Session IV

Chemical Abundances Constraints on Mass Assembly and Star Formation

3 - The Milky Way

Manuela Zoccali during her talk.

Gehard Hensler during his talk.

Chemical Abundances in the Universe:
Connecting First Stars to Planets
Proceedings IAU Symposium No. 265, 2009
K. Cunha, M. Spite & B. Barbuy, eds.

doi:10.1017/S1743921310000700

Chemo-dynamical substructure of the Galactic halo

Helio J. Rocha-Pinto

Universidade Federal do Rio de Janeiro, Observatório do Valongo, Brazil
email: `helio@astro.ufrj.br`

Abstract. Deep recent surveys have considerably improved our picture of the outer Galactic halo by unveiling a complex level of substructuring in the form of streams, stellar clouds and debris systems. Here I discuss some of the recent findings and present their general properties.

Keywords. Galaxy: Halo, Galactic structure, tidal streams

1. Introduction

Eggen, Lynden-Bell & Sandage (1962; hereafter ELS) provided a first coherent picture for the formation of our Galaxy as the outcome of the dissipative collapse of a self-gravitating perturbed gas. Stars formed during the collapse would show a quite spherical distribution and the remaining gas would settle in an equilibrium disk configuration where star formation would proceed in a more steady pace. In spite of its simplicity, this scenario has some serious drawbacks, since its halo and disk components do not properly resemble the real halo and disk(s) inferred from the observations. For instance, it is presently known that the age range in the halo globular clusters is larger than the expected time scale for dissipative collapse formation of the halo (Sarajedini *et al.* 1997; De Angeli *et al.* 2005; Marín-Franch *et al.* 2009). Moreover, some clear and smooth chemokinematical trends found by ELS for the Galaxy are likely to have been formed by the particular local mixture of the main Galactic populations contributing to the stellar content of the solar neighborhood (Carollo *et al.* 2007, 2009).

ΛCDM models aimed at explaining the observed large scale structure of the distribution of galaxies have a much better performance at issues that are seen as failures of the monolithic dissipative collapse model. These give a quite intuitive explanation for the formation of the Galaxy as a hierarchical process, driven by the successive mergers of smaller subgallactic units into larger ones, making room for the existence of a population of faint satellites in the outskirts of the present-day bright gallaxies. Nevertheless, the predicted number of these satellites in the Local Group is a order of magnitude or more larger than the presently known number of its satellite dwarfs (Moore *et al.* 1999; Kravtsov *et al.* 2004; Strigari *et al.* 2007; see also Tollerud *et al.* 2008 and Koposov *et al.* 2009). Several attempts have been made to solve this *missing satellite problem*, ranging from deep observations which could increase the present census of Local Group faint satellites (Willman *et al.* 2005a,b; Martin *et al.* 2006; Zucker *et al.* 2006a,b; Walsh *et al.* 2007; McConnachie *et al.* 2008; Liu *et al.* 2008) to reassessment of events in the early Universe that could hinder the lighten up of these, mainly dark, satellites (Simon & Geha 2007; D'onghia & Lake 2008; Madau *et al.* 2008; Bovill & Ricotti 2009; Yang *et al.* 2009).

Despite this inconsistency, it is clear that the Galaxy has experienced a number of merger events in its quite recent past, on account of the presence of nearby satellite galaxies. Their number should have been higher in the past and the outcome of their interactions with the Milky Way (MW) can probably still be found as statistically significant substructures somewhat detached from the smooth stellar population distributions of the typical, canonical Galactic components. Halo substructures are also found in other spiral galaxies (e.g., Shang *et al.* 1998, Ibata *et al.* 2007, 2009; Herrmann *et al.* 2009; Martínez-Delgado *et al.* 2009a,b), and may be a quite common phenomenon attesting the tumultuous hierarchical formation of these systems.

It happens that much of the definition of what is a canonical Galactic component is somewhat biased towards what we expect from an ELS-type galaxy, especially in the case of the Galactic halo, which is expected to be an old, well-mixed, kinematically hot and non (or slightly) rotating component. Any deviation from this particular type of halo is a possible signature of past merger events between the MW and its satellite companions. This can lead to conflicting interpretations: the Virgo stellar overdensity (Jurić *et al.* 2008), the second largest MW halo substructure in angular size in the sky, can be the signature of a triaxial halo instead of the cloudy debris of a former satellite galaxy (Newberg *et al.* 2007; but see Bell *et al.* 2007).

