Chemical Tagging of Tidal Tail Star Candidates of NGC 6362 Postprint

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Abstract

The inner Milky Way disk globular cluster NGC 6362 appears to exhibit tidal tails composed of stars that have proper motions and positions in the color–magnitude diagram similar to those of cluster stars. Because recent results seem also to show that these stars are distributed across the regions least affected by interstellar absorption and reproduce the observed composite star field density map, we carried out a detailed spectroscopic analysis of a number of chemical element abundances of tidal tail star candidates in order to investigate the relationship between them and NGC 6362. From European Southern Observatory' s VLT@FLAMES spectra we found that the red giant branch stars selected as the cluster' s tidal tail stars neither have overall metallicities nor abundances of Mg, Ca, Sc, Ti, Cr, Ni and Ba similar to the cluster' s ones. Moreover, they are mainly alike to stars that belong to the Milky Way thick disk, some of them could be part of the thin disk and a minor percentage could belong to the Milky Way halo star population. On the other hand, since the resulting radial velocities do not exhibit a distribution function similar to that of the cluster' s stars, we concluded that looking for kinematic properties similar to those of the cluster would not seem to be as suitable of an approach for selecting the cluster' s tidal tail stars as previously thought.

Full Text

Preamble

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Chemical Tagging of Tidal Tail Star Candidates of NGC 6362

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Abstract

The inner Milky Way disk globular cluster NGC 6362 appears to exhibit tidal tails composed of stars with proper motions and positions in the color-magnitude diagram similar to those of cluster members. Recent results further indicate that these stars are distributed across regions least affected by interstellar absorption and reproduce the observed composite star field density map. Motivated by these findings, we conducted a detailed spectroscopic analysis of multiple chemical element abundances for tidal tail star candidates to investigate their relationship with NGC 6362. Using VLT@FLAMES spectra from the European Southern Observatory, we found that the red giant branch stars selected as cluster tidal tail stars neither have overall metallicities nor abundances of Mg, Ca, Sc, Ti, Cr, Ni, and Ba similar to the cluster' s values. Instead, they primarily resemble stars belonging to the Milky Way thick disk, with some possibly part of the thin disk and a minor fraction potentially belonging to the Milky Way halo population. Furthermore, since the resulting radial velocities do not exhibit a distribution function similar to that of the cluster' s stars, we conclude that searching for kinematic properties similar to those of the cluster may not be as suitable an approach for selecting tidal tail stars as previously thought.

Key words: methods: observational –techniques: spectroscopic –(Galaxy:) globular clusters: general –(Galaxy:) globular clusters: individual (NGC 6362)

1. Introduction

Recently, Zhang et al. (2022) published a stringent compilation of Milky Way globular clusters with robust detections of extra-tidal structures. Their catalog includes 46 globular clusters classified as follows: 27 with tidal tails, 4 with extended envelopes, and 15 without observed extended features. The detection of tidal tails around Milky Way globular clusters is a research avenue of significant importance for understanding a wide variety of issues. For instance, globular clusters associated with destroyed dwarf progenitors should show tidal tails (Carballo-Bello et al. 2014; Mackey et al. 2019), while globular clusters formed in dark matter mini-halos should present tails with relatively large velocity dispersion (Malhan et al. 2021). The extension and shape of tidal tails also inform us about the dynamical history of a globular cluster as a consequence of its interaction with the Milky Way (Hozumi & Burkert 2015; de Boer et al. 2019), among other attributes.

The innermost globular cluster in Zhang et al. (2022)' s compilation is NGC 6362 (galactocentric distance RGC = 5.5 kpc; Baumgardt & Vasiliev 2021), which shows tidal tails. Zhang et al. (2022) included NGC 6362 as a globular cluster with tidal tails based on the work of Kundu et al. (2019), who identified 73 of the highest-ranked extra-tidal red giants with Gaia Data Release 2 (DR2) proper motions within 3σ around the mean cluster proper motion. However, escaping stars should show a velocity dispersion larger than that for outermost bound stars (Wan et al. 2021; Piatti 2023), which is not the case for these 73 extra-tidal giant candidates. Additionally, NGC 6362 should not have tidal tails composed of kinematically cold stars, because Kundu et al. (2019) showed that the orbit of NGC 6362 is chaotic, which means that it washes out (accelerating) those stars (Mestre et al. 2020).

