Astro2020 Science White Paper
Mass Spectroscopy of the Milky Way

Thematic Areas:
☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☑ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract:

Milky Way stars encode the history of our Galaxy’s formation and are tracers of its hidden components. The last decade has witnessed resurgent interest in studies of the Milky Way, catalyzed by imaging surveys on 2-4m class telescopes and revolutionized by precision, all-sky astrometric data from the Gaia satellite. Ground-based imaging surveys have now covered the entire sky, cataloging stars to very faint magnitude limits and unveiling structure on a range of scales, discovering faint companion dwarf galaxies and globular clusters, their shredded remnants, and large scale streams. In the Galactic disk, Gaia’s precision photometric and astrometric measurements have revealed 6D phase space substructure never before observed (e.g., snail shells, ridges, etc.) that may probe the galactoseismological effect of the Galactic bar or perturbing satellite galaxies.

With several massively-multiplexed spectroscopic instruments imminent, and even more ambitious ones planned, the coming decades will be the age of spectroscopy, much as past decades have been the age of imaging. These instruments will drive discovery by enabling spectroscopic studies of the Milky Way at unprecedented scales.

Here we sketch out how an all-sky spectroscopic survey of $\sim 10^8$ stars, in combination with Gaia, can produce a 6D map of the Milky Way that constrains the shape and substructure of the dark matter halo, reveals the metallicity, $\alpha/\text{Fe}$, and elemental abundances of stars across the Galaxy, probes the 6D phase space substructure of the Galactic disk and its origins, and leads to the serendipitous discovery of rare and unusual objects, some unimagined. Realizing the full scientific potential of this opportunity for the US astronomical community will require: guaranteed long-term (multi-year) access to the new capabilities to enable dedicated large-scale surveys of the Milky Way; resources to plan and carry out the necessary surveys, interpret the data, and archive the results; and public access to the data and software tools to carry out the science.
1 Introduction

Over the last century we have measured or inferred much about the global structure of our home, the Milky Way galaxy, yet we are only beginning to glimpse its detailed shape, formation history, and future evolution. While the broad structural components of the Galaxy are understood, their substructure, which provides clues to the dynamical and star formation history of the Galaxy, is poorly known. Importantly, the small scale structure of dark matter (the Galaxy’s largest mass component) remains unknown.

The last decade has witnessed resurgent interest in the Milky Way, fueled by numerous wide-field imaging surveys (notably the Sloan Digital Sky Survey and the Dark Energy Survey) which have uncovered numerous new dwarf galaxies and stellar streams. Nearly the entire sky is being mapped to faint magnitudes ($R \sim 23-24$ mag; Figure 1)—a result of the continually improving efficiency and pixel real estate in wide-field imaging cameras—and we now realize that the dynamic formation history of the Milky Way is plainly visible in the tidally shredded substructure of the stellar distribution. The rising wave of imaging, which will crest in the first half of the next decade with LSST, will produce nearly complete 2D maps of the stellar distribution, precision multi-band photometry, and classifications based on photometric colors and time variability.

The discovery horizon for the 2020s is massive spectroscopy. The advent of highly multiplexed and efficient spectrographs offers the opportunity to use spectroscopy as a discovery tool rather than a scarce resource for imaging follow up. Initial spectroscopic surveys (e.g., of $\sim 1$ million stars by SDSS I-IV, LAMOST, GALAH, RAVE) have already begun to reveal the dynamics of tidal streams and find complex (and sometimes coherent) elemental abundance patterns across the different structural components of the Galaxy. Several new highly multiplexed wide-field multi-object spectrographs are about to achieve first light (e.g., SDSS-V, DESI, 4MOST, WEAVE, PFS). These can be dedicated, in the coming decade, to detailed spectroscopic studies of the Milky Way of unprecedented scope, enabling a modern multi-dimensional view of the Milky Way and its history.

