Massive Runaway Binaries in the NGC 3603 Star Cluster (Postprint)

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Abstract

The origin of massive stars and massive binaries in non-cluster environments is one of the key issues for understanding massive star formation and evolution. Dynamical encounter processes within young massive star clusters represent an important channel for producing massive runaway stars. We selected two colliding wind system candidates, MTT68A and MTT71, located in the periphery of the young massive star cluster NGC 3603 in the Milky Way, and investigated their origin as interacting massive binary systems by analyzing *Chandra* X-ray observations and astrometric results from the *Gaia* second data release (DR2). Analysis of the X-ray data reveals that their X-ray spectra contain an Fe XXV emission line component; compared to normal O-type stars, fitting with a two-temperature plasma model yields a relatively high temperature for the hot component ($\gtrsim$;2.0;keV), and the ratio of X-ray luminosity to bolometric luminosity is also relatively high ($\gtrsim$;$10^{-5.8}$). These spectral characteristics further support the interpretation that they are colliding wind systems. Based on the proper motion information from the *Gaia* DR2 database, MTT71 has proper motion values similar to those of NGC 3603 as a whole, suggesting that it likely formed in association with the cluster. In contrast, relative to NGC 3603 as a whole, MTT68A exhibits a relative proper motion of $\sim$;4.1;mas,·,yr^{-1}, and its opposite direction points toward the vicinity of the cluster center. This proper motion result indicates that MTT68A is likely a massive binary system ejected from the core region of the cluster; based on the projected distance from MTT68A to the cluster center and the magnitude of the relative proper motion, we estimate that this ejection event occurred approximately 20;kyr ago. The possible dynamical mechanism is three-body or four-body interactions, and searching for massive stars with opposite relative proper motion on the opposite side of the cluster will help verify this hypothesis.

Full Text

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Abstract

The origin of massive stars and massive binaries outside cluster environments is a key question for understanding massive star formation and evolution. Dynamical encounter processes within young massive clusters represent an important pathway for producing massive runaway stars. We selected two colliding-wind system candidates, MTT68A and MTT71, located in the periphery of the young massive Galactic cluster NGC 3603, and investigated their origin as interacting massive binary systems through analysis of Chandra X-ray observations and astrometric results from Gaia Data Release 2 (DR2). Our X-ray spectral analysis reveals Fe XXV emission line components in their spectra, elevated high-temperature component temperatures ($\gtrsim 2.0$ keV) when fitted with a two-temperature plasma model, and high X-ray-to-bolometric luminosity ratios ($\gtrsim 10^{-5.8}$) compared to typical O-type stars. These spectral features further support their interpretation as colliding-wind systems. Based on proper motion information from Gaia DR2, MTT71 exhibits proper motions similar to the NGC 3603 cluster as a whole, suggesting it likely formed in association with the cluster. In contrast, MTT68A shows a relative proper motion of ~ 4.1 mas$\cdot$yr^{-1} with respect to NGC 3603, with its direction pointing back toward the cluster center. This proper motion result indicates that MTT68A is likely a massive binary system ejected from the cluster core region. We estimate that this ejection event occurred approximately 20 kyr ago based on MTT68A's projected distance from the cluster center and its relative proper motion magnitude. The likely dynamical mechanism involves three-body or four-body interactions, and searching for massive stars with opposite relative proper motions on the opposite side of the cluster would help verify this hypothesis.

Keywords: stars: massive, stars: winds and outflows, stars: kinematics and dynamics, stars: individual: MTT68, MTT71, proper motions

1 Introduction

Massive stars tend to form in clustered environments. Observed massive stars in non-clustered environments likely originate from ejection processes during early cluster evolution, meaning massive stars do not form in isolation. Possible ejection mechanisms include supernova explosions in binary systems and three-body or four-body interactions among stars in dense clusters. A significant fraction of massive field stars and runaway stars are binary systems, with approximately 40% of main-sequence O-type stars undergoing interaction processes with companions, which influences and even alters the evolution of massive stars themselves. Therefore, investigating and determining the origin of massive binary systems outside clusters not only tests and constrains massive star formation theory but also provides the foundation for studying interaction processes and subsequent evolution of massive binary systems.

Previously, limited by the lack of high-precision proper motion measurements, studies of massive star ejection processes could only be conducted indirectly, such as by searching for bow shocks associated with high-velocity stars—though these only form when stellar velocities exceed the local sound speed. With the release of high-precision astrometric data from the Gaia satellite, research on ejection processes of young massive stars from clusters has become more direct. Gaia's sub-milliarcsecond astrometric precision enables us to obtain proper motion data for massive stars within 10 kpc with precision better than 3 $\mathrm{km\cdot s^{-1}}$, allowing effective identification of massive runaway stars.

