The surroundings of the Milky Way globular cluster NGC 6809

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ABSTRACT
We study the outer regions of the Milky Way globular cluster NGC 6809 based on Dark Energy Camera (DECam) observations, which reach nearly 6 mag below the cluster main sequence (MS) turnoff. In order to unveil its fainter outermost structure, we built stellar density maps using cluster MS stars, once the contamination of field stars was removed from the cluster color-magnitude diagram. We found that only the resulting stellar density map for the lightest stars exhibits some excesses of stars at opposite sides from the cluster centre that diminish soon thereafter at ~ 0.32°. Studied globular clusters with apogalactic distances smaller than that of NGC 6809 (5.5 kpc) do not have observed tidal tails. The lack of detection of tidal tails in the studied inner globular cluster sample could be due to the reduced diffusion time of tidal tails by the kinematically chaotic nature of the orbits of these globular clusters, thus shortening the time interval during which the tidal tails can be detected. Further investigations with an enlarged cluster sample are needed to confirm whether chaotic and non-chaotic orbits are responsible for the existence of globular clusters with tidal tails and those with extra-tidal features that are different from tidal tails or without any signatures of extended stellar density profiles.

Key words: Galaxy: globular clusters: general – techniques: photometric – globular clusters: individual: NGC 6809

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1 INTRODUCTION
The formation of stellar streams or tidal tails due to the stripping or dissolution of Milky Way globular clusters has long been understood as a consequence of their tidal interaction with their host galaxy. Indeed, Montuori et al. (2007) performed detailed N-body simulations to show that tidal tails are generated in globular clusters as a consequence of their interaction with the densest components of the Milky Way (e.g. the bulge and the disc) and may result in multi-component tidal tails after repeated apocentre passages (Hozumi & Burkert 2015). However, rather than from tidal shocks, Küpper et al. (2010, 2012) analytically and numerically showed that tidal tails and the substructures within them can develop from the epicyclic motions of a continuous stream of stars escaping the clusters, regardless of whether the clusters’ orbits are circular or eccentric.

From an observational point of view, there have been many investigations of the outermost regions of globular clusters with the goal of detecting extra-tidal structures and tidal tails. From the early color-matched star counts of photographic plates by Grillmair et al. (1995), Lehmann & Scholz (1997), and Leon et al. (2000), our sensitivity to such structures has increased by orders of magnitude with the introduction of wide-field digital sky surveys (e.g., Odenkirchen et al. 2001; Belokurov et al. 2006; Grillmair & Johnson 2006; Grillmair 2009; Grillmair & Carlin 2016; Shipp et al. 2018) and are now reaching equivalent surface brightnesses below 35 mag/arcsec² by incorporating Gaia DR2 proper motions (e.g. Ibata et al. 2019; Grillmair 2019). The results are interesting, with some globular clusters having bona fide tidal tails, while others have irregular extended halos or clumpy substructures, and still others have simple King (1962) radial profiles without any apparent extra-tidal features. Piatti & Carballo-Bello (2020) carried out a comprehensive compilation of the relevant observational results obtained to date with the aim of understanding the conditions that determine whether or not a globular cluster can develop tidal tails. From 53 globular clusters included in their final compilation, 14 have observed tidal tails and 17 show no detectable signatures of extra-tidal structures.

When exploring kinematic properties (orbital eccentricity, inclination and semi-major axis) in combination with the ratio of mass lost by disruption to the initial cluster mass, Piatti & Carballo-Bello (2020) found that there are no obvious clues to differentiate globular clusters with and without tidal tails. The lack of detection of tidal tails in the studied inner globular cluster sample could be due to the reduced diffusion time of tidal tails by the kinematically chaotic nature of the orbits of these globular clusters, thus shortening the time interval during which the tidal tails can be detected. Further investigations with an enlarged cluster sample are needed to confirm whether chaotic and non-chaotic orbits are responsible for the existence of globular clusters with tidal tails and those with extra-tidal features that are different from tidal tails or without any signatures of extended stellar density profiles.
tidal tails. They also found that, contrary to the predictions of Balbinot & Gieles (2018), globular clusters with larger apogalactic distances and with a smaller remaining fraction of cluster mass than Pal5 - a well known globular cluster with a long tidal tail (Odenkirchen et al. 2001; Grillmair & Dionatos 2006) - are not necessarily candidates for developing tidal tails. Furthermore, globular clusters with observed tidal tails have apparently retained a larger fraction of their mass and have smaller apogalactic distances than that of Pal 5. Yet globular clusters with extra-tidal features or King (1962) profiles span very similar parameter values. Even initial mass is uncorrelated with the presence of tidal tails.

