Galactic substructures as tracers of dark matter and stellar evolution

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English Summary

Two of the most important questions in modern astronomy are:

- What is the nature of dark matter?
- How do galaxies form and evolve?

Dark matter, in contrast to ordinary matter, does not interact with light and is therefore invisible to us. Although it does interact with other matter through gravity, and according to the standard cosmological model had a fundamental impact on all structure formation in the Universe, its essence is still unknown and we have yet to directly detect it. Similarly, much of the processes governing galaxy formation and evolution are still shrouded in mystery. Although cosmological simulations have made a crucial contribution to advancing our understanding of both dark matter and galaxy formation processes, theoretical models and simulations can only take us part of the way: observational data is needed to compare with the predictions of the models and discriminate between them. Our own Galaxy, the Milky Way, is an ideal laboratory for unravelling these secrets for it is only in the Milky Way where we are afforded a uniquely detailed inside view of a galaxy and where we can measure our observables with a precision that is unparalleled. The implications of these local observations, however, reach beyond just the Milky Way, helping us place constraints on the larger Universe and physics.

The total mass, overall shape and the way in which the mass is distributed within the Galaxy are some of the most important and essential properties of the Milky Way that allow for meaningful comparison with models. The Milky Way, like all similar galaxies, contains not only ordinary, visible matter, but also large quantities of dark matter. Specifically, the visible sections of galaxies are embedded in a vast dark matter halo. Therefore, when we talk about the mass of the Galaxy, we also consider its dark matter content. The challenge lies in how to measure this dark contribution and the answer is: through its gravitational effect on the visible matter.

To make these measurements many scientists have turned their eyes towards a type of Galactic substructure called stellar streams. Stellar streams are (mostly) narrow, long trails of stars that follow nearly the same path around the Galaxy. They formed from stellar clusters, such as globular clusters or dwarf galaxies, which were torn apart due to the tidal forces of the Milky Way's gravity: the force of gravity pulls stars a little stronger on the side of the cluster that is closest to the centre of the Milky Way and a little weaker on the far side of the cluster compared to the centre of the cluster. If the difference between these forces grows large, the stars at the far and near ends of the cluster can escape the cluster all together. Since the velocities of these stars are nearly identical to the velocity of the original cluster, these stars begin to orbit the Galaxy at nearly the same trajectory as the cluster itself, and all other stars that escape the cluster in the same manner. The stars that escape the cluster on the near side are slightly more bound to the Galaxy and thus race ahead of the progenitor cluster, while those at the far side will trail behind the cluster. Over time these tails of stars stretch out further and further, elongating the stream. This process results in the narrow arcs of stars we call stellar streams. An illustration of a typical stream structure is presented in Figure 5.6.1. The key property that makes stellar streams so interesting is that each stream approximately maps out a single orbit around the Galaxy. As orbital trajectories are dependent on the mass they orbit, they can thus directly inform us about the mass distribution in the Galaxy. Stellar streams can therefore reveal fundamental properties not only of our own Galaxy, but through comparisons with models, of the Universe in general.

However, streams are not the only type of Galactic substructure that can unlock insight into larger puzzles. Open clusters, loosely bound groups of

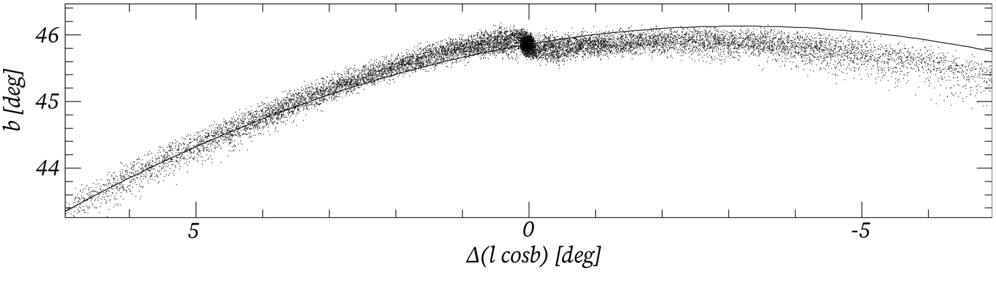

Figure 5.6.1: A model of a stellar stream in Galactic coordinates, with the orbit of the progenitor shown as a black line. Image credit: Dehnen et al. (2004).

stars that move through the Galaxy together, are as important a driver of stellar evolution studies, as stellar streams are for dark matter and galactic evolution research. All members of an open cluster were formed at the same time from the same molecular cloud, thus they all have nearly identical ages, chemical compositions, distances and space velocities, the only differences between them being their distinct initial masses. These circumstances make open clusters ideal controlled environments for developing and testing stellar evolution theories. As the stars are the same age and of same chemical composition, the differences in their current evolutionary stages are determined solely by their initial mass which allows clear verification of evolution models. Furthermore, as all stars within a cluster are effectively at the same distance their relative brightness is only determined by the differences in their intrinsic luminosity: stars that appear brighter are inherently more luminous and therefore more massive.

