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Discovery of Tidal RR Lyrae Stars in the Bulge Globular Cluster M62*

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Abstract

The RR Lyrae (RRL) rich globular cluster M62 (NGC 6266) is one of the most massive globular clusters in the Milky Way, located in the dense region of the Galactic bulge, where dynamical processes that affect the survival of globular clusters are maximized. Using *Gaia* second data release data we have found clear evidence for an excess of RRLs beyond the cluster tidal radius of M62, associated partly with stars stripped into the Galaxy field. This is confirmed with new Visible and Infrared Survey Telescope for Astronomy Variables in the Via Lactea Extended survey observations, which discard any differential reddening effect as the possible cause of the observed RRL density excess. We also determined the orbit of M62 using accurate new measurements of its distance, radial velocity, and proper motions, finding that its orbit is prograde with respect to the direction of the Galactic rotation. Orbits are integrated in the non-axisymmetric galactic model `GravPot16`, which includes the perturbations due to the central Galactic bar. M62 shows a particular orbital behavior, having a dynamical signature of the bar-bulge region. The small extra-tidal RRLs extensions that are observed are roughly aligned toward the galactic center, and the direction is almost perpendicular to the galactic plane, not with its motion along its orbit. This may be a clear sign of bulge-crossing shocks during the last passage close of the cluster toward its perigalacticon. M62 would be the first clear observed case of bulge shocking in the inner Galaxy acting on a globular cluster.

Key words: Galaxy: bulge – Galaxy: evolution – Galaxy: kinematics and dynamics – globular clusters: general

1. Introduction

Globular clusters that we observe today in the Milky Way are the survivors of a much larger initial population that was decimated by dynamical processes, chiefs among them being tidal disruption and dynamical friction (Fall & Rees 1977, 1985). The tidal disruption of globular clusters has been widely discussed (e.g., King 1962; Tremaine et al. 1975; Chernoff et al. 1986; Capuzzo-Dolcetta 1993; Weinberg 1994; Gnedin & Ostriker 1997; Meylan & Heggie 1997; Vesperini & Heggie 1997; Combes et al. 1999; Lotz et al. 2001; Capuzzo-Dolcetta et al. 2005; Balbinot & Gieles 2017), and prominent examples of tidal tails have been observed (e.g., Leon et al. 2000; Odenkirchen et al. 2001; Belokurov et al. 2006; Grillmair & Johnson 2006; Jordi & Grebel 2010). In this Letter we report the discovery of a potential extra-tidal RR Lyrae (RRLs) population, likely the results, in projection on the plane sky, of the relics of the bulge shocking.

M62 is one of the most massive globular clusters in the Milky Way, and also one of the richest clusters in RRL variable stars (Contreras Ramos et al. 2010). This cluster has an extended blue horizontal branch (BHB) and a strong extreme-ultraviolet (EUV) excess observed by the *International Ultraviolet Explorer* (*IUE*; Dorman et al. 1995), and dynamically it does not appear to have suffered core collapse yet (Beccari et al. 2006). It is located in the Galactic bulge at $l, b = (353.57458, +07.31956)$ deg, at a distance of $D = 6.9$ kpc (Harris 1996), and its orbit confines the cluster to the bulge (Dinescu et al. 2003).

This cluster is interesting also because it has a double main sequence. This is indicative of a composite stellar population (Milone 2015), like ω Cen (the largest Galactic globular cluster), which has been proposed to be the remaining nucleus of an accreted dwarf galaxy.

In addition, this cluster shows evidence for overdensity features beyond the tidal radius (Han et al. 2017). However, the cluster is located in a field with significant differential reddening (Minniti et al. 1992; Contreras Ramos et al. 2005) that severely diminishes the capacity to recognize extra-tidal stars.

Because of its known physical properties (location, mass, radius, and 3D velocity), M62 is an ideal laboratory to explore the effects of the different dynamical processes that affect the survival of massive clusters in the inner regions of the Milky Way.

In particular, in this Letter we discuss the effects of tidal disruption on M62 using RRLs in the *Gaia* second data release (DR2) database (Gaia Collaboration et al. 2016, 2018a; Clementini et al. 2018), and new near-infrared (NIR) observations of the Visible and Infrared Survey Telescope for Astronomy (VISTA) Variables in the Via Lactea Extended

* Based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programs 179.B-2002 and 298.D-5048.

