Science at the edges: internal kinematics of globular clusters’ external fields

Abstract:
The outer regions of globular clusters can enable us to answer many fundamental questions concerning issues ranging from the formation and evolution of clusters and their multiple stellar populations to the study of stars near and beyond the hydrogen-burning limit and to the dynamics of the Milky Way. The outskirts of globular clusters are still uncharted territories observationally. A very efficient way to explore them is through high-precision proper motions of low-mass stars over a large field of view. The Wide Field InfraRed Survey Telescope (WFIRST) combines all these characteristics in a single telescope, making it the best observational tool to uncover the wealth of information contained in the clusters’ outermost regions.
Exploring uncharted territories

Over the last two decades, our simple concept of globular clusters (GCs) as “spherical, kinematically-isotropic, non-rotating systems composed of a single stellar population” has radically changed, thanks to exquisite spectroscopic, photometric and astrometric studies (the last two mainly made possible by the Hubble Space Telescope, HST). The vast majority of these studies have been focusing on the clusters’ cores and surrounding central regions. As a consequence, the outskirts of GCs and out to beyond their nominal tidal radius formally remain “uncharted territories” from the observational point of view.

Multiple stellar populations. Essentially all GCs studied with high precision (e.g., Piotto et al. 2015, and references therein) show clear evidence of multiple stellar populations (mPOPs). Stars of different populations form distinct sequences on a color-magnitude diagram (CMD, e.g., Bellini et al. 2017b, see Fig. 1). These sequences can also be traced to different abundances of light elements (such as Na, O, Al, Mg observed spectroscopically; see e.g., Gratton et al. 2012 and references therein), helium (which is hard to observe spectroscopically, Pasquini et al. 2011; Dupree et al. 2011; Milone et al. 2018b), and iron (e.g., Marino et al. 2009). First stellar generations have a composition typical of the proto-galactic interstellar matter out of which they formed. Subsequent generations have increasingly higher helium, N and Na, and are depleted in C and O. mPOPs are a ubiquitous feature of GCs, but no two clusters are alike (Renzini et al. 2015).

While photometry and spectroscopy have begun to shed some light on the mPOP phenomenon in terms of chemical properties, multiplicity of distinct sequences and ranges of ages, many questions remain still unanswered, e.g.: What sequence of events led to the formation of mPOPs? How did formation processes and dynamical evolution shape today’s GCs? The structural and kinematic properties of GCs are two additional key pieces of information to help us build a complete picture of the formation and evolution of GCs and their mPOPs. In this respect, the measurement of stellar proper motions (PMs) represents a very effective way to constrain the structure, formation and dynamical evolution of these ancient stellar systems and, in turn, that of the Milky Way itself.

Some mPOP formation scenarios propose second-generation stars to form more centrally concentrated than first-generation stars (e.g., D’Ercole et al. 2008). As GCs evolve over time, two-body relaxation processes tend to progressively erase this initial spatial segregation, starting from the clusters’ cores and moving towards the outskirts. The GCs’ core relaxation time is short—a few $10^7 - 10^8$ yr—compared to the age of GCs of $12 - 13 \times 10^9$ yr, so first- and second-generation stars are now fully mixed and isotropic in the central regions. Numerical simulations predict that the outer regions of massive GCs, characterized by a longer two-body-relaxation time, should still retain fossil memory of the initial segregation of second-generation stars (e.g., Vesperini et al. 2013). This is indeed what has been observed in some GCs (e.g., Bellini et al. 2009b, 2013; Simioni et al. 2016).

Kinematically, stars in GCs are expected to diffuse outwards preferentially along radial orbits, resulting in an increased radial anisotropy of their velocity-dispersion profile. Over many two-body relaxation times stars tend to have a more isotropic velocity profile. Second-generation stars were born at a later stage (and more centrally segregated) than first-generation stars, so that we expect them to show a higher degree of velocity anisotropy than first-generation stars. The velocity-dispersion anisotropy can be directly measured via PMs alone as the ratio between the tangential ($\sigma_{\text{tan}}$) and the radial ($\sigma_{\text{rad}}$) components of the velocity dispersion, and cannot be done by
NGC 6752
NGC 5139
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Figure 1: (Left:) UV CMD of NGC 5139 (ω Cen), from Bellini et al. (2017a). Right: IR CMD of NGC 6752, from Milone et al. (2019). In both cases, multiple sequences are clearly visible on the CMDs. The UV filters F275W and F336W trace key molecular bands (in particular OH and NH) that help to differentiate between first- and second-generation stars. The IR color F110W–F160W (J−H) is particularly sensitive to oxygen variations below the main-sequence knee.

just using line-of-sight velocities, since two directions of motion are needed. The outskirts of GCs represent the best place to still find second-generation stars more radially anisotropic than first-generation stars (e.g., Richer et al. 2013; Bellini et al. 2015, 2018). Furthermore, pinpointing the radial distance at which the isotropy-to-radial-anisotropy transition happens can help us set tight constraints on the time evolution of mPOPs and the dynamical history of GCs.

