The disruption of the low-mass globular cluster E 3

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ABSTRACT

We use Gaia DR2 photometry and proper motions to search for the hypothetical tidal tails of the Galactic globular cluster E 3. Using a modified version of a classical decontamination procedure, we are able to identify the presence of an extended structure emerging from the cluster up to \(r \sim 1\) deg from its center, thus suggesting that this poorly studied cluster is undergoing a tidal disruption process. These low surface-brightness structures are aligned with the direction to the Galactic center, as expected for a cluster close to its perigalacticon. Different scenarios to explain the important amount of mass lost by this cluster are discussed.

Key words: (Galaxy): globular clusters: general, (Galaxy): halo

1 INTRODUCTION

The structure and evolution of Galactic globular clusters (GCs) is affected by the tidal stress exerted by the Milky Way, which varies in time as these systems move along their orbits within the Galaxy, while being exposed to strong interactions with the densest Galactic components (e.g. Combes et al. 1999). This process led to the formation of stellar streams or tidal tails, such as the ones generated by the disruption of Pal 5 (Odenkirchen et al. 2003; Grillmair & Dionatos 2006; Kuzma et al. 2015); one of the most extended structures observed among the ones generated by the family of Galactic GCs. In recent years, as new datasets have become available, it has been possible to unveil more of these low surface-brightness tails, making evident that this is a common feature in Galactic clusters and that their formation is a manifestation of their orbital parameters and dynamical evolution (see summary of detections and discussion in Piatti & Carballo-Bello 2020).

With the arrival of Gaia, we have a new opportunity to reveal and trace tidal structures across the sky in areas well beyond their tidal radii, by including new parameters (e.g. parallaxes, proper motions) that were not available in previous photometric surveys. Different approaches have been proposed to exploit such a precious dataset with that aim, from a modified version of the classical statistical decontamination procedure (Carballo-Bello 2019), to a 5D mixture modelling technique, which is capable of systematically detecting tidal tails in the surroundings of the most massive halo GCs (Sollima 2020). However, as we move to the low-mass end in the distribution of Galactic GCs, the search for faint tails becomes a difficult task because of the limitations on successfully separating the cluster content from the fore/background stellar populations.

On the other hand, low-mass clusters may favour the generation and detection of tidal tails. As shown by Babinot & Gieles (2018), the average mass of an escaping star in a low-mass cluster is higher (and therefore brighter) than those in a high-mass cluster, making its tidal tails more clearly visible. This can be the case for low-mass clusters showing hints of formation of tails and/or tidal disruption (e.g. Whiting 1, Pal 13 and AM 4; Carraro et al. 2007, 2008; Carballo-Bello et al. 2017; Piatti & Fernández-Trincado 2020; Shipp et al. 2020).

With a present-day mass of only around \(3 \times 10^3\)\(\text{M}_\odot\) (Baumgardt et al. 2019, see other basic parameters in Table 1), the star cluster E 3 (also known as C 0921-770 and ESO 37-1; Lauberts 1976) is one of the least massive GCs in our Galaxy, and belongs to the population of oldest clusters (Marín-Franch et al. 2009). Unlike the great majority of Galactic GCs, it does not show evidence of multiple stellar populations (Salinas & Strader 2015; Monaco et al. 2018). Since multiple populations are produced by the ability to retain enriched material in the early life of a cluster, an absence of them indicates that the initial mass of the cluster was also lower than the bulk of Galactic GCs. The sparse nature of this cluster, together with a dearth of low mass stars in its color-magnitude diagram (CMD), were noticed early on, hinting at a tidal removal of stars (van den Bergh et al. 1980; McClure et al. 1985), and giving the cluster its

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nicknamed a “dying globular cluster”. In this work, we explore Gaia DR2 data trying to detect the hypothetical tidal tails resulting from the disruption of E 3.

2 GAIA DATA

The European Space Agency (ESA) mission Gaia is providing precise positions, kinematics and stellar parameters for more than one billion star, and will help us to understand the origin and evolution of our own Galaxy by exploring its current structure with unprecedented detail (Gaia Collaboration 2016). We have used the five-parameter astrometric solution (positions, proper motions and parallaxes) and \((G, G_{\text{BP}}, G_{\text{RP}})\) photometry provided by the second data release of this mission Gaia Collaboration (2018) to identify likely members of E 3 in its surroundings.

