Rediscovering the Tidal Tails of NGC 288 with Gaia DR2

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ABSTRACT
NGC 288 is a Globular Cluster (GC) in the Milky Way having observed extra tidal structure, without confirmed tidal tails. \textit{Gaia} DR2 provides photometric and astrometric data for many of the stars in NGC 288 and its extra tidal structure. To compare with \textit{Gaia} data, we simulate an \textit{N}-body model of a star cluster with the same orbit as NGC 288 in a Milky Way potential. The simulation shows that the cluster forms tidal tails, which are then compressed along the cluster’s orbit when the cluster is at apocentre, and are expected to be a diffuse bipolar structure. In this letter, we present a comparison between the projection of the simulation and observations from \textit{Gaia} DR2. We find that both the simulation and the results share comparable trends in the position on the sky and proper motions of the extra-tidal stars, supporting the presence of tidal tails around NGC 288.

Key words: methods: \textit{N}-body simulations — methods: numerical — globular clusters: general — globular clusters: individual: NGC 288 — The Galaxy: structure

1 INTRODUCTION
GCs are gravitationally bound groupings of old stars, formed in the early Galaxy. If a cluster is tidally filling (e.g. Hénon 1961), such that stellar orbits within the cluster reach the tidal radius (Jacobi radius), we expect to see a signature of stars escaping the cluster via tidal stripping. Tidal stripping results in escaping stars populating tidal tails around the cluster which provide information about the orbit of the cluster, allowing us to constrain the gravitational potential of the Galaxy (e.g. Bovy et al. 2016). GCs that are considered to be tidally filling yet are lacking in tidal tails are proposed to have undergone additional interactions that prevent the formation of tidal tails (e.g. Gnedin et al. 1999; Baumgardt et al. 2010; Piatti 2018). For example, a GC can experience a tidal shock, where a strong tidal field will prevent prominent tails from forming (e.g. Gnedin et al. 1999). Alternatively, a high percentage of dark matter can cause an increase in the tidal radius, inhibiting stars from escaping and forming tidal tails (e.g. Baumgardt et al. 2010; Sollima et al. 2016; Creasey et al. 2018).

Another potential explanation for a tidally filling GC that is not exhibiting clear tidal tails is simply that they are difficult to observe owing to the current orbital phase of the cluster, or the projection onto the sky of its tail stars, or a combination of the two. Without proper motions ($\mu_\alpha, \mu_\delta$) from the second data release (DR2; Gaia Collaboration et al. 2018a) of the European Space Agency’s \textit{Gaia} mission (Gaia Collaboration et al. 2016), we can better constrain the orbits of GCs and determine whether their orbital phase or projection effects affect the detection of tidal tails. For example, when a cluster is at apocentre the tails will contract towards the cluster, reducing their length and visibility. However, the signature of the tails should remain visible in the proper motions of individual stars.

NGC 288 is a GC currently without confirmed tidal tails. However, it is thought to be tidally filling and thus should be subject to tidal stripping (Baumgardt et al. 2010). NGC 288 resides sufficiently nearby ($d = 8.9$ kpc from our Sun; Harris 1996, 2010 edition) that a relatively large number of cluster member stars are within the \textit{Gaia} limiting magnitude, making it an ideal candidate for further study.

While the lack of observed tidal tails has led previous studies to suggest NGC 288 contains a large amount of dark matter, it is instead possible the non-detection is due to projection effects combined with the fact that the cluster is near or at apocentre (Dinescu et al. 1997; Gaia Collaboration et al. 2018b). Additionally, NGC 288 experienced a
tidal shock when passing through the disc, also decreasing the extent of the tidal tails (Gnedin et al. 1999). Therefore, it is expected that any existing tidal tails around NGC 288 would be much shorter than in other clusters known to have pronounced tidal tails, such as Pal 5 (e.g. Odenkirchen et al. 2003; Erkal et al. 2017).