Halo tidal substructures are diverse in shape and properties, as shown by Johnston *et al.* (2008) in a study of the morphology of tidal debris in merger-built haloes. Three main halo groups — as well as transition groups — can be distinguished, according to the distribution of the debris system around the galaxy and in phase space: the ‘mixed’, ‘cloudy’ and ‘great circles’ morphology. Each of these halo morphologies is produced by a particular accretion history such that the characterization the phase-space and chemical content of the halo substructure allows the uncovering of the MW accretion history.

2. Techniques for finding substructure

A number of techniques allows the identification of halo substructures. Those include:

- stellar density plots as a function of distance and/or position in the sky;
- color–magnitude diagrams (see, for instance, Walsh *et al.* 2009);
- Kinematical coherence in velocity phase space;
- Clustering in the angular momentum-energy diagram (Helmi *et al.* 1999; Klement *et al.* 2009); and
- Chemical abundance anomalies

Since the angular size of the halo substructures can vary substantially, the tracer used in their mapping depends on the kind of substructure one is looking for. Large substructures (star clouds and dSph tidal debris) are better traced by luminous stars like M giants, red clump giants, blue horizontal branch and RR Lyrae stars, whereas faint substructures (cold streams and GCs tidal tails) require the use of turnoff stars in order to enhance the signal of the structure in sky. Commonly a CMD filter technique — a.k.a., the ‘matched-filter’ technique (Rockosi *et al.* 2002) — allows a pre-selection of stars that consistently follows a theoretical single stellar population or the empirical CMD of a globular cluster having a given age and metallicity. The CMD filter is run in magnitude, enhancing the signal of potentially existing stellar overdensities at particular distance moduli (e.g., Grillmair 2006a, 2009; Liu *et al.* 2008).

Once a suspicious halo substructure is found, it is important to confirm its significance by comparing it with the expected stellar content, in the approppriate parameter space, predited by a consistent Galactic model like the Besanon (Robin *et al.* 2003), the TRILEGAL (Girardi *et al.* 2005) and GALFAST model (Ivezić 2009). An alternative to making a comparison with model predictions is to use the stellar content accross the main Galactic reference planes as symmetric templates for the canonical Galaxy (Rocha-Pinto *et al.* 2004, 2006); however, it must be stressed that this last check can yield false overdensities if the stellar halo is triaxial (Newberg *et al.* 2007) or towards regions having selective reddening R_V very different from the R_V of their symmetric fields.

3. Sagittarius et alli

Figure 1 shows the approximate sky distribution of most of the presently known halo substructure in an aitoff projection using Galactic coordinates. By far, the largest debris feature in the Galactic halo is created by the disruption of the Sgr dSph (Ibata *et al.* 1994, Majewski *et al.* 2003, 2004, Newberg *et al.* 2002). Debris from Sgr are distributed according to a mix–great circle transition morphology with at least two clearly visible wraps (Belokurov *et al.* 2006). The two wraps of the Sgr tidal stream are displaced because of the precession of the Sgr orbital plane, and this puts a strong constraint to the shape of the Galactic dark halo being spherical or slightly prolate (Fellhauer *et al.* 2006), although the analysis of other parts of this debris system suggest other halo shapes (Helmi 2004a,b; Law *et al.* 2003; Johnston *et al.* 2005). Recently, Law *et al.* (2009) have suggested that this conflict can be solved the dark matter halo is triaxial.

