GALACTIC STRUCTURE IN THE SURVEY AGE

A White Paper for the Gemini High-Resolution Spectrograph

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The Astro2010 Decadal Report has clarified that surveys will play an increasingly prominent role in astrophysical research in the coming decade. The high priority placed on the LSST, the imminent launch of Gaia, and the success of the Kepler and CoRoT surveys in finding interesting stars shows that large photometric surveys of Galactic stars are (or will be) powerful tools for data mining. The obvious next steps will be spectroscopic follow-up of large numbers of stars fainter than those observed by SDSS and 2MASS, as well as the detailed analyses of individual objects. High-resolution spectroscopy plays a unique role in the ability of the scientific community to examine stars and other interesting targets expected to be found from these surveys. Immediate scientific questions to be addressed include how galaxies like the Milky Way were formed, how their components (disk, bulge, halo) are both observationally distinct and intimately connected, and the physical nature of transient and variable events. In this white paper, we focus only on the important roles that a high-resolution spectrograph (R>35,000) on the Gemini telescopes could have on studies of Galactic structure in the survey age. In Sections (1) and (2), we briefly describe current and upcoming surveys, emphasizing how a high-resolution spectrograph on a large telescope is essential. In Section (3), we describe some specific science cases that can be addressed by the combination of surveys and follow-up.

(1) The Photometric Surveys

Gaia (e.g., Lindegren 2010) is an astrometric survey that will provide distances and proper motions for stars down to V=20. For stars near the turnoff, this accuracy in parallax can provide well-determined ages, if the composition is also known. Its spectrographic capabilities are more limited, measuring a sample of elements down to V=15 in a narrow wavelength range near the calcium triplet. Clearly, Gaia will identify populations through kinematics and photometry where high-resolution follow-up of faint targets will provide critical information about distant or rare objects in the Galaxy.

A new region of parameter space will be opened by **PanSTARRS** (pan-starrs.ifa.hawaii.edu) and the **LSST** (Ivezic et al. 2008). These photometric time-domain surveys will provide many expected targets (e.g., RRLyr stars throughout the Galaxy) as well as a variety of transient events. While photometry will provide some of the information to classify these events, spectroscopic follow-up will be vital, both to gather complete information on known classes as well as give the most information possible about unexpected events. The LSST will survey the southern sky using a 6.5-meter telescope, and the *brightest* objects it will record have 16th mag. This magnitude would be in range of an 8-10 meter telescope for high-resolution spectroscopic follow-up.

SkyMapper (Keller et al. 2007) has begun to provide the first modern optical survey of the Galaxy in the Southern Hemisphere, and its multi-color photometry, with filters selected to be sensitive to features in stellar spectra, and temporal coverage will identify interesting classes of stars across the Galaxy. However, as a photometric survey, its abundance information is limited and radial velocity measurements are absent.

(2) Spectroscopic Surveys

SEGUE (Yanny et al. 2009) and **LAMOST** (e.g. Newberg et al. 2009) are low-resolution spectroscopic surveys of Galactic stars with V> 14-20. These surveys have indentified or will identify the targets needed to complete the picture of disk structure, such as stars with interesting metallicities at known distances and heights above the plane. However, these data are insufficient for getting the abundances needed for “chemical tagging” (Freeman & Bland-Hawthorn 2002, see discussion below), which will require high-resolution spectroscopy on a large aperture telescope.

Two high-resolution survey projects on mid-size telescopes, **APOGEE** (H-band) (Schiavon & Majewski 2010) and **HERMES** (optical) (www.aao.gov.au/HERMES), will start the exhausting project of mapping of the Galactic disk and probing the Galactic bulge, but both will have limited capability to reach the farthest distances across the Galaxy. APOGEE is expected to provide high-resolution H band spectra over a short wavelength interval to H=12.5, while HERMES will obtain 4 short wavelength regions in the optical to V=14. A high-resolution spectrograph on larger telescopes is required for deeper insights into Galactic structure. For example, there is some evidence that ‘in situ’ measurements give a different picture of the Galaxy than measurements deduced from visitors to the solar neighborhood (the only stars that can be observed with smaller aperture telescopes). Therefore, viewing the Galaxy at all distances is necessary.