More recently, Piatti (2018) and Shipp et al. (2018) made contrasting observations of extra tidal structure around NGC 288. Piatti (2018) observes a diffuse halo structure up to \( \sim 2.5 \) times the tidal radius of NGC 288 using PanSTARRS-PS1 (Chambers et al. 2016), while Shipp et al. (2018) observes extra-tidal structure resembling tidal tails that extends to \( \sim 5.5^\circ \) to the south of the GC using the Dark Energy Survey (DES; e.g. Collaboration: et al. 2016). Shipp et al. (2018) construct a model of NGC 288 displaying tidal tails, although the orientation of the structure found in their simulation does not match the observation.

In this letter, we explore the possibility that the tidal tails of NGC 288 have been compressed at apocentre and are lost in projection. We make use of proper motion data from Gaia DR2 to explore the extra-tidal structure around NGC 288 and compare to a simulation of a cluster with the same orbit. In Section 2 we present details on the simulation, and in Section 3 we discuss the selection and treatment of data from Gaia DR2. In Section 4 the simulation is compared to the observations from Gaia, while Section 5 describes our conclusions and the potential for further analyses.

## 2 SIMULATION

In order to determine how we expect the positions and velocities of the tidal tail stars of NGC 288 are oriented on the plane of the sky at different phases of its orbit, we perform an \( N \)-body simulation of a star cluster over the last 4 Gyr of NGC 288’s orbit. The simulation was performed using the GYRFALCON code (Dehnen 2000, 2002) and a softening length of 1.5 pc in the NEMO toolkit (Teuben 1995). The cluster’s orbit was integrated using GALPY (Bovy 2015) in a Galactic potential assumed to be the MWPotential2014 model from Bovy (2015), with the proper motions of NGC 288 from Gaia DR2 (Gaia Collaboration et al. 2018b). Stel-
lar positions and velocities for the model cluster were assigned based on a Plummer distribution function with an initial mass of 37, 200M⊙ and a scale radius of 5 pc. It should be noted that the initial mass and size of our model cluster are not intended to perfectly reproduce a NGC 288-like cluster after 4 Gyr of evolution, as the main purpose of the model is to determine the properties of stars which have escaped the cluster.

As the model cluster evolves, stars escape NGC 288 via tidal stripping and populate its tidal tails as expected for a tidally filling GC (see Figure 1). Tidal shocks and the strong tidal field experienced by NGC 288 along its orbit prevent the tails from becoming long and distinct (as otherwise seen in GCs such as Pal 5; e.g. Odenkirchen et al. 2003; Erkal et al. 2017). However, within a few tidal radii of the model cluster, a clear tidal tail signature is present. The tidal tails are most difficult to observe when the cluster is near apocentre, as the cluster is able to catch up to the leading tail while approaching apocentre, and the trailing tail is able to catch up to the cluster. This behaviour is clear in the left panels of Figure 1, which illustrates the model cluster as it approaches its current position at apocentre in galactocentric coordinates. Observations of the tails become more difficult when the cluster is projected onto the plane of the sky, as seen in the right panels of Figure 1, with projection effectively removing any trace of the tails in position space. For visual purposes, the section of RA $\geq$ 180° has been flipped to negative in order to better illustrate the tails in the position space projection (right panels of Figure 1).

3 OBSERVATION

To search for potential extra-tidal stars around NGC 288, we first select all stars observed by Gaia within a box 15 times the limiting radius centred on NGC 288 (where the limiting radius is 1.35 arcmin; Harris 1996). The resulting dataset contains 117,480 stars for which we have both astrometric and photometric data, as well as their respective errors. The top panel of Figure 2 shows the colour-magnitude diagram (CMD) for the dataset as queried from Gaia. Absolute magnitude was calculated using $G$ photometry data, assuming that all GC stars are at the same distance as the GC itself (8.9 kpc). This assumption allows us to calculate reliable absolute magnitudes for cluster stars and stars that have recently escaped. However, foreground and background stars with incorrect magnitudes will contaminate the dataset. Thus, care must be taken to select NGC 288 stars, which are visible within the CMD, before searching the extra-tidal structure around the cluster.