In spite of being a dwarf spheroidal galaxy, Sgr had a complex chemical enrichment history. This can be attested by the $-1.58 < [\mathrm{Fe/H}] < -0.71$ range shown by its stars (Marconi *et al.* 1998) and the $-2.0 < [\mathrm{O/H}] < -0.2$ range found in its planetary nebulae (Kniazev *et al.* 2008). Moreover, there is a well-marked stellar population (Bellazzini *et al.* 2006) and abundance gradient (Chou *et al.* 2007, 2009) along the Sgr tidal stream: Stars supposed to be captured earlier have lower metal content than late-captured stars

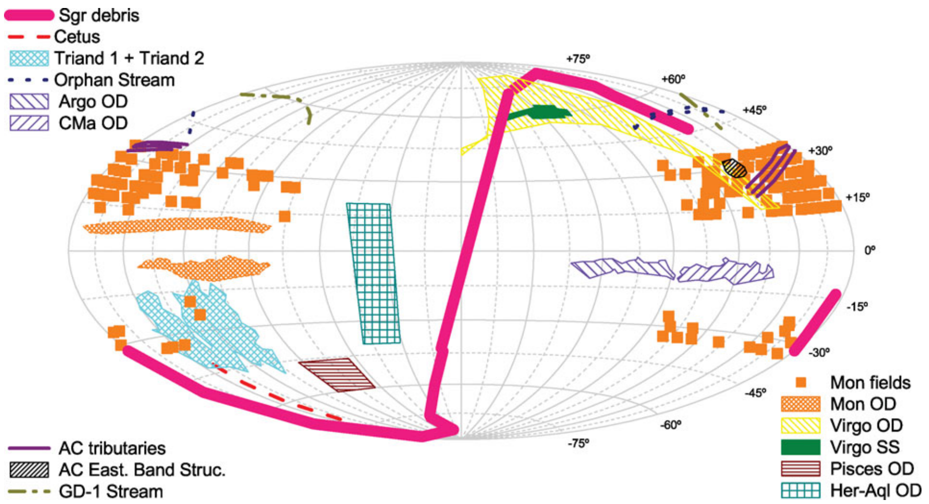

Figure 1. Aitoff projection showing the distribution of some of the presently known halo substructure in Galactic coordinates: Sgr tidal stream (Majewski *et al.* 2003), candidate Monoceros fields (Rocha-Pinto *et al.* 2003), Monoceros Northern and Southern 'arcs' (Martin *et al.* 2004; Rocha-Pinto *et al.* 2006), Canis Major (Martin *et al.* 2004), Argo (Rocha-Pinto *et al.* 2006), TriAnd 1 and 2 clouds (Rocha-Pinto *et al.* 2004; Martin *et al.* 2007), Virgo OD (Jurić *et al.* 2008), Virgo SS (Keller *et al.* 2009), Pisces (Watkins *et al.* 2009), Hercules-Aquila cloud (Belokurov *et al.* 2007a), Orphan stream (Belokurov *et al.* 2006), GD-1 stream (Grillmair & Dionatos 2006), Cetus stream (Newberg *et al.* 2009), Anticenter stream — tributaries and Eastern Band Structure (EBS; Grillmair 2006b). Acheron, Cocytos, Lethe and Styx (Grillmair 2009) — not shown in this plot — are located near the region where the Orphan and GD-1 cross each other. See the eletronic version of this paper for a colored version of this plot.

and even lower than the metal content of Sgr-bound stars. Because it is not possible that chemical enrichment has occurred inside the stream — on account of negligible, if any, star formation in the debris —, this gradient is likely to trace the evolution of Sgr itself: The early captures are expected to have taken the less bounded stars from the dSph outskirts where less chemical enrichment are expected to have happened. Chemical enrichment proceeded in the Sgr main body in a perturbed and less gaseous environment, so that later captures correspond to a more metal-rich population, but not as rich as the Sgr galaxy where star formation continued much longer (Chou *et al.* 2007). Chou *et al.* concludes that this puts into doubt some attempts to look for captured halo stars by comparing the chemical content of the stellar populations in the halo and in the Milky Way satellites (e.g., Geisler *et al.* 2007) since abundances from halo stars accreted from mergers should not be similar to the abundances of the present-day survivor satellites.

