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Kinematical evolution of Globular Clusters

Maria A. Tiongco[1], **Enrico Vesperini**[1] **and Anna Lisa Varri**[2,3]

[1]Department of Astronomy, Indiana University, 727 E 3rd St, Bloomington, IN 47405, USA
email: mtiongco@iu.edu

[2]Institute for Astronomy, University of Edinburgh, Royal Observatory
Blackford Hill, Edinburgh EH9 3HJ, UK

[3]Department of Astronomy, Graduate School of Science, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan

Abstract. We present several results of the study of the evolution of globular clusters' internal kinematics, as driven by two-body relaxation and the interplay between internal angular momentum and the external Galactic tidal field. Via a large suite of N-body simulations, we explored the three-dimensional velocity space of tidally perturbed clusters, by characterizing their degree of velocity dispersion anisotropy and their rotational properties. These studies have shown that a cluster's kinematical properties contain distinct imprints of the cluster's initial structural properties, dynamical history, and tidal environment. Building on this fundamental understanding, we then studied the dynamics of multiple stellar populations in globular clusters, with attention to the largely unexplored role of angular momentum.

Keywords. methods: numerical, globular clusters: general

1. Introduction

The synergy between many recent photometric, spectroscopic, and astrometric studies is revealing that globular clusters deviate from their traditional image of dynamically simple and single stellar population systems. Complex internal kinematical features such as velocity dispersion anisotropy and rotation, and the existence of multiple stellar populations are some of the key observational findings.

There is now a numerous and growing amount of studies focused on the internal kinematics of GCs: from large radial velocity samples of individual stars in clusters (e.g., Bellazzini *et al.* 2012; Boberg *et al.* 2017), to proper motions studies using *HST* (e.g., Watkins *et al.* 2015; Bellini *et al.* 2017) and *Gaia* (e.g., Bianchini *et al.* 2018; Sollima *et al.* 2019) data, and also to velocity fields from IFU spectrographs (e.g., Fabricius *et al.* 2014; Kamann *et al.* 2018). These studies have shown that GCs have significant rotation and anisotropic velocity dispersion, which have huge implications on their dynamical history and their formation.

The observations of the internal kinematics have advanced to where it is also possible to detect kinematical differences between multiple stellar populations in GCs. Examples of such studies include Cordero *et al.* (2017), Milone *et al.* (2018), Libralato *et al.* (2019), and Cordoni *et al.* (2019). The kinematics of multiple stellar populations are an important part of the puzzle to uncovering the mechanism of their formation.

The amount of progress on the observational front calls for a renewed effort on the theoretical front to explore the previously mentioned implications on the dynamical history and formation of GCs. We have created a large suite of N-body simulations (ran with NBODY6, Nitadori & Aarseth 2012) designed to explore the dynamical evolution of tidally limited star clusters, focusing on the evolution of their velocity dispersion anisotropy and rotation. These studies provide a theoretical framework to interpret these many recent kinematical studies, but also to identify possible kinematical features to guide future observational studies.

2. The Building Blocks: Kinematical Evolution of Globular Clusters

Evolution of velocity dispersion anisotropy: The evolution of the anisotropy radial profile depends on the cluster's initial structural properties and external tidal environment. Initially compact clusters (compared to their Roche lobe) develop strong radial anisotropy in their outer regions through expansion due to two-body relaxation, and then gradually lose their radial anisotropy as the cluster loses mass to escaping stars. On the other hand, more extended clusters (i.e., filling their Roche lobe) do not have room to expand and are isotropic or slightly tangentially anisotropic. For more details, see Tiongco *et al.* (2016a).

Evolution of rotational properties: The strength of rotation in a cluster is gradually weakened by dynamical evolution: two-body relaxation redistributes angular momentum outward, from the inner regions to the outer regions, and escaping stars also carry away angular momentum. Rotation in GCs today must have been stronger in the past, and thus rotation should be a key ingredient in modeling the early properties of GCs. See Tiongco *et al.* (2017) for more details.

Clusters are also traditionally assumed to be in synchronous rotation with their orbital motion. However, our simulations show that preferential escape of stars on prograde orbits within the cluster (see Keenan & Innanen 1975) interferes with the process of tidal synchronization. The rotation that results is still solid-body, but the slope is equal to about *half* of the cluster's orbital angular velocity instead of equal to it in the case of full tidal synchronization (Tiongco *et al.* 2016b).

The evolution of the rotational properties in a GC is thus driven by the combined effects of the decreasing intrinsic rotation and partial synchronization.

Interplay between angular momentum and tidal field: In Tiongco *et al.* (2018), we relaxed some simplifying assumptions that are traditionally imposed in simulations of rotating star clusters by allowing the initial rotation axis of the cluster to be oriented in a generic direction relative to the tidal field and the cluster's orbital plane. The interplay between a cluster's internal evolution and the interaction with the host galaxy can produce complex morphological and kinematical properties, such as precession of the cluster's rotation axis and a variation in the orientation of the rotation axis with distance from the cluster center.

