

Close encounters involving RAVE stars beyond the 47 Tucanae tidal radius.

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ABSTRACT

The most accurate 6D phase-space information from the Radial Velocity Experiment (RAVE) was used to integrate the orbits of 105 stars around the galactic globular cluster 47 Tucanae, to look for close encounters between them in the past, with a minimum distance approach less than the cluster tidal radius. The stars are currently over the distance range $3.0 \text{ kpc} < d < 5.5 \text{ kpc}$. Using the uncertainties in the current position and velocity vector for both, star and cluster, 105 pairs of star-cluster orbits were generated in a Monte Carlo numerical scheme, integrated over 2 Gyr and considering an axisymmetric and non-axisymmetric Milky-Way-like Galactic potential, respectively. In this scheme, we identified 20 potential cluster members that had close encounters with the globular cluster 47 Tucanae, all of which have a relative velocity distribution (V_{rel}) less than 200 km s^{-1} at the minimum distance approach. Among these potential members, 9 had close encounters with the cluster with velocities less than the escape velocity of 47 Tucanae, therefore a scenario of tidal stripping seems likely. These stars have been classified with a 93% confidence level, leading to the identification of extratidal cluster stars. For the other 11 stars, V_{rel} exceeds the escape velocity of the cluster, therefore they were likely ejected or are unassociated interlopers.

Key words: Stars: kinematics - globular clusters: individual (47 Tucanae)

1 INTRODUCTION

47 Tucanae is the second most massive/luminous ($\sim 1.1 \times 10^6 M_\odot$) Galactic globular cluster (Lane et al. 2010a), one of the closest to the Milky Way ($\sim 4.02 \text{ kpc}$, McLaughlin et al. 2006), and “a test-bed for Galaxy formation models”, with a valuable reservoir of stars of different types useful to understand the formation process of multiple stellar populations in globular clusters. Recent studies on self-enrichment scenarios by massive AGBs, oriented to explain abundance patterns, support the idea that 47 Tucanae was possibly ~ 7.5 times more massive than it is now (e.g., Ventura et al. 2014). 47 Tucanae exhibits a split or spread main sequence of stars and multiple subgiant branches (Anderson et al.

2009), multiple red giants branches (Milone et al. 2012), and a third population visible only in the subgiant branch (Ventura et al. 2014). These multiple sequences have been detected from high-precision photometry.

During the last years, it has become clear that 47 Tucanae is not the only Galactic globular cluster exhibiting multiple stellar populations, but it shows unusual kinematic properties (Lane et al. 2010b). Recently detected high velocity dispersion profile at large radii, suggests an ongoing evaporation, and under this scenario escaping stars could form tidal tails (Lane, Küpper & Heggie 2012). In this regard, extra-tidal stars associated with 47 Tucanae are yet to be uncovered (Lane, Küpper & Heggie 2012), and their detection from colour-magnitude diagrams (CMD) proves difficult due to strong pollution by the Small Magellanic Cloud (SMC) in the background (Leon, Meylan & Combes 2000).

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In the present paper we characterize the orbits of a sample of stars in the RAVE survey around 47 Tucanae, with distances between 3.0 kpc to 5.5 kpc. Under a Monte Carlo scheme, star-cluster orbits pairs are integrated in an axisymmetric and non-axisymmetric Milky-Way-like Galactic potential, searching for close encounters in the past. The probability¹ of occurrence is evaluated for stars having close encounters in the past with the cluster within such time. Two cases are proposed in our Monte Carlo scheme: (*i*) Stars having encounters with relative velocity less than the cluster's escape velocity are considered to be likely tidal stripping, and (*ii*) Stars with relative velocity greater than this escape velocity are considered to be likely ejected, which can be explained by some scenarios involving black holes, or binary system interactions (e.g., Gvaramadze, Gualandris & Portegies Zwart 2009; Pichardo et al. 2012a; Lützgendorf et al. 2012; Lind et al. 2015).

This procedure is similar to the one by Fernández-Trincado et al. (2015a,b) for globular cluster ω Centauri, and it is applied here for the first time to 47 Tucanae. The dynamical history of clusters which are believed to have been more massive in the past, provides very useful information to understand the formation of the Galactic halo. To date, RAVE has gathered half-a-million medium resolution ($R \sim 7500$) spectra of stars in the southern sky, and because RAVE input catalogue is magnitude limited ($9 < I < 13$), the stellar sample is essentially homogeneous and free of kinematic biases. The advent of unprecedented accuracy 6D phase-space data from large survey such as Gaia, fed into Monte Carlo simulations like the one presented in this paper, will be particularly valuable to help us characterize the kinematics of stars in and out the tidal radius of Galactic globular clusters.