These considerations provide strong motivation for deciphering whether NGC 6362 truly belongs to the group of globular clusters with observed tidal tails, making it a compelling science case due to its position in the inner Milky Way. Precise abundances of some chemical elements for Kundu et al. (2019)' s highest-ranked extra-tidal stars could provide the final link between the extra-tidal star candidates and NGC 6362. We assumed that chemical abundances significantly deviating from the mean values known for NGC 6362 point to a star formation scenario not related to that of the cluster itself.

We therefore embarked on an observational campaign to obtain spectra of these selected stars in order to derive abundances of different chemical elements and investigate their relationship with NGC 6362. These results will also help assess the validity of some criteria used to select these stars as the highest-ranked extra-tidal stars. In other words, we attempt to shed light on the suitability of the frequently applied criterion to detect tidal tails based on similar proper motions for cluster members and tidal tail stars (e.g., Sollima 2020).

In Section 2 we present the acquired observational material, and in Section 3 we derive different astrophysical properties of the target stars. Section 4 is devoted to the discussion of their chemical element abundances. Finally, Section 5 summarizes the main conclusions of this work.

2. Observational Data

The red giant stars selected by Kundu et al. (2019) as tidal tail candidates of NGC 6362 have proper motions within 3σ of the mean cluster proper motion (Vasiliev 2019). They are also located beyond the cluster Jacobi radius (Moreno et al. 2014) and are distributed in the color-magnitude diagram along the cluster red giant branch. Figure 1 illustrates their spatial distribution and their location in the cluster color-magnitude diagram (figure built from Table 3 of Kundu et al. 2019). Red symbols represent the stars observed in this work. In the left panel, the size of the symbol is proportional to the star’ s brightness, and the black circle represents the cluster’ s Jacobi radius (Moreno et al. 2014).

We accommodated as many stars as possible across the FLAMES spectrograph’ s field-of-view (Pasquini et al. 2002) attached at the European Southern Observatory (ESO) ‘s Very Large Telescope (program 113.2661.001, PI: Piatti). By applying the completeness expression of Piatti (2017), which allowed us to account for the tidal tail stars’ spatial coverage and their distribution in the color-magnitude diagram, we found that the finally selected star sample, represented with red circles in Figure 1, statistically represents approximately 80% of the whole Kundu et al. (2019) red giant sample brighter than G = 18.0 mag.

We used the FLAMES@GIRAFFE spectrograph with the MEDUSA 132 fiber component and the HR14 grism (6290–6690 Å), which provides a dispersion of 0.05 Å pixel^{-1} with a resolution of R = 17,000, appropriate for measuring abundances of different chemical elements with sufficient accuracy to chemically distinguish stars formed in NGC 6362 or elsewhere. We obtained spectra of the selected stars with a total exposure time of 2235 s per observed science field (five different pointings), and typical airmass and seeing of 1.34–1.45 and 0.45–0.76, respectively. Fifteen sky spectra were also taken simultaneously for each science field.

The data were processed in the standard way following the FLAMES@GIRAFFE ESO pipeline, which includes zero-subtraction, flat-field correction, wavelength calibration with a standard Th-Ar lamp, extraction of one-dimensional spectra, etc. By comparing the observed position of several sky emission lines with their rest-frame position using the sky line atlas by Osterbrock et al. (1996), we confirmed that no significant wavelength shifts exist. Finally, sky-subtracted spectra were extracted from all the multi-object spectroscopy exposures.