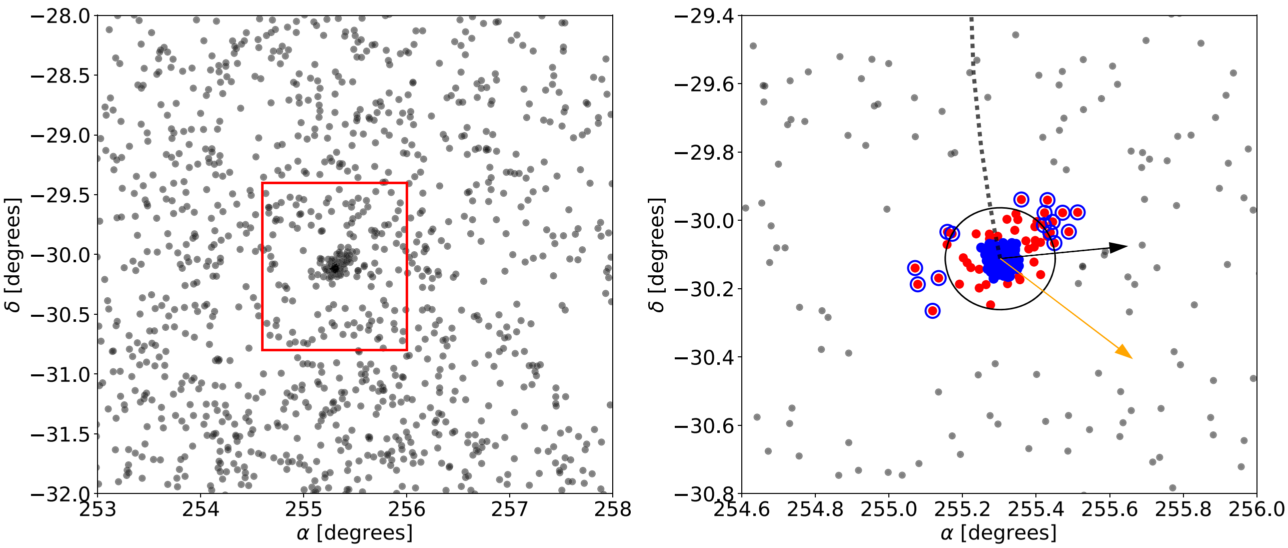

Figure 1. Left panel: large-scale distribution of RRLs (black dots) in the vicinity of the globular cluster M62. Right panel: zoom-in the M62 region (indicated by a red box in the left panel), showing individual RRL stars in our sample, with the cluster tidal radius overplotted. Most of the cluster RRLs are located within $5r_h \approx$ 5 arcmin of the cluster center (blue dots). The filled red circles designate RRLs with $K_s < 14.5$, while the blue open circles designate the RRLs outside the cluster tidal radius. The black and orange arrows point to the Galactic center and to the Galactic plane, respectively. The black dotted line curve is the orbital path of the cluster.

public survey (VVVX; Minniti et al. 2010; Saito et al. 2012). The latter are important to complement the existing optical observations that make difficult the search and interpretation of the possible tidal tails in the presence of differential reddening.

This Letter is organized as follows. In Section 2 we describe the data used for the discovery of extra-tidal RRL stars in M62. In Section 3 we present the M62 orbital models. In Section 4 we discuss the two dominant dynamical processes, dynamical friction versus tidal disruption. Finally, our conclusions are summarized in Section 5.

2. Discovery of Extra-tidal RRLs in M62

Recently, Clementini et al. (2018) presented the first all-sky map of RRL and Cepheid variable stars observed by the *Gaia* mission during the first 22 months of science operations, including new RRL discoveries. We explored these *Gaia* DR2 RRLs in the region surrounding the globular cluster M62. The density distribution of RRLs in the vicinity of this globular cluster is presented in Figure 1, which shows a clear and small extension of extra-tidal candidates extending from the cluster in the southwest to northeast direction, beyond the tidal radius of the cluster, ($R_t = 8.97$ arcmin, Harris 1996), and aligned $\sim 74°$ away from the predicted orbital path of M62 and roughly aligned ($\sim 19°$) toward the galactic center direction. It is very likely that the tidal tails visible in Figure 1 are the results of bulge shocking and likely related to its strong interaction with the Galactic bar.

