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The tale of the Milky Way globular cluster NGC 6362 – I. The orbit and its possible extended star debris features as revealed by Gaia DR2

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ABSTRACT

We report the identification of possible extended star debris candidates beyond the cluster tidal radius of NGC 6362 based on the second Gaia data release (Gaia DR2). We found 259 objects possibly associated with the cluster lying in the vicinity of the giant branch and 1–2 magnitudes fainter/brighter than the main-sequence turn-off in the cluster colour–magnitude diagram and which cover an area on the sky of ∼4.1 deg² centred on the cluster. We traced back the orbit of NGC 6362 in a realistic Milky Way potential, using the GRAVPOT16 package, for 3 Gyr. The orbit shows that the cluster shares similar orbital properties as the inner disc, having peri-/apogalactic distances, and maximum vertical excursion from the Galactic plane inside the corotation radius (CR), moving inwards from CR radius to visit the inner regions of the Milky Way. The dynamical history of the cluster reveals that it has crossed the Galactic disc several times in its lifetime and has recently undergone a gravitational shock, ∼15.9 Myr ago, suggesting that less than 0.1 per cent of its mass has been lost during the current disc-shocking event. Based on the cluster’s orbit and position in the Galaxy, we conclude that the possible extended star debris candidates are a combined effect of the shocks from the Galactic disc and evaporation from the cluster. Lastly, the evolution of the vertical component of the angular momentum shows that the cluster is strongly affected dynamically by the Galactic bar potential.

Key words: globular clusters: individual: NGC 6362 – Galaxy: kinematics and dynamics.

1 INTRODUCTION

Extra-tidal stellar material associated with globular clusters is spectacular evidence for satellite disruption at the present day, which provides significant clues about the dynamical history of the clusters and their host galaxies. Globular clusters evolve dynamically under the influence of the gravitational potential well of their host galaxy (Gnedin & Ostriker 1997; Murali & Weinberg 1997; Leon, Meylan & Combes 2000; Kunder et al. 2018; Minniti et al. 2018), resulting in the escape of the stars close to the tidal boundary of the cluster, consequently forcing the cluster cores to contract and envelopes to expand (e.g. Leon et al. 2000; Kunder et al. 2014). Therefore, globular clusters are important stellar systems to study the evolution, structure and dynamics of their host galaxy.

Globular clusters lose stars mainly due to dynamical processes like dynamical friction, tidal disruption, bulge and disc shocking, and evaporation (Fall & Rees 1977, 1985). Dynamical friction is due to the gravitational pull of the field stars that are accumulated behind the cluster motion. These stars slow down the cluster and pull...
some of the loosely bound stars away from it. This effect is more pronounced in the bulge of the Galaxy where the density of field stars is higher. Dynamical friction has been proposed in many studies (Chandrasekhar 1943; Mulder 1983; White 1983; Tremaine & Weinberg 1984; Capuzzo-Dolcetta & Vicari 2005; Arca-Sedda & Capuzzo-Dolcetta 2014; Moreno, Pichardo & Velázquez 2014) but the observational evidence has been more elusive, while tidal disruption have been observed (Leon et al. 2000; Odenkirchen et al. 2001; Belokurov et al. 2006; Grillmair & Johnson 2006; Grillmair & Mattingly 2010; Jordi & Grebel 2010; Niederste-Ostholt et al. 2010; Balbinot et al. 2011; Sollima et al. 2011; Kuzma et al. 2015; Myeong et al. 2017; Navarrete, Belokurov & Koposov 2017) and studied by many (King 1962; Tremaine, Ostriker & Spitzer 1975; Chernoff, Kochanek & Shapiro 1986; Capuzzo-Dolcetta 1993; Weinberg 1994; Gnedin & Ostriker 1997; Meylan & Heggie 1997; Vesperini & Heggie 1997; Combles, Leon & Meylan 1999; Lotz et al. 2001; Capuzzo Dolcetta, Di Matteo & Micocchi 2005; Küpper, Lane & Heggie 2012; Majewski et al. 2012a, b; Torres-Flores et al. 2012; Fernández Trincado et al. 2013; Knierman et al. 2013; Mulia & Chandar 2014; Fernández Trincado et al. 2015a,b, 2016a,b, 2017a,b,c; Rodruck et al. 2016; Hozumi & Burkert 2015; Balbinot & Gieles 2018; Myeong et al. 2018; Kundu, Minniti & Singh 2019; Mackereth et al. 2019).

