al. 2011)



Suzaku XIS data

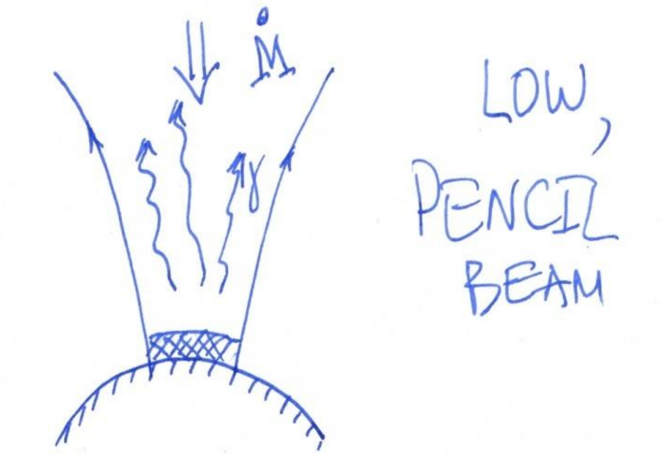
High state, L_x ~3x10^{36}

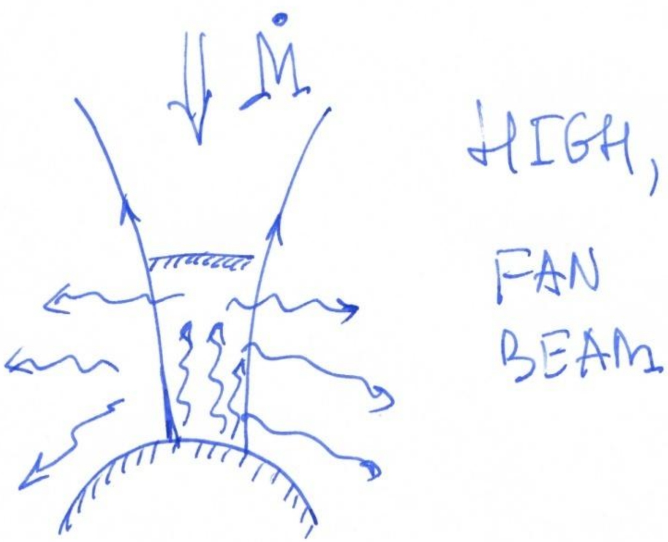


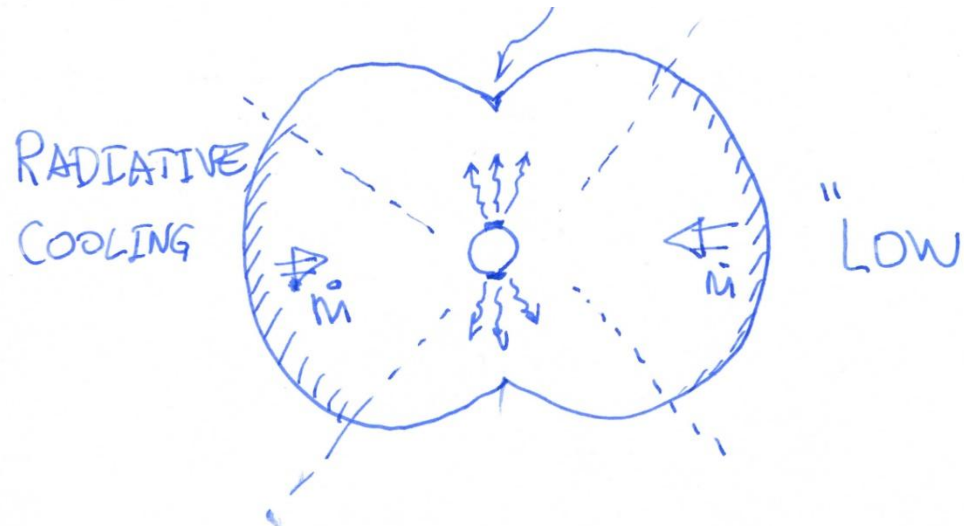
Low state: spectrum is softer L_x~3x10^{35}

