

30. The motion of globular clusters

THE SPACE MOTIONS of globular clusters in our Galaxy, and of the dwarf spheroidal galaxies in orbit around it, depend on our Galaxy's gravitational potential, and therefore its mass distribution. Together with knowledge of their chemistry and ages, these provide strong constraints on theories of formation of our Galaxy, including when and how the halo and disk actually formed.

Studies of the motions of stars *within* globular clusters, based on their proper motions, extend back to the days of photographic plate measurements more than a century ago. Establishing and understanding the nature of their Galactic orbits has been a problem tackled since the 1950s. By the 1980s, studies had revealed systematic orbital motion for more than 60 clusters, velocity dispersions increasing with distance from the Galactic centre, and a Galactic rotation curve revealing the existence of a massive Galaxy halo extending out to at least 30 kpc.

In the 1990s, Lynden-Bell (1995) identified streams of clusters tracing out the orbits of satellites that had long since merged with the Galaxy, including streams associated with the Magellanic Clouds, Fornax, and the Sagittarius dwarf. And they listed 22 clusters whose bulk proper motions were predicted to exceed 1 mas yr^{-1} .

THE TOTAL MASS of our Galaxy itself can be determined, through Newton's laws, from the orbits of these distance objects. When Gaia was under consideration by ESA in 2000, the best mass estimates were based on the known motions of 27 systems beyond 20 kpc.

Estimates at that time concluded that the total mass of our Galaxy is $2.3^{+3.9}_{-1.6} \times 10^{12} M_{\odot}$, while the mass within 50 kpc is $5.5^{+0.1}_{-1.1} \times 10^{11} M_{\odot}$. These uncertainties meant that the mass, and extent, of the Milky Way halo was one of the least well-known of all Galactic parameters.

Further advances in understanding cluster orbits have been limited by incomplete knowledge of their space velocities. Specifically, although their distances and radial velocities could be estimated, a complete orbit determination also requires the two components of the transverse motion on the sky, along with the gravitational potential in which the clusters move.

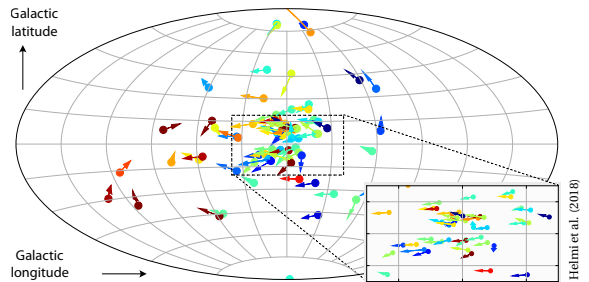
NO STARS in globular clusters were bright enough to be observed by Hipparcos. But in the mid-1980s, during the preparation of the Hipparcos input catalogue (the list of stars defining its observing programme), careful effort was devoted to including a number of bright reference stars lying close to a small number of selected globular clusters, specifically to provide an inertial reference frame for studies of their space motions.

In the absence of nearby Hipparcos stars, other studies have had to try to rely on background quasars and distant galaxies to define an 'absolute' reference frame.

With the Hipparcos results in 1997, some progress in understanding and explaining their orbits was duly made in the case of 38 halo clusters (Dinescu et al. 1999), and four low-latitude inner Galaxy clusters (Dinescu et al. 2003). They found, for example, space velocities all smaller than the escape velocity of the Galactic bulge, concluding that all were confined to the bulge region.

WITH THE developments over the past 20 years, what were the insights expected from Gaia?

It was anticipated that Gaia's high-accuracy astrometry of globular clusters would shed further light on: the mass of our Galaxy; their formation and evolution (e.g. which formed *in situ* and which were accreted); the effect of external tides and of physical processes within the cluster; the existence of remnant streams; whether they formed in mini-halos, or are devoid of any dark matter; and whether they host intermediate mass black holes.



Space motions for 75 globular clusters observed by Gaia (colours are related to their radial velocities)

A FIRST INDICATION of what the Gaia data will mean for globular cluster studies was made by Helmi et al. (2018). They used the Gaia DR2 astrometry, parallaxes and proper motions, to examine the space motions of 75 Galactic globular clusters. This represents about half of those known in our Galaxy, and focused on the most nearby clusters, within about 12–13 kpc. Radial velocities, measured by Gaia, are available for 57 of them.