NGC 6362 is a nearby low-mass globular cluster with intermediate metallicity, located in the bulge/disc of the Milky Way galaxy (Carretta et al. 2010). It has an age of ~12.5 ± 0.5 Gyr, which is enough to evolve under the gravitational potential of the Milky Way. Therefore, identifying possible tidal tails around NGC 6362 is especially intriguing to study the cluster dynamics in the bulge/disc region, which is poorly understood. Recently, Baumgardt & Hilker (2018) presented a catalogue of masses, structural profiles, and velocity dispersion values for many Galactic globular clusters including NGC 6362. They found that this cluster fits a King profile with a constant velocity dispersion as a function of radius, hence there was no evidence of a tidal tail. However, their measurements were concentrated to the inner regions, extending only out to 400 arcsec away from the centre.

In this work, we report the detection of potential extended star debris associated with NGC 6362. We have taken advantage of the exquisite data from Gaia Data Release 2 (Gaia Collaboration 2018) to search for such extended star debris features around NGC 6362. To give a proper explanation for the presence of the observed possible star debris, we time-integrated backward the orbit of NGC 6362 to 3 Gyr under variations of the initial conditions (proper motions, radial velocity, heliocentric distance, Solar position, Solar motion, and the velocity of the local standard of rest) according to their estimated errors. Our analysis indicates that the cluster is dynamically affected by the Galactic bar potential, presently experiencing a bulge/bar shocking, with considerable amount of mass-loss, which can be observed as stars present in the immediate neighbourhood of the cluster. A similar analysis was recently carried out by Minniti et al. (2018) for NGC 6266 (also known as M62) using extra-tidal RR Lyrae stars.

This paper is organized as follows. In Section 2, we select the possible star debris candidates beyond the cluster tidal radius of NGC 6362. In Section 3, we discussed the significance of the observed star debris. In Section 4, we determine its most likely orbit using novel galaxy modelling software called GRAVPOT16. In Section 5, we discussed the mass lost by the cluster due to various processes. The concluding remarks are summarized in Section 6.
the nominal value of the cluster, suggesting that these stars could possibly be evaporated material from NGC 6362. Therefore, to be sure that our candidate members are actually part of the cluster system, we selected those stars whose locations on the colour–magnitude diagram (CMD) clearly lie on or near the prominent main branches of NGC 6362, as illustrated by the red symbols in Fig. 2. A total of 259 possible extended star debris candidates passed these quality cuts as illustrated in Figs 1 and 2 (highlighted by red symbols).

To summarize, the possible star debris members of the cluster in Fig. 2 show the following: proper motions that are very concentrated as expected in the vector point diagram (hereafter VPD) of a globular cluster, and a CMD with the characteristic features of a globular cluster, e.g. the main sequence, the turn-off, the red giant branch, and some stars in the horizontal branch. It is important to note that the determination of the possible extended star debris of NGC 6362 could include some field stars as members or vice versa, in Section 3 we perform an estimation of the degree of contamination of the extracted members, i.e. the possible number of field stars that could have been labelled as possible extended star debris members of the cluster.

This finding gives possible clues about the recent dynamical history of NGC 6362, which suggests that this cluster could eventually form tidal tails or could also be associated with the recent encounter of the cluster with the disc.

Table 1 lists the main parameters of the 259 possible extended star debris. Fig. 2 shows consistently the validity of our probable extended star debris members that share an apparent proper motion close to the value for NGC 6362, suggesting these stars are probable members of the cluster.