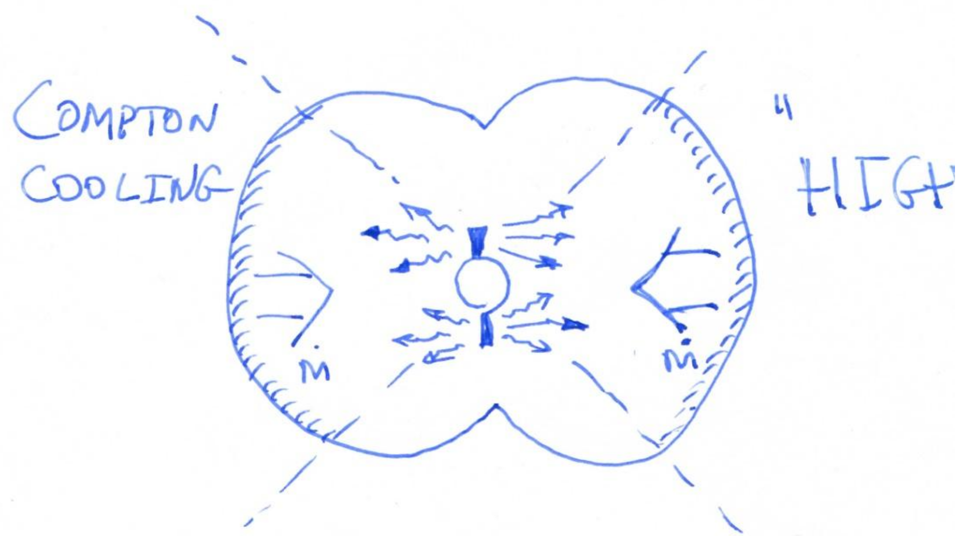
Most important: At off-state, phase of hard X-ray pulse changes by 90 degrees

cusp is almost stable

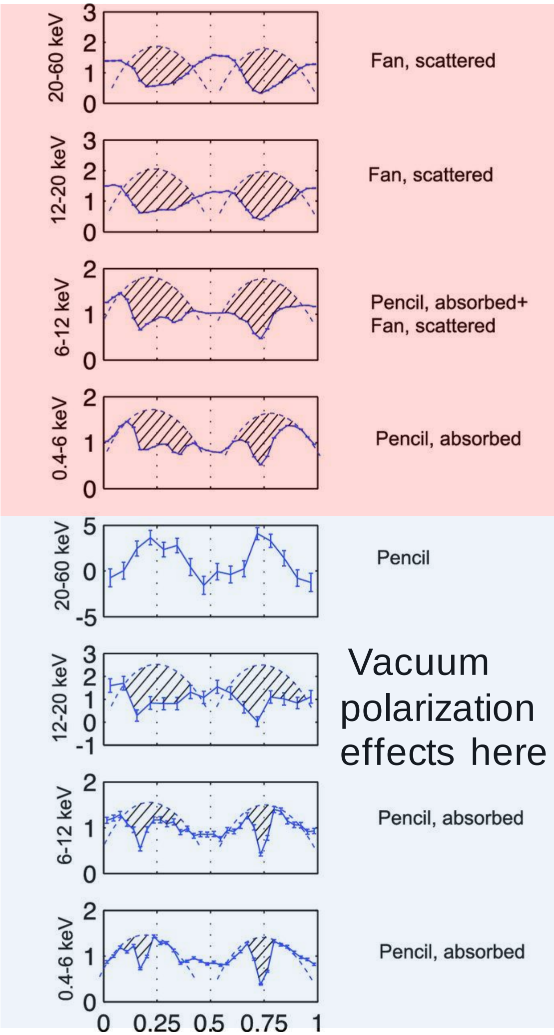








Pulse profiles of Vela X−1 as observed by Suzaku (in normalized counts from Doroshenko et al. 2011) at normal luminosity levels (four upper panels) and in an 'off' state (four lower panels).



