Modeling X-Ray emissions of Source CX63: A Cataclysmic Variable vs. Black Hole Analysis

Shwetha Nagesh

Abstract

CX63 is a CXOGBS source(Chandra Galactic Bulge Survey) ([1], [2]) that was classified as a cataclysmic Variable (CV), based on its accretion-dominated optical spectrum and optical variability ([5]). This source has a radio counterpart with a flux density of 0.24±0.04 mJy and a spectral index of –0.80±0.90 ([3]). The factors supporting the possibility of the source being a CV as against a BHXB are the narrow widths of the emission lines as presented in [5], where H has a FWHM of only 14.8 Å, or 677 km/s. The H line thus provides mildly suggestive evidence in favour of the hypothesis that CX63 is a CV, while a BHXB observed at a very low inclination angle could also have similarly narrow lines and explains the radio emission more naturally ([5]). Therefore, to investigate the nature of the source, I aim to model the X-ray data of this source with both CV and Black Hole models. By comparing the performance of these models across different exposure times and statistical metrics, I plan to determine which scenario, CV or black hole, best explains the observed characteristics of the source.

1 Introduction

The Chandra Galactic Bulge Survey (GBS; [1], [2]) is a multi-wavelength survey (including X-ray, near-infrared (NIR) and optical wavelengths) of the Galactic Bulge. The survey area spans two regions of 6×1 above and below the Galactic plane. The GBS was designed to detect X-ray sources and their optical/NIR counterparts, to allow the classification of discovered X-ray sources based on multi-wavelength photometric and spectroscopic observations. A similar survey of the Galactic bulge was carried out in the radio band (VLAGBS) with a high angular resolution (1.1") and sensitivity (maximum of 0.1 mJy) at 1–2 GHz. This complements the X-ray Chandra Galactic Bulge Survey, and investigates the full radio source population in this dense Galactic region (pattie 2024). This survey aids in classification of the very few objects which are detected in both X-rays and Radio. The crossmatch of this survey with CXOGBS X-ray sources resulted in 25 matches. Of these 25 sources, our focus is on CX63 (a CXOGBS source).
Based on its accretion-dominated optical spectrum and optical variability, CX63 was classified as a Cataclysmic Variable (CV), which is an accreting white dwarf binary system ([5]).

The radio counterpart for this source was observed in the VLAGBS. The source was observed to have a flux density of 0.24±0.04 mJy, and a spectral index of –0.80±0.90. ([3]). The radio counterpart is bright compared to the X-ray source, slightly above the radio-bright BHXB track, as few CVs manage to reach the radio/X-ray flux ratios of qBHXBs ([4]). If this source is assumed to be located at a distance >= 1kpc, the brightness of the radio emission would be among the brightest of any CV to date. The factors supporting the possibility of the source being a CV as against a BHXB is the narrow width of the emission lines as presented in [5], where H has a full-width at half-maximum (FWHM) of only 14.8 Å, or 677 km/s. The H line thus provides mildly suggestive evidence in favor of the hypothesis that CX63 is a CV, while a BHXB observed at a very low inclination angle could also have similarly narrow lines as well and explains the radio emission more naturally [5].
What makes this source worth exploring is that if this is a quiescent BHXB, this source would be even more interesting in that it will have been discovered while in quiescence, as it would be the first confirmed BHXB to be discovered in this way. A quasi-simultaneous X-ray/radio measurement could confirm this amazingly high radio/X-ray ratio ([3]).

2 Methods

For this study, we have generated the spectral files from NuSTAR simulation files with the help of XSPEC's fakeit tool. These simulation files include a set of response and background files. We have used a point source ARF extracted using a circular extraction region with a radius of 30 arcseconds Off-axis angle is 1-arcminute, Background for 30" radius extraction region, and a Response file for sources near the optical axis.

