The Galaxy Disk in Cosmological Context
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Stellar Populations and Dark Matter in the Milky Way Disk and in Local Group Galaxies

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Abstract. Our knowledge on the age structure, the chemical evolution, and the kinematics of the Galactic disk has grown substantially during the last years. Recent results on the properties of the stellar populations in the Galactic disk are summarized, and ongoing and future surveys and facilities are discussed. A short overview of recent mass estimates for the Milky Way is presented, and a brief summary of some of the key properties of the Galactic companions is given. The coming decade promises major breakthroughs in understanding our Milky Way, its disk, and the role of its satellites.

Keywords. surveys, Galaxy: abundances, Galaxy: disk, Galaxy: evolution, Galaxy: kinematics and dynamics, Galaxy: structure, galaxies: dwarf, galaxies: evolution, Local Group

1. Stellar Population Surveys of the Galactic Disk

During the last years we have made tremendous progress in learning about the stellar populations contributing to the Galactic disk as well as about the stellar constituents of other galaxies in the Local Group. These advances were made possible by new observational facilities such as space telescopes, large (8 to 10m-class) ground-based telescopes, and surveys with dedicated smaller telescopes. In understanding the Galactic disk, we continue to benefit from the unique heritage of the astrometric Hipparcos mission (Perryman *et al.* 1997) of the European Space Agency (ESA). The next decade looks particularly promising for Galactic astronomy: We will obtain an unprecedentedly deep and detailed picture of the kinematics and evolution of our Galaxy thanks to ESA's Gaia satellite (Perryman *et al.* 2001). This ESA cornerstone mission is scheduled to be launched at the end of 2011. Moreover, studies at many different wavelengths ranging from radio to gamma rays have contributed directly or indirectly to our understanding of the stellar population properties.

1.1. *The astrometric Hipparcos mission and the Geneva-Copenhagen Survey*

The Hipparcos (High Precision Parallax Collecting Satellite) satellite operated from 1989 to 1993. Hipparcos measured parallaxes for about 120,000 stars with a precision of 1 mas and for about 1 million stars with 30 mas or better. A re-reduction finally yielded the Tycho-2 catalog with 2.5 million stars, encompassing almost all objects down to the 11th magnitude in the V-band (Høg *et al.* 2000). These data include information on positions, motions, luminosities, and colors. The Hipparcos data have provided a basis for more than 1,600 refereed papers to date, revealing the tremendous impact of Hipparcos.

I will highlight here one of the many important studies obtained in part with Hipparcos data: The Geneva-Copenhagen Survey of the solar neighborhood (Nordström *et al.* 2004; Holmberg *et al.* 2007). The Geneva-Copenhagen Survey combines Hipparcos parallaxes,

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Tycho-2 proper motions, Strömgren $uvby\beta$ photometry, and radial velocities of more than 14,000 nearby F and G dwarf stars with metallicities and isochrone-based ages.

The Geneva-Copenhagen Survey confirms the G-dwarf problem and shows that radial metallicity gradients exist in the disk. While the mean metallicity of the Galactic disk does not change much with age, a large scatter in metallicity is found at all ages. The thin disk continues to be dynamically heated, and heating from stochastic spiral waves aggravates the kinematic identification of thick disk stars.

1.2. *Moving groups and kinematic substructure*

Hipparcos as well as other observations have contributed to the detection of kinematic substructure in the Galactic disk. The concept of "moving groups" was first introduced by Eggen, who worked extensively on this topic and identified a number of them (e.g., Eggen 1965). It has since been shown that moving groups can have several possible origins. The most frequent type of moving group consists of the stellar debris of star-forming aggregates (dissolving associations and open clusters). This is particularly common among young moving groups (e.g., López-Santiago *et al.* 2006), but also old moving groups that appear to be dispersing stellar aggregates have been identified both chemically and kinematically (e.g., HR 1614: De Silva *et al.* 2007; Feltzing & Holmberg 2000). Here we are witnessing the gradual production of field populations. Other moving groups appear to be due to dynamical resonances in the disk. This seems to be the case for the Hercules stream (Famaey *et al.* 2007) and also for the Pleiades, Hyades, and Sirius moving groups (Famaey *et al.* 2008). The third possible origin of moving groups are accretion events: In this case, moving groups are the debris of infalling objects (e.g., Helmi *et al.* 2006a; Arifyanto & Fuchs 2006). The Arcturus group seems to be one such example (Navarro *et al.* 2004), and there are also signs of debris streams at larger distances (e.g., Wyse *et al.* 2006). Ultimately, these detections hint at a possible merger origin of the thick disk.

