Understanding the Assembly History of the Milky Way with Observations of Dwarf Galaxies

A White Paper in Support of a High-Resolution Optical Spectrograph on Gemini

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Abstract

The hierarchical theory of galaxy formation rests on the idea that smaller galactic structures merge to form the massive galaxies that we see today. The past decade has provided extensive observational support for this scenario, driven in part by advances in high resolution spectroscopic instrumentation and chemical abundance analysis. The recent combination of wide-field imaging with low resolution multi-object spectroscopy has enabled the discovery of many kinematically cold satellite galaxies and tidal streams around the Milky Way and M31. Follow-up high-resolution spectroscopy has yielded abundance patterns for many tens of stars in these new systems, providing key evidence that the Milky Way halo and its dwarf satellites can be explained by Galactic chemical evolution models based on hierarchical assembly. In the next decade, several large photometric surveys (e.g. Skymapper, LSST) will yield many new dwarf galaxies. Properly exploiting these data sets will require new spectroscopic resources. A high resolution ($R > 20,000$) spectrograph with multiplexing capabilities (5-10 stars) over a modest field-of-view (20’) would allow detailed chemical abundance mapping of these system, providing a new test of hierarchical assembly models.

Introduction

In the hierarchical assembly of galaxy halos, dwarf galaxies interact gravitationally with their hosts, shedding stars, losing gas, and eventually tidally dissolving into the diffuse halo (Bullock & Johnston 2005). Most dwarf spheroidal galaxies (dSphs) have high mass-to-light ratios, old populations, and very little gas, all of which support the idea that they are stripped remnants that will eventually meld into their host halos, just as their predecessors did. The population of such dwarf galaxies that exist today may be the lone survivors from the cannibalistic construction of the Galactic halo. Hence, studying dwarf galaxies provides important constraints on this process as well as on the formation and evolution of galaxies less massive than the Milky Way. One of the most interesting questions is: What kind of systems were the “building blocks” of the Milky Way, and what is relation of any of the surviving dwarfs to those building blocks?

However, a close inspection of the chemical abundances of individual stars in the “classical” dSphs (e.g. Sculptor, Fornax, Sextans, Carina) obtained over the last decade complicates our understanding of the role of dwarf galaxies in building the Milky Way halo. The abundances suggest that the stellar halo, on average, is not chemically similar to many of its more luminous dSph satellites as would be expected in this picture. In particular, at [Fe/H] > -2, the [α/Fe] ratios are lower in dSph stars than in comparable halo stars (Venn et al. 2004; Tolstoy et al. 2009). Because [α/Fe] indicates the timescale of star formation in a stellar system, it appears that the surviving classical dSphs formed stars for Gyrs longer than the objects that presumably contributed to the Milky Way halo. Moreover, only a few extremely metal-poor objects with metallicities of [Fe/H] < -3 (hereafter EMP stars) have been found in these systems, but recently updated calibrations (Starkenburg et al. 2010) and new methods (Kirby et al. 2008) show that future surveys are expected to yield numerous EMP stars.

More recent observations of stars in the newly discovered ultra-faint ($L_{\rm tot} \leq 10^5 L_\odot$; Martin et al. 2008) dwarf galaxies yielded relatively large numbers of EMP stars in the least luminous systems (Kirby et al. 2008). Their abundance patterns do match those of equivalent halo stars (Frebel et al. 2010b; Norris et al. 2010b; Simon et al. 2010; Norris et al. 2010a). This has again opened up the debate whether just the least luminous dwarf galaxies contributed to the most metal-poor material found in the (primarily outer) stellar halo, and how galaxy formation on the smallest scales may have proceeded.

Opportunities in this Decade

The coming decade will be the “decade of surveys,” with SDSS-III and photometric surveys like SkyMapper (Keller et al. 2007), LSST (Tyson 2002), and Pan-STARRS (Kaiser et al. 2002). Each survey will yield many new, faint dwarf galaxies whose stars are in need of spectroscopic follow-up for a full characterization of the host system. Medium-resolution ($R \sim 6000$) spectra can be used to establish stellar membership, measure kinematics, and determine Fe abundances (and to a limited extent α-elements), but the study of any additional chemical elements rests solely on the availability of high-resolution spectroscopy. For the tiniest dwarfs with the smallest velocity dispersions, which are the most interesting for a variety of subjects (including the nature of dark matter), high-resolution data may also prove critical for providing robust mass estimates.

The near-field cosmological topic of metal-poor stars in dwarf galaxies has received substantial recent attention. There are several reviews outlining the latest developments in the field, and motivating future observations aimed at addressing galaxy formation on small scales (Tolstoy et al. 2009; Koch 2009; Frebel 2010). Finally, the US decadal survey has listed the study of low-metallicity objects and how they can be employed to study the early Universe among their primary science goals.