For Black hole, we assumed a simple powerlaw model with photoelectric absorption (phabs*powerlaw) and for the Cataclysmic Variable, we assumed an emission spectrum from hot diffuse gas, also paired with photoelectric absorption (phabs*mekal). The normalization parameters for both these models were adjusted such that they returned the expected flux of 2.014e-13 ergs/cm/s withing 3.0 keV to 79.0 keV (NuSTAR's operational energy range). The model parameters are listed in tables 1 and 2. The spectral files for each of these models were generated at four different exposures: 30ks, 300ks, 3000ks, and infinite kilo seconds (1e9 ks). In order to predict the nature of the source, we tried modelling the Black hole spectra with the Cataclysmic variable model and vice versa. The idea behind this experiment is as follows: If a selected spectral file fits both the models, we conclude that the Signal-to-Noise Ratio for that data is to low for us to arrive at a conclusion. On the other hand, if we see that the data can be well described by one model and not by the other, we can disregard the model that yields a poor fit, which will help us establish a better understanding of the source's nature. Thus, in order to compare the eight different fit results, we use Cash statistics, assuming a Poissonian distribution of data. Although this would serve as the main criterion, we also employ Chi-square test, Pearson's original chi-square test, Anderson-Darling test and Kolmogorov Smirnoff test as Test-statistics to gauge the fit results.

Table 1: CV Model Parameters (`phabs*mekal`)

Parameter	Value/Range	Unit
`phabs.nH`	0.5	cm^{-3}
`mekal.kT`	7 – 13	keV
`mekal.nH`	0.5	cm^{-3}
`mekal.Abundanc`	0.1 – 0.7	–
`mekal.Redshift`	0	–
`mekal.switch`	0	–
`mekal.norm`	$1 \times 10^{-5} - 2 \times 10^{-4}$	–

Table 2: BH Model Parameters (`phabs*powerlaw`)

Parameter	Value/Range	Unit
`phabs.nH`	0.5	cm^{-3}
`powerlaw.PhoIndex`	1.8 – 2.3	–
`powerlaw.norm`	$3.088 \times 10^{-5} - 7.088 \times 10^{-5}$	–

3 Results

Table 3: Statistical Test Results for CV Model (`phabs*mekal`) on BH Spectra

Statistic	30 ks	300 ks	3000 ks	Infinite ks	Unit/Note
Bins	1.32	1.56	2.01	3.34	–
C-Statistic	1.309 339	1.438 174	2.013 863	9.924 666 34	–
Degrees of Freedom	1.29	1.53	1.98	3.31	–
C-Statistic P-Value	4.359	6.906	4.197	0.0000	–
Chi-Squared	1.398 719 74	1.115 921 86	1.437 836 90	3.389 046 56	–
Pearson Chi-Squared	3.342 135 73	9.258 019 2	2.460 795 0	2.7485	–
Anderson-Darling	1.209 90	1.139 21	1.022 97	4.1012	ln(AD)
Kolmogorov-Smirnov	−5.737	−9.435	−1.0785	−1.0131	$\ln(D)$

With certain parameters fixed (as mentioned in tables 1 and 2), we proceeded to vary the Photon index between 1.8 and 2.3, and the Normalization factor between 3e-5 and 7e-5 for the Black hole model. Similarly, for the Cataclysmic Variable model, we varied the plasma temperature between 7 keV and 13 keV, Metal abundances between 0.1 and 0.7, and the Normalization between 1e-5 and 2e-4.

Justifying the values assigned to the parameters: the density of the Hydrogen column in our field of view (nH) was fixed at 5e-21 based on the result obtained from w3nH, which calculates the Hydrogen column density based on the object's sky coordinates. Since the

Table 4: Statistical Test Results for BH Model (`phabs*powerlaw`) on CV Spectra

Statistic	30 ks	300 ks	3000 ks	Infinite ks	Unit/Note
Bins	1.34	1.56	1.58	3.33	–
C-Statistic	1.326 010	1.840 722	1.847 091	1.572 422 498	–
Degrees of Freedom	1.31	1.53	1.55	3.30	–
C-Statistic P-Value	4.445	4.40	5.18	0.0000	–
Chi-Squared	1.301 823 81	1.715 932 32	1.832 866 95	4.403 421 91	–
Pearson Chi-Squared	6.4136	3.3115	3.5368	1.2031	–
Anderson-Darling	4.6858	4.3540	4.2201	3.1737	ln(AD)
Kolmogorov-Smirnov	−9.833	−8.095	−8.114	−9.049	$\ln(D)$

source is Galactic, the redshift is set to 0, and fixing switch at 0 allows the model to predict the metal abundance in the source. It should be noted that we strictly limit the number of test values (N in the code)assigned to each parameter must be strictly less than 10. This is because, the number of calculations performed for each statistical test is N raised to the numberof free parameters for that model. And for higher values of N, the code takes a long time to execute and may also end up crashing the kernel. The spectral files were read-in using PyXspec and on performing the fit, we obtained the values listed in Tables 3 and 4.