Although we cannot directly select cluster stars by their Gaia parallaxes, $\pi$, owing to high errors at the distance of NGC 288 (8.9 kpc), we know that stars close to our Sun with good parallaxes are not part of the cluster. Thus, we remove any star considered nearby to our Sun at an arbitrarily chosen distance of $d \leq 5$ kpc, with fractional parallax errors of less than 10% ($\sigma_\pi/\pi \leq 0.1$). We calculate distance naively as $d = 1/\pi$, since we do not require precise distances to make this cut. We also remove stars with high proper motion errors, where $\sigma_{\mu_\alpha} > 1$ mas yr$^{-1}$. In addition, we exclude data that has less than 8 visibility periods and nonzero astrometric noise as suggested by Arenou et al. (2018). Finally, we removed any stars without colour information leaving 23,224 stars in the sample.

To extract stars that are members of NGC 288 or have recently escaped, we aim to identify stars with low relative proper motions compared to NGC 288 that populate a clean Main Sequence (MS) and Red Giant Branch (RGB) in the CMD. We used the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm (Ester et al. 1996) from the scikit-learn module (Pedregosa et al. 2011) to select clusters of stars from our NGC 288 candidates in proper motion, colour, and absolute magnitude space. Parallaxes from Gaia were not used, due to high errors in the parallax data at the distance of NGC 288.

DBSCAN is a cluster finding algorithm that searches for regions of high density in a given parameter space, without a pre-assumed number of clusters to find. Since our parameter inputs to DBSCAN include CMD axes, DBSCAN will establish different stellar types as DBSCAN clusters. The four parameters used in DBSCAN were scaled such that similar ranges were used for both colour and absolute magnitude. This allowed DBSCAN to weight the two properties equally, with a greater weight assigned to the proper motions.

DBSCAN is parameterized by epsilon and minimum samples (Pedregosa et al. 2011), which are used to determine cluster membership. DBSCAN begins by assuming all stars in the sample are ‘noise’, not belonging to any cluster. The algorithm then steps through each star, determining the number of other stars within an epsilon-radius of it, where epsilon is measured in this work with a Euclidean distance metric. If the number of stars in the epsilon-radius exceeds minimum samples, the central star is considered a ‘core star’ of the cluster. Once all core stars are identified, DBSCAN classifies any star within the epsilon-radius of a core star that is not itself a core star, as a ‘border star’, leaving the remainder as noise. The algorithm then chains together core stars that can be connected to each other by stars in a shared epsilon-radius to create the final cluster classification.

Using an epsilon distance of 0.028 and a minimum samples of 23, DBSCAN finds 1,711 stars along the MS including the main sequence turn off (MSTO) and the RGB. The strict epsilon and minimum samples values were chosen as a balance between maximising the size of the sample, while retaining a clear CMD with a MS, MSTO and RGB. However, this means it is possible that less stars are found by the DBSCAN process than may truly exist in the GC and its tails. A range of 0.018-0.037 and 10-50 were found to give similar results and trends when used for epsilon and minimum samples, respectively. Choices of epsilon and minimum samples are interdependent, and many combinations will provide similar results. Furthermore, an increase in epsilon requires an increase in minimum samples to preserve these results.

To illustrate the stars we have determined as current or recent members of NGC 288, we plot the CMD of our final dataset following application of the DBSCAN algorithm (red) over the dataset following the cuts described in this section (grey), in the bottom panel of Figure 2. Similarly to Piatti (2018), we trace the cluster along the MS including the MSTO and RGB. The horizontal branch stars, though prominent in the original data set, are removed by the astrometric excess noise cut discussed earlier. Mass segregation within the GC causes these horizontal branch stars to be
contained within the inner regions of the cluster, which we confirmed by examining their $\alpha$ and $\delta$. Thus, the subsequent analysis of the tail stars is unaffected by their removal.

4 COMPARISON

We expect the proper motions of tail stars to be dependent on their position relative to the cluster. This kinematic signature of the tidal tails existing around NGC 288 is observable for the first time with Gaia. Figure 3 shows the stars from the simulation (top panel) and the Gaia data after applying the DBSCAN algorithm (bottom panel) in position-space, coloured by $\mu_\alpha$ relative to the cluster. The black circle represents the limiting radius ($r_\ell$). We have divided the panels of Figure 3 into quadrants QI-QIV counterclockwise starting in the top right corner to aid in the analysis.