They also investigated whether the internal dynamical evolution of globular clusters might be influenced by escaping stars and correlate in some way with the presence of tidal tails. In this respect, they considered different relationships between the core, half-mass and Jacobi radii, the ratio of the cluster age to the respective relaxation time and the ratio of mass loss to the total cluster mass. The results show that, irrespective of the presence or absence of any kind of extra-tidal structure, the globular clusters can reach an advanced stage in their internal dynamical evolution even if they have lost a relatively large amount of mass by tidal stripping. It therefore seems that there is no currently known parameter that enables us to confidently predict the presence or absence of tidal tails for any given cluster.

In order to enlarge the number of globular clusters from which to make meaningful conclusions about the existence of tidal tails, we here study NGC6809 (M 55), an inner Milky Way globular cluster whose outermost regions has been paid little attention. As far as we are aware, the cluster is included in the catalog of Harris (1996, 2010 Edition) with a tidal radius of 0.26", see also, Moreno et al. 2014. Recently, de Boer et al. (2019) estimated a slightly larger tidal radius (0.32") from Gaia DR2 data. The results obtained in this work particularly allowed us to speculate on a possible mechanism to explain the presence or absence of tidal tails in globular clusters. In Sections 2 and 3 we describe the Dark Energy Camera data used and the analysis carried out of the external cluster regions. Section 4 discusses the resulting stellar density maps. Section 5 summarizes the main conclusions of this work.

2 DATA HANDLING

With the aim of mapping the cluster outermost structures, we used publicly available observations (program ID : 2019B-1003, PI : Carballo-Bello) carried out with the Dark Energy Camera (DECam), attached to the prime focus of the 4-m Blanco telescope at Cerro Tololo Inter-American Observatory (CTIO). DECam provides a 3 deg$^2$ field of view with its 62 identical chips with a scale of 0.263 arcsec pixel$^{-1}$ (Flaugher et al. 2015). The gathered observations of NGC6809 consists of 4x600 sec g and 4x400 sec r images, respectively. In order to derive the atmospheric extinction coefficients and the transformations between the instrumental magnitudes and the SDSS ugriz system (Fukugita et al. 1996), we used nightly observations of 5 SDSS fields at a different airmass.

The images were processed with the DECam Community Pipeline (Valdes et al. 2014), while the photometry was obtained from the images with the point-spread-function fitting routines of DAOPHOT II/ALLSTAR (Stetson et al. 1990). The final catalog includes positions and standardized g and r magnitudes of stellar objects with $\text{sharpness} \leq 0.5$ to avoid the presence of bad pixels, cosmic rays, galaxies, and unrecognized double stars in our subsequent analysis. In order to quantify the photometry completeness, DAOPHOT II was also employed to add synthetic stars with magnitudes and positions distributed similarly to those of the measured stars to an image, and carrying out the photometry for the new image as described above. The resulting magnitudes for the synthetic stars were then compared with those used to create such stars. We found that the magnitudes for a 50% completeness level turned out to be 23.4 mag and 23.3 mag for the g and r bands, respectively (see, also, Piatti et al. 2020, 2021).

Figure 1 shows the variation of the interstellar reddening $E(B-V)$ across the DECam field of view, with $E(B-V)$ values downloaded from Schlafly & Finkbeiner (2011) provided by the NASA/IPAC Infrared Science Archive. As can be seen, $E(B-V)$ values across the entire DECam field of view span a range of $\sim 0.06$ mag, which is smaller than the known lower limit for a cluster to be considered affected by differential reddening ($\Delta E(B-V) > 0.11$ mag Burki 1975). Nevertheless, we corrected the g and r magnitudes of each star by using the $E(B-V)$ color excesses according to the positions of the stars in the sky. From the dereddened magnitude $g$ and $r$ magnitudes, we built an intrinsic color-magnitude diagram (CMD) for a circular region centred on the cluster and with a radius of 0.15", with the aim of highlighting the cluster features. Figure 2 shows the resulting CMD, as well as that for a reference field region of equal cluster area located far from the cluster, for comparison purposes. As can be seen, a long well populated cluster MS is clearly visible in the left panel, in addition to that of the Sagittarius dwarf galaxy, as first reported by Mandushev et al. (1996).

