Investigating High Mass X-ray Binary Systems Through Spectral Modeling and Light Curve Analysis

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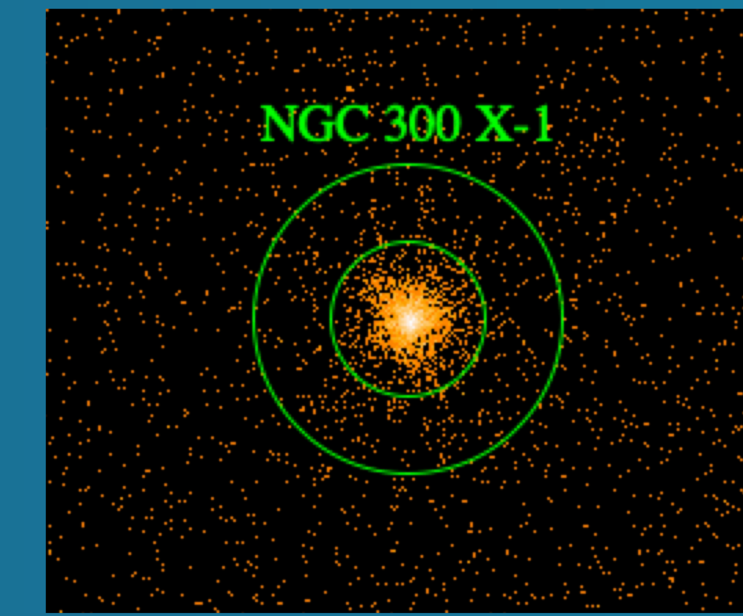
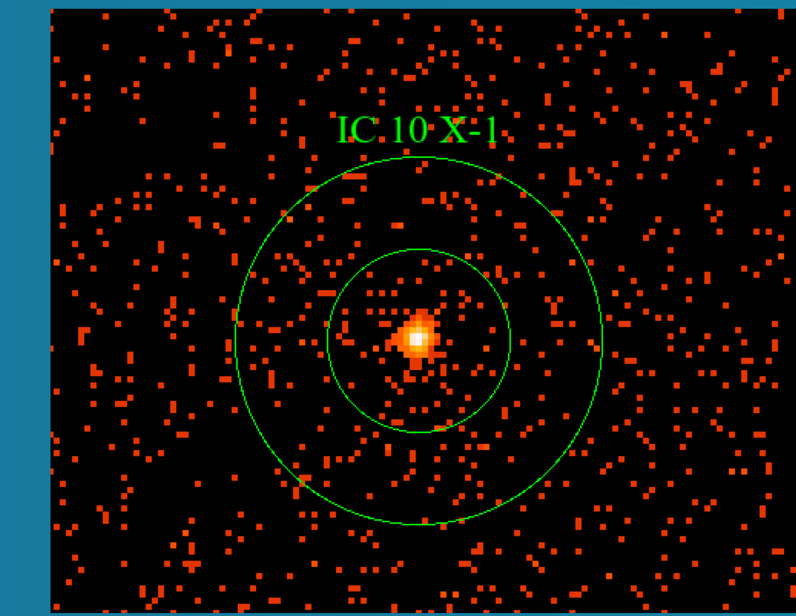




Abstract

A High mass X-ray binary (HMXB) system is one in which a compact object, either a black hole or neutron star, is in a stable orbit around a massive companion star. In these systems, X-ray photons are emitted from the accretion disk around the compact object as a result of magnetohydrodynamic turbulence. We utilize both new and archival data from the Chandra and XMM-Newton space-based observatories to capture these X-ray photons. For the IC 10 X-1, and NGC 300 X-1 systems, we compile multiple observations to construct phase-resolved light curves, mapping its ingress, eclipse, and egress. We then fit the region specific data of IC 10 X-1 with parameters informed by both literature values as well preliminary modeling of the system. Our fits yield values consistent with published estimates for black hole spin and luminosity, with a relatively steep power-law index, and produce black hole mass of $12.4623^{+2.9154}_{-1.2270}\ M_{\odot}$. Finally, we incorporate this mass into a Lagrange point diagram to provide a visualization of the systems dynamics.

The Physical Picture

In a HMXB system, the companion star continuously emits charged particles from its surface, called its stellar wind. Portions of this wind are captured gravitationally by the compact object, spiraling towards the accretion disk.

