



SPECTRAL STUDIES OF SUPER-EDDINGTON OUTBURSTS OF BE/X-RAY BINARIES IN THE MAGELLANIC CLOUDS

³Institute of Accelerating Systems and Applications

M. KOUZIS¹, G. VASILOPOULOS^{2,3} ¹Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ²National and Kapodistrian University of Athens





GOALS & MOTIVATION

Be X-ray binaries (BeXRBs) are highly variable systems that host the majority of X-ray pulsars (XRPs).

Moreover, the most luminous outbursts of BeXRBs are known to break through the Eddington limit, and offer our nearest window onto Super-Eddington (SE) accretion. The Becker & Wolff (2007) [3] model (BW07) has successfully reproduced XRP spectra in the super-critical regime, particularly for luminosities in the range of 10^{37} - 10^{38} erg s⁻¹. However, its application to SE sources remains limited.

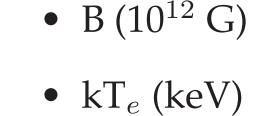
This motivated us to (see [8]):

- Apply BW07 model to spectra of XRPs in the Magellanic Clouds (MCs) with luminosities exceeding 10^{38} erg s⁻¹.
- Search the BW07 parameter space in order to identify selfconsistent solutions that conserve energy.

THE MODEL

BW07 model treats thermal and bulk Comptonization of the hot gas captured in a plane parallel accretion column (AC) with seed photons emitted via blackbody, bremsstrahlung, cyclotron processes. This physical model is applicable above a critical luminosity, where radiation pressure significantly influences the dynamics of the accreting material and becomes dominant [2]. The BW07 model and its adaptations [4] have been effective in reproducing the observed AC spectra in super-critical sources.

It is described by seven main free parameters:



• \dot{M} (10¹⁷ g s⁻¹) We can write ξ and δ in terms of the parallel $(\sigma_{||})$, perpendicular (σ_{\perp} taken as the Thomson scattering) and average ($\bar{\sigma}$) cross-sections.

$$\delta = \frac{a \sigma_{||}}{3 \overline{\sigma}} \frac{m_e c^2}{k T_e} = 4 \frac{y_{\text{bulk}}}{y_{\text{thermal}}}$$

$$\xi = \frac{\pi r_0 m_p c}{\dot{M} \sqrt{\sigma_{\perp} \sigma_{||}}}$$

$$a = \frac{32\sqrt{3}}{49 \ln(7/3)} \frac{G M_* \xi}{R_* c^2} = 0.2 \left(\frac{M_*}{M_{\odot}}\right) \left(\frac{R_*}{10 \text{ km}}\right)^{-1} \xi$$

OBSERVATIONAL DATA

We analyzed 13 *NuSTAR* observations from 5 systems in the Small and Large Magellanic Cloud (SMC, LMC) during major outbursts. RX J0520.5-6932 (J0520) in the LMC where three observations were performed during its 2014 and 2024 major outbursts. For SMC X-2 in the SMC we worked on four observations that were performed during its 2015 and 2022 major outbursts. RX J0209.6-7427 (J0209) in the Magellanic Bridge, where one observation was performed during its 2019 major outburst. XTE J0052-723 (SXP 4.78) with three observations during its 2018 outburst and XTE J0111.2-7317 (SXP 31) with two observations during its 2025 outburst, both in the SMC. NuSTAR data were reduced with nupipeline version 0.4.8 and CALDB version 20240315.

PARAMETRIC INVESTIGATION

As reported in [7], the BW07 model may yield solutions that violate the energy. Taking this into account, we performed a Monte Carlo (MC) parametric investigation and identified self-consistent solutions for radiative spectra for all model parameters.