During the last half decade, Monoceros seemed to be a low-latitude analogous of the Sgr stream. Its discovery in 2002, by Newberg *et al.* (2002) more or less coincided with the final data release of the 2MASS, prompting some groups to try to fully map it accross mildly obscured lines of sight of the Galactic plane (e.g., Rocha-Pinto *et al.* 2003, Martin *et al.* 2004). The feature is very large, having associated overdensities over $\leqslant 40°$ in b and $\leqslant 160°$ in l. It occupies a distance range of 6-8 kpc from the Sun, becoming probably thicker at $l \geqslant 210°$. Monoceros is not only seen as a spatial overdensity but also as a chemically peculiar feature (Ivezić *et al.* 2008), resembling very much a disrupted dSph debris system. It may be may be connected with other low-b 2MASS overdensities (CMa, Martin *et al.* 2004; Argo, Rocha-Pinto *et al.* 2006) which have been proposed as remanent cores of the disrupted dwarf. Nevertheless, there is still an inconclusive debate over the nature of these two overdensities (Rocha-Pinto *et al.* 2006, Bellazzini *et al.* 2006, Momany *et al.* 2004, 2006; Mateu *et al.* 2009). Particularly, on account of the absence of an inequivocal core and its confusion with the Galactic disk beyond $l \geqslant 225°$, we still miss a clear picture of the morphology of this system. It could be a ring, as proposed by Ibata *et al.* (2003), a stream with a yet to-be-confirmed core or a star cloud debris system like Virgo. Some lines of sight crossing Monoceros also show evidence for somewhat farther overdensities which could be independent from Monoceros: the Anticenter Stream (A-C Stream) and three narrow ‘tributary cold streams running nearly parallel to it (Grillmair 2006b; Grillmair *et al.* 2008). Grillmair advances an interesting hypothesis that the tributaries could be debris from satellite clusters of the parent galaxy which created the A-C Stream. Note that the A-C Stream should not be confused with the Galactic Anticenter Stellar Stream (GASS), an alternative name for Monoceros used by Rocha-Pinto *et al.* (2003), Crane *et al.* (2003) and Frinchaboy *et al.* (2004), although stars from the A-C stream may have been mixed up with stars from Monoceros in the early analysis of these lines of sight.

The first ‘cloudy’ debris discovered around the Milky Way was Triangulum-Andromeda, a.k.a, TriAnd (Rocha-Pinto *et al.* 2004; Majewski *et al.* 2004). TriAnd has some curious properties: it is a very faint substructure, occupying nearly 30° × 40° in the sky. By the time of its discovery, it was not clear how to produce puffed-up debris clouds like this, but Johnston *et al.* (2008) have shown that this morphology can be quite common. A thinner, farther structure (named ‘TriAnd 2’) was found in the same region by Martin *et al.* (2007). Majewski *et al.* (2004) and Martin *et al.* (2007) estimate a surface brightness of $\mu \sim 32$ mag arcsec^{-1} for both TriAnd’s. Considering Fig. 4 from Johnston *et al.* (2008), cloud debris having this surface value may correspond to an accretion event 6-8 Gyr ago. In Peñarrubia *et al.* (2005)’s model TriAnd is explained as a past wrap of the Monoceros debris system. However, Majewski *et al.* (2010; in this proceedings) argues that TriAnd is chemically very distinct from Mon.

A large set of halo substructures was unveiled in the analysis of the SDSS stellar content, ranging from several cold streams to new ultrafaint satellite galaxies. Among them, a large debris system is the Virgo Stellar Overdensity (VOD; Jurić *et al.* 2008), whose existence has been suspected since the early 2000 from an overdensity of RR Lyrae in the QUEST survey (Vivas *et al.* 2001). It has the morphology of a star cloud, like TriAnd, with no apparent center. VOD could be part of the Sgr leading tail (Martínez-Delgado *et al.* 2007), but Newberg *et al.* (2007) and Yanny *et al.* (2009) argue that the Sgr tail passes at a different distance along the same line of sight. Just like for Monoceros and TriAnd, smaller substructures (including the Virgo Stellar Stream, a.k.a VSS) seem to share the VOD distance range and have possibly an independent origin (Duffau *et al.* 2006; Prior *et al.* 2009; Keller *et al.* 2009).

