ABSTRACT

The Sloan Digital Sky Survey (SDSS) provided the first detailed maps of substructure in the Galactic halo, including the “Field of Streams” by Belokurov et al. in 2006. This review provides a brief summary of what Stellar streams tell us about the formation and evolution of the Galactic halo. SDSS data has shown that the substructure comprises 30% of the inner halo and increases with larger galactocentric radii, showing that accretion has occurred throughout its history. Comparing older and younger stellar populations shows that the accretion rate of the halo has remained constant over the past few Gyr. Models of the halo using stellar streams shows that the halo is most likely triaxial and oblate, however observations have not ruled out models with a spherical halo. The introduction of the Large Synoptic Survey Telescope in the next decade will provide even more answers about stellar streams and their insights in to the Galactic halo.
1 Introduction

The Sloan Digital Sky Survey (SDSS) has resulted in numerous astronomical discoveries, and one of its most important may be the discovery of substructure in the Galactic Halo. Since the launch of SDSS in 1998, more than 18 stellar streams and halo substructures have been discovered, all of which shed light on the formation and evolution of the Milky Way. The most famous of these discoveries, the “Field of Stream” by Belokurov et al (2006), showed four distinct streams, all of which can be seen in Figure 1. These streams are believed to be remnants of dwarf spheroidal galaxies that were accreted by the Milky Way.

The first evidence for stellar streams in the Galactic Halo was found in 1994 by Ibata et al. who discovered the Sagittarius dwarf spheroidal galaxy. Its subsequent stream was imaged by Majewski et al. (2003) using the Two Micron All Sky Survey (2MASS). Since this discovery, many other important streams have been mapped. The Monoceros overdensity (Newberg et al., 2002), the Orphan stream (Belokurov et al., 2007), the Hercules-Acquila cloud, as well as the Virgo Stellar Stream (Duffau et al., 2006) were all discovered using SDSS. These features continue to be identified, even in the outer reaches of the halo, as shown by Drake et al. (2013) who unveiled evidence for substructures out to 100 kpc. Many more of these features are predicted to exist based on comparisons to M31 (Conn et al., 2014) and even 14 years after the first data release SDSS is still shedding light on new streams (Grillmair, 2014).

What does the discovery of these streams mean in terms of the formation and evolution of the Milky Way? This paper lays out current results and understandings of stellar streams and their place in galactic formation and evolution. Section 2 highlights a few prominent streams and explores their characteristics. Section 3 analyses how stellar streams fit in to the formation of the Milky Way Halo through the accretion of satellite galaxies. Section 4 analyses how tidal debris affects models of the halo, including triaxiality and how it pertains to the ΛCDM model. Conclusions and future projects are discussed in section 5.
2 Prominent Streams: Features and Origins

2.1 Sagittarius Stream

Discovered in 1994 by Ibata et al. and first imaged in 2003 by Majewski et al., the Sagittarius stream is the most prominent substructure in the Galactic halo. It is located $\approx 16$ kpc from the Galactic centre, and follows the orbit of the Sagittarius dwarf spheroidal galaxy (Belokurov et al., 2006). The stream is composed of at least 2 branches, A and B, with the possibility of a 3rd located beyond branch A (Fellhauer et al., 2006). Belokurov et al. (2006) mapped this stream using SDSS data by using a colour cut to pick out main sequence turnoff stars, and is visible in Figure 1. The stream also shows a bifurcation, which Fellhauer et al. (2006) argue can only be caused if the halo is roughly spherical (see section 4 for further discussion).
2.2 Monoceros Overdensity

The Monoceros stream is located ≈15-18 kpc from the Galactic centre, and was discovered by Newberg et al. (2002). SDSS data has been used to map this stream, and it forms a ring around the Galactic plane. Conn et al. (2012) suggest three possible origins: tidal debris from an accreted dwarf galaxy, perturbations of the Galactic disk from a nearby satellite galaxy, or that it may not be a stream at all, but a warping of the disk. The authors derived distances, metallicities, and density maps for the feature and conclude that it was not created by a perturbed satellite galaxy because the stars are too metal-poor to have formed in the disk. Better models are needed to distinguish between accretion and disk warping (Conn et al., 2012).

2.3 Orphan Stream

Also discovered by Belokurov et al. (2006) using SDSS data, the Orphan stream is located between ≈20 and 32 kpc. This stream includes old metal-poor stars, which suggests an extragalactic origin. Its large distance gradient ends close to the dwarf spheroidal UMa II, and Belokurov et al. (2007) suggest that it may be the origin of the stream.

3 Formation of the Halo

The question of how the halo of the Milky Way formed is an old one. Previous studies have shown that the halo is composed of metal poor stars with a high degree of random motions suggesting that they formed around the same time as the Milky Way (Bell et al., 2008). However, despite knowing when the stars were formed, it was only recently that evidence for the location of their formation has been presented. This section explores the different properties of the stellar halo as found using stellar streams.