1.3. *Ongoing kinematic surveys: RAVE as an example*

The Radial Velocity Experiment (RAVE, 2003–2011) measures the radial velocities and chemical composition of up to 1 million luminous stars in the southern sky (Steinmetz *et al.* 2006; Zwitter *et al.* 2008). The data are taken at the 1.2m UK Schmidt Telescope with the 6dF spectrograph of the Anglo-Australian Observatory (Australia). RAVE explores the chemistry and kinematics of our local neighborhood in the Milky Way with spectra in the near-infrared Ca II triplet region (R = 7,500) across a magnitude range of $9 < I < 12$.

Combining RAVE spectra with CORAVEL (Correlation Radial Velocities; used for the Geneva-Copenhagen Survey), Seabroke *et al.* (2008) searched the local Galactic disk for streams. They were able to exclude nearby crossings of both the Sagittarius stream and the Virgo overdensity. Concentrating on 500 pc around the Sun, Klement *et al.* (2008) could to retrieve several previously identified moving groups and found one new stream candidate on a radial orbit.

RAVE in combination with ELODIE radial velocities and infrared photometric star counts from 2MASS together with UCAC2 proper motions were used to separate stars of different luminosity classes and measure the scale heights of the thin and the thick disk toward the poles (225 ± 10 pc and 1048 ± 36 pc, respectively). The data indicate that the thick disk cannot have formed through a continuous process from the thin disk (Veltz *et al.* 2008). With red clump stars towards the South Galactic poles, the inclination of the velocity ellipsoid 1 kpc below the plane was found to be $7.3° \pm 1.8°$ (Siebert *et al.* 2008). Together with other constraints this argues in favor of a nearly spherical halo and

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a disk scale length of ~ 2.6 kpc. For further details see the contribution of Steinmetz in these proceedings.

1.4. *Recent/ongoing optical and infrared surveys*

Vast data sets from ground-based photometric and spectroscopic stellar surveys are either already available or are currently being obtained, and additional survey projects are planned. These data are changing and refining our understanding of the stellar populations in our Galaxy and its neighbors. The past and ongoing surveys are usually carried out with small and medium-sized telescopes, which continue to be immensely useful for survey applications. The observations are often complemented by targeted follow-up studies with large telescopes.

Microlensing surveys such as EROS (Expérience de Recherche d'Objets Sombres, e.g., Derue *et al.* 2001) MACHO (Massive Compact Halo Objects, e.g., Alcock *et al.* 1998), and OGLE (Optical Gravitational Lensing Experiment, e.g., Szymanski *et al.* 1996) had the detection of dark matter candidates as their main goal, but they also yielded valuable data on Galactic structure and on stellar populations in the halo, disk, and bulge, particularly on their variable stars.

The studies of the Quasar Equatorial Survey Team (QUEST) have led to the discovery of detailed substructure in the Galactic halo as traced by RR Lyrae stars (Vivas *et al.* 2001; Vivas & Zinn 2006; Duffau *et al.* 2006). The Century Survey Galactic Halo Project relies on blue horizontal branch stars selected from 2MASS and the SDSS (both see below). These data trace the metal-poor thick disk and inner halo, their metallicity distribution functions and their kinematics (Brown *et al.* 2003, 2005, 2008). Also other surveys including time-domain data are being used to uncover substructure in the Galactic halo, e.g., the Southern Edgeworth-Kuiper Belt Object survey (SEKBO; see Keller *et al.* 2008 for results).

