A new mechanism for state transition in Be X-ray binaries

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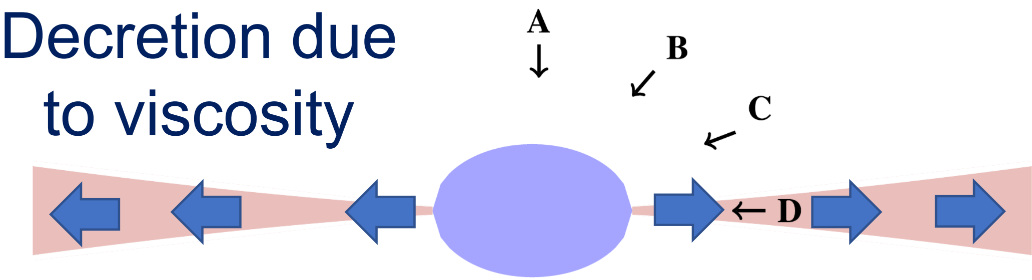
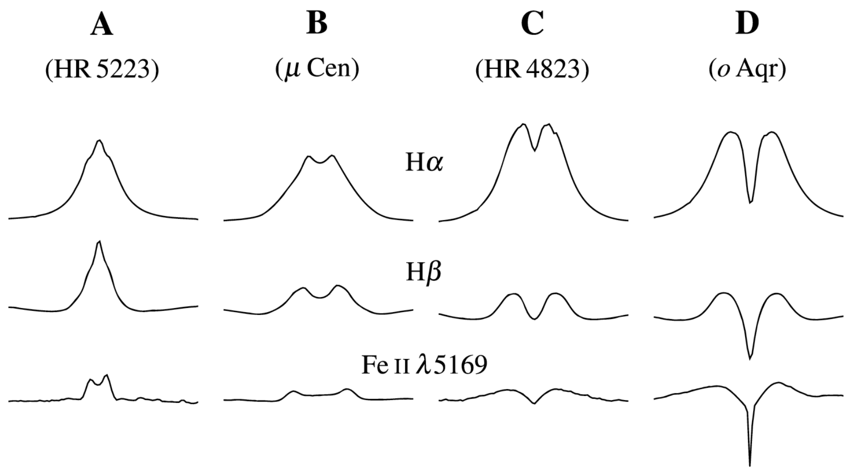
Be stars

- Rapidly rotating, early-type stars with Balmer lines in emission
- Central star surrounded by circumstellar *decretion disk* made of gas ejected from the star