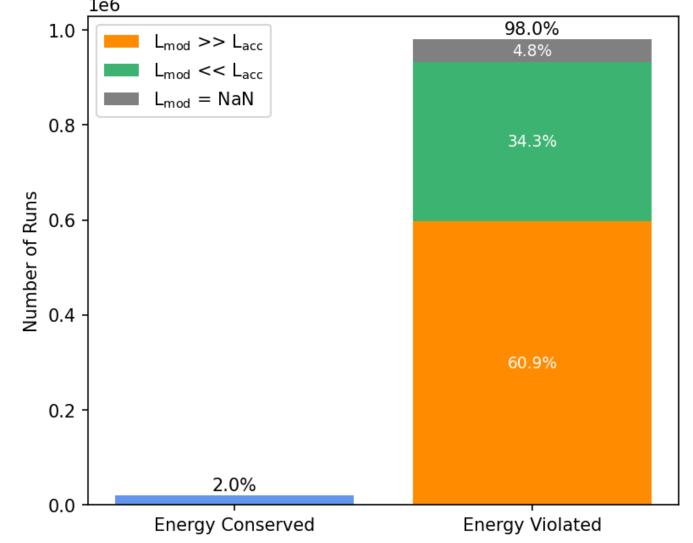


Figure 1: Energy conservation classification of model runs. Blue bar shows energy-conserving solutions. Violations are subdivided into $L_{\rm mod} \gg L_{\rm acc}$ (orange), $L_{\rm mod} \ll L_{\rm acc}$ (green), and undefined $L_{\rm mod}$ (gray). Percentages are shown in each bar.

Setting an acceptance limit of < 20% between the model and accretion luminosity, only 2% of the initial sample yielded energy-conserved solutions, see Fig. 1.