In this paper we test the viability to using the integration of orbits in a Monte Carlo numerical scheme, looking at the relative velocity of encounters occurred within the cluster tidal radius, which has been extensively tested with the results of N -body simulations. The paper is structured as follows: In Section 2, we briefly describe the accurate RAVE data set available in ~ 120 sq. deg. centred on 47 Tucanae; in Section 3, we describe the Monte Carlo numerical scheme used to constrain potential cluster members; results and discussion are presented in Section 4 and in Section 5, we summarize the main conclusions of this paper.

2 SAMPLE SELECTION

We selected a subsample of candidates stars for a 120 deg^2 area centered on 47 Tucanae (see 1) from the RAVE DR4 public data (Kordopatis et al. 2013), with very accurate radial velocity (signal-to-noise ratio better than 20, allows us to ensure radial velocity errors $< 2 \text{ km s}^{-1}$; (e.g., Hawkins et al. 2015). We assumed the distance estimates based on the

¹ The probability can be quantified in the same manner as in (Fernández-Trincado et al. 2015a), i. e., $Prob = \text{Number of orbits having close encounters with the cluster} / N_{total}$, where $N_{total} = 1 \times 10^5$ Monte Carlo simulations

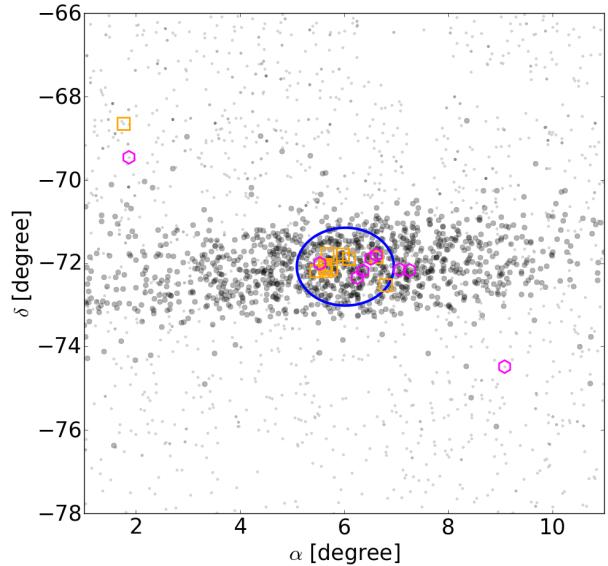


Figure 1. Spatial distribution for 20 potential extra tidal stars associated with 47 Tucanae: magenta open symbols mark the positions of stars candidates with relative velocity less than the escape velocity of the cluster ($V_{rel} < 68.8 \text{ km s}^{-1}$), orange open symbols marks the positions of stars candidates with relative velocity greater than the escape velocity of the cluster. All these stars are currently well outside 47 Tucanae's tidal radius ($r_t > 56 \text{ pc}$), whose projection on the sky is shown with the large blue circle shows. The black dots are stars in the RAVE survey (present-day) in the same direction of the cluster. The grey filled dots show the present-day expected angular distribution of debris stars as predicted by N -body particles from Lane, Küpper & Heggie (2012) around 120 deg^2 area centered on 47 Tucanae. (A color version of this figure is available in the online journal).

Bayesian approach of Binney et al. (2014), with errors less than 20%. The RAVE DR4 catalog is complemented with several proper motions in the literature, however, we have decided to use the UCAC4 proper motions (Zacharias et al. 2013) because those are available for all our sample, and the proper motions are less affected by potential systematic uncertainties than in other catalogues (Vickers, Röser & Grebel 2016).

The systematic radial velocity of 47 Tucanae is not enough to separate likely cluster members from Galactic foreground stars (e.g., Meylan, Dubath & Mayor 1991). To minimize Galactic contamination, we select stars with heliocentric distances between 3.0 kpc to 5.5 kpc.

These limits in distance were adopted based on the distance spread of the expected tidal debris stars as predicted by an N -body simulation of 47 Tucanae orbiting the Milky Way (Lane, Küpper & Heggie 2012). Figure 1 shows the present-day angular positions of N -body particles.