2 The Gaia Revolution and the Spectroscopic Opportunity

The incipient revolution in our understanding of the Milky Way has been catalyzed by the public release of data from the Gaia spacecraft, launched by the European Space Agency in 2013. Over its 10-year mission, Gaia will measure precision astrometric parallaxes, proper motions and photometric data for more than a billion stars to $G \approx 20-21$ mag, or nearly 1% of the entire stellar population! Gaia’s proper motion accuracy is $\approx 0.25$ mas/yr at the faint limit, corresponding to a velocity accuracy of $\approx$ tens of km/s at characteristic halo distances of $\approx 50$ kpc; LSST will offer comparable precision to even fainter magnitudes. In addition, Gaia will provide radial velocity measurements and limited abundance information for a subset of brighter stars (to $G \lesssim 16$ mag). The missing ingredient is spectroscopy of $G \gtrsim 16$ stars in order to measure radial velocities, spectral types, metallicities and chemical abundances for most visible stars in the Galaxy.

Spectroscopic surveys of very large numbers of stars are required to sample Galactic substructure in detail. High resolution data is ideal for detailed elemental abundances, but high signal-to-noise ratio spectroscopy at even moderate resolutions ($R \sim 3000-5000$) can yield sufficiently accurate radial velocities, metallicities, $\alpha$/Fe and several elemental abundances (Fernández-Alvar et al. 2015; Ting et al. 2017). Spectroscopic typing of stars improves distance estimates and
helps to identify spatially dispersed groups through their shared 3D kinematics and abundances. Spectroscopy is essential to correctly identify members of bound groups (e.g., dwarf galaxies or globular clusters) even beyond their tidal radii. It can also drive the discovery of rare populations of stars (e.g., high velocity stars, outer halo stars, magnetically anomalous stars). Dense sampling is needed to map the small scale structure in the stellar kinematics. Here we highlight a few science cases that would benefit from a large spectroscopic survey of $\sim 10^8$ Milky Way stars.

### 3 Mapping the Dark Galaxy

Dark matter is an essential ingredient in our current cosmological model, but all attempts to identify it have failed. The astronomical laboratory is our current best hope to constrain the nature of dark matter, and the existence and power spectrum of dark matter substructure can uniquely constrain the particle mass. The Milky Way halo provides an ideal laboratory: in addition to a smooth (perhaps triaxial) component, $\sim 10\%$ of the halo mass is predicted to be in the form of dark matter clumps (e.g., Diemand et al. 2008). Halo star kinematics can probe both the large- and small-scale dark matter distribution, but are critically dependent on the availability of spectroscopy of large samples of halo stars across the entire extent of the halo.

#### 3.1 Probing halo dark matter at small and large scales

The perturbation of narrow stellar streams (e.g., Figure 2a) by dark matter subhalos is one of the most promising ways to constrain the dark matter power spectrum on small scales (e.g., Bovy 2016, Erkal et al. 2017). Interactions between streams and dark matter halos can be detected as gaps in the stream stellar density and through their associated radial velocity perturbations, or alternatively through the combined statistical impacts of many encounters. Both methodologies critically depend on deep samples of stars with high accuracy radial velocities. To detect the perturbation induced by a $\sim 10^5 M_\odot$ subhalo, a velocity precision of $\sigma_{RV} \sim 0.1\ km\ s^{-1}$ is required, while the statistical technique requires identifying large numbers (i.e., lower luminosity stars) of high quality stream members (i.e., $\sigma_{RV} \lesssim 10\ km\ s^{-1}$).

Satellite galaxies are expected to generate gravitational density wakes in the dark matter halo of the Milky Way, leading to the decay of the satellite’s orbit. These wakes are detectable with current

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Figure 1: $r$-band depth maps (equatorial projection) from the NOAO Science Archive (left; from K. Olsen; red line is the Galactic plane) and PanSTARRS (right; from D. Farrow/PS1 Consortium). With most of the sky already mapped to faint magnitudes ($r \sim 23\ mag$), stars can now be identified to the outermost reaches of the halo for spectroscopy. Spectroscopy can uncover the Milky Way’s accretion history and map the shape and structure of its dark halo.
Figure 2: *Left:* The shape and kinematics of the stellar tidal streams (like the Pal 5 stream shown here; Bonaca et al. 2019) can help constrain dark matter substructure in the halo. Isolating the stars in the stream from the Galactic foreground and backgrounds, and measuring their kinematic motions requires spectroscopy of large numbers of faint stars. *Right:* Satellite galaxies orbiting in the dark halo of the Milky Way generate gravitational ‘wakes’ in the Galaxy’s stellar distribution. These are detectable as large-scale, correlated radial velocity perturbations, as shown in this simulation of the LMC - Milky Way merger by Garavito-Camargo et al. (2019).

