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THE MILKY WAY TOMOGRAPHY WITH SDSS AND LSST

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Abstract. The accurate multi-band SDSS photometry to a faint limit and over a large fraction of the sky has enabled tomographic studies of the Milky Way structure: for main sequence stars, the photometric distance estimates are sufficiently precise (∼10%) to directly map the three-dimensional distribution of stars at distances exceeding 10 kpc, and to study distributions of various other parameters. In particular, the SDSS photometry also enables fairly precise metallicity estimates (∼0.2 dex) for F and G stars, and comparison of positions measured by SDSS and half a century earlier Palomar Observatory Sky Survey results in accurate proper motions (random errors of ∼3-5 mas/yr). We summarize recent SDSS results based on this tomographic approach, and discuss what further progress in this context can be expected from the Large Synoptic Survey Telescope (LSST). LSST will obtain similar imaging data as SDSS to about 5 magnitudes deeper limit, and over twice as large sky area.

1. INTRODUCTION

The current cosmological paradigm states that the Universe had its beginning in the Big Bang. Galaxies, the fundamental building blocks of the Universe, formed soon after the Big Bang. A major objective of modern astrophysics is to understand when and how galaxies formed, and how they have evolved since then. Our own galaxy, the Milky Way, provides a unique opportunity to study a galaxy by measuring and analyzing the properties of a large number of individual stars. Because these stars can be studied in great detail, their characterization will provide clues about galaxy merging process that cannot be extracted from observations of distant galaxies.

Most studies of the Milky Way can be described as investigations of the stellar distribution in the seven-dimensional space spanned by the three spatial coordinates, three velocity components, and metallicity. Depending on the type, quality, and quantity of data, such studies typically concentrate on only a limited region of this seven-dimensional (7-D) space (e.g. the nearby solar neighborhood, pencil beam surveys, kinematically biased surveys), or consider only marginal distributions (e.g. number density of stars irrespective of their metallicity or kinematics, proper motion surveys without metallicity or radial velocity information).

In order to simultaneously explore the stellar distribution in the full 7-D space, a data set needs to be both voluminous (to enable sufficient spatial, kinematic and metallicity resolution) and diverse (i.e. accurate distance and metallicity estimates, as well as radial velocity and proper motion measurements are needed), and the samples need to probe a significant fraction of the Galaxy. The Sloan Digital Sky Survey (hereafter SDSS, York et al. 2000), with its imaging and spectroscopic surveys, and the Two Micron All Sky Survey (Skrutskie et al. 2006) with its all-sky coverage, have recently provided such data sets.

Here we highlight a few results from recent work based on SDSS data by Jurić et al. (2008, hereafter J08) and Ivezić et al. (2008a, hereafter I08). A common aspect of both papers is the "tomographic" approach: the photometric distance estimates are sufficiently precise (∼10%) to directly map the three-dimensional distribution of stars and various other properties. We also use these results to illustrate what can be expected from the next generation of imaging surveys, such as the Large Synoptic Survey Telescope (Ivezić et al. 2008b).