Table 1 lists the observed stars alongside their equatorial coordinates, Gaia Data Release 3 (DR3; Gaia Collaboration et al. 2016; Babusiaux et al. 2023) photometry, and average signal-to-noise ratio (S/N) along the whole wavelength range of each spectrum. One science field, which includes stars #116, 118, 119, and 126, was observed on two different nights, the first under poor weather conditions. From this night, only the spectrum of #116 could be extracted with a reasonable S/N ratio. We therefore used the spectra of star #116 from both nights to check internal consistency in the radial velocity (RV) and chemical element abundance measurements.

Finally, we retrieved processed spectra of NGC 6362’ s red giants from the ESO archive taken with FLAMES@GIRAFFE and an instrument setup similar to ours (program 093.D-0618(A), PI: Dalessandro). The main aim of using these data is to validate our procedure for deriving abundances of chemical elements by comparing our resulting values with those of Mucciarelli et al. (2016).

3.1. Radial Velocity Measurements

We measured RVs by cross-correlating the observed spectra with the Arcturus spectrum from Hinkle et al. (2000). All spectra were continuum normalized before the cross-correlation procedure, and the Arcturus spectral resolution was degraded to match the resolution of our science spectra. We used the IRAF.FXCOR task, which implements the algorithm described in Tonry & Davis (1979) for constructing the cross-correlation function of each (object, Arcturus) spectral pair. In addition to the RVs, FXCOR returns the cross-correlation function (CCF) normalized peak (h), which indicates the degree of similarity between the correlated spectra, and the Tonry & Davis ratio (TDR) defined as TDR = a/σ , where σ is the root mean square (rms) of the CCF antisymmetric component. The resulting RVs are associated with h values greater than 0.8. We finally carried out the respective heliocentric corrections using the IRAF task RVCORRECT.

Table 1 lists the resulting heliocentric RVs with their respective uncertainties. The difference in RVs measured for star #116, observed on two different nights, was 0.00 ± 0.41 km s^{-1}, where the error comes from the propagation of both individual RV uncertainties. We compared our resulting RVs with those from Gaia DR3 for four stars in common (#44, 116, 188, and 213) and found a difference (Gaia DR3–our) of 0.14 ± 1.28 km s^{-1}.

3.2. Stellar Atmospheric Parameters

To obtain initial estimates of effective temperature (Teff) and surface gravity (log g) for chemical abundance analysis, we derived photometric parameters using Gaia DR3 photometry (see Table 1). The effective temperatures were computed from Gaia BP − RP colors, previously corrected for interstellar absorption using the E(B − V) values of Piatti (2024) and the total to selective absorption ratios given by Chen et al. (2019). The reddening-corrected $(BP - RP)_0$ colors were then transformed to Johnson $(R - I)_0$ using the transformation equations derived by Pancino et al. (2022). Finally, we employed the suitable correlation between the metallicity-sensitive Johnson $(R - I)_0$ color and Teff derived by Alonso et al. (1999).

The surface gravity was calculated using the equation:

$$\log g = 4.44 + \log M_* + 4 \log T_{\mathrm{eff}}/5780 + 0.4(V_0 - (m - M)_0 + BC(V) - 4.75)$$

(Venn et al. 2017), where M* = 0.75 is the typical mass of an old red giant branch star; V_0 is the dereddened Johnson V magnitude (calculated from Pancino et al. 2022’ s transformation equations); $(m - M)_0$ = 14.42 mag (Baumgardt & Vasiliev 2021) is the true cluster distance modulus; and BC(V) is the Alonso et al. (1999, Equation (18)) bolometric correction, for which we adopted a cluster mean metallicity [Fe/H] = -1.07 ± 0.01 dex (Massari et al. 2017).

