Exploring BeXRBs Major Outbursts: Insights from X-ray and Optical Variability

G. Vasilopoulos[1,2]

[1]National and Kapodistrian University of Athens

[2]Institute of Accelerating Systems and Applications

Motivation & Goals

Be X-ray binaries (BeXRBs) [2] - featuring Be-type stars as donor companions – stand out for their remarkable variability, including prominent outbursts in both X-ray and optical wavelengths. Extensive monitoring through X-ray observatories such as Swift and the optical OGLE survey, enable detailed studies of long term BeXRB variability [3], and have provided unique datasets for analyzing major outbursts over the past decades.

- *Context of this work:* Major X-ray outbursts are often accompanied by strong optical flares that evolve parallel to the X-ray outburst [5, 6].
- *Our goal:* We aim to provide a simple quantitative explanation for the optical flares with an application to a sample of the brightest outbursts of BeXRBs.
- *How we did this?* We constructed a numerical model to study X-ray irradiation of the Be disk in a BeXRB system.

The Model

We start with a given temperature profile [1]:

$$T_{\rm disk}(r) = \frac{T_\star}{\pi^{1/4}}\left[\sin^{-1}\left(\frac{R_\star}{r}\right) - \frac{R_\star}{r}\sqrt{1-\frac{R_\star^2}{r^2}}\right]^{1/4}. \quad (1)$$

where $T_\star$ and $R_\star$ are the Be star temperature and radius. Then, given an X-ray source (L_X), at a distance $d_{\rm ele}$ the temperature change ΔT of a geometrical element is computed from:

$$T^4_{\rm new} = T^4_{\rm initial} + \frac{(1-a)L_X\cos\phi_{\rm ele.}}{4\pi\sigma d^2_{\rm ele}}, \quad (2)$$

where a is the albedo of the star or disk.

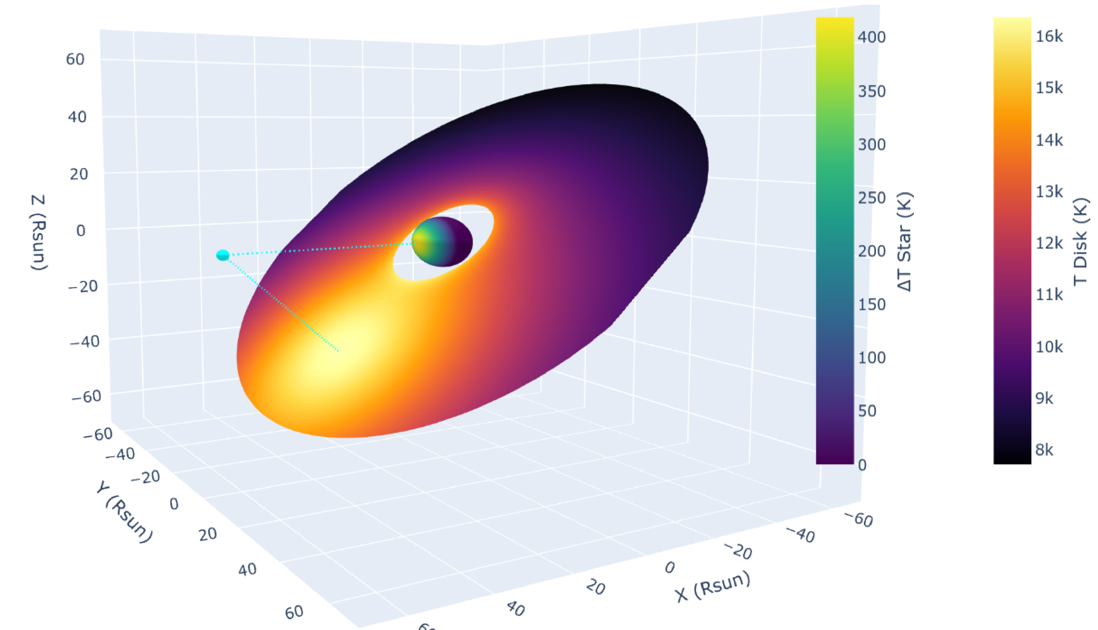

Figure 1: Example of model setup, all objects are to scale apart from the NS size (cyan color). For $L_X = 10^{39}$, $R_{\rm in} = 2R_{\rm Be}$], $T_0 =$ 30,000 K, $R_{\rm out} = 9R_{\rm Be}$, and $i = 45^\circ$.