We explore the expected Galactic contamination based on the updated version of the Besançon

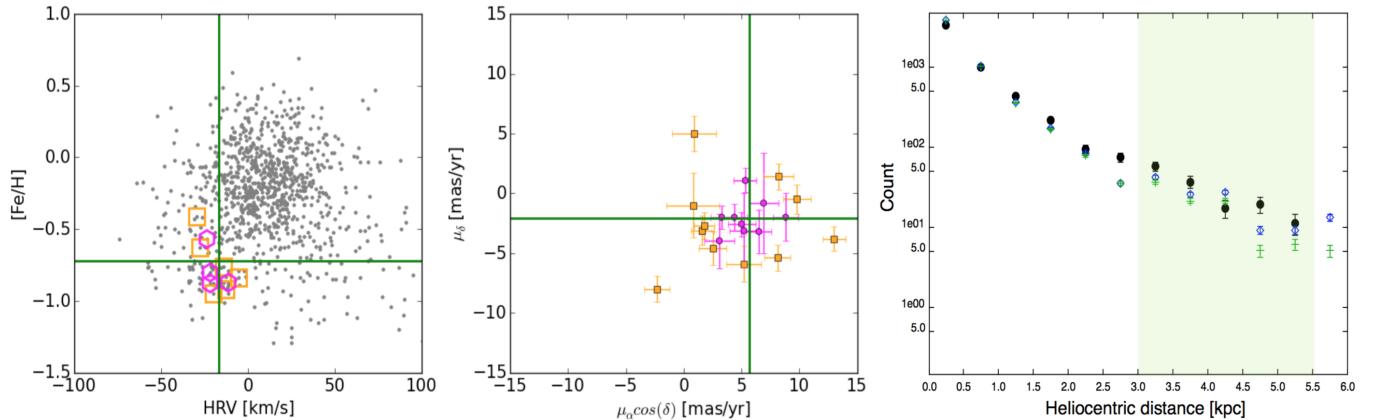


Figure 2. Left panel: Radial velocity-metallicity distribution for stars candidates similar to the nominal radial velocity and metallicity ($[Fe/H]$) of 47 Tucanae (horizontal and vertical lines). Grey dots mark RAVE field stars in the same direction of the cluster (see Figure 1). Central panel: Proper motions distribution for stars with relative velocity less (magenta symbols) and greater (orange symbols) than the escape velocity of the cluster, as in Figure 1. The nominal proper motions of the cluster is marked with the green horizontal (μ_δ) and vertical ($\mu_\alpha \cos(\delta)$) lines. Right panel: Expected cumulative distribution of heliocentric distances for foreground stars from the Galaxy, obtained from mock samples from the Besançon Galaxy model (blue diamonds). The green crosses shows the contribution of the Galactic disk. The black full circles shows the cumulative distribution of heliocentric distances from the RAVE sample in the same direction. The green region indicates the established limits in this work to identify extra tidal stars. (A color version of this figure is available in the online journal).

Galaxy model (Robin et al. 2014). From the right panel of Figure 2, one can estimate that the Galactic disk and halo contributes $\sim 1.7\%$ and $\sim 1.0\%$ respectively, of all stellar population for distances greater than 3.0 kpc of the Sun, and 0.1% and 0.6% for distances greater than 5.5 kpc. An excess of stars between 3 kpc and 5 kpc from the RAVE DRA4 as compared to the Besançon Model using the same selection function in both datasets, is naturally caused by the presence of the cluster in the observed field.

Our final sample has 105 RAVE stars with 6D phase-space information.

3 MILKY-WAY-LIKE GALACTIC MODEL AND ORBITS

for the orbits computations, we used semi-analytic Milky Way gravitational potential models, including axisymmetric and non-axisymmetric ones, where dynamical friction is ignored. For the non-axisymmetric Galactic model, we first scaled the Allen & Santillan (1991) bulge-disk-halo axisymmetric model following a Monte Carlo scheme, taking the Local Standard of Rest (LSR) parameters (R_0, Θ_0) = $(8.3 \pm 0.23 \text{ kpc}, 239 \pm 7 \text{ km s}^{-1}$) given by Brunthaler et al. (2011), and proceed to transform all the mass of the scaled bulge into a prolate or boxy bar following the procedure given by Pichardo, Martos & Moreno (2004). The bar component approximates the three dimensional mass density distribution of the Freudenreich (1998) Galactic bar model, based on COBE/DIRBE observations of the Galactic center. In addition, our model includes the three dimensional model for a two-armed spiral com-

ponent, called PERLAS, given by (Pichardo et al. 2003); these arms are built with a small fraction of the mass of the scaled disk. The relevant parameters employed in the bar and the spiral arms are the following: the pitch angle of the spiral arms is $i = 15.5 \pm 3.5$, and the initial angle between the bars major axis and the Sun-Galactic center line is $= 20$ deg; the ratio of the mass in the spiral arms to the mass of the disk component is $M_{\text{arms}}/M_{\text{disk}} = 0.04 \pm 0.01$; the angular velocities of the bar and spiral arms are respectively $\Omega_{\text{bar}} = 55 \pm 5 \text{ km s}^{-1} \text{ kpc}^{-1}$, $\Omega_{\text{arms}} = 25 \pm 5 \text{ km s}^{-1}$ (Moreno, Pichardo & Velázquez 2014).