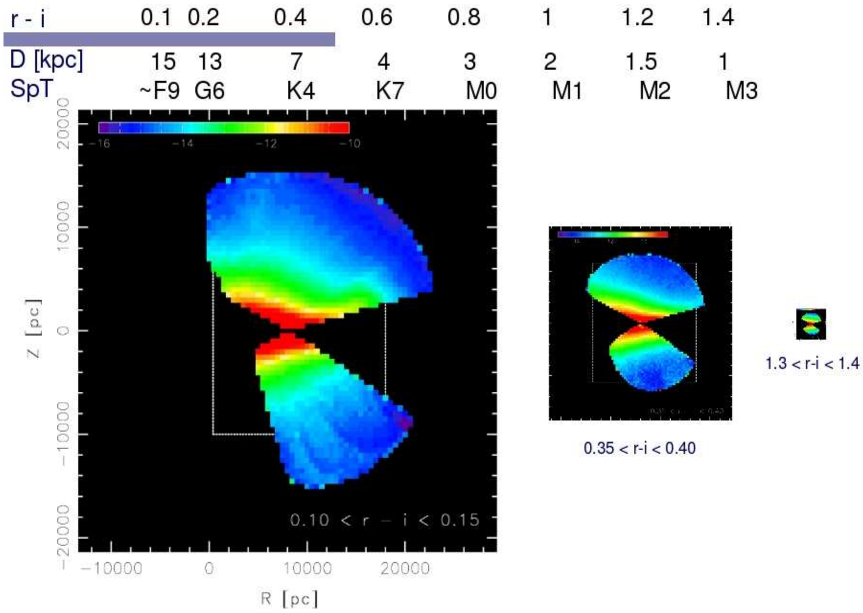

Figure 1: The stellar number density as a function of Galactic cylindrical coordinates R (distance from the axis of symmetry) and Z (distance from the plane), for different $r-i$ color bins, as marked in each panel (J08). The density is shown on a logarithmic scale, and coded from blue to red as shown in the legend (black pixels are regions without the data). Each pixel value is the median for all polar angles, and the resolution of the data region is about 60×60 pixels. The three panels have the same number of pixels and level of detail, but are shown here on the same spatial scale to demonstrate how the Galaxy can be studied on different scales by selecting stars of different color. The relationship between the $r-i$ color, corresponding distance limit for SDSS sample, and spectral type is shown in the legend on top.

2. STELLAR NUMBER DENSITY MAPS

Using photometric data for 50 million stars from SDSS Data Release 4, J08 have constructed 3-dimensional maps (data cubes) of the stellar number density distribution for 19 narrow color bins that span spectral types from mid-F to early M. As the bin color is varied from the reddest to the bluest, the subsamples cover distances ranging from 100 pc to 15 kpc. Distance to each star is estimated using a maximum likelihood implementation of photometric parallax method, and stars are binned and counted in small 3-dimensional pixels whose size depends on dynamical range provided by each color bin and Poisson noise limits (typically there are 250,000 pixels per map). Examples of 2-dimensional projections of the resulting maps are shown in Fig. 1.

These maps are a powerful tool for studying the Milky Way's stellar number density distribution. Traditional methods for modeling stellar counts in the magnitude-color space need to adopt a large number of poorly known functions such as the initial mass function, the mass-luminosity relationship, the luminosity function, and geometric description of the postulated components such as disks, bulge and halo. Instead, with these number density maps the Milky Way's structure can be studied without any a priori assumptions about its components. *With these maps analysis of the Milky Way's structure is now akin to studies of external galaxies.*

The description of these maps is not a trivial task because of the rich substructure. While halo substructure has been known for a while (e.g. Ivezić et al. 2000, Yanny et al. 2000, Vivas et al. 2001, Majewski et al. 2003, and references therein), these new maps demonstrate that the thin and thick disk substructure is equally complex. Nevertheless, the gross behavior can be captured by assuming "standard" Galaxy models based on two exponential disks and a power-law halo. J08 determined the best-fit parameter values for full two-dimensional smooth models and further refined them using residual minimization algorithms. The complex Galaxy substructure becomes readily discernible in residual maps obtained by subtracting the best-fit smooth Galaxy models from the data, as shown in Fig. 2. When using different color bins, the clumps discernible in residual maps are detected in different apparent magnitude ranges, but at the *same geometric positions*. This consistency strongly argues that the overdensities are not artefacts of the adopted photometric parallax relation.