The accretion disk is extremely energetic, with its innermost regions reaching temperatures around 1 keV (~1 million Kelvin!). X-ray photons are emitted from this disk: soft X-rays from thermal emission, and hard X-rays originating in the corona, a region of highly energized electrons. Some of these hard X-rays are reflected off the accretion disk, producing emission lines in the observed spectra (Figure 1).

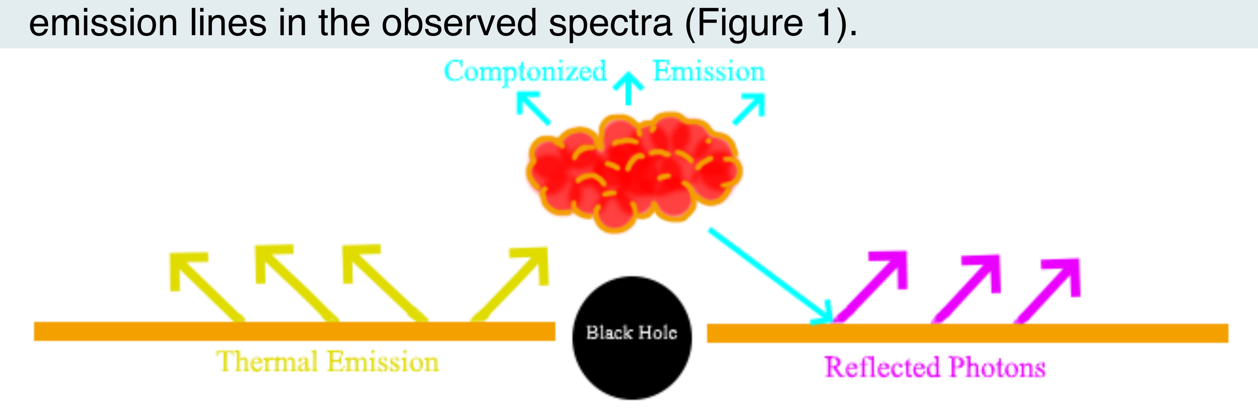


Fig. 1

The disk's energy is powered by magneto-rotational instability(MRI), in the following process(Figure 2):

1.Two particles are linked magnetically (acting like a spring), are placed at a small displacement.
2.Under Keplerian motion, the orange (inner) particle moves faster than the green(outer).
3.Magnetic tension transfers angular momentum from the orange particle to the green, amplifying their displacement, leading to displacement in the disk.

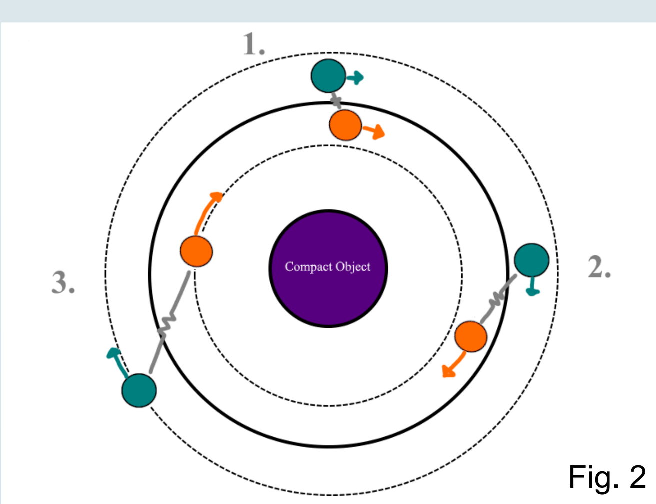


Fig. 2

Light Curve Modeling

To construct the eclipse profiles of the IC 10 X-1 and NGC 300 X-1 HMXB systems, we combine archival data from Chandra and XMM-Newton, along with a new Chandra observation of IC 10 X-1. Eclipse profiles are defined by

$$\phi = \frac{T - T_0}{P} \ (\text{mod } 1).$$

Where P is the orbital period (1.457 days for IC 10 X-1, and 1.366 days for NGC 300 X-1), and T_0 represents a chosen epoch value.

For XMM-Newton, we extract data from the MOS1 detector using the SAS software, applying pattern grading (PATTERN ≤12), removing bad pixels (FLAG == 0), performing background subtraction and filtering for Good Time Intervals (GTIs) using lccorr. Chandra data is extracted with the CIAO software and is pre-graded for evt2 files, but we reprocess all event files to ensure high-quality data. Background subtraction is performed manually, and GTIs are filtered through dmextract.

