Searching for a Hidden Compact Object in the System Lyra X-1

Abstract

Lyra X-1 is a newly discovered system in the Lyra constellation that bears a strong resemblance to the only known WR-HCO system, Cygnus X-3. Considering Lyra X-1 as a WR-HCO candidate system presents a unique opportunity to learn more about the dynamics and evolution of high-mass systems with extreme objects. Observing this system with *XMM-Newton* would provide insight into high-mass systems and would either establish as only the second known WR-HCO system within our galaxy or hint at new underlying physics that may help our understanding of the extreme objects found in systems like Lyra X-1 and Cygnus X-3.

Scientific Justification

Wolf-Rayet (WR) stars are rare stars with extreme masses ($M = 10 – 80M_\odot$, more typically $10 – 25M_\odot$), temperatures, and luminosities ($L = 1.5 \cdot 10^5 – 2.0 \cdot 10^6\ L_\odot$) and are considered a late-stage, short-lived ($\tau = 0.5$ Myr) evolutionary branch of O-type stars. They are characterized by broad spectral emission lines of ionized helium, nitrogen, carbon, oxygen, and—in the case of younger and more massive WR stars—hydrogen, in otherwise continuous spectra. The exact spectrum of a WR star depends upon its subtype: the WN subtype exhibits broad nitrogen spectra, while the WC and WO subtypes exhibit broad carbon and oxygen spectra, respectively (Crowther 2007). Another notable feature of WR stars is their extreme solar winds and mass outflow rates which are powered by their intense luminosities. These winds and outflows are important for enriching the surrounding region with metals, especially in high-mass star formation regions (Crowther 2007).

Some WR systems are known or suspected to harbour hidden compact objects (HCOs). Cygnus X-3 is the only such system known to contain an HCO within the Milky Way galaxy (Zdziarsky 2012). Cygnus X-3 demonstrates high radio emissions and relativistic jets, both of which are uncharacteristic of a typical X-ray source. The high mass-loss rate of $\dot{M} = 10^{-5}\ M_\odot$/yr and the fact that the system has high gamma-ray emissions are further indicative that Cygnus X-3 is not comprised of a lone WR star. This has led previous researchers, such as Abdo et al. (2009) and van Kerkwijk et al. (1992), to conclude that Cygnus X-3 is comprised of a WR donor star that is accreting onto a secondary compact object—either a neutron star (NS) or a stellar-mass black hole (BH)—within the system. Further observations with *Chandra*, as well as analysis of binary parameters such as the period (0.19969 d) and the high mass-lass rate further corroborated these conclusions (Zdziarsky 2012). Using these parameters, Zdziarsky et al. (2012) were able to place constraints on the masses of the two objects, finding the mass of the WR star to be $M_{WR} = 10^{+3.9}_{-2.8}\ M_\odot$ and that of the binary companion to be $M_{companion} = 2.4^{+2.1}_{-1.1}\ M_\odot$. Notably, the mass range of the companion—which is known to be a compact object—places it within range of being either an NS or a BH and potentially providing insight into the gap between the upper limit on NS masses and the lower limit on BH masses, also known as the mass gap. However, due to the lack of X-ray pulsations as well as the strong radio signal and a general spectral resemblance to that of BH spectra for the compact object, it is likely that the Cygnus X-3 system is comprised of a WN-type WR star with a BH binary companion (Zdziarsky 2012).

The recently-observed system, Lyra X-1, is a magnitude $m_V = 7.2$ object located approximately 7 kpc away in the Lyra constellation (J2000 coordinates: 18:51:42.3, +36:12:30) and is a candidate for another system which may contain an HCO, as demonstrated in Phillips et al. (2025). Archival *Gaia* data provided spectral data that suggested a strong presence of ionized nitrogen, one of the properties consistent with a WN-type WR star. A short (10 ks) observation with *Chandra* detected a hard X-ray source at the same coordinates in the 2.0 – 10.0 keV energy range with a flux of approximately $3 \cdot 10^{-13}$ erg/cm/s, and a follow-up observation at 5.2 GHz with the *Algonquin Radio Telescope* showed a strong radio source at the position of Lyra X-1 (Phillips 2025). Further optical observations have revealed no objects within 7" of Lyra X-1 that have an apparent magnitude of less than 20.0. Further observations of this system with a greater exposure time would be crucial in determining if it is, in fact, a WR star with an HCO.