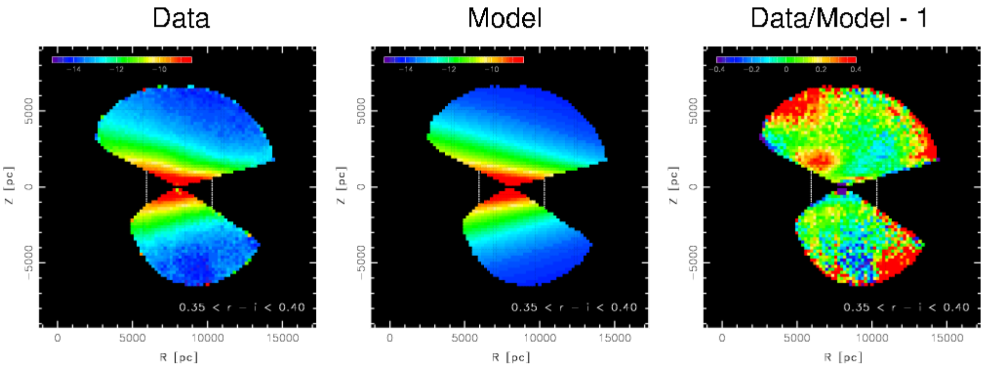

Figure 2: The left panel shows the measured stellar number density as a function of Galactic cylindrical coordinates for stars with 0.35< $r-i$ <0.40. The middle panel shows the best-fit smooth model taken from J08, and the right panel the normalized (data-model) difference. Note the large overdensities visible in the right panel.

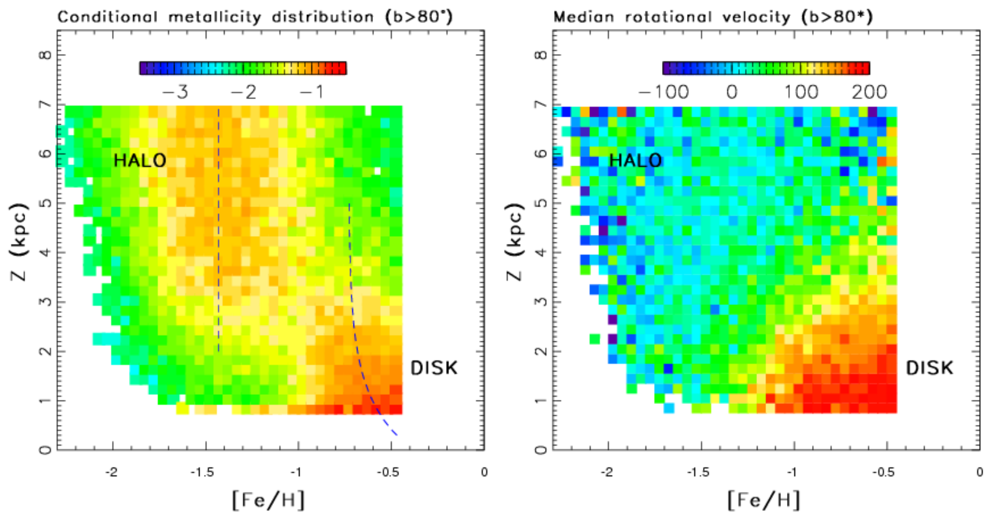

Figure 3: The left panel shows the full metalicity distribution, as a function of the distance from the Galactic plane, for about 60,000 stars within 10 degrees from the North Galactic Pole (I08). The distribution is displayed on a logarithmic scale and color-coded as shown in the inset. Two distinct Galaxy components, halo and disk, are evident. High-metallicity disk stars dominate close to the plane, while low-metallicity halo stars dominate beyond 3 kpc from the plane. The dashed lines mark the median metallicity for each component. The median metallicity for disk stars shows a gradient, while halo stars have spatially invariant metallicity distribution. These two components with distinct metallicity distributions also have different kinematics. The right panel shows the median rotational velocity component for the same stars as in the left panel. The velocity is determined from displacements of stars on the sky over half a century that lapsed between the Palomar Observatory Sky Survey (POSS) in the 1950s and SDSS. The high-metallicity disk stars have large rotational velocity (about 200 km/s, see the inset), while the low-metallicity halo stars display behavior consistent with no net rotation. The rotational velocity for disk stars decreases with the distance from the Galactic plane, while it is constant for halo stars, similarly to the behavior of their metallicity distributions.

