SPECTRAL STUDIES OF SUPER-EDDINGTON ACCRETING NEUTRON STARS IN THE MAGELLANIC CLOUDS

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MOTIVATION & GOALS

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. Importantly, all these sources exhibit cyclotron resonant scattering features (CRSF), which provide a direct measure of the NS surface magnetic field strength.
This motivated us to (see [9]):

- 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 self-consistent solutions that conserve energy.
- Take into account the correction implied by the height of CRSF formation.

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:

- B (10^{12} G)
- kT_e (keV)
- $\dot{M}$ (10^{17} g s^{-1})
- r_0 (m)
- D (kpc)
- ξ
- δ

We can write ξ and δ in terms of the parallel ($\sigma_{||}$), perpendicular ($\sigma_\perp$) and average ($\bar{\sigma}$ taken as the Thomson scattering) cross-sections.

$$\delta = \frac{a}{3}\frac{\sigma_{||}}{\bar{\sigma}}\frac{m_e c^2}{kT_e} = 4\frac{y_{\rm bulk}}{y_{\rm thermal}}$$

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

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

OBSERVATIONAL DATA

We analyzed eight *NuSTAR* observations from three 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. *NuSTAR* data were reduced with `nupipeline` version 0.4.8 and CALDB version 20240315.

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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.