IC 10 X-1 light curves are shown in Figure 3, with observation 15803 (red dots) used for spectral fitting, and observation 29793 (blue dots) representing the latest Chandra observation. NGC 300 X-1 light curves are shown in Figure 4, illustrating the effect of distance on data quality as IC 10 X-1 is ~750 kpc from earth where NGC 300 X-1 is ~200 kpc.

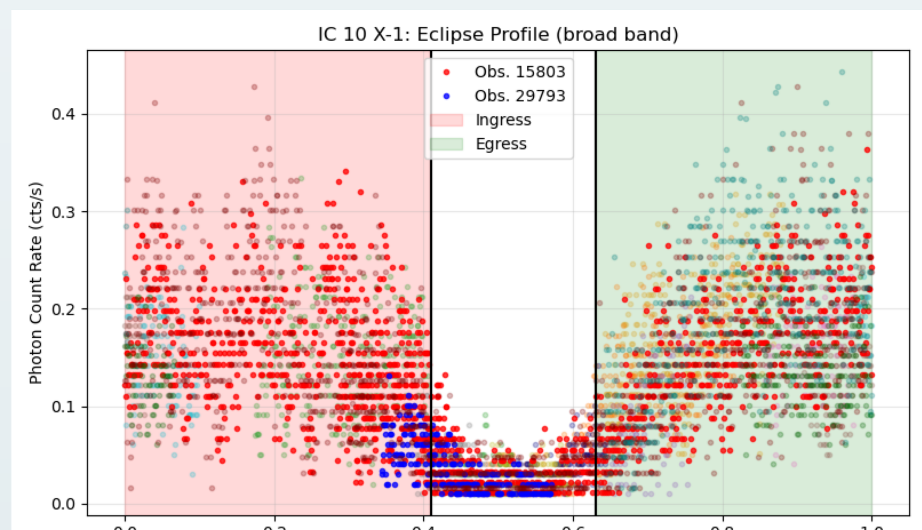


Fig. 3

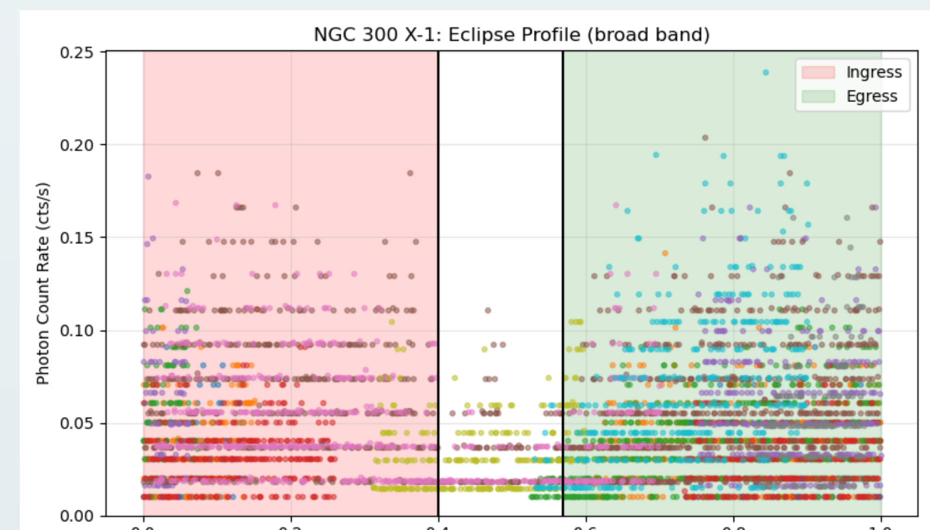


Fig. 4

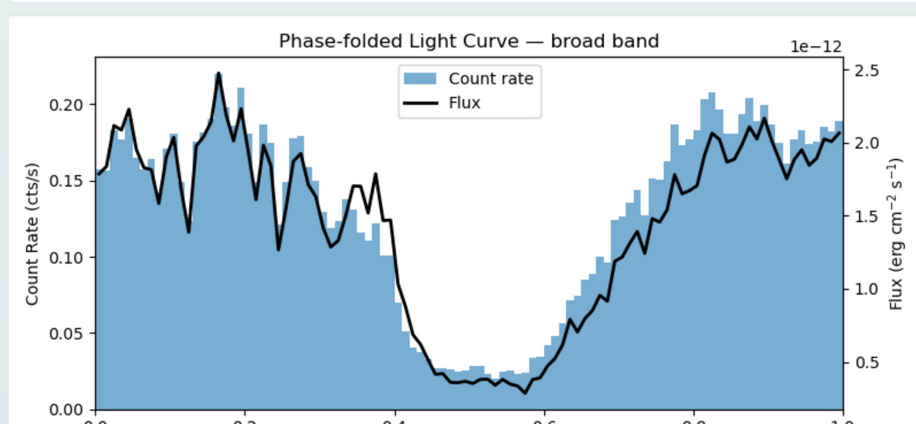


Fig. 5

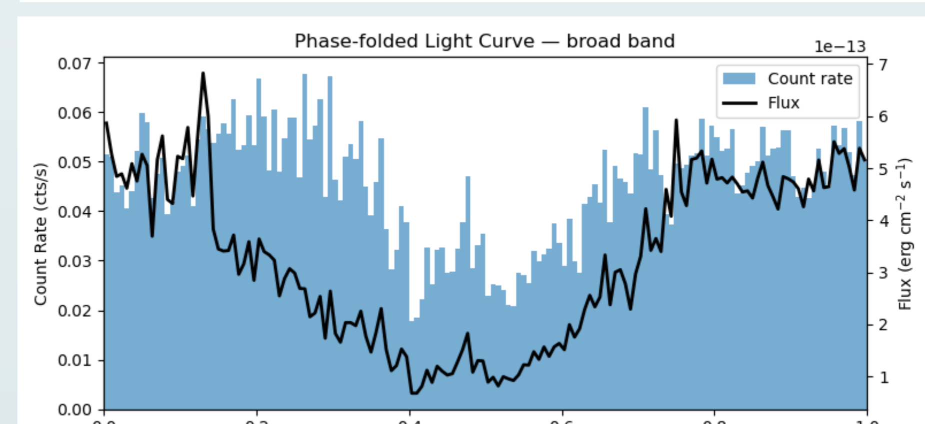


Fig. 6

After constructing the light curves, we phase-bin the data by averaging the count rate within each bin. Folding the spectra through the detector response matrix (mapping photon energy to detected pulse height) allows us to generate flux using a simple phabs * powerlaw model. We then weight the flux according to the ratio of the specific count rate to the mean count rate of the observation, providing an estimate of flux variation over time (Figures 6 and 7).

