Detection of a Diffuse Extended Halo-like Structure around 47 Tuc

Andrés E. Piatti1,2
1 Consejo Nacional de Investigaciones Científicas y Técnicas, Av. Rivadavia 1917, C1033AAJ, Buenos Aires, Argentina; andres@oac.unc.edu.ar
2 Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, 5000, Córdoba, Argentina

Abstract

We constructed for the first time a stellar density profile of 47 Tucanae (47 Tuc) out of ~5.5 times its tidal radius (rt) using high-quality deep BV photometry. After carefully considering the influence of photometric errors, and Milky Way and Small Magellanic Cloud composite stellar population contamination, we found that the cluster stellar density profile reaches a nearly constant value from ~1.7rt outward, which does not depend on the direction from the cluster’s center considered. These results visibly contrast with recent distinct theoretical predictions on the existence of tidal tails or on a density profile that falls as r−4 at large distances, and with observational outcomes of a clumpy structure as well. Our results suggest that the envelope of 47 Tuc is a halo-like, nearly constant low-density structure.

Key words: globular clusters: individual (47 Tucanae) – techniques: photometric

1. Introduction

Extended structures around Galactic globular clusters (GGCs) have been observed in a non-negligible number of objects (e.g., see Carballo-Bello et al. 2012). Olszewski et al. (2009) found an unprecedented extra-tidal, azimuthally smooth, halo-like diffuse spatial extension of the NGC 1851, while Correnti et al. (2011) discovered an extended stellar halo surrounding the distant NGC 5694. M2 was also found to be embedded in a diffuse stellar envelope extending to a radial distance of at least five times the nominal tidal radius (Kuzma et al. 2016). Compelling evidence of long tidal tails have also been reported in the field of Pal 5 (Odenkirchen et al. 2003), Pal 14 (Sollima et al. 2011), Pal 15 (Myeong et al. 2017), and NGC 7492 (Navarrete et al. 2017), among others. From a theoretical point of view, N-body simulations have shown that the detection of extended envelopes around GGCs could be due, for instance, to potential escapers (Küpper et al. 2010) or potential observational biases (Balbinot & Gieles 2017).

Recent theoretical models argued over very distinct features of the envelope of 47 Tucanae (47 Tuc). Lane et al. (2012) modeled the cluster orbital motion to determine the locations and the stellar densities of cluster tidal tails, which were predicted to be an increase of 3%–4% above the Galactic background. The tails would seem to emerge from the cluster center toward opposite directions that are connected by a line oriented northeast to southwest. On the other hand, Peñarrubia et al. (2017), using statistical arguments and numerical techniques, derived cluster stellar density profiles, assuming that they are embedded in a dark matter halo. They found that the cluster densities asymptotically approach ρ ∼ r−4 at large distances. Models with no dark matter produce much less shallower profiles.

From an observational point of view, some previous results suggested a clumpy structure around the cluster (Chen & Chen 2010). However, they are based on 2MASS photometry that barely reaches the cluster’s main-sequence (MS) turnoff region. Leon et al. (2000) also pointed out the serious challenge the contamination of Small Magellanic Cloud (SMC) stars represented, causing them not to be able to trace the cluster radial density profile in the direction of the galaxy.

In this Letter, we describe how we accomplish constructing a radial stellar density profile of 47 Tuc out of ~5.5rt in the direction of the SMC and between ~1.7 and 3.7rt for any other direction from the cluster center. Nevertheless, these outcomes will greatly benefit, for instance, from the ongoing DECam surveys (Abbott et al. 2016). In the following, we describe the collection and processing of the data set and the subsequent analysis performed in order to produce the radial density profile as a function of the position angle (PA). Finally, we briefly discuss our results.

