# GLOBULAR CLUSTER KINEMATICS WITH GAIA

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## ABSTRACT

With a targeted accuracy of 10 $\mu$as yr$^{-1}$ at V = 15 mag, Gaia will be able to determine the space motions of most galactic globular clusters with an accuracy of a few km s$^{-1}$ or better. This will dramatically improve our knowledge of how globular clusters evolve and how they and the Milky Way as a whole have formed. It will also be possible to follow tidal streams from dissolving clusters over many orbits by kinematically selecting their members, which will constrain the form of the galactic potential and give important insights into the nature of dark matter.

We illustrate how Gaia will improve our knowledge on the kinematics and dynamics of globular clusters and what can be learned by comparing the observational data from Gaia with the results of large scale NBODY simulations, possible with e.g., GRAPE6 or the future GRAPE8 computers.

Key words: Astrometry; Methods: numerical; Globular clusters: general.

## 1. INTRODUCTION

Understanding the way galaxies have formed and evolved is one of the great challenges of astrophysics in the 21st century. The Gaia satellite will be a major step in this direction since it will allow the study of one particular example galaxy, the Milky Way, in unprecedented detail and with an accuracy unachievable for any other galaxy. With a targeted accuracy of about 10 $\mu$as at V = 15 mag and a few hundred $\mu$as at V = 20 mag for positions and parallaxes, the distances and proper motions of a large sample of Milky Way stars will become known. In addition, Gaia will also provide radial velocities for about $10^8$ stars brighter than V = 17, allowing a determination of their space motions, and photometric information for the target stars.

An important target for Gaia will be globular clusters since they are among the oldest objects in the universe and understanding the details of their formation and evolution can give important insights into the way galaxies have formed. In addition, by studying the motion of stars stripped from the clusters due to the tidal interaction with the Milky Way, one can determine the galactic potential and constrain the clumpiness of its dark matter halo which will give important clues about the nature of the dark matter itself.

## 2. GLOBULAR CLUSTERS IN THE LIGHT OF GAIA

The expected accuracy of Gaia is large enough that individual parallaxes and proper motions of the brightest stars in globular clusters can be determined with accuracies of a few $\mu$as. Cluster distances will also be precisely known with Gaia, since one can either average the parallax information of the member stars as determined by Gaia, or use secondary distance indicators which will be much better calibrated with Gaia than what is possible now. It is therefore safe to assume that with Gaia, cluster velocities and distances will have relative errors of less than 1%, and the resulting orbital parameters will be determined with similar precision.

This allows a range of fundamental problems to be addressed: First, our understanding of cluster evolution will be improved significantly. $N$-body simulations show that the lifetimes of clusters and the role that different dissolution processes (internal vs. external) have for the cluster evolution depend on the cluster orbits (Baumgardt & Makino 2003). So far, it has been difficult to determine the main driving force for the evolution of globular clusters since their orbits are only poorly constrained. In addition, the number of cluster stars is too large to presently allow star-by-star simulations of individual clusters within a reasonable amount of computing time.

By the time Gaia data will become available, computer power will have increased sufficiently to carry out direct $N$-body simulations of globular clusters, most notably through the development of the GRAPE computer series in Japan (Makino et al. 2003): The so far most advanced GRAPE6 computers allow the simulation of star clusters with up to $10^5$ stars within a month of computing time, and with GRAPE8, the successor of the GRAPE6, simulations with $5 \times 10^5$ stars will become feasible. Once the cluster orbits are determined by Gaia, it will therefore be possible to follow the evolution of individual clusters and study how individual clusters and the galactic globular cluster system as a whole have changed over a Hubble time. This will allow questions like: the form of the initial mass function of stars in globular clusters, the initial number of globular clusters and the fraction of surviving clusters, and the fraction of halo stars that could have been born in globular clusters, to be addressed.

