Star Clusters: From the Milky Way to the Early Universe
Proceedings IAU Symposium No. 351, 2019
A. Bragaglia, M. Davies, A. Sills & E. Vesperini, eds.

doi:10.1017/S1743921319006525

Internal kinematics of multiple stellar populations in globular clusters

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Abstract. Spectroscopy and photometry have revealed existence, complexity and properties of the multiple stellar populations (mPOPs) hosted in Galactic globular clusters. However, the conundrum of the formation and evolution of mPOPs is far from being completely exploited: the available pieces of information seem not enough to shed light on these topics. Astrometry, and in particular high-precision proper motions, can provide us the sought-after answers about how mPOPs formed and have evolved in these ancient stellar systems. In the following, I present a brief overview of the observational results on the internal kinematics of the mPOPs in some GCs thanks to *Hubble Space Telescope* high-precision proper motions.

Keywords. (Galaxy:) globular clusters: general, stars: kinematics, astrometry

Globular clusters (GCs) are complex systems, and part of their complexity has been revealed to us thanks to high-precision proper motions (PMs). We know that GCs rotate in the plane of the sky (e.g., Bianchini *et al.* 2018); present velocity anisotropies (Bellini *et al.* 2017 and references therein); and reach only a partial level of energy equipartition (see Libralato *et al.* 2018).

GCs are also known to host multiple stellar populations (mPOPs; see Piotto *et al.* 2015; Milone *et al.* 2017). For decades, mPOPs have been investigated photometrically and spectroscopically, but now the contribution of astrometry is steadily growing. High-precision PMs, mainly obtained with *Hubble Space Telescope* (*HST*) data, have shown kinematic differences among the mPOPs in some GCs. The main findings are summarized in the following.

1. Internal kinematics of the mPOPs

Second-generation (2G) stars, regardless of the formation channel with which they were born, formed initially more centrally concentrated than first-generation (1G) stars (e.g., Vesperini *et al.* 2013). Then, 2G stars slowly diffused outward preferentially along radial orbits as the result of two-body encounters. After many two-body relaxation times, differences between the spatial distributions and kinematics of 1G and 2G stars are washed out.

This homogenization process is first reached in the GCs' cores where the local two-body relaxation time is relatively short. This has been observed thanks to *HST* PMs. Anderson & van der Marel (2010) investigated the core of the GC ω Cen and found that 1G and 2G main-sequence (MS) stars have the same velocity dispersions within the errors.

Libralato *et al.* (2019) recently analyzed NGC 6352, a GC for which the 1G-2G mPOP tagging is quite straightforward in ultraviolet/optical color-magnitude diagrams (Fig. 1). 1G and 2G stars in the innermost ∼1.5 core radii of the cluster share the same spatial distribution and kinematic properties within the errors (Fig. 2).

