Searching Gaia for extended structure in Globular Clusters

Pete B. Kuzma[iD], Annette M. N. Ferguson[iD] and Jorge Peñarrubia

Institute for Astronomy, University of Edinburgh, Blackford Hill,
Edinburgh, Scotland, EH9 3HJ
email: pbkuzma@roe.ac.uk

Abstract. A growing number of studies are revealing that many Milky Way globular clusters possess extended stellar structures beyond their traditional boundaries. Just how ubiquitous these structures are, and how they originate, are key questions to explore. In this contribution, we present a Bayesian technique that we have developed to separate probable members of globular clusters from the dominant Milky Way fore/background at large clustercentric radii and hence facilitate quantitative analyses of these intriguing structures. We demonstrate the promise of our method by showing how it recovers the known extended features around Palomar 5 and NGC 7089.

Keywords. globular clusters: general, globular clusters: individual (NGC 7089, Palomar 5), Galaxy: halo, surveys

1. Introduction

Over the last two decades, our understanding of globular clusters (GCs) as simple stellar populations has been transformed. Most, if not all, Milky Way (MW) GCs show various anticorrelations in light element abundances (e.g., Milone *et al.* 2017) which suggest complexity in either the early star formation or chemical enrichment histories of these objects. Equally intriguing is the fact that the more massive GCs in the MW are home to stellar populations that also vary in [Fe/H] and other heavy elements (e.g., Suntzeff & Kraft 1996; Milone *et al.* 2015). This has led several authors to suggest that these massive clusters could be the nuclear remnants of long since accreted dwarf galaxies (Bekki & Freeman 2003). Almost all studies of chemical anomalies have thus far focused on stars lying well within the traditional boundaries of GCs (i.e., $\lesssim$ 1-2 half-light radii) but an important question is whether new insight can come from studying chemical trends at larger radii.

Indeed, studies that shown that a number of GCs possess extended structures at large radii, reaching out to several half-mass radii in some cases. These peripheral structures are of very low surface brightness and were mostly elusive until the era of large synoptic surveys and deep wide-field imagers on large telescopes. Most extended structures detected to date fall into one of two classes. The first concerns tidal tails (e.g., Palomar 5 and NGC 5466; Odenkirchen *et al.* 2001; Belokurov *et al.* 2006) which are long thin structures that emanate from the cluster in diametrically-opposed directions and are typically closely aligned with the cluster orbit. These features are completely expected for clusters that are dissolving in a tidal field (e.g., Dehnen *et al.* 2004) although to date surprisingly few clear examples of this phenomenon are known.

The second type of extended structure seen around GCs is a diffuse spherical stellar envelope. These features have now been detected in several cases and appear particularly common around the more massive GCs of the MW (often the same objects which display

internal heavy element abundance variations) (Kuzma *et al.* 2016, 2018). These structures have not yet been fully-explored and remain poorly understood. Models of GC disruption fail to reproduce the size of the extended stellar envelopes detected around NGC 1851 or NGC 7089, leading some authors to suggest that these features could be evidence that these GCs were originally the nuclei of accreted dwarf galaxies (Bekki & Yong 2012). In a similar vein, Peñarrubia *et al.* 2017 suggest that the existence of an extended stellar component could be consistent with the presence of a dark matter halo surrounding the GC.

A much quantitative analysis of these outer GC structures is required in order to fully understand their ubiquity, nature and relationship to stars in the MW halo. A major challenge is the extremely low stellar density of GC outskirts and that fact that they are buried in a heavy veil of foreground/background contamination from MW field stars. The ability to separate probable cluster members from the MW contaminants by photometry alone is only partially effective. In 2018, the Gaia space mission had its second data release (DR2), which contains precision astrometry and photometry for over a billion stars (Gaia Collaboration *et al.* 2016, 2018). The addition of astrometry is particularly important for the identification of extended structures in GCs (e.g., Carballo-Bello 2019). Here, we present a Bayesian technique that we have developed to search for extended structures surrounding GCs with DR2.