The Two Micron All Sky Survey (2MASS, Skrutskie *et al.* 2006) mapped the entire sky in the near-infrared JHK bandpasses using 1.3m telescopes. The 2MASS data base has been of enormous value for numerous stellar and Galactic studies, including, perhaps most spectacularly, the all-sky view of the tidal tails of Sagittarius as traced by M giants (Majewski *et al.* 2003) and of other overdensities (e.g., Rocha-Pinto *et al.* 2003, 2004, 2006). Also the IJK Deep Near-Infrared Southern Sky Survey (DENIS, Epchtein *et al.* 1999), carried out with a 1m telescope at the European Southern Observatory (ESO, La Silla, Chile) has been used for a large number of stellar and Galactic structure studies, for instance, in order to constrain the scale height and the scale length of the Galactic disk and its dust layer (Unavane *et al.* 1998).

The UKIRT Infrared Deep Sky Survey (UKIDSS; 2005–2012) includes a large-area survey (4000 $\deg^2$) and a Galactic plane survey (GPS, 1800 $\deg^2$; Lucas *et al.* 2007) in the JHK infrared passbands. The GPS will ultimately contain 2 billion sources and is already proving to be useful in combination with data obtained in other wavelength ranges such as the Isaac Newton Telescope (INT) Photometric Hα Survey of the Northern Galactic Plane (IPHAS), which covers 1800 $\deg^2$ of the plane. The IPHAS point source catalog will contain ~ 80 million sources (Drew *et al.* 2005) and is a valuable tool for stellar population studies in the disk. The UKIDSS GPS, an excellent resource for Galactic structure studies in the inner Milky Way, was already used recently to refine the position angle and extent of the long Galactic bar (Cabrera-Lavers *et al.* 2008).

The Spitzer Space Telescope conducted a survey of the Galactic plane in four infrared bands. The data of the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) have provided spectacular results on the spiral structure and bar of our Galaxy as well as detailed information on embedded star-forming regions (see, e.g.,

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Benjamin *et al.* (2003, 2005) and Benjamin, these proceedings). A recent GLIMPSE result is the recognition that our Milky Way appears to have only two major spiral arms as well as several less prominent spiral fragments.

1.5. *The SDSS, SEGUE, and results for the Galactic disk and halo*

Not all of these surveys were initially designed for stellar population studies or for Galactic science. For instance, the Sloan Digital Sky Survey (SDSS) (e.g., York *et al.* 2000; Grebel 2001; Stoughton *et al.* 2002) originally had cosmological applications as its main science driver, but it inevitably observed numerous stars of the Galactic thin and thick disk and in the Galactic halo. The SDSS is the largest photometric and spectroscopic sky survey undertaken to date. It uses a dedicated 2.5m telescope at Apache Point Observatory (USA) and is mapping more than one quarter of the sky. The availability of such a large, deep, and homogeneous data set led to, e.g, an improved determination of the vertical disk structure (Chen *et al.* 2001) and to the discovery of new Galactic substructure (Odenkirchen *et al.* 2001a, 2003, Rockosi *et al.* 2002; Newberg *et al.* 2002, 2003; Yanny *et al.* 2003, Peñarrubia *et al.* 2005; Grillmair & Dionatos 2006, Grillmair 2006, Grillmair & Johnson; Belokurov *et al.* 2006a). The new substructure consisted both of disrupting star clusters as well as new overdensities in the Milky Way such as the Monoceros ring and new tails of the Sagittarius dwarf galaxy.

In recognition of the potential of the SDSS for studies of Galactic structure and evolution, the subsequent continuations of the survey – SDSS-II and SDSS-III – dedicated a substantial amount of survey time to Galactic science projects, in particular, to the Sloan Extension for Galactic Understanding and Exploration (SEGUE, see Newberg *et al.* 2003 and Rockosi 2005). SEGUE (I+II) will obtain close to 600,000 spectra from ~ 380 to 910 nm ($R = 2000$). APOGEE, the Apache Point Observatory Galactic Evolution Experiment, will take H-band spectra of 100,000 red giants in the bulge and disk with $R \sim$ 20,000. SEGUE II and APOGEE are currently the main Galactic SDSS projects. The SDSS is expected to continue until 2014.