We derived spectroscopic Teff, log g, and microturbulent velocity (vt) for the studied stars together with [Fe/H] values based on excitation and ionization equilibrium. The equivalent widths (EWs) of Fe I and Fe II lines and those of other species (Mg, Ca, Sc, Ti, Cr, Ni, Ba) were measured using DAOSPEC (Stetson & Pancino 2008) and its up-to-date internal list of more than 400 lines with their respective oscillator strengths and excitation potentials. We alternatively checked EW values of weak lines using the IRAF.SPLOT routine to manually measure the EWs. From the resulting EW list, we removed lines with no EW value or with $q > 1$, where q is a quality parameter derived from a comparison between residuals observed in the spectrum in the immediate neighborhood of the line and typical residuals in the spectrum as a whole.

The spectral line analysis to determine the chemical composition of the stars was performed with MOOG (Sneden 1973; Sobeck et al. 2011). MOOG requires mainly two inputs: a line data file and a model atmosphere file. The former is primarily the above DAOSPEC output format with slight arrangement differences. For the latter, we adopted Kurucz (2005) models generated with the ATLAS code (Kurucz 1970). The models were interpolated for any set of (Teff, log g, vt, [Fe/H]) using the Python interpolator pyKMOD. We began by interpolating models with photometric Teff and log g values, then ran MOOG to obtain chemical element abundances. We iterated this loop until reaching convergence at ΔTeff = 5 K, Δlog g = 0.05, and Δvt = 0.05 km s^{-1}.

To achieve excitation and ionization equilibrium, the program simultaneously: (1) varies Teff values seeking zero slope in the (Fe I, Fe II) abundance versus excitation potential relationship; (2) varies vt seeking zero slope in the Fe I abundance versus reduced EW relationship; and (3) varies log g seeking similar Fe I and Fe II abundance values. Since Fe I and Fe II abundance values changed as well, each iteration used an interpolated model with updated overall metallicity. During chemical abundance analysis, we removed some chemical elements with only one EW measurement.

The resulting stellar atmospheric parameters (Teff, log g, vt, and [Fe/H]) are listed in Table 1. The mean and dispersion of [Fe/H] come from the average of all Fe I and Fe II abundance values. Table 2 lists the mean and dispersion of the remaining measured chemical elements corresponding to the final adopted stellar atmosphere model. These values represent the standard deviation of all available chemical element abundance values, which in turn come from the final atmospheric parameters adopted according to the convergence uncertainties mentioned above. The difference between abundance values obtained for star #116 observed on two different nights ranged from 0.00–0.07 dex depending on the chemical element. For NGC 6362' s red giants, we obtained a mean metallicity of [Fe/H] = -1.08 ± 0.03 dex, in excellent agreement with Mucciarelli et al. (2016), so we did not apply corrections to our metallicities due to systematic errors.

4. Analysis and Discussion

NGC 6362 has been recently targeted to accurately estimate its astrophysical properties. Massari et al. (2017) obtained ESO@FLAMES.UVES high-resolution spectra for 11 cluster red giant branch stars and derived a mean cluster RV and [Fe/H] of -15.03 ± 2.07 km s^{-1} and -1.07 ± 0.01 dex, respectively. They also derived mean cluster abundances of 17 chemical elements, including [Mg/Fe] = 0.54 ± 0.01 dex, [Ca/Fe] = 0.26 ± 0.02 dex, [Sc/Fe] = 0.18 ± 0.04 dex, [Ti/Fe] = 0.24 ± 0.04 dex, [Cr/Fe] = -0.05 ± 0.02 dex, [Ni/Fe] = -0.02 ± 0.01 dex, and [Ba/Fe] = 0.61 ± 0.01 dex. We used this cluster chemical tagging to assess the origin of a representative sample of stars selected by Kundu et al. (2019) as the cluster' s tidal tail candidates.

There are several relevant implications regarding the existence or absence of NGC 6362' s tidal tails, including whether its tidal tails are kinematically cold or hot, whether NGC 6362 is in regular or chaotic orbital motion, and what extended criteria for detecting globular clusters' tidal tails based on kinematic properties are appropriate. Some recent results focused on analysis of deep images across an area of 4 square degrees centered on the cluster (Piatti 2024), which converged toward a relatively smooth stellar density between 1 and 3.8 cluster Jacobi radii, with a slight difference smaller than two times the background stellar density fluctuation between the mean stellar density of the southeastern hemisphere and that of the northwestern one, with the latter being higher. Moreover, the spatial distribution of Kundu et al. (2019)' s tidal tail stars agrees well not only with the observed composite star field distribution but also with the region least affected by interstellar absorption. These results would seem to suggest that NGC 6362 does not have clearly detectable tidal tails.