2. Extended Structures with Gaia

Our method is based on a mixture model technique within a Bayesian framework. The goal is to identify stars residing up to many half-light radii that have spatial, kinematic and photometric properties that are consistent with GC membership. For the examples presented here, we start by retrieving all stars that reside within a four-degree radius of the target cluster and proceed to apply a number of data quality cuts to eliminate clear contaminants. In particular, we removed:

• field dwarf stars by excluding stars with a Gaia colour-index of $(G_{BP} - G_{RP}) > 1.6$ mag
  • very nearby stars (lying within 3 kpc) which have a well-measured parallax
  • stars with poor or no astrometric solution based on their re-normalized unit weight error†
  • stars fainter than $G_{Gaia} > 19.5$ mag.

Subsequently, we further select stars that lie within a few sigma of the appropriate cluster isochrone (Dartmouth Stellar isochrone; Dotter *et al.* 2008). While this photometric selection removes most of the field contamination in the vicinity of the cluster, there remains a non-negligible population of unrelated stars along any given sightline. Finally, we feed this remaining sample into our mixture model which takes the form of:

$$\mathcal{L}_{tot} = f_{cl}((1 - f_{ex})\mathcal{L}_{cl} + f_{ex}\mathcal{L}_{ex}) + (1 - f_{cl})\mathcal{L}_{mw} \tag{2.1}$$

where $\mathcal{L}_{cl/ex/mw}$ are the likelihood functions for the cluster, extended structure and MW foreground respectively and $f_{cl/ex}$ are the normalization factors between the 3 components. Each likelihood function contains both a proper motion component (modelled as a multi-variate Gaussian distribution) and a spatial distribution component. Concerning the latter, we utilise a King (1962) model for the cluster, a linear gradient for the foreground and a quadrupole-like distribution for the extended structure. The motivation for the choice of a quadrupole to model the peripheral structure is the flexibility it allows for the detection of either symmetrical tidal tails, an extended spherical envelope or no feature at all. The posterior distributions are computed using PyMultinest (Buchner *et al.*
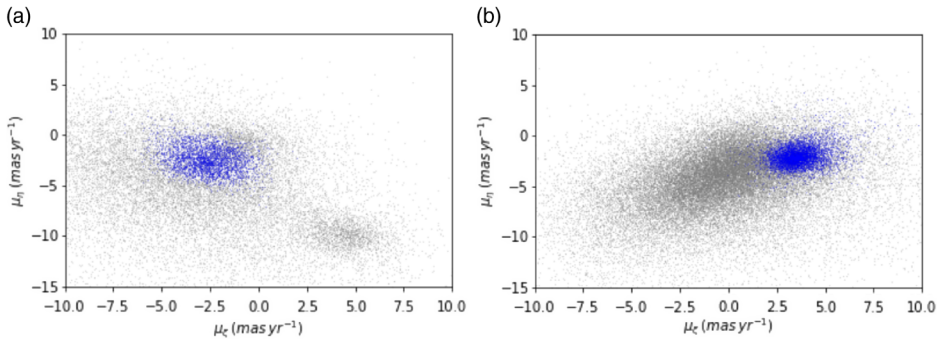
† See GAIA technical note GAIA-C3-TN-LU-LL-124-01

Figure 1. Proper motion distribution of photometricaly-selected stars for (a) Pal 5 and (b) NGC 7089. In blue are the stars with a $P_{mem} >= 0.3$ and in grey are stars with $P_{mem} < 0.3$. Each cluster is easily isolated with our method.
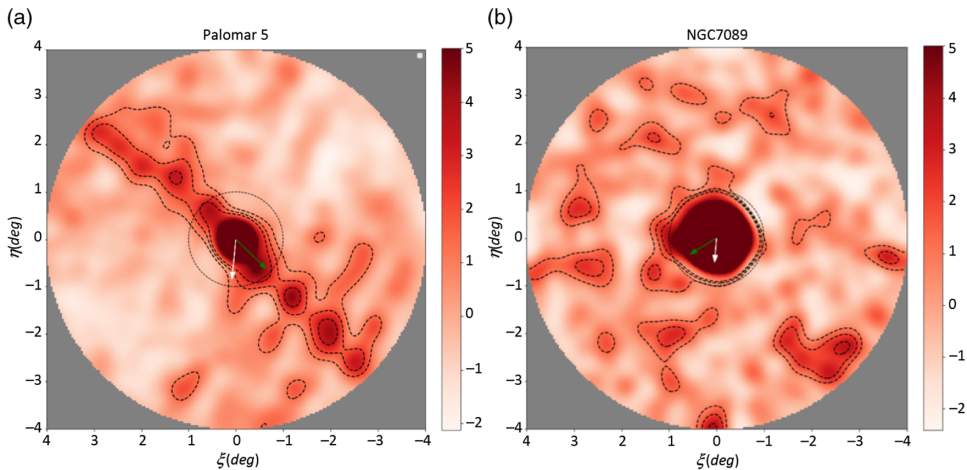

Figure 2. 2D surface density distributions of (a) Pal 5 and (b) NGC 7089. Green arrow indicates the direction of the proper motion and the white arrow indicates the direction of the Galactic center. A central 1 deg radii is shown by the dashed ring. In both cases, the known extended structures are clearly recovered.

