93. The mass of the Milky Way

WHAT IS THE MASS of our Milky Way galaxy? Why is it important to know? Why is it so difficult to measure? And what is Gaia contributing to our knowledge?

IN THEIR REVIEW of the structural and kinematic properties of our Galaxy, and the state of knowledge pre-Gaia, Bland-Hawthorn & Gerhard (2016) placed its mass at somewhere between $0.5-3\times10^{12}M_\odot$.

Despite being one of its most fundamental parameters, and despite decades of intense effort, today's best mass estimates still span a significant range.

Why is it important to know? Accurate determination of the mass profile of the Milky Way has implications for our understanding of the dynamical history of the Local Group, including both its past evolution and any future interactions. And, perhaps even more fundamentally, the mass of a galaxy (and its mass distribution) are intrinsically linked to the formation and growth of structure in the Universe.

Consequently, a better understanding of the mass and mass distribution of our own Galaxy provides a better picture of where it sits in a cosmological context, in particular whether it is typical or atypical and, hence, how much of what we learn about the Milky Way can be applied to other galaxies.

WHY IS IT so difficult to measure? The main problem is that, while the masses of the principal baryonic components (the supermassive black hole at its centre, the central bulge, and the flattened disk) are reasonably well determined, its other major component, the halo, is dominated by dark matter. And it is our inability to see dark matter directly that gives rise to the greatest uncertainty in estimating its mass.

The problems do not end here. We can only hope to measure the mass of the dark matter which has had time to 'virialise' in the Galaxy, the so-called 'virial mass' defined within some adopted 'virial radius'. How far out to measure is usually expressed as the mass within a region in which the average density exceeds some multiple of the mean density of the Universe.

It is the distribution of dark matter which controls the motion of distant 'tracer' objects. These include halo stars and globular clusters as powerful probes of the inner halo, while dwarf spheroidal galaxies offer better coverage further out. In their compilation of total mass estimates between 1999–2014, Bland-Hawthorn & Gerhard (2016, Table 8) also quote estimates from the kinematics of halo streams, from the kinematics of hypervelocity stars, and from modelling of the escape velocity.

But all of these estimates remain sensitive to assumptions such as which of its satellites are bound, the shape and extent of the dark matter halo, and the velocity anisotropy of the halo and of its satellite system.

And this takes us to one of the key problems faced by all mass estimates based on kinematics: while we need to know the total space velocity of each tracer, we seldom have knowledge of all three components of motion; typically, we only have line-of-sight velocities.

Since the Sun is relatively close to the Galactic centre, most line-of-sight velocities probe mainly the component of motion in the Galactocentric radial direction, providing little information about their tangential motions. As a result, estimated masses pre-Gaia depended strongly on the assumptions used for the tangential motions: the so-called mass–anisotropy degeneracy.

ACCORDING TO Bland-Hawthorn & Gerhard (2016), the analysis of halo star kinematics typically results in relatively low values, $M_{200}\lesssim10^{12}M_\odot$ (where M_{200} denotes the mass within 200 kpc). Here, the main uncertainties are the lack of stellar tangential velocities from proper motions, along with the need to extrapolate from spatially limited samples to the scale of the virial radius.

Satellite galaxies reach to larger radii, with uncertainties coming from small numbers and, again, a lack of proper motions. Estimates based on satellite and globular cluster kinematics typically result in higher values, $M_{200}=1-2\times10^{12}M_\odot$ if the Leo I dwarf galaxy (with its large line-of-sight velocity) is assumed to be bound to the Milky Way; or $M_{200}\lesssim10^{12}M_\odot$ if it is considered as unbound (Bland-Hawthorn & Gerhard, 2016).

One estimate of our Galaxy's total mass that doesn't depend on the choice or details of a tracer population is the so-called 'timing mass'.

In the original formulation by Kahn & Woltjer (1959), the Milky Way and M31 proto-galaxies are assumed to have had a small separation at the time of the Big Bang, subsequently moving apart as they participated in the Hubble flow. If there is sufficient mass, their expansion is reversed. Given an estimate of the age of the Universe, together with their present separation and approach velocity, the equations of motion can be solved to give the mass of the Galaxy, along with that of the Local Group.

Timing mass estimates in subsequent work (e.g. Li & White, 2008) have been lowered due to improved relative space motions, and more accurate estimates of the solar reflex motion. With current mass estimates for M31 being comparable to that of the Milky Way, the timing mass provides an upper limit to the Galaxy's virial mass of $\lesssim 1.6 \times 10^{12} M_\odot$ (van der Marel et al., 2012).