Stellar Abundances in Dwarf Galaxies

In order to test ΛCDM formation scenarios thoroughly, their predictions must be verified with observations of dwarf galaxies in various stages of disruption. Cosmologically motivated simulations and star formation models make different predictions about the kinematic and chemical profiles of dSphs based on their sizes and distances. To make progress, spectroscopic observations of kinematics and chemistry in the currently accessible dwarf galaxies need to obtained and compared with model predictions as well as halo star abundances.

Recent focus has been on the ultra-faint dwarf galaxies that appear to harbor relatively large populations of the lowest metallicity stars. Detailed chemical abundances in these systems (Frebel et al. 2010b) provide observational constraints on early star formation and the possibility that dwarf galaxies are the building blocks of the Milky Way. This work is challenging because the targets are very faint for high-resolution spectroscopy ($V > 17$). Current 8–10 m telescopes can obtain spectra with adequate signal-to-noise to measure detailed chemical abundances only for the very brightest stars in these galaxies.

As is outlined below, high-resolution abundances provide a number of crucial insights into astrophysical ques-

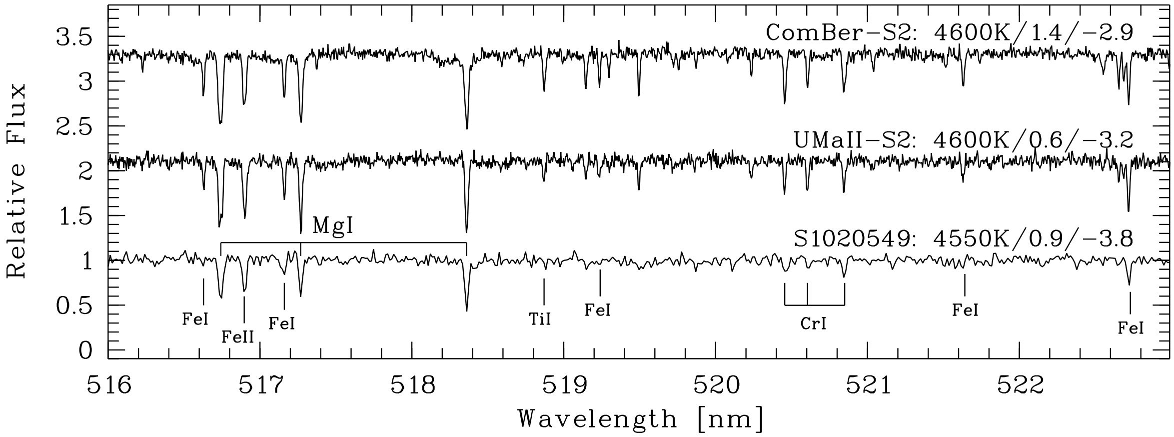

Figure 1: Comparison of high-resolution ($R \sim 35\,\mathrm{K}$) spectra (around the Mg b triplet lines at 5170 Å) of the Sculptor star S1020549 with [Fe/H] ~ -3.8 with two metal-poor stars ([Fe/H] ~ -3.2 and -2.9) located in the ultra-faint dwarf galaxies Ursa Major II and Coma Berenices (Frebel et al. 2010b). All three stars have similar effective temperatures. Even though S1020549 has a much lower metallicity than the two other objects, their abundance patterns are nearly identical, suggesting that early chemical evolution may be universal in all galaxies. The total exposure time for S1020549 was 7.55 h; at $V = 18.2$ this star is among the faintest metal-poor stars observed at high resolution. Because S1020549 is so metal-poor, a high-resolution spectrum with sufficient S/N to measure very weak absorption lines is mandatory. The signal-to-noise (S/N) ratio of the binned spectrum is $S/N \sim 22$ per 66 mÅ pixel at ~ 4600 Å and $S/N \sim 56$ per 133 mÅ pixel at ~ 6400 Å. From Frebel et al. (2010a).

tions such as the origin and evolution of the chemical elements, early star and galaxy formation, and the formation of the Galactic halo (and by extension the halos of other galaxies).

Constraints on cosmological simulations of first galaxy formation

The high-redshift origin of surviving UFDs is currently a matter of vigorous debate, with suggestions including H_2-cooling minihaloes (Bovill & Ricotti 2009; Muñoz et al. 2009), as well as atomic cooling haloes (Koposov et al. 2009; Li et al. 2010; Macciò et al. 2010). Based on high-resolution spectroscopic abundances of ultra-faint dwarf galaxy stars the latter was found to be more plausible in terms of providing viable formation sites for the first Pop II stars. Moreover, these systems may have had only one single Pop III enrichment event that determined the chemical nature of the entire galaxy (Frebel & Bromm 2010). Establishing or disproving these claims with additional abundance data (tens to hundreds of stars rather than just a few stars) for at least some UFDs will provide important constraints on the feedback physics in these early systems and the nature of the first galaxies more generally. These observations will provide an excellent local complement to space-based high-redshift searches for the earliest galaxies with HST and JWST.