- High state: Pulse maximum in the hardest channels is shifted by ~90 deg relative to low state
- Low state: Pencil-beam at $E>E_{cyc}$, vacuum polarization effects at $E_{vac}<E<E_{cyc}$, absorption dominates scattering below E_{vac}

Shakura N et al. MNRAS 2013;428:670-677

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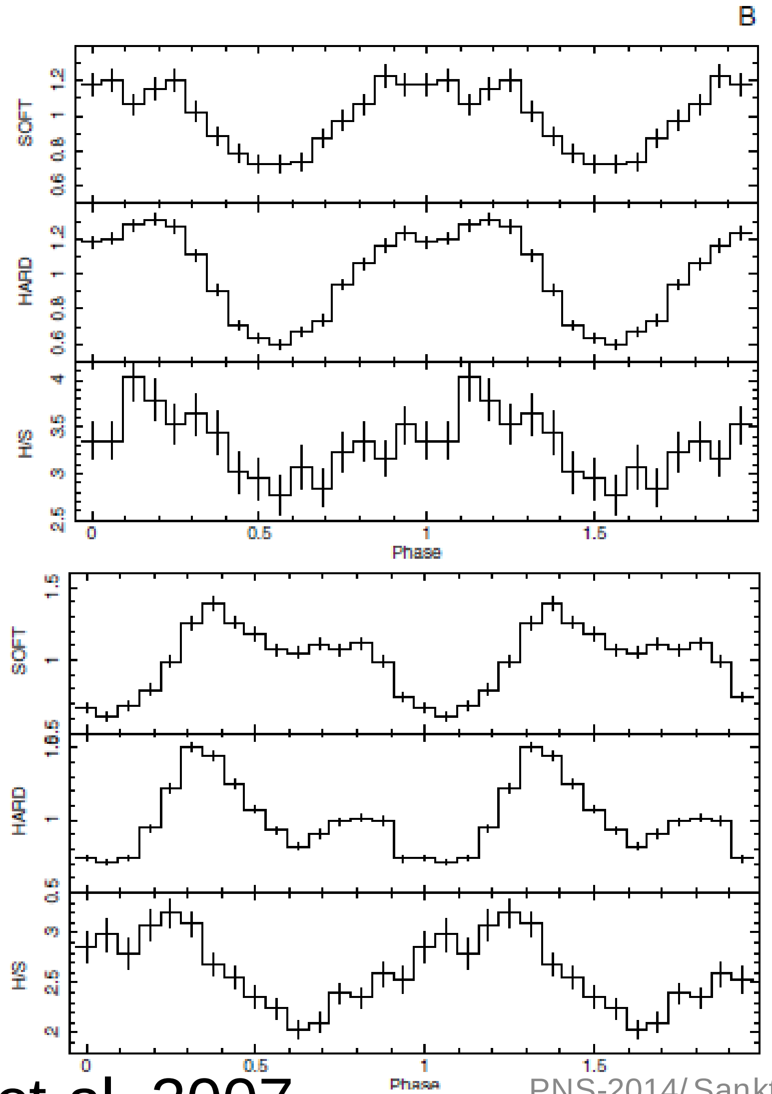
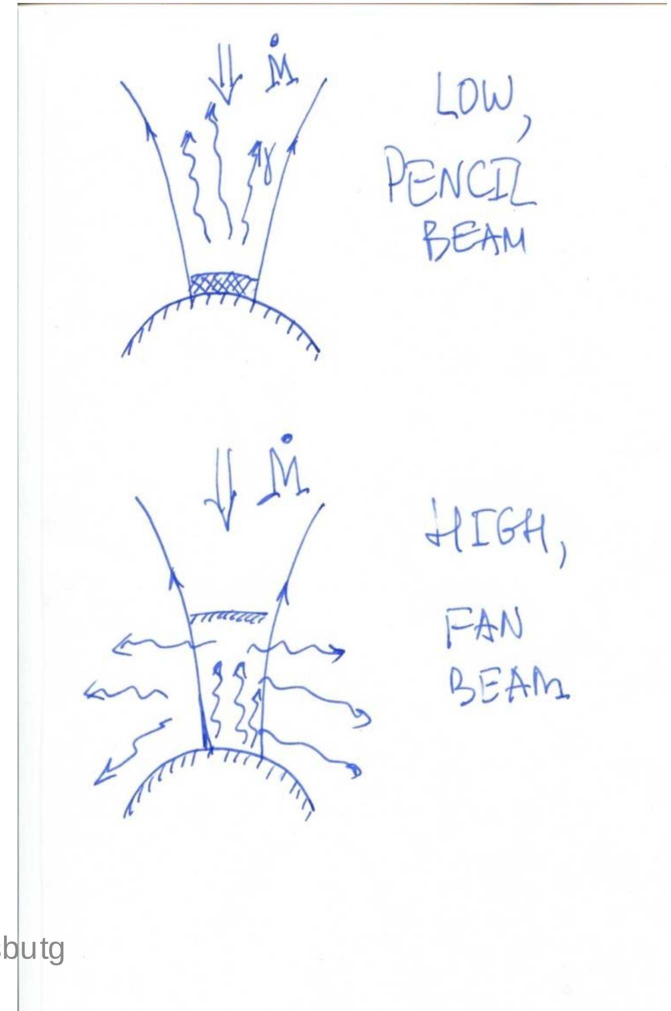
Back to SFXT