Using the *Gaia* RRL catalog of Clementini et al. (2018), we measure a background density of bulge RRLs of $N = 71 \pm 6$ RRL/sq. deg. in a 2 sq. deg. field surrounding the cluster. We find an excess of a dozen RRLs beyond the tidal radius of M62, in a region where fewer than three RRLs were expected. Arguably, this is only a $\simeq 3\sigma$ result with small number statistics, but the asymmetry is even more marked if we consider stars inside of the tidal radius. For example, considering stars outside $2/3\ r_t = 6r_h$ from the cluster center, we count 8 RRLs in the southwest direction of the cluster and 25 in the northeast direction of the cluster (versus 5 expected field RRLs for the same area).

The total number of M62 RRLs is $N = 209$ (Contreras Ramos et al. 2010), most of which are located inside $5r_h \approx$ 5 arcmin of the cluster center (Figure 1). Therefore, the RRL excess is significant, of the order of $\sim 10\%$ of the total, and this is probably a lower limit because of the projection effect of the cluster orbital inclination. Apparently, if all of these are RRLs extracted from the cluster it would be a significant effect, as it would imply that the future survival of M62 is restricted to a few Gyr. However, careful modeling is needed in order to predict the future orbital decay in the presence of the cluster mass loss.

The field of M62 exhibits significant differential reddening (e.g., Minniti et al. 1992; Contreras Ramos et al. 2005; Alonso-García et al. 2012), and the variable extinction may severely diminish the capacity to recognize extra-tidal stars. In order to check for the effects of differential reddening we inspect the NIR photometry of the VVVX survey. Figure 2 shows the reddening corrected optical-NIR color–magnitude and color–color diagram for this cluster, covering a region inside its tidal radius. Overplotted are the *Gaia* RRL stars in the field, discarding the background RRLs with $K_s > 14.5$. It is important to determine that this RRL excess is not a chance alignment of stars along the line of sight. Because RRLs are primary distance indicators, they are optimal tracers as the photometry can confirm that they are located at the distance of M62, $D = 6.9$ kpc (Harris 1996).

RRL variable stars show periodic variations in their magnitudes and colors, which account for the observed scatter, because the color–magnitude and the color–color diagrams are based on single-epoch NIR photometry. Figure 2 also shows that the influence of reddening is not significant in this RRL sample.

We have to characterize the extra-tidal RRL in M62 in order to check if they belong mostly to the field or to the cluster, or to

