

Community Science with BigBOSS

Carles Badenes, Jennifer Johnson, Joan Najita, Casey Papovich, Caty Pilachowski,
Connie Rockosi, Greg Rudnick, & Verne Smith

Executive Summary

Community science with the BigBOSS instrument offers the opportunity to carry out *in this decade* science programs that address major science themes from *New Worlds, New Horizons*. In this document, the BigBOSS Community Science Committee explores representative projects that illustrate the diversity of science that would be enabled by an open access (publicly funded) community science component. Because we anticipate that demand for community access to BigBOSS would be very high and the science highly compelling as well as cost-efficient, we encourage NSF to support community science with BigBOSS and ensure open access to this unprecedented capability.

Background

[BigBOSS](#) is a project to build a 5000-fiber, moderate resolution ($R \sim 3000-4800$) multi-object spectrograph with a 3° diameter field of view for the 4m Mayall telescope at Kitt Peak. It resulted from the call issued in 2009 by NOAO for a Large Science Program at the Mayall. The project is proposed by the BigBOSS collaboration, which has the primary scientific goal of conducting a Stage IV Dark Energy project. The project will characterize the equation of state of dark energy by measuring the imprint of baryon acoustic oscillations on galaxies and the Lyman alpha forest and the growth of large scale structure. These measurements will be accomplished through an unprecedented redshift survey of 22 million galaxies and 2.5 million QSOs over $14,000 \text{ deg}^2$. As proposed, the BigBOSS Key Project will utilize approximately 500 nights on the Mayall over 5 years, with the majority of the costs for construction and the Key Project survey operations to be supported by DOE funds.

The Large Science Program call specified that the BigBOSS instrument would be [available for general use by the astronomical community](#), contingent on continued support of the Mayall by NSF. Such a highly multiplexed spectroscopic capability has been called out in the Astro2010 Decadal Survey report, *New Worlds, New Horizons* (*NWNH*; Appendix D) and the 2012 NSF Astronomy Portfolio Review Committee report as offering tremendous perceived scientific value to the astronomical community. Indeed, the investigations enabled by BigBOSS would address a host of science questions, beyond dark energy, that are called out in *NWNH* (Table 1).

The present document, written by the BigBOSS Community Science Committee (BBCSC), illustrates the community science potential of BigBOSS by exploring several

representative science cases (Table 2) in some detail, making use of the expected sensitivity of the BigBOSS instrument. The science cases were chosen to illustrate the

- diversity of science that can be addressed with BigBOSS; the
- likely high impact of BigBOSS community science on *NWNH* science themes; and
- how highly multiplexed spectroscopy opens creative new avenues of investigation.

Convened by NOAO, the BigBOSS Community Science Committee (BBCSC) is charged with articulating the potential of community science with BigBOSS and describing the extent to which the US astronomical community would benefit from open access to the BigBOSS instrument and BigBOSS archival data.

The potential for community science with BigBOSS was previously explored in a community workshop held in Tucson in September 2011, which attracted approximately 70 participants from the astronomical community. The workshop focused on four science themes (Galactic, Extragalactic, Transient, and Diffuse Media science) and strategies to address these with BigBOSS. The specific science cases explored at the workshop and the hardware, software, and interface needs to support these are documented in detail in a workshop report. The relevance of these community science cases to the science themes of *NWNH* has been summarized in a publicly available whitepaper ([Pilachowski et al. 2011, astro-ph/1211.0285](#)).

As in the community workshop, in the current effort, the BBCSC considered several possible modes in which the BigBOSS instrument, as proposed by the collaboration, could be used to carry out community science:

- Archival data from the survey and calibration fields;
- “Synchronous” observing that makes use of the available “community fibers” during the BigBOSS Survey observations; 10-20% of the 5000 fibers will be unallocated for cosmology or calibration targets in any given survey field, which amounts to a total of several million fibers over the lifetime of the Key Project;
- Dedicated “PI” surveys or projects carried out independently of the Key Project, e.g., after the completion of the Key Project or during bright/grey time during the Key Project.

Summary of Findings

The following sections describe the representative science cases we explored. These examples illustrate how:

- There is highly compelling community science with BigBOSS that addresses major *NWNH* themes (Table 1). The timescale on which BigBOSS would begin operations (2018) allows this science to be carried out *in this decade*.