Furthermore, two massive stars in a close binary system can form a colliding-wind system. High-velocity stellar winds from both stars collide, forming shocks that produce bright X-ray radiation. Therefore, studying their X-ray variability and spectral characteristics can help us confirm the existence of colliding-wind systems.

To investigate binary ejection in young massive clusters, we combined X-ray observations with high-precision proper motion measurements to study two colliding-wind system candidates, MTT68 and MTT71, in the periphery of the NGC 3603 cluster. NGC 3603 is located on the outer edge of the Sagittarius arm at a distance of 7.6 kpc from the Sun and is a rare dense (core radius $r_{\rm core} = 4.8''$ or 0.18 pc) young massive cluster (age ≈ 2 Myr).

Moffat et al. detected numerous X-ray point sources in NGC 3603, among which MTT68 and MTT71 were considered possible colliding-wind systems due to their elevated X-ray-to-bolometric luminosity ratios. MTT68 and MTT71 are located in the periphery of NGC 3603 (at distances of $85''$ and $106''$ from the cluster center, respectively) with spectral types O2If* and O4III. Huenemoerder et al. (hereafter H19) used high-resolution spectroscopic observations from the Chandra X-ray Observatory to obtain more detailed X-ray timing and spectral analysis results for both targets, also suggesting they might be colliding-wind systems, though they did not reach definitive conclusions due to limited observation duration (exposure time 47 ks). Additionally, Roman-Lopes confirmed through Hubble Space Telescope (HST) F656N-band images that MTT68 consists of two massive stars, A and B, and also suggested MTT68A is a binary system based on broad Paβ, N III λ21150, and N IV λ4058 emission lines in near-infrared and optical spectra.

This paper aims to further investigate the properties of the MTT68A and

MTT71 binary systems through analysis of Chandra X-ray imaging spectroscopy data and to study their origin using astrometric results from Gaia Data Release 2 (DR2). The structure of this paper is as follows: Section 2 introduces the observational data and processing procedures for MTT68 and MTT71, Section 3 presents the X-ray spectral analysis of MTT68 and MTT71 and analyzes the kinematic characteristics of both targets using Gaia DR2 data, Section 4 discusses their X-ray radiation mechanisms and kinematic origins, and Section 5 states the main conclusions.

2 Observations and Data Processing

We utilized five Chandra observations targeting the NGC 3603 cluster. The observation log numbers, instruments used (all Advanced CCD Imaging Spectrometer-Imaging Array, ACIS-I), exposure times, observation start dates, and principal investigator information are listed in Table . We processed the Level 1 event files following standard procedures using CIAO software (version 4.12) and the calibration database (version 4.9.3) to uniformly reprocess and generate Level 2 event files. After removing time periods with anomalous photon count rates, the cumulative exposure time was 493 ks.

Simultaneously, we used HST F656N narrow-band filter images from the Hubble Legacy Archive to identify the source of MTT68's X-ray emission. In the HST observations, the X-ray point source MTT68 is resolved as a visual binary system composed of MTT68A and MTT68B, with a separation of $0.38''$, approaching Chandra's limiting resolution. To determine whether MTT68's X-ray emission originates primarily from MTT68A or MTT68B, we used the HST/F656N image as a reference and corrected the Chandra image coordinates by selecting and comparing the positions of five isolated optical-X-ray counterparts in the cluster periphery across both band images. After coordinate correction, the relative positions of MTT68's Chandra X-ray emission centroid and MTT68A's F656N optical emission centroid are shown in Figure [Figure 1: see original paper]. We found that MTT68's X-ray emission centroid is closer to MTT68A (offset $\sim 0.04''$–$0.07''$, comparable to the coordinate uncertainty) and far from MTT68B (offset $\gtrsim 0.34''$). We therefore conclude that MTT68's X-ray emission primarily represents the properties of MTT68A, meaning MTT68's X-ray characteristics mainly reflect MTT68A rather than MTT68B.

After excluding observations where the target point source fell on CCD gaps, we selected four observations for subsequent timing and spectral analysis (MTT68: 00633, 12329, 12330, 13162; MTT71: 12328, 12329, 12330, 13162). The selected source and background regions for MTT68 and MTT71 are shown in Figure [Figure 2: see original paper].