We have retrieved all the information available for an area of the sky within 5 deg from the center of E 3. To ensure a good quality photometry and astrometry for all the sources throughout our analysis, we only consider sources with \(G_{\text{BP}} \leq 18.5\) and \(G_{\text{RP}} \leq 18.5\) within a radius of 5 arcmin from the center of E 3 (coordinates from Baumgardt et al. 2019). The radial velocity was taken from Monaco et al. (2018).

### Table 1. Basic parameters of the cluster E 3 (Baumgardt et al. 2019)

| Parameter | Value |
|-----------|-------|
| R.A.      | 140.238 deg |
| Dec       | -77.282 deg |
| \(d_0\)   | 8.1 kpc    |
| \(d_{GC}\) | 9.4 kpc    |
| \(r_c\)   | 0.8 arcmin (1.9 pc) |
| \(r_h\)   | 2.7 arcmin (6.3 pc) |
| \(r_t\)   | 10.2 arcmin (24.1 pc) |
| Mass      | \(2.9 \times 10^5\) \(M_\odot\) |
| \(v_t\)   | 12.6 km s\(^{-1}\) |

### Figure 1.

CMD corresponding to all the Gaia objects within \(r \leq 3\) arcmin from the center of E 3 (coordinates from Baumgardt et al. 2019). The red box indicates the position of the objects used to define the \(\sigma, \mu_{\alpha^*}\) and \(\mu_\delta\) ranges considered in our procedure.

\[
\tau = 1 - \frac{N_{\text{cluster}}}{N_{\text{field}}} \frac{A_{\text{cluster}}}{A_{\text{field}}} \tag{1}
\]

where \(N\) and \(A\) correspond to the number of stars in a given \((G_0, G_{\text{BP}}, G_{\text{RP}}, \mu_{\alpha^*}, \mu_\delta)\) cell and the total area for each population (cluster or control field), respectively. Unwanted effects in the results due to the way in which we divide the spaces are avoided as much as possible by shifting the grids in each dimension by \(1/3 \varepsilon\), yielding 81 different configurations and weight values. In this work, we add an additional step and compare our target sample with 1000 randomly selected subsamples of field stars, occupying 20% of the initial field area. With the latter process we address the likely variation of star density in the surroundings of our area of interest, specially because of its proximity to the Galactic plane. We finally assign to each star the mean value \(\overline{\tau}\) resulting from the 81,000 iterations.

As shown in Figure 1, E 3 has a poorly populated main sequence (MS) of stars with \(G_0 \geq 18\) and only the section of the diagram around its tentative MS turn-off is well defined (see the much deeper CMD in de la Fuente Marcos et al. 2015). This low density of cluster members clearly affects the morphology of the CMD and an important fraction of fore/background stars are also identified in its brighter and redder section. In order to reduce the number of polluters in our final sample, we limit our method to the ranges in parallax and proper motions defined by the stars likely associated with E 3 with \(17.8 \leq G_0 \leq 18.5\) and \(0.6 \leq (G_{\text{BP}} - G_{\text{RP}}) \leq 1\) (see selection box in Figure 1). To define those ranges, we

3 METHODOLOGY

With the purpose of estimating the probability of each star of belonging to E 3, we follow the procedure described and used in Carballo-Bello (2019) to unveil extra-tidal features around NGC 362. This method considers color, magnitudes and proper motions of the stars in the region under study and compare their distribution in the same planes for a sample of control field stars. We select an area around E 3 of \(1.5\) deg \(\times\) \(1.5\) deg where we expect to identify the tentative members left by the clusters in its surroundings. As control sample, we used those located in a region beyond \(r = 1.5\) deg and with an equivalent total area. The \((G_0, G_{\text{BP}} - G_{\text{RP}}, \mu_{\alpha^*}, \mu_\delta)\) space is divided into a grid of cells, where the cell size \(\varepsilon\) are \(\varepsilon_{G_0} = 0.2\), \(\varepsilon_{G_{\text{BP}} - G_{\text{RP}}} = 0.2\), \(\varepsilon_{\mu_{\alpha^*}} = 0.5\) and \(\varepsilon_{\mu_\delta} = 0.5\).
have obtained the error-weighted distributions of $\sigma$, $\mu_\alpha^*$, $\mu_\delta$, for stars with $r \leq 3$ arcmin (similar to the $r_b$ of this cluster) and $90 \leq r$ [arcmin] $\leq 120$ using a bin size of 0.03, 0.3, 0.3, respectively. Parallax values have been corrected by adding a zero point of 0.04 mas (e.g. Maiz Apellániz 2019).

