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Insights on the Optical and Infrared Nature of MAXI J0709-159: Implications for High-Mass X-ray Binaries

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Abstract

In our previous study (Bhattacharyya et al., 2022), HD 54786, the optical counterpart of the MAXI J0709-159 system, was identified to be an evolved star, departing from the main sequence, based on comparisons with non-X-ray binary systems. In this paper, using color-magnitude diagram (CMD) analysis for High-Mass X-ray Binaries (HMXBs) and statistical t-tests, we found evidence supporting HD 54786's potential membership in both Be/X-ray binaries (BeXRBs) and supergiant X-ray binaries (SgXBs) populations of HMXBs. Hence, our study points towards dual optical characteristics of HD 54786, as an X-ray binary star and also belonging to a distinct evolutionary phase from BeXRB towards SgXB. Our further analysis suggests that MAXI J0709-159, associated with HD 54786, exhibits low-level activity during the current epoch and possesses a limited amount of circumstellar material. Although similarities with the previously studied BeXRB system LSI $+61^\circ$ 235 (Coe et al., 1994) are noted, continued monitoring and data collection are essential to fully comprehend the complexities of MAXI J0709-159 and its evolutionary trajectory within the realm of HMXBs.

Keywords: Classical Be stars, Circumstellar disks, Photometry, HMXB

1. Introduction

High-mass X-ray binaries (HMXBs) are binary systems composed of a compact object (possibly a neutron star or a black hole) and a massive companion star, which can be typically an O or B type star (Reig, 2011). They are important sources of X-ray emission in the Galaxy and other star-forming regions, as well as probes of stellar evolution and feedback. HMXBs can be classified into different subtypes based on the properties of their companion stars and their X-ray variability. Two of the most prominent subtypes are Be/X-ray binaries (BeXRBs) and supergiant X-ray binaries (SgXBs) (Reig, 2011).

Be/X-ray binaries (BeXRBs) consist of a compact object orbiting a Be star, which is a non-supergiant B-type massive star that exhibits Balmer emission lines and infrared excess due to the presence of a circumstellar gaseous disc (e.g., Reig, 2011; Rappaport and van den Heuvel, 1982). The compact object accretes matter from the decretion disc (Okazaki and Negueruela, 2001) of the Be star. A study by Belczynski and Ziolkowski (2009) found that neutron stars (NSs) are more frequently observed companion for BeXRBs. Many BeXRBs are transient sources that exhibit periodic or sporadic outbursts of X-ray emission, lasting from minutes to weeks, when the compact object interacts with the disc or the stellar wind originating from the Be star (e.g., Monageng et al., 2017; Okazaki and Negueruela, 2001). The orbital periods of BeXRBs range from tens to hundreds of days, and the eccentricities are usually high. They are the most common subtype of HMXBs in the Galaxy and in nearby galaxies such as the Magellanic Clouds (Reig, 2011).

We previously performed a follow-up study (Bhattacharyya et al., 2022) on the recent detection of two X-ray flaring events by MAXI/GSC observations in soft and hard X-rays from MAXI J0709-159 in the direction of HD 54786 (LY CMa), on January 25, 2022. Using optical spectroscopy and multi-epoch photometry, we primarily focused on the nature of the optical counterpart of MAXI J0709-159, which is the less-studied Be star HD 54786. We estimated that the star's effective temperature was 20000 K and found that it is evolving off the main sequence in the Color-Magnitude Diagram. Our analysis also suggested that HD 54786 is a BeXRB system having a compact object companion, probably a neutron star. However, that study was based on a sample of catalogs of non X-ray binary systems. So we became motivated to perform further analysis of this object using some well known HMXB catalogs to complement the previous study and better understand such systems. Here, we present an optical photometric analysis of the location of HD 54786 in relation to well known HMXB systems. By focusing on the optical properties of this system, we gain important insights about the circumstellar disc, which not only aids in better understanding the characteristics of HMXBs but also sheds light on the nature of standalone Be stars.