Other cloudy SDSS overdensities have been reported in the literature: Hercules-Aquila (HerAql; Belokurov *et al.* 2007a) and Pisces (Sesar *et al.* 2007; Watkins *et al.* 2009; Kollmeier *et al.* 2009). HerAql occupies an angular size of ~80° × 50° and can be seen above and below the Galactic plane (Belokurov *et al.* 2007a), lying between 10 to 20 kpc from the Sun toward $l \sim 40°$. Belokurov *et al.* (2007a) proposes that it could be a new structural component of the inner halo. However, the southern regions of this overdensity (not covered by the presently available SDSS data) still need to be properly mapped before confirming this hypothesis. The Pisces overdensity has been initially seen by Sesar *et al.* (2007) as an overdensity of RR Lyrae stars in SDSS Stripe 82. Later, Watkins *et al.* (2009) independently found it and christened it that way. It is centered at $(l, b) \sim (80°, -55°)$, at a distance of ~80 kpc. Watkins *et al.* (2009) estimates its total mass as a few $10^4 M_\odot$. Kollmeier *et al.* (2009) have spectroscopically confirmed the existence of the overdensity and suggests that Pisces can be a new Milky Way satellite dwarf galaxy possibly in the process of disruption.

A great deal of attention has been given to the discovery of cold streams in SDSS on account of the deepness of the survey which allows reaching the distant turnoff stars of these narrow substructures. The most well studied of these are the Orphan Stream (Belokurov *et al.* 2007b; Grillmair 2006a) and the 63°-long Grillmair-Dionatos 1 Stream (Grillmair & Dionatos 2006). Other reported discoveries are Acheron, Cocytos, Lethe and Styx (Grillmair 2009) — a creative pattern of designations to avoid the boring repetition of constellation names in several different astronomical objects — and Cetus (Newberg *et al.* 2009). Structures like these can persist over timescales of 2-4 Gyr (Younger *et al.* 2008) and are particularly interesting because they trace the orbit of their parental body (e.g., Willett *et al.* 2009) and allow the constraining of the Galactic potential (Koposov *et al.* 2009; Eyre & Binney 2009).

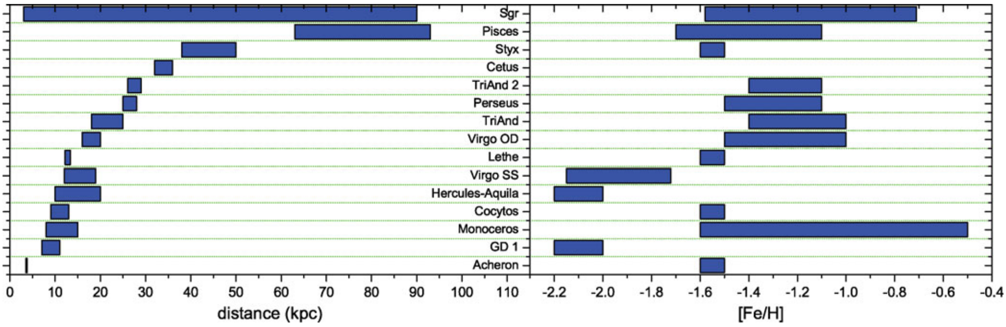

Figure 2. Distance and metallicity ranges for some of the presently known halo substructures.

It is not very easy to find halo structures by exclusively looking for correlations between chemical anomalies and spatial positions. In spite of it, Roederer (2008) has showed that the "kinematically diverse outer halo population is also chemically diverse", suggesting that they were formed in "regions where chemical enrichment was dominated by local SN events." Also, there are some chemically distinct overdensities in the SDSS data as Monoceros, Virgo and an unnamed significantly overabundant region in Figure 9a from Ivezić *et al.* (2009) at 2-3 kpc above the Galactic plane.

4. General properties of the halo substructures and conclusions

In Figure 2, I show the metallicity range of some know substructures. The metallicity distribution for each structure is not completely typical of the canonical (inner) halo, but there are presently no spectroscopic abundance determinations for several of them, so that Figure 2 can not be taken as more than an illustrative diagram of the chemical properties of the halo substructures. Future chemical abundance surveys (e.g., APOGEE, HERMES) may allow a more systematic chemical tagging of the signatures of recent past merging events and the discovery for chemically peculiar, possibly captured, stars like SDSS J234723.64+010833.4 (Lai *et al.* 2009).