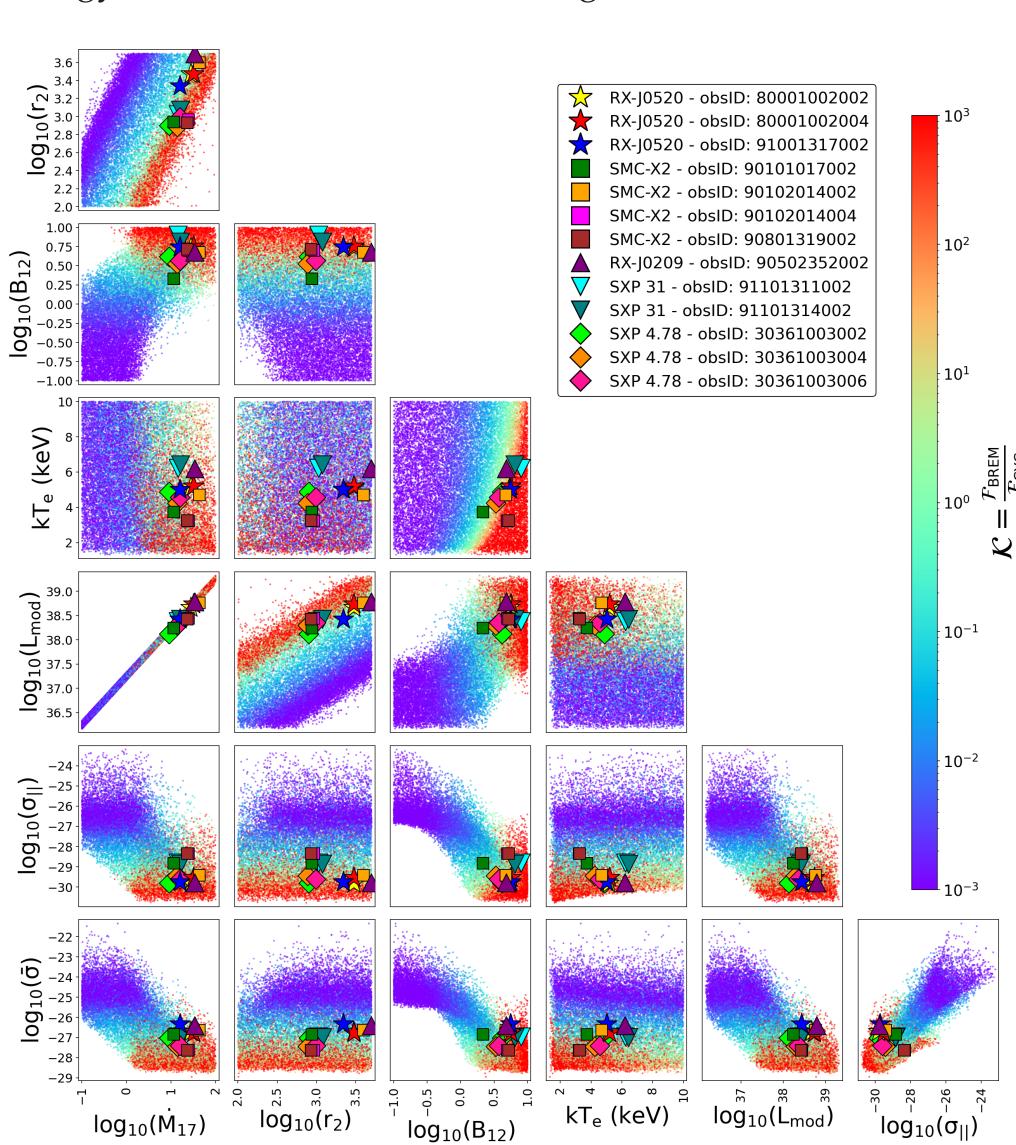


Figure 2: Scatter plots of the bwcycl parameters and the integrated $0.1–100~{\rm keV}$ X-ray luminosity. Points are color-coded by the ${\cal K}$ ratio: warm colors (yellow-red) indicate BREM-dominated spectra $(\mathcal{K} > 1)$, cold colors (blue–purple) mark CYC-dominated spectra ($\mathcal{K} < 1$), and light green shows balance ($\mathcal{K} \sim 1$). Only energyconserving solutions are shown; best-fit results from multiple observations are overlaid, with distinct symbols per source and colors per observation.

BW07 APPLICATION TO MCS SYTEMS

The fitting process was facilitated in xspec [1]. The best-fit parameters lie well under the energy-conserved parameter space, see Fig. 2.

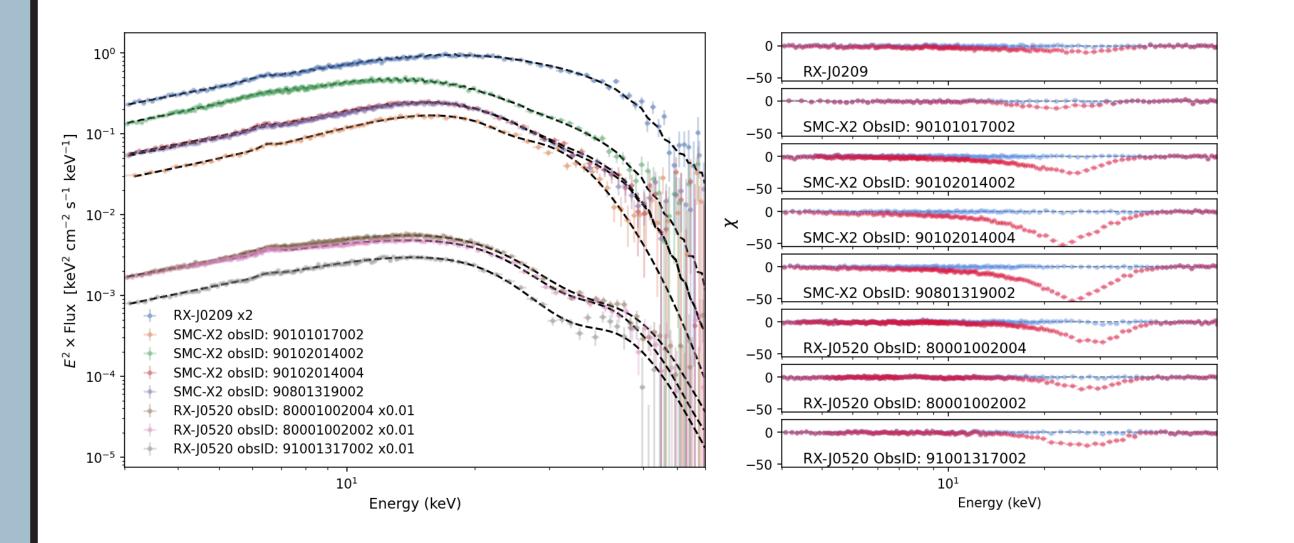


Figure 3: Left panel: Unfolded NuSTAR spectra (3–70 keV) fitted with gabs* (BWcycl + gauss). Right panel: residuals with (blue) and without (red) CRSF.