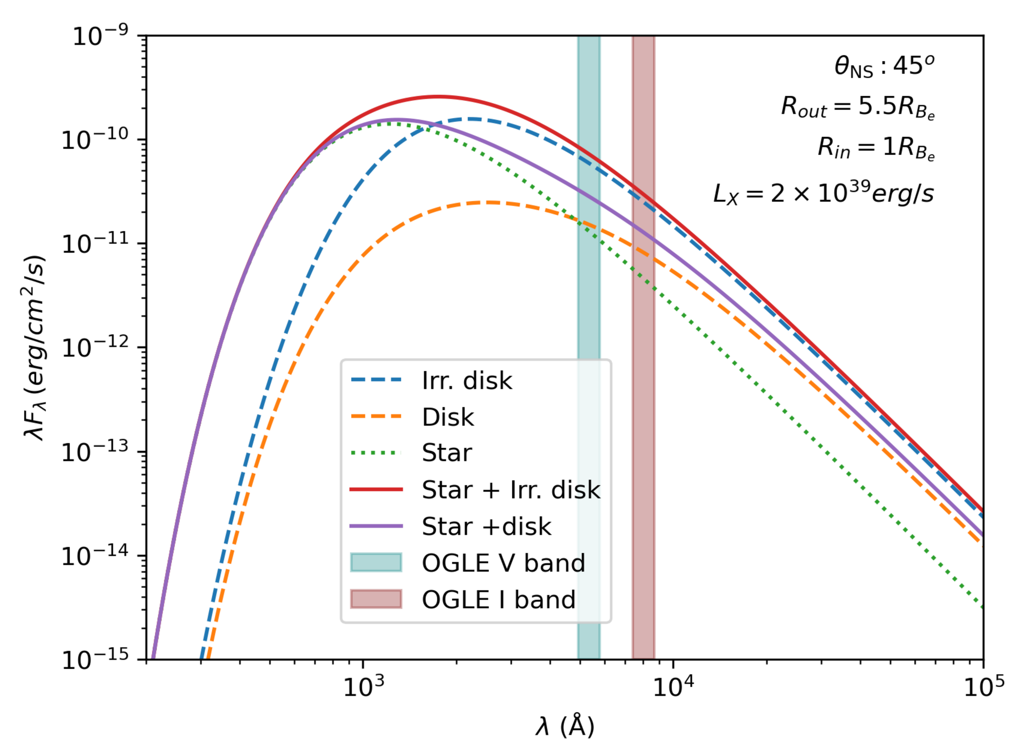

Figure 2: Example of computed SED.

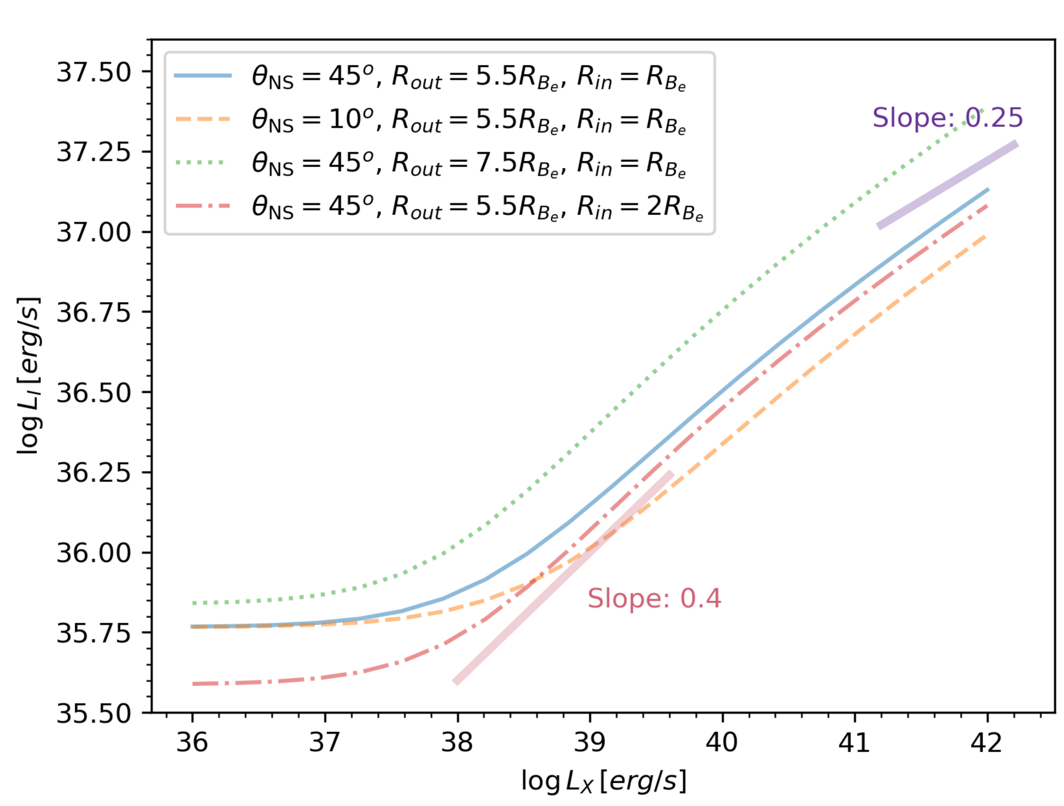

Figure 3: Parametric Investigation: Evolutionary tracks of optical flares luminosity as a function of L_X for different model parameters.