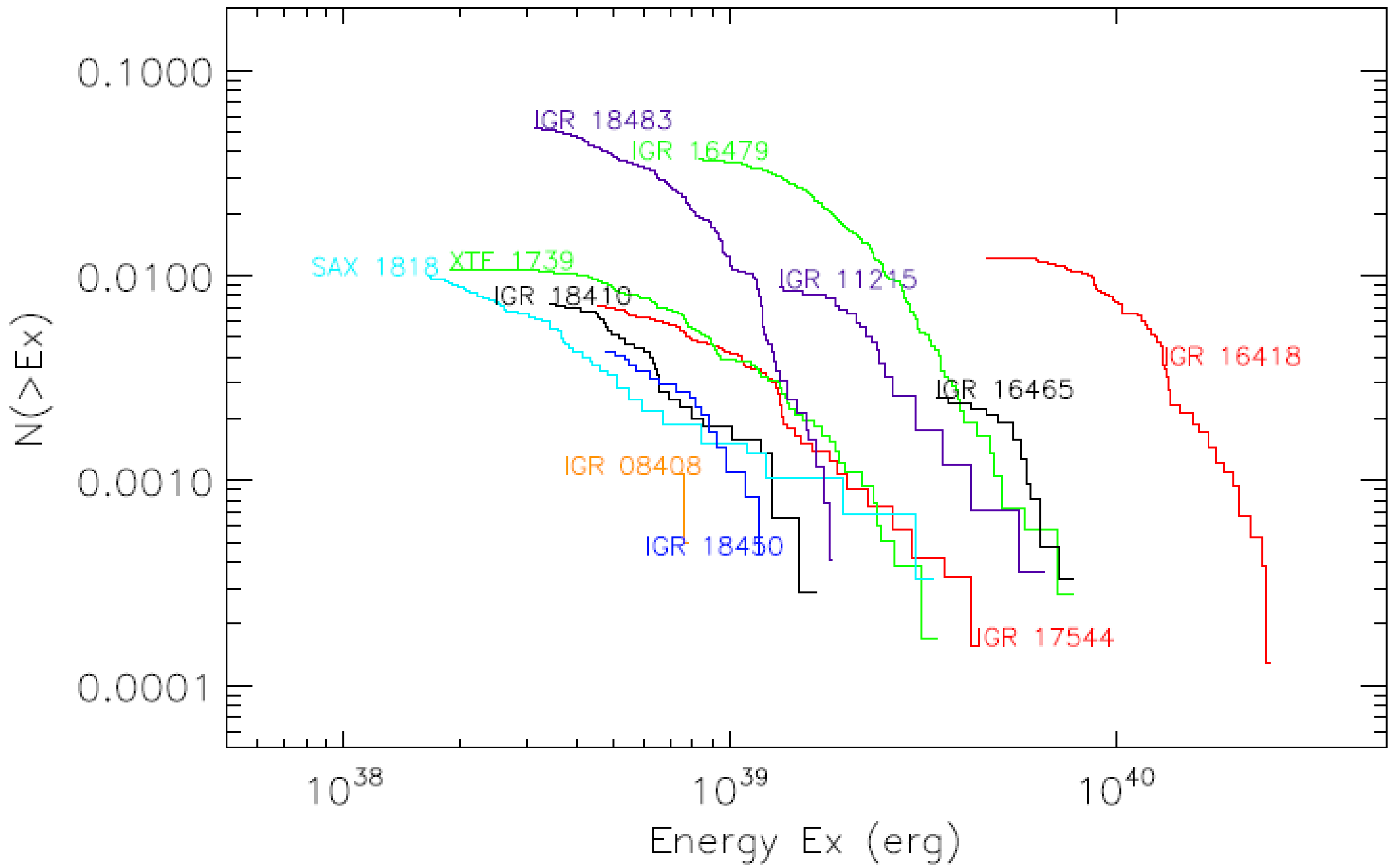
SFXT IGR J11215, P*=187 s

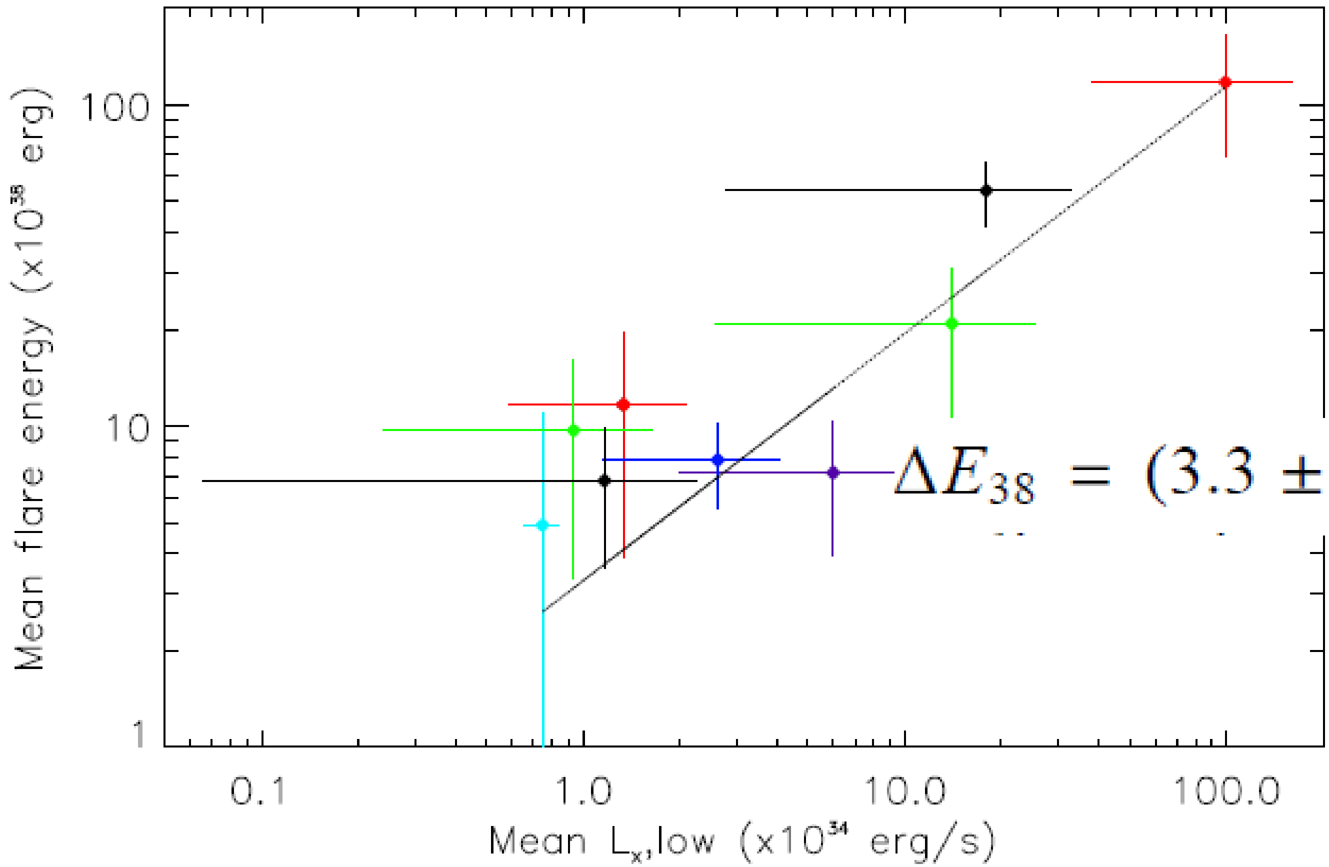




Sidoli et al. 2007

Bright flares in SFXT (INTEGRAL, 17-50 keV)



