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On the origin of the clumpy streams of Palomar 5

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Abstract. In this paper we report a study (see Mastrobuono-Battisti et al., 2012) about the formation and characteristics of the tidal tails around Palomar 5 along its orbit in the Milky Way potential, by means of direct N-body simulations and simplified numerical models. Unlike previous findings, we are able to reproduce the substructures observed in the stellar streams of this cluster, without including any lumpiness in the dark matter halo. We show that overdensities similar to those observed in Palomar 5 can be reproduced by the epicyclic motion of stars along its tails, i.e. a simple local accumulation of orbits of stars that escaped from the cluster with very similar positions and velocities. This process is able to form stellar clumps at distances of several kiloparsecs from the cluster, so it is not a phenomenon confined to the inner part of Palomar 5's tails, as previously suggested.

Key words. Galaxy: halo – (Galaxy:) globular clusters: individual: Palomar 5 – Galaxy: evolution – Galaxy: kinematics and dynamics – Methods: numerical

1. Introduction

Palomar 5 (Pal 5) is an outer Milky Way globular cluster (GC) which presents some peculiar characteristics: a very low mass, $M_{tot} = 5 \times 10^3 M_{\odot}$, a large core radius, $r_c = 24.3$ pc, and low central concentration, c=0.66 (see Odenkirchen et al., 2002). Moreover, it is surrounded by two massive tidal tails emanating from opposite sides of the cluster and populated by stars escaped from the system (Odenkirchen et al., 2001, 2003; Grillmair & Dionatos , 2006; Jordi & Grebel, 2010). With an overall detected extension of 22° on the sky, corresponding to a projected spatial length of more than 10 kpc, Pal 5's tails are so elongated and massive that they contain more stellar mass than the one currently estimated to be in the system itself (Odenkirchen et al., 2003). Pal 5's streams are characterized by the presence of inhomogeneities: stellar density gaps (underdense regions) and clumps (overdense regions) are particularly visible in the trailing stream, with the most evident and massive overdensities found between 100 and 120 arcmin from the cluster center (Odenkirchen et al., 2003). As Capuzzo-Dolcetta et al. (2005) and Di Matteo al. (2005) showed, the presence of similar substructures in globular cluster tidal

Send offprint requests to: A. Mastrobuono-Battisti tails can be related to kinematic effects and local decelerations in the motion of stars, later identified by K*ü*pper et al. (2008, 2010, 2012) and Lane et al. (2012) as "epicyclic cusps", i.e. regions where stars escaping from the cluster slow down in their epicyclic motion, as seen in the cluster reference frame. However, while all these works were successful in showing that complex morphological substructures can be formed in the tidal streams of globular clusters, until now no simulation or model has been able to reproduce convincingly the only stellar clumps robustly observed in the tails of a Galactic GC: those of Pal 5. Even in the most complete numerical study of Pal 5's stellar streams realized in the last years, Dehnen al. (2004) have not succeeded in reproducing the clumpy nature of the stream. This lead them to propose that the observed clumps may be the effect of Galactic substructures (as giant molecular clouds or dark matter subhalos) not accounted to in their simulations. The hypothesis that the gravitational effects of dark subhalos can generate a complex morphology in tidal tails, with overdensities and gaps, has been recently confirmed by Yoon et al. (2011). However, in the results presented by Mastrobuono-Battisti et al. (2012) and summarized in this paper, we show that the inhomogeneous tails of Pal 5 can be reproduced also without invoking any lumpy dark halo, just as an effect of epicyclic motion of stars.