It is important to note that small variations in the form of the potential do not lead to significant changes in the properties of the computed orbits (see Figure 3). Table 2 show the comparison in both Galactic potentials (axisymmetric and non-axisymmetric structures) of the relative velocity between the stars and 47 Tucanae.

To study the kinematics of our sample in the Milky Way, we compute the orbits considering a series of Monte Carlo sampling simulations. We employ the six-dimensional phase space coordinates of these stars and those associated with the Galactic model, and consider their corresponding uncertainties as 1σ variations, plus the uncertainties of the Galactic parameters in a Gaussian Monte Carlo sampling in the same manner as Moreno, Pichardo & Velázquez (2014). Each run has its corresponding sampled Galactic model and star's initial orbital conditions. The adopted Solar motion with its uncertainties is $(U, V, W)_\odot = (-11.1 \pm 1.2, 12.24 \pm 2.1, 7.25 \pm 0.6) \text{ km s}^{-1}$ (Schönrich, Binney & Dehnen 2010; Brunthaler et al. 2011).

Computations considered the effect of the quoted un-

Table 1. Positions and velocities of 47 Tucanae.

Parameter	Value	Reference
Distance from the Sun	4.02 ± 0.35 kpc	1
$\alpha(J2000)$	00 : 24 : 05.67	1
$\delta(J2000)$	-72 : 04 : 52.62	1
$\mu_\alpha \cos(\delta)$	(5.64 ± 0.20) mas yr $^{-1}$	2
μ_δ	(-2.05 ± 0.20) mas yr $^{-1}$	2
V_r	(-16.85 ± 0.16) km s $^{-1}$	3
r_t (tidal radius)	56 pc	4
V_0 (escape velocity)	68.8 km s $^{-1}$	5

(1) McLaughlin et al. (2006); (2) Anderson & King (2004); (3) Lane et al. (2010b); (4) Harris (1996); (5) Gnedin et al. (2002).

certainties in the position and velocity of the LSR on the Galactic potential. These uncertainties are taken as 1σ variations, and a Gaussian Monte Carlo sampling generates the parameters to compute the present-day positions and velocities of the cluster and star. Uncertainties in the solar motion are also taken into account. Our Monte Carlo numerical scheme used all these values (e.g., Pichardo et al. 2012a; Moreno, Pichardo & Velázquez 2014).

For 47 Tucanae itself, we calculated the orbit based on its current distance, proper motions, radial velocity, and positions as listed in Table 1. For the selected sample, the 6D phase-space information is used in the Monte Carlo numerical scheme, taking into account the observational uncertainties of R_0 , Θ_0 , and RAVE data. We ran 10^5 star-cluster pair of orbits, looking for close encounters 2 Gyr backwards in time. This would be the time needed to build up tidal tails from the cluster (e.g., Lane, Küpper & Heggie 2012), detectable today as RAVE stars associated with 47 Tucanae beyond the cluster's tidal radius.

The minimum approach distance d_{min} , is the straightforward indicator of close encounters between RAVE stars and 47 Tucanae along their orbits, e.g., if at the time of the encounter the star is within the tidal radius of 47 Tucanae ($d_{min} < 56$ pc). The adopted value (d_{min}) is in agreement with the data from Harris (1996), where the surface density drops to zero at 56 pc from the centre of the cluster for an adopted King profile.

Then, encounters with the adopted d_{min} and relative velocity smaller than the escape velocity, $V_0 = 68.8$ km s $^{-1}$, are considered as "tidally stripped" from the cluster, while encounters with relative velocity larger than the escape velocity and relative velocity $V_{rel} < 200$ km s $^{-1}$, are consistent with stars being "ejected" from the cluster by means of three-body encounters or black hole interactions (e.g., Leonard 1991; Pichardo et al. 2012a; Lind et al. 2015, see references therein). Figure 3 shows the relative velocity (V_{rel}) distribution functions for 20 potentially members of 47 Tucanae.

In particular, we analyzed possible encounters in the recent 300 Myr; in this time interval, 47 Tucanae has about one perigalactic passage, since the orbital period reported for the cluster spans between 190 ± 4 to 193 ± 4 Myr (e.g., Dinescu, Girard & van Altena 1999).