- The demand for community science access to BigBOSS would be very high. Although the science cases described below are a small fraction of the science to which the community aspires, they alone require many 100s of nights to carry out (Table 2).
- The science legacy of BigBOSS data, both the Key Project survey and community science observations, would also be high. This motivates community access to all archival BigBOSS data.

Table 1. *NWNH* Science Addressed by the BigBOSS Key Project and BigBOSS Community Science

<i>NWNH</i> Theme	Science Frontier topic	Addressed by BigBOSS?	Where described
Discovery	Planets and habitability	Community Science	Sec. 5
	Time Domain	Community Science	Sec. 4
Origins	Galaxies and Large scale structure	Community Science	Sec. 1
	Fossil record of galaxy assembly and evolution	Community Science	Sec. 3
	Black holes	Community Science	Sec. 4.4
	Stars and Planets		
	Epoch of Reionization		Sec. 2
Understanding the Cosmic Order	Flows of baryons in & out of galaxies and black holes	Community Science	Sec. 2
	Mass/energy/ Chemical cycles within galaxies	Community Science	Sec. 1, 2, 3
	Effect of rotation and magnetic fields on stars	Community Science	Sec. 5
	Progenitors of Type Ia SNe and how they explode	Community Science	Sec. 4.1, 4.3
	Diversity of planetary systems and signs of life		
Frontiers of knowledge	Nature of inflation	BigBOSS Key Project	BigBOSS website
	Accelerating Universe	BigBOSS Key Project	BigBOSS website
	Nature of dark matter and neutrinos	BigBOSS Key Project	BigBOSS website
	Nature of compact objects		
	Chemistry of the universe		

Table 2. Representative Community Science Projects

Theme	Project	Area	No. Sources	Mode/Time Requirement	Comment
Galaxy Evolution	Galaxy Evolution Survey	100 sq. deg.	400,000 galaxies	110 nights	Some in calibration fields.
Diffuse Medium	Outflows & Circumgalactic Medium	BigBOSS Key Project	1000s galaxies; 1 million QSOs	Community fibers + archival spectra	
	Rare pairs	BigBOSS Key Project	~10,000 galaxies	Com. Fib. + archival spectra	
	Dust Reddening	30 sq. deg.	1000 galaxies in each of 10 pointings	30 hours	PI program
Galactic Structure	Galactic Archaeology Survey	12,500 sq. deg.	>10 million stars	500 nights	Large survey
Time Domain	Stellar Binaries	12,500 sq. deg.	>10 million stars	Piggyback on Galactic Archaeology	5 hr time lag
	Binary Black Holes				
	Cost-free Supernova Survey	BigBOSS Key Project	Millions of galaxies	Com. Fib.	
	Reverberation Mapping	Several 7 sq. deg. fields	1000s	Com. Fib. + archival	Calib. Fields, weekly for 5 yrs
Stellar Activity & Planetary Systems	Stellar Activity in Kepler field	115 sq. deg.	100,000 stars	20 nights/yr for 10 yrs.	8 hr/field/yr spread out over 1-2 months

1. Galaxy evolution with BigBOSS

Gregory H. Rudnick & Casey Papovich

Introduction

Understanding the processes by which galaxies form and evolve has been an enduring topic of great interest in astrophysics. It has been the driver of some of the largest and most successful projects in astronomy (SDSS) and has received a high priority in the 2010 New Worlds New Horizons Decadal survey. Indeed, thanks to decades of effort we have made great strides in understanding the galaxy population as a whole and how it has evolved and transformed over time. Many of these tremendous advances were driven by large spectroscopic surveys covering substantial swaths of lookback time (e.g. SDSS, DEEP2, zCOSMOS). Despite this progress, we are woefully ignorant of some of the fundamental elements of galaxy evolution:

- What is the efficiency with which gas is converted to stars in galaxies and how does this depend on a galaxy's properties, e.g. halo mass, environment, assembly and star-formation and feedback history?
- What are the star formation, accretion, assembly, and chemical enrichment histories of galaxies? What governs/drives these and how do they account for the diverse properties of present-day galaxies?
- What stopped star formation in passive galaxies and what keeps it off?
- Is there a simultaneous buildup in stellar mass and metallicity and how is this regulated by feedback and the supply and recycling of gas?
- What are the relative roles of mergers and star formation in the growth of galaxies at different stellar and halo masses?