Detailed observations of WR binary systems with compact objects will give us great insight into high-mass binary system evolution. Observation will allow us to determine whether or not Lyra X-1 is a binary system made up of a WR star and HCO companion, with spectral pulsations implying an NS companion or the lack of detectable pulsations implying a BH companion. We could then analyze only the second known WR system with an HCO and compare it against Cygnus X-3 to place constraints on the evolution of high-mass systems with HCOs, or, in the case that observation rules out the possibility of an HCO, our analysis would suggest some new underlying physics with high-mass stellar evolution. Furthermore, previous spectral data of various WR star types, as well as spectral analyses of supernova remnants and mass estimates of both types of object, have shown that WR stars are strong candidates for progenitors to Type Ib and Type Ic supernovae and long gamma-ray bursts (Crowther 2007). Observing Lyra X-1 could shed light onto the mechanisms which cause these extreme events and may present insight into the formation of NS-BH or BH-BH binary systems. In any case, a detailed observation of Lyra X-1 presents an opportunity to learn much about high-mass stellar evolution and binary systems.

Technical Justification

Using the NASA WebSpec tool, we predict that the Fe Kα line hard X-ray flux is faint for Lyra X-1 at $F = 3.1 \cdot 10^{-13}$ erg/cm^2/s. We also assumed a typical WR stellar wind, and standard chemical abundances for a WN-type WR star (Table 01), such that we could model it with XSpec's vapec tool. This gave us a $kT \approx 0.59 \pm 0.04$ keV (Table 01) for the plasma in the WR stellar wind. We also modeled the system with an XSpec photon index power law model, which came out to be $\Gamma \approx 1.97 \pm 0.09$ (Table 01) which is well within the bounds of what we would expect for a system with an accreting compact object. Finally, using a Gaussian distribution model, we predicted a peak in the hard X-ray band at an energy of $kT_\alpha \approx 6.40 \pm 0.03$ keV (Table 01). This peak corresponds to what we would expect for a Fe Kα line, demonstrating that the expected hard X-ray flux is within a detectable range. Notably, we also predicted that with a 50 ks observation the normalized flux should not be any less than $F = 10^{-3}$ count/s/keV (Figure 01) or $F = 10^{-6}$ count/s/channel (Figure 02) across the entire energy range we modelled. The randomized distribution presented in Figure 03 supports the accuracy of our model across the entire energy spectrum.

Given these model characteristics and the magnitude m_V of the system, we propose that a 50 ks *XMM-Newton* observation of Lyra X-1 with the EPIC-pn detector, operated in full-frame mode with the medium filter would be ideal to resolve the system in high detail due to the detector's fast timing resolution and large effective area at 6.4 keV. The relatively flat spectrum in the 0.5 to 10.0 keV range, and the predicted pulsations for an NS binary companion, make *XMM-Newton* the ideal telescope for observing this system due to its strength across both soft and hard X-rays and the EPIC-pn detector's 73.4 ms time resolution while in full-frame mode. The 99.9% live time of the EPIC-pn detector in full-frame mode also ensures that our observation of Lyra X-1 will capture all of the details that shorter observations, or observations with less live time, would be able to see. This would give us further insight into the spectrum and characteristics of Lyra X-1, including whether or not it has detectable pulsations that would likely indicate an NS HCO within the system.

