Star Clusters: From the Milky Way to the Early Universe
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Gaia results for star clusters and dwarf galaxies in the Milky Way

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Abstract. The second data release of the *Gaia* mission coupled with ground-based spectroscopic observations has allowed the determination of the orbital parameters for almost all of the Galactic globular clusters, as well as for the known dwarf spheroidal galaxies orbiting the Milky Way. Moreover, it has led to the discovery of dwarf galaxies that were accreted by the Galaxy long ago and that are now completely disrupted. By exploiting their dynamics in combination with the globular clusters age-metallicity relation, we investigated the clusters-to-dwarfs connection. We found that about 60 globulars likely formed *in situ*, and associated those that were accreted to the dwarf galaxy progenitor they likely formed in.

Keywords. Galaxy: globular clusters: general, Galaxy: kinematics and dynamics, Galaxy: evolution

1. Introduction

Determining the kinematic properties of the stellar systems orbiting around the Milky Way like globular clusters (GCs) or dwarf galaxies is a powerful tool to investigate their origin and evolution, as well as that of our Galaxy itself, but has so far been a major challenge.

The most difficult task has historically been the measurement of clusters and galaxies proper motions. These systems are typically located at large distances from us (Harris 1996; McConnachie 2012), and their proper motions are thus very small. Moreover, repeated observations well separated in time are required to detect a motion on the plane of the sky. This is why the first efforts in this direction appeared only in the 90's (e.g. Cudworth *et al.* 1992; Dinescu *et al.* 1999), and were based on ground-based instrumentation.

Thanks to its much better depth and resolution, the *Hubble Space Telescope* (HST) allowed astronomers to push these kind of studies to more distant clusters and galaxies (e.g. Piatek *et al.* 2002; Piatek *et al.* 2006; Sohn *et al.* 2012; Massari *et al.* 2013), and to measure their proper motions with precision of the order of few$\times$0.1 mas/yr.

However, it is with the advent of the second data release of the *Gaia* mission (Gaia Collaboration, Prusti *et al.* 2016; Gaia Collaboration, Brown *et al.* 2018) that an actual revolution took place. Thanks to its continuous scanning of the sky, proper motions with typical precision of one order of magnitude or more better than previously achieved have been systematically measured for almost all of the Galactic GCs (Gaia Collaboration, Helmi *et al.* 2018; Vasiliev 2019; Baumgardt *et al.* 2019), the known dwarf spheroidal (dSph) galaxies (Gaia Collaboration, Helmi *et al.* 2018) and several tens of Ultra-faint dwarf galaxies (Simon 2012; Fritz *et al.* 2018; Kallivayalil *et al.* 2018; Massari & Helmi 2018; Pace & Li 2019). The quality of Gaia data in combination with that of HST also

