31. The motion of dwarf spheroidals

Dwarf spheroidal galaxies, or dSph, are small, low-luminosity galaxies comprising an old stellar population with very little dust. In contrast to dwarf elliptical galaxies, they are roughly spheroidal in shape. Some two dozen are known as companions to either the Milky Way or to the Andromeda Galaxy (M31). They are named after the constellation in which they are found.

The first known, Sculptor and Fornax, were discovered by Harlow Shapley in 1938, where he described them as *'unlike any known stellar organisation'*. But despite weighing in at around 10^7 solar masses, further discoveries were challenged by their low luminosities and low surface brightnesses.

ESO/Digitized Sky Survey 2

By the late 1990s, their rarity seemed to be in conflict with the ΛCDM (Lambda cold dark matter) cosmological model, which predicted that massive galaxies like the Milky Way should be surrounded by many dark matter dominated satellite halos.

This conflict eased with the discovery of around a dozen very faint Local Group dwarfs from the Sloan Digital Sky Survey around 2000, and a similar number discovered by the Dark Energy Survey around 2015.

The distinction between dwarf spheroidals and globular clusters is not always sharp: one discriminant may be the presence of a significant amount of dark matter in the former, and its absence in the latter.

As typified by Sextans and Hercules, their orbits, structure, and internal dynamics, often appear to be affected by the gravitational forces of the galaxy (either the Milky Way or M31) that they are orbiting.

Better knowledge of their structures and orbits would have numerous implications, ranging from the scale of the formation of the smallest galaxies in the Universe to constraints and challenges for cosmological models, to the effect of the environment on their dynamical and chemical evolution, and to constraints on the form of the hot gaseous halo of the Milky Way.

These kinds of specific studies were keenly anticipated in the scientific case for Gaia presented to the ESA advisory committees at the time of its selection in 2000, when just eight dwarf satellite galaxies were known. As we stated there:

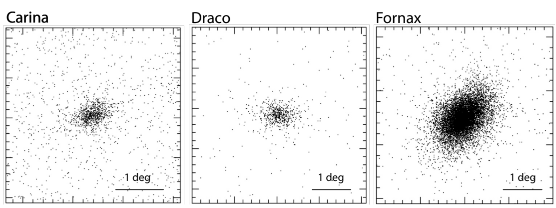
> "These dwarf spheroidal galaxies provide key dynamical tracers of the outer mass distribution of the Milky Way, at larger distances than any other available tracer. For the nearer dwarfs, especially Ursa Minor, Gaia will allow internal dynamical studies... Ursa Minor is unique among the dwarf spheroidal galaxies in showing marginal evidence for minor axis rotation, an indicator of possible triaxiality, tidal perturbation by the Milky Way, or non-isothermality in the dark matter... The Gaia proper motions will provide excellent discrimination between field stars, and provide a clean test of the expectation that all these dwarf galaxies are parts of extended tidal tails."

In their study of the motions of globular clusters and dwarf spheroidal galaxies with Gaia DR2, Helmi et al. (2018) examined the nine 'classical' dwarf spheroidals as examples of what can be achieved.

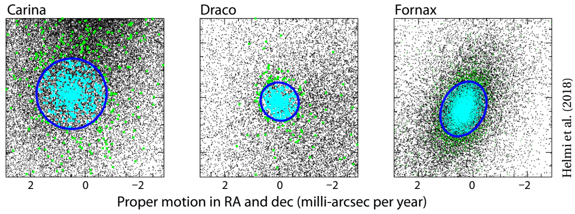
Their selection of stars as candidate galaxy members proceeded by selecting Gaia objects within a one or two degree field satisfying the two most basic criteria: from the Gaia astrometry, as lying within 2σ of the system's mean proper motion. And from the Gaia photometry, as stars populating the red giant branch and blue horizontal branch of these old stellar populations.

This possibility of selection according to proper motion reveals, in many cases, asymmetries in the distribution of the stars on the sky.

Thus, in the examples shown here, there is an indication of tidal streams in the case of Carina, and there are spatial asymmetries in the case of Fornax.



Helmi et al. (2018)



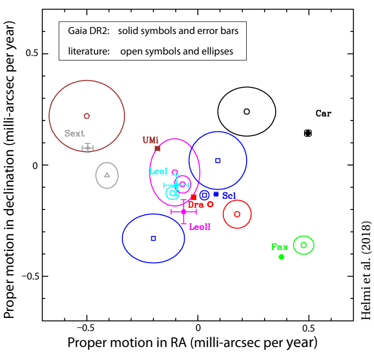
Gaia DR2 distances to dwarf spheroidal galaxies

