Spectroscopic Surveys of Stars in Dwarf Galaxies

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First Light  *(Movie by Wise, Abel, Koehler, 2009)*

First Stars fill the Universe with light, ionizing gas in the intergalactic medium, impacting galaxy formation, and initiating chemical complexity.

“The smallest galaxies may not contribute a large fraction of matter, but they carry signatures of the earliest epochs of star formation.”  JBH
A Dwarf Galaxy in Formation (m10)

\[ z = 30.0 \]

Magenta is cold molecular/atomic gas (T < 1000 K),
Green is warm ionized gas (10^4 - 10^5 K),
Red is 'hot' gas (> 10^6 K).

Credit: FIRE simulations, https://fire.northwestern.edu/visualizations/
Approaching the threshold of galaxy formation

*Bullock & Boylan-Kolchan 2017*
SDSS images of the northern sky, shown in a Mercator-like projection. The color indicates the distance of the stars (red nearby, blue distant), while the intensity indicates the density of stars on the sky.

Credit: V. Belokurov and SDSS-II.
In Astronomy - we have photometry/imaging and spectroscopy!
Study these stars

In order to learn about this epoch

Roen Kelly (http://discovermagazine.com/2015/dec/13-the-archaeology-of-stars)
SDSS APOGEE has, for the first time, provided a homogeneous database of high quality, high resolution infrared spectra for ~150,000 stars. It’s unique IR sensitivity provides a punch through the blankets of obscuring Galactic dust in its most crowded regions.

SDSS BOSS adds ~350,000 stellar spectra to the SEGUE databases, for a total of ~0.5M stars.

*Credit: S. Majewski et al. 2015, SDSS-III collaboration*
The spectra of ~900,000 LAMOST + ~225,000 APOGEE giant stars to systematically investigate the spatial density, Galactocentric rotation velocity and velocity ellipsoid, and chemical abundance of stars as a function of position in the Galaxy.
## Comparison of multi object spectroscopic surveys

<table>
<thead>
<tr>
<th>Class</th>
<th>Facility / Instrument</th>
<th>First Light (anticipated)</th>
<th>Aperture (M1 in m)</th>
<th>Field of View (sq. deg)</th>
<th>Etendue</th>
<th>Multiplexing</th>
<th>Wavelength coverage (μm)</th>
<th>Spectral resolution (approx)</th>
<th>IFU</th>
<th>Dedicated facility</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4-m</strong></td>
<td><strong>Comparison</strong></td>
<td><strong>Existing</strong></td>
<td>2.5</td>
<td>1.54</td>
<td>7.6</td>
<td>640</td>
<td>0.38 - 0.92</td>
<td>1800</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td></td>
<td><strong>Guo Shoujing / LAMOST</strong></td>
<td><strong>Existing</strong></td>
<td>4</td>
<td>19.6</td>
<td>746</td>
<td>4000</td>
<td>0.37 - 0.90</td>
<td>1000</td>
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<tr>
<td></td>
<td><strong>AAT / HERMES</strong></td>
<td><strong>Existing</strong></td>
<td>3.9</td>
<td>3.14</td>
<td>37.5</td>
<td>392</td>
<td>windows</td>
<td>28000, 50000</td>
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<tr>
<td></td>
<td><strong>WHT / WEAVE</strong></td>
<td>2018 a</td>
<td>4.2</td>
<td>3.14</td>
<td>43.5</td>
<td>960</td>
<td>0.37 - 0.96</td>
<td>windows</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td></td>
<td><strong>Mayall / DESI</strong></td>
<td>2019 b</td>
<td>4</td>
<td>7.1</td>
<td>89.2</td>
<td>5000</td>
<td>0.36 - 0.98</td>
<td>20000</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td></td>
<td><strong>VISTA / 4MOST</strong></td>
<td>2022 c</td>
<td>4</td>
<td>4.1</td>
<td>51.5</td>
<td>2436</td>
<td>0.39 - 0.95</td>
<td>windows</td>
<td>5000</td>
<td>No</td>
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<tr>
<td><strong>8-m</strong></td>
<td><strong>VLT / MOONS</strong></td>
<td>2020 d</td>
<td>8.2</td>
<td>0.14</td>
<td>/4</td>
<td>1000</td>
<td>0.65 - 1.80</td>
<td>windows</td>
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<td>No</td>
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<tr>
<td></td>
<td><strong>Subaru / PFS</strong></td>
<td>2021 e</td>
<td>8.2</td>
<td>1.25</td>
<td>66</td>
<td>2394</td>
<td>0.18 - 1.76</td>
<td>windows</td>
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<td></td>
<td><strong>10 m</strong></td>
<td><strong>MSE</strong></td>
<td>2027</td>
<td>11.25</td>
<td>1.52</td>
<td>151</td>
<td>4329</td>
<td>0.36 - 0.95 (50%)</td>
<td>windows</td>
<td>Second generation</td>
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</tbody>
</table>