The identification of a globular cluster' s tidal tail stars has frequently been addressed by searching for stars kinematically consistent with the mean kinematic properties of globular clusters where the stars formed (Sollima 2020; Xu et al. 2024). However, rather than looking for kinematic properties (proper motions, RVs) similar to the cluster' s, recent literature suggests focusing on the dispersion of radial and tangential velocity components, as well as angular momentum (Malhan et al. 2021, 2022). This approach appears more suitable for describing the kinematic properties of tidal tail stars, since stars must reach velocities different from cluster members to escape, and the Milky Way potential imprints different accelerations on them, causing mean kinematic properties to vary along tidal tail extensions (Piatti et al. 2023; Grondin et al. 2024). To identify tidal tail stars following this approach, knowledge of the mean path of a cluster' s tidal tail stars in kinematic space is required, which according to Grillmair (2025, and references therein) can be obtained by combining color-magnitude diagram and kinematic filtering with orbit integration and predictions based on modeling stripping stars. Alternatively, a kinematic analysis of the sample stars following the approach described in Nissen & Schuster (2010), including use of a Toomre diagram, could more clearly indicate whether they belong to thin disk, thick disk, or halo populations. Since the main aim of this study is to assess the formation scenario of Kundu et al. (2019)' s selected stars, we defer such analysis to future work.

In this context, we probed whether the RVs of Kundu et al. (2019)' s tidal tail stars are consistent with the mean cluster RV by comparing our results (Table 1) with the mean RV value of NGC 6362. We found that two stars (#119 and 126) fall within 1σ, and twelve other stars (#44, 48, 49, 53, 116, 118, 157, 168, 173, 185, 223, and 224) are within 3σ, representing 9% and 60% of the studied sample, respectively. Figure 2 illustrates this finding. We recall that the stars selected by Kundu et al. (2019) are within 3σ of the mean cluster proper motion.

This outcome suggests that even in the most relaxed scenario (RV statistics within 3σ), a significant percentage of the star sample is not coherent with the mean cluster RV, unlike when proper motions are considered. This discrepancy draws attention to possible weaknesses in selection criteria for tidal tail stars based on kinematic properties. Furthermore, if we restricted the RV range to 1σ of the mean cluster RV, the small number of stars complying with that requirement indicates either that the 3σ sample is contaminated by field stars (due to the large difference in star numbers between 1σ and 3σ samples) or that tail stars reach kinematic properties different from the cluster soon after escaping (due to the RV spread of stars located just outside the Jacobi radius).

To find more conclusive evidence on the origin of the studied stars—that is, to confirm or refute whether they formed in NGC 6362—we analyzed their chemical properties (Hanke et al. 2020, and references therein). Unlike kinematic features, the abundance of chemical elements remains almost unchanged along stellar lifetimes. In this respect, Marino et al. (2019) showed that the metallicity difference between first and second generation stars in NGC 6362 is Δ[Fe/H] = 0.03 dex. We compared our resulting [Fe/H] values with the mean metallicity of NGC 6362 and found that [Fe/H]star − [Fe/H]NGC6362 is smaller than the respective associated errors added in quadrature only for stars #52 and #186. Figure 2 shows that the metallicity spread of the studied stars is as large as the metallicity dispersion found in the Milky Way disk star field population. Star #52 has different Mg, Sc, Ti, Cr, and Ba abundances than NGC 6362' s red giants (see Massari et al. 2017), while star #186 does not share any of the estimated chemical element abundances with NGC 6362. Furthermore, their RVs are remarkably different from the cluster' s (they are placed just outside the cluster' s Jacobi radius), even though we assumed tidal tail stars can have RVs different from the mean cluster RV. Therefore, it seems unlikely that any of the studied stars formed in NGC 6362.