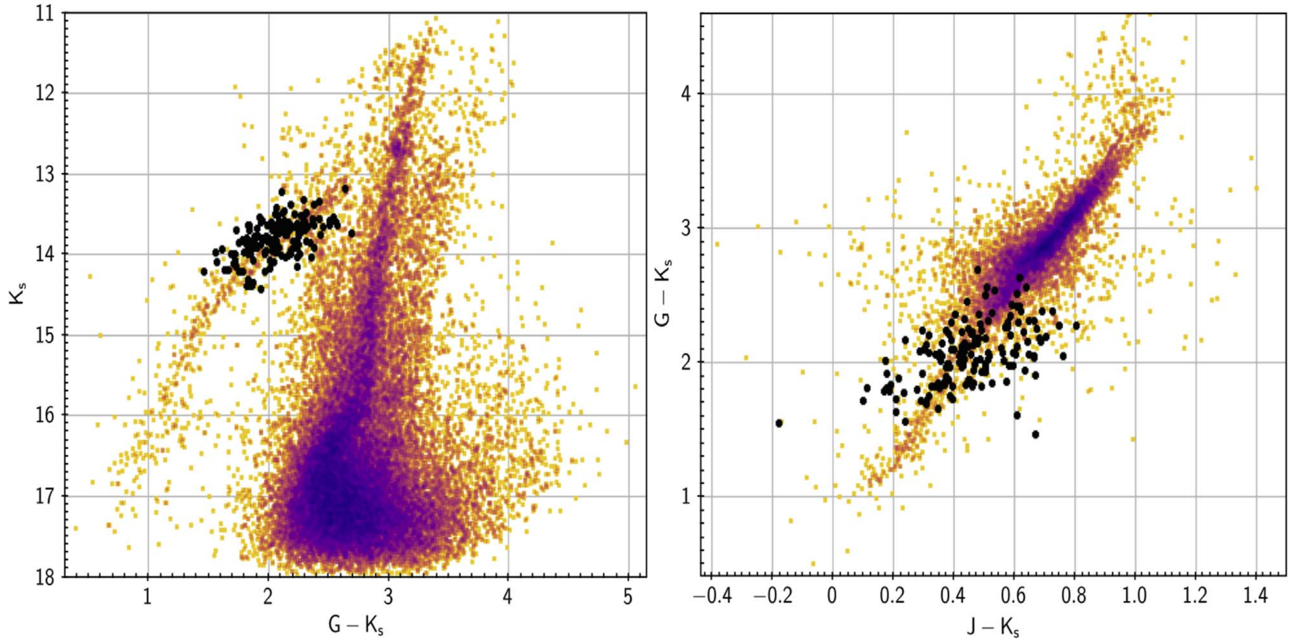

Figure 2. Left panel: optical-NIR color–magnitude diagram of M62 from the VVVX survey, after correcting from differential reddening using the extinction maps in Alonso-García et al. (2012). The *Gaia* RRL with VVVX photometry are overplotted as large black circles. Right panel: optical-NIR color–color diagram of M62 from the VVVX survey, overplotted with the *Gaia* RRLs (large black circles). The observed RRL scatter in these diagrams is due to the fact that the VVVX NIR photometry comes from single-epoch observations, and that their photometry is not corrected for differential reddening.

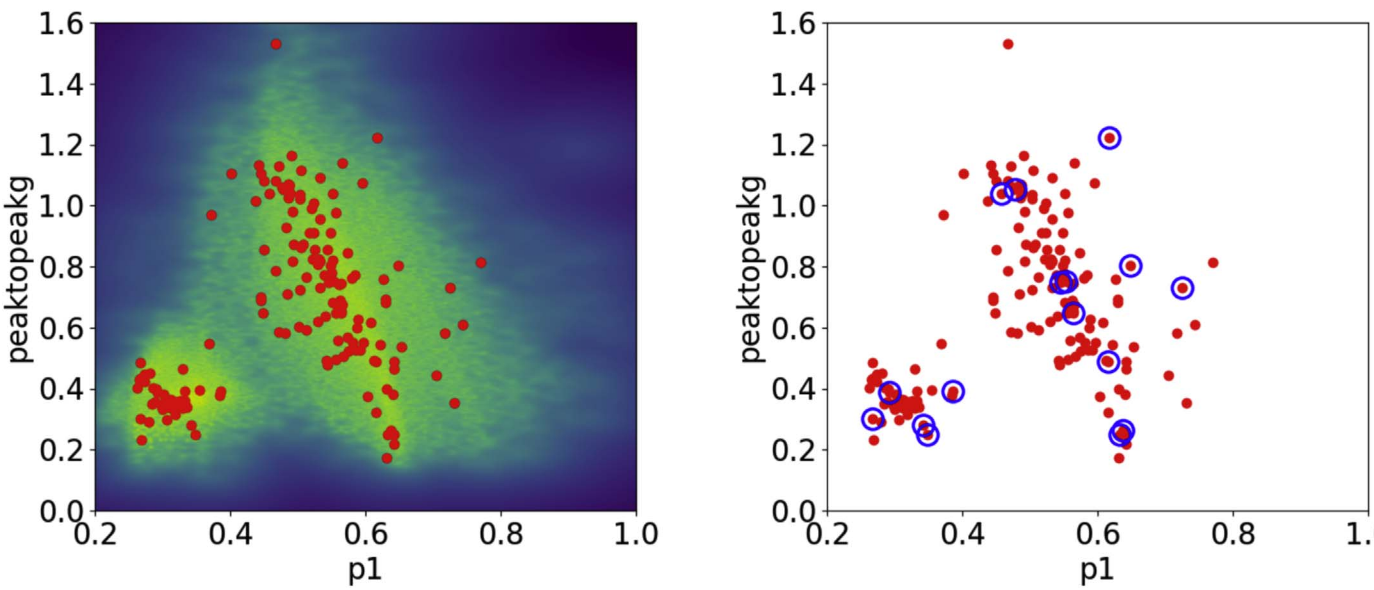

Figure 3. Left panel: kernel density estimate (KDE) smoothed distributions of the amplitude vs. period for field RRL stars from *Gaia* DR2 data (see Clementini et al. 2018) with the M62 RRLs (red dots) in our sample overplotted. Right panel: comparison of the Bailey diagram for stars in the main body of M62 (red dots) with the RRLs located outside of the tidal radius of the cluster (blue open circles).

