Overview

SDSS has explored, in unprecedented detail, the nature and variety of the stellar populations of the Galaxy

Through DR-7:
- *ugriz* for ~200,000,000 stars
- Spectroscopy for over 400,000 stars

Follow-up and understanding *just beginning*
A Quick Summary

From hot to cool …

- Cataclysmic Variables
- Horizontal Branch Stars and Blue Stragglers
- RR Lyraes
- F/G/K stars (including metal-poor stars)
- sdM stars
- L/T dwarfs
Cataclysmic Variables

Astrophysical significance

- White dwarf primary / mass-transferring secondary (donor)
- Laboratory for accretion and magnetic phenomena
- Sites of dwarf novae / Type Ia SN

Sample references

- Schmidt et al. (2008), PASP 120, 160
- Szkody et al. (2007) AJ 134, 185

SDSS Science Enabled

- Period distributions explored to shorter timescales
- Categorical assignments of variety of behavior
- Identification of pulsating WDs
Typical CV spectra  Szkody et al. (2003)
Horizontal Branch Stars and Blue Stragglers

Astrophysical Significance

- HB stars: longest lived (luminous) post main-sequence objects
- Position on horizontal branch sensitive to metallicity and age
- Blue stragglers: (Apparently) longer-lived main-sequence stars, in reality may be formed from mass transfer, or truly younger stars (captured from other galaxies)

Sample References

- Sirko et al. (2004), AJ 127, 899
- Sirko et al. (2004), AJ 127, 914

SDSS Science Enabled

- HB / BS probes of distant structure in Galaxy
- Tracers of mass profile of Galaxy
- Distance brackets for high velocity clouds of hydrogen
- Tracers of velocity ellipsoid (and MDF) of outer halo
SEGUE Sample Spectra – Field Horizontal-Branch Stars
Distinguishing HB from BS

Xue et al. (2008)

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(normalized flux density vs. wavelength)

H\(_\delta\) and H\(_\gamma\) transitions for BHB and BS.
Mass Profile / Total Mass of Galaxy

Xue et al. (2008)
RR Lyraes

Astrophysical Significance
- Pulsating horizontal-branch stars
- Useful information obtained from photometry alone
- Period traces luminosity ([Fe/H], possibly age)
- Fundamental calibrators for extragalactic distance estimators

Sample References
- De Lee et al. (MSU Thesis, and in preparation)
- Bramich et al. (2008) MNRAS 386, 887
- Sesar et al. (2007), AJ 134, 2236
- Ivezic et al. (2005), AJ 129, 1096

SDSS Science Enabled
- Tracers of structure in inner/outer halo
- Exploration of Oosterhoff dichotomy (apparent division of pulsation periods for field and GC RR Lyraes)
**ugriz Light Curves from SN Survey**

**QUEST SN Survey**

Complimentary coverage to QUEST survey

De Lee (MSU thesis)
De Lee et al. (in prep)
Galactocentric Radial Velocity Distribution of SDSS RR Lyraes as a Function of $|Z|$
F, G, and K Stars

Astrophysical Significance

- “Normal” main-sequence and giant stars
- Main sequence ages 3 – 15 Gyrs
- Most common (luminous) stars
- Tracers of stellar formation and evolution in disk/halo/dwarf galaxies

Sample References

- Rockosi et al. (in preparation)

SDSS Science Enabled

- Unbiased tracers of Metallicity Distribution Function (MDF) of disk / thick disk / halo
- Tracers of kinematics and structure in the inner halo and the outer disk
- Searches for “cold streams” of debris from accretion events
SEGUE Sample Spectra – F Turnoff Stars

- $T_{\text{eff}} = 6866$
  - $\log(g) = 4.19$
  - $[\text{Fe/H}] = -2.00$

- $T_{\text{eff}} = 6103$
  - $\log(g) = 3.37$
  - $[\text{Fe/H}] = -2.37$

- $T_{\text{eff}} = 6438$
  - $\log(g) = 4.66$
  - $[\text{Fe/H}] = -2.69$

- $T_{\text{eff}} = 6286$
  - $\log(g) = 3.02$
  - $[\text{Fe/H}] = -2.24$

- $T_{\text{eff}} = 6591$
  - $\log(g) = 3.84$
  - $[\text{Fe/H}] = -0.21$

- $T_{\text{eff}} = 6039$
  - $\log(g) = 3.18$
  - $[\text{Fe/H}] = -3.26$

Wavelength [Å]
SEGUE Sample Spectra – K Giant Stars

- $T_{\text{eff}} = 5828$
  - $\log(g) = 3.28$
  - $[\text{Fe/H}] = -0.79$

- $T_{\text{eff}} = 4876$
  - $\log(g) = 2.76$
  - $[\text{Fe/H}] = -1.32$

- $T_{\text{eff}} = 5648$
  - $\log(g) = 3.29$
  - $[\text{Fe/H}] = -0.70$

- $T_{\text{eff}} = 5419$
  - $\log(g) = 2.38$
  - $[\text{Fe/H}] = -2.79$

Wavelength [Å]
Metal-Poor Stars

Astrophysical Significance

- Low mass (and local !) fossils of chemical evolution over history of the Universe
- Best probes of individual element formation processes (e.g., SNe II, SN Ia, s-process, r-process)