Orbital information is also essential to follow the tidal tails of globular clusters. So far, a clear detection of tidal tails has been possible for only few globular clusters, most notably Pal 5 (Odenkirchen et al. 2003), since the membership selection was based on photometric criteria alone. Gaia will allow to select stars in tidal tails on the basis of photometric, proper motion and parallax information, leading to a much better separation of members and non-members. It will also provide velocity information for the stars in the tails. From the way the tidal tails are distributed over the sky and the velocity gradient of the stars along the tails, the distribution of (dark) matter in the galaxy can be inferred (see e.g., Helmi 2004). Furthermore, a clumpy matter distribution tends to heat stars in the tidal tails and, over a long timescale, disperse the tails completely. With Gaia it will therefore be possible to study the amount of sub-structure in the dark matter of the galaxy. Such studies will allow important insights into the nature of dark matter.

Knowing the cluster orbits, it will also be possible to search for clusters with common orbital parameters and hence common origins and look for connections between individual globular clusters and dwarf galaxies. One can also study changes in the mean orbital parameters as a function of age and/or metallicity. An accurate picture of the formation history of the Milky Way should emerge from such studies.

Finally, Gaia will also measure the velocity dispersion of stars in globular clusters, except in the centres of very dense globular clusters where crowding might be a problem and additional information from ground- or space-based telescopes is necessary. This data will be an important input for the dynamical modelling of globular clusters. It will constrain the amount of mass segregation in globular clusters and the dark matter content in their outer parts.

Knowing the velocity dispersion is also essential to study if globular clusters contain concentrations of unseen matter in their centres. One reason of such unseen matter concentrations could be intermediate-mass black holes (IMBHs, Gerssen et al. 2002). Although the evidence for them in galactic globular clusters is still controversial (Baumgardt et al. 2003), the problem is nevertheless of great importance since e.g., the dynamical evolution of globular clusters is driven by encounters of stars in their centers and IMBHs would be important targets for gravitational wave detectors like LISA. One promising way for the detection of IMBHs would be to find the rise in the velocity dispersion of stars which they would cause if residing in the centres of globular clusters.

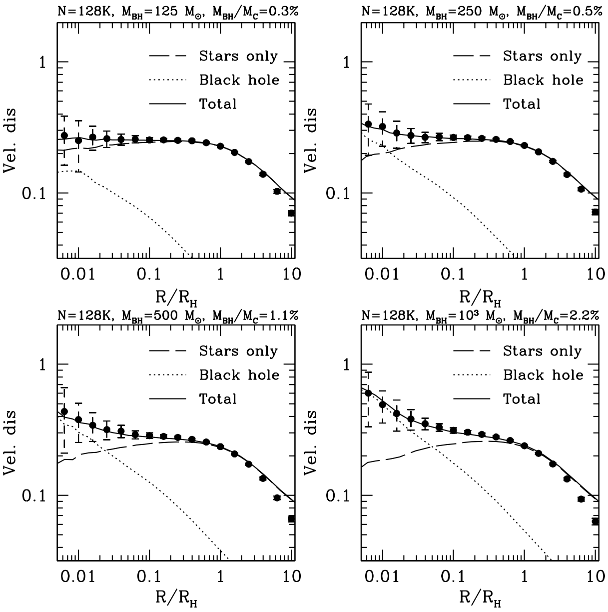

*Figure 1. Projected velocity dispersion of star clusters containing $N = 131\,072$ stars and black holes of varying masses. Dashed lines show the expected velocity dispersions inferred from the observed distribution of bright stars and Jeans equation. In the centres, they fall below the observed ones due to the contributions of the IMBH (dotted line). Error bars show the expected errors in a globular cluster if only the brightest 5% of all stars can be observed. Only IMBHs with masses $M_{BH}/M_C \geq$ 0.5% can be detected dynamically (from Baumgardt et al. 2005).*

Figure 1 shows the expected velocity dispersion of stars for 4 globular clusters which contain the same number of stars but IMBHs of different masses. It can be seen that low-mass IMBHs with $M_{BH}/M_C <$ 0.5% cause only a small deviation from the expected velocity dispersion due to the stars alone and are therefore nearly impossible to detect dynamically if only the brightest 5% of all cluster stars can be observed. For higher-mass black holes detection becomes possible if the velocity dispersion is known over a large enough range in radius. Although it will not be possible to observe the innermost stars with Gaia, the Gaia data will nevertheless be extremely useful to have a large enough range in $r$ where the velocity dispersion is known and also to fix the overall mass-to-light ratio of the cluster.

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