a combination of both. In the case of tidal disruption, we expect that they belong to the cluster. In order to characterize the extra-tidal RRL, we compare them with the field and cluster RRLs using the color–magnitude, the color–color, and the period-amplitude (Bailey) diagrams (Figures 2 and 3). These comparisons, however, are not conclusive, as it is clear from these diagrams that the parameters of the M62 RRLs are similar to those of the field stars. This situation would improve and a better discrimination between cluster and field stars will be possible when the final *Gaia* data release delivers more accurate individual RRL proper motions (PMs) in a few years.

3. The Orbit of M62

Having found a clear excess of extra-tidal RRLs in M62, it is important to determine the cluster orbit in order to seek for possible explanations for this feature. Dinescu et al. (2003) measured the PMs and computed the orbit for this cluster, finding a prograde orbit confined to the bulge. In this section we recompute the orbit, using the new *Gaia* PM data, and the novel Galaxy modeling algorithm `GravPot16`[10] (J. G. Fernández-Trincado et al., in preparation).

[10] https://Fernández-trincado.github.io/GravPot16/

We have integrated the orbits following similar procedures that we have applied elsewhere (Fernández-Trincado et al. 2016a; Contreras Ramos et al. 2018), using four different bar pattern speed values ($\Omega_{\rm bar} = 35,\ 40,\ 45,\ 50\,{\rm km\,s^{-1}}$) and the same dynamical model configuration as described in Contreras Ramos et al. (2018). Figure 4 shows the central values of the orbits, revealing that M62 is a globular cluster that is trapped in the Galactic bar structure, and in resonance, as shown by the boxy orbital structure in the *X*- versus *Y*-plane. Figure 5 shows the time evolution of the vertical component of the angular momentum L_z in ${\rm km\,s^{-1}\,kpc^{-1}}$, where negative L_z in our reference system means that the cluster orbit is prograde (in the same sense as the disk rotation), confirming that the cluster is dynamically trapped into the bar potential. We have also computed Monte Carlo simulations using the range of input uncertainties, for two different sets of initial configurations (radial velocities and PMs). For the orbital results shown in Figure 4, we have used the following initial inputs: $\mu_{\rm R.A.} = -4.96 \pm 0.01\,{\rm mas\,yr^{-1}}$, $\mu_{\rm decl.} = -2.96 \pm 0.01\,{\rm mas\,yr^{-1}}$, $V_r = -71.0 \pm 0.7\,{\rm km\,s^{-1}}$, and $D = 6.9$ kpc, estimated from 53 selected cluster members[11] with available PMs and radial velocity from *Gaia* data. We have also run the same simulations using slightly different inputs taken from (Gaia Collaboration et al. 2018b), e.g.,: $\mu_{\rm R.A.} = -5.33 \pm 0.01\,{\rm mas\,yr^{-1}}$, $\mu_{\rm decl.} = -2.98 \pm 0.01\,{\rm mas\,yr^{-1}}$, and $V_r = -74.9 \pm 0.8\,{\rm km\,s^{-1}}$, but find that the results do not change at all. In addition to overall agreement between the inputs adopted in this work and Helmi's values, our results also agree remarkably well with the more recent measurements of PMs and radial velocity for M62, e.g.,: $\mu_{\rm R.A.} = -5.06 \pm 0.01\,{\rm mas\,yr^{-1}}$, and $\mu_{\rm decl.} = -3.02 \pm 0.01\,{\rm mas\,yr^{-1}}$ from Vasiliev (2018). We note that the computed orbital elements are similar, even adopting the recent available inputs of M62, and therefore do not affect the results presented in this Letter.

The Monte Carlo solutions confirm that the cluster is trapped in the structure of the bar, independently of the adopted bar pattern speeds. Changing the bar pattern speed changes the resonance orbital family (Figure 4), but the cluster remains trapped into the bar potential. We added a white star symbol to indicate the present cluster position, and a square to show the end position after the integrations.