2. Data

Here, we utilized the data adopted from some important HMXB catalogs, such as those of Liu et al. (2006), Kretschmar et al. (2019) and Neumann et al. (2023). We selected and extracted two major classes of HMXBs, supergiants and Be stars, as indicated by the classification flags provided in these catalogs. By adhering to this classification criteria, we categorized the flagged objects accordingly. HMXBs associated with Be stars are classified as the "Bexrb" category, representing BeXRBs. Likewise, any HMXB flagged or associated with a supergiant was included in the category labeled "Sgxrb," denoting Supergiant X-ray Binaries (SgXBs). SgXBs consist of a compact object orbiting a highly evolved, luminous supergiant star (Reig, 2011). These persistent sources display varying X-ray luminosity levels depending on the mass accretion rate from the supergiant's strong stellar wind. Having orbital periods spanning between days to months, SgXBs constitute approximately 30% of the Galactic population of HMXBs (Drave, 2013).

We identified a total of 65 systems associated with Be stars, which we classified as "Bexrb", and 33 systems associated with supergiants, classified as "Sgxrb." From this sample, we selected 37 "Bexrb" systems and 17 "Sgxrb" systems for further analysis since these stars have *Gaia* magnitude data (G, $G_{\rm BP}$, and $G_{\rm RP}$; Gaia Collaboration et al., 2021), Gaia photometric distance (Bailer-Jones et al., 2021) and extinction parameters (obtained from Green et al., 2019) available.

3. Results

3.1. *Gaia* CMD analysis

In our previous study, we determined the photometric position of HD 54786 in the *Gaia* (Gaia Collaboration et al., 2021) color-magnitude diagram (CMD) and compared its location with samples of previously studied B-type (Huang et al., 2010), Be stars (Bhattacharyya et al., 2021, and references therein), giant stars (Hohle et al., 2010) and supergiants (Georgy et al., 2021). It was noticed that this star is located near the top of the distribution of B and Be stars, situated inside the distribution of giant stars and below that of supergiants (see Fig. 2a in Bhattacharyya et al., 2022).

In this study, we constructed the *Gaia* CMD for HD 54786 using data from the well-known HMXB catalogs mentioned in Sect. 2. Considering its *Gaia* DR3 distance and $A_{\rm V}$ value of 0.93 (as estimated from the Green's map; Green et al., 2019), we plotted the corresponding M_G versus $G_{\rm (BP-RP)0}$ CMD for the star and over-plotted the previously well-studied HMXB sample. It is noted from Pecaut and Mamajek (2013) that the ZAMS line does not extend beyond B9 spectral type in M_G and $G_{\rm (BP-RP)0}$ values. So we utilized the closely matching 60 Myr isochrone track from MESA (Modules for Experiments in Stellar Astrophysics) isochrones and evolutionary tracks (MIST) (Choi et al., 2016; Dotter, 2016), which is over-plotted in the CMD with $V/V_{\rm crit} = 0.4$ (critical rotation fraction), since that is the only model available in the MIST database for a rotating system as our sample shows features of Be star (Bhattacharyya et al., 2022). Moreover, we adopted the metallicity value of [Fe/H] = 0, corresponding to solar metallicity $Z_\odot = 0.0142$ (Asplund et al., 2009) for the tracks. The CMD showing the location of HD 54786, with the representative locations of the selected extinction corrected "Bexrb" and "Sgxrb" systems is presented in Fig. 1.