3. The Next Level: Kinematical Evolution of Multiple Stellar Populations

The understanding of the evolution of the kinematical properties in globular clusters provides the foundation for understanding the dynamical evolution of the kinematics of multiple stellar populations in clusters.

The initial conditions of this study (Tiongco *et al.* 2019) are modeled after the results of Bekki (2011), who carried out a set of hydrodynamical simulations to model the formation of a second-generation (2G) population in a rotating cluster composed of first-generation (1G) stars. As the gas released from the first generation cools and settles into the cluster's innermost regions, a second generation forms in a subsystem that is more spatially concentrated and more rapidly rotating.

We focus on the *long-term* dynamical evolution of a system like this, and on the evolution of the kinematical properties rotation and velocity dispersion anisotropy. Figure 1 shows the evolution of the rotation curves of the two populations in one of our simulations. The rotational velocity, v_{rot} is normalized to $\Omega r_{J,i}$, the speed of co-rotation with the cluster's orbital motion at the initial Jacobi radius. The effects of two-body relaxation

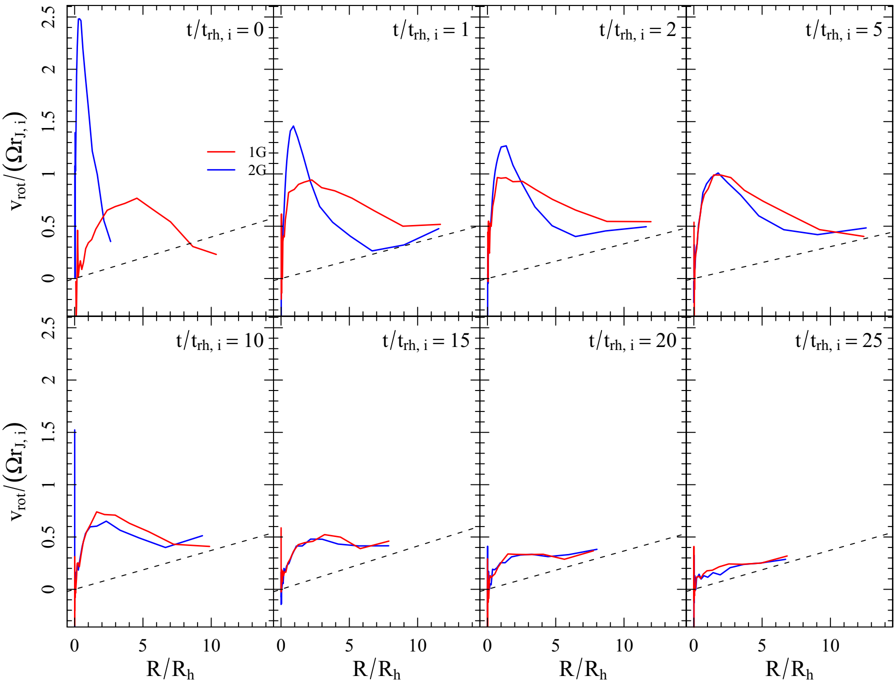

Figure 1. Time evolution of the radial profiles of the rotational velocity for a multiple stellar population cluster model. The rotational velocity, v_{rot} is normalized to $\Omega r_{J,i}$, the speed of co-rotation with the cluster's orbital motion at the initial Jacobi radius. Radius is normalized to the half-mass radius.

gradually erase the initial differences between the spatial and kinematical properties of the two populations. The profiles in Figure 1 illustrate how the rotational velocity profiles of the two populations evolve to become increasingly similar over time. After the rotational profiles of the two populations become indistinguishable, they then share the same evolution towards increasingly smaller values of the rotational velocity.

Figure 2 shows the evolution of the velocity dispersion anisotropy profiles in the same model. We use for the anisotropy parameter, σ_T/σ_R, the ratio of the tangential velocity dispersion to the radial velocity dispersion using the velocities projected onto the plane perpendicular to the line of sight. Drawing parallels to Tiongco *et al.* (2016a), the 2G's velocity anisotropy profile evolution is similar to a tidally underfilling cluster. The 2G population expands and creates an excess of radial orbits in the outer regions, and this is reflected in Figure 2 as 2G's evolution is characterized by a growing radial anisotropy in its outer regions. On the other hand, the less concentrated and more tidally filling 1G population does have room to expand and never develops a strong radial anisotropy.

Eventually, we will have many more observations of the internal kinematics of multiple stellar populations in globular clusters that may provide important clues to the mechanism behind the formation of multiple populations. We conclude here cautioning that the observation of the kinematical differences (or lack of differences) depends on the cluster's dynamical age and having a favorable line of sight to the cluster for the observational diagnostic used (e.g. radial velocities or proper motions). Dynamically old clusters have effectively lost the spatial and kinematical fingerprints of the formation epoch and dynamical history, and projection effects combined with the availability of only partial kinematical information may also limit our ability to identify existing kinematical differences, or reveal them but in a much weaker form.