According to Bland-Hawthorn & Gerhard (2016), the halo star kinematic studies provided (at least pre-Gaia) the largest and most reliable data sets. They gave an average of $M_{200} = 1.1 \pm 0.3 \times 10^{12} M_\odot$, or equivalently $M_{\rm vir} = 1.3 \pm 0.3 \times 10^{12} M_\odot$, consistent with the upper limit from the timing mass.

This compares with a *baryonic* mass of $M_{\rm b} = 6.3 \pm 0.5 \times 10^{10} M_\odot$ (stars and cold gas), or $8.8 \pm 1.2 \times 10^{10} M_\odot$ when including a contribution from the hot corona. This, in turn, leads to a baryonic mass fraction (out to some chosen virial radius) of $6 \pm 1\%$, well short of the 'universal' value of about 16%.

Given these complexities of the determination of our Galaxy's mass, it should not come as a surprise that the advent of the Gaia data has led to a flurry of some 20–30 papers to date, targetting a re-analysis of some of these methods, and in particular using the more complete space motions of halo stars, globular clusters (see essay #30 for Gaia's contributions), and dwarf spheroidal galaxies (see essay #31). In this fast-changing landscape, I will provide a current snapshot.

Employing data from DR2, Callingham et al. (2019) inferred the Galaxy's total mass by comparing model satellites in the EAGLE cosmological hydrodynamics simulations with the dynamics of 10 of the 'classical' Milky Way satellites with six-dimensional phase-space measurements (i.e. positions and velocities), including updated proper motions from Gaia (including the LMC, the SMC, Draco, and Ursa Minor).

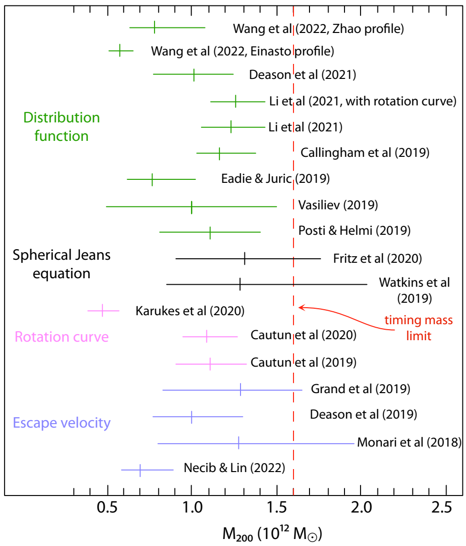
In this 2-d space, the orbital properties of satellite galaxies vary according to the host halo mass, which can then be inferred from the likelihood that the observed satellite population is drawn from this distribution function. They inferred a mass of $1.17^{+0.21}_{-0.15} \times 10^{12} M_\odot$.

Fritz et al. (2020) used a somewhat similar approach based on Gaia DR2 proper motions of 45 satellite galaxies to find a mass of $1.43^{+0.35}_{-0.32} \times 10^{12} M_\odot$ within 273 kpc, extrapolating to a virial mass of $1.51^{+0.45}_{-0.40} \times 10^{12} M_\odot$.

Watkins et al. (2019) used the Gaia DR2 proper motions of 34 halo globular clusters within 21.1 kpc. They determined the mass of the Milky Way inside the outermost globular cluster as $0.21^{+0.04}_{-0.03} \times 10^{12} M_\odot$, leading to an implied virial mass of $1.28^{+0.97}_{-0.48} \times 10^{12} M_\odot$.

Various mass determinations have followed with Gaia EDR3 in 2020, using various related methods and assumptions, including modelling halo tracers using spherical, power-law distribution functions.

As one example, Wang et al. (2022) used Gaia EDR3 proper motions for about 150 Milky Way globular clusters, combined with constraints from the rotation curve (over distances of 5–25 kpc). They derived a total mass in the range $0.536^{+0.081}_{-0.068} \times 10^{12} M_\odot$ to $0.784^{+0.308}_{-0.197} \times 10^{12} M_\odot$, depending on the dark matter profile (Zhao or Einasto), values at the lower end of current estimates.



These, and some of the other results based on Gaia DR2 and EDR3, are shown here (adapted from Wang et al., 2022), colour-coded by methodology.

What can we conclude from this present state of affairs? Perhaps first, that while the formal errors are often much smaller than they were pre-Gaia, and while a value of $\sim 10^{12} M_\odot$ appears favoured, current estimates are still affected by the choice of tracers and model assumptions. Second, the Gaia results are nonetheless providing much new insight into its physical complexity. Third, that the Galaxy mass, dominated by its dark matter halo, remains relatively poorly characterised… our imperfect understanding of this dark matter halo, and its substructure, epitomised by the 'too-big-to-fail' problem (Boylan-Kolchin et al., 2011), still persists!