GCs at the edge (and beyond). While mPOPs are now the hottest topic in GC studies, there are several other open key questions regarding GCs as a whole that could potentially be substantially clarified with a thorough analysis of the clusters’ outer regions.

- **What is the role of angular momentum in cluster formation and evolution?** A large number of GCs exhibits a significant degree of systemic rotation (e.g., Bellazzini et al. 2012; Fabricius et al. 2014; Bianchini et al. 2018; Ferraro et al. 2018; Kamann et al. 2018). The overwhelming majority of these studies is based on line-of-sight (LOS) measurements. A combination of LOS measurements with PMs will allow us to derive the three-dimensional kinematic profile (see left panel in Fig. 2), which can be used to shed light on this important topic (e.g., Bellini et al. 2017c).

- **What is the current state of energy equipartition in clusters?** For over forty years, GCs were expected to evolve towards a state of complete energy equipartition over many two-body relaxation times, so that the stellar velocity dispersion $\sigma_{\text{vel}}$ scales with stellar mass $m$ as $\sigma_{\text{vel}} \propto m^{-\eta}$, with $\eta = 0.5$ (Spitzer 1969, 1987). However, recent simulations (e.g., Trenti & van der Marel 2013; Bianchini et al. 2016; Webb & Vesperini 2017) show that GCs can only reach partial energy equipartition, and that the value of $\eta$ depends on the distance from the cluster’s center and on stellar mass. Measuring the detailed state of
energy equipartition of a GC requires high-precision PM measurements for a large number of stars over a wide range of stellar masses (e.g., Bellini et al. 2018) and radial distances (e.g., Libralato et al. 2018; see the second panel of Fig. 2).

**What can we learn from stars near and beyond the hydrogen-burning limit?** There exists a minimum mass below which a star cannot ignite thermonuclear burning of hydrogen. This hydrogen-burning limit (HBL) separates main-sequence stars from brown dwarfs, which are characterized by a large difference in luminosity for a small variation in mass. The best place to observe stars near (and beyond) the HBL is in the outskirts of GCs, where crowding is low and low-mass stars are the majority. In addition, stars in GCs are all at the same distance and age from us, so that a difference in luminosity directly translates into a difference in mass. Because GCs are old, stars with masses below the HBL had time to fade away from those above the limit, creating a clear gap in the luminosity function (e.g., Bedin et al. 2001; Dieball et al. 2016, see the third panel of Fig. 2) that can be used, e.g., to provide an independent age estimate for the clusters. Proper motions are needed to identify bona-fide cluster members near the HBL from background unresolved galaxies.

**What is the role of the Galactic tidal field?** During their evolution, GCs tend to become radially anisotropic the farther from their cores. In the outermost cluster regions, where the interaction of cluster stars with the Galactic tidal field becomes significant, stars with more radial orbits are preferentially lost in the field. As a result, the velocity field of surviving stars is expected to become isotropic or even slightly tangentially anisotropic (see, e.g., Takahashi & Lee 2000; Baumgardt & Makino 2003; Vesperini et al. 2014; Tiongco et al. 2016, right panel of Fig. 2). The interplay between the Galactic tidal field and the stellar orbits in a GC is still poorly constrained observationally, and it is not clear how deep into the cluster’s potential well the influence of the tidal field can be.

**Tidal tails as a powerful dynamical tool.** The internal dynamical evolution of GCs, driven by two-body relaxation along with the effects of disk and bulge tidal shocks, causes cluster stars to escape, forming tidal tails. These tidal tails are present as departures in the surface density profiles at large radii, with a break from a King profile (King 1966) at the tidal...
radius followed by a power-law-like decline which varies from cluster to cluster (but see also the role of potential escapers, e.g., de Boer et al. 2019). Evidence of tidal tails has been found in several GCs (see, e.g., Grillmair et al. 1995; Odenkirchen et al. 2001, 2003; Grillmair & Johnson 2006; Kunder et al. 2014; Ibata et al. 2019), implying this might be a common feature. The identification and analysis of these tails, together with their shape, extension, orientation and stellar content, provides a wealth of information on the cluster dynamical evolution, on the evolution of its stellar-population content and mass function, on the cluster’s orbit and on the Galactic potential (see, e.g., Heggie & Hut 2003; Binney & Tremaine 2008), and on the possible fingerprints of dark matter substructures (Bonaca et al. 2018). In addition, some mPOP formation models (e.g., D’Ercole et al. 2008) predict GCs to have been much more massive at birth, with most of their first-generation stars now lost into the field. Measuring the population ratio of extra-tidal stars would provide critical elements to prove or dismiss these theories. Extra-tidal stars are rare, and the most-obvious places to look for them are the immediate surroundings of GCs, just outside their tidal radius along the direction of motion of the clusters.