The efforts dedicated to Galactic science are leading to substantial progress in our understanding of Galactic structure and chemistry. Jurić *et al.* (2008) estimated the distances to some 48 million stars in the SDSS and mapped their three-dimensional density distribution from 20 to 100 kpc across 6,500 deg^2. These authors recovered previously known overdensities such as the Monoceros feature of Yanny *et al.* (2003) and identified two new extended stellar overdensities including the Virgo density enhancement, which extends across 1,000 deg^2. They suggest that the Virgo overdensity may be a dwarf galaxy merging with the disk. All of the detected overdensities are comparatively close to the Galactic disk; the remainder is fairly smooth. Jurić *et al.* find the Galactic thin and thick disk well-described by exponential disks. The resulting scale lengths and scale heights are 2,600 and 300 pc for the thin disk and 3,600 and 900 pc for the thick disk, respectively. The data support an oblate halo.

Allende Prieto *et al.* (2006) analyzed spectroscopy and photometry of 22,770 SDSS stars. They show that the metallicity distribution of thick-disk G-dwarf stars at vertical distanced of $1 < |z| < 3$ kpc from the Galactic plane peaks at [Fe/H] ~ -0.7 dex and that it lags behind the local standard of rest (LSR) rotation by 63 km s^{-1}. The authors do not detect a thick disk metallicity gradient across 5 to 14 kpc from the Galactic center, nor do they find a vertical gradient. However, they do find a decline in rotational velocity with increasing distance from the plane. In contrast to the relatively narrow metallicity range of the thick disk, they find a wide range of metallicities in the halo peaking at [Fe/H] ~ -1.4 dex. While most of the star formation in the halo seems to have occurred 11 Gyr or longer ago, some of the thick disk stars appear to be $\geqslant 2$ Gyr younger. Ivezić

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et al. (2008) derive spectroscopic and photometric metallicity estimates for 60,000 F and G main-sequence stars and discuss the metallicity distribution functions. They show that the Monoceros feature is distinct in metallicity and rotates faster than the LSR.

Carollo *et al.* (2007) analyzed SDSS spectra and demonstrate that the Galactic halo consists of two components. The inner halo exhibits an overall prograde rotation with a peak metallicity at [Fe/H] ~ -1.6 dex, while the outer halo shows net retrograde rotation and is more metal-poor (peak metallicity ~ -2.1 dex). This dichotomy and the properties of the outer halo seem to favor an accretion origin. In a structural analysis of ~ 4 million main-sequence turn-off stars, Bell *et al.* (2008) find substantial substructure in the halo, consistent with expectations from a halo built out of the debris of disrupted satellites.

1.6. *Other spectroscopic studies of the Galactic disk*

The past two decades have seen a large number of high-resolution spectroscopic studies of stars in the Galactic disk and in other Milky Way components. Results of only very few of these studies can be mentioned here. An abundance gradient with Galactocentric radius was found in studies using a variety of tracers including Cepheids, open clusters, and H II regions (Luck *et al.* 2006; Chen *et al.* 2003; Maciel & Costa 2008). These relatively mild gradients tend to become flat at large Galactocentric radii. Individual element abundance ratios indicate that Type II supernovae dominated the enrichment in recent star formation events in the outer disk (Yong *et al.* 2006), in contrast to what is observed in the solar neighborhood. Since older open clusters and field stars reach their lowest metallicities at shorter Galactocentric distances (~ 11 kpc) than the younger Cepheids (~ 14 kpc), the Galactic disk seems to have grown with time (Yong *et al.* 2006). The deviant abundance ratios of a small number of Cepheids – lower [Fe/H] and higher [α/Fe] – may indicate that they formed as a consequence of recent merger events (candidates include the Monoceros feature or Canis Major).

The thick and the thin disk are quite distinct in their abundances (e.g., Bensby *et al.* 2005; Brewer & Carney 2006; Reddy *et al.* 2006). Generally, thick disk stars are enhanced in [α/Fe] as compared to thin disk stars. Only the most metal-poor thin disk stars are α-enhanced; the ratios decline toward solar values for [Fe/H] > -1 dex. In contrast, for the thick disk the decline begins at higher metallicities ([Fe/H] ~ -0.4). Heavy s-process elements are enhanced in thin disk stars relative to thick disk stars, while the thick disk seems to be dominated by Type Ia supernova enrichment. The thick disk does not show variations in its abundance ratios beyond Galactocentric distances of 5 kpc or with vertical distance from the plane (Bensby *et al.* 2005). The differences in nucleosynthetic history support an independent evolutionary history of the thin and the thick disk (Brewer & Carney (2006)).