Decretion due to viscosity

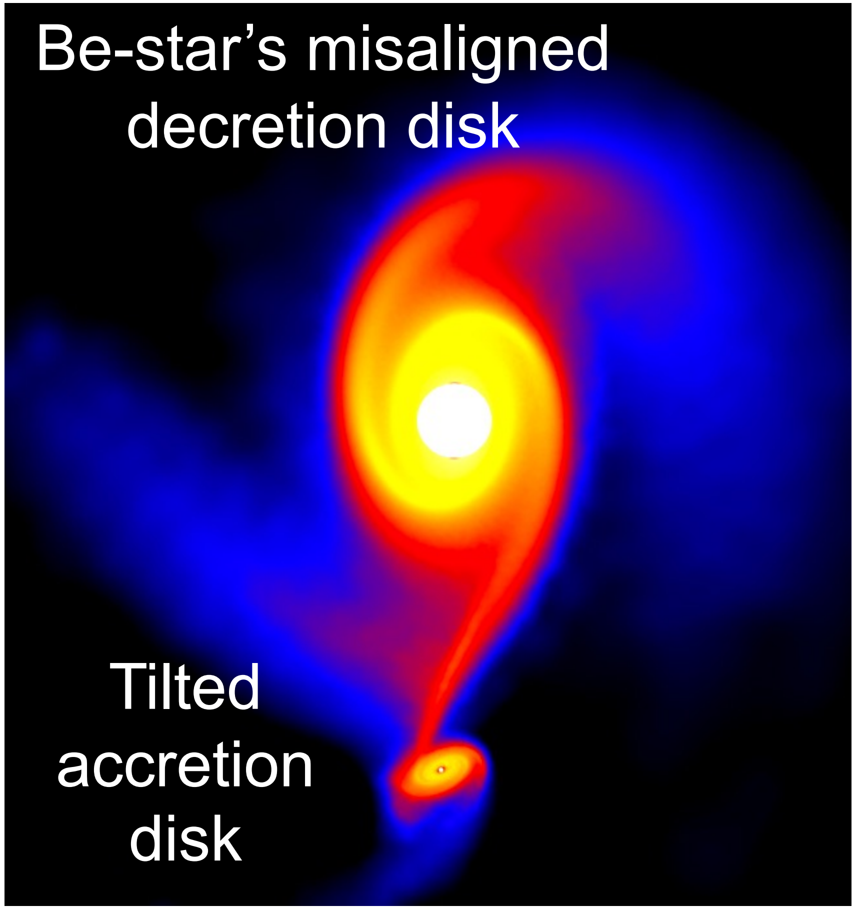




(Rivinius+ 2013)

Be X-ray binaries (BeXRBs)

- **Classification:** large sub-class of high mass X-ray binaries (~50% of the identified systems)
- **System:** Be star + (mostly) neutron star
- **Orbit:** wide (10 d < P_{orb} < 300 d) and <u>eccentric</u> (0.3 < e < 0.9)
- **X-ray activity:**
  - Occasional outbursts ($L_X > 10^{36}$ erg/s)
  - In quiescence most of the time



Outbursts vs. Quiescence

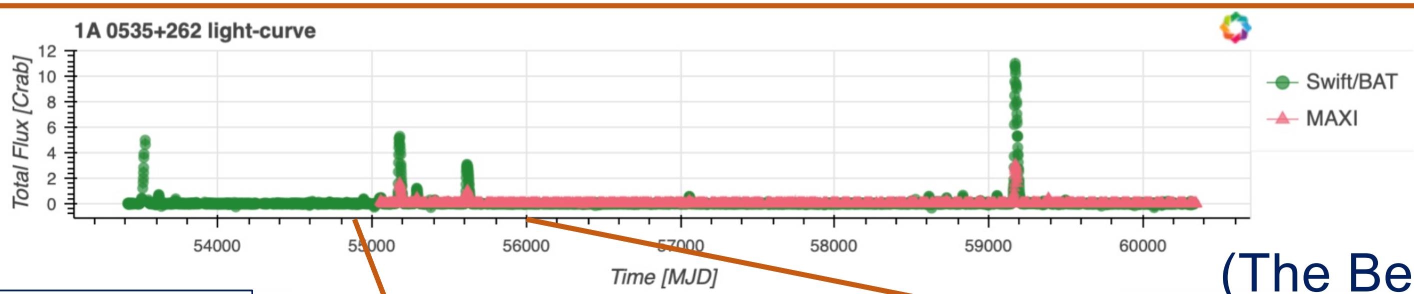
Outbursts

$L_X \gtrsim 10^{36}\,\mathrm{erg\,s^{-1}}$

Wide gap!

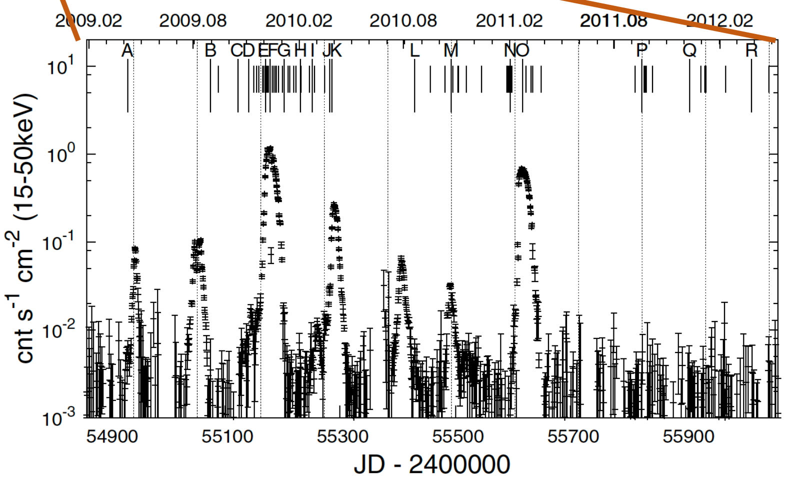
Quiescence

$L_X \lesssim 10^{34}\,\mathrm{erg\,s^{-1}}$



(The BeXRB monitor, ESA)

X-ray light curve of A0535+262 (P_{orb}=110d, e=0.47, P_{spin}=104s)