4 Discussion

Of all the statistical tests used, we base our primary analysis on the the result of Cash-statistics and the associated p-value, as we assume poissomian distribution for the data. Although we also use Chi-Squared Statistic and Pearson Chi-Squared Statistic, they function of the assumption of a Gaussian data distribution. Both Chi-Squared Statistic and Pearson Chi-Squared Statistic measure the goodness of the fit but with different normalization factors. A good fit typically has a C-statistic p-value > 0.05, reduced chi-squared ≈ 1, and low AD/KS statistics. A poor fit has a low p-value (< 0.05), high reduced chi-squared (1), and high AD/KS, letting us disregard the model. On analysing the tables 3 and 4, although P-value > 0.05 suggests a good fit, the low SNR can mask the mismatches, thereby rendering the test unreliable. As an obviously noticeable trend, the very high Chi-squared statistic, Pearson Chi-squared statistic, and Anderson Darling statistic indicate a poor fit. Although the variations in Kolomogorov Smirnoff results are not as drastic as the other test results, the moderate fir still indicates a mismatch. Based on these criteria and justifications, we see that both models are a poor fit for the data provided.

5 Conclusions

Based on the results discussed in the previous section, we conclude that all cross-fits yield poor fits, thereby making it difficult or rather impossible to decide the suitable model to describe the data, and hence the nature of the source. In particular, the low-exposure data have very high SNR, making it difficult to arrive at a conclusion and the infinite exposure data are overfit by the model, although not obvious from the results. Since the obtained test results are not enough to categorise this source, the result is inconclusive. Although we can partly attribute this to the sensitivity of NuSTAR data, these dicrepancies could also arise from the choice of the models.
Therefore, as a part of future works, we plan to explore this with more and different models, using data from XMM-Newton.

6 Acknowledgements

I would like to thank my research advisor, Prof. Thomas J. Maccarone (Department of Physics and Astronomy, Texas Tech University) for guiding me through this project.

References

[1] Peter G Jonker, CG Bassa, Gijs Nelemans, D Steeghs, Manuel AP Torres, TJ Maccarone, RI Hynes, Sandra Greiss, J Clem, A Dieball, et al. The galactic bulge survey: outline and x-ray observations. *The Astrophysical Journal Supplement Series*, 194(2):18, 2011.

[2] Peter G Jonker, Manuel AP Torres, Robert I Hynes, Thomas J Maccarone, Danny Steeghs, Sandra Greiss, Christopher T Britt, Jianfeng Wu, Christopher B Johnson, Gijs Nelemans, et al. The galactic bulge survey: completion of the x-ray survey observations. *The Astrophysical Journal Supplement Series*, 210(2):18, 2014.

[3] EC Pattie, TJ Maccarone, CT Britt, CO Heinke, PG Jonker, DR Lorimer, GR Sivakoff, D Steeghs, J Strader, MAP Torres, et al. An arcsecond view at 1–2 ghz into the galactic bulge. *Monthly Notices of the Royal Astronomical Society*, 531(2):2191–2212, 2024.

[4] Margaret E Ridder, Craig O Heinke, Gregory R Sivakoff, and Andrew K Hughes. Radio detections of two unusual cataclysmic variables in the vla sky survey. *Monthly Notices of the Royal Astronomical Society*, 519(4):5922–5930, 2023.

[5] MAP Torres, PG Jonker, CT Britt, CB Johnson, RI Hynes, Sandra Greiss, D Steeghs, TJ Maccarone, F Özel, C Bassa, et al. Identification of 23 accreting binaries in the galactic bulge survey. *Monthly Notices of the Royal Astronomical Society*, 440(1):365–386, 2014.