It is important to note that most of the stars inside $2 \times r_{\text{half-max}}$ of the cluster are spread in proper motions, as illustrated by black dots in Fig. 2, consequently one may be lead to conclude that it is related to contamination by foreground/background stars that would seem to be the most likely explanation for the significantly higher proper motion values. Thus, we also expect that our sample may be significantly contaminated from other Galactic stellar populations (see Section 3). To alleviate this situation, a detailed chemical abundance analysis will be necessary to understand their relation, if any, with the cluster.

3 SIGNIFICANCE OF THE DETECTION OF POSSIBLE EXTENDED STAR DEBRIS AROUND NGC 6362

It is important to note that the main tracers of the possible extended star debris of NGC 6362 identified in this work are main-sequence (MS) stars and subgiant stars 1–2 mag fainter and brighter than the MS turn-off (TO), respectively. However, the cluster stars beyond cluster tidal radius are hidden in the CMD due to the combination of the contributions of a minor fraction of cluster members and foreground/background stellar populations from the different Milky Way components (mainly the thin/thick disc, and halo).
In this sense, we attempt to estimate the significance of the detection in our photometry and PMs space. For this purpose, we have compared the observed stellar counts with those computed from the synthetic CMDs generated with the updated version of the Besançon Galaxy model for the same line of sight and solid angle, after correcting for completeness. For a more detailed description of the Besançon Galaxy model, we refer the readers to Robin et al. (2003, the full, basic description), Robin et al. (2014, update on the thick disc), Robin et al. (2017, update on kinematics), and Lagarde et al. (2017, update on the stellar evolutionary models). The observed stars considered to derive the significance of a subjacent population are those contained in the CMD and PM space as illustrated in Fig. 2.

We calculated the expected number of Milky Way stars over the survey area and in distance range \( D_\odot > 3 \) kpc from the Besançon Galaxy model. We found \( N_{\text{model}} \sim 167 \pm 13 \) stars in the area of the Gaia footprint around NGC 6362. The cited error is Poisson statistics. We can then estimate the significance of the detection with respect to the synthetic model in the following manner: 

\[
\delta \approx \sqrt{\left( N_{\text{model}} - N_{\text{extra-tidal}} \right) / \left( N_{\text{model}} + N_{\text{extra-tidal}} \right)^2},
\]

where \( N_{\text{extra-tidal}} \) is the number of observed stars following the criteria described above. We obtain a \( \delta \sim 4.5 \) detection above the foreground and background population.

Another way to perform an estimation of the degree of contamination of the extracted members relies upon applying our method in adjacent regions (defined with the same area than our explored region) around the cluster, as illustrated in Fig. 1. Performing an analysis like that mentioned in the beginning of Section 2 but counting all the stars in the field instead of only those potential members around the cluster, we obtain rough estimates of the expected contamination in our sample. We note that the incompleteness of the Gaia DR2 catalogue itself has not been taken into account in our computations, therefore, our estimates are upper limits to the actual completeness for the most favourable cases.
Table 2. NGC 6362 – Sun parameters.

| Parameter          | Value        | Reference |
|--------------------|--------------|-----------|
| NGC 6362           |              |           |
| α (°), δ (°)       | 262.979, −67.048 | (a)       |
| Distance (kpc)     | 7.6          | (a)       |
| Rperi (kpc)        | 4.71         |           |
| Rapo (kpc)         |              |           |
| μx (mas yr⁻¹)      | −5.507 ± 0.052 | (a)       |
| μy (mas yr⁻¹)      | −4.747 ± 0.052 | (a)       |
| VS (km s⁻¹)        | −14.58 ± 0.18 | (a)       |
| Tidal radius (pc)  | 30.73        | (b)       |
| Mass (M☉)          | ~10⁴        | (b)       |
| Metallicity        | −1.07        | (d)       |
| Age (Gyr)          | 12.5 ± 0.5   | (e)       |
| Sun                |              |           |
| Rperi (kpc)        | 8.3          | (f)       |
| U⊙, V⊙, W⊙ (km s⁻¹)| 11.10, 12.24, 7.25 | (f)       |
| Vl⊙ (km s⁻¹)       | 239          | (f)       |

