Halo streams as relics from the formation of the Milky Way

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Abstract. In this contribution we discuss the expected properties of our halo if our Galaxy had been built from mergers of smaller systems. Using both analytic arguments and high-resolution simulations, we find that the Galactic halo in the Solar neighbourhood should have a smooth spatial distribution and that its stellar velocity ellipsoid should consist of several hundred kinematically cold streams, relics from the different merging events. We also discuss observational evidence which supports this hierarchical picture: two stellar streams originating in the same system that probably fell onto the Milky Way about ten Gyr ago. Finally we address what future astrometric missions like FAME or GAIA may reveal by observing the motions of nearby halo stars.

1. Introduction

In recent years, considerable theoretical effort has been put into understanding the properties of galaxies within the hierarchical paradigm of structure formation in the Universe (e.g. Kauffmann et al. 1999). Our own Galaxy can play a very important role in constraining these models. For the Milky Way we have access to kinematics, distances, ages and chemical compositions of individual stars, information which is available for no other system. Thus observable substructure leftover by the different merging events could be just at hand.

The natural place to look for the stars of the various systems that merged to build up the Milky Way is the Galactic halo, since as such systems disrupt they leave trails of stars along their orbits. An ensemble of disrupted galaxies would thus naturally produce a spheroidal component. What imprints do these mergers leave on the present day distribution of halo stars? What are the observational requirements (accuracies, sample sizes) that will enable us to test from this perspective if our Galaxy was built hierarchically?

2. Characterising the signatures: Theoretical approach

Numerical simulations of the disruption of satellite galaxies which probe the outer parts of the Galaxy only, show that, after many Gyr of evolution, their stars are distributed in coherent spatial structures almost along great circles in the sky (Johnston, Hernquist & Bolte 1996). When the satellite’s orbits probe the inner Galaxy (i.e. with apocentres smaller than 30–40 kpc), the Galactic disk (breaking the spherical symmetry) makes the orbital plane precess
in space thus transforming the two-dimensional streams in three-dimensional structures. The stars appear now distributed almost homogeneously in space, and so the signatures of the different mergers experienced have disappeared (almost completely) in configuration space as shown in Figure 1.

Because phase-space density is a conserved quantity, the satellite galaxies initial high values strongly constrain how the debris can spread out in phase-space. As the satellite’s stars spread out in space, they define streams: kinematic structures such as those shown in Figure 2. These streams are the characteristic signatures of mergers, and should thus be visible in the kinematics of halo stars in the Solar neighbourhood if our Galaxy was indeed built hierarchically.

Helmi & White (1999) find that, if the whole $10^9 L_\odot$ stellar halo was built from disrupted satellites, the velocity ellipsoid in the Solar neighbourhood should
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consist of 300 – 500 stellar streams with internal velocity dispersions of \( \sim 5 \) km s\(^{-1}\). These results are based on numerical simulations and analytic calculations that model the disruption of a single satellite galaxy, and the evolution of its debris streams in a static potential. But note that this case is dramatically different from the hierarchical picture that we hope to test here.

With this in mind, we analysed high-resolution simulations of the formation of a cluster in a ΛCDM cosmology (Springel 1999). After scaling down the cluster to a galactic size halo (by a factor \( \sim 12 \) in radius and in circular velocity) we analysed the evolution of the debris originating in the different halos that merged to build up the “Galaxy”. We found that the debris streams behave in a similar fashion to the streams moving in a static potential (Helmi, White & Springel, in preparation). From these high-resolution simulations we can determine the number of dark-matter streams as a function of distance from the halo centre. We find that in what would be the “Solar neighbourhood” of the scaled halo, one should expect approximately 1000 dark streams (Figure 3). Note, however, that the scaling used above is independent of the assembly time of the halo, which thus means that one may expect a slightly larger number of streams for a galactic halo than for a scaled-down version of a cluster halo. In general a galactic halo (being assembled about 10 Gyr ago) will have had more time to relax than a cluster halo (typically assembled \( \sim 8 \) Gyr ago), and so the streams to spread out in space. We estimate that this number cannot be more than a factor \( \sim 2 \) larger.

How do these results compare to our estimates derived for the stellar halo before? How many star streams should we observe in the Solar neighbourhood? Each dark matter halo will contribute by about a factor of ten more

Figure 3. Mass-weighted number of streams in boxes of 2.72 kpc on a side for a high-resolution simulation (66 million particles) of the formation of a cluster in a ΛCDM cosmology scaled to a Milky Way halo, as a function of distance from the centre of the scaled halo. The thick grey line going through the data points corresponds to the median mass-weighted number of streams, derived for boxes at the same distance from the centre.
dark streams than stellar ones, since baryons are generally clustered in the inner roughly one-tenth of their host halo. Also due to this segregation, the baryons orbital properties do not exactly follow those of their dark matter counterparts. A typical star in the Solar neighbourhood has a period of 0.25 Gyr, with an apocentre of about 11 kpc. A typical dark matter particle will have an apocentre of the order of 20 kpc, corresponding to an orbital timescale of the order of 0.3 Gyr. Because the time for dispersal scales as $1/t^3$, this implies that the naively expected number of star streams should be doubled. In synthesis, if we break the 2000 dark streams (now scaled to take into account the earlier assembly of a galactic halo) into ten contributors, each one of these will give rise to $20 \times 2$ stellar streams, if our scalings are roughly right. This estimate brings us close to the result derived initially: we should expect about four hundred stellar streams in the Solar neighbourhood.