Finally, we compute the hardness ratio as the ratio of average counts in the hard band to the average counts in the soft band:

$$HR = \frac{H_{\text{avg}} - S_{\text{avg}}}{H_{\text{avg}} + S_{\text{avg}}}.$$

This ratio is plotted over time for each observation in Figures 7 (IC 10 X1), and 8(NGC 300 X-1).

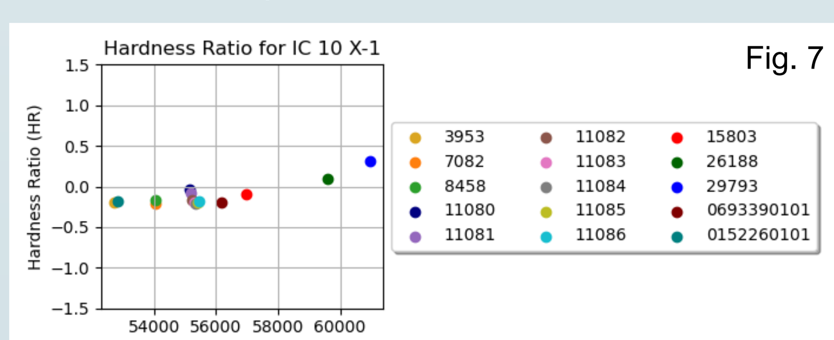


Fig. 7

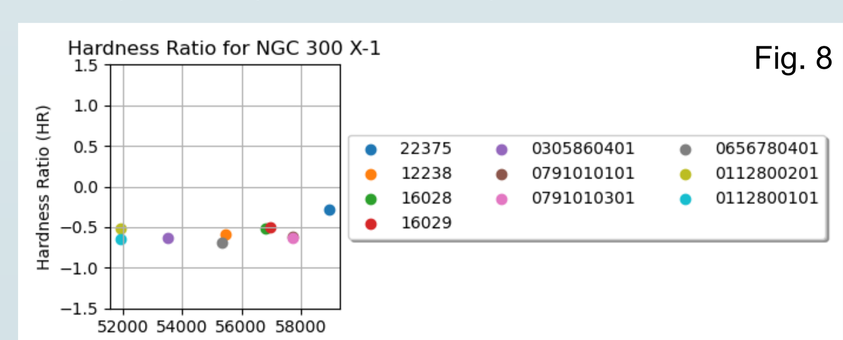


Fig. 8

Spectral Fitting of IC 10 X-1 (Obs. 15803)

Spectral modeling of observation 15803 was performed using Sherpa, an extension of CIAO that allows XSPEC models to be applied to Chandra data. Observation 15803 was selected as it covers the full orbital period of IC 10 X01, allowing clear separation into ingress, eclipse, and egress regions. Their respective spectra is shown in Figure 9.