Note. (a) Vasiliev (2019); (b) Moreno et al. (2014); (c) Dalessandro et al. (2014); (d) Massari et al. (2017); (e) Dotter et al. (2010); (f) Brunthaler et al. (2011).

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4 THE ORBIT OF NGC 6362

We estimated the probable Galactic orbit for NGC 6362 in order to provide a possible explanation to the possible extended star debris identified in this work. For this, we used a state-of-the-art orbit integration model in an (as far as possible) realistic gravitational potential, that fits the structural and dynamical parameters of the galaxy to the best we know of the recent knowledge of the Milky Way. For the computations in this work, we have employed the rotating ‘boxy/peanut’ bar model of the novel galactic potential model called GRAVPT161 along with other composite stellar components. The considered structural parameters of our bar model, e.g. mass, present-day orientation and pattern speeds, are within observational estimations: 1.1 × 10¹⁰ M☉, 20° and 35–50 km s⁻¹ kpc, respectively. The density profile of the adopted ‘boxy/peanut’ bar is exactly the Model-S as in Robin et al. (2012), while the mathematical formalism to derive a correct global gravitational potential of this component will be explained in a forthcoming paper (Fernández-Trincado et al., in preparation).

GRAVPT161 considers on a global scale a 3D steady-state gravitational potential for the Galaxy, modelled as the superposition of axisymmetric and non-axisymmetric components. The axisymmetric potential is made up of the superposition of many composite stellar populations belonging to seven thin discs following the Einasto density-profile law (Einasto 1979), superposed along with two thick disc components, each one following a simple hyperbolic secant squared decreasing vertically from the Galactic plane plus an exponential profile decreasing with Galactocentric radius as described in Robin et al. (2014). We also implemented the density profile of the interstellar matter component with a density mass as presented in Robin et al. (2003). The model, also correctly accounts for the underlying stellar halo, modelled by a Hernquist profile

As already described in Robin et al. (2014), and surrounded by a single spherical dark matter halo component Robin et al. (2003). Our dynamical model has been adopted in a score of papers (e.g. Fernández-Trincado et al. 2016a, b, 2019a,b,d,e). For a more detailed discussion, we refer the readers to a forthcoming paper (Fernández-Trincado et al., in preparation).

For reference, the Galactic convention adopted by this work is: X-axis is oriented towards l = 0° and b = 0°, and the Y-axis is oriented towards l = 90° and b = 0°, and the disc rotates towards l = 90°; the velocity components are also oriented along these directions. In this convention, the Sun’s orbital velocity vector is [U⊙, V⊙, W⊙] = [11.1, 12.24, 7.25] km s⁻¹ (Brunthaler et al. 2011). The model has been rescaled to the Sun’s galactocentric distance, 8.3 kpc, and the local rotation velocity of 239 km s⁻¹.

For the computation of the Galactic orbits for NGC 6362, we have employed a simple Monte Carlo scheme for the input data listed in Table 2, and the Runge–Kutta algorithm of seventh-eighth order elaborated by Fehlberg (1968). The uncertainties in the input data (e.g. distance, proper motions and line-of-sight velocity errors), were propagated as 1σ variations in a Gaussian Monte Carlo resampling in order to estimate the most probable regions of the space, which are crossed more frequently by the simulated orbits as illustrated in Fig. 2. The error bar for the heliocentric distance is assumed to be 1 kpc. We have sampled half million orbits, computed backward in time during 3 Gyr. Errors in the calculated orbital elements were estimated by taking half million samples of the error distributions and finding the 16th and 84th percentiles as listed in Table 3. The average value of the orbital elements was found for half million realizations, with uncertainty ranges given by the 16th and 84th percentile values, as listed in Table 3, where rperi is the average perigalactic distance, rapo is the average apogalactic distance, and Zmax is the average maximum distance from the Galactic plane.