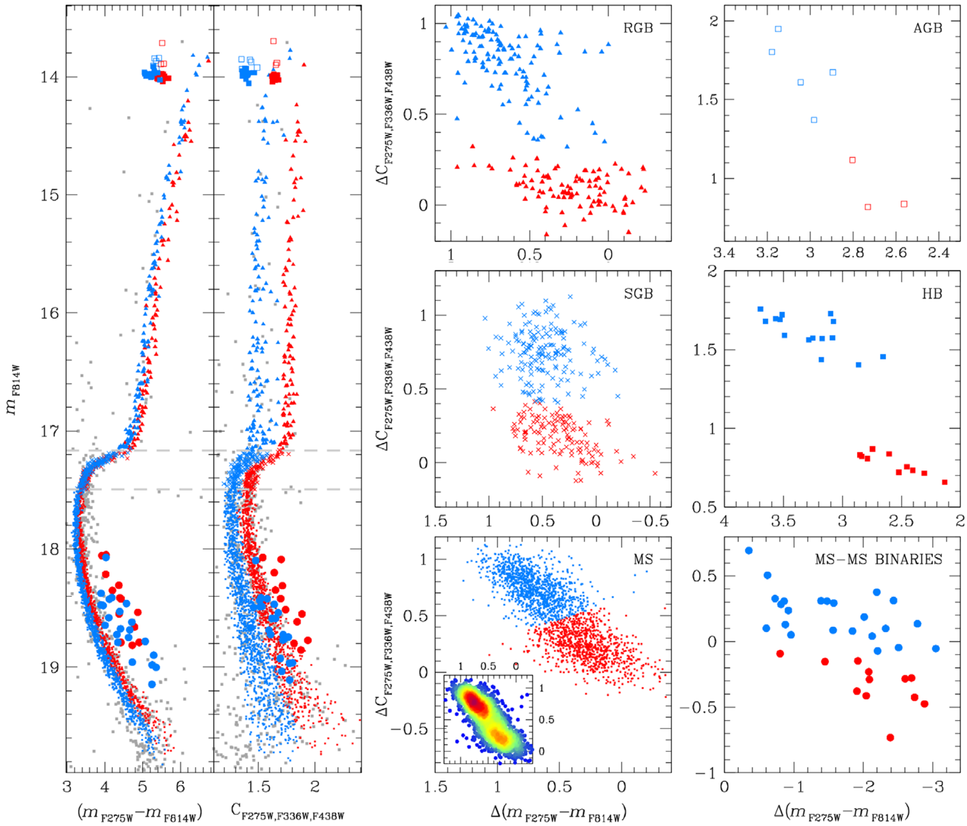

Figure 1. Tagging of 1G (red points) and 2G stars (azure points) of NGC 6352 using ultraviolet/optical two-color diagrams or "chromosome maps". (Figure from Libralato *et al.* 2019.)

In the clusters' outskirts, the two-body relaxation time is longer than that in the core and can reach a few Gyrs in some massive GCs. Thus, some clusters could still preserve fossil fingerprints of the initial different spatial segregation and kinematics between 1G and 2G stars. In these cases, we expect to find 2G stars more radially anisotropic ($\sigma_{\rm rad} > \sigma_{\rm tan}$) than 1G stars. The maximum of this radial anisotropy should be reached a few half-light radii from the GCs' centers. Then, the degree of such anisotropy decreases outward (Vesperini *et al.* 2014; Tiongco *et al.* 2016). Again, mainly thanks to *HST* PMs, we have observed these features in some GCs.

Richer *et al.* (2013; and later Milone *et al.* 2018 and Cordoni *et al.* 2019 by means of Gaia DR2 PMs) showed that 2G stars in the outskirts of 47 Tuc are more radially-anisotropic than 1G stars. Bellini *et al.* (2015) showed that the two most He-enhanced 2G populations of NGC 2808 are more radially anisotropic than the other mPOPs between 1.5 and 2 half-light radii from the center of the cluster. Libralato *et al.* (2018) analyzed the kinematics of the mPOPs of NGC 362, and found a marginal signature of 2G stars having a lower tangential velocity dispersion than 1G stars.

Finally, Bellini *et al.* (2018) analyzed the internal kinematics of the GC ω Cen in a field at ~3.5 half-light radii from the cluster's center. After the most evident mPOPs were identified along the MS of the cluster (Fig. 3), the authors analyzed the internal PMs of 1G and 2G stars. Again, 2G stars showed to be more radially anisotropic than 1G stars (Fig. 4). Interestingly, 1G stars in this field are rotating faster and appear to