The CMD shows distinct regions for the distributions of BeXRB and SgXB systems. In light of this, we sought to evaluate the involvement of HD 54786 in these two subclasses of HMXBs, i.e. "Bexrb" and "Sgxrb" distributions. To accomplish this, we conducted single t-tests using the SciPy Python module (Virtanen et al., 2020). One-sample t-tests were chosen due to their ease of interpretation; if the obtained p-value is higher than a chosen significance level (e.g. 0.05), we can conclude that there is evidence of a significant similarity between the samples. In this study, the resulting p-values from the t-test for both the "Bexrb" and "Sgxrb" cases were higher than 0.05, suggesting that the results lacked statistical significance, failing

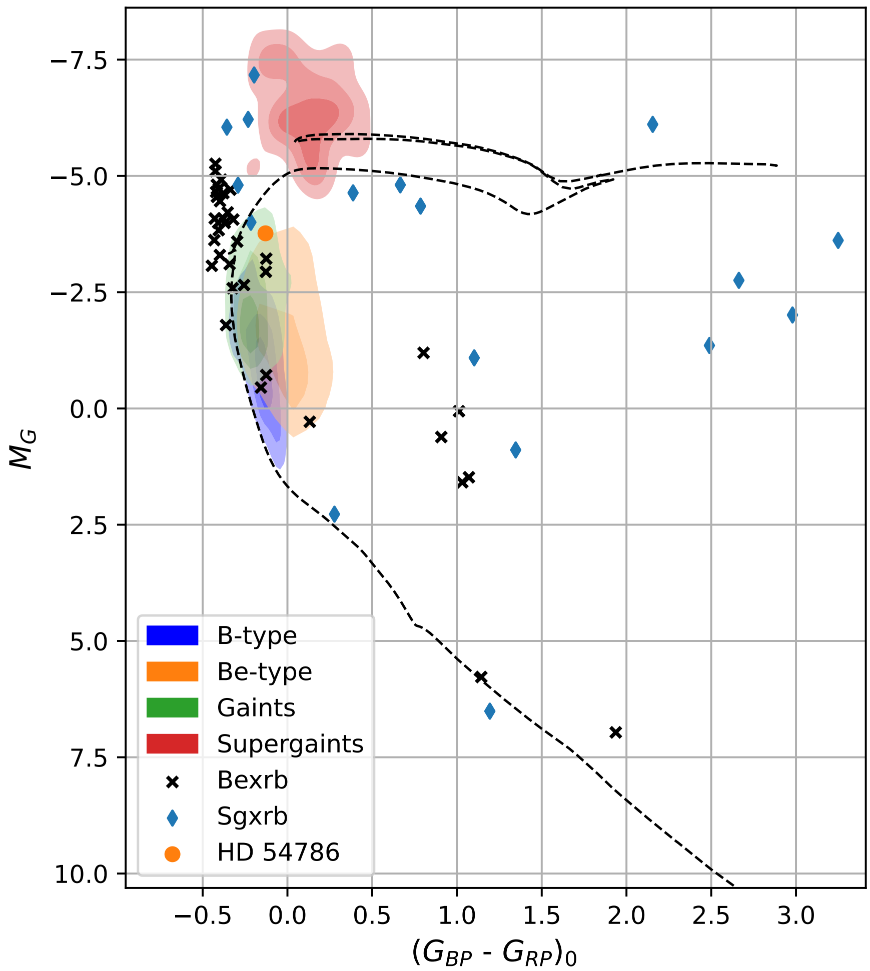

Figure 1: The *Gaia* CMD of HD 54786 having extinction corrected *Gaia* M_G and $(G_{BP}$ - $G_{RP})_0$ magnitudes has been represented. The *Gaia* G and $(G_{BP} - G_{RP})$ magnitudes are obtained from Gaia Collaboration et al. (2021). The probability distribution (Gaussian fitted at three contour levels) of the B, Be stars, giants and supergiants are shown in blue, orange, green and red shaded colors, respectively (Bhattacharyya et al., 2022). The black dashed line in the plot represents the 60 Myr isochrone with $V/V_{crit} = 0.4$ (critical rotation fraction) and [Fe/H] $= 0$ (the top black dashed line is the blue loop part of the same isochrone). The black cross and the blue diamond markers indicate the "Bexrb" and "Sgxrb" systems, respectively.

to support the null hypothesis that HD 54786 does not belong to any distribution. The average p-values obtained were 0.3 and 0.4, respectively. Despite the higher p-value for the "Sgxrb" category, it is premature to classify HD 54786 as a supergiant associated system, given its proximity to the BeXRB value. Nonetheless, this analysis does support HD 54786's membership in both the "Bexrb" and "Sgxrb" populations, indicating its optical characteristics resemble those of X-ray binary stars, representing a distinctive stage in its evolutionary pathway towards SgXB from BeXRB.