2. Data Analysis and Discussion

We made use of publicly available 600 s B and 300 s V images obtained at the 4 m Blanco telescope (CTIO) with Mosaic II (36’ × 36’ camera array) as part of a search for extra tidal structures in GGCs (CTIO 2009B-0199; PI: Olszewski). The 14 studied fields are placed around 47 Tuc (see Figure 1); between 1.7 and 5.5 times its tidal radius, =56 pc; (Harris 1996), and the other 2 Milky Way (MW) fields are located at ~9°3 northwest of the cluster center. This data set, which also includes calibration images (zero, domeflats, skyflats) and standard field images, was processed as described in, e.g., Piatti (2012, 2015) and Piatti et al. (2012). Mean extinction coefficients of 0.211 ± 0.024 (B) and 0.142 ± 0.014 (V) and color terms of −0.093 ± 0.004 (B) and 0.038 ± 0.005 (V) were obtained, with an rms of 0.030 (B) and 0.027 (V). Point-spread-function photometry was performed as extensively described, for instance, in Piatti et al. (2014), Piatti & Bastian (2016), and Piatti & Cole (2017). Particular success in isolating bona fide stellar objects was achieved by using roundness values between −0.5 and 0.5 and sharpness values between 0.2 and 1.0. Errors in V and B − V were <0.010 mag for V < 19.0 mag. Figure 2 depicts the color–magnitude diagram (CMD) obtained for stars in field #1 of 47 Tuc and for one MW field. The former is dominated by the SMC stellar population, namely, the old MS turnoff, the subgiant and red giant branches, and the red clump superimposed on 47 Tuc’s MS (see, e.g., Piatti 2012, 2015). We have superimposed a theoretical isochrone from Bressan et al. (2012) of log(t yr−1) = 10.10, [Fe/H] = −0.7 dex, (m − M)v = 13.37 mag, and E(B − V) = 0.033 mag (Harris 1996).
We dereddened the studied fields using the $E(B - V)$ values as a function of galactic coordinates obtained by Schlafly & Finkbeiner (2011) from a recalibration of the Schlegel et al. (1998) extinction map. The average color excess for the surveyed region is $E(B - V) = 0.030 \pm 0.003$ mag. In order to build the cluster density profile, we counted the number of stars distributed inside the delineated region drawn in Figure 2. The latter comprises the upper cluster MS and the onset of the subgiant branch, and minimizes the contamination from the SMC. As for cleaning the observed field CMDs from the MW contamination, we applied the procedure outlined by Piatti & Bica (2012) and successfully used elsewhere (see, e.g., Piatti 2014; Piatti et al. 2015; Piatti 2017). The MW CMDs served as the reference field CMD, which was subtracted from those observed around 47 Tuc. Statistically speaking, no residual was left. This is because of the relatively small number of stars in the MW CMD and of the uniformity of the MW stellar population throughout the surveyed region. Indeed, we used two synthetic CMDs generated from the Besançon galactic model (Robin et al. 2003), one centered on 47 Tuc and the other one at the position of our MW field and, after applying the
aforementioned cleaning precepts, we found no stars in the decontaminated CMD. Figure 3 shows with magenta dots the observed stars in each 47 Tuc field that was subtracted using this procedure. As can be seen, the MW marginally affects the cluster CMD region where we carry out the star counts.

The contamination from the SMC represents a more serious challenge, mainly because its CMD changes with the position in the sky. In particular, the region delineated to count cluster stars is contaminated by supergiants stars, so that the younger (closer to the SMC center) a composite SMC stellar population, the larger the number of supergiants. In order to cope with this stellar pollution we used two equal-sized adjacent regions to the larger the number of supergiants. In order to cope with this stellar pollution we used two equal-sized adjacent regions to that traced in Figure 2 (see the gray contours in Figure 3). We used these areas to build their respective luminosity functions, using every star not subtracted previously (those drawn with green symbols). Then, we adopted the average of both luminosity functions to subtract the respective number of stars per magnitude interval from the defined cluster star count region. We used intervals of $\Delta V = 0.10$ mag and subtracted the appropriate number of stars randomly. A similar method was employed by Olszewski et al. (2009). The stars that survived this step were drawn with black symbols in Figure 3.