(3) Going beyond the Solar Neighborhood

(i) Origin of the Thick Disk:
Disk formation is one of the main unsolved problems in galaxy formation. In the Milky Way disk, we have an excellent record of its entire history from the analysis of stars throughout the disk. The impact of heating and accretion from satellite encounters, the settling of infalling gas at early epochs, and the effect of radial mixing can be discerned by the orbits of stars combined with their chemistry (e.g., Brook et al. 2007, Schoenrich & Binney 2009, Navarro et al. 2010). In the solar neighborhood, it is already clear that there are correlations between kinematics and abundance ratios in *local* stars (e.g. Bensby et al. 2004, see Figure 1). To test fully the predictions of simulations requires an inventory of the properties of both the thick and thin disks, including their ages, their metallicity distribution functions, their abundance gradients for both old and young stars, and their scale-heights as a function of radius. Detailed analyses of individual stars with high-resolution spectroscopy will play a crucial role by observing samples of targets (such as members of kinemetic sub-groups, or stars with very precise ages) culled from larger samples as well as by calibrating photometric and lower resolution spectroscopic surveys.

(ii) Formation of the Galactic Bulge:
Studying the bulge is hampered by its distance from us and by the high and uncertain reddening, but it provides the best opportunity to examine a spheroid in detail. The Galactic bulge harbors a

complex stellar population, both chemically and kinematically. For example, recent observations show evidence for both a metal-poor hot component and metal-rich cold component (e.g. Howard et al. 2009, Babusiaux et al. 2010), but observations have been confined to a very few windows in the bulge. An example of current work in exploiting surveys is the observation of bulge main-sequence stars that are lensed by other stars in the Galaxy (e.g Johnson et al. 2007) (Figure 2). These events are found by the **OGLE** (e.g. Udalski 2003) and **MOA** (e.g. Hearnshaw et al. 2005) photometric surveys, and the follow-up high-resolution spectroscopy obtained has unique information on the distribution of metallicity and abundance ratios as a function of age and position in the bulge. However, even with magnification from microlensing, these targets usually have V~15 or fainter and can only be observed for a few hours; therefore large apertures are required. The number of microlensing events detected will only increase with the advent of the **OGLE IV** survey, with the Korean Microlensing Telescope, and ultimately, with the

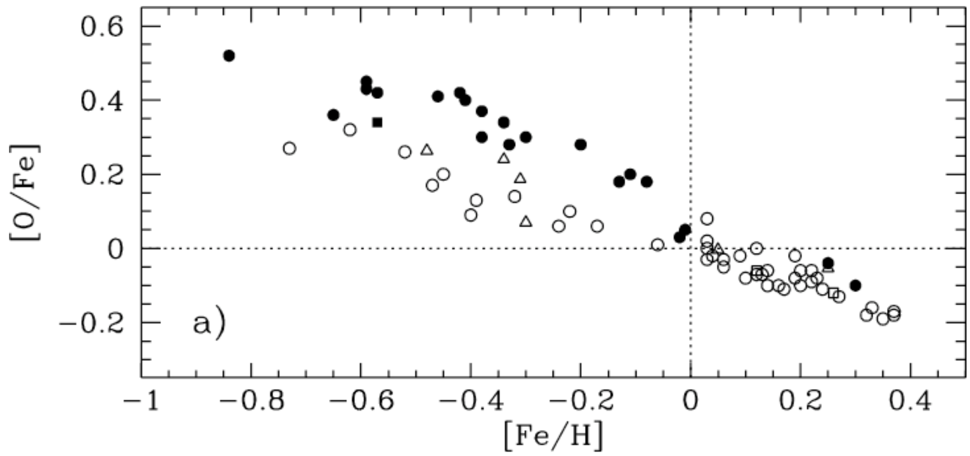

Figure 1: [O/Fe] vs. [Fe/H] for kinematically selected thin disk (open symbols) and thick disk (filled symbols) stars from Bensby et al.(2004)