3 STELLAR DENSITY MAPS

The strategy to build the cluster stellar density map consists in using cluster’s members distributed across the DECam field of view. Therefore, 1) we traced five different segments along the cluster Main Sequence (MS); then 2) we decontaminated them of field stars, and finally 3) we built their stellar density maps with all the measured stars that remained unsubtracted from the field star cleaning procedure. The five different segments were traced to monitor any variation in the spatial distribution of stars at large distances from the cluster centre, because lower-mass stars can be more easily stripped away from the cluster than their higher-mass counterparts.

In order to clean the cluster CMD, we followed the recipe used by Piatti & Bica (2012), which was satisfactorily applied elsewhere (e.g. Piatti et al. 2018; Piatti & Carballo-Bello 2019) According to that method, we need to define a cluster and a star field areas of equal size. Figure 1 shows a rectangle which delimits both regions, the latter being that outside the rectangle. The method consists in defining boxes

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centred on the magnitude and color of each star in the star field CMD; then to superimpose them on the cluster CMD, and finally to choose the closest star to the centre of each box to be subtracted. We used CMD boxes of \((\Delta g_0, \Delta(g - r)_0) = (1.0 \text{ mag}, 0.25 \text{ mag})\). We cleaned the cluster CMD regions delimited by the segments traced in Fig. 2.

Because of the relatively large extension of the cleaned cluster area (1.3' × 1.3'; see Fig. 2), we imposed the condition that the spatial positions of the stars to be subtracted from the cluster MS segment were chosen randomly. We then looked for a star with \((g_0, (g - r)_0)\) values within the (magnitude, color) box, taking into account the photometric errors. The outcome of the cleaning procedure is a cluster MS segment that likely contains only cluster members; their spatial distributions relies on a random selection. For this reason, we executed 1000 times the decontamination procedure, and defined a membership probability \(P(\%)\) as the ratio \(N/10\), where \(N\) is the number of times a star was found among the 1000 different outputs. In the subsequent analysis we only kept stars with \(P > 70\%\).

Stellar density maps were constructed for each cleaned CMD segment and for stars with fixed \(P\) values using the scikit-learn software machine learning library (Pedregosa et al. 2011) and its kernel density estimator (KDE). We employed a grid of 500×500 boxes on the cluster field and allowed the bandwidth to vary from 0.005\(^\circ\) up to 0.040\(^\circ\) in steps of 0.005\(^\circ\). We adopted a bandwidth of 0.025\(^\circ\) as the optimal value. The background level was estimated from the stars distributed in the reference star field. We split this area in boxes of 0.10\(^\circ\) × 0.10\(^\circ\) and counted the number of stars inside them. With the aim of enlarging the statistics, we randomly shifted the boxes by 0.05\(^\circ\) along the abscissas or ordonates and repeated the star counting. Finally, we derived the mean value of the star counts coming from all the defined boxes. We then estimated its standard deviation from a thousand Monte Carlo realisations of the stellar density map, shifting the positions of the stars along \(\Delta(RA)\times\cos(Dec)\) or \(\Delta(Dec.)\) randomly (one different shift for each star) before recomputing the density map. Figure 3 shows the resulting density maps that represent the deviation from the mean value in the field in units of the standard deviation, that is, \(\eta = (\text{signal} - \text{mean value})/\text{standard deviation}\), for a signal above the mean value. These density maps are useful tools to identify extra-tidal features distributed
not uniformly around the cluster’s main body, as it is the case for the presence scattered debris, tidal tails, etc.

4 ANALYSIS AND DISCUSSION

The produced stellar density maps of each segment look different for the three chosen probability $P$ values. This is because a relative large area was cleaned by spatially selecting stars to subtract randomly. This means that the larger the $P$ values, the more similar the resulting density maps to the intrinsic distribution of cluster stars. For this reason, we rely our analysis on the stellar density maps built with stars with $P > 70\%$, and show those for $P > 30\%$ and $> 50\%$ to illustrate the impact of using stellar density maps with smaller $P$ values.