Figure 2 also show the Galactocentric distance ditribution of these substructures. Several of the cloudy overdensities are located between 20-30 kpc in remarkable agreement with the predictions by Johnston *et al.* (2008). Nevertheless, because these substructures can have diverse origins, comparisons between their distances are not much significant.

It is likely that several other cold streams like these exist in the outer halo (Sales *et al.* 2008). A typical MW-size galaxy should have $> 10\%$ of its halo in the form of substructures (Johnston *et al.* 2008). A similar estimate was made by Starkenburg *et al.* (2009) from a star pair analysis of the pencil-beam survey Spaghetti project. As an example of the prolific abundance of substructures in the halo, three new stellar overdensities were announced when this article was being prepared (Keller 2009). The majority of presently known halo substructures comes from two very recent photometric surveys: SDSS and 2MASS. Considering that SDSS has mapped $\sim$1/3 of the sky down to r $\sim$23 and 2MASS has mapped $>$99% of the sky down to $K_S \sim 15$, there are still much to be searched both in sky and spectral coverage and the several upcoming surveys (GAIA, DES, Pan-STARRS, SIM, etc.) will provide a whole lot of new structures improving our charactrization of the outer halo and our understanding of the Milky Way build up.

Acknowledgements

I acknowledge the finantial support by the brazilian agencies FAPERJ and CNPq.

References

Bell, E. F., Zucker, D. B., Belokurov, V., *et al.* 2007, *ApJ*, 680, 295
Bellazzini, M., Ibata, R., Martin, N., *et al.* 2006, *MNRAS*, 366, 865
Bellazzini, M., Newberg, H. J., Correnti, M., Ferraro, F. R., & Monaco, L. 2006, *A&A*, 457, L21
Belokurov, V., Zucker, D. B., Evans, N. W., *et al.* 2006, *ApJ*, 642, L137
Belokurov, V., Evans, N. W., Bell, E. F., *et al.* 2007a, *ApJ*, 657, L89
Belokurov, V., Evans, N. W., Irwin, M. J., *et al.* 2007b, *ApJ*, 658, 337
Bovill, M. S., Ricotti, M. 2009, *ApJ*, 693, 1859
Carollo, D., Beers, T, C., Lee, Y. S., *et al.* 2007, *Nature*, 450, 1020
Carollo, D., Beers, T, C., Chiba, M., *et al.* 2009, *astro-ph*/0909.3019
Chapman, S. C., Ibata, R., Irwin, M., *et al.* 2008, *MNRAS*, 390, 1437
Chou, M.-Y., Majewski, S. R., Cunha, K., *et al.* 2007, *ApJ*, 670, 436