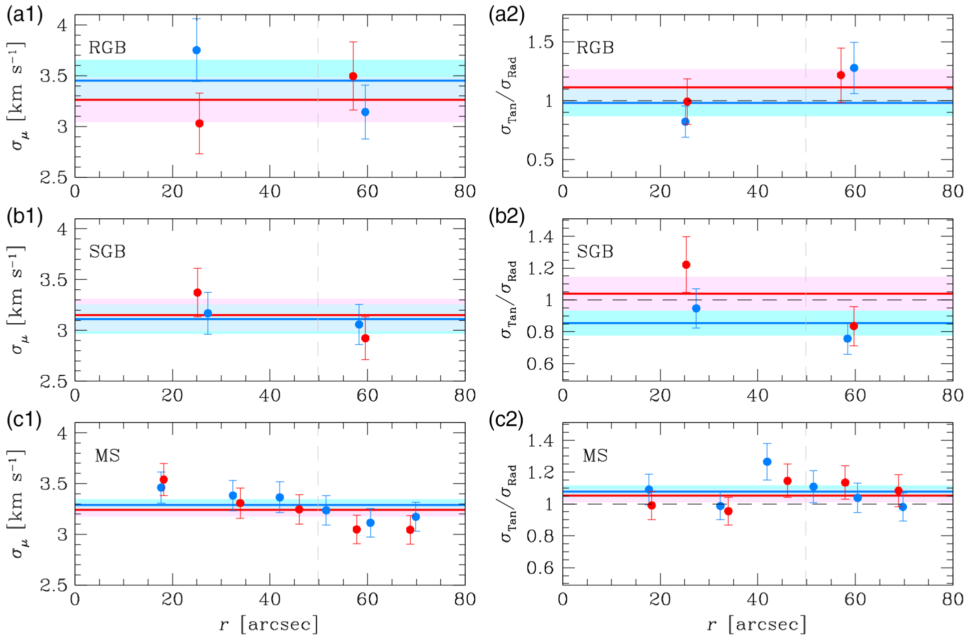

Figure 2. Velocity-dispersion (left panels) and anisotropy (right panels) radial profiles of red-giant branch (top), sub-giant branch (middle) and MS (bottom) stars of NGC 6352. Kinematics of 1G stars are shown in red; 2G stars are plot in azure. All mPOPs in the core of this cluster share the same kinematics. (Figure from Libralato *et al.* 2019.)

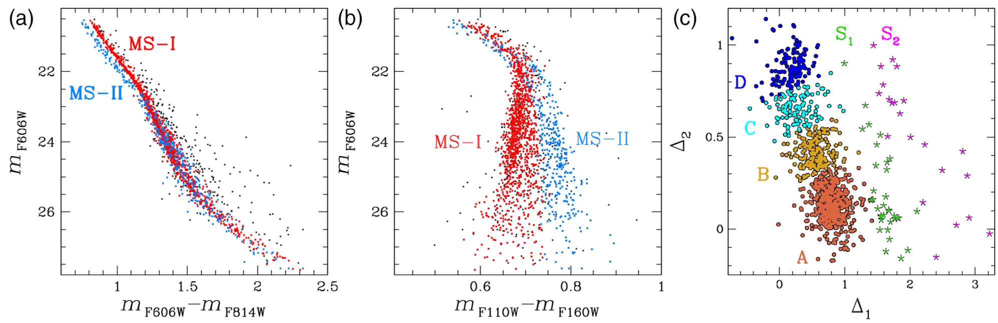

Figure 3. Color-magnitude and color-color diagrams of ω Cen stars in an *HST* field at ∼3.5 half-light radii from the cluster's center. Each of the two main components of the MS (MS-I and MS-II) is made up of different sub-populations. (Figure from Bellini *et al.* 2018.)

have a lower degree of energy equipartition than 2G stars. This is the first time that the level of energy equipartion was measured independently for different mPOPs.

2. Conclusions

High-precision PMs are one of the most-effective tools to study the kinematics of GCs as a whole and, in particular, of their mPOPs. Velocity dispersion, rotation in the plane of the sky, level of energy equipartition and radial distribution are key ingredients to understand the initial dynamical configuration, the formation and the evolution of the mPOPs (see, e.g., Hénault-Brunet *et al.* 2015).

https://doi.org/10.1017/S1743921319006525 Published online by Cambridge University Press