(Moritani+ 2013)

On mechanism(s) for state transition

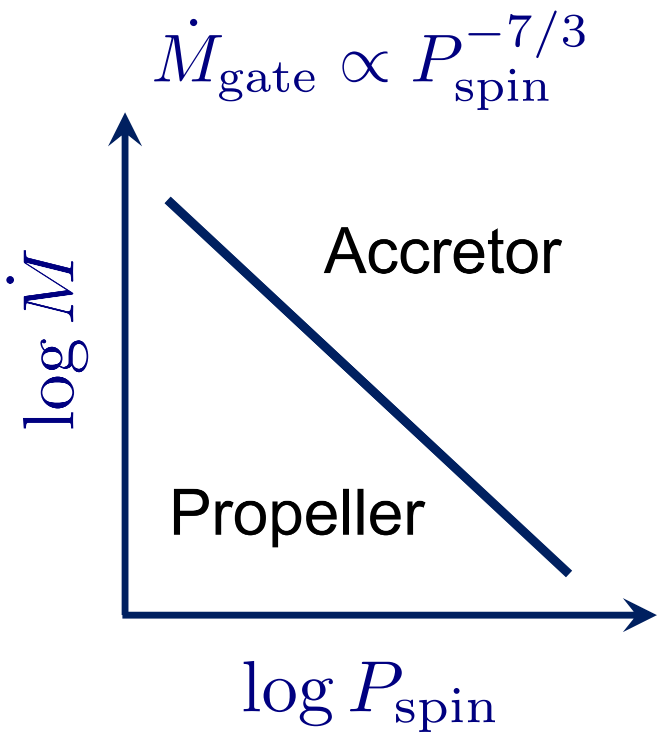
Widely accepted scenario

Centrifugal inhibition of accretion by NS's rotating magnetosphere (= propeller mechanism)

There is observational support for a couple of systems with relatively short P_{spin} (~4 sec)

⇨ For much longer P_{spin}, however, it is unlikely that the same mechanism works at a similar range of $\dot{M}$.

⇨ **What causes the state transition in these systems? Stellar wind?** ⇦ SW collides with AD in misaligned systems



Models and samples

Sample BeXRBs

- 13 systems with well determined/constrained parameters

Stellar wind

- Isotropic mass loss with Bjorklund+ (2021)'s mass-loss rate recipe
- $v(r) = v_\infty (1 - r/R)^\beta$, where $\beta = 0.8$ and $v_\infty = 2.6 v_{\rm esc}$ (Vink+ 2001)
- Collides with accretion disk at 45 degrees

Accretion flow

- Standard disk (SD) or Advection dominated accretion flow (ADAF)
- Truncated at $0.4R_{\rm Hill}$ at periastron (Paczynski 1977; Hamilton & Burns 1992)

Condition for wind-driven ablation of AD

- Wind $P_{\rm ram} > P_{\rm gas}$ of SD/ADAF at $0.4R_{\rm Hill}$ ⇒ No accretion for $\dot{M}_{\rm acc} < \dot{M}_{\rm crit}$

Sample systems

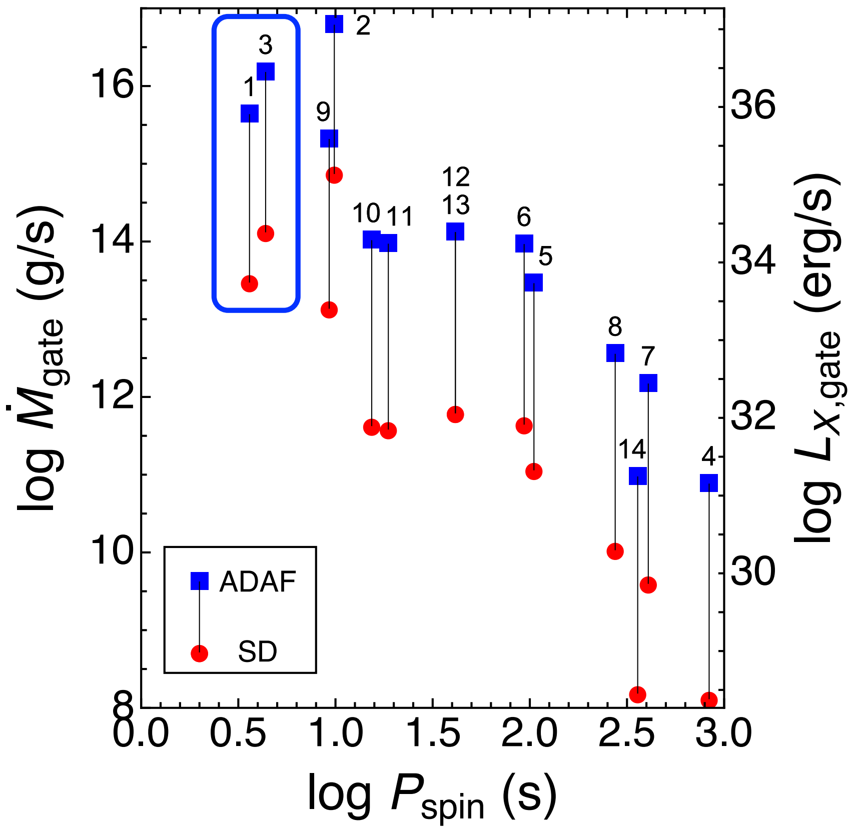
Table 2. List of Be/X-ray binaries in the Milky Way galaxy to which all parameters to apply our model are known or constrained.

