Structure and substructure in the stellar halo of the Milky Way

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Summary

The role of galactic cannibalism in the Universe

Galaxies are systems composed of stars, planets, dust, gas, ice molecules and dark matter, and they are characterised by the emission of light in a wide range of wavelengths, which allow us to study the nuclear and chemical reactions that power them. The nuclear reactions take place in stars, whereas most the chemical reactions take place in the so called interstellar medium (gas clouds and dust grains) or in planets and circumstellar clouds. Galaxies are governed by gravity, which holds together all their elements and sets the basic constraints for their overall structure and evolution.

The first galaxies formed out of very small overdense seeds spread throughout the Universe, through the gravitational accretion of dark matter and gas clouds and the later birth of stars. These overdensities were the result of quantum fluctuations that followed the Big Bang and were amplified during the Inflation period. However, the size (and number) of galaxies today cannot be fully explained by the simple gravitational accretion of gas over the whole history of the Universe. It is explained, though, by a process called galactic cannibalism. In this process *the big fish eats the smaller fish*, meaning that the largest (most massive) galaxy brings closer, breaks apart and incorporates the material of the smaller (less massive) galaxy. The largest galaxy is basically exerting its gravitational pull on the smaller galaxy in a destructive way. When both galaxies are of similar mass and size, we call this process *major merging*, and when they are of different masses, we call it galactic cannibalism or *minor merging*. Galactic cannibalism and major merging can explain not only the size and number of galaxies observed nowadays, but also their history and morphology.

But galactic cannibalism is not just a theoretical construct, since galaxy mergers of varying magnitudes have now been observed in a large number of galaxies. Despite the large distances between galaxies, provided enough time (the life time of the Universe is 13,800 million years!), gravity ensures that many galaxies will move close enough to each other to merge or to have one of them cannibalise the other, in a recurrent process.

In the context of the current cosmological framework —the Λ Cold Dark Matter model, which attempts to explain the dynamics and evolution of the

Universe—, galactic cannibalism is a major driver for galaxy evolution, and together they are often referred to as the Hierarchical Formation scenario. This theory succeeds in explaining the evolution of the Universe both at cosmological and galactic scales.

The *life record* and the *fossil record* of galaxies

Since the process of galactic cannibalism has been ongoing for most of the Universe's history, it is natural to search not only for current examples of it but also for the traces of previous events.

Ongoing or recent episodes of galactic cannibalism can be recognised by the stellar debris and the dissolving remnant of the galaxy being torn apart. Because galactic cannibalism is a slow process, the satellite galaxy often has time to complete a few orbits around the larger galaxy before being completely destroyed. As the satellite galaxy is progressively stripped off its gas and stars, these constituents keep a path close to the original orbit of the satellite, but spread out forming a stream or a partial shell, depending on the ellipticity and energy of the orbit (see Figure 1.2 for an example).

Old episodes are harder to identify since, by now, their stellar debris have already abandoned the original orbit and have mixed up with the "indigenous" stars. Nonetheless, both chemical tagging and kinematic properties can be used to group stars with a similar origin provided their collective fingerprint is different from that of the local stars.

Globular clusters, which are small spherical associations of stars mostly born from the same parental gas cloud in the outskirts of galaxies, can also be tidally stripped and cannibalised by their host galaxy.

Our host galaxy, the Milky Way, is no exception to the process of galactic cannibalism and hierarchical growth. The current research suggests that it has not undergone any major merger at least in the last $10,000$ million years (a merger between two galaxies of comparable mass), but instead various minor accretion events. In addition, it is currently in the process of cannibalising several satellite galaxies and a few globular clusters. This makes the outskirts of our galaxy (the region away from the galactic disk, known as the halo) a very interesting place.

This thesis

This thesis has focused on expanding our knowledge of the outskirts of our own galaxy, the Milky Way, with two particular aims. The first aim has been to understand the overall underlying distribution of stars in the halo, and the second aim has been to identify and characterise new satellite galaxies and stellar streams resulting from ongoing cannibalisation events.