The resulting parallax distribution (upper panel in Figure 2) shows several peaks and it is not possible to clearly identify the component associated with E3. There is a prominent group of stars with values compatible with the mean parallax reported for this GC ($\sigma \sim 0.12$ mas; Baumgardt et al. 2019). However, the exclusion of stars with negative or large values may notably bias our sample, thus altering our capacity of detecting the extra-tidal structures (see discussion about usage of Gaia DR2 parallaxes in Luri et al. 2018). In order to avoid the lost of information, especially for such a low-density cluster at $d_0 \sim 8$ kpc where Gaia parallaxes have large uncertainties, we do not impose restrictions on the $\sigma$ values. On the other hand, the distributions obtained for $\mu_\alpha^*$ and $\mu_\delta$ and shown in the middle and bottom panels in Figure 2, respectively, allow us to assume that most of the stars likely associated with E3 are contained within 1 standard deviation around the mean values at $\mu_\alpha^* = -2.7 \pm 0.9$ mas yr$^{-1}$ and $\mu_\delta = 7.2 \pm 0.9$ mas yr$^{-1}$, which are in good agreement with the proper motions derived by Baumgardt et al. (2019) for this cluster. Since we expect that most of the stars lost by GC are low-mass MS members, we focus our analysis on the $0.6 \leq (G_{BP} - G_{RP})_0 \leq 1$ and $G_0 \geq 17.8$ section of the CMD.

From the initial sample of 161 733 stars in our area of interest ($r \leq 90$ arcmin), we proceed in our analysis with a total of 2077 stars satisfying the criteria described above. As for the control field sample, 1463 out of the 127798 objects observed by Gaia in the $90 \leq r$ [arcmin] $\leq 120$ area around E3 were used in our method.

4 RESULTS AND DISCUSSION

The density map shown on the left panel of Figure 3 was generated by summing the individual weights in bins of 5 arcmin x 5 arcmin. The result was smoothed using a Gaussian filter with a width equivalent to 3 bins and converted into a significance ($S$), which represents the standard deviations over the mean value in the field ($S = \text{signal} - \text{< signal}>)/\text{error}_{\text{signal}}). At first glance, a low-significance structure is detected in the surroundings of E3, which is oriented in the north-south direction and up to distances of $\sim 1$ deg ($\sim 140$ pc) from the cluster center (assuming the Baumgardt et al. (2019) heliocentric distance). No further limitations have been imposed to $G_0$ in our procedure given that it seems reasonable to expect that fainter stars (with larger photometric errors) will have smaller mean $\tau$ values and a lower impact in the resulting density map. Indeed, the north-south structure unveiled by our technique is observed even when the density map is built with stars with different $G_{\text{omax}}$ values in the range $18.5 \leq G_{\text{omax}} \leq 20$. Moreover, the orientation of these tails is not altered when different bin sizes and/or filter widths are used.