3.1 Energy (E) and angular momentum (L_z) from the Monte Carlo numerical scheme

An important point must be noted about the Monte Carlo scheme used in this investigation: A star may have been ejected from 47 Tucanae, and its resulting energy (E) and angular momentum (L_z) from the stripping/ejection process may be completely different from the progenitor cluster. To illustrate this point, we explain the following example: the energy and angular momentum of 47 Tucanae are simulated taking into account a Monte Carlo gaussian sampling of the cluster's radial velocity, distance, proper motions, etc., within their quoted errors. Then, a set of 10^5 Monte Carlo L_z versus E points are generated, producing the distribution of grey dots observed in Figure 4, where the blue symbol refers to the average value $\langle E \rangle = -1486$ km 2 s $^{-2}$ and $\langle L_z \rangle = 1389$ km s $^{-1}$ kpc. In the same figure, four ellipses show the 1-, 2-, 3- and 4- σ regions of the distribution. We first consider stars being ejected from the cluster with a relative velocity of 20 km s $^{-1}$, 40 km s $^{-1}$, and 60 km s $^{-1}$ towards many different directions defined by a fine grid of points on the celestial sphere centered at the cluster. We compute for each direction the values E and L_z of the ejected star (magenta dots in Figure 4). It is clear from Figure 4 that many of these points may lie far from the 4 σ curve, and then can be very different from the values (L_z , E) of the cluster. Based on the above discussion, the value of E and L_z cannot be used as a sufficient conditions to identify stars escaping from 47 Tucanae in our Monte Carlo simulations.

3.2 N-body simulations as testbed in the integration of orbits using a Monte Carlo numerical scheme

To supplement our results, we also investigated the orbits for a suite of N -body simulations of satellites undergoing tidal disruption along 47 Tucanae-like orbits (present-day) in the Milky Way potential (e.g., Lane, Küpper & Heggie 2012). We have selected randomly 500 particles (see Figure 1) and randomly assigned observational errors, to account for observational uncertainties that prohibit us from accurately knowing the true position, space motion, and therefore orbits of both 47 Tucanae and the 500 particles. For each particle we integrate 1×10^5 orbits looking for close encounters in the same way as already mentioned above. For the Galactic gravitational potential we employed our proposed non-axisymmetric mass model. The resulting relative velocity (V_{rel}) distribution function of N -body particles are also shown in Figure 5 and Figure 6.

We note that as we start with the current structure of the cluster, which is then tidally stripped along its orbit, the final cluster system in our model has slightly different properties than 47 Tucanae, but our Monte Carlo approach for orbits integration is still effective to identify close encounters between the N -body particles and 47 Tucanae-like.

We find that 93% of the N -body particles encounters occurred within the tidal radius of 47 Tu-

canae and do not exceed their escape velocity. These results allow us clearly quantify the confidence level of our technique of integration using a Monte Carlo approach to find probable extra tidal stars candidates nearly 47 Tucanae. The initial conditions (N -body particles) follow the typical observed uncertainties of stars observed in RAVE survey in the same field, i.e., the errors in proper motions are assumed to be < 5 mas/yr, in radial velocity < 10 km s $^{-1}$, and the uncertainties in distances are on the order of 20%. Under this assumption we demonstrate with a 93% of confidence level that N -body particles associated to disrupting particles from 47 Tucanae, can be identified as potentially members.

To facilitate the reproducibility and reuse of our results, we have made the Monte Carlo simulations available in a public repository at <https://github.com/Fernandez-Trincado/47Tucanae-NbodySimulations>.

4 RESULTS AND DISCUSSION

Figure 3 shows the relative velocity distribution functions (V_{rel}) during close encounters (star - cluster) for 20 potential members of 47 Tucanae. We found that 45% (9 stars) of those stars may have escaped from the cluster with a velocity less than the escape velocity, satisfying a possible scenario of tidally stripping, while 55% of the stars listed in Table 2 seems likely ejected from the cluster with velocities greater than the escape velocity. Also, Figure 3 shows that moderate changes in the form of the Galactic potential and the 47 Tucanae gravitational force² itself result in non-significant changes in our predicted results (see Table 2).

The RAVEID, number of Monte Carlo orbits having close encounters, the most frequent relative velocity, and the most frequent encounter time (τ_{enc}), are listed in Table 2.