This work

The topics in this Thesis can be divided into two branches, the first following our endeavour to constrain the Galactic mass distribution with stellar streams and the second detailing our study of the Hyades open cluster. Both of these topics of study were, in part, motivated by the arrival of observational data sets that are revolutionary both in their precision and volume. Indeed, we are currently in the golden age of Galactic astronomy incited largely by the European Space Agency's Gaia space mission. Gaia maps the positions and velocities of more than a billion stars in the Milky Way providing us with an extraordinary wealth of data. This treasure trove is further enriched by complementary observations from multiple planned or ongoing ground-based large-scale spectroscopy surveys such as APOGEE, WEAVE, H3, S5, DESI, 4MOST and SDSS-V. The advent of this phenomenal data is therefore the resounding answer to the question of why is now the right time to undertake these studies.

A second source of inspiration to undertake the stellar stream studies at this time comes from a novel method of data analysis. Developing analysis methods for streams is a great challenge and although a variety of methods have been proposed, they all share the same essential limitation: they cannot (practically) be applied to multiple stellar streams simultaneously. This is far from an ideal scenario if we want to take the utmost advantage of the prodigious new data we are witnessing the arrival of. This novel method, however, is designed to allow us to do just this.

Within this method, the trajectories of stream stars are described not by positions and velocities but by integrals of motion. Integrals of motion are physical quantities that are conserved along the entire orbit of a star. Which quantities are conserved depends on the geometry of the system we are dealing with, for example, in spherically symmetric mass distributions, there are three integrals of motion: energy, angular momentum, and the z-component of the angular momentum vector. And the specific values these are set at depend on the star's initial position and velocity, but also on the Galactic mass distribution.

Not only can the integrals of motion be used to describe the full path of a single star, they can also act as a metric characterising the similarity of the orbits of stars within the same stream. If all stream stars were sharing the exact same orbit, their integrals of motion would be equal. Stars on neighbouring orbits, however, form a tight cluster in integrals of motion space instead. This inherent clustering behaviour is key to the method used in this work to measure the Galactic mass profile. The rationale for this method is as follows. Knowing the positions and velocities of a sample of stream stars, the unknown for the calculation of integrals of motion is the Galactic mass distribution. We can assume a trial model for this mass distribution and calculate the integrals of motion. If the integrals of motion do not cluster, we can conclude that the model for the mass distribution we chose, is not a good representation of the true Galactic mass distribution. We keep trying with different trial mass distribution models until we find one that does produce a tight cluster in integrals of motion space - this model represents the true Galactic mass distribution the best.

The clustering method had previously been demonstrated only on artificially created stream data but in **Chapter 2** we apply the method to observed stream data for the first time. We derive constraints on the Milky Way's mass distribution by analysing a collection of four stellar streams, both individually and jointly. The study finds that different streams yield different estimates for the Galactic mass distribution, attributing this to systematic uncertainties. We also see hints that some streams might be more affected by systematic biases than others. Although single stream fits are found to be unreliable, we also learn that the systematic biases of single streams can be counteracted when a combination of streams is simultaneously analysed. This result strongly points to the conclusion that many streams should be analysed together to reach a consensus estimate for the mass distribution of the Milky Way.

In **Chapter 3**, we investigate the systematic uncertainties of our setup more rigorously. Our goal in this Chapter is to see if we can pinpoint which stream properties make them more susceptible to deliver biased results. To do this, we adopt simulated streams found in FIRE galaxy evolution simulation for our analysis. Working with simulated streams allows us to directly compare our results to the known mass distribution of the simulated galaxy and thus identify the suspicious streams. Our analysis establishes a clear connection between the quality of the results a stream yields and their current location along their orbit: the streams that happen to be near their closest approach to the Galactic centre, the pericentre, consistently return worse constraints. We hypothesize that this behaviour is fundamental, rather than tied to our own clustering method, and linked to the pericentre stream's inability to distinguish between different Galactic mass distribution models efficiently.

When in previous Chapters we have dealt with the analysis of clearly defined stellar streams, in **Chapter 4** we move to more complex data sets: the target of our analysis is the general Galactic stellar halo. Although the stellar halo is known to be mainly populated by a large set of criss-crossing stellar streams, most of these streams formed a long time ago and have stretched out so far on their orbits, that it is extremely difficult to unravel them and determine which star belongs to which stream or which stars have no stream origin altogether. Therefore, in this Chapter, we apply the clustering method to the stellar halo sample, as it were, "blindly". Another complicating factor is that the stellar halo constitutes the furthest stars in the Galaxy and their observed position and velocity typically have high uncertainties. Therefore, to properly interpret our results we, concurrently, apply the clustering method to a population of streams from FIRE simulations where (i) a significant fraction of interloper stars have been added to the stream population, and/or (ii) realistic measurement errors have been assigned to each star.

In **Chapter 5**, we move from the topic of stellar streams to the study of open clusters. Specifically, this Chapters investigates the open cluster closest to us, the Hyades. Using the newly available Gaia data, we identify new candidate members for the cluster by analysing their space velocity and looking for common patterns. Next, using the high fidelity cluster members, we derive improved-precision distances to them using kinematic arguments: assuming the stars in the cluster are all moving with the same space velocity, any observed discrepancies from this velocity can be attributed to their variations in distance. These kinematic distances allow us to calibrate the brightness of stars: any differences in brightness that are only due to the stars' varied distances are counteracted and the residual their intrinsic brightness. These intrinsic brightnesses are only governed by the current evolutionary stage of each star enabling us to make comparisons with stellar evolution models.