BeXRBs Major outbursts

BeXRBs - literature values

Name	Distance (kpc)	Date[(a)] (MJD)	L_X (10^{38} erg/s)	$P_{\rm orb}$ / e / $a\sin i$ (d) / – / (ls)	Spectral Class	A_I
LXP 8.04	50	56675	4	23.97 / 0.037 / 105	O9Ve	0.0885
SMC X-2	60	57300	7	18.38 / 0.07 / 73.7	O9.5 III–V	0.0735
SMC X-3	60	57630	25	45.07 / 0.231 / 189	B1–B1.5IV–V	0.066
SXP 4.78	60	58450	1.8*	20-100 / – / –	B1–3IIIe	0.144
SXP 5.05	60	56556	1.3*	17.13 / 0.155 / 142.4	B0.2Ve	0.114
Swift J0243.6+6124	5.5	58067	20	27.7 / 0.103 / 115.5	O9.5Ve	1.9

Flares & Outbursts

We modeled optical data during Major outbursts to measure optical flare intensity A_I (see table above).

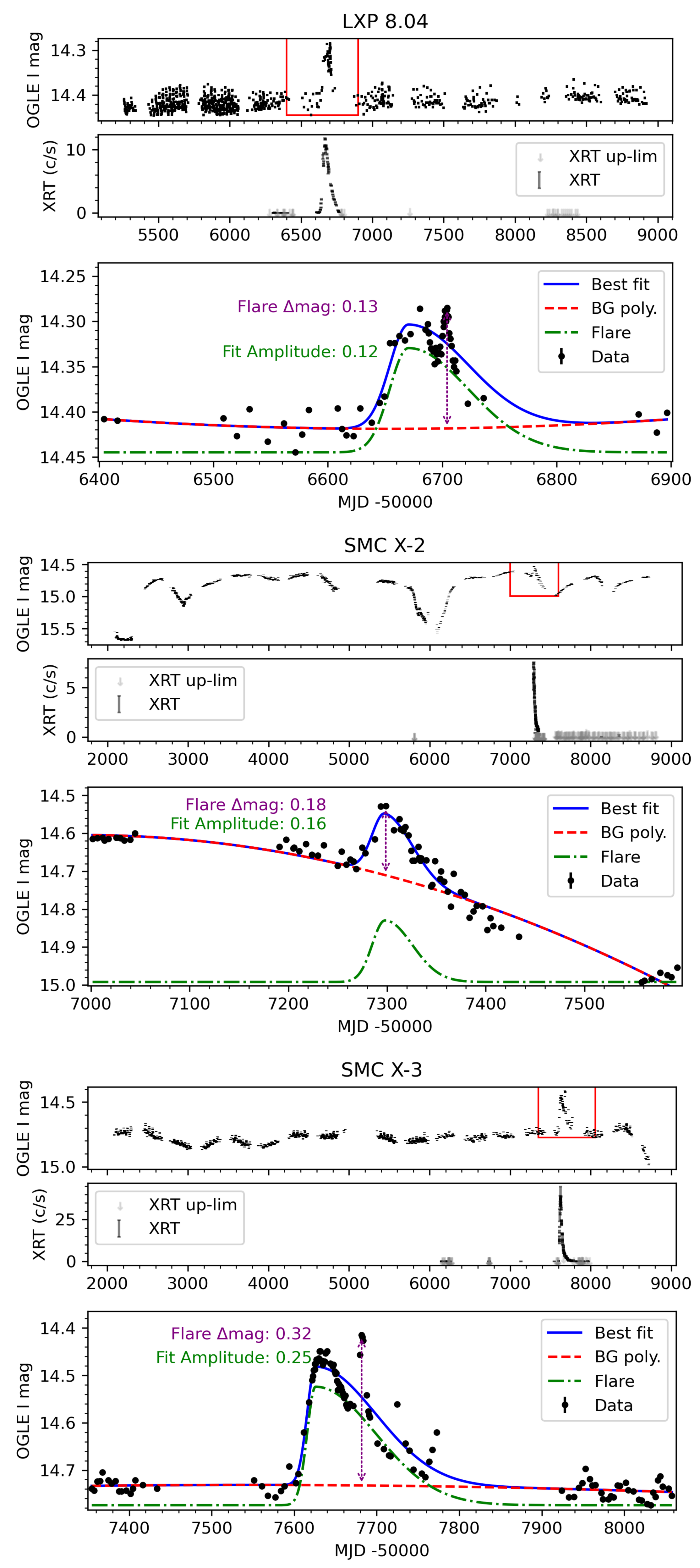

Figure 4: Optical flares during major outbursts from BeXRBs.

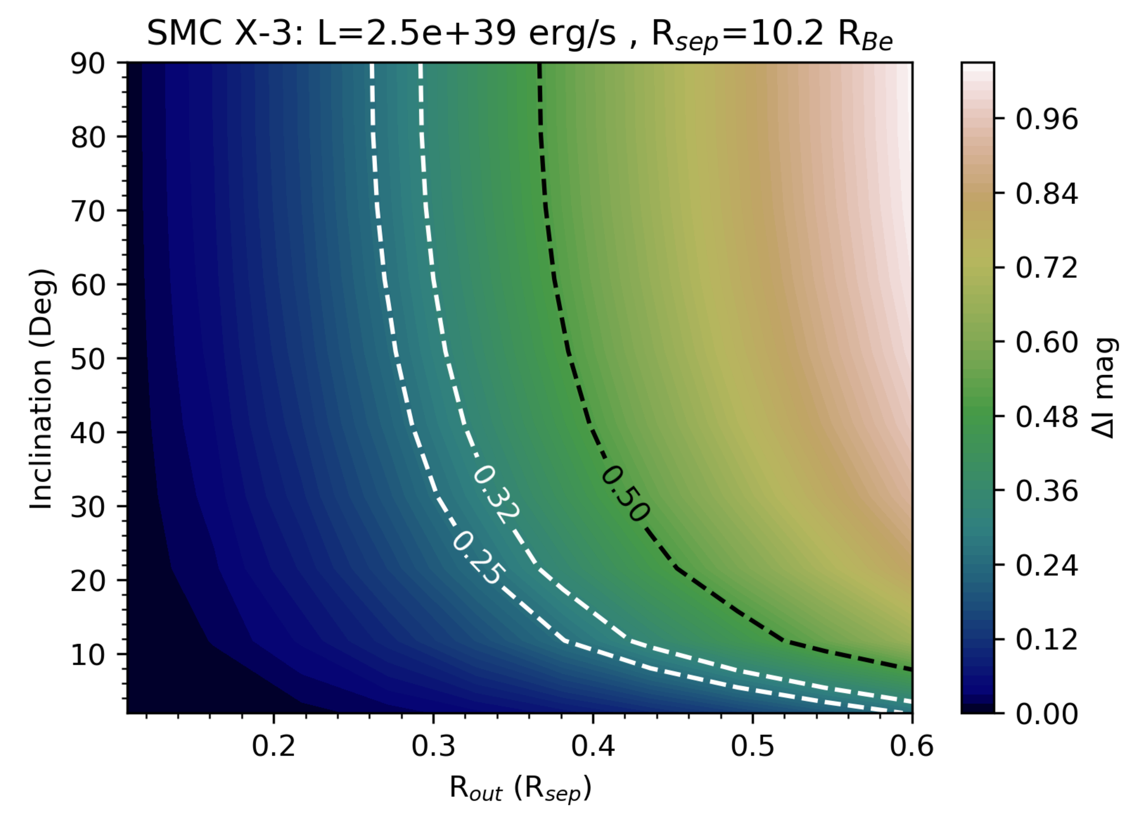

Figure 5: Heat map of simulated flare intensity (ΔI) as a function of inclination (Be disk vs NS orbital plane) and Be Disk outer radius. White contours indicate the observed ΔI.