Additionally, we queried Gaia DR2 catalog information for MTT68A and MTT71, including source IDs, right ascension α, declination δ, proper motion in right ascension direction μ_α, and proper motion in declination direction μ_δ. The query results are listed in Table . The last column of Table shows the tangential velocity magnitude v_{2D} of MTT68A relative to NGC 3603 (detailed in Section 3.3). We searched for astrometric data within a $5''$ radius centered on the coordinates of MTT68A and MTT71 in the HST/F656N images, converted the coordinates from the J2015.5 epoch in Gaia DR2 to the J2000 epoch, and further updated the coordinate systems of the HST/F656N and X-ray images by comparing them with surrounding objects. After coordinate correction, we found that the coordinates listed in Gaia DR2 are closer to MTT68A, with coordinate errors much smaller than the separation between MTT68A and MTT68B ($0.38''$). We therefore conclude that the corresponding proper motion information reflects the motion of MTT68A.

3 Analysis

3.1 X-ray Variability of MTT68 and MTT71

We used the CIAO dmextract script to extract X-ray variability data for MTT68 and MTT71 during the effective exposure times of each available observation. The variability data were binned with a time interval of 1 ks, and the resulting 0.4–8.0 keV light curves are shown in Figure [Figure 3: see original paper].

We applied the Kolmogorov-Smirnov test (K-S test) at a 5% significance level to examine the variability of MTT68 and MTT71. No significant variability was found for either MTT68 or MTT71 in individual observations. When combining all observations, we found no significant variability for MTT71, while MTT68 showed variability between observations at this significance level, with an amplitude of approximately 52%. Therefore, in the subsequent spectral analysis, we merged all observations for MTT71 but performed separate analyses for each individual observation of MTT68.

3.2 Chandra X-ray Spectra of MTT68 and MTT71

We used the CIAO specextract script to extract X-ray spectra for MTT68 and MTT71 from each available observation and generated corresponding response files. The resulting spectra are shown in Figure [Figure 4: see original paper].

We analyzed the obtained spectra using XSPEC software (version 12.11.1). Considering that X-ray radiation from O-type stars originates from shock-heated plasma produced by wind-ISM interactions and that typical emission lines are present in the obtained spectra (such as Si XIII around 1.8 keV and S XV around 2.4 keV), we fitted the spectra using the hot plasma model APEC. We first attempted a foreground-absorbed single-temperature plasma model (Tbabs*APEC), but the fit results were unsatisfactory (normalized residual to degrees of freedom ratio χ^2/dof between 1.16–1.46). To improve the fit quality, we employed the two-temperature plasma model TBabs*(APEC + APEC), commonly used for analyzing X-ray radiation from massive star wind systems (see reference [24]), and obtained acceptable fit results (χ^2/dof between 0.95–1.11). The low- and high-temperature components represent the temperature range of the stellar wind hot plasma. The spectral fitting results for MTT68's four observations and MTT71's combined observation are presented in Table . The best-fit model parameters including foreground absorption (equivalent neutral hydrogen column density N_H), hot plasma elemental abundance Z, temperatures of the two components kT_1 and kT_2, and emission measures EM_1 and EM_2 are shown in columns 2–7. Column 8 shows the fit residual χ^2 and degrees of freedom dof. Error values for each parameter represent the 90% confidence interval limits. We also derived the intrinsic X-ray luminosities of MTT68 and MTT71 in the 0.4–8.0 keV energy band from the best-fit models and calculated their ratios to bolometric luminosity, $L_X/L_{\rm bol}$ (column 9). Bolometric luminosity information was taken from reference [25] and scaled to a distance of 7.6 kpc. Additionally, we fitted the Fe line profile near 6.7 keV using a Gaussian function, with the resulting line center energy LineE shown in the last column of Table .