2. Models and initial conditions

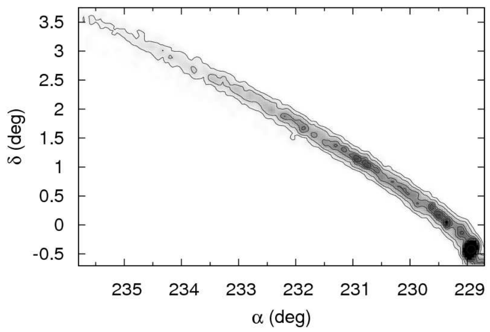
2.1. N-body simulations and restricted three-body methods

We used N-body, direct summation simulations to investigate the formation and characteristics of Pal 5's tidal tails (see Mastrobuono-Battisti et al., 2012, for more details). To run the simulations we used a modified version of NBSymple (Capuzzo-Dolcetta et al., 2011), a high performance direct N-body code implemented on a hybrid CPU+GPU platform. In this code, the effect of the external galactic field is taken into account by mean of an analytical representation of its gravitational potential (see Sect. 2.2). To smooth the mutual interaction between particles we adopted a softening length, $\varepsilon = 0.03$ pc. The time integration of the particles trajectories was done using the second-order leapfrog method. The average relative error per time step was less than 10^{-13} for the cluster both isolated or in the Galactic potential. The result of the N-body simulations were compared to simplified, restricted three-body models, where we used the same initial conditions adopted to run the simulation but, at each time step, instead of considering the mutual interactions, we evaluated the interaction with the global gravitational potential of the cluster and with the Galactic potential for each particle. Finally, similar to Lane et al. (2012), we produced streaklines to visualize in a more clear way the spatial distribution, at the present time, of stars that have escaped from Pal 5 in the last Gyrs. To do so, we integrated the orbit of a point mass representing Pal 5 barycenter, and, at each time step, released two particles at distance $r_{\rm max} = 120$ pc from it, along the instantaneous Galactic center and anticenter directions, and with a velocity equal to that of the cluster. The motion of these escapers is integrated in time, taking both the effects of the GC and Galactic potential into account.

2.2. Globular cluster and Galaxy models

The Galactic potential is from Allen & Santillan (1991), whose model consists of a spherical central bulge and a flattened disk, plus a massive *smooth* spherical halo. For the GC we adopted the parameters of the "model A" described by Dehnen al. (2004) which consists of a single-mass King model (King, 1966) with tidal radius $r_t = 56$ pc, $W_0 = 2.75$, and $M_0 = 2\times10^4\,M_\odot$; we used $N = 15360$ particles for the N-body representation of this model.

To obtain the orbital initial conditions, we integrated a test particle with Pal 5's present position and velocity backward in time for the same time interval as chosen by Dehnen al. (2004), i.e. 2.95 Gyr, in the Galactic potential. Then we translated the positions and velocities of the King model to coincide with those of the cluster barycenter 2.95 Gyr ago, and we integrated the whole cluster 2.95 Gyr forward in time.



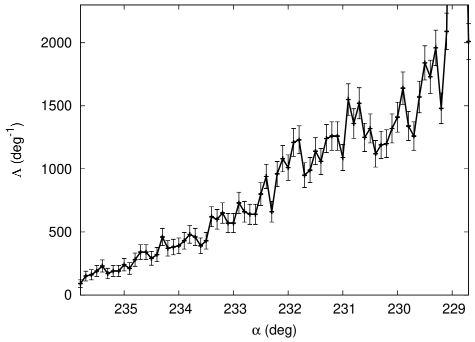


Fig. 1. Upper panel: The trailing tail at the end of the N-body simulation. The contour lines in the tails refer to 740, 2200, 4800, 6300 and 7400 $M_{\odot}/deg^2$. Bottom panel: Linear density of the trailing tail shown in the upper panel, as a function of the right ascension α. The cluster is on the right of the panel. Error bars are Poisson errors. From Mastrobuono-Battisti et al. (2012).