Conclusion

Lyra X-1 presents an interesting opportunity to examine what may be the second-known WR-HCO system within the Milky Way galaxy, only after Cygnus X-3. Previous observations in the X-ray, optical, and radio bands have suggested strong similarities between the two systems, including properties consistent with a WN-type WR star and an HCO companion. The system's unique position, with very little background interference, makes the system a strong candidate for detailed observing with X-ray observatories such as *XMM-Newton*. A 50 ks observation of Lyra X-1 with the *XMM-Newton* EPIC-pn detector in full-frame mode would provide unprecedented spectral and timing resolution for such an extreme and rare system. We choose the *XMM-Newton*'s EPIC-pn detector for this observation as it is ideal for measuring the relatively flat spectrum in both hard and soft X-rays, its strong live time, large effective area, and ability to detect pulsations that would be indicative of an NS binary companion. Observation of Lyra X-1 presents an opportunity to learn much about high-mass systems and WR stellar winds in both scenarios, either confirming it as an WR-HCO system or disproving that hypothesis and confirming Lyra X-1 as another type of system that produces hard X-rays. In either case, an *XMM-Newton* observation of Lyra X-1 will place constraints on the dynamics of high-mass systems and provide insight into high-mass stellar evolution, helping to refine future models including the mass gap, and may even present some new underlying physics for extreme objects like NS, BH, or WR stars and the formation of the former two.

Appendix

Table 01: XSpec Simulation Data for Lyra X-1

Quantity	Value	Error
Column Density (N_H) [cm^{-3}]	0.6185350000	-0.0474519, +0.0492523
Line Energy (kT) [keV]	0.5853290000	-0.0348928, +0.039095
Helium [Solar Abundance]	1.5000000000	
Carbon [Solar Abundance]	0.1000000000	
Nitrogen [Solar Abundance]	5.0000000000	
Oxygen [Solar Abundance]	0.5000000000	
Neon [Solar Abundance]	1.0000000000	
Magnesium [Solar Abundance]	1.0000000000	
Aluminum [Solar Abundance]	1.0000000000	
Silicon [Solar Abundance]	1.0000000000	
Sulfur [Solar Abundance]	1.0000000000	
Argon [Solar Abundance]	1.0000000000	
Cadmium [Solar Abundance]	1.0000000000	
Iron [Solar Abundance]	1.0000000000	
Nickel [Solar Abundance]	1.0000000000	
Redshift	0.0000000000	
Redshift Norm	1.71267e-04	-3.69593e-05, +4.57675e-05
Photon Index (Γ)	1.9772700000	-0.0929967, +0.0922625
Photon Index Norm	1.15488e-04	-1.14713e-05, +1.19481e-05
Fe Kα Line Energy (kT_a) [keV]	6.4007500000	-0.026697, +0.0274457
Sigma (σ)	0.0500000000	
Sigma Norm	3.12532e-06	-5.97117e-07, +5.96743e-07