Chou, M.-Y., Cunha, K., Majewski, S. R., *et al.* 2009, *astro/ph*, 0911.4364
Crane, J. D., Majewski, S. R., Rocha-Pinto, H. J., *et al.* 2003, *ApJ*, 594, L119
De Angeli, F., Piotto, G., Cassisi, S., *et al.* 2005, *AJ*, 130, 116
D'Onghia, E. & Lake, G. 2008, *ApJ*, 686, L61
Duffau, S., Zinn, R., Vivas, A. K., *et al.* 2006, *ApJ*, 636, L97
Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, *ApJ*, 136, 748
Eyre, A. & Binney, J. 2009, *MNRAS*, 400, 548
Fellhauer, M., Belokurov, V., Evans, N. W., *et al.* 2006, *ApJ*, 651, 167
Frinchaboy, P. M., Majewski, S. R., Crane, J. D., *et al.* 2004, *ApJ*, 602, L21
Geisler, D., Wallerstein, G., Smith, V. V., & Casetti-Dinescu, D. I. 2007, *PASP*, 119, 939
Girardi, L., Groenewegen, M. A. T., Hatziminaoglou, E., & da Costa, L. 2005, *A&A*, 436, 895
Grillmair, C. J. 2006a, *ApJ*, 645, L37
Grillmair, C. J. 2006b, *ApJ*, 651, L29
Grillmair, C. J. 2009, *ApJ*, 693, 1118
Grillmair, C. J., Carlin, J. L., & Majewski, S. R. 2008, *ApJ*, 689, L117
Grillmair, C. J. & Dionatos, O. 2006, *ApJ*, 643, L17
Helmi, A. 2004a, *ApJ*, 610, L97
Helmi, A. 2004b, *MNRAS*, 351, 643
Helmi, A., White, S. D. M., de Zeeuw, P. T., & Zhao, H. 1999, *Nature*, 402, 53
Herrmann, K. A., Ciardullo, R., & Sigurdsson, S. 2009, *ApJ*, 693, L19
Ibata, R. A., Irwin, M. J., Lewis, G. F., Ferguson, A. M. N., & Tanvir, N. 2003, *MNRAS*, 340, L21
Ibata R., Martin N. F., Irwin M., *et al.* 2007, *ApJ*, 671, 1591
Ibata, R., Mouhcine, M., & Rejkuba, M. 2009, *MNRAS*, 395, 126
Ivezić, Ž. 2009, *astro-ph*/0911.2661, p. 16
Ivezić, Ž., Sesar, B., Jurić, M., *et al.* 2008, *ApJ*, 684, 287
Johnston, K. V., Bullock, J. S., Sharma, S., *et al.* 2008, *ApJ*, 689, 936
Johnston, K. V., Law D. R., & Majewski, S. R. 2005, *ApJ*, 619, 800
Jurić, M., Ivezić, Ž., Brooks, A., *et al.* 2008, *ApJ*, 673, 864
Keller, S. C. 2009, *astro-ph*/0911.0951
Keller, S. C., Da Costa, G. S., & Prior, S. L. 2009, *MNRAS*, 394, 1045
Klement, R., Rix, H.-W., Flynn, C., *et al.* 2009, *astro-ph*/0904.1003
Kniazev, A. Y., Zijlstra, A. A., Grebel, E. K., *et al.* 2008, *MNRAS*, 388, 1667
Kollmeier, J. A., Gould, A., Shectman, S., *et al.* 2009, *ApJ*, 705, L158
Koposov, S. E., Rix, H.-W., & Hogg, D. W. 2009, *astro-ph*/0907.1085
Koposov, S. E., Yoo, J., Rix, H.-W., *et al.* 2009, *ApJ*, 696, 2179
Kravtsov, A. V., Gnedin, O. Y., & Klypin, A. A. 2004, *ApJ*, 609, 482
Lai, D. K., Rockosi, C. M., Bolte, M., *et al.* 2009, *ApJ*, 697, L63
Law, D. R., Johnston, K. V., & Majewski, S. R. 2003, *ApJ*, 619, 807
Law, D. R., Majewski, S. R., & Johnston, K. V. 2009, *ApJ*, 703, L67
Liu, C., Hu, J., Newberg, H., & Zhao, Y. 2008, *A&A*, 477, 139
Madau, P., Kuhlen, M., Diemand, J., *et al.* 2008, *ApJ*, 689, L41
Majewski, S. R., Kunkel, W. E., Law, D. R., *et al.* 2004, *AJ*, 128, 245
Majewski, S. R., Ostheimer, J. C., Rocha-Pinto, H. J., *et al.* 2004, *ApJ*, 615, 738
Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Ostheimer, J. C. 2003, *ApJ*, 599, 1082
Marconi, G., Buonanno, R., Castellani, M., *et al.* 1998, *A&A*, 330, 453
Marín-Franch, A., Aparicio, A., Piotto, G., *et al.* 2009, *ApJ*, 694, 1498
Martin, N. F., Ibata, R. A., Bellazzini, M., *et al.* 2004, *MNRAS*, 348, 12
Martin, N. F., Ibata, R. A., Irwin, M. J., *et al.* 2006, *MNRAS*, 371, 1983
Martin, N. F., Ibata, R. A., & Irwin, M. 2007, *ApJ*, 668, L123
Martínez-Delgado, D., Peñarrubia, J., Gabany, R. J., *et al.* 2009a, *ApJ*, 689, 184
Martínez-Delgado, D., Peñarrubia, J., Jurić, M., Alfaro, E. J., & Ivezić, Ž. 2003, *ApJ*, 660, 1264
Martínez-Delgado, D., Pohlen, M., Gabany, R. J., *et al.* 2009b, *ApJ*, 692, 955
Mateu, C., Vivas, A. K., Zinn, R., Miller, L., & Abad, C. 2009, *AJ*, 137, 4412