Credit: The MSE Project Book
Comparison of multi object spectroscopic surveys

Credit: The MSE Project Book
So where are we today?
Spectroscopic surveys today

<table>
<thead>
<tr>
<th>Survey</th>
<th>Stars</th>
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<tbody>
<tr>
<td>SDSS/SEGUE LRS</td>
<td>~500,000</td>
</tr>
<tr>
<td>RAVE MRS</td>
<td>~500,000</td>
</tr>
<tr>
<td>Gaia-ESO HRS</td>
<td>100,000</td>
</tr>
<tr>
<td>APOGEE 1+2 HRS</td>
<td>250,000</td>
</tr>
<tr>
<td>GALAH HRS</td>
<td>350,000</td>
</tr>
<tr>
<td>LAMOST LRS</td>
<td>~1 million</td>
</tr>
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</table>

For dG studies

<table>
<thead>
<tr>
<th>Telescope</th>
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<tbody>
<tr>
<td>Keck DEIMOS</td>
</tr>
<tr>
<td>VLT FLAMES, FORS</td>
</tr>
<tr>
<td>Magallen M2FS</td>
</tr>
<tr>
<td>MMT Hectochelle</td>
</tr>
<tr>
<td>AAT AAOmega</td>
</tr>
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</table>
LMS Studies (R<5000)

1. Membership RV
2. Dynamical mass $\sigma(RV)$
3. Metallicitiy $\sigma[Fe/H]$
Fig. 7.— Size, mean metallicity and dynamical mass-to-light ratio vs absolute magnitude, for Galactic globular clusters (black points) as well as dwarf spheroidal satellites of the Milky Way (blue points with errorbars) and M31 (red points with errorbars). Quantities plotted for Tuc 2 and Gru 1 are adopted from K15 and this work. Data for globular clusters and dSphs are adopted, respectively, from the catalog of Harris (1996, 2010 edition; we include only clusters with velocity dispersion measurements) and the review of McConnachie (2012).
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LMS Studies have been critical in addressing ...

1. Missing satellite problem
2. Too big to fail, [M/L]
3. Core-cusp nature of dark matter

Hydrodynamic simulations (gas+DM) reveal ...

1. Reionization suppresses dG masses
2. Important effects of feedback in dGs
3. Streams dynamics and co-moving stars

Wheeler et al. 2019: *FIRE simulations* 
$\lesssim 10^{10} \, M_\odot$ halos, with 30 $M_\odot$ resolution
Bullock & Boylan-Kolchan 2017

cores

cusps

\[ \alpha [1.5\% \, R_{200}] \]

\[ \log_{10}(M_*/M_{\text{halo}}) \]

-5  -4  -3  -2  -1

Ultra-faint Dwarfs  Classical Dwarfs  Bright Dwarfs

NIHAO  FIRE-2

\( M_*=\bar{\rho}, M_{\text{halo}} \)

NFW
Remaining questions: does this fit the data? and the roles of CDM, WDM, SIDM ...