We identified 9 stars in the direction of the 47 Tucanae globular cluster with probabilities greater than 0.5% having been ejected from the cluster, with relative velocities less than escape velocity, $V_{rel} < V_0$, within the past 2 Gyr. Our identification is based on the integration of orbits under a Monte Carlo approach, which allowed us to classify potential members with a 93% of confidence level. Figure 1 shows that these stars appear to have the same [Fe/H] metallicities, radial velocity, and proper motions than 47 Tucanae. We also note that four stars (J000728.5–692755, J002815.8–720903, J002900.8–721005, J003621.6–742854) outside of the tidal radius have similar proper motions to the cluster, and are potential candidates for membership.

We find 11 stars in our sample that exceeds the escape velocity of the cluster, $V_{rel} > V_0$, during the close encounters with 47 Tucanae. This velocity can be explained by some peculiar scenarios

² A static potential assuming a King profile (?) has been considered for the cluster itself.

Table 2. Ejection parameters for 20 more likely RAVE stars having close encounters with 47 Tucanae, obtained with the axisymmetric (first line) and non-axisymmetric (second line) potentials. For each star the ID from RAVE catalogue and the number of orbits (N_{orb}) having close encounters with the cluster are given in column 1, and 2. The relative velocity (V_{rel}) and the encounter time are given in column 3, and 4.

RAVEID	N_{orb}	V_{rel} km s $^{-1}$	τ_{enc} Myr
$V_{rel} < V_0$			
J002627.2–714744	5748	36.15	0.499
	5835	37.61	0.146
J002604.0–715323	4815	25.52	0.498
	4588	25.01	0.146
J002525.7–721039	4700	63.74	0.498
	4797	62.29	0.141
J002900.8–721005	4170	25.28	0.499
	4007	22.80	0.146
J002500.9–722038	3968	45.33	0.498
	3898	42.97	0.146
J002815.8–720903	3634	54.93	0.498
	3440	54.22	0.146
J002207.1–720033	3484	37.90	0.498
	3449	46.50	0.146
J003621.6–742854	1435	35.57	2.499
	1330	25.66	1.146
J000728.5–692755	717	45.52	2.499
	479	33.09	2.146
$V_{rel} > V_0$			
J002259.7–720706	4842	84.63	0.482
	4979	74.41	0.143
J002628.5–715013	4313	106.0	0.490
	4262	95.07	0.146
J002422.5–715329	3776	85.90	0.498
	3893	83.21	0.145
J002235.8–721111	3424	146.29	0.497
	3491	144.03	0.138
J002353.2–714712	3196	85.26	0.496
	3140	82.78	0.146
J002710.9–723109	3180	75.15	0.494
	3313	72.97	0.146
J002243.4–714631	2839	75.74	0.499
	2911	76.45	0.146
J002149.9–721102	2299	95.99	0.497
	2305	82.84	0.139
J002230.3–720141	2237	187.68	0.498
	2273	194.81	0.001
J002232.0–720649	1944	87.79	0.499
	2097	77.95	0.146
J000701.7–683829	1123	165.39	1.498
	1552	154.66	1.001

containing black holes and/or binary system. However, we noted that these velocities were not observed in our N -body particles experiment, which may be because the N -body simulations do not incorporate binary systems. We evaluated every observable and found that relatively large proper motions, shown as orange symbols in Figure 2, can produce large observed relative velocity, therefore significantly changing one of the components of the orbital velocity vector. Our results cannot rule out the possibility that these stars are associated with the 47 Tucanae progenitor system or if they are unassociated interlopers, whose orbits coincide with the cluster's one. Only the determination of accurate chemical abundances could help to constrain true cluster members in this scenario. We will investigate in more detail the physical process that imprint out these high velocities, on a large sample of other Galactic globular cluster with extra tidal stars candidates. With the very accurate radial velocity, distance and proper motions from the upcoming six-dimensional phase-space data set that will be produced by the Gaia space mission, we will be able to do a more complete characterization of the velocity vector.