As seen in Table , the four spectral fits for MTT68 show slight differences and differ more significantly from the combined fit for MTT71. For MTT68, the foreground absorption equivalent neutral hydrogen column density N_H from multiple observations ranges between (1.8–2.1) $\times 10^{22}$ cm^{-2}, while MTT71 experiences lower foreground absorption ($N_H = (1.6 \pm 0.1) \times 10^{22}$ cm^{-2}). This result is slightly higher than the neutral hydrogen column density estimated from optical or near-infrared extinction values [20, 26] and also slightly higher than the X-ray spectral analysis results of H19 [21]. However, we note that MTT68's optical radiation experiences stronger extinction than MTT71, and both suffer stronger extinction than the central cluster of NGC 3603, a difference consistent with our X-ray spectral fitting results (see reference [19]). The discrepancy with H19's results may stem from using different foreground absorption models (phabs versus TBabs). The low-temperature component temperatures for MTT68 and MTT71 are roughly between 0.6–1.0 keV, while MTT68's high-temperature component ranges between 4.4–9.2 keV and MTT71's high-temperature component is lower ($kT_2 = (2.0 \pm 0.2)$ keV). The Fe line center near 6.7 keV indicates it likely originates from Fe XXV radiation, consistent with the high-temperature component fitting results of 20–100 MK. Compared to MTT68, MTT71's X-ray-to-bolometric luminosity ratio is roughly an order of magnitude lower but still far exceeds the typical value for single O-type stars ($\sim 10^{-7}$) [27]. Both the high-temperature component and X-ray luminosity are consistent with H19's results, but our better data quality allows us to place more stringent constraints on the corresponding parameters. Based on these spectral features—including high-temperature components of $\sim 10^7$–10^8 K, Fe XXV emission lines, and elevated $L_X/L_{\rm bol}$ ratios—we conclude that MTT68 and MTT71 are likely colliding-wind systems. More detailed discussion is presented in Section 4.1.

Furthermore, our spectral analysis of MTT68's four observations yielded inconsistent elemental abundance results (0.4–0.9 $Z_\odot$, see Table), while stellar wind elemental abundances should not vary significantly over short timescales. However, the hot plasma elemental abundance derived from X-ray imaging spectroscopy is not an independent model parameter, as both plasma temperature and deviations from collisional ionization equilibrium can affect the abundance fitting results. We will further discuss the metallicity differences obtained from various observations in Section 4.1.

3.3 High-Precision Proper Motion Measurements of MTT68A and MTT71 from Gaia

To determine the origin of MTT68A and MTT71, we compared their proper motions from Gaia DR2 (Table) with the overall proper motion of NGC 3603. We adopted the cluster's bulk proper motion estimated by Kalari et al. [14]: $\mu_\alpha = (-5.54 \pm 0.30)$ mas·yr^{-1}, $\mu_\delta = (1.99 \pm 0.39)$ mas·yr^{-1}. The relative proper motion results are shown in Figure [Figure 5: see original paper].

MTT71 shows consistent absolute proper motion with NGC 3603, with deviations even smaller than the proper motion measurement uncertainties in Gaia DR2. This result suggests MTT71 is likely a member star that formed in association with NGC 3603. After subtracting the cluster's bulk proper motion from MTT68A's absolute proper motion, a significant relative proper motion remains: $\Delta\mu_\alpha = (-2.5 \pm 1.1)$ mas·yr^{-1}, $\Delta\mu_\delta = (3.3 \pm 0.9)$ mas·yr^{-1}. The direction of this proper motion points back toward the cluster center (impact parameter $5.3''$), indicating MTT68A may have been ejected from the cluster core region.

Based on MTT68A's current proper motion relative to NGC 3603 and its projected distance from the cluster center, we calculate the ejection timescale to be approximately 20 kyr. This ejection timescale is much shorter than the cluster's age, indicating MTT68A was recently ejected from the cluster. Assuming MTT68A is at the same distance as NGC 3603, its relative tangential velocity with respect to the cluster core is 148 km·s^{-1}. This velocity exceeds NGC 3603's escape velocity, making it likely that MTT68A will become a massive binary system in a non-clustered environment or even a runaway binary system. In Section 4.2, we will further discuss the dynamical mechanisms that ejected MTT68A based on the runaway star scenario.

4 Discussion

4.1 X-ray Radiation Origin of MTT68 and MTT71

Our analysis in Section 2 demonstrates that MTT68's X-ray radiation primarily reflects the properties of MTT68A, and Section 3.2 shows that both MTT68 and MTT71 exhibit X-ray luminosities exceeding those expected from single O-type stars. Harnden et al. [27] established a correlation between X-ray luminosity L_X and bolometric luminosity L_{bol} for single O-type stars, expressed as $L_X/L_{\text{bol}} \approx 10^{-7}$ [28]. Sciortino et al. investigated possible correlations between X-ray radiation and other properties of hot stars but found no relationships with rotation, wind velocity, or mass-loss rates [29]. Therefore, the X-ray radiation from MTT68 and MTT71 requires additional hot plasma production mechanisms.