and future facilities as stellar overdensities and large-scale coherent radial velocity perturbations in the stellar halo. The measured morphology of the wake can lend insights into the nature of the dark matter particle, because different flavors of dark matter (i.e., cold, self-interacting, or fuzzy) predict different wake morphologies (Garavito-Camargo et al. 2019; Figure 2b; see also Astro2020 white paper by R. Sanderson et al.). Radial velocities of large samples of halo field stars also constrain the shape of the dark matter halo (Loebman et al. 2014, Wegg et al. 2018).

### 3.2 Accretion history

The Milky Way stellar halo encodes the accretion history of the Galaxy. Because dynamical times in the halo are long, the stellar kinematics preserve forensic evidence of past mergers. Accreted dwarf galaxies with simple initial star formation histories may be identified using both kinematics and chemical homogeneity, even if they have been completely tidally shredded (e.g., Roederer et al. 2018, Hasselquist et al. 2019). Spectroscopic observations can therefore, in principle, reconstruct the entire merger history of the Milky Way. Stars from accreted systems will appear—depending on the degree of phase-space mixing—as shells, clouds, well-preserved stellar streams, or as part of the smooth halo. While the majority of the stellar halo has likely been contributed by a single massive old merger, all other merger events will have extremely low surface brightness and spread over the large areas of the Milky Way from the inner halo to the halo outskirts at a distance of 100-200 kpc. Because the outer halo represents a tiny fraction of all stars at high Galactic latitude (a surface brightness of 33 mag/arcsec$^2$ or 10 stars/deg$^2$ at a distance of 50 kpc), large-area, deep spectroscopy is the only efficient way to probe these structures.
3.3 Remnants of the early universe and population III stars

The halo is a treasure trove for remnants from the early universe, since its stellar populations are contributed by some of the most metal-poor galaxies. Some of these may have formed stars in extreme low-metallicity gas, perhaps prior to reionization. Some Pop III halo stars may have also formed \textit{in situ} in the Milky Way halo at early times. These very rare halo stars encode the chemical signature of the early universe and provide invaluable constraints on the yields of the first generation of supernovae and their progenitors. Currently only 6 stars are known with iron-abundances $[\text{Fe/H}] < -5$ (1/100,000 of the solar abundance); half were identified from SDSS spectroscopy (Aguado et al. 2018). Spectroscopy is the critical ingredient. Because target selection based on broad-band or narrow-band photometry fails at $[\text{Fe/H}] < -3.5$, massive spectroscopy at moderate resolution is needed to reliably identify these rare objects.

4 Studies of the Milky Way Disk

The standard simplistic picture of the Milky Way galaxy includes two co-planar rotating thin and thick disk components. However, the results from various surveys have begun to illustrate how immensely complicated the disk is. Recent results from \textit{Gaia} reveal that the 6D phase space of the disk is replete with substructure morphologies never before observed, namely snail shells and ridges that may reflect the influence of the Galactic bar or the passage of a satellite galaxy (Antoja et al. 2018; Trick et al. 2019; Laporte et al. 2019). The results herald the emergence of the field of galactoseismology (Widrow et al. 2012).

Existing spectroscopy of disk stars to date also reveals entangled chemical, kinematic and morphological trends (APOGEE; Hayden et al. 2015). The trends may reflect the disk formation process or later dynamical mixing, e.g., stellar migration. Most current disk surveys suffer from very sparse sampling of the disk substructures and are local (i.e., biased towards solar neighborhood). To further understand the dynamics and origins of the disk, it is essential to complement the shallow \textit{Gaia} spectroscopy samples with spectroscopy of fainter stars for RV and chemical measurements.