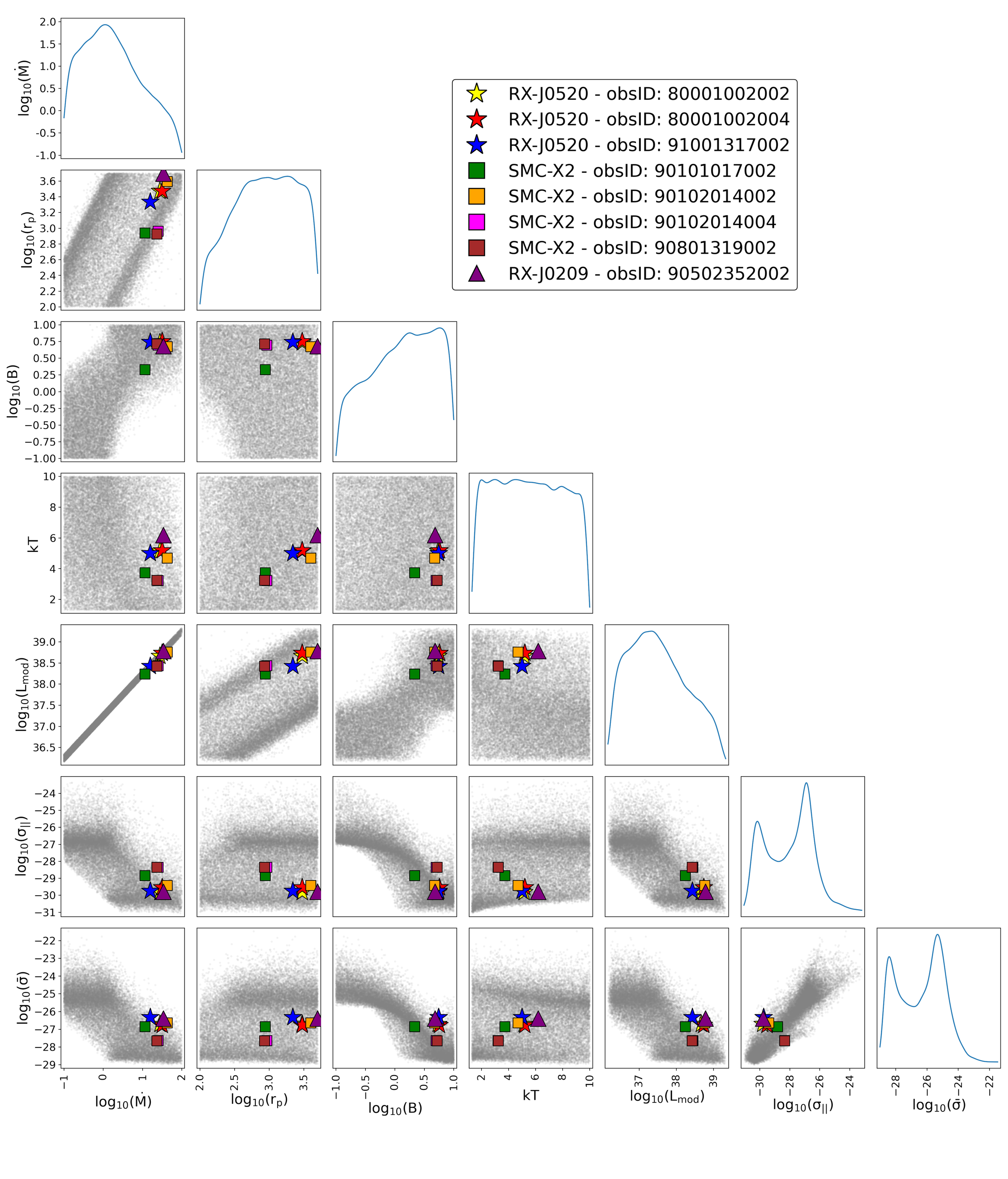

Figure 1: Energy conserved BW07 solutions (grey points).

Setting an acceptance limit of $< 20\%$ between the X-ray and accretion luminosity, only 3% of the initial sample yielded energy-conserved solutions.

CYCLOTRON LINE FORMATION

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

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

The CRSF is imprinted at some height above the NS surface. The surface cyclotron energy that is linked to the intrinsic magnetic field is given by $E^{obs}_{cycl} = E^{surf}_{cycl} \times f_{GR} \times f_{DE} \times S_{dip}$ [5], where f_{GR} and f_{DE} are the corrections from gravitational redshift and Doppler effect, respectively, and S_{dip} the dipole term.

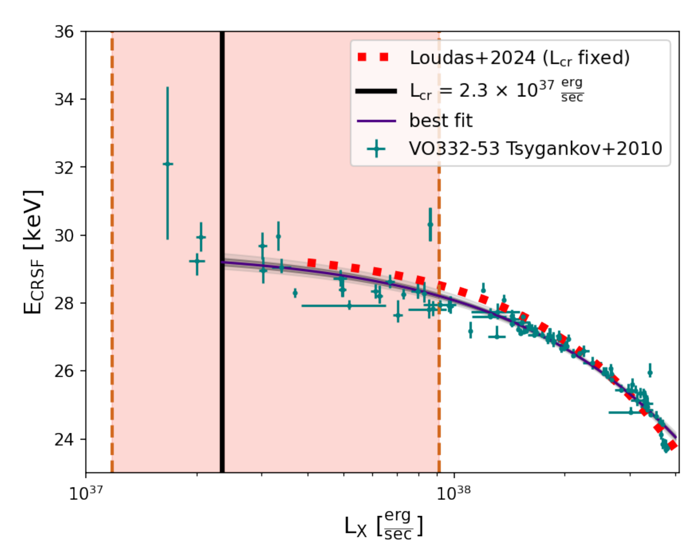

Figure 2: Observed cyclotron-line energy evolution of the source V0332+53 with X-ray luminosity.

In our analysis, we adopt the correction factor found in the case of V0332-53 [8]. Therefore, for the fitting process, the magnetic field is calculated as $B_{\rm BW07} = \frac{E^{obs}_{cycl}}{11.57{\rm keV}} \times \mathbf{2}$.