Using this approach, J08 analysis results in the following key findings:

- The data confirmed prior evidence for a Galaxy consisting of a halo and an exponential disk component; however, these smooth components are also punctuated by numerous localized overdensities (the substructure).
- The substructure, by now well known in the halo, permeates the thick disk as well. While consistent with merger remnants, the origin of the identified substructure could not be determined with certainty.
- All parameters (scales, normalizations, flattening, and the power law index) of the Galactic disk and halo are determined using a dataset 400 times larger than in any previously published analysis, and an iterative fitting method that accounts for substructure. The large sky area breaks all degeneracies inherent in

the multi-parameter model. In summary, the distribution of stars in the Milky Way disk and the halo is now better known than ever.

- A very large, diffuse, substructure in the halo, covering over 1000 deg^2 of the sky at distances of 6-15 kpc is seen towards the Virgo constellation and dubbed the Virgo overdensity. While likely a merger remnant, its true nature is still unknown and requires further study.

2. 1. STELLAR METALLICITY DISTRIBUTION AND KINEMATICS

Encouraged by the demonstrated feasibility of direct mapping as the method of choice for analysis of large-scale photometric studies, I08 used it to obtain an unbiased, three-dimensional, volume-complete metallicity distribution of $\sim$2.5 million F/G stars at heliocentric distances of up to $\sim$8 kpc. SDSS spectroscopic metallicity was used to calibrate a photometric metallicity indicator based on the $u-g$ and $g-r$ colors, and an explicit metallicity dependence term was added to the photometric parallax relation. This study also had a kinematic component, with velocities deduced from SDSS-POSS proper motion. I08 found that

- The metallicity distribution function (MDF) of the halo and its kinematics are clearly distinct and separate from those of the disk (see Fig. 3).
- The median metallicity of the disk exhibits a clear vertical (with respect to the Galactic plane; Z) gradient. The MDF of the disk at $Z > 0.5$ kpc is consistent with no gradient in the radial direction ($6 < R$/kpc < 10). The spatial variation of the median metallicity does not follow the distribution of stellar number density (see Fig. 4).
- Disk stars show a rotational velocity gradient with distance Z from the Galactic plane. However, there is no correlation between the metallicity and rotational velocity of stars at $Z > 0.4$ kpc, in conflict with traditional thin/thick disk decomposition.
- The Monoceros stream is seen as a structure with different metallicity distribution than its surroundings.

2. 2. EXPECTATIONS FROM LSST

The LSST design is driven by four main science themes: constraining dark energy and dark matter, taking an inventory of the Solar System, exploring the transient optical sky, and mapping the Milky Way (Ivezić et al. 2008b). It will be a large, wide-field ground-based system designed to obtain multiple images covering the sky that is visible from Cerro Pachón in Northern Chile. The current baseline design, with an 8.4m (6.5m effective) primary mirror, a 9.6 deg^2 field of view, and a 3,200 Megapixel camera, will allow about 10,000 square degrees of sky to be covered using pairs of 15-second exposures in two photometric bands every three nights on average. The system is designed to yield high image quality as well as superb astrometric and photometric accuracy. The survey area will include 30,000 deg^2 with $\delta < +34.5°$, and will be imaged multiple times in six bands, *ugrizy*, covering the wavelength range 320–1050 nm. About 90% of the observing time will be devoted to a deep-wide-fast survey mode which will observe a 20,000 deg^2 region about 1000 times in the six bands during the anticipated 10 years of operations. These data will result in databases including about 20 billion objects, and will serve the majority of science programs.