This finding complements our previous results by specifically revealing the dual nature of HD 54786, thus further enriching our understanding of its evolutionary significance.

3.2. Hα vs. *J–K* study

We then performed an analysis involving the Hα and extinction corrected $(J-K)$ plot to gain a photometric perspective on the circumstellar disk around the primary object in HMXB systems. This kind of analysis has been extensively conducted by Coe et al. (1993, 1994) to explore the properties of the BeXRB objects LSI +61° 235 and A1118-616. Here, we utilize the same plot to understand the location of the optical counter part (HD 54786) of the X-ray source MAXI J0709-159 among the candidate sources. In Fig. 2, we present the Hα vs. intrinsic $(J-K)$ plot for a sample of field Be stars (Dachs and Wamsteker, 1982; Ashok et al., 1984) along with two BeXRB objects (mentioned above). The Hα equivalent width (EW) for HD 54786 was measured to be -16.9 Å, as reported in Bhattacharyya et al. (2022). The observations were conducted using the Himalayan Chandra Telescope (HCT) located at the Indian Astronomical Observatory (IAO), Ladakh, India on February 1, 2022, precisely six days after the reported flare (Serino et al., 2022). IAO is operated by the Indian Institute of Astrophysics (IIA), Bangalore. On the other hand, the J and K magnitudes were obtained from the 2MASS catalog (Cutri et al., 2003). These magnitudes were corrected using the values provided by Green et al. (2019) to account for extinction.

In Fig. 2, the orange star symbol represents the location of the two BeXRB objects from (Coe et al., 1993, 1994). The green star symbol indicates the location of HD 54786 (MAXI J0709-159), while the blue diamond symbol depicts the location of field Be stars taken from Dachs and Wamsteker (1982) and Ashok et al. (1984). The figure clearly illustrates that the positions of HMXBs, specifically the two BeXRBs in this case, can vary significantly based on the state of the circumstellar medium (CSM) of each system.

Coe et al. (1993) proposed that the CSM of LSI $+61°$ 235, being of low density and/or temperature, results in negligible energy in the near-IR region, leading to the conclusion that the system exhibits low-level activity during that time and has little material around the Be star. Similarly to HD 54786 (MAXI J0709-159), which is located close to LSI $+61°$ 235 in the Hα vs. $(J-K)$ plot, our object may also have a scarcity of material around the Be star and experience a low level of activity, as the Hα observation took place six days after the flare. A weak infrared (IR) excess may be attributed to free-free emission in the disc or shell structure surrounding a Be star, which is a common observation in both Be stars and several X-ray systems associated with Be stars (Coe et al., 1988).