(Also, pre-enrichment by first stars; Wheeler et al. 2019)
HRS Studies (R>20,000)

1. Chemical evolution in dGs
2. Supernova et al. yields
3. Origin of the Elements
Tolstoy et al. 2009 (FLAMES “DART”)
Theler, Jablonka, et al. 2019 (FLAMES)
Haywood et al. 2018 (APOGEE + Gaia DR2) 
stars associated with Gaia-Enceladus

Also corresponding to the high and low 
$[\alpha/\text{Fe}]$ stars from Nissen & Schuster 2010
Matsuno et al. 2019 (SAGA database + Gaia DR2)  
Gaia-Enceladus and Highly-retrograde component  

Gaia-Enceladus corresponds to the low \([\alpha/Fe]\) stars from Nissen & Schuster 2010  
But not the highly-retrograde component
Myeong et al. 2019 (APOGEE + Gaia DR2) suggest the highly-retrograde component is a separate dG remnant, the Gaia-Sequoia.

**Figure 9.** The action-space map, metallicity distribution and abundance patterns for the halo stars in APOGEE DR14 (Abolfathi et al. 2018; Leung & Bovy 2019). Gaia Sausage remnant set ($c \sim 0.9$ with $|J_\phi/J_{\text{tot}}| < 0.07$ and $(J_z - J_R)/J_{\text{tot}} < -0.3$) and the high energy retrograde set ($c \sim 0.6$ with $J_\phi/J_{\text{tot}} < -0.5$ and $(J_z - J_R)/J_{\text{tot}} < 0.1$) are shown with blue and red. Rest of the halo stars are shown in grey.
Monty, Venn, et al. 2019
re-analysed stars from Stephens & Boesgaard 2002
(similar to Matsuno et al. 2019)

no evidence for high [Ba/Fe]
Additional source for r-process elements nucleosynthesis

Recognized the next year as NSMs, kilonova afterglow
(e.g., GW170817, Drout et al. 2017, Abbott et al. 2017)
Asked: *are NSMs ubiquitous or stochastic events?*

Answer: need dGs with more stars, examined Draco

- High Ba (and others) from single r-process event *like in Ret II*
- Low Ba (and others) from sporadic r-process events *also seen in Ret II*
Hirai et al. 2019

Multiple sources for Sr (wrt Ba, Fe, Zn)
RMS, ECSN, NSM, AGB
Exciting to see HRS in dGs breaking degeneracies in ubiquity and/or stochastic r-process nucleosynthesis sites
Formed in an iron-group pocket, and suggested stochastic mixing of SN Ia yields

Figure 26. Abundance distribution for Car-612 relative to Galactic stars at its metallicity of [Fe/H] = −1.3. The Galactic abundances are estimated from the distributions in Figures 9–17. The gray shaded area represents a (mean) error in the Galactic abundance of ±0.2 dex. The cyan shaded area represents an offset by −0.7 dex, i.e., if Car-612 were to have a metallicity of −2.0. Note that at
Norris et al. 2017 (6 more Carina dG stars formed in iron pockets)

Iwamoto Type II + various SNIa yields
Finding these stars in dGs (e.g., Carina) provides/proves the environment with stochastic processes for their formation.
Building from Kobayashi & Nomoto (2009):

- If single-degenerate, MCh SNe Ia produce $[\text{Ni}/ \text{Fe}] > 0$ and explode later than double-degenerate SNe Ia which produce $[\text{Ni}/ \text{Fe}] < 0$.

- Then the $[\text{Ni}/\text{Fe}]$ evolution in the Leo I and Fornax dGs may indicate a transition from double-degenerate, sub-MCh to single-degenerate, near- MCh SNe Ia.
Exciting work on SN Ia yields and breaking degeneracies
SN Ia progenitors & yields from abundances of stars in dGs.
Conclusions

1. dGs are our window to the early Universe, providing less complex environments to study dark matter and break degeneracies in galactic modelling.

2. LMS - as more UFDs are discovered in deep imaging surveys, need basic parameters.

3. HRS - new environments to test stellar nucleosynthesis & origin of the elements.