The chemical tagging results lead us to conclude that some Milky Way field stars located along the line-of-sight toward NGC 6362 can have proper motions and positions in the color-magnitude diagram consistent with the mean cluster proper motion and cluster sequences (Kundu et al. 2019). However, while the latter appears to be a valid selection criterion, the former does not. Indeed, kinematics of highest-ranked tidal tail stars can show variation in their motions along tidal tails, as judged by some observational (Piatti 2023; Grillmair 2025) and theoretical (Grondin et al. 2024) results.

We finally used the derived abundances of some chemical elements to further constrain the origin of the studied stars. We employed different compilations of Milky Way thick and thin disk and halo field stars: Reddy et al. (2003, thick disk); Venn et al. (2004, thick and thin disks and halo); Reddy et al. (2006, thick disk); and Nissen & Schuster (2010, halo), constructing Figure 3. The [X/Fe] trend with [Fe/H] has a slope close to zero for Cr and Ni, showing no clear difference among the three field star populations. For Ba, we found no measures for halo stars available. From Mg, Ca, and Ti relationships, it is possible to distinguish a somewhat bimodal distribution along the Y-axis for thick disk field stars with some overlap of thin disk field stars around the most metal-poor peak. Halo stars generally expand the whole measured range of these chemical element abundances, mainly populating very metal-poor overall metallicities. From this scenario, we speculate that most studied stars belong to the Milky Way disk; some could be part of the thin disk, and a minor percentage might be halo stars.

5. Conclusions

We undertook a spectroscopic tagging analysis of a sample of stars cataloged as tidal tail star candidates of the Milky Way globular cluster NGC 6362. Confirming their status as escaped stars from the cluster is important for our understanding of globular cluster formation and evolution, and for reaching consensus about applicable procedures in searching for globular cluster tidal tail stars. From measurements of individual RVs, metallicities, and abundances of some chemical elements, we determined whether the studied stars formed in NGC 6362 and were later unbound from the cluster’ s body due to interaction with the Milky Way. We concluded that:

1. Despite similar values derived for some particular properties in some stars, none of the studied stars share the mean cluster chemical element abundances within estimated uncertainties. Therefore, the selected stars, which statistically represent nearly 80% of all red giant branch tidal tail candidates, do not appear to have formed in NGC 6362. From the lack of confirmation of red giant branch tidal tail stars, we speculate that NGC 6362 does not have detected tidal tails. This conclusion agrees with the recent outcome by Piatti (2024), who showed that the spatial distribution of tidal tail star candidates remarkably matches that of the observed composite star field distribution and the regions least affected by interstellar absorption.

2. In agreement with the above result, individual RV measurements cover a wide range of values typical of stars belonging to the composite Milky Way field star population. Although variation in RVs of tidal tail stars is expected, this is not the case here because they have different metallicities.

Our present values contrast with their similar proper motions within 3σ and their location along the red giant branch in the cluster color-magnitude diagram (Kundu et al. 2019). This means kinematic properties do not appear as suitable as previously thought when searching for globular cluster tidal tails. Beyond uncertainties in Gaia DR2 that could lead to errors in considering some field stars as cluster tidal tail candidates, the criterion of filtering stars with similar mean globular cluster kinematics does not seem appropriate because tidal tails already exhibit coherent variation of star motions along them.

3. The observed stars, distributed along the line-of-sight toward NGC 6362, appear to belong mainly to the thick disk, as judged by derived abundances of some chemical elements compared with previous compilations of Milky Way field stars. We do not discard the possibility that some pertain to the thin disk, and even a small percentage to the Milky Way halo. The outcome that studied stars could be Milky Way field stars agrees well with the cluster having a chaotic orbit (Kundu et al. 2019), which means its tidal tails were swept while approaching the innermost Milky Way regions.

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