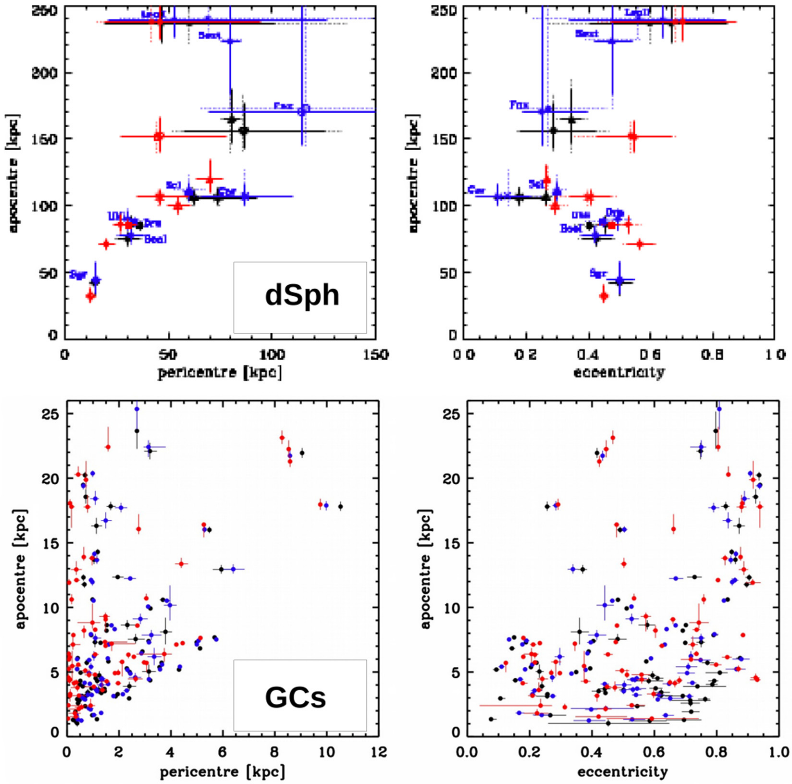

Figure 1. Orbital parameters of globular clusters (lower panels) and dwarf spheroidals (upper panels). Figure adapted from Fig. 20 and Fig. 22 of Gaia Collaboration, Helmi *et al.* (2018).

enabled to measure for the first time the internal 3D kinematic in two of the dSph satellites, namely Sculptor and Draco (Massari *et al.* 2018; Massari *et al.* 2020).

With this unprecedented data set in hand, it is now possible to determine the dynamical properties of GCs and dwarfs, and to look for features that could reveal a common origin. If so, GCs could effectively be used as powerful tracers of the assembly history of the Milky Way.

2. State-of-the-art

The combination of *Gaia* proper motions with radial velocity measurements coming from ground based spectroscopy, together with the assumption of a certain shape for the Galactic potential (see e.g. McMillan 2017), has permitted for the first time the precise determination of the orbital parameters of the known GCs (Vasiliev 2019; Baumgardt *et al.* 2019) and dwarf spheroidal galaxies (Gaia Collaboration, Helmi *et al.* 2018).

As shown in Fig. 1, GCs span a wide range of values in terms of apocenter, going from few kpc up to several tens of kpc, while their pericenter is rarely larger than 10 kpc. Their orbital eccentricity also varies significantly from case to case, spanning uniformly the allowed range of values from 0 (circular orbit) to 1. On the other hand, the known dwarf spheroidal galaxies tend to populate a more limited range of orbital parameters. For example, their pericenter is typically larger than 30 kpc, and their eccentricity never exceeds a value of ~ 0.6. Therefore the discrepancies between the two classes of objects might lead to the conclusions that GCs and dSph are not (or are only weakly) related, and that they independently formed and populated the surroundings of the Milky Way.

It should be noted that the sample of dwarf spheroidal galaxies that we can observe today is biased, as it lacks all the dwarfs that were accreted long ago and are now fully destroyed and only exist as stellar streams. However, thanks to the unique capabilities of Gaia, we can now investigate these systems as well.

In fact, the combination of Gaia kinematic and photometric information with chemical abundances coming from ground based spectroscopy (e.g. Abolfathi *et al.* 2018) enabled the discovery and the characterisation of at least three dwarfs that were accreted long ago by our Galaxy.

(*a*) The first is *Gaia*-Enceladus (Helmi *et al.* 2018, see also Belokurov *et al.* 2018), a massive dwarf ($M_\star \sim 6 \times 10^8$ $M_\odot$, see also Fernandez-Alvar *et al.* 2018) accreted about 10 Gyr ago (see also Haywood *et al.* 2018) that probably represents the last major merger event experienced by our Galaxy.

(*b*) The second is the progenitor of the Helmi streams, first discovered by Helmi *et al.* (1999) and recently characterised by Koppelman *et al.* (2019) as an old (> 11 Gyr) and less massive galaxy ($M_\star \sim 10^8$ $M_\odot$), probably accreted between 5 and 8 Gyr ago.

(*c*) The third is the Sequoia galaxy, discovered by Myeong *et al.* (2019) as a strongly retrograde and metal-poor feature of the Galactic Halo and associated to a former dwarf galaxy with a stellar mass of $M_\star \sim 5 \times 10^7$ $M_\odot$, accreted about ~ 10 Gyr ago.

These galaxies add to the first dwarf galaxy ever discovered to be disrupting within the Galactic potential well, that is the Sagittarius dwarf spheroidal (Ibata *et al.* 1994).

Thanks to the discovery of these systems, it is now possible to re-address the possible link between GCs and the population of dwarf galaxies. Did some of the GCs form in these ancient progenitors outside the Milky Way, and then were brought in during the dwarfs accretion events?