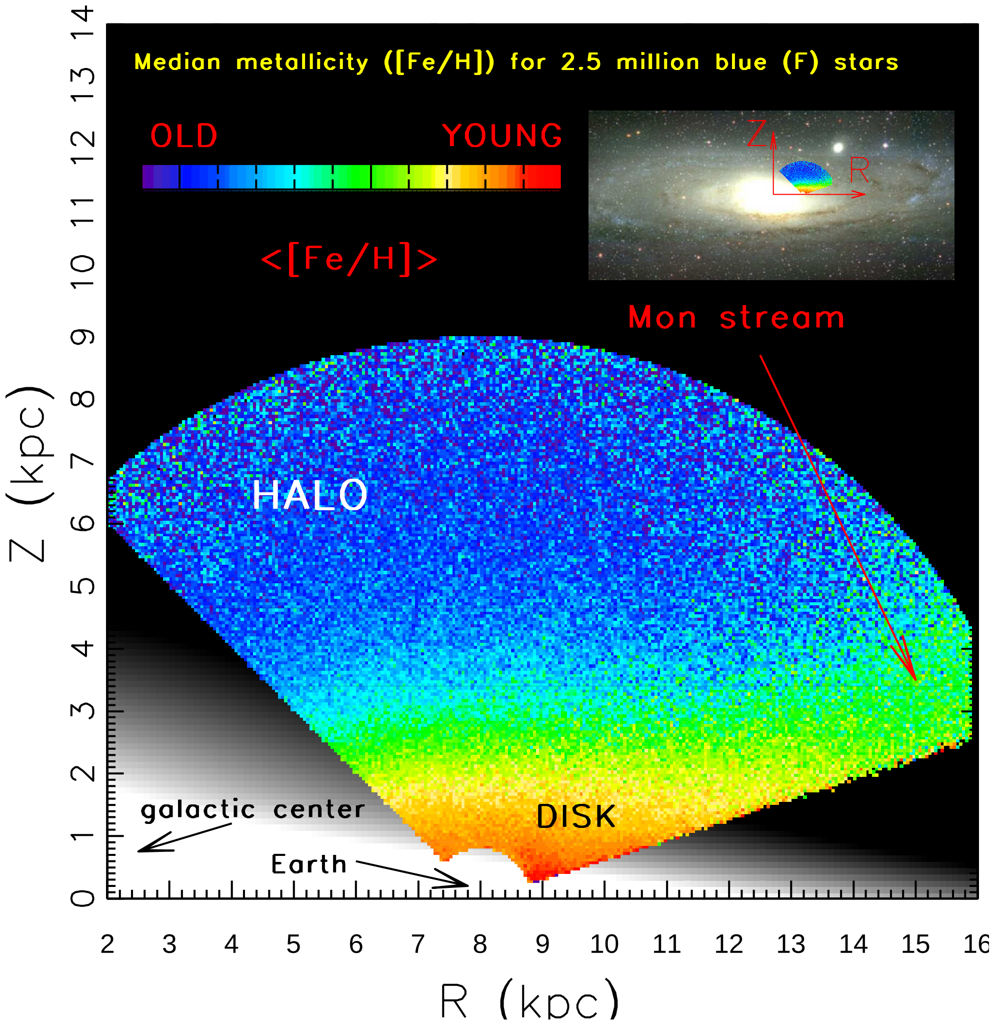

Figure 4: The median metallicity map for 2.5 million main-sequence F-type stars within 10 kpc from the Sun (I08). The metallicity is estimated using $u - g$ and $g - r$ colors measured by SDSS, and linearly color-coded according to the legend from [Fe/H]=−1.5 (blue) to [Fe/H]=−0.5 (red). The position and size of the mapped region, relative to the rest of the Milky Way, is illustrated in the top right corner, where the same map is scaled and overlaid on an image of the Andromeda galaxy. The gray scale background shows the stellar number density generated using the J08 best-fit model. The gradient of the median metallicity is essentially parallel to the Z axis, except in the Monoceros stream region, as marked. LSST will extend this map out to 100 kpc, using a sample of over 100 million main-sequence F stars.