In both the top and bottom panels of Figure 3, a diagonal overdensity of stars is noticeable surrounding the cluster, primarily in QI and QIII. The overdensity in the simulation is composed of tail stars that have recently escaped the cluster. Thus, the fact that we observe the same overdensity in the data implies that stars are escaping NGC 288. The trend in $\mu_\delta$ within the overdensity is clear in the simulation, though slight enough that it is not clear in the data, owing to the proper motion uncertainties. The distribution of proper motion error for the tail stars peaks at $\sigma_{\mu_\delta} \approx 0.2$ mas yr$^{-1}$, with a mean of $\bar{\sigma}_{\mu_\delta} \approx 0.4$ mas yr$^{-1}$.

Outside the diagonal overdensity, few stars are seen in QI for both the model and observational cluster plots. Stars outside $r_\ell$ are moving away from the cluster with high proper motion relative to the cluster. In QII, a greater number of stars are moving with high positive proper motion, whereas in QIV a greater number of stars are moving with highly negative proper motion, although it includes some stars with positive proper motions. In QIII, the distribution of proper motions is reasonably even. These trends are qualitatively consistent between the simulation and the Gaia data.

For further comparison, we employed the two sided Kolmogorov-Smirnov (KS) test (Kolmogorov 1933; Smirnov 1948) for the hypothesis that the proper motions from the simulation and the Gaia data are drawn from the same continuous distribution. The p-values for QI, QII, QIII & QIV are 0.12, 0.13, 0.08 and $5.7 \times 10^{-5}$, respectively. For QI, QII & QIII, the p-value is greater than 1%, and therefore, the test does not reject the hypothesis. For QIV, the p-value is less than 1%. However, QIV has the least amount of data points in both the simulation and the Gaia data, so we expect the KS test to be less reliable in this quadrant.

The stars with high positive proper motion in QII are predominantly stars from the end of the trailing tail of NGC 288, thus exhibiting the same net proper motion in declination. This is supported by the simulation results in Figure 1, where the stars moving into apo centre have a positive $\mu_\delta$, but a near zero $\mu_\alpha$. QII & QIV contain a mix of leading and trailing tail stars. This overlapping of the tidal tails in RA and Dec is due to the motion and position of tidal stars, as they collapse inwards towards the cluster when at apo centre, essentially losing the clear tidal tail signature that would otherwise be observed.

5 SUMMARY

Gaia DR2 contains photometric and astrometric data for many of the stars in and around GCs. The newly available proper motions, in particular, are advantageous in studying GCs such as NGC 288, where tidal tails are expected to exist, but have yet to be confirmed via observations. We use data from Gaia DR2 to examine the possibility that while tidal tails do exist around NGC 288, they are difficult to observe due to a combination of the GC’s orbital phase and the observed projection of the GC.

We perform an N-Body simulation of a cluster on the same orbit as NGC 288 and find that although the cluster contains tidal tails, projection effects in conjunction with the orbital phase of the GC, cause the tails to be nearly undetectable at this time using stellar positions alone, appearing only as an overdensity around the cluster. We compare the simulation with observations from Gaia DR2 and find that the simulated and observed results display comparable trends in the $\mu_\delta$ of cluster stars. We show in both the
Figure 3. Position of stars in both the simulation (top panel) and from the Gaia data (bottom panel), coloured by proper motion in declination, $\mu_\delta$, relative to the cluster. The black circle in the two plots represents the limiting radius of the cluster, and the dashed lines divide the Figure into four quadrants which are referenced in the analysis. Comparable trends are apparent in the overdensity of stars about the cluster.

simulation and the observations that stars are moving away from the cluster with high proper motions relative to the cluster. These results illustrate that the cluster has moved into apocentre with stars from the leading and trailing tails converging around the cluster. Thus, only traces of the tidal tail signature can be observed at this orbital phase. While the high errors in proper motion and low star counts in the observations prevent us from explicitly confirming the detection of tidal tails around NGC 288, there is a good qualitative match between the simulation and the data.

Future Gaia data releases will come with lower uncertainties for proper motions and parallaxes, allowing for further investigation into the tidal tail structure about NGC 288. However, in this work we show that NGC 288 is consistent with being a normal tidally filling GC with tidal tails. We do not require a high dark matter content or complex tidal history to reproduce the observations.

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