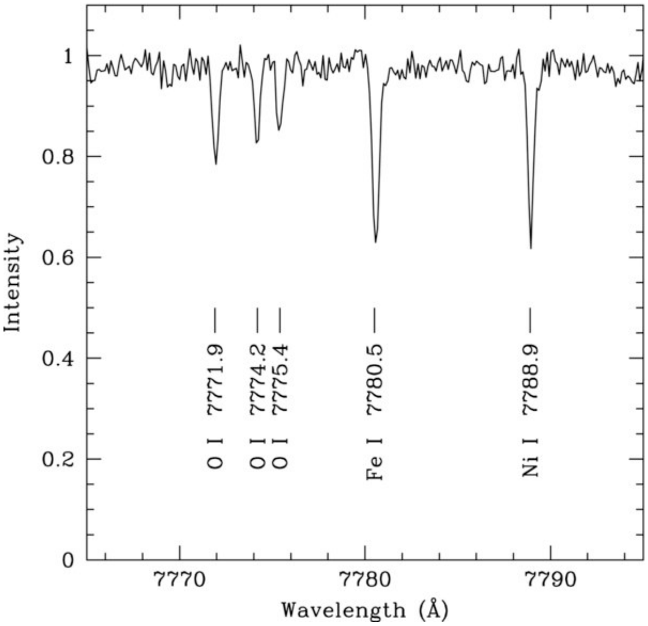

Figure 2: Part of a high-resolution spectra from a I~21 main-sequence star in the bulge, obtained in 45 minutes on the MIKE spectrograph on Magellan (Epstein et al. 2010). This observation was only possible because the star was magnified by a factor of ~1000 during a microlensing event. Even with such an extreme magnification, a large aperture was needed to obtain spectra of the star when it had I~14. The oxygen triplet in this star is shown. Measurement of such relatively weak lines is not possible with a lower resolution spectra.

WFIRST mission. For the study of the highly extincted regions of the Galactic disk and bulge, by observing giants or dwarfs, high-resolution infrared spectra are crucial (e.g., Cunha et al. 2007). The connection between the disk and bulge, comparing the chemical evolution of theses two Galactic components requires study of the b=0 region in the inner Galaxy, where reddening makes optical observations almost impossible.

(iii) Formation of the Galactic Halo:
The Galactic halo is full of substructure from the large number of accretion events (e.g., Ibata et al. 1994, Bell et al. 2008, Johnston et al. 2008). Even those events that are not spatially distinct are chemically/kinematically distinct. Among the many recent examples is the work of Nissen & Schuster (2010), which found two separate populations in the halo, separated in their alpha-element abundance ratios as well as in Na and Ni. The amount of structure found around M31 is also impressive, with streams as far as 150 kpc from the center of M31 (McConnachie et al. 2009). A major advance expected from the next round of surveys is the ability to identify these kinds of correlations in the Milky Way, and to build a complete history of the formation of the halo. Once structures have been identified in photometric, low-resolution spectroscopic, and smaller-aperture high-resolution surveys (as described above), it will be critical to follow up targets down to faint magnitudes to discern the properties and extent of the satellite debris. As the smaller samples that have been studied so far make clear, the chemical differences are not confined to a single element or group of elements (Fulbright et al. 2002, Venn et al. 2004), so abundances of large numbers of elements are vital for this work.