In order to reduce the number of free parameters, we used the CRSF as a direct measure of the local magnetic field where the scattering occurs:

$$E_c = \frac{eB\hbar}{m_e c} \approx 11.57 \left(\frac{B}{10^{12} \text{ G}}\right) \text{ keV}.$$

For the fitting process, the magnetic field is calculated as [5]

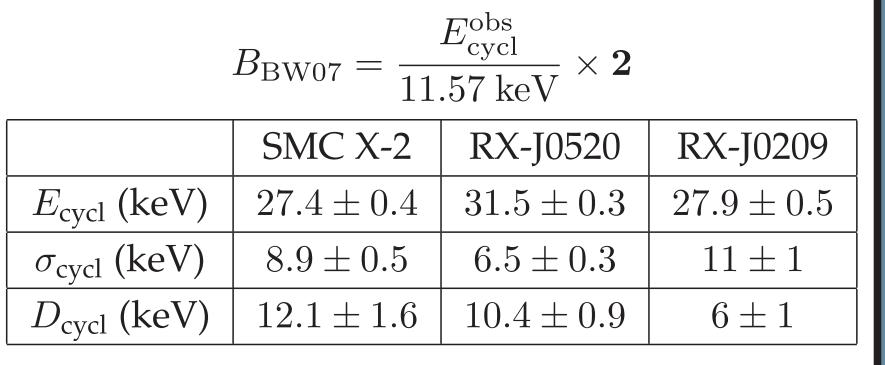


Table 1: Cyclotron line parameters.

ACCRETION GEOMETRY IN SE REGIME?

Known HID patterns [6] seem to break well above the Eddington limit.

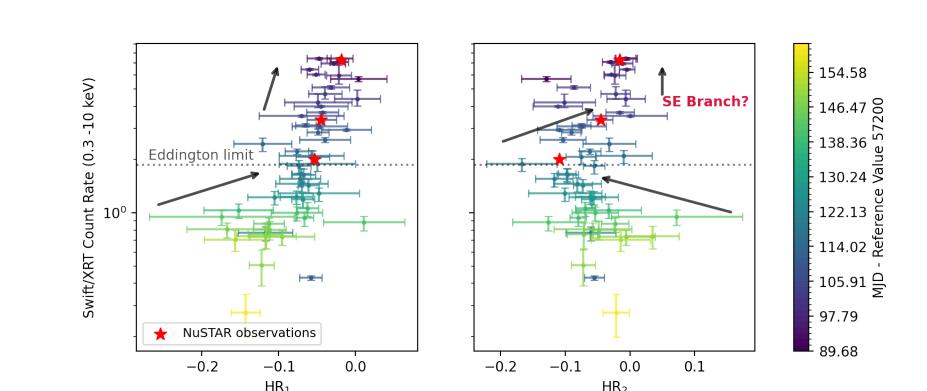


Figure 5: Hardness intensity diagram (HID) of SMC X2 outburst using Swift/XRT data.

