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Internal kinematics of Globular Clusters: Current state of the art, issues, and what to expect from the future

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Abstract. The advent of the *Gaia* mission is bringing astrometry to a new renaissance. Although *Gaia* will make important breakthroughs in many different scientific areas, stars in the crowded central fields of globular clusters (GCs) and at the faint end of the color-magnitude diagram are and will be out of *Gaia*'s reach. The *Hubble Space Telescope* (*HST*) is an excellent astrometric tool that has allowed us to distinguish and measure positions and brightness of faint stars in pencil-beam fields down to the very center of some GCs. *Gaia* and *HST* are two wonderful, complementary tools, but are yet far from being able to offer a complete dynamical picture of GCs. There is now great prefiguration for what the next-generation telescopes will be able to do, both ground- and space-based. This document highlights strengths and weaknesses of different facilities at different spatial and spectral regimes.

Keywords. instrumentation: adaptive optics, detectors, high angular resolution; telescopes; techniques: photometric; astrometry; stars: kinematics, evolution, Population II; Galaxy: globular clusters: general.

The groundbreaking discovery that virtually all globular clusters (GCs) host multiple stellar populations (mPOPs, e.g., Gratton *et al.* 2012; Piotto *et al.* 2015; Milone *et al.* 2017 and references therein) has revolutionized our traditional view of GCs as "simple stellar populations" and clearly revealed a much more complex picture. A new era in GC research has de-facto started, and numerous new questions have been raised concerning star formation and dynamical processes driving the formation and evolution of mPOPs.

In contrast to all the attention that has been devoted so far to photometry and spectroscopy of mPOPs, little is known thus far regarding their kinematic properties, and almost all of what is known is based on spectroscopic line-of-sight (LOS) velocity measurements (e.g., Jeffreson *et al.* 2017; Cordero *et al.* 2017; Ferraro *et al.* 2018; Kamann *et al.* 2018, just to list the most recent works).

Proper motions (PMs) offer a significant improvement and provide several advantages over LOS velocity studies. High-precision measurements of the plentiful main-sequence (MS) stars can be obtained, thus providing better statistics of the kinematic quantities of interest (e.g., Bellini *et al.* 2014), and a direct measurement of the state of energy equipartition (e.g., Bellini *et al.* 2018; Libralato *et al.* 2018). More importantly, they can directly reveal the velocity-dispersion anisotropy of the cluster and of each subpopulation (e.g., Watkins *et al.* 2015; Bellini *et al.* 2015, 2018). The measurement of stellar PMs in GCs represents therefore a very effective way to constrain the structure, formation and dynamical evolution of these ancient stellar systems.

In addition to the study of mPOPs, there are many more open questions regarding the dynamics of GCs as a whole that remains unanswered to date, from the possible presence

Table 1. Strengths and weaknesses of current and near-future ground- and space-based facilities for the study of the internal kinematics of GCs and their mPOPs. See the text for details.

	Spatial coverage			Spectral Coverage		
	Core	Intermediate	Outskirts	UV	Optical	Near IR
Gaia	✗	✓	✓	✗	✓	?
HST	?	✓	✗	✓	✓	✓
Extreme MCAOs	✓	✗	✗	✗	?	✓
JWST	?	✓	✗	✗	✗	✓
WFIRST	✗	✓	✓	✗	✗	✓
LUVOIR	✓	✓	✗	✓	✓	✓

of intermediate mass black holes (IMBHs) at their centers (e.g., Greene *et al.* 2019 and references therein) to the role of the Galactic tidal field. Last but not least, very little is known about the kinematics of stars in the outskirts of GCs and out to beyond their tidal radius (e.g., Bellini *et al.* 2019).

Several ground- and space-based facilities that are currently online or that will be available in the near future are or will be instrumental in the study of the internal kinematics of GCs. There is no one-size-fits-all facility, and some telescope/instrument combinations are, e.g., more appropriate for the study of the GCs' cores, while others will excel in the GCs' outskirts. Table 1 summarizes the main characteristics of current and near-future facilities for the study of the internal kinematics of globular clusters and their multiple stellar populations. Each line represents a ground- or space-based telescope, starting from current facilities on top and moving down toward near-future facilities.

Three columns concern the spatial coverage: we identified three critical regions: "Core", "Intermediate", and "Outskirts". The "Core" is where IMBHs are supposed to be, and where some stellar exotica (e.g., massive white dwarfs or blue strugglers) are more abundant. Intermediate regions—say, between 2 and 5 half-light radii—are where it is more likely to find fossil kinematic differences between different mPOPs. Stars in the GCs' outskirts are characterized by very low velocity dispersion (of the order of 1–2 km/s), low stellar density (mainly faint MS stars due to mass segregation). The outskirts is where the effects of the Galactic tidal field are more prominent. Different facilities are more appropriate for the study of different regions.

