UNCOVERING THE NATURE OF TIDAL TAILS IN PALOMAR 14

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Abstract. We have detected in deep CFHT images a pair of tidal tails extending over one degree around the distant globular cluster Palomar 14. Their characteristic S-shape and association with an extended power-law departure from the usual density profile makes this surprising detection unambiguous. We briefly discuss the mechanisms that could give rise to these tails at such large galactocentric distances and the implications for the nature of this globular cluster.

Keywords: globular clusters, stellar populations, galaxy, galactic halo, statistical methods

1 Introduction

Palomar 14 stands out as one of the most interesting globular clusters of the outer Galactic halo. Faint, extended, sparse but distant, it turns out to be an ideal site for testing gravitation in the weak acceleration régime (Baumgardt et al. 2005; Jordi et al. 2009; Sollima & Nipoti 2010; Küpper & Kroupa 2010). The properties of this globular cluster are therefore essential to assess the suitability of the system to test gravitation at these scales.

Discovered in 1960 (Arp and van den Bergh 1960), it was soon established as being distant (~ 70 kpc) and relatively metal rich ([Fe/H]~ -1.5) for a globular cluster in the outer halo.

At this large distance, SDSS data (e.g. Jordi and Grebel 2010) appear to be too shallow to detect faint features, as they can only probe the sparsely populated upper RGB. Deep observations, reaching well below the turn off, are required, as well as over a wide field (e.g. Chun et al. 2010).

Within the framework of a systematic campaign to explore the outer Galactic halo (Martínez Delgado et al. 2004), we have carried out CFHT observations of a series of clusters to disentangle internal evolutionary effects (stellar mass loss, binary heating, two-body relaxation) from external effects (tidal shocks, tidal stripping). Both effects lead to the eventual disruption of the cluster through a continuous loss of stars, which may be forming characteristic tails around the cluster. Naively, one would expect these tails to be more important at small galactocentric distances, as indeed observations have revealed in an increasingly larger fraction of globular clusters (Grillmair et al. 1995; Leon et al. 2000; Odenkirchen et al. 2001, 2003; Grillmair & Dionatos 2006; Belokurov et al. 2006; Zou et al. 2009).

2 Tidal tails in Palomar 14

Our CFHT observations of Palomar 14, covering a wide area to a depth comparable with previous HST observations (Dotter et al. 2008), reveal a pair of tails, extending over one degree (see Fig. 1), and Sollima et al. 2011, for details). Using the isochrones from Marigo et al. (2008) and adopting as priors the observed metallicity [Fe/H]$=-1.6$ (Armandroff et al. 1992) and [α/Fe]$=+0.3$ Ferraro et al. (1999), we used the Bayesian inference method developed by Hernandez & Valls-Gabaud (2008) to measure the maxima of the marginalised posterior distribution probability functions of age ($t = 13.2 \pm 0.3$ Ga) and distance ($d = 71 \pm 2$ kpc).

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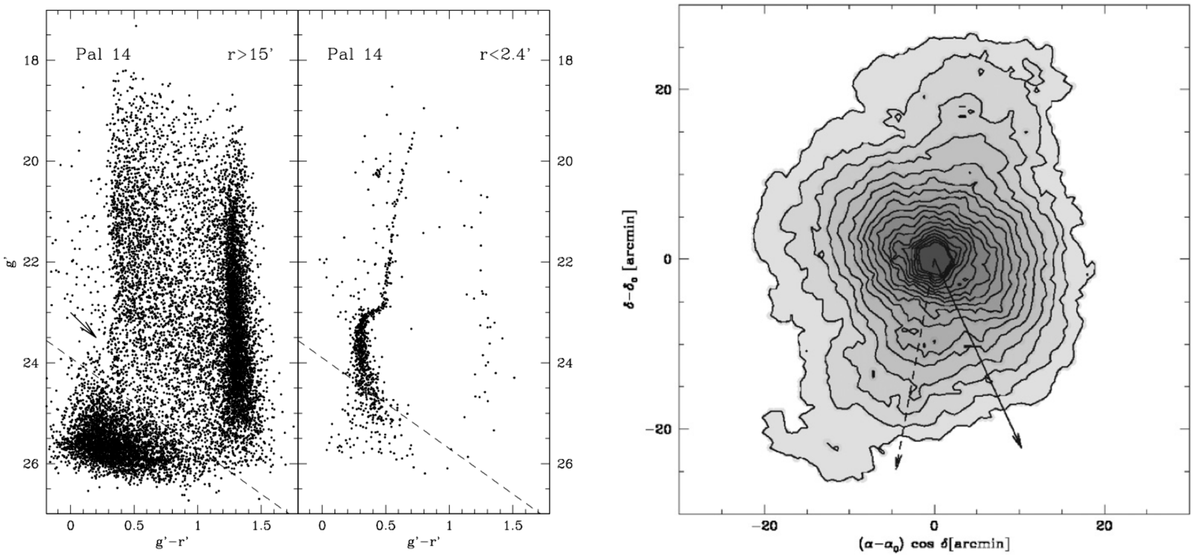