Figure 5 also shows the variation of the cluster Galactocentric distance R_G with time, starting from the initial position to a fraction of the orbit integration time. The cluster has recently passed through the apogalacticon, the most distant point along its orbit, and is now heading for perigalacticon. Although this cluster is presently located at $R_G = 1.7$ kpc, it can get as close as $R_{\rm peri} = 0.2$ kpc from the Galactic center during its orbital motion. The cluster tidal disruption and mass loss would be critical during these perigalactic passages. However, we have not considered mass loss that may be considerable and would produce orbital delay for the cluster. A full exploration of M62 models, including the possible effects of dynamical friction and tidal evaporation, is warranted.

4. Discussion

The small extra-tidal extension of RRLs observed beyond the tidal radius of M62 is roughly (∼19°) aligned toward the galactic center and the direction almost perpendicular to the galactic plane and not with its motion along its orbit. Given its position in the Galaxy, this cluster is probably suffering a strong bulge shocking, with the tail almost aligned toward the tidal directions after being compressed during the crossing by its perigalacticon. They are therefore much less likely to be field stars associated to the so-called gravitational wake effect that exerts a drag force that slows down the cluster motion (Tremaine & Weinberg 1984; Capuzzo-Dolcetta & Vicari 2005; Arca-Sedda & Capuzzo-Dolcetta 2014).

In the particular case of M62, we see a concentration of stars aligned ∼74° away from the predicted orbital path of M62 (Figure 1), as expected of tidally stripped cluster stars (e.g., Fernández-Trincado et al. 2015, 2016b), with a huge extension in the northeast part, possibly attributed to that they do not all escape from a single Lagrange point on the edge of the cluster.

Weighting all that evidence, we conclude that the extra-tidal excess of RRLs seen in Figure 1 is indeed a signature of tidal debris around M62 caused by tidally stripped stars in the bulge region. It is very likely that the tidal tails of M62 are the relics of the bulge shocking from the last passage close to the galactic center.

This globular cluster, therefore, is a prime target to compute detailed dynamical models, in order to estimate its survival time before it is dragged into the innermost Galactic region. This finding supports the idea of the former globular cluster member stars have been indeed recently found in the inner bulge (Fernández-Trincado et al. 2017; Schiavon et al. 2017), suggesting that tidal effects in the Galactic bulge could have been efficient over time.

In addition, using future measurements of individual radial velocities in combination with the PMs measured by *Gaia*, would make it possible to compute the dynamics of the individual stars surrounding this cluster. Unfortunately, the recent M62 radial velocity measurements of Kamann et al. (2017) are all located inside of the cluster tidal radius. Also, it would be important to map different stellar tracers (such as red clump giants and BHB stars) in a large field around M62 in order to search for more extended tidal tails. This would be a daunting task, owing to the differential reddening and high stellar field density.

5. Conclusions

The RRL-rich globular cluster M62 is one of the most massive globular clusters in the Milky Way. It is located in the dense bulge region, deep in the Galactic potential well where dynamical processes that affect the survival of globular clusters are maximized.

Using *Gaia* DR2 RRLs from Clementini et al. (2018), we have found clear evidence for an excess of stars beyond its tidal radius. This is confirmed with new VVVX observation that discard any differential reddening effects as the possible cause of the observed stellar density excess. This extra-tidal excess can be interpreted either as the detection of the cluster "tidal tails," or as dissolving cluster stars due to tidal forces inside the bulge, and particularly evidence of bulge shocking.

We determined the orbit of M62 using accurate new measurements of its distance, radial velocity, and PMs. We find that its orbit is prograde and confined to the Galactic bulge, in agreement with the earlier results by Dinescu et al. (2003). In addition, we find that M62 is probably trapped in a resonance orbit within the Galactic bar. This orbital configuration within the dense bulge region, along with the cluster mass and velocity, would maximize the effects of bulge shocking.

[11] A two-dimensional Gaussian smoothing routine was applied in PM space for stars with $g < 17$ mag. Two samples are computed: all stars within twice the cluster radius and stars outside the cluster's radius, then the outside sample is subtracted from the full sample. A 2D Gaussian is fit to the remaining peak and membership probabilities are assigned.