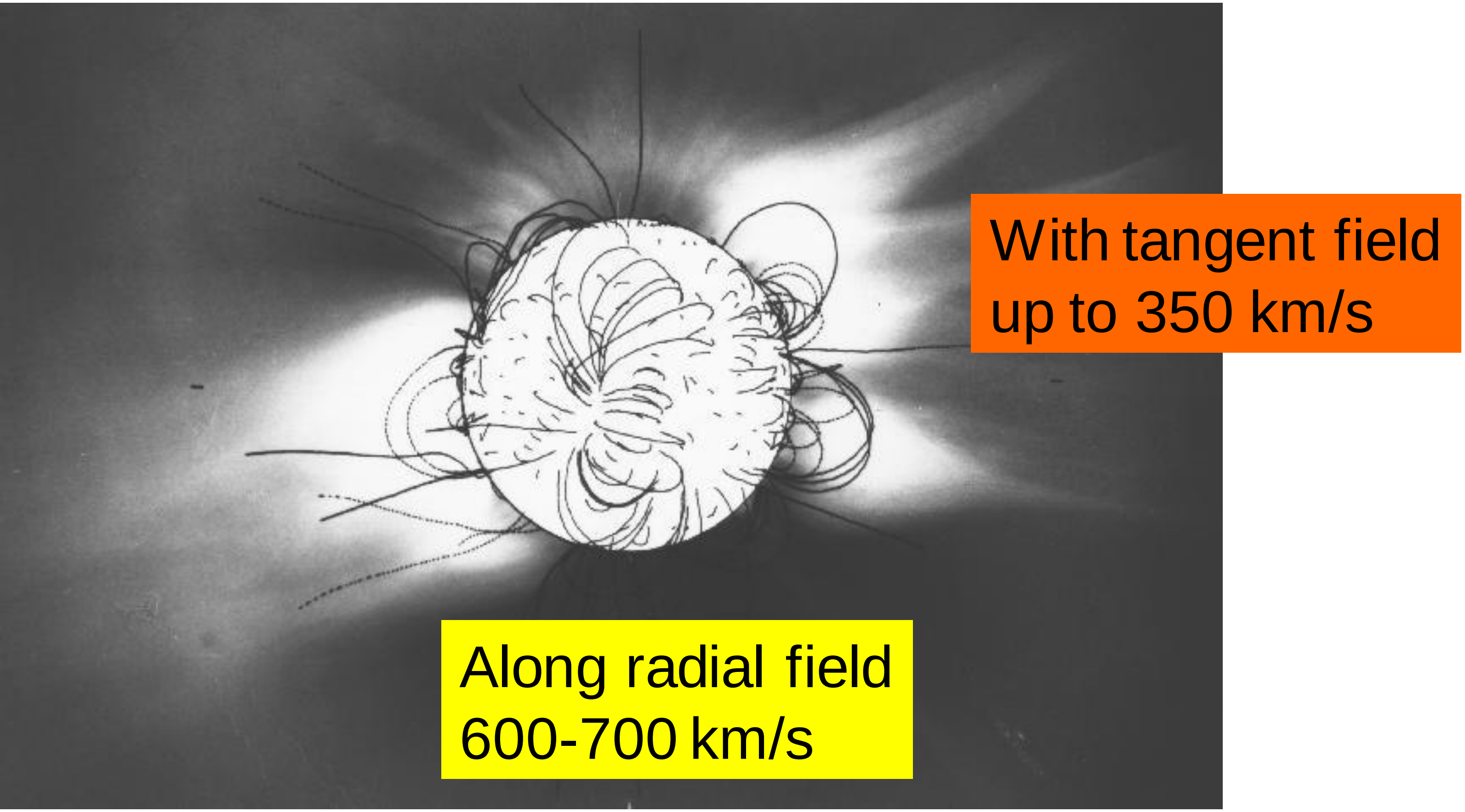


$$\Delta E_{38} = (3.3 \pm 1.0) L_{34}^{0.77 \pm 0.13}$$

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

$$\Delta E = 0.1 \Delta M c^2 \qquad v_8 \sim 0.62$$

Role of stellar wind magnetic field



Solar wind: Tangent magnetic field ➔ 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 1. Summary of current knowledge of magnetic fields in early-type stars.

	A and late B	**O and early B**
Magnetic subset ($\lesssim 10\%$)	$B \sim 200$ G to 30 kG steady, large-scale Chemical peculiarities (Ap/Bp) *Fossil field*	$B \sim 200$ G to 10 kG steady, large-scale *Fossil field*