McConnachie, A. W., Huxor, A., Martin, N. F., *et al.* 2008, *ApJ*, 688, 1009

Moitinho, A., Vázquez, R. A., Carraro, G., *et al.* 2006, *MNRAS*, 368, L77

Momany, Y., Zaggia, S., Bonifacio, P., *et al.* 2004, *A&A*, 421, L29

Momany, Y., Zaggia, S., Gilmore, G., *et al.* 2006, *A&A*, 451, 515

Moore, B., Ghigna, S., Governato, F., Lake, G., *et al.* 1999, *ApJ*, 524, L19

Newberg, H. J., Yanny, B., Cole, N., *et al.* 2007, *ApJ*, 668, 221

Newberg, H. J., Yanny, B., Rockosi, C., *et al.* 2002, *ApJ*, 569, 245

Newberg, H. J., Yanny, B., & Willett, B. A. 2009, *ApJ*, 700, L61

Peñarrubia, J., Martínez-Delgado, D., Rix, H.-W., *et al.* 2005, *ApJ*, 626, 128

Prior, S. L., Da Costa, G. S., Keller, S. C., & Murphy, S. J. 2009, *ApJ*, 691, 306

Robin, A. C., Reylé, C., Derrière, S., & Picaud, S. 2003, *A&A*, 409, 523

Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., & Crane, J. D. 2003, *ApJ*, 594, L115

Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., *et al.* 2004, ApJ, 615, 732

Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., *et al.* 2006a, ApJ, 640, L147

Rockosi, C. M., Odenkirchen, M., Grebel, E. K., *et al.* 2002, *AJ*, 124, 349

Roederer, I. U. 2009, *AJ*, 137, 272

Sales, L. V., Helmi, A., Starkenburg, E., *et al.* 2008, *MNRAS*, 389, 1391

Sarajedini, A., Chaboyer, B., & Demarque, P. 1997, *PASP*, 109, 1321

Shang, Z., Zheng, Z., Brinks, E., *et al.* 1998, *ApJ*, 504, L23

Sesar, B., Ivezić, Ž., Lupton, R. H., *et al.* 2007, *AJ*, 134, 2236

Simon, J. D. & Geha, M. 2007, *ApJ*, 670, 313

Starkenburg, E., Helmi, A., Morrison, H. L., *et al.* 2009, *ApJ*, 698, 567

Strigari, L. E., Bullock, J. S., Kaplinghat, M., *et al.* 2007, *ApJ*, 669, 676

Tollerud, E. J., Bullock, J. S., Strigari, L. E., & Willman, B. 2008, *ApJ*, 688, 277

Vivas, A. K., Zinn, R., Andrews, P., *et al.* 2001, *ApJ*, 554, L33

Walsh, S. M., Jerjen, H., & Willman, B. 2007, *ApJ*, 662, L83

Walsh, S. M., Willman, B., & Jerjen, H. 2009, *AJ*, 137, 450

Watkins, L. L., Evans, N. W., Belokurov, V., *et al.* 2009, *MNRAS*, 398, 1757

Willett, B. A., Newberg, H. J., Zhang, H., Yanny, B., & Beers, T. C. 2009, *ApJ*, 697, 207

Willman, B., Dalcanton, J. J., Martínez-Delgado, D., *et al.* 2005, *ApJ*, 626, L85

Willman, B., Blanton, M. R., West, A. A., Dalcanton, J. J., Hogg, D. W., Schneider, D. P., Wherry, N., Yanny, B., & Brinkmann, J. 2005, *AJ*, 129, 2692

Yang, X., Mo, H. J., & van den Bosch, F. C. 2009, *ApJ*, 693, 830

Yanny, B., Newberg, H. J., Johnson, J. A., *et al.* 2009, *ApJ*, 700, 1282

Younger, J. D., Besla, G., Cox, T. J., Hernquist, L., Robertson, B., & Willman, B. 2008, *ApJ*, 676, L21

Zucker, D. B., Belokurov, V., Evans, N. W., *et al.* 2006a, *ApJ*, 643, L103

Zucker, D. B., Belokurov, V., Evans, N. W., *et al.* 2006a, *ApJ*, 650, L41