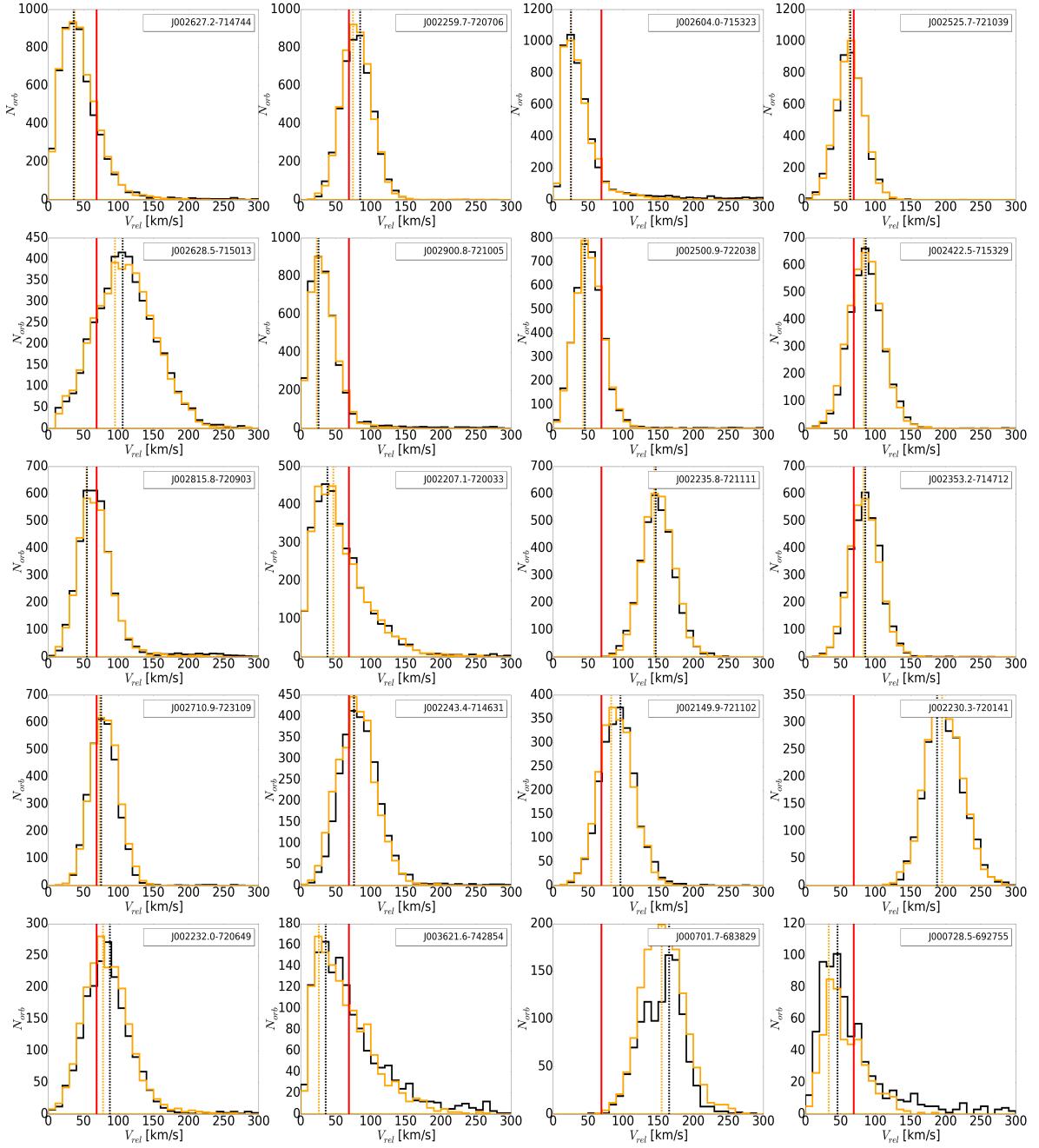


Figure 3. Relative velocity (V_{rel}) distribution functions for 20 stars having close encounters with 47 Tucanae (see Section 3) in an axisymmetric Galactic potential (black line), and non-axisymmetric (orange line) Galactic potential of the Milky Way. The vertical red line marks the escape velocity from 47 Tucanae, $V_0 = 68.8 \text{ km/s}^{-1}$, and the vertical dashed line refers to the more frequent relative velocity listed in Table 2. The distributions are accumulated from 10^5 Monte Carlo realizations of the clusters and star orbits. (A color version of this figure is available in the online journal).

For the remainder of the studied sample (85 RAVE stars) we have not found a significant number of close encounters with 47 Tucanae ($< 0.01\%$ probability or < 10 orbits).

Assuming that our sample (stars listed in Table 2) are true extra tidal stars associated to 47 Tucanae, it is interesting to compare their metallicity distribution ([Fe/H]) with that of clusters stars ($r_t < 56$ pc) and field stars. The metallicity distribution observed in the left panel of Figure 1, of our candidates listed in Table 2, is comparable to the nominal $[Fe/H] \sim 0.72$ for this cluster (Harris 1996). Figure 1 indicates that these stars candidates, as a group, have similar abundances [Fe/H] to 47 Tucanae, and fall approximately 0.5 dex from the mean metallicity of field stars in the same part of the sky.