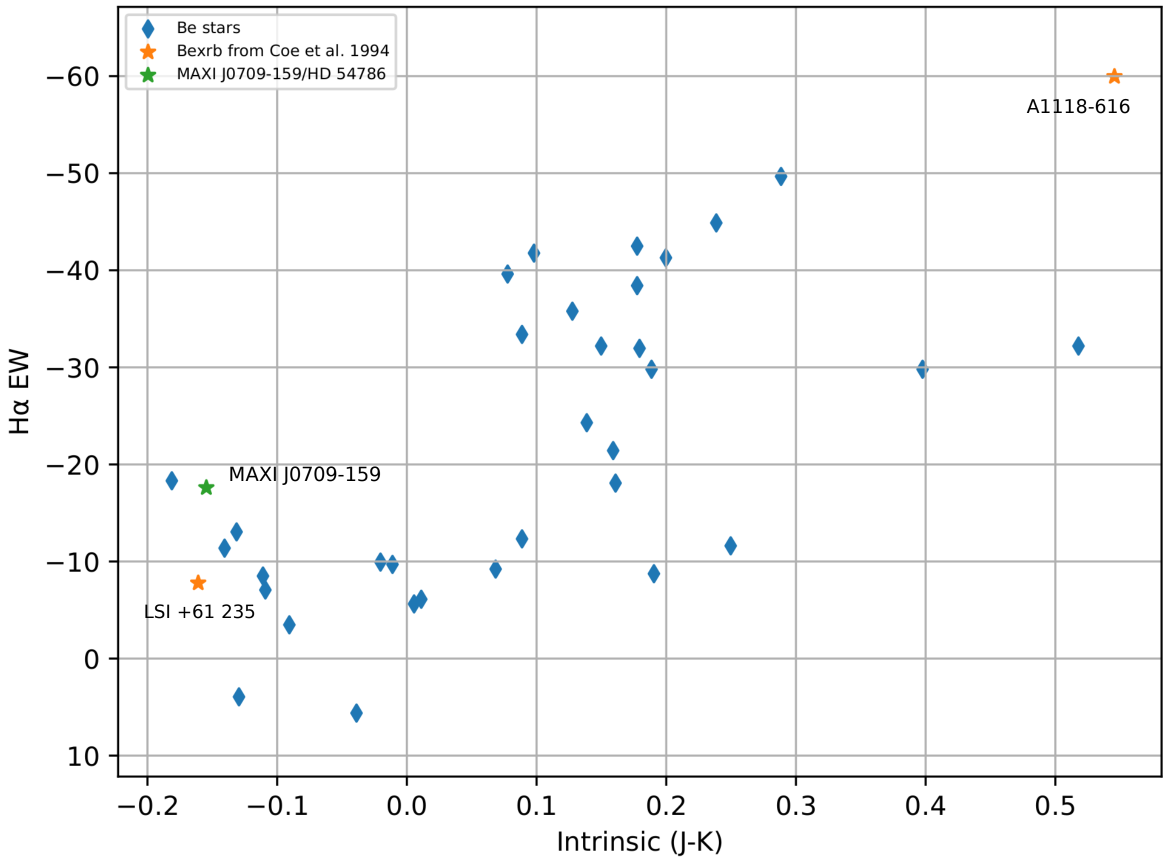

Figure 2: Plot of Hα versus intrinsic $J-K$ for MAXI J0709-159 observed on February 1, 2022 (Green star symbol). The location of the other two HMXB are marked in orange marker. The blue diamond symbols are for the field Be stars from Dachs and Wamsteker (1982) and Ashok et al. (1984). The diagram indicates that the location of HMXB (BeXRB in this case) can differ vastly based on the state of the CSM of the particular system. In case of MAXI J0709-159, it is obtaining comparatively smaller disc size.

4. Conclusions

In our previous study (Bhattacharyya et al., 2022), we established HD 54786 as an evolved star departing from the main sequence by comparing with non-X-ray binary systems. Here, the CMD analysis based on HMXB, coupled with t-tests, increases the probability that HD 54786 maybe a member of both the "Bexrb" and "Sgxrb" populations of HMXBs, signifying its dual optical characteristics as an X-ray binary star and its distinct evolutionary phase from BeXRB towards SgXB stage.

We also utilized the Hα vs. $J-K$ plot to gain insights into the circumstellar disk around the primary object in HMXB systems, the current analysis indicates that the system MAXI J0709-159 is currently exhibiting low-level activity, with less amount of material surrounding the Be star HD 54786. The current state of our object shows similarities to the study on LSI $+61^{\circ}$ 235 by Coe et al. (1994), although that system benefited from extensive monitoring data, which proved extremely valuable in understanding the behavior of this intricate system. Continued monitoring and data collection are crucial in unraveling the complexities of MAXI J0709-159 and its evolution within the context of HMXBs.

Further Information

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Author contributions

This work is part of a collective effort with contributions from all the co-authors.

Conflicts of interest

The authors declare no conflict of interest.

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