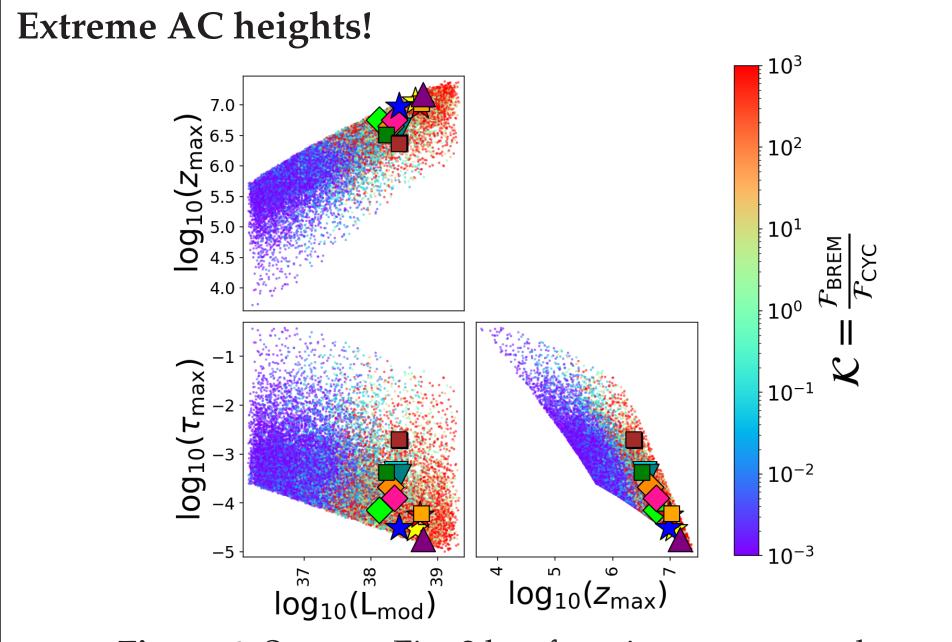


Figure 6: Same as Fig. 2 but focusing on $z_{\rm max}$ and $\tau_{\rm max}$

CONTACT INFO

M.K.: makouz@camk.edu.pl

Authors acknowledge support from the Hellenic Foundation for Research and Innovation (H.F.R.I.) through ASTRAPE (Project ID 7802).

BW07 APPLICATION TO MCS SYTEMS

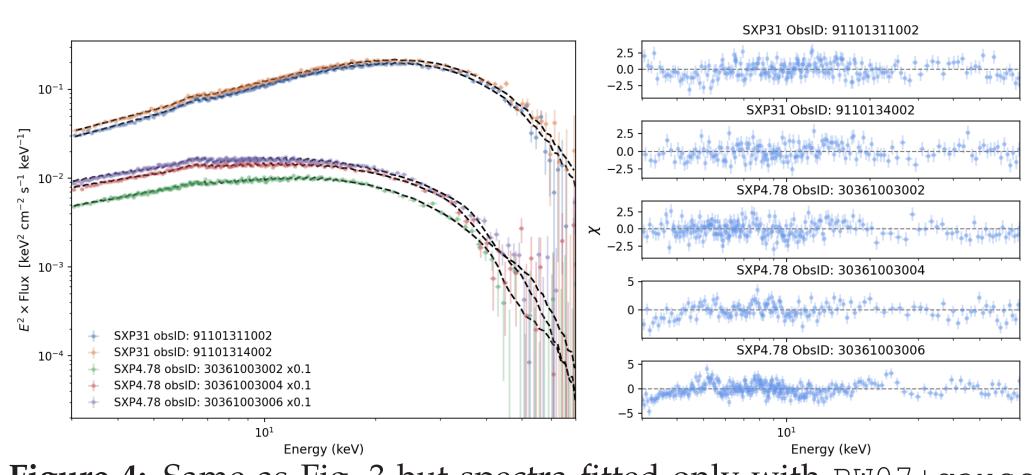


Figure 4: Same as Fig. 3 but spectra fitted only with BW07+gauss model.

CONCLUSIONS

- BW07 parameter space is successfully explored identifying energy-cornserved solutions for SE accretion.
- A physically motivated model like BW07 is able to reproduce the spectral shape of SE sources in the MCs.
- "Non-physical" geometrical solutions for SE sources. Need for another adequate configuration.
- Altered accretion mechanism during SE regime? Pattern breaks may correspond to a change in accretion regime.

REFERENCES

- Arnaud K. A., 1996, in Astronomical Society of the Pacific Conference Series, Vol. 101, Astronomical Data Analysis Software and Systems V, Jacoby G. H., Barnes J., eds., p. 17
- [2] Becker P. A. et al., 2012, A&A, 544, A123
- [3] Becker P. A., Wolff M. T., 2007, ApJ, 654, 435
- [4] Becker P. A., Wolff M. T., 2022, ApJ, 939, 67
- [5] Loudas N., Kylafis N. D., Trümper J., 2024, A&A, 689, A75
- [6] Reig P., Nespoli E., 2013, A&A, 551, A1
- [7] Thalhammer P. et al., 2021, A&A, 656, A105
- [8] Vasilopoulos G. et al., 2025, Astronomische Nachrichten, 346, e20240114