Rest of population	Subgauss fields detected in two stars, probably present in all stars? *Failed fossil field*	No direct detections Indications of magnetic activity *Subsurface convection dynamo*

How to produce an outburst?

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

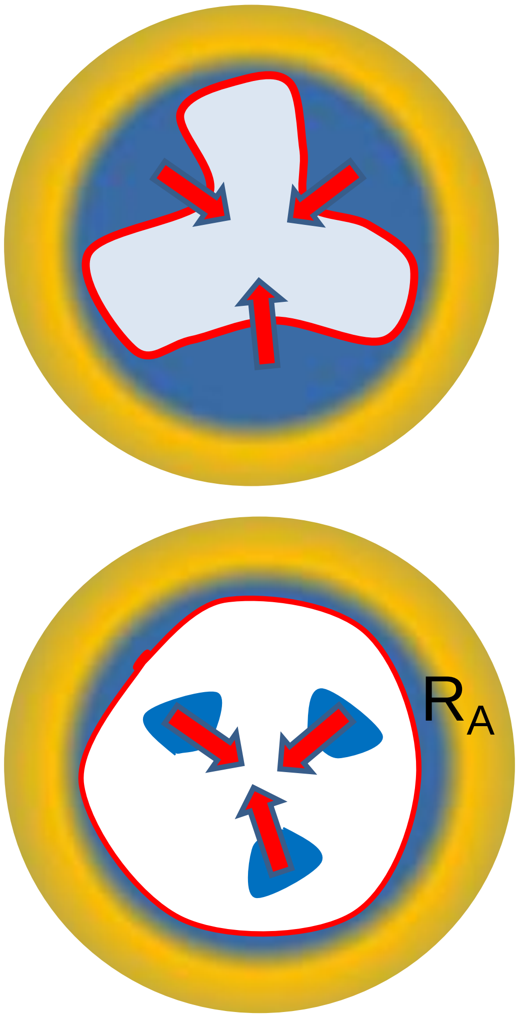
$$L_{x,low} \simeq 5\times 10^{35}[\frac{erg}{s}] f(u)_{rad} \left(\frac{M}{10M_{\odot}}\right)^{2.76-2/3} \left(\frac{v_{\infty}}{1000km/s}\right)^{-1} \left(\frac{v_{w,NS}}{500km/s}\right)^{-4} \left(\frac{P}{10d}\right)^{-4/3}$$