Meléndez *et al.* (2008) suggest that the local thick disk and the Galactic bulge show the same abundance patterns, indicative of similar chemical enrichment histories, and that they may have formed on similar time scales. Generally, the thick disk is believed to have formed early and rapidly about 12 Gyr ago, and there appears to have been a time delay between the formation of the thick and the thin disk (e.g., Freeman & Bland-Hawthorn 2002). Scenarios for the formation of the thick disk include heating of an early thin disk caused by mergers or interactions, or the formation of the thick disk from the early accretion of satellites. Other scenarios suggest that gas-rich, turbulent disks with giant star-forming clumps (Elmegreen *et al.* 2008) or massive, clustered star formation (Kroupa 2002) lead to disk thickening. There is some transition or overlap in stellar properties between the thick and the thin disk, and Bensby *et al.* (2007) have shown that some stars in the thick disk even reach solar metallicities. They conclude that after pronounced chemical enrichment over a period of ~ 3 Gyr, this process ended

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some 8–9 Gyr ago. There is also evidence for a gradual transition between the thick disk and the halo beyond distances of 4 kpc above the Galactic plane: Here the mean stellar metallicity is ~ -1.7 dex. The rotational gradient decreases with increasing distance from the plane, and at distances beyond 5 kpc stars show mainly inner-halo properties with a mean [Fe/H] = −2 dex (Brown *et al.* 2008).

2. Future Stellar Population Surveys of Galactic Disk

2.1. *Future optical and infrared ground-based imaging surveys*

The VISTA Hemispheric Survey (VHS) is one of the ESO Public Surveys to start 2009. It will contribute to an infrared imaging map of the southern sky (20,000 deg^2) that reaches 4 mag deeper than 2MASS and DENIS. These data will complement optical surveys such as the SSS (see below) and will be particularly useful for structural studies, determinations of the low-mass stellar mass function, etc. The European Galactic Plane Surveys (EGAPS) seek to combine the various ongoing and planned surveys with the Isaac Newton Telescope (INT, Spain) and the VLT Survey Telescope (VST, Chile) to map the complete Galactic plane ($10^\circ \times 360^\circ$) down to 21st magnitude in various optical bands. EGAPS comprises individual northern and southern surveys like IPHAS, VPHAS+, and UVEX. The surveys aim mainly at stellar astrophysics.

The Panoramic Survey Telescope & Rapid Response System (Pan-STARRS or PS1; 2008 – 2013; Kaiser 2006) is a northern photometric survey that will reach five times lower luminosities than the SDSS and that will add the time domain. PS1 uses a custom-built 1.8m telescope on Haleakala (USA) with a three-degree imager. PS1 will observe three quarters of the sky. It will be particularly useful for identifying halo substructure, but it will also cover more of the Galactic disk at greater depths than previous surveys. The Southern Sky Survey (SSS, Keller *et al.* 2007) is an automated photometric survey mapping the southern hemisphere with a new 1.3m telescope at Siding Spring Observatory (Australia; to start in 2009). The SSS will provide data for Galactic (sub-)structure, and for variable sources, complementing the northern SDSS and PS1 photometry.

The Large Synoptic Survey Telescope (LSST) is a planned 8.4m telescope with a field of view of 9.6 deg^2. It will map 20,000 deg^2 every three nights using up to six broad-band filters. LSST will reach r $\sim$ 27.5. First light is expected in 2014. With its time-lapse imaging, coverage, and depth, LSST will be a fabulous facility for Galactic science.

2.2. *Future kinematic and chemistry surveys*

The Large Sky Area Multi-Fiber Spectroscopic Telescope (LAMOST) is a wide-field spectroscopic survey that will be carried out with a custom-built 4m telescope at Xinglong Station (China). Up to 4,000 stars can be observed simultaneously with a resolution of 1000 – 2000. LAMOST is an ideal facility to map the chemical composition and kinematics of stars in the Milky Way (Zhao *et al.* 2006).