3. Finding the streams: Observational approach

Over the years, an increasing number of observations have been suggesting the presence of substructure in the halo of the Galaxy (e.g. Eggen 1965; Rodgers & Paltoglou 1984; Majewski, Munn & Hawley 1994). Detections of lumpiness in the velocity distribution of halo stars are becoming increasingly convincing, and the discovery of the Sagittarius dwarf satellite galaxy (Ibata, Gilmore & Irwin 1994) is a dramatic confirmation that accretion and merging continue to affect the Galaxy. However direct evidence that the bulk of the Milky Way’s population of old stars was built up from mergers had been lacking until quite recently. Using kinematic data from the HIPPARCOS satellite, Helmi et al. (1999) have found two halo star streams which share a common progenitor: a single coherent object disrupted during or soon after the Milky Way’s formation, and which probably resembled the Fornax and Sagittarius dwarf spheroidal galaxies. The kinematic properties of the sample of halo stars used are shown in Figure 4, with the stars identified as members of the streams highlighted. This figure should be compared to Figs. 1 and 2, which correspond to a simulation set up to reproduce the properties of the streams. The presence of these streams was also confirmed later by Chiba & Beers (2000) in a much larger sample.

Samples of halo stars in the vicinity of the Sun are currently too small to be useful to fully test the hierarchical picture and the predictions made in the previous section. Since the expected number of streams is approximately 500, the required samples should preferably have 2000 or more stars with good kinematics. To detect the clumpy nature of the velocity ellipsoid in the Solar neighbourhood, this ellipsoid should be broken up into the streams, in which case the required accuracy should be $\sigma \leq 120/(500)^{1/3}$ km s$^{-1}$ or $\sigma \leq 15$ km s$^{-1}$, values that can be reached presently. To detect the individual streams one may require a $3\sigma$ distinction or 5 km s$^{-1}$ accuracy.

4. Testing the paradigm: The future

Future astrometric satellites will measure with very high accuracy the motions of thousands to many millions of stars in our Galaxy. Whereas SIM is a targeted mission (and will thus not be useful to test in the Solar neighbourhood the pre-
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Figure 4. Distribution of nearby halo stars in velocity space for our original sample of giants with [Fe/H] ≤ −1.6 dex and distances ≤ 1 kpc (solid circles) and for the extended sample of more metal-rich and more distant giants (open circles). Candidates for our detected substructure are highlighted in grey: triangles indicate more metal–rich giant stars at distances > 1 kpc, diamonds more metal–rich giants at ≤ 1 kpc, squares metal–poor giants at > 1 kpc, and circles metal–poor giants at ≤ 1 kpc. Here we used kinematic data from the HIPPARCOS satellite, and radial velocities, metal abundances and photometric distances obtained from ground based data.

dictions described above), FAME promises to measure positions and parallaxes for about 4 × 10^7 stars. For stars brighter than V ∼ 5 it will do so to better than 50 µas in parallax and 50 µas yr^{-1} in proper motion, and at V ∼ 15 these accuracies will be degraded by an order of magnitude. On the other hand, the proposed ESA astrometric satellite GAIA will provide very precise astrometry (<10 µas in parallax and <10 µas yr^{-1} in proper motion at V ∼ 15, increasing to 0.2 mas yr^{-1} at V ∼ 20) and multicolour photometry, for all 1.3 billion objects to V ∼ 20, and radial velocities with accuracies of a few km s^{-1} for most stars brighter than V ∼ 17, so that full and homogeneous six-dimensional phase-space information will be available.

Helmi & de Zeeuw (2000) have run numerical simulations of the disruption of satellite galaxies in a Galactic potential with the aim of building up the entire stellar halo. Using these simulations, they generate artificial FAME and GAIA catalogues in which they look for the signatures left by the accreted satellites. They find that disrupted satellite galaxies may be recovered after a Hubble time as lumps in the space of integrals of motion. Using energy, angular momentum and its z-component to define such a space, they look for the clumps using a Friends-of-Friends algorithm. For a simulated GAIA catalogue they are able to recover 50% of all accreted objects, whereas for a FAME catalogue (using radial velocities accurate to 15 km s^{-1}) the recovery rate is ∼ 15%, an effect which is due to the lower accuracies and the brighter limiting magnitude (i.e. the samples with good kinematic information are smaller). However both missions should be able to test the hierarchical formation paradigm on our Galaxy by measuring the amount of halo substructure in the form of nearby kinematically cold streams. In Figure 5 the two-point correlation function in velocity space is shown for four realizations of the artificial FAME and GAIA catalogs, each
Figure 5. The two-point correlation function for particles (assuming luminosities of giant stars) inside spheres of 1 kpc radius around the Sun (defined as 8 kpc from the Galactic centre on the Galactic disk) computed as the weighted average over five realizations of the FAME and GAIA catalogues. The different symbols correspond to spheres at different locations of the “Sun” on the Solar circle.

corresponding to a different position of the “Sun” along the “Solar circle”. The presence of kinematically cold streams is visible as an excess of pairs in the bins corresponding to small velocity differences. And, even with velocity errors of the order of 20 km s⁻¹, it will be possible to determine that the clumpy nature of the halo velocity ellipsoid in the Solar neighbourhood.

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