Separating the regions allows us to focus on modeling the accretion disk spectra, and noting the similarity between the ingress and egress regions, we choose to use the ingress dataset.

We fit a TBabs * (slimbh + powerlaw) model to the data where slimbh provides a relativistic thermal emission component, powerlaw accounts for Comptonized emission, and TBabs models absorption. Slimbh also allows us to probe the black hole's spin, inclination, luminosity, and mass.

We initialize our model with parameter values guided by the literature as well as preliminary fitting. We restrict inclination $i = 71^{\circ}$, distance to the binary $D = 750$ kpc, and a steep power law index $\Gamma = 5.4$. After fitting, we find nH $= 0.634 \ \pm \ 0.015 \ 10^{22}$ atoms/cm^2. We then pass the luminosity, and black hole mass and spin to the Sherpa function, get_draws(), a Markov chain Monte Carlo (MCMC) method for Bayesian Low-Count X-ray Spectral (BLoCXS) analysis. The resulting posterior distributions are shown in Figure 11, providing estimates for the fitted parameters.

Finally, we use the fitted black hole mass to compute the Lagrange points of the system (Figure 12). Obtaining the mass of the companion star as well as the separation between the two bodies, we are able to calculate all other relevant constraints for the Lagrange points. We are also able to estimate the Roche-Lobe radius through the Eggleton approximation.

Fig. 9

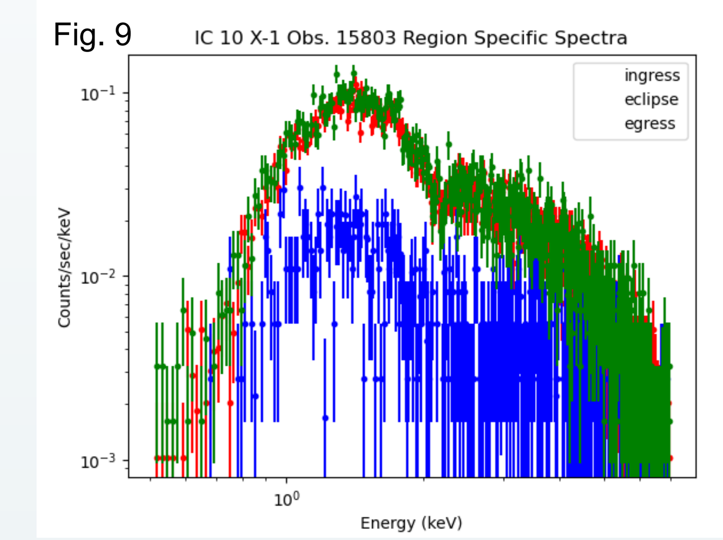
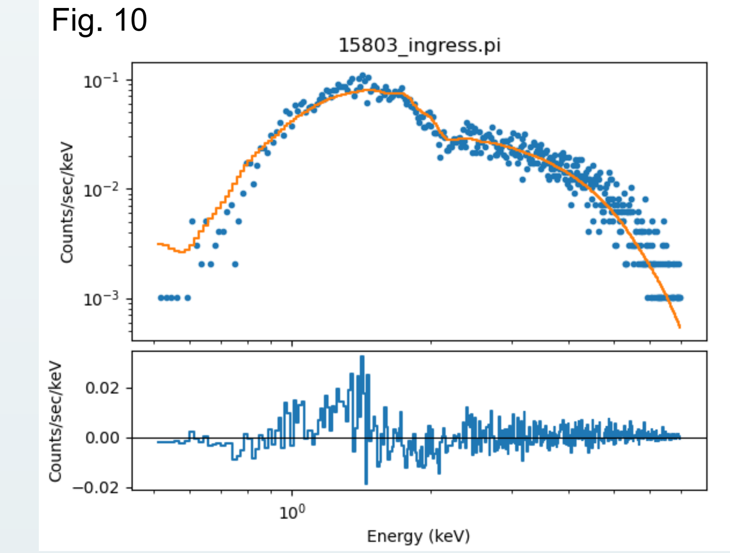