3. GCs and their progenitors

In order to answer this question, we exploited two fundamental properties of these systems: their integrals of motion (IOMs) and their age-metallicity relation (AMR). The IOMs (energy and angular momentum) are conserved quantities and as such can be used to discriminate GCs with a similar origin. GCs born in the same progenitor should have similar values of their IOMs. The AMR is another powerful tool to asses the common origin of GCs. In fact, as shown e.g. in Leaman *et al.* (2013), the shape of the AMR depends primarily on the mass of the progenitor: the larger the mass, the higher the normalisation and the more metal-rich the knee of the relation, as defined by the younger clusters.

Unlike the IOMs, that have been determined for almost all of the Galactic GCs, the AMR is only available for a smaller sample because of the challenge in measuring precise and accurate absolute ages† (Forbes & Bridges 2010; Vandenberg *et al.* 2013). An homogeneous set of ages is now available only for 69 GCs (Massari *et al.* 2019). This is why, contrarily to what has been done in previous studies (Marin-Franch *et al.* 2009; Leaman *et al.* 2013; Kruijssen *et al.* 2019), we will use the AMR only as a constraint to better refine the GCs-dwarfs associations that are based on the IOMs.

3.1. *IOMs*

We started by determining clusters that formed *in-situ*. To do so, we first defined Bulge clusters as all the cluster with an orbital apocenter smaller than 3.5 kpc, thus selecting 36 GCs. Then, we defined as Disk clusters all those having *i*) maximum height from

† Metallicities are instead available and have been taken from Carretta *et al.* (2009)

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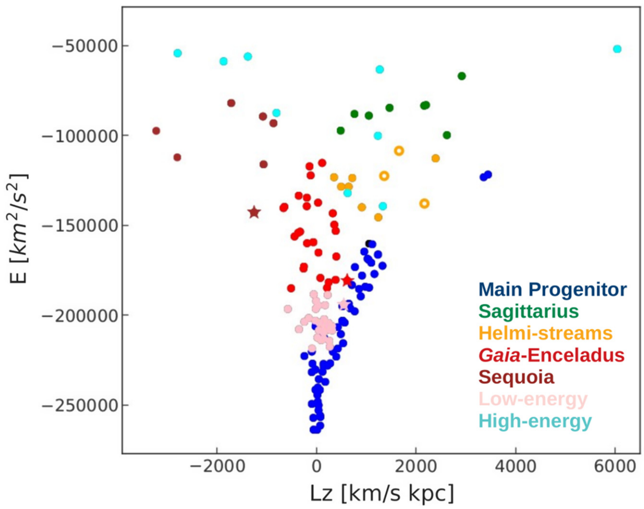

Figure 2. Distribution of the GCs in the Energy-angular momentum space. The colour-coding represents the clusters association with each known progenitor. Figure adapted from Fig. 3 of Massari *et al.* 2019.

the disk $Z_{\max} < 5$ kpc and *ii*) those with orbital circularity† $\mathsf{circ} > 0.5$. This added 28 clusters, two of which were removed from the selection based on their location in the young and metal-poor branch of the AMR. Therefore the total number of *in-situ* GCs amounts to 60.

Concerning the *accreted* GCs, each one has been associated to a progenitor based on the consistency between its location in the IOM space and that of the progenitor's stellar debris (as defined in Helmi *et al.* 2018; Koppelman *et al.* 2019 and Myeong *et al.* 2019). By adopting this prescriptions, 28 clusters were associated to *Gaia*-Enceladus, 10 to the progenitor of the Helmi-streams and 7 to the Sequoia galaxy. Based on the findings by Sohn *et al.* 2018 (see also Massari *et al.* 2017), 8 GCs were associated to Sagittarius. However, sometimes the stellar debris of different progenitors overlap in the IOM spaces. This is why for some of the clusters (open symbols in Fig. 2) the association could only be tentative. Better kinematic data and in particular accurate age measurements are required in order to more precisely assess the origin of these GCs.

After these assignments, 36 clusters were left with no known progenitors. 25 are located in a coherent region of the IOM space, at low energy and about null angular momentum. We labelled this possible structure as Low-Energy group. The remaining clusters are all located at high energy and span a wide range in angular momentum. Likely they do not have a common origin, but have rather been accreted from different, still unknown low-mass progenitors. We labelled this group as High-Energy. The distribution of all the analysed clusters in the IOM space and their association to the known progenitor is shown in Fig. 2.