While the southern arm, an apparently narrower structure, seems to be better aligned with the cluster center, the northern component seems to be more dispersed, with a lower mean significance, and distributed along an axis which is slightly shifted from the central coordinates of E3. Misaligned tails, specially in those sections far away from the cluster center, have been observed in other Galactic GCs exhibiting tidal tails (e.g. Navarrete et al. 2017). We have explored whether these tails are associated with gradients in the extinction or the distribution of Gaia DR2 sources over the field. As shown in the middle panel in Figure 3, there is a variation in the Schlafly & Finkbeiner (2011) $E(B-V)$ values, with a maximum and minimum values of $E(B-V)$ $\sim 0.3$ and 0.1, respectively, with a $\sigma$ $\sim 0.06$. Therefore, although we observe a few extinction peaks in our area of interest, those variations are not reflected in our results. Moreover, since completeness of Gaia might be affected, among other factors, by its scanning laws, we also checked for variations in the density of stars throughout our field by counting stars with $G \geq 20.5$ in the original catalog (see analysis of the completeness of Gaia in Boubert et al. 2020). Besides the expected smooth gradient of star counts towards higher Galactic latitudes and the Milky Way plane (see right panel in Figure 3), there are no hints of incompleteness in the faint end of the
models to the distribution within in Figure 3, we fitted King (1966) and Elson et al. (1987) perors or/and the presence of tidal tails as the one observed profile, which may indicate the presence of potential escapers (e.g. Pal 5 and NGC 5466, Odenkirchen et al. 2003; Belokurov et al. 2006, respectively). Since we only have individual weights for all the stars in the field instead of a decontaminated catalog, we generated the radial distribution shown in Figure 4 by summing their weights over concentric rings centered in E 3 rather than counting cluster stars. In order to locate the tentative position of the break in the profile, which may indicate the presence of potential escapers or/and the presence of tidal tails as the one observed in Figure 3, we fitted King (1966) and Elson et al. (1987) models to the distribution within $r = 8 \text{arcmin}$. The bulk of stars ($r \sim 5 \text{arcmin}$) is well fitted by both models with $r_C = 0.7 \pm 0.1 \text{arcmin}$ and $\gamma_1 = 12 \pm 0.2 \text{arcmin}$ for the King model and with $r_{\text{eff}} = 0.8 \pm 0.1 \text{arcmin}$ and $\gamma = 2.7 \pm 0.2$ for the Elson power-law template. The structural parameters derived here are in good agreement with those obtained by Baumgardt et al. (2019). Beyond $r \sim 5 \text{arcmin}$, the deviation of the observational profile from both fits suggests the existence of a group of potential escapers, followed by a distribution that slowly decays up to distances much larger than the King tidal radius of E 3.

There is enough evidence showing that the morphology of the tidal tails in a GC is affected by the orbit followed by the cluster (e.g. Montuori et al. 2007; Carballo-Bello et al. 2012; Küpper et al. 2012; Piatti & Carballo-Bello 2020; Sollima 2020). More specifically, numerical simulations and the systematic search for extratidal content in Galactic GCs have shown they are often aligned with the orbit of the cluster, specially in the regions well beyond its tidal radius (e.g. Montuori et al. 2007; Klimentowski et al. 2009). In order to confirm whether it is also the case of these tails, we compute a tentative orbit for E 3 using the galpy package (Bovy 2014) and assuming the Reid et al. (2014) values for the distance of the Sun to the Galactic center and its circular velocity set at $R_0 = 8 \text{kpc}$ and $V_0 = 240 \text{km s}^{-1}$, respectively. As for the cluster, we have used the mean proper motions derived from Figure 2, the radial velocity from Monaco et al. (2018) and set at $v_r = 12.6 \text{km s}^{-1}$, and the heliocentric distance estimated by Baumgardt et al. (2019).

The resulting orbits are overplotted on the left density map shown in Figure 3. The tidal tails unveiled in this work are found well beyond its tidal radius ($r_t = 24 \text{pc}$), poorly correlated with the orbit of the cluster but aligned with the direction to the Galactic center. E 3 has crossed its perigalacticon at $d_{\text{GCper}} \sim 9 \text{kpc}$ only $\sim 20 \text{Myr}$ ago, thus according to Montuori et al. (2007), the inner tidal tails should point towards the Galactic center and they are only good tracers of the orbital path at large scales. Since we are not able to reveal any other overdensities in the surroundings of E 3 following the methodology described in Section 3, even when we increase the area analysed, we may suggest that the ori- entation of the structures detected here results more from the orbital stage of the cluster than from a reflection of its path around the Milky Way. It is also important to emphasize the difficulties found to properly determine the main basic parameters associated with the orbit of such a faint GC, as evidenced by the difference between the reported radial velocities measurements for this cluster (de la Fuente Marcos et al. 2015; Salinas & Strader 2015; Monaco et al. 2018).