Constraints on Chemical Enrichment in Dwarf Galaxies

Understanding the enrichment processes and chemical evolution in galaxies is of general importance for all of astrophysics. Dwarf galaxies are relatively simple systems (no significant mergers) and thus offer a unique opportunity to study the relevant aspects of their evolution in great detail. As part of that, the observed chemical abundance patterns in dSphs can be compared with self-contained star formation models (Lanfranchi & Matteucci 2004; Marcolini et al. 2008). As star formation proceeds, [Fe/H] increases, but after ~ 1 Gyr, Type Ia supernovae begin to lower [α/Fe]. Therefore, the “knee” in the [α/Fe] vs. [Fe/H] plane indicates the metallicity reached by about 1 Gyr, which in turn indicates the vigor of star formation.

Comparing the stellar abundances not only of α-elements, but heavier ones, such as Fe-peak or neutron-capture elements (e.g., Sr, Ba, Eu), to supernova yield predictions provides important constraints on supernova and nucleosynthesis physics. Moreover, the (top-heavy?) inital mass function can be probed with the chemical signatures of the most metal-poor stars in these dwarf galaxies. Such knowledge is crucial for a more complete understanding of the formation mechanisms of small galaxies in the early Universe.

Constraints on the formation of the Galactic Halo

In the coming decade, synergy between model predictions and observations will advance our understanding of the formation of the Milky Way halo. It is difficult to directly observe the progenitor systems of the bulk of the halo because they have already been destroyed. However, it is possible to connect the properties of surviving dSphs and stellar halos using models of galactic star formation and chemical enrichment. These simulations make predictions about the kinematics (Helmi et al. 1999; Font et al. 2006b) and chemistry (Font et al. 2006a) of the relics of accretion events. Testing these predictions will require coordinated spectroscopic surveys focused on measuring as many chemical abundances (as well as radial velocities) as possible for a large number of stars in different types of dwarf galaxies.

Measurements of different abundance groups such as α-elements, neutron-capture elements, and carbon will provide important constraints on the production mechanisms and their specific environments in the early universe. This will ultimately shed light on the origin of the halo star abundance patterns (many of which are unexplained at present; e.g., the large number of carbon-enhanced EMP stars) and thus offer a more differentiated view of what the cosmological origin of the most metal-poor halo stars are. This, in turn, will support or challenge the theory of the hierarchical assembly of galaxies.

Summary of Technical Requirements

We propose the following technical requirements for a multi-object, high-resolution spectrograph. The work with dwarf galaxies requires long exposure times since all targets are faint ($V = 18-20$). Experience has shown that minimum exposure times of 8 h with MIKE (6 hours with HIRES) are required for targets with $V \sim 18.5$ (in good weather conditions with seeing around 0.7”). While a standard single-object spectrograph can pursue this work, adding multi-object capability would dramatically increase the observing efficiency (even if several wavelength settings have to be covered) and provide a unique instrument to the Gemini community.

The blue end of wavelength range is driven by critical absorption features such as neutron-capture element Sr at 4215 Å and carbon from a CH feature at $\sim$ 4300 AA. The red end is limited by the Li line at 6707 Å.

Wavelength coverage (possible): 4200 to 7000 Å; good blue efficiency important since targets are mostly giants
Wavelength coverage (effective): several order chunks in the above range, with sufficient filters available
Filters: at least several hundred Å wide; e.g., CH at 4300 Å; Ba at 4550 Å; Mg at 5200 Å etc
Resolution: 20K and 40 K modes
Total efficiency: $>$ 10% to get above read noise in ~ 1 h exposures for ~ 19 mag targets
Object Mode: Large FoV ($\sim 20'$), $5-50$ objects (targeting more than $\sim 5-10$ stars simultaneously probably requires a fiber rather than multi-slit design); sufficient for low star density in dwarf galaxies
Existing similar facilities: MMT/Hectochelle (240 fibers, only one order at 40K, reduced limiting magnitude due to mirror size and seeing limitations at site), VLT/Flames-Giraffe ($\sim$130 fibers, 300 Å coverage)
Comments: IMACS+MOE on Magellan was intended for a similar purpose but the limiting magnitude is only

16 – 17 mag. The M2FS spectrograph (under construction for Magellan) will provide single-order coverage for 256 stars, or multiple orders for correspondingly fewer targets.

Or, if MOS capabilities are not being sought, individual stars can still be observed:

Wavelength coverage: 3300 to 8700 Å; good blue efficiency important since targets are mostly giants
Resolution: 20K and 40 K; e.g. 0.7” and 1.0” slit widths
Total efficiency: $> 15\%$ to get above read noise in ~ 1 h exposures for ~ 19 mag targets
Existing similar facilities: VLT/UVES, Magellan/MIKE, Keck/HIRES

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