System	Spectral type	M_* ($M_\odot$)	R_* ($R_\odot$)	$T_{\rm eff}$ (K)	$\dot{M}_{\rm SW}$ ($M_\odot\,{\rm yr}^{-1}$)	$P_{\rm orb}$ (d)	e	$P_{\rm spin}$ (s)	$E_{\rm cyc}$ (keV)	B_0 (10^{12} G)
4U 0115+634	B0.2V	19	8	26,000	5.7×10^{-10}	24.3	0.34	3.61	12	1.35
Swift J0243.6+6124	O9.5V	18.9	7.7	32,000	5.4×10^{-9}	28.3	0.092	9.86	146	16.4
V 0332+53	O8.5V	20	8.8	34,000	1.9×10^{-8}	34.3	0.3	4.38	28	3.15
X Per	B0V	17.5	7.4	30,000	2.3×10^{-9}	250.3	0.11	837	29	3.26
A 0535+262	O9.7III	25	15	31,500	7.2×10^{-8}	110.6	0.47	104	50	5.63
GRO J1008−57	B1-2V	12.6	6.1	23,200	7.5×10^{-11}	249.48	0.68	93.5	78	8.78
1A 1118−616	O9.5V	18.9	7.7	32,000	5.4×10^{-9}	24	$<0.09^{(a)}$	407	55	6.19
GX 304−1	B2V	10.9	5.7	20,900	2.0×10^{-11}	132.2	0.462	275	54	6.08
2S 1553−542	B1-2V	12.6	6.1	23,200	7.5×10^{-11}	31.3	0.035	9.28	23-27	$2.81^{(b)}$
Swift 1626.6−5156	B0-2V	14.2	6.5	25,500	2.6×10^{-10}	132.9	0.08	15.36	10	1.13
KS 1947+300	B0V	17.5	7.4	30,000	2.5×10^{-9}	41.5	0.034	18.7	12	1.35
EXO 2030+375	B0III	20	15	28,000	2.5×10^{-8}	46.03	0.41	41.4	$36^{(c)}$	4.05
	B0V	17.5	7.4	30,000	2.3×10^{-9}					
SAX J2103.5+4545	B0V	17.5	7.4	30,000	2.3×10^{-9}	12.665	0.4055	359	$12^{(c)}$	1.35

(a) $e=0$ is adopted. (b) $E_{\rm cyc}=25\,{\rm keV}$ is adopted. (c) Detection claimed but not confirmed.

On the propeller effect in sample systems

- P_{spin} < 10s: State transition at $\dot{M} \sim 10^{36}\,\mathrm{erg\,s^{-1}}$ by propeller is OK.
- P_{spin} > 100s: Propeller is unlikely the mechanism for state transition.