Despite the low eccentricity ($e = 0.2$) of the orbit in which E 3 is placed, this cluster has lost a remarkable fraction of stars compared to the rest of Galactic GCs with sim-

Figure 3. Left: density map generated for the surroundings of E 3. The plotted contours correspond to the range $1.5 \leq S \leq 5$, with increments of $0.25$. The solid yellow line represents the tentative orbit of the cluster, while the red arrow indicates the direction of the Galactic center. Middle: $E(B-V)$ map for the same sky area, with 30 contour levels in the range $0.1 \leq E(B-V) \leq 0.3$. The overplotted black contours correspond to the $S = 1.5$ region from the left panel. Right: distribution of sources originally found in Gaia DR2 with $G > 20.5$. 

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ilar orbital parameters (Piatti & Carballo-Bello 2020). Its core radius is also comparable or larger than the ones observed in the other members of that same family of GCs, and dynamically looks like a more evolved cluster. Using Eq. 5 in Piatti et al. (2019), we estimate that the fraction of cluster mass lost by tidal heating for E 3 is $M_{\text{dis}}/M_{\text{in}} = 0.42$. Assuming that all the stars in our field have similar masses and that the extended low-density tails start at $r \approx 15$ arcmin (based on a visual inspection of the left panel in Figure 3), we sum weights in the area enclosed by the $S = 1.5$ contour and estimate that the outer structures contain, as an upper limit, a total mass equivalent to the $\sim 40\%$ of the current mass of E 3 (around a half of the stars lost by the cluster). Such an important mass loss could have been thus originated in a more complex encounter between this GC and any of the Milky Way components, when most of the low-mass stars were ripped out and only the core of original stellar system survived.

In this context, E 3 may have been formed within an already accreted dwarf galaxy. The Galactic halo, which is mostly result of the continuous merging and accretion of minor satellites (e.g. Rodriguez-Gomez et al. 2016), is populated by a progeny of tidal streams and overdensities. The Helmi streams, a family of stellar substructures in the Solar neighbourhood (Helmi et al. 1999), represents an important source of stars in the Galactic halo (~15%) and may also contributed with GCs, which are now members of the Milky Way GC system (Koppelman et al. 2019). Although E 3 was not included in the initial sample of GCs likely accreted by the Milky Way, Massari et al. (2019) added this cluster in the candidates list based on its orbital properties and a less restrictive selection criterion. Therefore, the violent process that partially dissolved E 3 may correspond to the accretion of a massive galaxy ($M \sim 10^8M_\odot$) into the Milky Way, whose disruption led to the formation of the Helmi streams. Interestingly, the orbit of this cluster crosses the paths in the sky of the Eastern Banded Structure, the Anticentric Stream (Grillmair 2006), and the Monoceros ring (e.g. Slater et al. 2014), which seem to result from the distortion of the Galactic disk due to its interaction with satellite stellar systems (Deason et al. 2018; Laporte et al. 2020), including the Sagittarius dwarf galaxy. Favouring its extra-Galactic origin, accreted GCs without a clear surviving progenitor galaxy as in the case of E 3 are often found surrounded by extended stellar structures (e.g. Carballo-Bello et al. 2018).

The detection of tidal tails in low-mass systems such as E 3 allows us to gain insights into the the disruption and survival of GCs in the Milky Way, and how their evolution is probably related to their extra-Galactic origin. Future Gaia data releases will provide an opportunity to locate the hypothetical stellar stream originated by the violent disruption of this cluster.

5 CONCLUSIONS

E 3 represents a unique case of a Galactic GC on a orbit with low inclination and eccentricity, with an important mass loss due to a single (or several) episodes during its evolution. In this work, we have tried to unveil the hypothetical tidal tails around this cluster by applying a very restrictive version of a procedure designed to identify likely members of Galactic GCs beyond their tidal radii.

Our results show that a low-significance substructure emerging from the cluster is aligned with the direction towards the Galactic center, as expected for clusters which are close to their perigalacticon. However, that substructure does not contain enough stars to account for the mass lost by E 3. Future Gaia data releases might allow us to trace the rest of the tidal structure generated by the disruption of this cluster and establish whether the survival of this GC is related to its evolution within an accreted dwarf galaxy or peculiar born conditions.

DATA AVAILABILITY

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

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