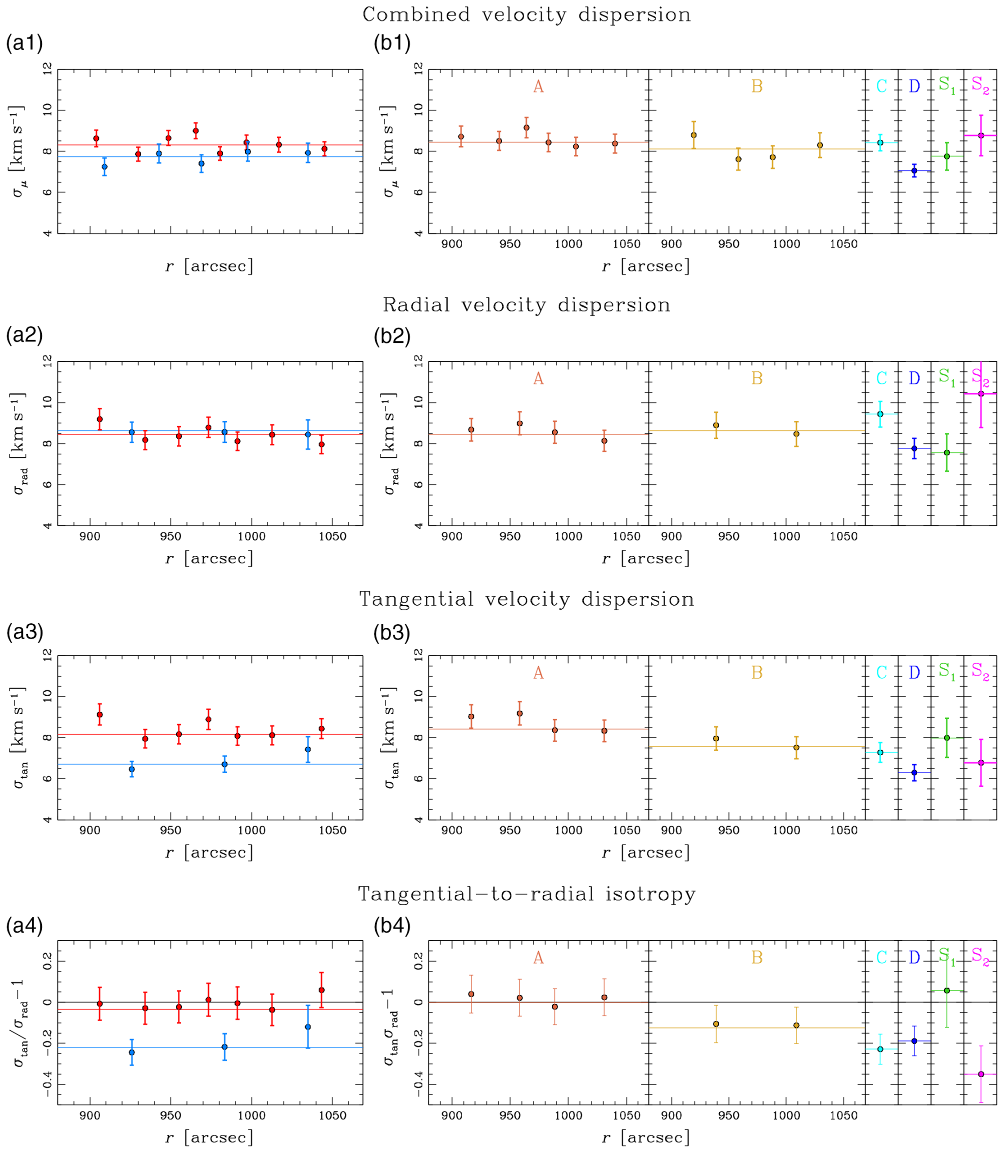

Figure 4. Internal kinematics of the mPOPs in the MS of ω Cen. A clear radial anisotropy ($\sigma_{\rm rad} > \sigma_{\rm tan}$) is visible in the kinematics of MS-II stars (in azure) and its different subcomponents (groups C and D). (Figure from Bellini *et al.* 2018.)

Acknowledgments

Based on observations with the NASA/ESA *HST*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

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