3.2. *AMRs*

Fig. 3 shows the AMRs for the clusters associated to each progenitor. Each group shows well defined and tight AMRs, this lending support to the IOM selection described above. Moreover, it is remarkable that the shape of the AMRs, described with the analytical formula taken from Massari *et al.* (2019, green lines in Fig. 3), nicely recovers the mass

† circularity is defined as $\mathsf{circ} = L_Z/L_{Z,\rm circ}$, where $L_{Z,\rm circ}$ is the angular momentum of a circular orbit with cluster's energy, and equals $+/-1$ for co-planar circular prograde/retrograde orbits respectively.

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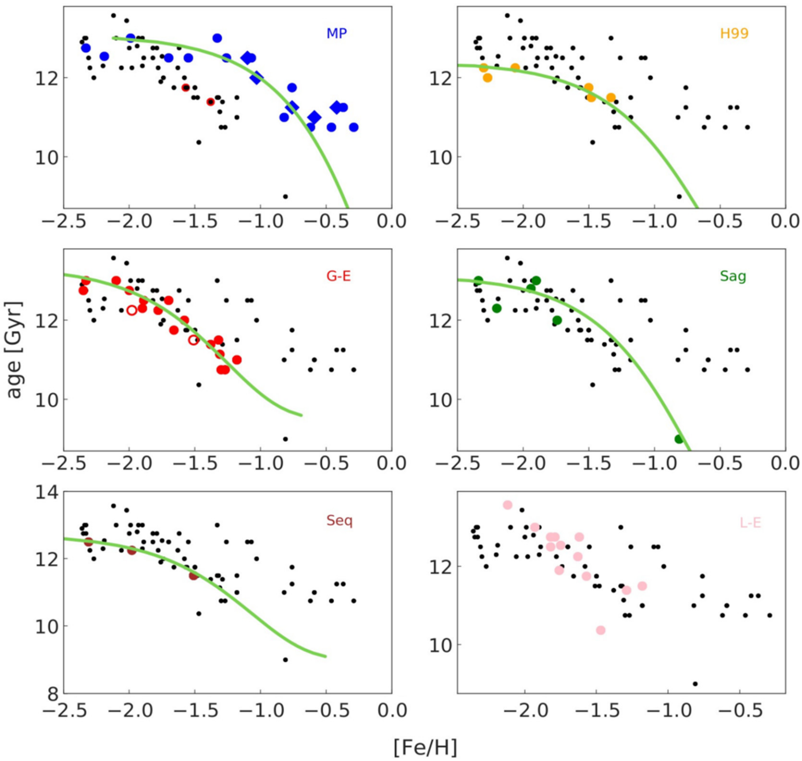

Figure 3. AMRs for the clusters associated to each dwarf progenitor. Figure adapted from Fig. 5 of Massari *et al.* 2019.

scale of the progenitors as reported in the literature. In particular, the main progenitor is clearly the most massive, and the knee of the AMR of its cluster is in fact located at the highest metallicity. On the contrary, the progenitor of the Helmi streams and the Sequoia dwarf are the least massive dwarfs, and the AMRs of their clusters are indeed those with the lowest normalisation. Finally, *Gaia*-Enceladus and the Sagittarius dwarf have similar stellar mass, and the AMRs of their GCs are indeed very similar. Last, we note that also the clusters associated to the Low-Energy group describe a tight AMR, with a shape comparable to that of *Gaia*-Enceladus or Sagittarius, possibly with an even higher normalisation. If this structure will be revealed by future investigations as real, then it might belong to a significant merger event that took place long ago in the evolutionary history of the Galaxy.

4. Conclusions

The second data release of the *Gaia* mission has allowed for the first time to investigate the dynamical properties of GCs and dwarf galaxies, both still existing and already disrupted after their merging with the Galaxy, in order to assess a possible formation link. By exploiting the IOMs and the AMRs, we found that about 60 of the Galactic GCs have formed *in situ*, whereas the remaining have likely been accreted from external progenitors. In particular, we associated 28 GCs to *Gaia*-Enceladus, 10 to the progenitor of the Helmi streams, 8 to Sagittarius and 7 to the Sequoia dwarf galaxy. Of the remaining 36, 25 seems to be associated to a coherent, low-energy structure in the IOM space. The observed AMRs of each group are well defined and reflect remarkably well the mass scale of the progenitors as found in the literature.

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Improved kinematic data and especially a complete and accurate sample of GCs absolute ages is required to make progress in the field and to better pin down associations that are now only tentative.

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