1	4U 0115+634	9	2S 1553−542
2	Swift J0243.6+6124	10	Swift 1626.6−5156
3	V 0332+53	11	KS 1947+300
4	X Per	12	EXO 2030+375 (B0III)
5	A 0535+262	13	EXO 2030+375 (B0V)
6	GRO J1008−57	14	SAX J2103.5+4545
7	1A 1118−616		
8	GX 304−1		

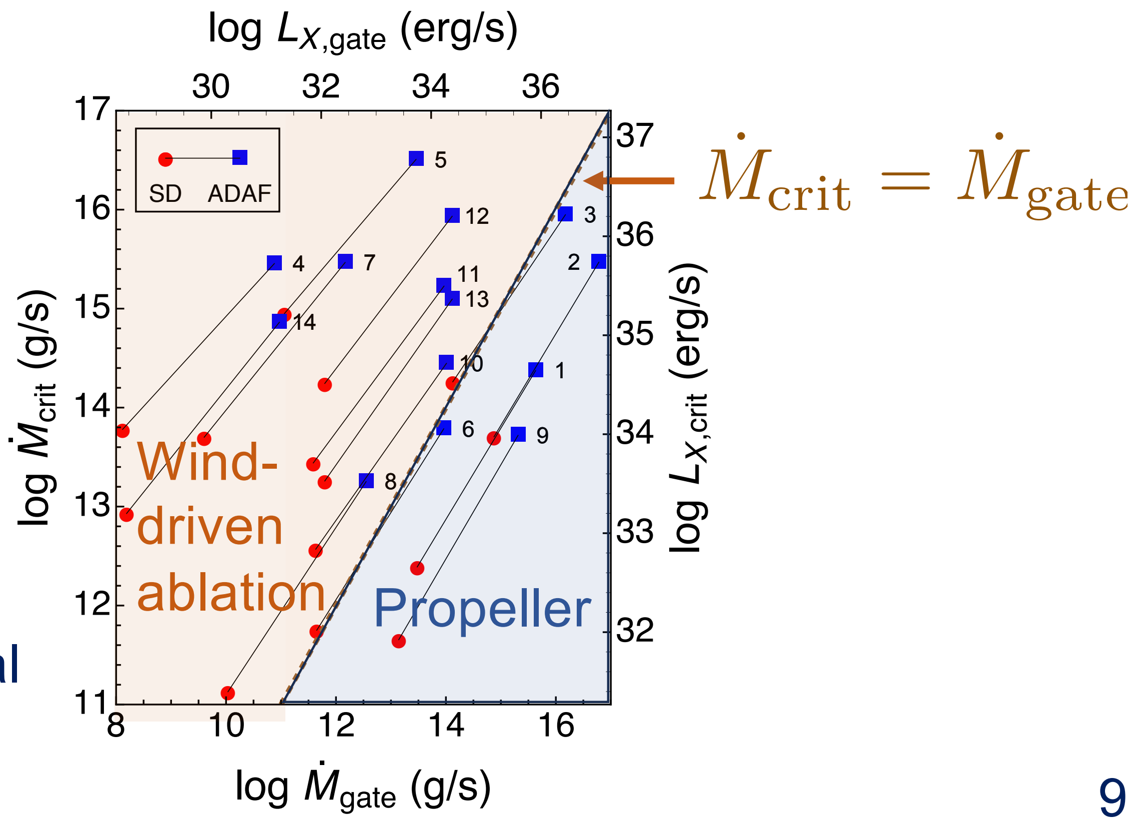
System with observational evidence for propeller

Wind-driven ablation vs. centrifugal inhibition

- $\dot{M}_{\rm gate} > \dot{M}_{\rm crit}$ (propeller effect > wind effect) in some systems.
- In other systems, wind-driven ablation is more likely the mechanism for state transition.

1	4U 0115+634	9	2S 1553-542
2	Swift J0243.6+6124	10	Swift 1626.6–5156
3	V 0332+53	11	KS 1947+300
4	X Per	12	EXO 2030+375 (B0III)
5	A 0535+262	13	EXO 2030+375 (B0V)
6	GRO J1008–57	14	SAX J2103.5+4545
7	1A 1118-616		
8	GX 304–1		