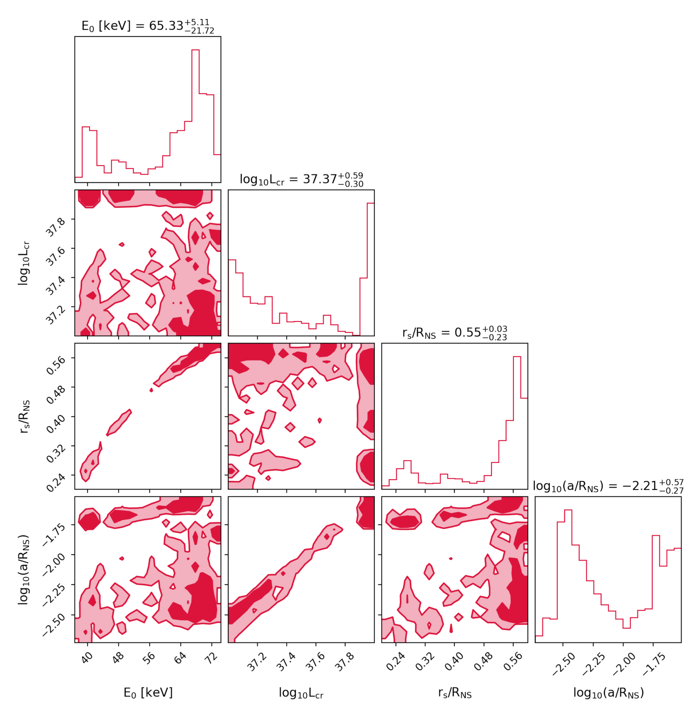

Figure 3: Corner plot of V0332-53 using the [5] model with critical luminosity as a free parameter.

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. 1.