The Wide-Field Multi-Object Spectrograph (WFMOS) is being developed by an international consortium for use with the Gemini and Subaru telescopes. One of the key projects with WFMOS will be Galactic archaeology. The Japanese JASMINE astrometry mission will be complemented by WINERED, a near-infrared high-resolution ($R \sim 20,000$) spectrograph currently under construction. It will provide radial velocities and chemical abundances for Galactic bulge stars.

2.3. *Stellar imaging survey missions from space*

The NASA Explorer mission WISE (Wide-Field Survey Explorer; launch 2010) will map the Milky Way in the infrared during its six-month mission. The data will provide an

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image of the Milky Ways stellar populations with a much reduced dust extinction, useful for, e.g., Galactic structure studies.

One of the proposed ESA Cosmic Vision missions is EUCLID, which aims at cosmic shear and photo-z measurements (the merger of the DUNE concept of Refregier *et al.* 2008 and the SPACE concept of Cimatti *et al.* 2008). EUCLID would deliver diffraction-limited optical and infrared images down to $\sim$ 24th magnitude (wide visual and H-band) of 20,000 deg^2 outside of the Galactic plane. Observations of the plane are under discussion. If approved, this mission (potential launch year: 2018) would deliver an exquisite, deep data set for Galactic structure studies, stellar mass functions, etc.

2.4. *Future space astrometry missions*

ESA's cornerstone mission Gaia will survey the entire sky down to G $\sim$ 20, covering up to one billion stars. Apart from astrometry accurate to 12 – 25 μas at 15th magnitude and about 100 – 300 μas at G $\sim$ 20, Gaia carries out low-dispersion spectrophotometry with $R = 3$ to 30 nm pixel^{-1} covering a wavelength range from 330 – 1000 nm. From these low-dispersion spectra various photometric passbands can be synthesized. In addition, Gaia obtains spectroscopy with $R = 11,500$ centered on the Ca II triplet. With the wealth of data that Gaia will provide it will truly revolutionize Galactic astronomy, providing six-dimensional phase space information along with physical stellar parameters, metallicities, and to some extent possibly [α/Fe] estimates. What Gaia will be able to accomplish for studies of Galactic structure, of the accretion history of our Milky Way, and other topics is described in Bailer-Jones' contribution in these proceedings and references therein.

The Japanese JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration) satellite is expected to carry out near-infrared astrometry of sources with z-band magnitudes from 6 to 14 with a proper-motion accuracy of $\sim$ 4 μas year^{-1} (Gouda *et al.* 2006). It may be launched in 2016 or later. It is preceded by a small technical demonstrator mission, Nano-Jasmine (launch planned 2010), which will observe stars brighter than 8th mag. JASMINE will provide an interesting complement to Gaia's optical astrometry particularly in the disk and bulge, as its data will be less affected by dust extinction.

NASA's Space Interferometry Mission (SIM) is a pointed mission (not an all-sky survey) with considerably higher astrometric accuracy than Gaia ($\sim$ 4 μas at V = 20). Due to its measurement technique it will only observe comparatively few selected objects (Unwin *et al.* 2008). SIM's status is yet to be decided, but if it were to fly it would probably start only in 2016. One of SIM's approved key projects, "Taking Measure of the Milky Way" (PI: Majewski), is designed to provide an accurate map of the mass distribution within our Galaxy.

3. Recent Studies of the Dark Matter Content of the Milky Way

In order to constrain the dark matter content of the Milky Way, one aims at deriving the enclosed mass out to as large Galactocentric distances as possible. Here a few recent results based on stellar populations are presented. Ultimately, these studies seek to determine the circular velocity curve ($V_{circ}(R)$) or the escape velocity curve ($V_{esc}(R)$). The work summarized below does not tell us much about the estimated dark matter content of the Galactic *disk*, but rather of the Milky Way as a function of distance or as a whole.

Smith *et al.* (2007) measured the local escape speed and used that result to also estimate the total mass of the Milky Way. They use 16 high-velocity stars from the RAVE survey and combined them with 17 high-velocity stars from other surveys, resulting in a sample of 33 stars in total. Smith *et al.* (2007) find that the local escape velocity lies in the range of $(498 < V_{esc} < 608)$ km s^{-1} with a median $V_{esc} = 544$ km s^{-1}. Since V_{esc}^2 is

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much larger than $2V_{circ}^2$ they conclude that there must be a significant amount of mass outside of the solar circle. Adopting different halo models, they derive a virial mass of the Milky Way of $\sim 1.4 \cdot 10^{12}$ M$_\odot$, corresponding to a virial radius of $R_{vir} \sim 305$ kpc and a circular velocity at the virial radius of $V_{circ}(R_{vir}) \sim 142$ km s^{-1}.