The path forward

Observational requirements. All the science cases listed above share specific needs:

1. **Wide field of view.** The tidal radius of GCs ranges from several arcmin up to about 1 degree, and tidal tails obviously extend further out, so the wider the field of view of a telescope, the more efficient and less time consuming observations will be.

2. **Deep, near-IR.** Because of the effects of mass segregation, bright, massive stars are more centrally concentrated, while the cluster outskirts are dominated by faint, less massive stars. Because of stellar evolution, stars spend about 99% of their life time as (faint) MS stars, and the remaining 1% as (bright) evolved stars. It follows that the vast majority of stars in the outskirts of GCs are faint, low-mass stars. Low-mass stars emit most of their light at redder wavelength than their brighter counterparts, especially at the faint end, so that an efficient observational strategy would employ near-IR rather than optical or UV filters.

3. **Cluster-field decontamination.** The stellar density in GCs quickly drops moving outwards from the core, and soon foreground and background sources become the dominant sources of contamination. With this respect, PMs represent the best tool to clearly isolate cluster members from the field population.

4. **Astrometric precision.** Typical velocity dispersions of stars in the outskirts of GCs are of the order of a just a few km s$^{-1}$. Proper-motion errors need to be subtracted in quadrature from the observed velocity dispersions to obtain the stellar intrinsic velocity dispersion, and typically astrometrists discard PM measurements if their error is larger than half that the intrinsic velocity dispersion (e.g., Bellini et al. 2014; Watkins et al. 2015; Libralato et al. 2018). At the typical GC distance of 10 kpc, a ≲1 km s$^{-1}$ PM relative precision translates into an angular precision of ≲20 μas yr$^{-1}$.

*Gaia’s end-of-mission PMs of around 20 μas yr$^{-1}$ are expected to be limited in magnitude to stars brighter than G∼17 (Pancino et al. 2017). This limit implies that only the few evolved stars present in the clusters’ outskirts would have PM measurements of the required precision, thus severely limiting the available statistics and make most of the proposed investigations
Figure 3: A typical-size GC (left) and one of the largest GCs (right) can easily be observed with just one or a few WFIRST pointings. The HST and JWST field of views are also shown, for comparison. In both panels, the red circle shows the nominal tidal radius of the clusters. Observations outside the tidal radius along the direction of motion of the clusters (red arrow) allows the study of tidal tails and the effects of the tidal field.

impossible. Even for the few closest GCs for which Gaia’s PMs are of adequate precision down to \( \sim 1 \) mag below the turn off, the range in mass of these stars is too narrow to derive meaningful values of \( \eta \).

**HST has a pencil-beam field-of-view.** To map the outer regions of typical GCs with the required precision would imply the need for hundreds of HST orbits in each of at least two epochs, and surveying several GCs in this way would simply be unfeasible (and unreasonable). JWST will have a similar astrometric performance and suffer from the same field-of-view limitations as HST.

**Ground-based telescopes are not precise enough.** Atmospheric effects and telescope flexures make their point-spread function and geometric distortion very unstable at the submas level. As a result, ground-based PM measurements typically have precisions of a few tenths of a mas yr\(^{-1}\) at best (e.g., Anderson et al. 2006; Bellini et al. 2009a, 2010; Libralato et al. 2014, 2015): at least an order of magnitude too large of what is need by the proposed studies. Current and near-future adaptive-optic-equipped (AO, e.g., Keck, E-ELT, US-ELTs) detectors can in principle have a better astrometric performance than HST, but their field-of-view is/will be even smaller than that of HST.

**WFIRST represents the perfect tools for the proposed investigations:** it combines the astrometric capabilities of HST with a single-shot spatial coverage typical of that of wide-field ground-based telescopes (see The WFIRST Astrometry Working Group et al. 2017 for a detailed description of the expected WFIRST astrometric performance). Most GCs fit within one WFIRST pointing, and even the largest GCs can be observed with just two or three pointings (Fig. 3). Assuming a conservative 0.01 pixel position precision per single WFIRST image (as it is the case for HST, e.g., Bellini et al. 2011), a 20 \( \mu \)as yr\(^{-1}\) precision can be obtained in four years (the nominal mission lifetime) with about 200 exposures (or just 100 exposures if the mission is extended two more years). If the single-exposure precision can be improved by a factor of two (or more)—which is not unreasonable given the much more stable thermal environment of WFIRST’s orbit compared to that of HST’s low-Earth orbit—than these figures also scale down by the same factor, making what would otherwise be a hard or even impossible observing strategy relatively easy to achieve.
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