We counted the number of measured stars, i.e., stars seen in the observed CMDs without any cleaning procedure, distributed along the designed path in the 47 Tuc field CMDs as a function of the distance to the cluster center. To do this, we employed the method described by Piatti (2016) and Piatti et al. (2017 and references therein), based on star counts carried out within statistically meaningful sized boxes distributed throughout the whole field, and then computed the number of stars per unit area as a function of the distance $r$ to the cluster center. This method does not necessarily require a complete circle of radius $r$ within the observed field to estimate the mean stellar density at that distance. This is an important consideration as having a stellar density profile that extends far away from the cluster center allows us to estimate it with high precision. We binned the whole 47 Tuc fields mosaic (see Figure 1) into $0/15 \times 0/15$ boxes. While performing star counts in the designed 47 Tuc MS strip, we took into account that a star, owing to its errors, has the chance of falling outside it. This was done by repeating the star counting with the designed 47 Tuc MS strip shifted in magnitude and color by $\pm 0.01$ mag. We divided Figure 1 into eight angular sections that were $45^\circ$ wide centered on the cluster, which was suitable for our statistical purposes.

Radial profiles for stars that were kept unsubtracted after cleaning the CMDs from the MW and SMC field star contamination were also built. In this case, the uncertainties were estimated taking into account a $20\%$ fluctuation of the number of stars after cleaning the CMDs from the MW contamination ($\sim 4$ times larger on average than the negligible residuals from MW field star variation and cleaning procedure described above), and twice as large as the difference of the number of SMC stars subtracted using both previously constructed luminosity functions, in addition to photometric errors. We added in quadrature all the involved uncertainties. Figure 4 shows the results with black and magenta circles for observed and cleaned density profiles. We also included the King (1962) and Elson et al. (1987) profiles depicted with black and orange lines, respectively, for comparison purposes.

The resultant density profiles along the directions with negligible contamination by SMC stars ($-135^\circ \leq PA \leq 45^\circ$) and between 70 and 200 pc ($1.25$ and $3.6r_\odot$, respectively) show mean stellar excesses of $\log(\text{stars/deg}^2) = 1.8 \pm 0.2$. We found slightly larger values ($1.9 \pm 0.3$) along the remaining directions ($45^\circ < PA < 225^\circ$), possibly due to residuals of SMC stellar populations. Note that along $PA = 90^\circ$ our density profile just starts at the cluster King (1962) radius and expands until $\sim 310$ pc ($5.5r_\odot$). We recall that these density profiles have been built using mainly upper MS stars, while fainter MS stars...
could also unveil these extra tidal structures (Carballo-Bello et al. 2012) that have not been used because the SMC overshadows them. These outcomes suggest that: (i) 47 Tuc is not tidally limited to its King (1962) radius; (ii) the cluster extends out to at least $\sim 5.5 r_t$; and (iii) from $\sim 1.7 r_t$ outward there is a halo-like and nearly constant low-density structure.

We did not find evidence of tidal tails as suggested by Lane et al. (2012). According to the authors they should emerge from the cluster as illustrated by the straight line in Figure 1 and with peak stellar densities of $\sim 85 - 120$ stars deg$^{-2}$. Our results show stellar densities of the same order as those predicted by the models, though. Chen & Chen (2010) found a clumpy structure around 47 Tuc’s center at distances <250 pc that makes the cluster slightly flattened in shape (axial ratio of 0.86) with a PA of the major axis of 120° (see the ellipse in Figure 1). They used 2MASS photometry for stars brighter than $K_s = 15.6$ mag, just barely above the limiting magnitude of such a database, which in turn nearly coincides with the cluster MS turnoff magnitude. However, our results suggest that 47 Tuc’s envelope is more likely a diffuse structure, as the stellar density profiles look similar along any direction from the cluster center. Such profiles seem to be rather flat, in contrast with the $r^{-4}$ law suggested by Peñarrubia et al. (2017) as a prediction of expected stellar envelopes of GCs embedded in dark mini-halos. Olszewski et al. (2009) found a symmetric density profile with a power law of $r^{-1.24}$ profile out of $\sim 6 r_t$ in NGC 1851, instead, which is more like the one derived here for 47 Tuc. Although we did not uniformly survey all of the sky around 47 Tuc, the present outcome could suggest that Galactic tidal interactions have been a relatively inefficient process for stripping stars off the cluster (Dinescu et al. 1997, 1999).

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ORCID iDs
Andrés E. Piatti https://orcid.org/0000-0002-8679-0589

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