Fig. 3 shows the probability densities of the resulting orbits projected on the equatorial (left-hand column) and meridional (right-hand column) Galactic planes in the non-inertial reference frame where the bar is at rest. The orbital path (adopting central values) is shown by the black line in the same figure. The green and yellow colours correspond to more probable regions of the space, which are crossed more frequently by the simulated orbits. We found that most of the simulated orbits are situated in the inner bulge.

1https://gravpot.utinam.cnrs.fr
region, which means that NGC 6362 is on high eccentric orbit (with eccentricities greater than 0.45) reaching out to a maximum distance from the Galactic plane larger than 2 kpc with a perigalacticon of ~2 kpc and an apogalacticon of ~6 kpc. On the other hand, NGC 6362 orbits have energies allowing the cluster to move inwards from the bar’s corotation radius (CR, <6.5 kpc). In this region, a class of orbits appears around the Lagrange points on the minor axis of the bar that can be stable and have a banana-like shape parallel to the bar (see lower panel with $\Omega_{\text{bar}} = 50$ km s$^{-1}$ kpc in Fig. 3), while the Lagrange orbits librating around Lagrange points aligned with the bar are unstable and are probably chaotic orbits. Our model naturally predicts trajectories indicating that NGC 6362 is confined to the inner disc.

Additionally, in Fig. 4 we show the variation of the $z$-component of the angular momentum in the inertial frame, $L_z$, as a function of time and $\Omega_{\text{bar}}$. Since this quantity is not conserved in a model like GRAVOT16 (with non-axisymmetric structures), we follow the change, $\{-L_z, +L_z\}$, where negative $L_z$ in our reference system means that the cluster orbit is prograde (in the same sense as the disc rotation). Both prograde and prograde–retrograde orbits with respect to the direction of the Galactic rotation are clearly revealed for NGC 6362. This effect is strongly produced by the presence of the galactic bar, further indicating a chaotic behaviour.

It is important to mention that one major limitation of our model is that it ignores secular changes in the Milky Way potential over time and dynamical friction, which might be important in understanding the evolution of NGC 6362 crossing the inner Galaxy. An in-depth analysis of such dynamical behaviour is beyond the scope of this paper.

## 5 MASS-LOSS RATE IN NGC 6362

The detailed computations of destruction rates of globular clusters in our Galaxy due to the effects of bulge and disc shocking and dynamical friction, employing the Galactic model GRAVOT16, will be presented in a future study. However, for this work we have used destruction rates of the galactic cluster due to dynamical friction and bulge and disc shockings from the literature and added the corresponding destruction rate due to evaporation, to get an estimated value for its total mass-loss rate.

Moreno et al. (2014) (M + 14, hereafter) have computed destruction rates of globular clusters due to bulge and disc shocking, using a Galactic model that employs a bar component alike the GRAVOT16 model, but with a greater mass, the bar mass ratio being around 1.5. For the orbit of NGC 6362, the kinematic parameters used in the present analysis differ from those used by M + 14; however, both models give similar orbits, differing only in the maximum distance $z_{\text{max}}$ reached from the Galactic plane, which in our case is around 1.5 times that obtained by M + 14. With $t_b$, the characteristic lifetime due to bulge shocking, M + 14 obtain the corresponding present destruction rate $1/t_b = 1.35 \times 10^{-11}$ yr$^{-1}$, using a cluster mass $M_c \sim 10^5 M_\odot$. With the GRAVOT16 model and the decreased value of $M_c$ in Table 2, $1/t_b$ would be more than the reported value of $M + 14$, but the lower mass of the bar in GRAVOT16 would decrease this value. Thus, we consider the cited value of $1/t_b$ as representative for bulge shocking in our present analysis.