LSST will produce a massive and exquisitely accurate photometric and astrometric data set for about 10 billion Milky Way stars. The coverage of the Galactic plane will yield data for numerous star-forming regions, and the y band data will penetrate through the interstellar dust layer. Photometric metallicity measurements will be available for about 200 million main-sequence F/G stars which will sample the halo to distances of 100 kpc (I08). No other existing or planned survey will provide such a massive and powerful dataset to study the outer halo (including Gaia which is flux limited at $r = 20$, and Pan-STARRS which will not have the u band). The LSST in its standard surveying mode will be able to detect RR Lyrae variables (pulsating stars and standard candles) and classical novae (exploding stars and standard candles) at a distance of 400 kpc and hence explore the extent and structure of our own halo out to half the distance to the Andromeda galaxy. Thus, the LSST will enable studies of the distribution of main-sequence stars beyond the presumed edge of the Galaxy's halo, of their metallicity distribution throughout most of the halo, and of their kinematics beyond the thick disk/halo boundary. It will also obtain direct distance measurements via trigonometric parallax below the hydrogen-burning limit for a representative thin-disk sample.

The LSST data will revolutionize studies of the Milky Way and the whole Local Group (Saha et al. 2008). A few large programs that LSST will enable are:

- High-resolution studies of the distribution of stars in the outer halo in the six-dimensional space spanned by position, metallicity and proper motions, similar to those described here.
- The faintest ever search for halo streams, and galaxy satellites and intergalactic stars over much of the Local Group.
- Deep and highly accurate color-magnitude diagrams for over half of the known globular clusters, including tangential velocities from proper motion measurements.
- Mapping the metallicity, kinematics and spatial profile of the Sgr dwarf tidal stream.
- Detailed studies of variable star populations; 2% or better accurate multicolor light curves will be available for a sample of at least 50 million variable stars, enabling studies of cataclysmic variables, eclipsing binary systems, rare types of variables, etc.
- Discovery of rare and faint high proper motion objects: probing the faint end of the stellar mass function, and searching for free-floating planet candidates.
- Direct measurement of the faint end of the stellar luminosity function using trigonometric parallaxes. A complete census of the solar neighborhood to a distance of 100 pc based on trigonometric parallax measurements for objects as faint as $M_r = 17$. For example, LSST will deliver 10% or better distances for a sample of about 2,500 stars with $18 < M_r < 19$. There are only a handful of such stars known today (and Gaia will detect fewer than 100).
- A complete census of AGB stars in the Galaxy by searching for resolved envelopes and optical identifications of IR counterparts (e.g., from IRAS and Spitzer surveys), and by using long-term variability and color selection.
- A complete census of faint populations in nearby star forming regions using color and variability selection.

3. CONCLUSIONS

The formation of galaxies like the Milky Way was long thought to be a steady process that created a smooth distribution of stars, with this standard view exemplified by the Bahcall and Soneira (1980) and Gilmore, Wyse and Kuijken (1989) models, and described in detail by e.g. Majewski (1993). In these smooth models, the Milky Way is usually modeled by three discrete components described by relatively simple analytic expressions: the thin disk, the thick disk, and the halo. Instead, recent discoveries of complex substructure in the distribution of the Milky Way's stars (e.g. Ivezić et al. 2000, Yanny et al. 2000, Vivas et al. 2001, Newberg et al. 2002, Majewski et al. 2003, Belokurov et al. 2006, Grillmair 2006, Sesar et al. 2007, J08, I08) have deeply shaken this standard view. Unlike those smooth models that involve simple components, the new data indicate much more irregular structures, such as the Sgr dwarf tidal stream in the halo and the Monoceros stream closer to the Galactic plane. These recent developments, based on accurate contemporary large-area surveys, have made it abundantly clear that the Milky Way is a complex and dynamical structure that is still being shaped by the infall (merging) of neighboring smaller galaxies. This rapid progress in the way we view and study the Milky Way is expected to be maintained by next-generation surveys, such as LSST.

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