5 CONCLUSION

In this study, we have used for the first time the 6D phase-space data around Galactic globular cluster 47 Tucanae to compute pairs of star-cluster orbits in a Milky Way axisymmetric and non-axisymmetric Galactic potential following a kinematic Monte Carlo approach, looking for close encounters between the globular cluster and RAVE stars. Under this scheme, we constrain potential cluster former members based in their kinematic information and uncertainties. We identified 20 potential extra tidal stars, with kinematics and chemical pattern ([Fe/H]) similar to 47 Tucanae, and most likely ejected from the cluster 5 Myr ago (encounter times, τ , are listed in Table 2). We find with a 93% of confidence level that 9 of those stars could have been tidally stripped from 47 Tucanae, based on the frequency of close encounters and the low relative velocity observed during each approach. In the near future, high resolution spectroscopy will be used to confirm such association.

Throughout this work we demonstrate that a Monte Carlo approach to integrate pairs of orbits (star - cluster's) can be used with a high level of confidence to identify extra-tidal stars candidates formerly associated with the cluster, assuming a scenario of tidal stripping, where the relative velocity is less than the escape velocity of the cluster. This hypothesis has been extensively used in stellar debris studies of Galactic globular clusters systems (Lind et al. 2015; Fernández-Trincado et al. 2015b,a; Fernandez-Trincado et al. 2016). Here we extend its use to identify former members of a cluster that are now fully accreted into the Galactic halo.

We have found that the imprints of a rotating bar in a non-axisymmetric Galactic model does not affect the results of our simulations, and its influence can be neglected, in the problem being investigated in this paper.

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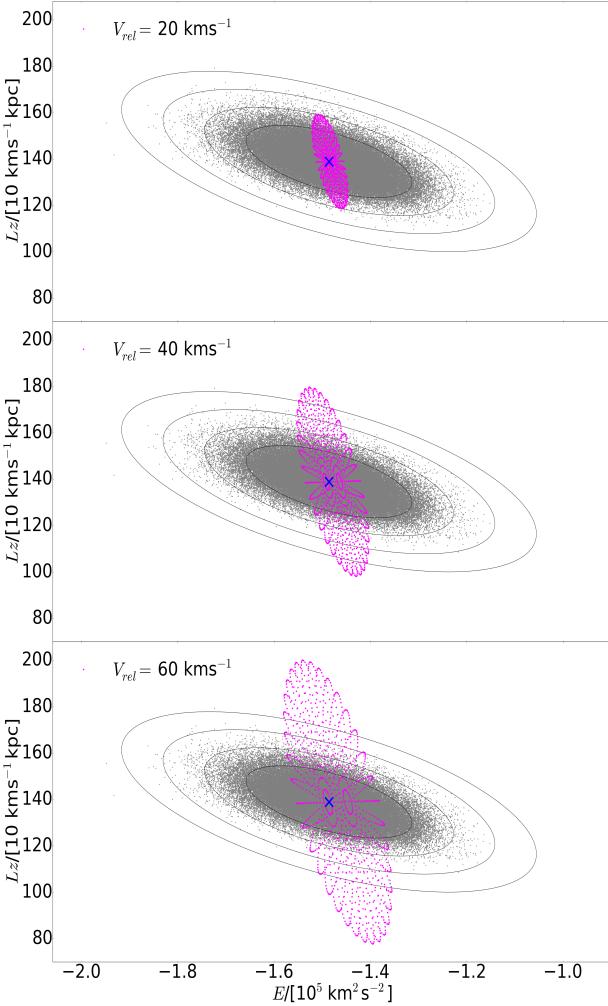


Figure 4. Orbital angular momentum (L_z) and energy (E) generated from 10^5 Monte Carlo simulations of 47 Tucanae (grey dots), taking into account Gaussian uncertainties. Magenta dots are simulated stars escaping from the cluster with relative velocities of 20 km s^{-1} (top panel), 40 km s^{-1} (middle panel) and 60 km s^{-1} (bottom panel). The blue symbol refers to the average values L_z and E from the distribution (grey dots) for the concentric ellipses (black lines) with 1σ , 2σ , 3σ , and 4σ .

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Figure 5. Relative velocity (V_{rel}) distribution functions for close encounters between particles from N-body simulations of satellites undergoing tidal disruption along 47 Tucanae (Lane, Küpper & Heggie 2012). The vertical line indicates the escape velocity from the cluster (red line) and the more probable relative velocity of the particle (grey line). The scale is the same in these frame, with the vertical axis normalized to unity, and the horizontal axis spans relative velocities from 0 km s⁻¹ to 300 km s⁻¹. (A color version of this figure is available in the online journal).



Figure 6. Same as Figure 5, but for simulations between 241 and 467. (A color version of this figure is available in the online journal).