3.1 Age and Metallicity

Stellar streams are a natural consequence of accretion. Simulations between interacting galaxies have demonstrated the formation of stellar streams and tidal tails as early as 1972 (Toomre & Toomre, 1972). They have also been shown to form along the orbit of satellite galaxies as tidal forces from the host galaxy strip stars away (Johnston, Hernquist, & Bolte, 1995).
Since these stars form under different initial conditions, they will also have distinct properties when compared to stars which formed in the Milky Way. The stellar distribution in the halo shows two distinct metallicity populations: \(\alpha\)-rich and \(\alpha\)-poor, where \(\alpha\) elements are defined as being any element with \(Z \leq 22\) (e.g. O, Mg, C, N). A recent study by Hawkins et al. (2014) studied the ages of \(\alpha\)-rich and \(\alpha\)-poor stars in the halo in order to determine whether they share the same origin. They began by estimating the \(\alpha\) abundance of F and G dwarfs from the SDSS through the relative abundances of spectral lines such as Mgb, KTi, KCa, and K1 (Hawkins et al, 2014). The authors estimated the main sequence turnoff temperature using a Sobel-Kernel edge detector algorithm, which assumes that a distributions of stellar temperatures will decline rapidly at the turnoff time (see Jofre & Weiss, 2011). The authors constructed a temperature distribution grid for different metallicities and optimizing the derivative. Combined with Yonsei-Yale isochrones from Demarque et al. (2004), the ages of the populations were estimated. The resulting fits show that the ages of both populations exceed 8 Gyr, which agrees with previous theories that the halo formed early on in the formation of the Milky Way (Hawkins et al, 2014). They also found that the \(\alpha\)-rich sample is older than the \(\alpha\)-poor sample, and also has a shallower age-metallicity relation. The authors indicate that the \(\alpha\)-rich stars formed in an area of rapid star formation, whereas the \(\alpha\)-poor population formed over much larger timescales. This suggests that the \(\alpha\)-poor sample formed in satellite galaxies, and were subsequently accreted into the Milky Way Halo (Hawkins et al, 2014).

### 3.2 Abundance of Substructure in the Halo

Two theories persist about how the halo was formed: accretion and in situ. The in situ model theorizes that the halo formed during the early collapse of the Milky Way, while the accretion model states that the halo stellar population was accreted from satellite galaxies. The resulting structure of the halo differs greatly based on which theory holds. The in situ model predicts a smooth distribution of stars, whereas the accretion model predicts many substructures spread throughout the halo. The most likely scenario is that the Galactic halo is composed of a population of stars pertaining to both formation mechanisms (Bell et al., 2008). This section explores different attempts to quantify the contributions from both scenarios.
3.2.1 Using Main Sequence Turn off Stars

The discovery of stellar streams reveals that accretion has occurred during the history of the Milky Way, however it does not immediately determine whether accretion was the dominant formation mechanism for the halo. Bell et al. (2008) studied SDSS data in order to indulge the theory that accretion was in fact the dominant way to build up a stellar halo. The authors used approximately 4 million main sequence turn off stars and fit oblate triaxial power law models to the data. The data was fit as to allow different halo shapes (prolate/oblate), as well as different power law density indices. Even with these free variables, not a single smooth model represented a good fit for the data. They were, however, able to constrain the oblateness of the halo, concluding that $c/a \simeq 0.6$. They conclude that since all smooth models are poor fits, especially in the outer halo, the halo is composed primarily of substructure. They conclude that the inner halo is composed of about 30% structure, and this number increases with distance from the Galactic centre. Furthermore, they conclude that their results show that the streams are not small perturbations on top of a smooth halo, but indicate that the Galactic Halo is dominated by substructure. These results support the theory that the halo was formed by the accretion of many dwarf spheroidal galaxies, and suggests that it is the dominant mechanism for building up a halo.

3.2.2 Using Blue Horizontal Branch Stars

Deason, Belokurov, & Evans (2011) explored the same question that Bell et al. (2008) asked: What is the dominant structure of the Galactic halo? Using SDSS data they created a large sample of blue horizontal branch (BHB) and blue straggler (BS) stars, which are generally A-type stars. They construct a maximum likelihood function, and use the function to obtain a fit for three common halo profiles: a single power law (equation 1), a broken power law (equation 1 with two different domains), and an Einasto halo (equation 4).

\[ \rho(r_q) \propto r_q^{-\alpha}, \quad r_q^2 = x^2 + y^2 + z^2 q^{-2} \]  