Fig. 10



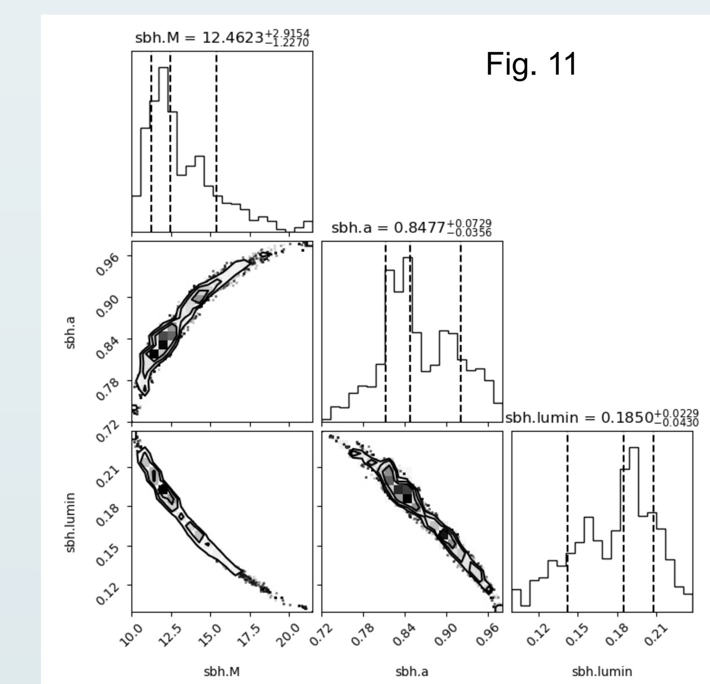


Fig. 11

Conclusion

In this study, we compiled light curve data for the twin HMXB systems IC 10 X-1 and NGC 300 X-1, combining archival observations with a new Chandra observation of IC 10 X-1. By fitting simple spectral models to each observation, we estimated the flux as a function of orbital phase.

Focusing on observation 15803 of IC 10 X-1, we applied the model TBabs*(slimbh + powerlaw) and obtained estimates for luminosity, black hole spin, and black hole mass consistent with literature values. Using this fitting mass, we approximated the Lagrange points and Roche-Lobe radius, providing a clearer visualization of the systems dynamics.

While our results are in agreement with previous studies, reducing uncertainty in black hole mass as well as improving residual symmetry would strengthen the model and ensure no important physics is being missed. Future work will apply similar spectral modeling to NGC 300 X-1, allowing us to compare the two HMXB systems in greater detail.

Acknowledgements

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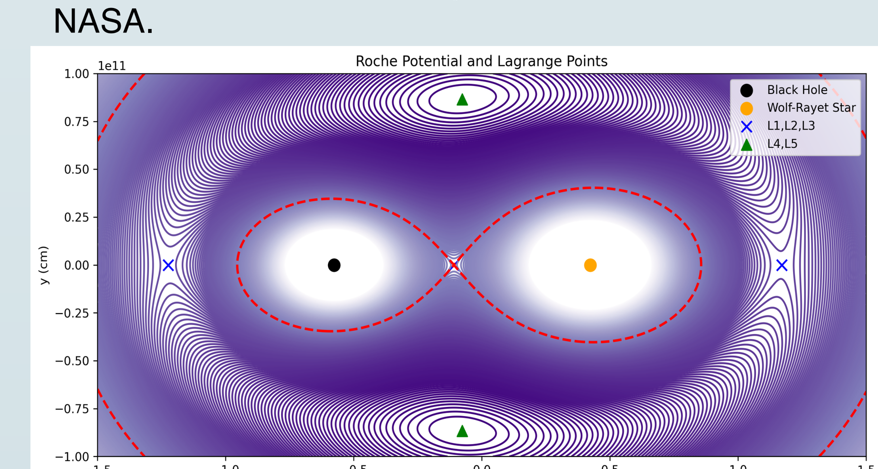

Fig. 12

Sources: Steiner, J. F., et al. 2016, *ApJ*, 817, 154, doi:10.3847/0004-637X/817/2/154, || Prestwich et al. 2007, *ApJL*, 669, L21 || Bhuvana & Nandi 2023, *MNRAS*, 519, 1524 || Hickox & Alexander 2018, *ARA&A*, 56, 625 || Carpano, S., Haberl, F., Crowther, P. A., & Pollock, A. M. T. 2018, *arXiv e-prints*, arXiv:1812.00662