Stellar density maps ($P > 70\%$) for the four brighter segments would not seem to show noticeable stellar excesses beyond the tidal radius compiled by Harris (1996). This tidal radius ($0.26^\circ$) readily matches the cluster extension (see right panels of Fig. 3). Note that Moreno et al. (2014) derived the same tidal radius, while de Boer et al. (2019) obtained a tidal radius slightly larger ($0.32^\circ$). From the density map for the faintest MS stars used (segment #5), excesses of stars at opposite sides from the cluster centre aligned roughly along the SE-NW direction for the fainter MS stars, that diminish soon thereafter, are seen. This finding confirms that less massive stars are prone to leave the cluster more easily. Nevertheless, we cannot rule out the presence of extended tidal tails, because some globular clusters show non-uniform tidal tails (see the literature compiled in Piatti & Carballo-Bello (2020)).

For the sake of the reader, we also built the cluster stellar radial profile using all the stars distributed in the five CMD segments (see Fig. 2). We focused on the outermost region ($r > 0.26^\circ$) where radial variations of the photometry completeness are negligible and where we are interested in finding cluster extra-tidal features. In order to generate the stellar density profile, we counted the number of stars in annuli of $0.025^\circ$ wide. Figure 4 depicts the resulting observed radial profile represented with open circles. We then estimated the mean background level using all the points.
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Figure 3. Stellar density maps for segments 1 to 2 (from top to bottom) according to Fig. 2 and for $P > 30$, 50 and 70 % (from left to right). The circles centred on the cluster indicate the estimated tidal radius $0.26^\circ$ (Harris 1996), $0.32^\circ$ (de Boer et al. 2019), and the Jacobi radius for the present Galactocentric position ($0.37^\circ$), respectively. Contours for $\eta = 2, 4, 6, \text{and} 8$ are also shown. We have painted white stellar densities with $\eta > 10$ in order to highlight the least dense structures.

located at distances larger than $0.50^\circ$ from the cluster centre, which turned out to be $\log(N_{bg}/N_0) = -0.25 \pm 0.03$. Once the mean background level was subtracted from the observed radial profile, we obtained the radial profile represented by open triangles in Fig. 4. For comparison purposes we superimposed the field star cleaned radial profile constructed from counts of stars found in the decontaminated cluster CMD with $P > 70\%$ and a King (1962)’s model using the parameters obtained by de Boer et al. (2019). As can be seen, an excess of extra-tidal stars remains in the field star cleaned radial profile.

According to Baumgardt et al. (2019), NGC 6809 describes an orbit around the Milky Way centre characterized by an inclination angle of $67.3^\circ$, and orbit eccentricity of 0.55, a semi-major axis of 3.6 kpc (see definition in Piatti 2019), and an apogalacticentric distance of 5.6 kpc. The present cluster heliocentric and galactocentric distances are 5.3 kpc and 4.0 kpc, respectively. Because of the cluster galactocentric distance variation, its Jacobi radius changes from 24.4 pc (perigalacticon) up to 39.9 pc (semi-major axis), and the cluster mass loss by tidal disruption reaches 25% of the initial cluster mass (see Piatti et al. 2019). The present cluster position is $\sim 1.5$ times closer to the apogalacticon than to the perigalacticon, and the corresponding extrapolated Jacobi radius turns out to be 43.0 pc, which is $\sim 1.7$ times the Harris (1996)’s tidal radius, drawn in Fig. 3.

NGC 6809 moves in the Milky Way with a prograde motion, which is the direction of motion of nearly 70% of globular clusters with apogalacticentric distances smaller than that of NGC 6809 (Piatti 2019). Massari et al. (2019) suggest that the cluster has had an accreted origin and that the progenitor could have been a small dwarf satellite (Forbes 2020). Such a cluster origin agrees well with the cluster age ($13.97 \pm 0.50$ Gyr; Valcin et al. 2020), its low metal-content ([Fe/H] = -1.99 dex; Marino et al. 2019), and the difference in sodium abundance between first and second generation stars. Indeed, Piatti (2020) found that globular clusters with sodium abundance enrichments larger than 0.3 dex hinted at an accreted origin, particularly the oldest globular clusters.
NGC 6809 has a sodium abundance enrichment of 0.72 dex (Piatti 2020).