Name	X [kpc]	Y [kpc]	Z [kpc]
Fornax	$-33.1^{+2.6}_{-2.7}$	$-51.1^{+4.1}_{-4.2}$	$-134.5^{+10.8}_{-11.0}$
Draco	$4.0^{+0.3}_{-0.3}$	$62.6^{+5.2}_{-4.5}$	$43.5^{+3.6}_{-3.1}$
Carina	$-16.7^{+0.9}_{-0.9}$	$-95.7^{+5.0}_{-5.3}$	$-39.7^{+2.1}_{-2.2}$
Ursa Minor	$-13.9^{+0.5}_{-0.6}$	$52.1^{+2.1}_{-2.0}$	$53.6^{+2.2}_{-2.0}$
Sextans	$-28.4^{+1.4}_{-1.3}$	$-57.0^{+2.8}_{-2.5}$	$57.9^{+2.6}_{-2.8}$
Leo I	$-115.5^{+7.6}_{-7.2}$	$-119.6^{+7.9}_{-7.4}$	$192.0^{+11.9}_{-12.6}$
Leo II	$-69.0^{+3.9}_{-3.8}$	$-58.3^{+3.3}_{-3.2}$	$215.2^{+11.9}_{-12.3}$
Sagittarius	$25.2^{+2.0}_{-1.8}$	$2.5^{+0.2}_{-0.2}$	$-6.4^{+0.5}_{-0.5}$
Sculptor	$3.1^{+0.2}_{-0.2}$	$-9.8^{+0.7}_{-0.7}$	$-85.4^{+5.7}_{-6.1}$
Bootes I	$22.7^{+1.1}_{-1.0}$	$-0.76^{+0.03}_{-0.04}$	$61.0^{+2.8}_{-2.7}$
LMC	$7.1^{+0.3}_{-0.3}$	$-41.0^{+2.0}_{-2.0}$	$-27.8^{+1.4}_{-1.4}$
SMC	$23.3^{+0.9}_{-0.9}$	$-38.1^{+1.5}_{-1.5}$	$-44.1^{+1.7}_{-1.7}$

In the maps of proper motion, where the same three example galaxies are shown here, stars surviving the astrometric and photometric selection criteria are shown as cyan dots. They clearly clump much more strongly in the diagrams than the likely non-members (shown as black points).

The extension in proper motion space is, however, considered most likely due to the errors of the present proper motions. The blue ellipses correspond to a 3σ dispersion around the mean values. Green points correspond to stars that fall within the photometric selection criterion, but outside the astrometric cut-off.

These dwarf spheroidal galaxies are typically very distant, ranging from about 26 kpc in the case of Sagittarius, to around 250 kpc in the case of Leo I, well beyond the Magellanic Clouds. Their bulk proper motions are consequently very small, rarely reaching 0.5 milli-arcsec per year. The best previous determinations of these tiny motions have mostly been made possible from the Hubble Space Telescope.



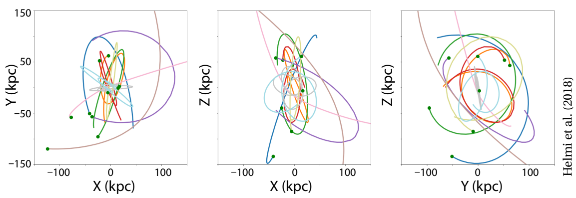
The agreement is reasonable, but the Gaia errors are much reduced. This is especially true for the galaxies for which more than a few hundred (and up to several thousand) members have been identified, such as Carina, Draco, and Fornax. Compared with HST observations, Gaia has the advantages of covering the entire galaxy, with the proper motions being in an absolute reference frame. The proper motion of the 'ultra-faint dwarf' Bootes I is also determined for the first time.

What I found most fascinating about these early results was the Galactic orbits that Gaia has been able to illuminate for these dwarf spheroidal galaxies.

Helmi et al. (2018) used their derived 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), to follow their orbits backwards in time around the Galaxy over the past 250 million years.

Detailed inspection shows that Draco and Ursa Minor have very similar orbits, and possibly constitute a physically connected group. However, the orbital planes of most others are different, with that of Sagittarius being orthogonal to those of Draco and Ursa Minor.

Most, it turns out, are on (slightly) prograde orbits, while Fornax is retrograde, qualitatively similar to what has been found for globular clusters. However, their orbital eccentricities are very different. Few have very eccentric orbits, with Carina even somewhat circular.



All this leads to two important conclusions. First, there is only a weak similarity, if any, between the orbits of globular clusters and dwarf spheroidals. Second, their eccentricity distribution is inconsistent with the findings of recent cosmological simulations, where they are predicted to be on rather radial orbits.

It has been suggested that the dwarf satellites of the Milky Way lie in a plane. Helmi et al. (2018) find, instead, that their orbits tend to be almost perpendicular to the Galactic plane, but spanning a range of orientations.

This implies that even though the orientation of the average orbit plane may be similar, they may rotate in the opposite sense. Sculptor and Sagittarius move in planes that are nearly perpendicular to each other, and to the Galactic disk.

This ordered complexity might indicate some collective infall from a preferred direction, perhaps a 'cosmic web filament' aligned with the z-axis. But it appears to exclude a single event underlying their origin.