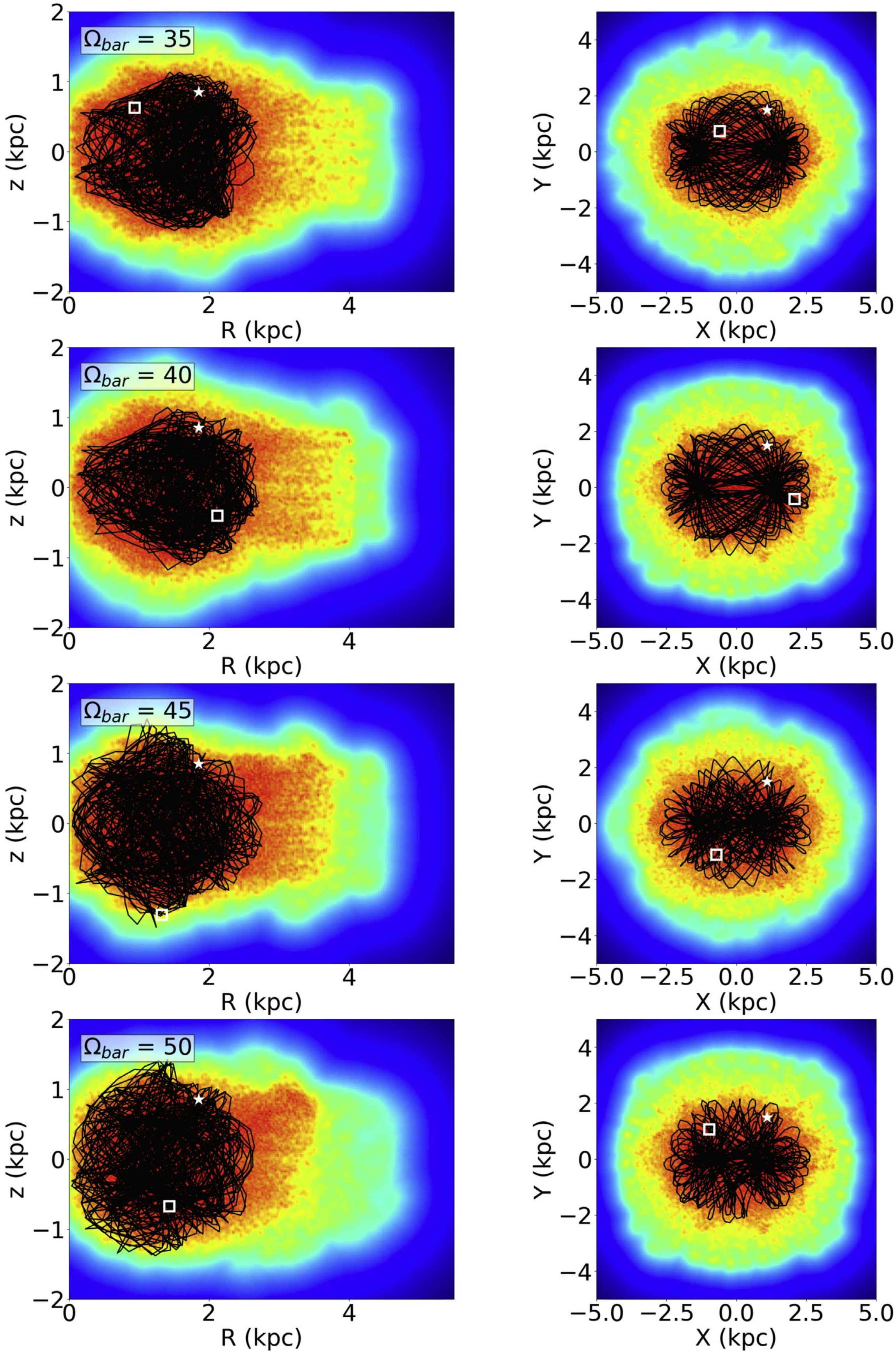

Figure 4. Orbital simulations for the globular cluster M62 in the z vs. R_G (left) and y vs. x (right) planes. The small white star marks the present position of the cluster, and the white square marks its final position. The solid black lines show the central orbital values, while the colored regions show the wider range of allowed orbits taking into account the errors in the initial parameters.