According to Montuori et al. (2007), the comparative denser Milky Way regions where NGC 6809 is moving through should facilitate the formation of tidal tails, which were not detected in this work. Meiron et al. (2020), from a suite of $N$-body simulations, find that massive clusters should totally disrupt in the presence of tidal fields, while typical halo globular clusters on moderately eccentric orbits lose mass at a low rate that they can survive for many Hubble times. This would not seem to match very well the case of inner Milky Way globulars either. Instead, the variety of prograde and retrograde orbits, with different eccentricities and inclinations found among globular clusters in the inner Milky Way rather resembles that of a kinematically chaotic mixing system (see, e.g. Price-Whelan et al. 2016a,b; Pérez-Villegas et al. 2018). Recently, Mestre et al. (2020) compared the behavior of simulated streams embedded in chaotic and non-chaotic regions of the phase-space. They find that typical gravitational potentials of host galaxies can sustain chaotic orbits, which in turn do reduce the time interval during which streams can be detected. Therefore, tidal tails in some globular clusters are washed out afterwards they are generated to the point at which it is impossible to detect them.

The percentage of mass lost in NGC 6809 due to tidal disruption by the Milky Way gravitational field is within the range of values of globular clusters moving within a sphere of radius equals to the apogalactic distance of NGC 6809 (between 15% and 48% of their initial masses; Piatti 2019; Piatti et al. 2019). Despite of such a relatively noticeable amount of cluster mass lost, none out of 9 globular clusters with apogalactic distance smaller than that of NGC 6809 in the compilation by Piatti & Carballo-Bello (2020) has tidal tails identified; NGC 5139, with an apogalactic distance of 7.0 kpc, is the innermost globular cluster with observed tidal tails. These findings led us to speculate on the possibility to differentiate globular clusters with tidal tails from those with non-observed ones based on the chaotic nature of the globular clusters’ orbits. Nevertheless, it must be recalled that a non-detection within 1 degree does not imply the possibility of the detection on larger scales, especially if supported by proper motions. Hence, the absence of observed tidal tails in NGC 6809, as well as in other globular clusters, could be due to a comparative shorter diffusion time of their tidal tails because they move in a kinematically chaotic scenario.

Figure 3. continued, for segments 3 to 4 (from top to bottom).
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Figure 3. continued, for segment 5. The grey and blue arrows in the right panel show the direction to the Milky Way centre and that of the motion of the cluster, respectively.

We point out, as a caveat, the relative small number of the studied cluster sample.

5 CONCLUSIONS

The external regions of globular clusters, particularly their tidal tails, have become the most sensitive tracers of the nature and distribution of dark matter in the Milky Way (Bonaca et al. 2019). Yet there is an ongoing debate as to whether the gaps observed in streams are due to dark matter subhalos, or to epicyclic motions of stars released from their parent clusters in discrete bursts. Particularly, Diakogiannis et al. (2014) carried out a detailed dynamical analysis of NGC 6809 and concluded that there is no sign of dark matter throughout the cluster.

Here we explored the outermost regions of NGC 6809. We built its CMD from DECam images centred on the cluster, which reached nearly 6 mag below the cluster MS turnoff. We constructed stellar density maps for stars distributed in five different magnitude intervals along the cluster MS. We found that only stars with a membership probability higher than 70% and \( \gtrsim 4 \) mag fainter than those at the MS turnoff exhibit some light excesses of stars at opposite sides from the cluster centre aligned roughly along the SE-NW direction, that diminish soon thereafter, at \( \sim 0.32^\circ \), which is the tidal radius estimated by de Boer et al. (2019). The direction of the cluster proper motion is nearly perpendicular to it, along the NE-SW vector, while the centre of the Milky Way points to the west from NGC 6809.

The lack of detection of tidal tails agrees well with recent results from numerical simulations, which suggest that the diffusion time of streams (tidal tails in globular clusters) is reduced by gravitational potentials that sustain chaotic orbits, thus shortening the time interval during which the streams can be detected. We found that globular clusters with apogalactic distances smaller than that of NGC 6809 have extra-tidal features that are different from tidal tails (7) or have no signatures of extended stellar density profiles (2). Globular clusters with detected tidal tails seem mostly to belong to the Milky Way outer halo.
Figure 4. Normalised observed (open circle), mean background subtracted (open triangle) stellar radial profiles and that for stars with $P > 70\%$ (filled circle). The horizontal lines represent the mean background level and its associated dispersion, while the vertical line represents the Jacobi radius for the present Galactocentric position ($0.37^\circ$), respectively. The blue solid line represents a King (1962)'s profile for the tidal radius obtained by de Boer et al. (2019) ($0.32^\circ$).

6 DATA AVAILABILITY

DECam images used in this work are publicly available at the https://astroarchive.noao.edu/portal/search/#/search-form webpage.

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