Sakamoto *et al.* (2003) perform a kinematic mass estimate employing (presumably) bound halo objects. They combine radial velocities and, where available, proper motions for 11 Galactic satellite galaxies, 137 globular clusters, and 413 field horizontal branch stars with heliocentric distances of up to 10 kpc in order to constrain the mass of the Milky Way. They find that several high-velocity objects including Leo I, Pal 3, and Draco affect the mass estimate significantly. At the distance of the Large Magellanic Cloud, the resulting Milky Way mass is $\sim 5.5 \cdot 10^{11}$ M$_\odot$. The total Galactic mass is $\sim 2.5 \cdot 10^{12}$ M$_\odot$ when Leo I is included or $\sim 1.8 \cdot 10^{12}$ M$_\odot$ without Leo I.

Battaglia *et al.* (2005) measure the radial velocity dispersion profile of the halo. They used 240 halo objects with distance and radial velocity measurements, including 24 objects beyond 50 kpc. Their sample includes 44 globular clusters, nine satellites, and a large number of field halo stars (horizontal branch and red giant stars). Battaglia *et al.* (2005) find that the radial velocity dispersion is almost constant out to 30 kpc with a value of 120 km s^{-1}. Then it decreases smoothly down to 50 km s^{-1} at $\sim$ 120 kpc. The authors conclude that in the case of a constant velocity anisotropy an isothermal profile can be excluded, whereas either a truncated flat halo model ($\sim 1.2 \cdot 10^{12}$ M$_\odot$) or a Navarro, Frenk, & White (NFW) profile with $\sim 8 \cdot 10^{11}$ M$_\odot$ are permitted by the data.

Xue *et al.* (2008) determine the circular velocity curve of the Milky Way out to 60 kpc using a sample of 2400 blue horizontal branch stars within $|z| \geqslant 4$ kpc and with SDSS photometry and spectroscopy. They derive an enclosed mass at 60 kpc of $\sim 4 \cdot 10^{11}$ M$_\odot$. Assuming an NFW halo profile, they estimate the virial mass of the Milky Way's dark matter halo to be $\sim 10^{12}$ M$_\odot$. This value is lower than previous estimates and questions whether the Galactic satellites are indeed bound. So the question of the total mass and dark matter content of the Milky Way still remain open.

4. Properties of the Satellites of the Milky Way

Our Milky Way is surrounded by a large number of satellites, whose census has been considerably extended in the last few years. While in the previous decades typically four or five new dwarfs were added to the Local Group per decade (van den Bergh 1999), deep imaging surveys recently led to a significant increase of candidate Local Group members. For a more detailed description of the different types of lower-mass dwarf galaxies and their properties see the review by Grebel (2001b). Most of the new galaxies are very faint, gas-deficient dwarf spheroidal (dSph) galaxies that appear to orbit either M31 or the Milky Way (e.g., Zucker *et al.* 2004, 2006a, 2006b, 2007; Belokurov *et al.* 2006b, 2007). The Milky Way alone gained at least ten newly recognized companions, and additional ones await confirmation.

The Milky Way has two comparatively massive, gas-rich, nearby neighbors, the Magellanic Clouds. The Clouds are interacting with each other and with the Milky Way, but it is unclear whether they are bound to our Galaxy or on their first passage (Besla *et al.* 2007). This in turn questions their role in the creation of the warp of the Galactic disk (Weinberg & Blitz 2006). Nonetheless, satellites are of particular interest as interaction partners of the Milky Way and as objects that may ultimately be accreted.