2014), and are sampled in order to assign each star a membership probability, P_{mem} between 0 and 1, which is defined as:

$$P_{mem} = \frac{f_{cl}((1 - f_{ex})\mathcal{L}_{cl} + f_{ex}\mathcal{L}_{ex})}{\mathcal{L}_{tot}} \tag{2.2}$$

where a probability of 1 indicates a definite cluster or extended structure star and a probability of 0 indicates a definite field star.

To demonstrate this technique, we present our findings for the globular clusters Palomar 5 and NGC 7089. Both clusters have been previously-shown to possess extended structure: tidal tails in the case of Pal 5 and a diffuse stellar envelope in the case of NGC 7089. Fig. 1 shows how stars with a membership probability of 0.3 or more lie with respect to the contaminating field populations in proper motion space (after the photometric selection has been applied). Our technique successfully identifies the cluster population even when it is very entangled with the field, as seen particularly with Pal 5. The two-dimensional surface density distributions of highly probable members are shown in Fig. 2, and in the case of Pal 5, the tidal tails are clearly recovered. The observed

"gaps" or periodic over-dense regions along the tails largely reflect the scanning patter of DR2 and should be remedied in future data releases. The envelope of NGC 7089 is also recovered out to the known radius of ∼1 deg and we see no strong deviations from spherical symmetry out to the detected edge.

3. Future Work

We have presented a demonstration of our technique using data for Pal 5 and NGC 7089. We are now applying our technique to a much larger sample of MW GCs to build up a census of GC outer structures and identify a sample of particularly interesting objects for detailed follow-up work. Indeed, our method provides samples of peripheral stars that will be prime candidates for spectroscopic analysis. Upcoming instruments such as WEAVE and 4-MOST, which are high multiplex spectrographs subtending enormous fields of view, are perfectly suited for measuring radial velocities and chemical abundances for GC stars at large clustercentric radii and such data are crucial for a complete understanding of the nature and origin of these features.

Acknowledgements

References

Bekki, K. & Freeman, K. C. 1996, *MNRAS*, 346, L11
Bekki, K. & Yong, D. 2012, *MNRAS*, 419, 2063
Belokurov, A., Evans, N. W., Irwin, M. J., *et al.* 2006, *ApJ*, 637, L29
Buchner, J., Georgakakis, A., Nandra, K., *et al.* 2014, *A&A*, 564, A125
Carballo-Bello, J., 2006, *MNRAS*, 486, 1667
Dehnen, W., Odenkirchen, M., Grebel, E. K. *et al.* 2004, *AJ*, 127, 2753
Dotter, A., Chaboyer, B., Jevremović, D. *et al.* 2008, *ApJSS*, 178, 89
Gaia Collaboration *et al.* 2016, *A&A*, 595, A1
Gaia Collaboration *et al.* 2016, *A&A*, 616, A12
King, I., 1962, *AJ*, 67, 471
Kuzma, P. B., Costa, G. S., Mackey, A. D. *et al.* 2016, *MNRAS*, 461, 3639
Kuzma, P. B., Da Costa, G. S., Mackey, A. D. 2018, *MNRAS*, 473, 2881
Milone, A. P., Marino, A. F., Piotto, G., *et al.* 2015, *MNRAS*, 447, 927
Milone, A. P., Piott, G., Renzini, A., *et al.* 2017, *MNRAS*, 464, 3636
Odenkirchen, M., Grebel, E. K., Rockosi, C. M., *et al.* 2001, *ApJ*, 548, L165
Peñarrubia, J., Varri, A. L., Breen, P. G. *et al.* 2017, *MNRAS*, 471, L31
Suntzeff, N. B. & Kraft, R. P. 1996, *AJ*, 111, 1913