Furthermore, the X-ray spectra of single O-type stars are typically soft. Under the assumption of collisional ionization equilibrium, fitting spectra with an optically thin hot plasma APEC model yields main component temperatures not exceeding 1 keV [24]. For O-type stars, optimal fits are typically achieved with two thermal components at approximately 0.3 keV and 0.7–1.0 keV [30, 31]. However, in our two-temperature plasma model fits to MTT68 and MTT71, the high-temperature component temperatures for MTT68's four observations all exceed 4.0 keV, while the combined spectrum of MTT71 yields a value near 2.0 keV. Additionally, the Fe XXV emission line near 6.7 keV is a distinctive feature of high-temperature plasma at $\sim 10^8$ K. Based on these temperature characteristics, the X-ray radiation from MTT68 and MTT71 should not originate from single O-type stars.

Mechanisms for producing such high-temperature plasma in massive stars include surface magnetic activity and colliding-wind mechanisms [24]. However, even in extreme cases of magnetically confined wind shocks, surface magnetic activity mechanisms struggle to produce X-ray radiation as strong as $\lg(L_X/L_{\mathrm{bol}}) \gtrsim -5.8$ [32]. We therefore infer that they are likely colliding-wind binaries. However, limited by observation duration (except for ObsID:00633, other observations span a 16-day period) and data quality, we did not observe orbital period modulation of the radiation, which would be definitive evidence for colliding-wind systems. Further X-ray observations and analysis will provide more definitive answers.

Additionally, the hot plasma in colliding-wind systems is likely in a non-ionization equilibrium state. We attempted to fit MTT68's individual observations using the plane-parallel shock model TBabs*pshock. The derived elemental abundances range between 0.38–0.66 $Z_{\odot}$, compared to 0.4–0.9 $Z_{\odot}$ from the two-temperature plasma model. While the metallicity differences are reduced, they remain significant. However, even the pshock model may be overly simplistic for spectral analysis of colliding-wind systems [33, 34], and more complex spectral modeling exceeds the capabilities of the Chandra X-ray data employed in this paper and the scope of this work.

4.2 Dynamical Mechanism for Ejecting MTT68A

The presence of a dense core in the cluster [18] containing numerous massive stars and binary systems enables NGC 3603 to efficiently produce massive runaway stars at its current evolutionary stage [8, 35]. The young age of NGC 3603 implies that MTT68A's ejection resulted from dynamical encounter processes, specifically binary-binary or binary-single star encounters in the cluster core. In the first scenario, the common outcome is an increased orbital eccentricity of the more massive binary and high-velocity ejection of the less massive binary. In the second scenario, the single star of lowest mass involved in the encounter is typically ejected at high speed, while the binary system recoils in the opposite direction. In both cases, the ejected high-velocity star gains kinetic energy at the expense of increased binding energy of the post-encounter binary. If the binary orbital separation is sufficiently small, it may eventually merge into a single star [36]. Therefore, if MTT68A was ejected into the cluster field through three-body or four-body encounters, a massive single star or binary should exist on the opposite side of NGC 3603 [8]. Searching the Gaia DR2 database for massive objects with opposite proper motions in the opposite direction would help verify this hypothesis.

5 Conclusions

Dynamical encounter processes in the cores of young massive clusters are an important pathway for producing massive stars outside clustered environments. We selected two colliding-wind system candidates, MTT68 and MTT71, in the periphery of NGC 3603 and studied their X-ray properties and origins through analysis of Chandra X-ray data and Gaia DR2 proper motion data. Our findings are:

1. Both the X-ray emission centroid of MTT68 and the point source position queried from Gaia DR2 are closer to MTT68A, indicating they reflect the properties of MTT68A rather than MTT68B.
2. The X-ray spectra of both MTT68A and MTT71 can be well fitted with a two-temperature hot plasma model, with high-temperature component temperatures $kT_2 \gtrsim 2$ keV. The presence of Fe XXV emission lines also supports these high-temperature components. Combined with their X-ray luminosities exceeding those expected from ordinary single O-type stars ($\lg(L_X/L_{\text{bol}}) \gtrsim -5.8$), we infer they are likely colliding-wind systems composed of two interacting massive stars.
3. According to Gaia DR2 information, MTT71 has absolute proper motion similar to the overall NGC 3603 cluster, suggesting it is likely a member star that formed together with the cluster. In contrast, MTT68A shows a relative proper motion of ~ 4.1 mas·yr^{-1} with respect to NGC 3603, with its direction pointing toward the cluster center. Therefore, MTT68A is likely a massive binary system ejected from the cluster approximately 20 kyr ago. Searching for massive stars with specific proper motions in the opposite direction will help us achieve a more comprehensive understanding of the dynamical encounter ejection mechanism.

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Note: Figure translations are in progress. See original paper for figures.