Figure 01: XSpec Simulation of Lyra X-1 as Counts vs Energy

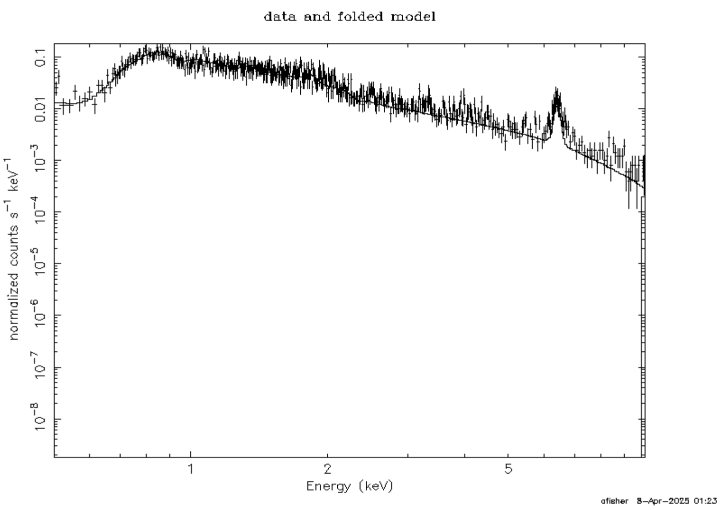


Figure 02: XSpec Simulation of Lyra X-1, Counts vs Channel

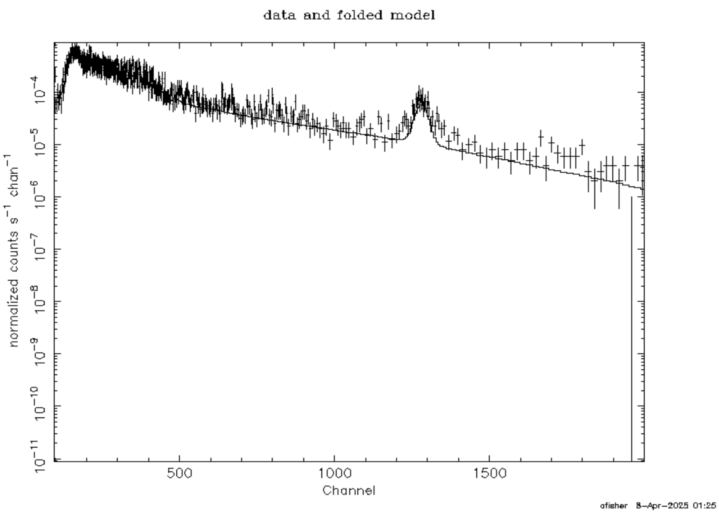
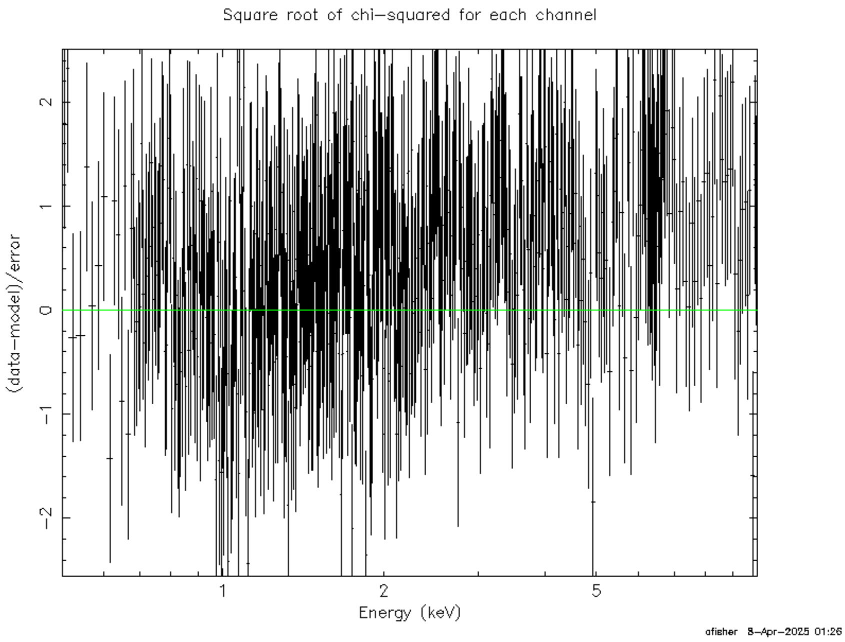


Figure 03: XSpec Simulation Reduced Chi-Squared vs Energy



References

Abdo A., et al., 2009, *Sci*, 326, 1512
Arnaud K., 1996, *ASPC*, 101, 17
Belczynski K., et al., 2013, *ApJ*, 764, 96
Crowther P., 2007, *ARAA*, 45, 177, doi: 10.1146/annurev.astro.45.051806.110615
ESA, 1998, *XMM-Newton SOC*, r2.22
NASA HEASARC, 2023, *WebSpec*, v4.12
Phillips A., et al., 2025, *FakeAJ*, 1, 25, doi: 10.0000/fake.source.01.0000
van Kerkwijk M., et al., 1992, *Nat*, 355, 703
Zdziarsky A., et al., 2012, *MonRAS*, 429, 104, doi: doi.org/10.1093/mnrasl/sls035