Fig. 1. *Left*: Colour-magnitude diagram (CMD) of Palomar 14. The right panel shows the CMD of the inner area within 2$'\!.$4, while the left panel presents the CMD of stars lying beyond a radius of 15$'$ from the centre. The arrow indicates a subtle excess of stars just below the turn off region. The dashed line is the approximate boundary where DAOPHOT does not discriminate between stars and (compact) galaxies. *Right*: Adaptively-smoothed maps of the stellar density around Palomar 14, from 3 to 20 times the average dispersion in background number counts using a matched filter provided by the inner CMD of Pal 14. The solid arrow gives the direction of the Galactic centre, while the dashed arrow shows the predicted proper motion direction in the Lynden-Bell & Lynden-Bell (1995) scenario where Pal 14 belongs to a stream with Fornax and Pal 15. See Sollima et al. (2011) for further details.

The density profile extends the one obtained by Trager et al. (1995) and McLaughlin & van der Marel (2005) and reveals that while the core radius remains unchanged by our observations, both the maximum Roche lobe radius and tidal radius are increased nearly four-fold. The maximum Roche radius, assuming the Galatic potential from Johnston et al. (1995), the above mentioned distance, total mass of 15,500 $M_{\odot}$and radial velocity of 72.3 km s^{-1}(Jordi et al. 2009), turns out to be 8$'\!.$2, much less than the estimated tidal radius of about 25$'$and implies that a substantial amount of stars will be lost along the orbit. The half-light radius is almost twice larger than previous measures (2$'\!.$23$\pm$0$'\!.$14 versus 1$'\!.$22). There are only 9 clusters in the updated list by Harris (1996)* which have larger half-light angular radii (NGC 5139, 5$'\!.$0; NGC 4161, 4$'\!.$33; NGC 4372, 3$'\!.$91; Terzan 1, 3$'\!.$82; NGC 104, 3$'\!.$17; NGC 3201 and HP 1, 3$'\!.$10; NGC 6366, 2$'\!.$92; Pal 5, 2$'\!.$73). Given the distance of Palomar 14, however, this scale translates into a linear radius of 46.1$\pm$2.9 pc, which makes it the largest in physical terms within the Milky Way. In fact, combined with its luminosity of 8130 $L_{\odot}$, this revised measure makes Pal 14 to stand as a transition object filling in the gap between the positions of classical globular clusters of the Milky Way and the ones of its satellites (see Fig. 9 and its discussion in Sollima et al. 2011).

We also detect a clear power-law extension from the classical profile (Plummer 1911), from about 10$'$ to 25$'$, with an exponent of -1.6 which is very similar to the one measured in several clusters (e.g Grillmair et al. 1995; Leon et al. 2000; Testa et al. 2000; Lee et al. 2003) as well as in numerical simulations (Johnston et al. 1999).

We used a matched filter algorithm (Rockosi et al. 2002) to quantify the extension and direction of the tails, through an adaptive density estimation (Silverman 1986), and a new statistic based on the ratio of Poisson number counts (Cerviño & Valls-Gabaud 2003). Fig. 2 shows the characteristic S-shape of tidal tails, where the inner isopleths appear twisted with respect to the outer ones in a way similar to the expectations from numerical simulations (e.g. Montuori et al. 2007; Peñarrubia et al. 2008; Klimentowski et al. 2009; Peñarrubia et al. 2009).