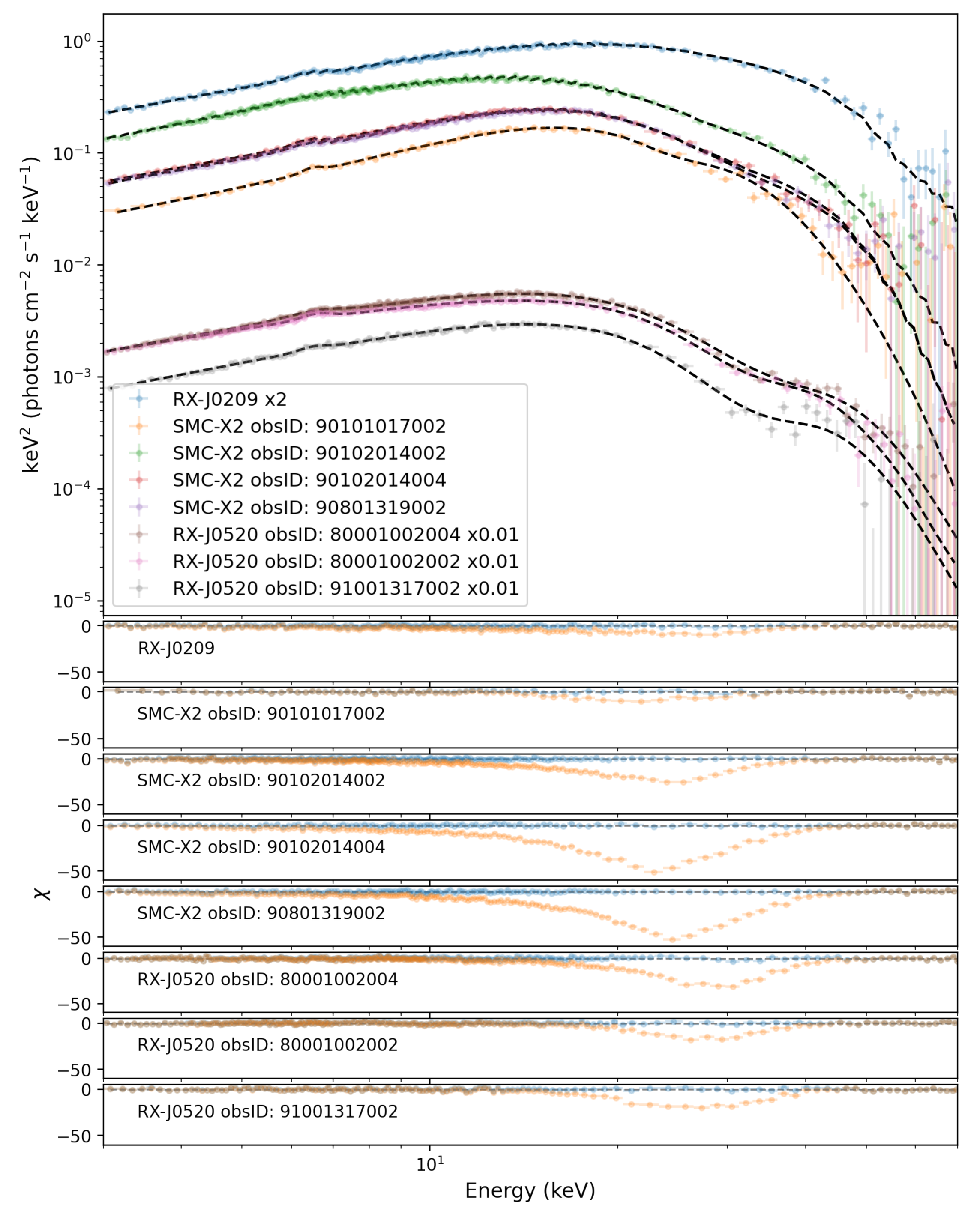

Figure 4: Upper panel: Unfolded *NuSTAR* spectra in 3-70 keV fitted with `gabs*(BWcycl + gauss)` model. Lower panel: Spectral residuals with (blue) and without (orange) CRSF component to the best-fitted model.

	SMC X-2	RX-J0520	RX-J0209
$E_{\rm cycl}$ (keV)	27.4 ± 0.4	31.5 ± 0.3	27.9 ± 0.5
$\sigma_{\rm cycl}$ (keV)	8.9 ± 0.5	6.5 ± 0.3	11 ± 1
$D_{\rm cycl}$ (keV)	12.1 ± 1.6	10.4 ± 0.9	6 ± 1

Table 1: Cyclotron line parameters for different sources.

HARDNESS INTENSITY DIAGRAM

RX J0520.5-6932, is a 8.04 sec XRP in the LMC. The 2013-2014 major outburst was followed by Swift/XRT.

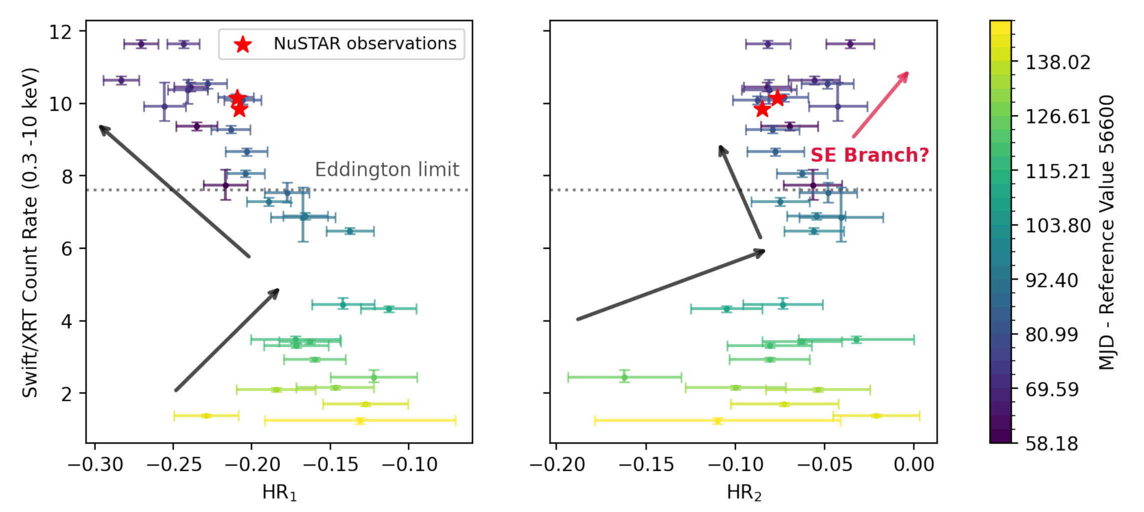

Figure 5: Hardness intensity diagram (HID) of RX J0520 outburst using Swift/XRT data.

$$HR_1 = \frac{M - S}{M + S} \qquad HR_2 = \frac{H - M}{H + M}$$

where H, M and S are the high (4-10 keV), medium (2-4 keV) and soft (0.3-2 keV) band count rates.
In the high intensity state and close to the Eddington limit, HR_1 follows a diagonal branch which is also reported in [6]. For the S band, however, there are extra caveats concerning the soft excess. In the case of HR_2, known HID patterns seem to break well above the Eddington limit. The data points change orientation.

CONCLUSIONS & FUTURE WORK

- The 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.
- Geometrical solutions (i.e. accretion column radius) yield to "nonphysical" conditions and cannot be acounted reliable for SE sources.
- Based on the best fit parameters of RX J0520 during the 2013-14 major outburst, we will probe its spectral transition and validate with Swift/XRT HID.

Stay tuned!