The majority of the Milky Way companions is dominated by old and metal-poor populations. The more luminous dwarf galaxies deviate from this trend however: The Magellanic Clouds have experienced star formation until the present day, the Fornax dSph

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stopped forming stars only a few hundred million years ago (e.g., Grebel & Stetson 1999), and galaxies like Leo I and Leo II were still active about a billion years ago (e.g., Grebel *et al.* 2003). While the "classical" dSph galaxies seemed to indicate that the duration of star formation activity and the intermediate-age population fraction correlates with distance from the primary (van den Bergh 1994), no such trend is seen when including the recent, very low-luminosity dwarfs, suggesting that intrinsic properties such as the baryonic mass content may be a more important factor. Nonetheless, spatial variations in star formation are observed even in those dSphs dominated primarily by old populations. While dwarf irregular galaxies show a number of scattered large-scale, long-lived star-forming regions with life times of 10 – 100 Myr (e.g., Grebel & Brandner 1998), in the lower-luminosity dwarfs the somewhat younger and/or somewhat more metal-rich populations are more centrally concentrated (Grebel 1997; Stetson *et al.* 1998; Hurley-Keller *et al.* 1999; Harbeck *et al.* 2001; Koch *et al.* 2006a), suggesting more extended activity in the central regions where star-forming material could be retained more easily.

In dwarf galaxies with long-lasting star formation histories no simple age-metallicity relation has been found thus far. Leo II, for instance, shows a flat age-metallicity relation over many Gyr (Koch *et al.* 2007a), which may be indicative of blow-out (see also Lanfranchi & Matteucci 2007) or dilution by gas accretion. The Small Magellanic Cloud shows a complex age-metallicity relation with substantial scatter at any age (Glatt *et al.* 2008a). Evidence for inhomogeneous enrichment has also been found in other dwarf galaxies (e.g., Kniazev *et al.* 2005; Koch *et al.* 2008a, 2008b). Marcolini et al. (2008) present theoretical models describing mechanisms for stochastic enrichment.

All nearby dwarf galaxies studied in detail thus far reveal evidence for old populations (although their fraction may vary), and their main-sequence turn-off ages are even consistent with a common epoch of substantial early Population II star formation (Grebel & Gallagher 2004). (The Small Magellanic Cloud is a possible exception at least as far as its globular clusters are concerned; see, e.g., Glatt *et al.* 2008b).

There is a growing body of data on detailed element abundance ratios for red giants in nearby dSphs based on high-resolution spectroscopy with 8 to 10m-class telescopes. Generally, dSphs exhibit lower [α/Fe] ratios at a given [Fe/H] than observed in Galactic halo stars of comparable metallicity (e.g., Shetrone *et al.* 2001; Fulbright 2002; Tolstoy et al. 2003; Sadakane *et al.* 2004; Geisler *et al.* 2005; Monaco *et al.* 2005; Sbordone *et al.* 2007, Koch *et al.* 2008). Very few very metal-poor stars with [Fe/H] < -2.5 have been found in dSphs thus far (Helmi *et al.* 2006b; Koch *et al.* 2007a), but a recent study succeeded in detecting such objects (Kirby *et al.* 2008). Both the differences in [α/Fe] ratios and the perceived deficiency in extremely metal-poor stars have been taken as arguments against low-mass dwarf galaxies being *dominant* contributors to the build-up of galaxies like the Milky Way (e.g., Shetrone *et al.* 2001), although they clearly did contribute (e.g., Carollo *et al.* 2007). The apparent planar alignment of dwarf satellites (e.g., Lynden-Bell 1982; Koch & Grebel 2006; Pasetto & Chiosi 2007; Metz *et al.* 2008; and references therein) can be interpreted as an indication of infall and subsequent interactions (e.g., D'Onghia & Lake 2008).

Considering only their present-day numbers, the possible contribution of dSphs to the overall mass of their "parent galaxy" is negligible, since with typical total masses of the order of a few 10^7 $M_\odot$ (e.g., Wilkinson *et al.* 2004; Koch *et al.* 2007a, 2007b; Gilmore et al. 2007; Walker *et al.* 2007; Strigari *et al.* 2008) they are up to five orders of magnitude less massive than galaxies like the Milky Way. Intriguingly, the above studies indicate that the radial velocity dispersion profiles of dSphs are flat and that these galaxies are likely strongly dark matter dominated, sharing the same mass of a few times 10^7 $M_\odot$ within 600 pc regardless of their baryon content or stellar luminosity.

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