*2010 revision available at `http://physwww.physics.mcmaster.ca/~harris/mwgc.dat`

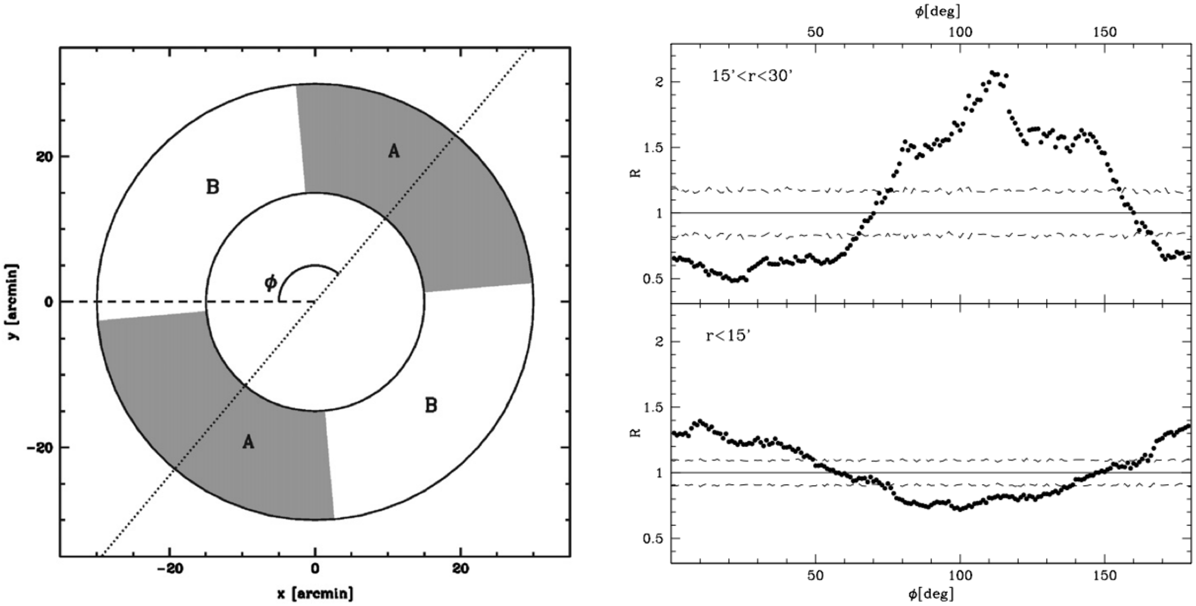

Fig. 2. *Left*: To assess the statistical significance of the anisotropic distribution of stars around Pal 14 (see Fig. 1), number counts in sectors A and B, oriented by an angle ϕ, are compared through the normalised ratio $\mathcal{R}(\phi) = (N_c^A\ N_f^B)/(N_f^A\ N_c^B)$ of counts in sectors A and B for field (f) and cluster members (c). *Right*: Dependence of the normalised ratio $\mathcal{R}$ as a function of position angle, for the inner (*bottom*) and outer (*top*) areas. The variation range for $\mathcal{R}$ around unity for an isotropic distribution is given by the dashed lines, which were obtained with 1,000 Monte Carlo simulations. In both the inner and outer areas, the test statistic is significantly larger than the null value for an isotropic distribution. Note that contiguous points are heavily correlated due to the common stars from one position angle to the next, yet the trend is unambiguous. Moreover, the maximum value in the inner area appears to differ in position angle by 100° to the one in the outer region, quantifying in a meaningful way the S-shape of the isopleths (Fig. 1). See Sollima et al. (2011) for further details.

3 Conclusions

An intriguing feature of the inferred isopleth map (Fig. 1 right), which characterises the typical S-shape of tidal tails detected in Palomar 14, is that the outer contours appear to be roughly in the proper motion direction expected in the cluster is part of a large-scale stream comprising Fornax and Palomar 15, as tentatively predicted by Lynden-Bell & Lynden-Bell (1995). Whether deeper observations will yield a better determination of the twisting of the outer isophotes and future measures of proper motions will confirm this association remain unclear at this point, yet we also note that Palomar 14 lies close to the large “disc of satellites” system which comprises most of the satellites of the Milky Way (e.g. Metz et al. 2009).

The ensemble of properties of Pal 14 reinforces this interpretation, which challenges the standard picture of globular clusters (Mateo 1998; Mackey & Gilmore 2004; Prieto & Gnedin 2008). Indeed, in the globular system of M31, new observations (McConnachie et al. 2009) have also revealed that most, if not all, of the globular clusters beyond a projected radius of about 30 kpc are associated with large coherent stellar streams (Mackey et al. 2010).

It would therefore not be very surprising if Palomar 14 provides further evidence within our Galaxy (e.g. Cohen et al. 2010) that outer halo globular clusters are part of a population that was accreted during the formation of the Milky Way.

Based on observations obtained with Megacam, a joint project of CFHT and CEA/DAPNIA, and processed in part with the TERAPIX facilities. This work was supported by grants MICINN/AYA2007-65090, CNRS/MAE PICASSO, and ANR POMMME (ANR 09-BLAN-0228).

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