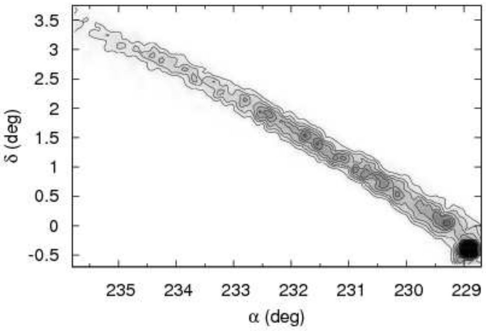


Fig. 2. The trailing tail of the cluster in the restricted three-body model. The contour lines in the tails refer to 470, 940, 1410, 1970, 2500 and 3300 $M_{\odot}/deg^2$. From Mastrobuono-Battisti et al. (2012).

3. Results and discussion

During its evolution, the simulated cluster has lost the most of its initial mass (88%), now redistributed into two long and narrow tidal tails. This tails are only apparently smooth: as it becomes evident plotting the cluster isodensity contours, their structure is actually complex and the stellar distribution is clearly inhomogeneous. In particular, as shown in the upper panel of Fig. 1, the densest substructures are all localized in the trailing tail. In this tail, our N-body simulation predicts there are two prominent density enhancements: the first located very close to the cluster (α < 230°) and the second starting at α=230.5° and ending at α=232°. The second region shows an underdense region in it, whose extension is ~ 0.5°. All these characteristics, at the same location, are also found in the observed streams (see Fig. 3 in Odenkirchen et al., 2003). Not only does the position of these clumps closely resemble the location of those observed in Pal 5's tails, but their linear densities (bottom panel of Fig. 1) – 2–3 times above the density of the surrounding streams – and the presence of underdense regions, with sizes of 0.5°-1°, also agree with those measured for Pal 5 (see Fig. 4, Odenkirchen et al., 2003). As shown in Fig. 2, these substructures are also visible in the isodensity contours of the simplified numerical model, at few degrees from the cluster center. These regions of over- and underdensities are due to the epicyclic motion of stars escaping from the cluster: stars lost at different times redistribute along the tail following a complex path, as shown by the streaklines in Fig. 3. This kinematic process, described and studied in a number of papers (K*ü*pper et al., 2008, 2010, 2012; Lane et al., 2012), is applied here for the first time to reproduce observed stellar streams, including both the position and the intensity of the observed stellar inhomogeneities. The epicyclic motion is thus able to form over- and underdensities in sev-

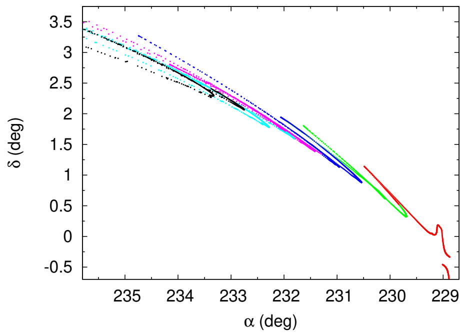


Fig. 3. Streaklines which show the positions, at the present time, of stars that have escaped from Pal 5 in the last 2.95 Gyrs. Different colors correspond to stars lost during different time intervals of 0.5 Gyr. From Mastrobuono-Battisti et al. (2012).

eral regions of the tails, at a variety of distances from Pal 5. If the orbit is integrated over longer times (~8 Gyr), streaklines indeed show that epicycle loops also form at distances of several kpc from the center. Moreover, since these substructures are also reproduced in models where the mutual gravity is neglected, it is possible to rule out Jeans instability as a possible mechanism responsible for their formation, as suggested by Quillen & Comparetta (2010).

4. Conclusions

We have studied the formation and characteristics of the tidal tails of the GC Pal 5 along its orbit in a smooth Milky Way potential by means of N-body simulations and simplified numerical models. For the first time, we were able to reproduce the observed inhomogeneous structure of Pal5's tidal tails using N-body simulations, without including any lumpiness in the Galactic halo. The epicyclic motion of stars along the tails is the main mechanism responsible for the formation of clumps. This result must be taken into account when using streams inhomogeneities to evaluate the granularity of the Milky Way dark halo.

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