The last three columns of the table pertain to the spectral coverage, from the ultraviolet to the near infrared. Again, different facilities are more appropriate for different wavelength regimes. UV and blue filters are very sensitive to CNO variations, since they cover OH, NH, CN and CH molecular absorption bands. Below the MS knee, near-IR imaging is sensitive to oxygen variation, due to the presence of H_2O absorption bands. Different stellar populations are characterized by different abundances of these elements. When He variation is also large (e.g., for the GCs NGC 2808, Piotto *et al.* 2007, and NGC 5139, Piotto *et al.* 2005) color-magnitude diagrams (CMDs) based on optical filters are also able to clearly separate mPOPs along the MS. UV observations are typically more demanding in terms or telescope time, especially when the targets are faint MS stars, which are more easily studied in the near IR.

In the table, we use the symbol "✓" when a particular spatial or spectral range can be analyzed in high detail with a given facility, while the opposite is marked by the symbol "⊗". The symbol "?" is reserved for cases with caveats. Here below we provide a brief description of the strengths and weaknesses of each facility listed in Table 1.

Gaia† is the ESA's flagship, all-sky astrometric mission. Well-measured stars in the *Gaia* catalog have astrometric errors of just a few μas/yr down to $G{\sim}16$–17 mag. *Gaia* suffers from downlink limitations, so that only a small, random sample of stars are recorded when the stellar density is high. As a consequence, the cores of GCs are usually out of *Gaia*'s reach (⊗), but everything else is at its fingerprints (✓), as long as one is limited to the study of evolved stars through optical bands. If an extended *Gaia NIR* mission will become a reality (see, e.g., Høg & Knude 2014; Hobbs *et al.* 2016), then *Gaia* will be able to measure improved PMs for $G{>}17$ stars and provide infrared photometry.

Hubble Space Telescope (HST)‡ has provided most of what we know today about the internal 2D kinematics of GCs. Despite its current high angular resolution (about 40–50 mas/pixel for the ACS and WFC3 detectors), the cores of most GCs are still too crowded for *HST*, and only the PM of bright MS stars typically have errors small enough to allow the study of the internal kinematics (?). Because of its pencil-beam field of view (a few square arcminutes), thorough investigations of the GCs' outskirts with *HST* are unfeasible (⊗). *HST*'s strengths resides at intermediate radial distances, where the stellar density is still high enough that many stars still fall within its small field of view (✓). *HST* is equipped with a wide range of filters from the UV (WFC3/UVIS) to the near IR (WFC3/IR), so that mPOPs can always be isolated photometrically.

Extreme multi-conjugate adaptive optics (MCAOs)§ are characterized by superber spatial resolution (just a few mas/pixel) and very narrow field of views (about 1 square arcmin). The are the ideal facilities for the study of GCs' cores (✓), so they are the best facilities to hunt for the presence of IMBHs. Outside the centermost regions, MCAO studies of GC dynamics start to become unfeasible due to field-of-view limitations (⊗). MCAOs operate in the IR (✓), therefore the study of blue strugglers might not be as ideal as with, e.g., the *HST*, unless MAVIS (a proposed optical MCAO to be mounted at the ESO VLT) becomes a reality (?).

James Webb Space Telescope (JWST)¶ will have a resolution very similar to that of *HST* (35 mas/pixel) but in the near IR. The field of view will also be comparable to that of *HST* detectors (a few square arcminutes). The JWST will be able to offer the similar astrometric capabilities to *HST* but it will be limited to IR filters.

† http://sci.esa.int/gaia/
‡ https://www.nasa.gov/mission_pages/hubble/main/index.html
§ https://www.eso.org/sci/facilities/eelt/, https://www.noao.edu/us-elt-program/, http://mavis-ao.org/mavis/
¶ https://www.jwst.nasa.gov/

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Wide-Field InfraRed Survey Telescope (WFIRST)† represents the perfect tool for the study of the GCs' outskirts (✓). It combines *HST*-level astrometry with a single-shot spatial coverage typical of that of wide-field ground-based telescopes (see The WFIRST Astrometry Working Group et al. 2017; Bellini *et al.* 2019 for a details). Most GCs fit within one WFIRST pointing, and even the largest GCs can be observed with just a few pointings. WFIRST can also be used at intermediate radial distances (✓) but, due to its relatively large pixel scale of 110 mas/pixel, GCs cores will most likely be out of WFIRST's reach (⊗). WFIRST will operate in the near IR (✓). WFIRST will also be equipped with a single red optical filter: yet, a single optical filter does not allow to construct optical CMDs with WFIRST data alone, so we give it a ⊗ for what concern its optical coverage. WFIRST will not have UV capabilities (⊗).

Large UV/Optical/IR Surveyor (LUVOIR)‡ represents the ideal astrometric successor of *HST*. Its 15-m design concept imager (HDI) will cover the full spectral range from near UV (✓) to near IR (✓), and will have a similar field of view to that of JWST or *HST* but with ∼10× increased spatial resolution, thus allowing the detailed kinematic study of GCs' cores (✓) also in the UV (to be compared to MCAOs) in addition to full spectra studies of intermediate regions (✓). Its limited field of view will make LUVOIR extremely inefficient for the thorough study of GCs' outskirts (⊗).

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† https://wfirst.gsfc.nasa.gov/
‡ https://asd.gsfc.nasa.gov/luvoir/

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