5 The Power of Serendipity

With large sample, wide-area, broad scope surveys comes the high likelihood of unexpected discoveries of rare, unusual objects and extreme outliers. Past examples of such discoveries include polluted white-dwarfs, common-envelope objects, hyper-velocity stars, extremely metal poor stars, and stars with unusual elemental abundances (Brown et al. 2018; Caffau et al. 2012; Farihi et al. 2017; Raddi et al. 2018). The serendipitous discovery of larger numbers of hyper-velocity stars ejected from near the super-massive black hole at the Galactic center will constrain the shape of the dark matter halo (Gnedin et al. 2005) and probe stellar populations in the dust-enshrouded Galactic center. While the anticipated ultra metal poor (perhaps Pop III?) stars (§3.3) are also likely to be found serendipitously, other exciting discoveries will come as a surprise. As one recent example, the 6D phase space information from \textit{Gaia} DR2 revealed 13 extragalactic interlopers, high velocity stars that appear to be \textit{inbound} toward the Milky Way (Marchetti et al. 2018), i.e., stars that have been ejected from \textit{other} galaxies. The small handful of stars now known were discovered among
the 7 million brightest stars ($G < 12$) from DR2. Many more of these interesting stars (and other flavors!) will be found in the $\sim 1.3$ billion stars in the entire Gaia sample.

6 A Massive Stellar Spectroscopy Survey

Gaia is deriving radial velocities for only $\approx 10\%$ of its targets, i.e., bright stars with $G < 16$ mag; the remaining $\approx 90\%$ of Gaia catalog stars (i.e., the $\approx 10^9$ stars with $16 < G < 20.5$) will have excellent astrometry and photometry but no spectroscopy. Massive ground-based spectroscopic surveys of the 2020s can remedy this problem and provide full 3D position, 3D kinematic, type and abundance data for a significant fraction of the fainter stars ($\sim 10\%$, or $\sim 100$ million stars).

This white paper illustrates just a few projects that such a survey will enable. With dense spectroscopy of halo stars, we will be able to not only identify new dwarf galaxies, globular clusters and streams and search for dynamical evidence of dark matter clumps, but also isolate the smooth halo to discover large-scale wakes produced by dwarf galaxy interactions with the Milky Way’s dark matter halo (§3.1). With dense spectroscopy in the Galactic disk, we will take the next steps in galactoseimology, probing 6D phase space substructure and its origins (§4). Throughout, rare and unusual objects, some unimagined, will be discovered serendipitously (§5). A ground-based survey using an instrument similar to the Dark Energy Spectroscopic Instrument (DESI) could provide spectra at resolution $R \approx 2000 - 5000$ for 100 million stars over $\sim 5$ years of dedicated operation. DESI is being deployed on the 4-m Mayall at Kitt Peak, with a 5000-fiber robotic positioner and a 3-degree field-of-view, becoming the fastest instrument for moderate-resolution spectroscopic surveys. A survey of this scale ($\sim 10^8$ stars) will allow us to characterize all the roughly 30 million $G \leq 20$ mag stars at high Galactic latitude over the footprint accessible from a single observatory (about 1/3 of the full sky). It will also permit us to make a serious incursion into the Galactic disk, observing about 70 million stars up to distances of several kpc from the Sun, and focusing in particular on the oldest (thick disk) populations. A survey to the Gaia faint limit would be complete to $M_G \approx 11$ (i.e., mid/early M stars) to 1 kpc.

7 Recommendations

In the coming decade, large-scale spectroscopic surveys have the potential to revolutionize our understanding of the structure and formation of the Milky Way. The survey described here is just one example, previously unthinkable, that can be accomplished in the 2020s on an existing facility, i.e., an existing highly multiplexed multi-object spectrograph on a 4-m class telescope. Although the hardware will exist, realizing such surveys will require: (1) Operational funding that supports long-term (multi-year) access by the US community to wide-field spectroscopic capabilities; (2) Resources to develop the scientific (observational and theoretical) and software infrastructure to plan and execute the surveys. Reliably identifying and interpreting observations will depend on dynamical modeling and simulations of the Galaxy as well as stellar atmosphere modeling. (3) Funding for software tools to analyze and interpret the observations and data archives to enable unanticipated discoveries. The last two include science platforms that allow data exploration, visualization, and analysis of massive spectroscopic samples, as well as their joint analysis and interpretation with related imaging and diverse spectroscopic data sets.
References

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