(1)

where $q$ defines the shape of the halo (prolate or oblate), and alpha describes the power law relation of the stellar density. The authors find that the broken power law, with the break at 27 kpc, and Einasto halo models fit the data well, whereas the single power law does not. The results show that the halo is not spherical in shape, which agrees with other findings and will be discussed in
section 4. The important result of this fitting is that the data can be modeled by a smooth distribution, indicating that the A-type stars are not in fact dominated by substructure. The authors hypothesize that the discrepancies from Bell et al. (2008) may be due to the different methods and stars used. (Deason, Belokurov, & Evans, 2011)

3.3 Accretion History

Now that it has been shown that accretion played an important part in forming the Galactic halo the question of when, and at what rate, the accretion occurred can be studied. Schlaufman et al. (2009) used spatial and radial velocity distributions of metal-poor main-sequence turnoff stars in order to study elements of cold halo substructure (ECHOS) in the inner halo. They observe 10 of these ECHOS based on small scale radial velocity clusters. Follow up work done in 2011 by Schlaufman et al. showed that these ECHOS are more iron poor and \(\alpha\)-rich than the smooth background. As discussed in section 3.1, this suggests that these structures were formed in satellite galaxies as opposed to in the Milky Way. Contrary to the study by Bell et al. (2008), the ECHOS are said to be remnant of ancient accretion events instead of more recent events. When these ECHOS were plotted they reveal an isotropic distribution. The authors conclude that about 1/3 of the stars found within the inner halo belong to substructures. This study was then compared to the results by Bell et al. (2008), since they looked at similar structures, but at an early look-back time. Since the resulting inner halo is composed of roughly the same percent of substructure, this suggests that ”the accretion rate over the past few Gyr has remained relatively constant”. This also supports the results of Hawkins et al (2014), who concluded that no major merger has occurred in the last few Gyr.

4 Stellar Streams and the \(\Lambda\)CDM Model

The discovery of stellar streams has had an important impact on the \(\Lambda\)CDM model of cosmology, since the model states that galaxies form as a result of mergers within a dark matter halo (Ibata et al., 2013). A common result of the CDM model of galaxy formation is that the halo is slightly triaxial, and to be more spherical at larger radii (Deg & Widrow, 2013). All three studies in section 3 concluded that the halo is oblate and triaxial. This section focuses
on the effects of a triaxial halo and what information this can give us about the Milky Way

4.1 Halo Triaxiality

4.1.1 Modelling Orbits

Deg & Widrow (2013) use the orbits of stars within the Sagittarius stream to model the shape of the dark matter halo. The orbits of the Sagittarius stream are used as it is believed that they are determined by the Galactic potential. The model below will result in predicted velocities for galactocentric radii, and the model is fit to the stars in the stream. They build upon results obtained by Law & Majewski (2010) who concluded that the Milky Way halo was triaxial and results in an oblate mass distribution. In order to build upon this model, Deg & Widrow (2013) use a Sersic bulge,

\[ \rho_b = \rho_0 \left( \frac{r}{R_e} \right)^{-p} e^{-b(r/R_e)^{1/n}} \]  \hspace{1cm} (2)

an exponential disk,

\[ \rho_d(R, z) = \frac{M_d}{4\pi R_d^2 z_d} e^{-R/R_d} e^{ch^2(z/z_d)} \]  \hspace{1cm} (3)

and an Einasto halo.

\[ \rho_h(r_t) = \rho_0 e^{-\frac{2}{\alpha}[(r_t/r_h)^{1/n} - 1]} \]  \hspace{1cm} (4)

where \( p = 1 - 0.6057/n + 0.0556/n^2 \), \( n \) is the Sersic index, \( b \) is a factor for which \( R_e \) encloses half the mass, \( R_d \) is the disk scale radius, \( M_d \) is the disk mass, \( z_d \) is the disk scale height, \( r_t \) is the triaxial radius, \( \rho_0 \) is the scale density, \( r_h \) is the scale radius of the halo, and \( \alpha \) controls the slope of the logarithmic density profile.

The bulge and disk are thus axisymmetric, and they also include a bar. They combine their model with a few observational constraints: heliocentric...
velocities of M giants in the Sagittarius stream, circular speed at the position of the Sun, and the shape of the circular speed curve at the Sun as described by the Oort constants. Using a Markov Chain Monte Carlo algorithm on their model with these observational constraints they present a number of Galactic properties. They conclude that the resulting shape of the halo is still roughly oblate and triaxial, and the short axis is aligned with the Galactic plane. This model can be seen in Figure 2. The authors do not, however, explain why the Sagittarius stream favours a triaxial halo, and this question is examined below. The authors caution that this fit does have its downfalls, since the halo lies in the same plane as the stream itself. This model also only encompasses a single stream, and a model that incorporates many streams would result in a more accurate model.