The first aim is covered in chapters 2 and 3 and makes use of observations carried out with the Canada-France-Hawaii Telescope (CFHT) in Hawaii, the Isaac Newton Telescope (INT) in the Canary Islands and the VLT Survey Telescope (VST) in Chile. The halo of spiral galaxies is an ellipsoidal component that extends beyond the disk and the bulge of the galaxies, thinly populated with stars in comparison to the other two components. Because of their low numbers and large distances, observing these stars in statistically useful numbers poses technical and instrumental challenges, and makes it difficult to infer general properties of the halo such as its exact shape or the dependence of the stellar number density with the distance from the centre of the Galaxy. Using extremely sensitive cameras in the previously mentioned telescopes (the MegaCam, the WFC and the OmegaCAM, respectively), we have obtained large samples of stars out to remarkable distances. With these data, we have been able to confirm that the density of stars in the halo decreases with distance as broken power law. We have also been able to set strong constraints in the shape of the stellar halo. These constraints indicate that the halo is moderately flattened towards the poles (as a mandarin or a walnut would be, as opposed to an egg standing vertical) but practically circular on its main plane (as seen from above).

The second aim is addressed in chapters 4 to 6. One of the main products of this thesis is a cross-correlation algorithm that allows us to exploit pencil-beam sky imaging surveys with only two colours to identify stellar overdensities in the halo, such as those that may be associated with streams, globular clusters or satellite galaxies. The power of this algorithm is that it yields competitive results where previously three colours (three photometric filters) were needed, reducing the observing time and costs. This algorithm also obviates the need for control or comparison sky fields near the target fields. Of course the traditional spatially-continuous wide-area surveys and the surveys with more than two colours still provide significant advantages, but this algorithm opens the door to using extremely deep, high quality archival data that has never been used before for this type of work.

Through this method, we have identified overdensities associated with three different streams (the Sagittarius stream, the Orphan stream and the Palomar 5 tails) and, in combination with independent measurements of the age and metallicity of the stars in those streams, we have derived accurate distances to them. Notably, we have expanded the catalogue of distance measurements to the Sagittarius stream along its Southern hemisphere tail and along its furthest Northern piece, and we have also identified two overdensities matching a predicted secondary nearby old wrap of this same stream, which needs further confirmation.

We have also used this algorithm in the search for stellar overdensities near globular clusters in the Milky Way. We do these in order to determine whether any of the globular clusters is associated with an underlying stream or overdensity. On the one hand, if a globular cluster was associated with a major stream, it would indicate that the globular cluster was part of the globular cluster system of the disrupted satellite galaxy that originated the stream. On the other hand, if a globular cluster was associated with a minor adjacent overdensity, it would suggest that the globular cluster was either slowly becoming internally unbound or that it was being cannibalised by the host galaxy. We have explored the vicinity of 23 globular clusters and found eight clear overdensities but potentially up to thirteen. Using distance estimations and the position of the overdensities in the sky (and occasionally kinematic comparisons), we have analysed whether the overdensities could be associated with a known stream or to the adjacent globular cluster. The three situations (no association, association with a major stream and possible association with a new overdensity) appeared in the sample, with a majority of no association cases.

Finally, we have applied the traditional techniques of distance slicing and density mapping to the first wide-area maps from the VST KiDS survey, in order to search for new streams and satellites. In these data products we have successfully recovered the expected major halo structures (such as the Sagittarius stream, the Virgo Overdensity and the Eastern Band Structure) and the Galactic thick disk contribution, as well as the tail of the Palomar 5 stream. No new streams or satellites have been unveiled due to the currently small area of newly sampled sky ($\sim 30\,\mathrm{deg}^2$) and to the still rather patchy state of these newly sampled areas. However, as the KiDS observations keep coming in, more data in new areas of the sky will become available. With currently only 10% of the total survey analysed and most of the data so far targeting previously surveyed areas of the halo, the future KiDS data releases should bring the chance for exciting discoveries in the halo of the Milky Way.