System with observational evidence for propeller

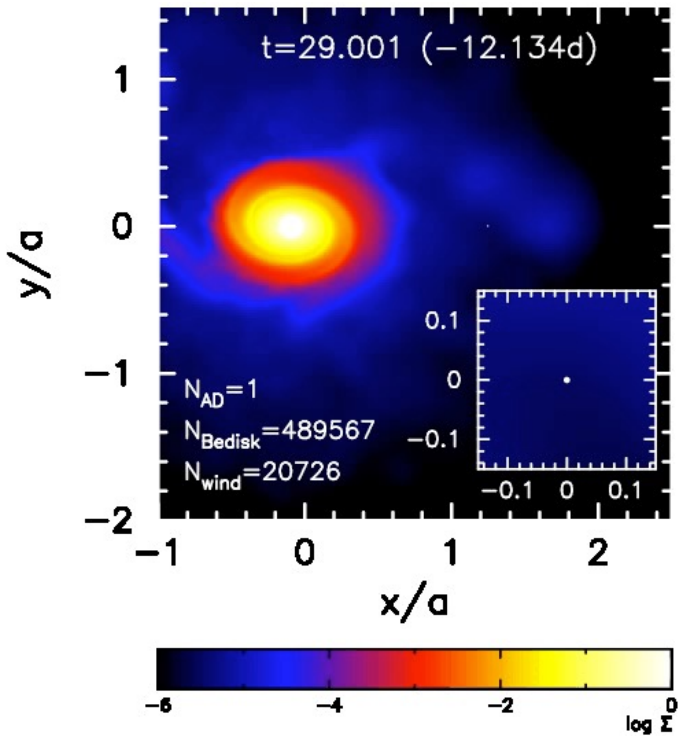


Be disk development and AD formation affected by stellar wind in misaligned BeXRBs: Numerical setup

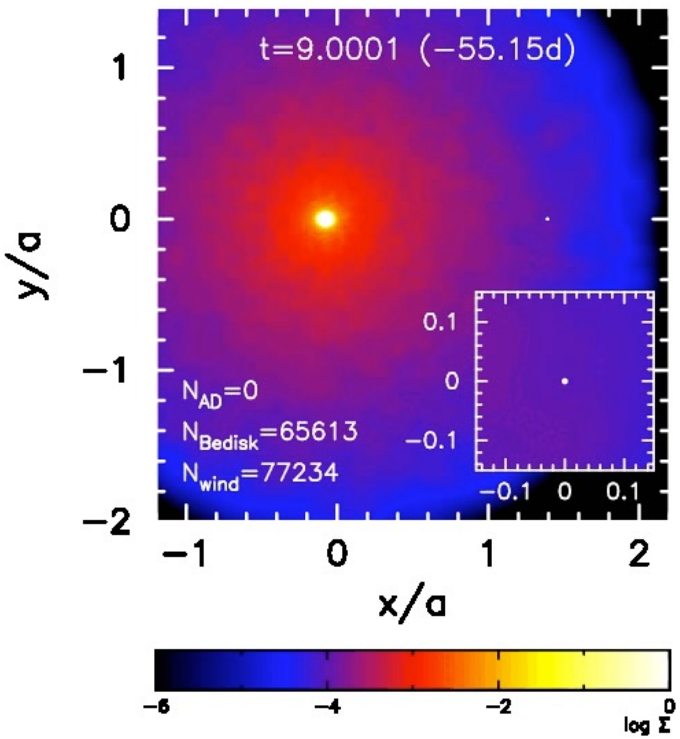
- Be disk tilted by 45 degrees about orbital major axis
- Constant mass injection of disk and wind particles.
- Artificial viscosity $\alpha_{\rm SPH} = 3,\ \beta_{\rm SPH} = 0$ to emulate $\alpha_{\rm SS} = 0.3$.
- To increase spatial resolution of AD, each particle is split into 13 particles when it enters Roche lobe of NS (Kitsionas & Whitworth 2007).
- External force is introduced to emulate $\beta = 1$ wind with $v_\infty = 2.6 v_{\rm esc}$ (Vink+ 2001).
- Targets: 4U0115+634 (B0.2Ve, P_{orb}=24.3d, e=0.34) and
  A0535+262 (O9.7IIIe, P_{orb}=110d, e=0.47)
- Wind mass-loss rates (Bjorklund+ 2021):
  $5.7 \times 10^{-10} M_{sun}$/yr (4U0115+634), $7.2 \times 10^{-8} M_{sun}$/yr (A0535+262).
- Optically thin radiative cooling with floor temperature at $0.6T_{eff}$.