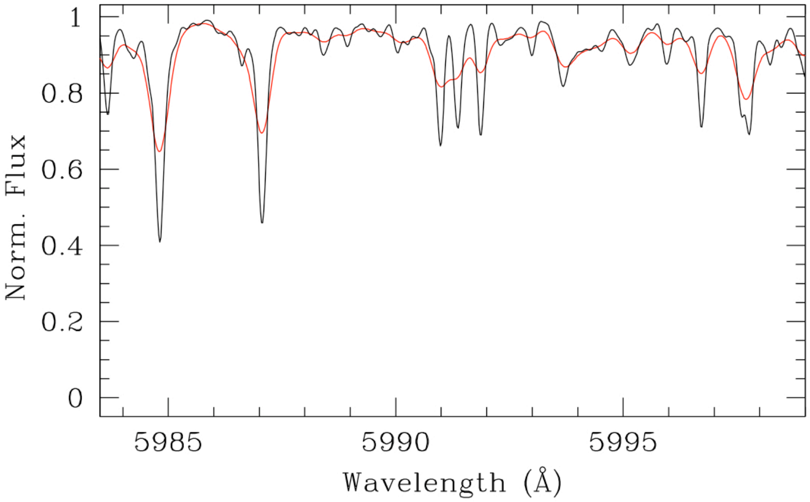

Figure 3: Synthetic spectra of a metal-rich star, illustrating the importance of high-resolution. The red line shows R=15,000, while the black line shows R=35,000. Clearly blending is considerably less important, continuum placement is easier and weaker features are discernable in the R=35,000 spectrum.

Desired Scientific Capabilities

As indicated throughout the discussion of the science case, many of the stars observed by these surveys that will be most advantageous to follow-up are faint for high-resolution spectroscopy and clearly require an instrument on a large-aperture telescope. For many of the science cases, the goal to trace the structure of the Galaxy chemically, ideally in as many elements as possible, which argues for large wavelength coverage and fairly high resolution (R~35,000) to see the lines of less abundant elements (see Figure 3). In addition, the surveys will be uncovering targets in both the northern (SEGUE, LAMOST, PanSTARRS) and southern (SkyMapper, LSST) hemispheres, so high-resolution capability confined to one hemisphere will miss opportunities for discovery provided by some surveys. For transient events, target-of-opportunity capabilities are a requirement.

Summary of Capabilities

High-resolution (ideally R > 35,000)
North and south telescopes
Target-of-opportunity triggering
Optical and infrared wavelength coverage

References

Babusiaux, C. et al. 2010, astroph/1005.3919
Bell, E. F. et al. 2008, ApJ, 680 295
Bensby, T., Feltzing, S., & Lundstrom, I. 2004, A&A, 421, 969
Brook, C. B., Kawata, D., Scannapieco, E., Martel, H., & Gibson, B. K, 2007, ApJ, 661
Cunha, K., Sellgren, K. Smith, V. V., Ramirez, S. V., Blum, R. D., & Terndrup D. M. 2007, ApJ, 669,1011
Epstein, C., Johnson, J. A., Dong, S., Udalski, A., Gould, A., & Becker, G. 2010, ApJ, 709, 447
Freeman, K. C. & Bland-Hawthorn, J. 2002, ARA&A, 40, 487
Fulbright, J. P. 2002, AJ, 123, 404
Hearnshaw, J. B. et al. 2005, astro-ph/0509420
Howard, C. D. et al. 2009, ApJ, 702, 153
Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 1941
Ivezic, Z. et al. 2008, astro-ph/0805.2366
Johnson, J. A., Gal-Yam, A., Leonard, D. C., Simon, J. D., Udalski, A., & Gould, A. 2007, ApJ, 655, L33
Johnston, K. V., Bullock, J. S., Sharma, S., Font, A. Robertson, B. E., & Leitner, S. N. 2008, ApJ, 689, 936
Keller, S. C., et al. 2007, PASA, 24, 1
Lindegren, L. 2010, IAU Symposium 261, 296
McConnachie, A. W., et al. 2009, Nature, 461, 66
Navarro, J. F., Abadi, M. G., Venn, K. A, & Freeman, K. C. 2010, astroph/1009.0020
Newberg, H. J. et al. 2009, BAAS, #21341514
Nissen, P. E., & Schuster, W. J. 2010, A&A, 511, L10
Schiavon, R. P. & Majewski, S. R. 2010, IAU Symposium 262, 428
Schoenrich, R. & Binney, J. 2009, MNRAS, 399, 1145
Udalski, A. 2003, AcA, 53, 291
Venn, K. A., Irwin, M., Shetrone, M. D., Tout, C. A., Hill, V., & Tolstoy, E. 2004, AJ, 128, 1177
Yanny, B., et al. 2009, ApJ, 137, 4377