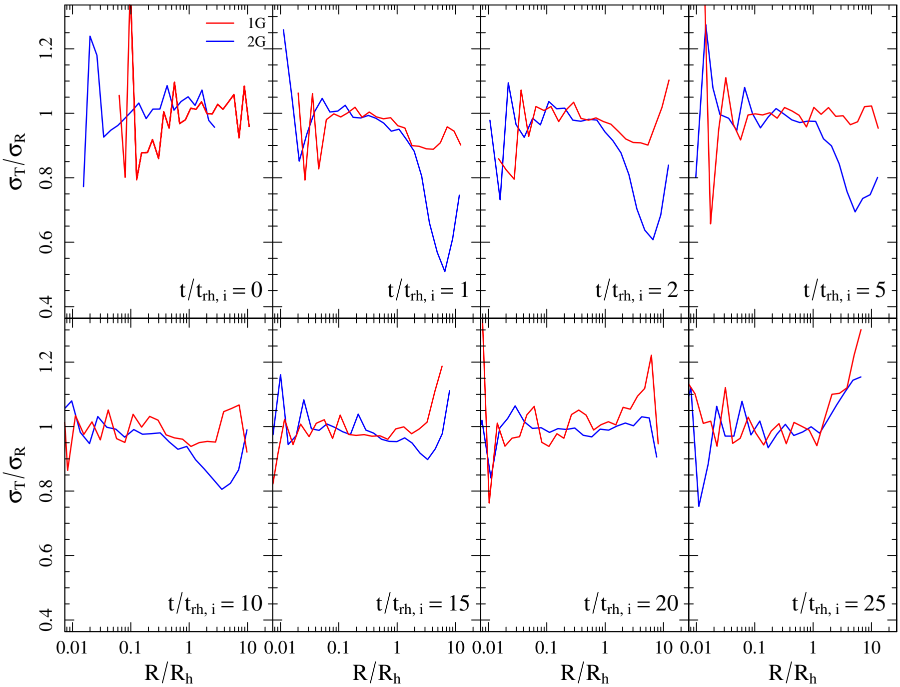

Figure 2. Time evolution of the radial profiles of the velocity dispersion anisotropy for a multiple stellar population model. The anisotropy parameter, σ_T/σ_R, is the ratio of the tangential velocity dispersion to the radial velocity dispersion using the velocities projected onto the plane perpendicular to the line of sight. Radius is normalized to the half-mass radius.

References

Bekki, K. 2011, *MNRAS*, 412, 2241

Bellazzini, M., Bragaglia, A., Carretta, E., *et al.* 2012, *A&A*, 538, A18

Bellini, A., Bianchini, P., Varri, A. L., *et al.* 2017, *ApJ*, 844, 167

Bianchini, P., van der Marel, R. P., del Pino, A., *et al.* 2018, *MNRAS*, 481, 2125

Boberg, O. M., Vesperini, E., Friel, E. D., *et al.* 2017, *ApJ*, 841, 114

Cordero, M. J., Hénault-Brunet, V., Pilachowski, C. A., *et al.* 2017, *MNRAS*, 465, 3515

Cordoni, G., Milone, A. P., Mastrobuono-Battisti, A., *et al.* 2019, *arXiv e-prints*, arXiv:1905.09908

Fabricius, M. H., Noyola, E., Rukdee, S., *et al.* 2014, *ApJL*, 787, L26

Kamann, S., Husser, T.-O., Dreizler, S., *et al.* 2018, *MNRAS*, 473, 5591

Keenan D. W. & Innanen K. A. 1975, *AJ*, 80, 290

Libralato, M., Bellini, A., Piotto, G., *et al.* 2019, *ApJL*, 873, 109

Milone, A. P., Marino, A. F., Mastrobuono-Battisti, A., *et al.* 2018, *MNRAS*, 479, 5005

Nitadori, K. & Aarseth, S. J. 2012, *MNRAS*, 424, 545

Sollima, A., Baumgardt, H., & Hilker, M. 2019, *MNRAS*, 485, 1460

Tiongco, M. A., Vesperini, E., & Varri, A. L. 2016a, *MNRAS*, 455, 3693

Tiongco, M. A., Vesperini, E., & Varri, A. L. 2016b, *MNRAS*, 461, 402

Tiongco, M. A., Vesperini, E., & Varri, A. L. 2017, *MNRAS*, 469, 683

Tiongco, M. A., Vesperini, E., & Varri, A. L. 2018, *MNRAS*, 475, L86

Tiongco, M. A., Vesperini, E., & Varri, A. L. 2019, *MNRAS*, 487, 5535

Watkins, L. L., van der Marel, R. P., Bellini, A., *et al.* 2015, *ApJL*, 803, 29