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

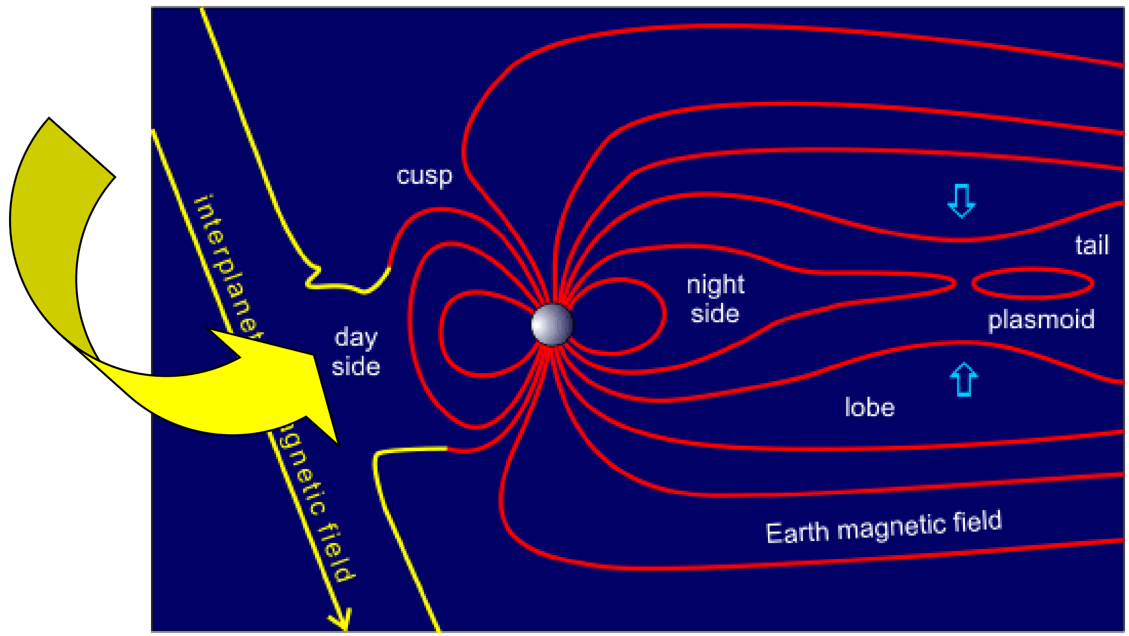
- **Magnetized wind → Decrease wind velocity (factor 2) → increase in Bondi accretion rate + reconnection → f(u)=1 →**

$$L_{x,\mathrm{outburst}} \simeq 2^5 \times 10 \times L_{x,low} \sim (300-1000) L_{x,low}$$

Plasma without magnetic field entries magnetosphere due to RT instability



Plasma with magnetic field opens magnetospheric boundary by magnetic reconnection



Difference between SFXT and steady HMXB

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

Conclusions

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

- Two states of plasma entrance the magnetopshere depending on cooling mechanism:

  L>3 x10^{35} erg/s Compton cooling dominates in the equatorial region of magnetosphere ➔ HIGH state

  L<3 x10^{35} erg/s radiative cooling dominates in the equatorial region of magnetosphere ➔ LOW state.

  Transition from high to low state is accompanied by ~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

1. Theory of quasi-spherical accretion in X-ray pulsars. Shakura, PK, Kochetkova, Hjalmarsdotter (MNRAS, 2012, 420, 216; arXiv:1110.3701)

2. On the nature of "Off" states in slowly rotating low-luminosity X-ray pulsars, Shakura,PK, Hjalmarsdotter, 2013, MNRAS, 428, 670 (arXiv:1209.4962)

3. Bright flares in Supergiant Fast X-ray Transients, Shakura, PK, Sidoli, Paizis, 2014, MNRAS 442, 2325

Thank you for your attention