Sample References

- Lee et al. (2008 a,b), AJ, in press – SSPP
- Allende Prieto et al. (2008), AJ, in press -- SSPP
- Beers et al. (in prep.) – Lowest metallicity stars from SDSS/SEGUE

SDSS Science Enabled

- Nature of the inner/outer halo populations of Milky Way
- Probe of the low-metallicity tail of the halo MDFs
- Probes of Star Formation Rate (SFR) and Initial Mass Function (IMF) of the “building blocks” of the halos
SSPP - Methodology II

Determine which method is available, mostly depending on g-r color and S/N; calculate robust mean from available parameters.

( The number in parenthesis is the number of estimates.)

Lee et al. 2007a,b; Allende Prieto et al. 2007
After selecting member stars of M 13, the cluster metallicity is calculated by fitting a Gaussian (left panel). We obtained $[\text{Fe}/\text{H}] = -1.62 \text{ (-1.63, Kraft & Ivans 2003)}$ with $\sigma=0.18$. Note how well the temperature and gravity are estimated along the CMD.
M 15, N = 95, Red: $[\text{Fe/H}]_\text{H} = -2.26$

Green: $<[\text{Fe/H}]>$ = -2.18, STD = 0.16

M 13, N = 291, Red: $[\text{Fe/H}]_\text{H} = -1.54$

Green: $<[\text{Fe/H}]>$ = -1.58, STD = 0.12

M 2, N = 79, Red: $[\text{Fe/H}]_\text{H} = -1.62$

Green: $<[\text{Fe/H}]>$ = -1.53, STD = 0.16

NGC 2420, N = 163, Red: $[\text{Fe/H}]_\text{H} = -0.44$

Green: $<[\text{Fe/H}]>$ = -0.38, STD = 0.10

M 67, N = 52, Red: $[\text{Fe/H}]_\text{H} = 0.02$

Green: $<[\text{Fe/H}]>$ = -0.09, STD = 0.04
Comparison SSPP vs. High-Res Spectroscopy
The Impact of SDSS on Searches for Metal-Poor Stars

(Integrated over 60 years Pre Sloan)

- **Metal-Poor** \([\text{Fe/H}] < -1.0\) 10,000+
- **Very Metal-Poor** \([\text{Fe/H}] < -2.0\) 4,000+
- **Extremely Metal-Poor** \([\text{Fe/H}] < -3.0\) 200+
- **Ultra Metal-Poor** \([\text{Fe/H}] < -4.0\) 5
- **Hyper Metal-Poor** \([\text{Fe/H}] < -5.0\) 2
- **Mega Metal-Poor** \([\text{Fe/H}] < -6.0\) 0
The Impact of SDSS on Searches for Metal-Poor Stars

<table>
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<th>Type</th>
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<tr>
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<td>2</td>
</tr>
<tr>
<td>Mega Metal-Poor</td>
<td>$&lt; -6.0$</td>
<td>0</td>
</tr>
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</table>
Four 8m class telescopes are collecting high-res follow-up spectroscopy of stars with [Fe/H] < -2.7 from SDSS/SEGUE.

Already, total number of targets is over 100 stars, growing rapidly.

Subaru sample alone has confirmed over 50 stars with [Fe/H] < -3.0.

Lowest at [Fe/H] = -3.7.

Among other projects, looking for differences in abundance patterns between the inner/outer halo stars.
A Matter of Calibration...

The SSPP is **CONSERVATIVE** at low [Fe/H]
ARTICLES

Two stellar components in the halo of the Milky Way

Daniela Carollo\textsuperscript{1,2,3,5}, Timothy C. Beers\textsuperscript{2,3}, Young Sun Lee\textsuperscript{2,3}, Masashi Chiba\textsuperscript{4}, John E. Norris\textsuperscript{5}, Ronald Wilhelm\textsuperscript{6}, Thirupathi Sivarani\textsuperscript{2,3}, Brian Marsteller\textsuperscript{2,3}, Jeffrey A. Munn\textsuperscript{7}, Coryn A. L. Bailer-Jones\textsuperscript{8}, Paola Re Fiorentin\textsuperscript{8,9}, & Donald G. York\textsuperscript{10,11}

The halo of the Milky Way provides unique elemental abundance and kinematic information on the first objects to form in the Universe, and this information can be used to tightly constrain models of galaxy formation and evolution. Although the halo was once considered a single component, evidence for its dichotomy has slowly emerged in recent years from inspection of small samples of halo objects. Here we show that the halo is indeed clearly divisible into two broadly overlapping structural components—an inner and an outer halo—that exhibit different spatial density profiles, stellar orbits and stellar metallicities (abundances of elements heavier than helium). The inner halo has a modest net prograde rotation, whereas the outer halo exhibits a net retrograde rotation and a peak metallicity one-third that of the inner halo. These properties indicate that the individual halo components probably formed in fundamentally different ways, through successive dissipational (inner) and dissipationless (outer) mergers and tidal disruption of proto-Galactic clumps.
Decoupling the Inner/Outer Halo