Figure 2: The halo model produced by Deg & Widrow (2013) oriented along the plane of the Sagittarius stream. The black points show the Sagittarius stream M giants and the yellow stars are SDSS field stars. The solid lines represent the axes of the oblate halo. The red, green, and blue star are the location of the Sgr dwarf galaxy, the sun, and the Galactic center. Finally, the dashed line is the orbit of the dwarf galaxy. Taken from Deg & Widrow (2013).
4.2 Modelling the Halo Using a Stream Fitting Algorithm

Does the Sagittarius stream mean that the halo must be triaxial? This question was explored by Ibata et al. (2013), who continued to build upon previous halo models such as Deg & Widrow (2013) and Law & Majewski (2010). They use a thin disk, a thick disk, a spherical bulge and a spherical halo in their model of the Milky Way. A stream fitting algorithm was used which creates a stellar stream at each iteration and determines the likelihood of the parameters based on the SDSS data. They also use an affine-invariant Markov chain Monte Carlo algorithm to fit their stream, and obtain a different conclusion than the previously discussed models. The resulting model can produce a non-triaxial halo if the rotation curve sharply rises between 20 and 60 kpc (Ibata et al., 2013). This curve can be seen in Figure 3. The authors conclude that this model is consistent with the ΛCDM model, and has not been ruled out by observations. The sharp rise in rotation is seen in M31, which means that is not unprecedented. A concern that the authors had is that the mass of the Milky Way will be much larger than previously measured, which would lead to the SMC and LMC being gravitationally bound to the Milky Way, contradicting observations (Ibata et al., 2013).

The take home message from this section is that flaws within both models constrain our ability to determine what type of halo profile exists in the Milky Way. While triaxiality has been shown to model the halo in multiple papers, the proposal made by Ibata et al. (2013) cannot be completely ruled out. Models with fewer constraints that use more powerful computational devices will be needed in order to form a more accurate conclusion.

4.3 Gravitational Potential

Another aspect of the Milky Way that can be studied by virtue of discovering stellar streams is the Galactic potential. Price-Whelan et al. (2014) presented an approach to this problem by creating a simulation that assumes the streams were initially close in phase space. They model the Galaxy using a Miyamoto-Nagai Disk, a Hernquist spheroid, and a triaxial halo, (see Miyamoto & Nagai, 1975; Law & Majewski, 2010; Price-Whelan et al., 2014)
since “successful inference with this potential demonstrates that it is possible to recover information about non-trivial potentials”. They combine this model with their code Rewinder, which determines the most probable location for which a star became tidally stripped from the dwarf galaxy and calculates the likelihood of each star becoming unbounded. They perform mock experiments using the data from the N body simulations in order to test Rewinder. They choose 8 stars: 4 from the leading tail and 4 from the trailing tail of the stream. The potential parameters described in their models are left free, and the same Monte Carlo method as used in the triaxial determination models was used. The resulting potential is calculated to within 1% based on their assumptions, which include a less than 2% uncertainty in the distance to the stars. The authors conclude that their method, coupled with the precise distances that will be obtained by Gaia in the near future, will only require 8 stars to measure the potential of the Milky Way. This dramatically improves current models, which require a large number of stars with less constrained kinematics (Price-Whelan et al., 2014). Thus, a more accurate and less computationally intensive method for determining the gravitational potential of the Milky Way has been proposed and will be able to obtain results once high...
accuracy measurements, from projects such as Gaia, are obtained.

5 Summary and Next Steps

This paper provides a brief overview of stellar streams and what they can tell us about the Milky Way. Studies of ages and metallicities by Hawkins et al. (2014) determined that the stars located in the streams are α-poor, which suggests that they originated in satellite galaxies. A model by Bell et al. (2008) using main sequence turnoff stars concluded that substructure dominates the galactic halo, however Deason, Belokurov & Evans found that A-type stars in the halo can be modeled by a smooth halo. Similar studies have found that ≈ 30% of the halo stars are associated with substructure. This result was used by Schlaufman et al. (2009) to show that the accretion rate has been rather constant over the last few billion years and that a major merger has not occurred within the past 8 Gyr. Finally, results pertaining to the shape of the halo were presented which showed that the halo is most likely triaxial, but it is still under investigation. A new model for calculating the gravitational potential using 8 precisely measures stars in a stream was also explored, and will be used in conjunction with Gaia.

This topic is more than worthy of an annual review, and as such the topics presented in this paper reflect only a few consequences of the discovery of substructure in the Galactic halo. Current observations have found upwards of 20 distinct substructures, and more are expected to exist. The Large Synoptic Survey Telescope (LSST) is an 8.4m telescope currently being constructed in Chile, which will survey the entire Southern sky deeper and faster than SDSS did in the North. LSST will illuminate even fainter substructures, and will be used to better constrain our current understanding of the Galactic halo.

References

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