L_X vs. $L_{\rm Opt}$ plane

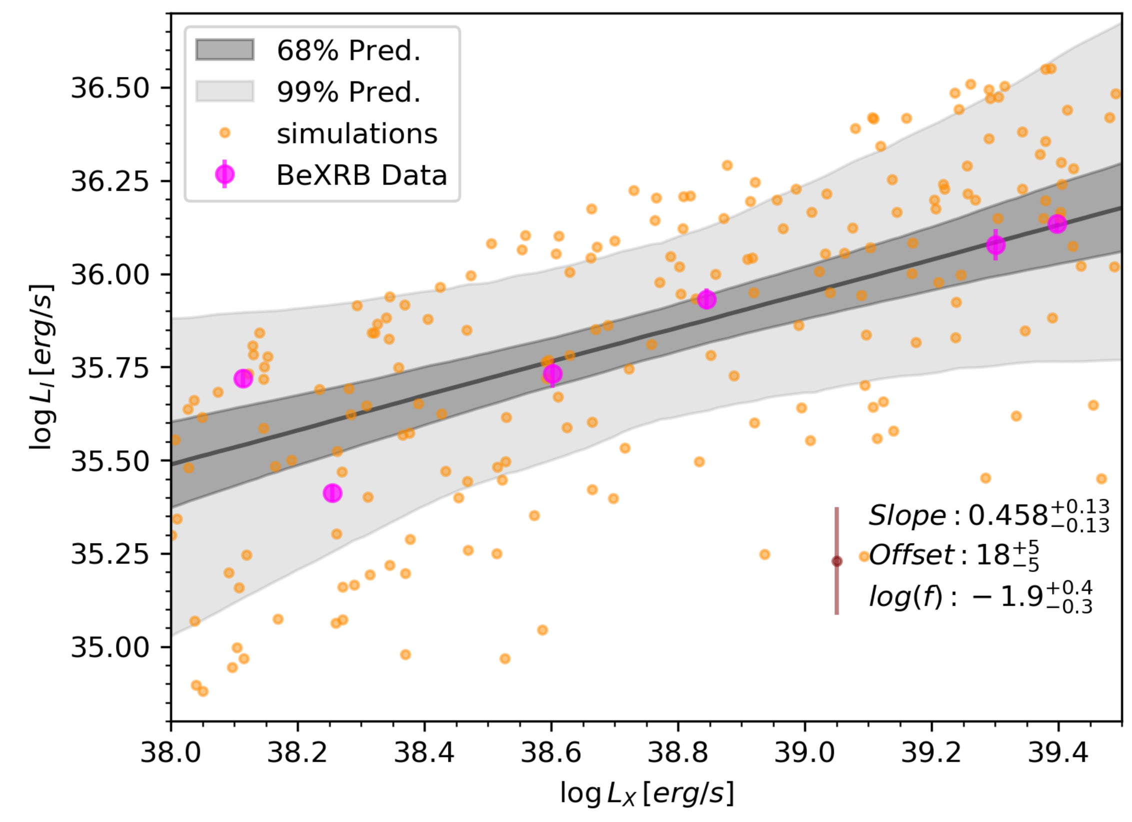

Figure 6: Flare intensity as a function of $log(L_X)$, where observed data from BeXRBs are plotted with magenta colors. The best-fit line (black) and the 68-99% prediction bands are plotted with gray shade, while model parameters are given in the legend. For the modeled excess variance we also plot an indicative spread with a maroon color, for easier comparison with the data. Orange points represent simulations for a random set of model parameters.

Conclusions & Future Work

From our modeling we found that the optical emission during major outbursts is consistent with being the result of X-ray irradiation of the Be disk. For individual systems, if this method is combined with independent constraints of the geometry of the Be disk, the binary orbital plane, and the plane of the observer, it can provide estimates of the Be disk size during major outbursts. Moreover, we computed a semi-analytical relation between optical flare luminosity and X-ray luminosity that is consistent with both model predictions and observed properties of flares (see Fig. 6).

Caveats & quick takes:

- Temperature profile: Alters quantitative results (e.g. heatmaps) but not qualitative (e.g. plane).
- Orbital modulation: We can see such signatures in lightcurves, we do not model it, however flares last multiple orbits, and thus this adds orbital "noise" to model.
- Color-Magnitude: yes we can predict variations during flares, early results in our paper [4].
- What about low L_X outbursts? A lot of uncertainty of baseline optical luminosity (Fig. 3), thus safe to stay close or above Eddington limit.
- Final thoughts? Degeneracy within parameters, like albedo and inner disk size. We ignore reflection from accretion disk, but it is on our todo list.

The current work in currently submitted and under review [4].

References

[1] Carciofi A. C., Bjorkman J. E., 2006, ApJ, 639, 1081
[2] Reig P., 2011, Astrophysics and Space Science, 332, 1
[3] Treiber H. et al., 2021, MNRAS, 503, 6187
[4] Vasilopoulos G., 2025, A&A subm.
[5] Vasilopoulos G. et al., 2014, A&A, 567, A129
[6] Yang H. N. et al., 2025, MNRAS, 536, 1357

Contact Info

Questions and feedback are welcome:
G.V: gevas@phys.uoa.gr

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