Carollo, D. et al. (2008, in preparation)

- New (more detailed) analysis of SDSS calibration stars (through DR-6)
- Around 15K unique stars within 4 kpc (instead of ~10K)
- Obtain fractions of TD, MWTD, Inner Halo, Outer Halo as a function of $|Z|$ and $[\text{Fe/H}]$
- Determine velocity ellipsoids of all (recognized) components
Behavior Inside/Outside 10 kpc
Fractions as a Function of $Z_{\text{max}}$
Median metallicity ([Fe/H]) for 2.5 million blue (F) stars

-1.5  -1  -0.5

<[Fe/H]>

Mon stream

b>80°

HALO

galactic center

DISK
By choosing directions close to the NGP, the proper motions (obtained from a re-calibration of the USNO-B catalog) sample only the U and V velocity components. This enables determination of the rotational properties for Galactic components as a function of distance and metallicity.

This map shows results for some 60,000 stars.
Breaking the [$\alpha$/Fe] Barrier

- [$\alpha$/Fe] for individual stars provides one connection between a given star and the nature of its progenitors (SN II, SN Ia)

- Long required high-res spectroscopy to obtain, so slow

- Now, with SDSS spectra, Lee et al. (2008, in prep) can measure [$\alpha$/Fe] accurate to $\sim0.1$ dex for S/N $> 20/1$ med-res spectra

- Already obtained for many tens of thousands of stars
[\alpha/\text{Fe}] vs. [\text{Fe}/\text{H}] for SDSS Calibration Stars

N = 17450 stars (Lee et al. in preparation)
Subdwarf M stars

Astrophysical Significance
- Low metallicity analogues of dM stars
- Longest main-sequence lifetimes ($T_{ms} \sim T_{yr}$) among metal-poor stars
- Likely (depending on IMF) most populous variety of metal-poor stars

Sample References
- Gizis, J. (1997), AJ 113, 806

SDSS Science Enabled
- Calibration of metallicity / molecular band relations
- Tracers of local kinematics of metal-poor stars
- Probes of low-mass IMF of low-metallicity stars
Cool Dwarf / Subdwarf Metallicity Sequence

\[ \log Z \sim 0.0 \]
\[ \log Z \sim -0.8 \]
\[ \log Z \sim -1.3 \]
\[ \log Z \sim -2.0 \]
New Classification Templates from SDSS

Lepine et al. (2008)
Large Numbers of Newly Discovered Cool Subdwarfs

Spectroscopically confirmed cool subdwarfs in SDSS

\[ \begin{align*}
\text{sdM} &= 1786 \\
\text{esdM} &= 500 \\
\text{usdM} &= 664
\end{align*} \]

Increases the all-sky census of spectroscopically confirmed cool subdwarfs (sdM/esdM/usdM) by an order of magnitude (10x).

Lepine et al. (2008)
Kinematics in UV plane from Proper Motions and Photometric Distances (NGP subsample)
L and T Dwarfs

**Astrophysical Significance**
- Brown dwarfs (non H fusing objects) with masses < 0.09 Mo
- Lowest mass non-planetary objects known
- No sustained source of thermonuclear energy, cool continuously, with initial spectral type set by mass

**Sample References**
- Burgasser et al. (2007), AJ 134, 1330
- Knapp et al. (2004), AJ 127, 3553
- Hawley et al. (2002), AJ 123, 3409

**SDSS Science Enabled**
- Luminosity and mass function of low mass objects
Example SDSS Spectra

Hawley et al. (2002)
Identified from Optical Dropouts, Spectroscopically studied in the near IR

Knapp et al. (2004)

Burgasser (2007)
Conclusions

SDSS has provided the single greatest leap forward in the observational studies of stellar populations in the Galaxy.

SDSS will continue to expand on this record during SDSS-III.

The great strides made by SDSS in the studies of galaxies, their properties and their spatial distributions, would not be possible without their stars (no optical light).

Understanding of the stellar populations in the Galaxy (and its satellites) is a prerequisite to understanding galaxy formation in general.
Much of the progress on studies of the stellar populations of the Galaxy *would NOT have been possible* without the personal passion for their study by the founders of SDSS.
SDSS results at last confirm binary evolution models that predict most CVs at short orbital periods (these are fainter and so missed by previous surveys with brighter limits)
Latest and Greatest from SDSS/SEGUE

**SDSS/SEGUE**

N = 16002
S/N > 10/1
Comparison with Elodie Library

- Comparison plots showing distributions and scatter plots for [α/Fe]_Fit - [α/Fe]_Lit and [α/Fe]_Lit values.
- Data points and histograms indicating normal distribution with mean and standard deviation noted.

Legend:
- Black dots: [Fe/H]_Lit values
- Red crosses: [α/Fe]_Fit values
Subclass and subtype segregation in color-color space
(= mass/metallicity grid)