Selecting according to distance and proper motions, Helmi et al. could identify stars out to each cluster's tidal radius, and down to a limit of about 20 mag.

The sheer numbers of individual stars that could be measured by Gaia in each of these clusters is worthy of mention, especially when contrasted with the inability to measure even a single star in any globular cluster by ESA's trailblazing astrometry mission, Hipparcos.

With Gaia, *several thousand* star members are detected and measured in each cluster. Some 20–30 000 are identified in a number, and more than 60 000 are counted in the case of the second nearest globular cluster known (after ω Cen), NGC 104. Also known as 47 Tucanae, or 47 Tuc, this is some 4000 pc distant, around 40 pc in diameter, and also visible with the naked eye.

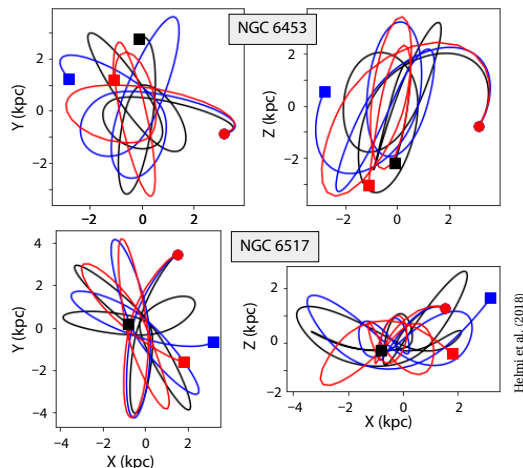
Mean globular cluster distances can then be derived. For example, for the nearest, 47 Tucanae, the mean parallax is 0.1959 ± 0.0002 milli-arcsec, corresponding to a distance of 5105 ± 5 pc. Remarkable!

THE BULK PROPER MOTIONS derived for each cluster are some one or two orders of magnitude larger than their parallaxes, and thus the measurements are typically both robust and significant. Their location in Galactic coordinates, and their space motions, could then be derived for all 75 clusters (see figure).

The outstanding quality of the DR2 data, together with the absolute reference frame (i.e. free of expansion and rotation) in which the proper motions are defined, has allowed the clear detection of rotation in five of their 75 globular clusters. For three of them (NGC 104, NGC 5139, and NGC 7078), this was already known, and rotation was also detected in NGC 5904 and NGC 6656.

Other interesting velocity structures can be seen in many. NGC 3201, for example, shows a very pronounced 'perspective contraction', a geometrical effect due to its large radial motion and its relatively large parallax.

In NGC 6397, considered to have been subject to core collapse, there is evidence of an expanding outer halo.



Galactic orbits of two globular clusters (face-on and edge-on) (different colours are for different Galaxy models)

THEY THEN used these positions and space motions, along with various state-of-the-art models of the Galaxy's mass distribution (for example comprising a stellar bulge, star and gas disks, and a dark matter halo), allowing Helmi et al. to follow their orbits backwards in time around the Galaxy over the past 250 million years.

The rather small differences in these predicted orbits over short timescales implies that the post-Gaia ability to predict their past orbits is impressively good. These predictions might therefore be used to search for the 'tidal tails' of some of the clusters, i.e. stars slowly lost from the cluster as it ploughs its way around the Galaxy.

Future studies of the orbital properties of the more distant globular clusters will also allow their relation to the present-day dwarf galaxy population to be examined. And if some of the globular clusters observed with Gaia are associated remnants of long-gone accreted galaxies, their stellar debris might be discovered and characterised using data from DR2 (and beyond).

WHILE FURTHER analysis, and much better data from Gaia, are both still forthcoming, it is now firmly expected that the Gaia data will eventually allow determining the mass distribution of our Milky Way Galaxy far out into the extremities of its dark matter halo.

In more technical terms, the data should allow resolving the degeneracy between the slope of the mass density profile and the orbital anisotropy. Its unknown anisotropy has been the limiting factor in attempts to pin down our Galaxy's mass to date, but Gaia DR2 has shown that this should soon be an observable quantity.

It is worth reiterating that, compared to the pre-Gaia era, errors have been reduced by roughly a factor 100. As Helmi et al. (2018) concluded: '*The measurements for these clusters are of outstanding quality, with the formal and systematic uncertainties being effectively negligible.*'