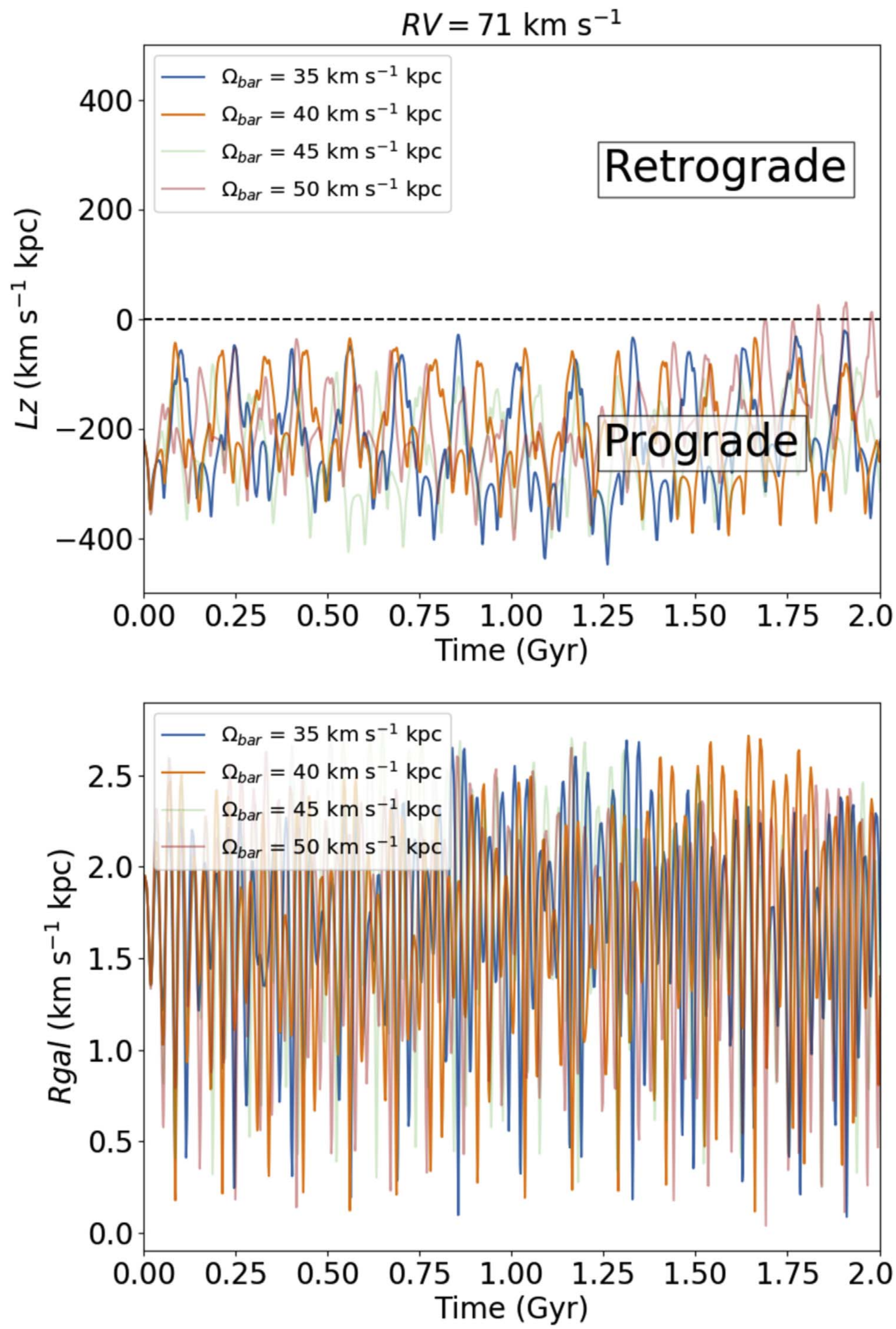

Figure 5. Top panel: time evolution of the vertical component of the angular momentum L_z in km s^{-1} kpc^{-1} for the M62 orbital integrations, showing that the orbit remains prograde at all times. Bottom panel: time evolution of the M62 Galactocentric distance R_G in kpc for the orbital simulations with different bar pattern speeds, as labeled. The cluster gets very close to the Galactic center (R_G 0.2 kpc) periodically.

We weighted the observational evidence against the possible dominant dynamical process that affects the survival of massive clusters in the inner regions of the Milky Way: tidal disruption. While the more feasible interpretation of the observed RRL excess as possible tidal tails cannot be ruled out, we argue that tidal disruption due to bulge shocking not too far from the Galaxy center is the best explanation in this case. This is because of the observed asymmetry in the RRL distribution that is opposite to the cluster motion, and because the tails are elongated mainly along the galactic density gradient.

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