- Typical base density of Be disk (~10^{-11} g/cm^3 at the inner radius)
  ⇨ No accretion in both systems, due to wind-driven ablation

4U0115+634
after ~30P_{orb} (~2 yr)

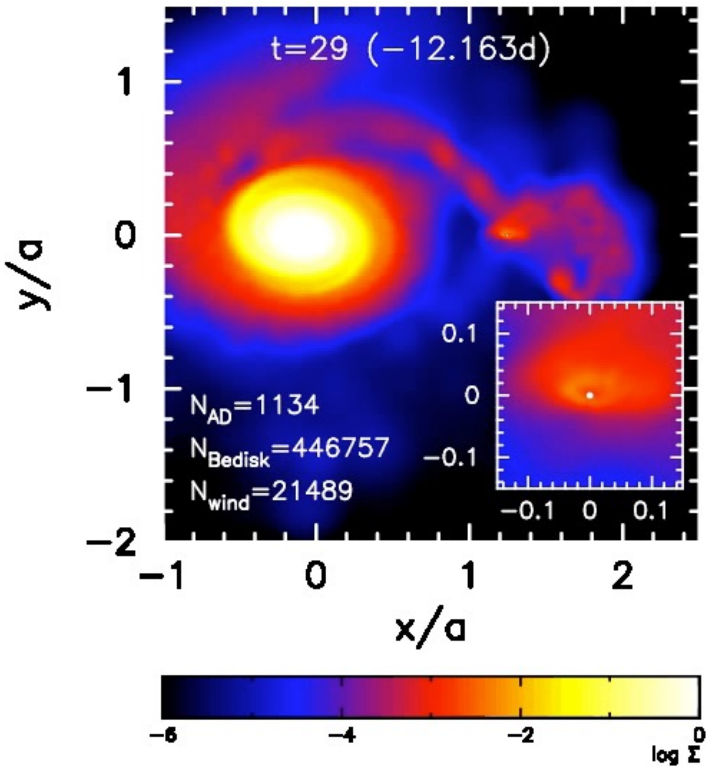


A0535+262
after ~10P_{orb} (~3 yr)

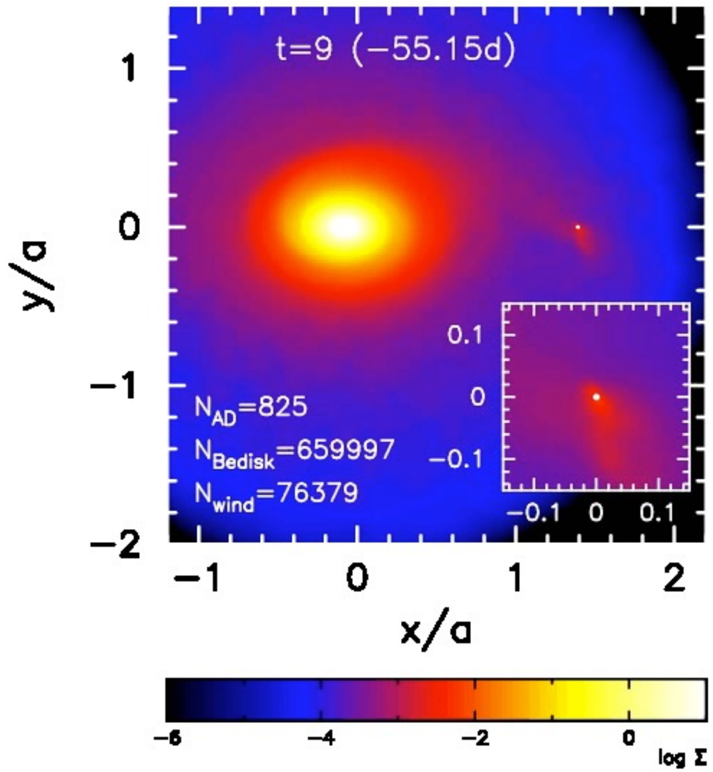


- In order for an accretion flow to be dense enough to survive wind-driven ablation, Be disk has to be denser than typical even in 4U0115+634, and much denser in A0535+262 with stronger wind.

4U0115+634
(x10 mass into Be disk)



A0535+262
(x100 mass into Be disk)



Summary

- We have studied the effect of Be-star's stellar wind on accretion dynamics in misaligned BeXRBs, analytically and numerically.
- Analytical comparison between wind ram pressure and AD gas pressure strongly suggests presence of systems where stellar wind controls transition between outburst and quiescent states.
- Numerical results support this idea, although more realistic simulations (with better modeling of wind and Be- and accretion disks) are needed for better understanding of the origin of X-ray activity of BeXRBs.