With respect to disc shocking, M + 14 obtain the present destruction rate $1/t_d = 2.12 \times 10^{-11}$ yr$^{-1}$, $t_d$ being the corresponding characteristic lifetime. With the GRAVOT16 model, this value would decrease due to the greater velocity of the cluster when it crosses the Galactic plane as it comes from a greater $z_{\text{max}}$ (Spitzer 1987), but with the lower cluster mass given in Table 2, $1/t_d$ would increase.
the presently available astrometric information from Gaia is not sufficient to determine with certainty how many of the stars may be truly extended star debris members. Nevertheless, this initial Gaia DR2 sample significantly contributes to the task of compiling a more thorough census of possible extended star debris in the area of the sky around NGC 6362, and portends the promising results to be expected from future spectroscopic follow-up observations.

If the newly discovered objects are part of the main cluster, these results would suggest the presence of an asymmetrically extended stellar material in the outer parts of the cluster whose surface density profile is mainly shaped by evaporation and/or tidal stripping at its current location in the Galaxy; tracing their dynamical evolution in the Milky Way (evaporation and tidal shocking). Also, there is no apparent correlation between the distribution of the newly identified extended star debris candidates and the orbit of the cluster, ruling out any evidence of elongation along the tidal field gradient.

The possible extended star debris candidates observed in the cluster can be either due to tidal disruption or dynamical friction or a combined effect of both. Therefore, to find an explanation for these extended star debris candidates, we computed the orbits for the cluster using four different values of $\Omega_{\text{bar}} = 35, 40, 45, 50$ km s$^{-1}$ kpc$^{-1}$. Half million orbits were computed for different initial conditions considering boxy bar potential perturbations in an inertial reference frame, where the bar is considered at an angle of $20^\circ$ with the line joining Sun and the Galactic centre. Earlier, Dinescu, Girard & van Altena (1999) also determined the orbital parameters for the cluster, but without the contribution of the bar to the potential. However, the $L_z$ evolution modelled here indicates that the cluster is affected by the bar potential of the Galaxy. Fig. 1 shows the asymmetric distribution of the possible extended star debris candidates along with the orbit of the cluster traced back for 3 Gyr with three different bar speeds.

Fig. 3 shows the orbit of the cluster in the meridional Galactic plane and equatorial Galactic plane simulated in the inertial reference frame. It is clear from the figure that the cluster is circulating the inner disc within a distance of 3 kpc above and below the disc. As the cluster never enters the bulge of the Galaxy, the dynamical friction experienced by the cluster is negligible, but this cluster has passed through the Galactic disc many times, experiencing a shock every time it crosses the disc. Due to these shocks, many stars must have been stripped away from the cluster. Hence, the observed extended star debris candidates can be a result of tidal disruption and shocks from the Galactic disc that happened more than 15.9 Myr. Thanks to the relatively short distance of NGC 6362 and its high release of unbound material during its current disc shocking, we estimate the mass variation to be of the order of $\sim 4.1 \times 10^{-6}$ M$_{\odot}$ yr$^{-1}$.

All the raw data used in this work are available through the VizieR Database (I/345/gaia2). Furthermore, in order to facilitate the reproducibility and reuse of our results, we have made available all the data and the source codes available in a public repository.²

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²https://github.com/Fernandez-Trincado/Tidal-debris-Gaia/tree/master/Ku
ndh%2B2019

6 CONCLUDING REMARKS

We have used the Gaia DR2 information along with the fundamental parameters of the cluster NGC 6362 to search for possible extended star debris candidates. We report the identification of 259 potential stellar members of NGC 6362 extending few arcminutes from the edge of the cluster’s radius. Both astrometric information and location of these possible extended star debris candidates on the CMD are consistent with the cluster membership. Unfortunately,
The Gaia mission website is http://www.cosmos.esa.int/gaia.

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