Observational data have and will continue to provide the answers to these kinds of questions, as simulations are heavily reliant on subgrid physics to study the baryonic astrophysics of galaxies within a cosmological context. The Sloan Digital Sky Survey (SDSS) illustrates the power of large spectroscopic surveys to measure key galaxy scaling laws from large statistically significant samples, and SDSS has established the "local" baseline for galaxy properties out to redshifts $z \sim 0.2$. To measure the evolution of galaxies requires a similar large-scale approach because galaxy properties (mass, metallicity, environment, SFH) are highly intertwined, driven by multiple processes (e.g., star formation, AGN activity, environment), and constantly themselves evolving. The largest redshift surveys that cover significant lookback time (DEEP2 and zCOSMOS) are inadequate to answer these questions as they are composed of $\sim 10^4$ galaxies at $z < 1.5$ and, at best, can measure mass-dependent evolution as a function of a single parameter, often color (e.g. Faber et al. 2007).

To measure galaxy evolution requires a large spectroscopic survey that spans most of cosmic time, enables accurate measurement of the physical properties of galaxies (not just redshifts) from the spectra, contains enough galaxies to study the relations between the many physical parameters, has enough volume to overcome the limitations of cosmic variance, and enables the linkage of galaxies with their dark matter halos.

Here we outline such a survey using the BigBOSS instrument on the 4-m Mayall telescope. Because of its tremendous multiplexing combined with a large area and a very sensitive and wide wavelength range spectrograph, BigBOSS will be one of the premier galaxy evolution machines in the coming decade.

Despite its plan to acquire spectra of 24 million galaxies, the main BAO survey planned by the BigBOSS collaboration is entirely inadequate for a large galaxy evolution survey for multiple reasons: 1) The sample is color selected, which makes it impossible to study the demographics of the whole galaxy population and restricts the sample to $0.7 < z < 1.4$; 2) the spatial sampling is too low to measure galaxy environments or relate galaxies to halo mass; and 3) the spectra will be too shallow to measure redshifts for non-star-forming galaxies at interesting masses. Therefore a community-led survey is necessary.

A Galaxy Evolution Survey with the BigBOSS spectrograph

Our goal is to track the evolution of a large fraction of the cosmic stellar mass over the last 8.5 Gyr of the history of the Universe, i.e., out to $z = 1.2$. We will accomplish this by: 1) performing a spectroscopic survey that targets every galaxy at $z < 1.2$ that is more massive than the main progenitor of present-day M^* galaxies; 2) using clustering measurements to link descendants and progenitors via their host dark matter halos; 3) inferring the joint distribution and evolution of the star formation rate, stellar mass, dynamical mass, gas-phase metallicity, redshift, environment, and star formation history; 4) assembling a sample large enough in number and over a large enough volume to make it an ideal complement to SDSS, but over 8.5 Gyr of cosmic time.

Large N, low S/N: Our survey strategy combines traditional methods - in which astrophysics are possible with moderate signal-to-noise ratio individual spectra - with Bayesian statistical modeling that allow one to determine the distribution function of physical parameters from large numbers of spectra whose signal-to-noise ratio is sufficient only for obtaining a redshift. This technique has been impressively demonstrated with data from Shu et al. (2012), who used noisy spectra from the Baryon Acoustic Oscillation Survey (BOSS) to derive the galaxy velocity dispersion distribution function from spectra for which the velocity dispersion could not be individually measured. This kind of analysis is becoming increasingly prominent in plans to model large data sets and enables science that has traditionally been out of the reach of 4-m telescopes. (The BigBOSS spectrograph + Mayall combination will be more efficient for spectroscopic surveys than any telescope + spectrograph combination available today, i.e., in 2013.) In order to robustly model of the distribution of physical properties from

BigBOSS spectra, we need the sensitivity to obtain a redshift measurement for every galaxy. This drives our baseline exposure time requirement.

Signal-to-Noise constraints: Zheng et al. (2007) used a clustering analysis based on SDSS and DEEP2 to link galaxies to their dark matter halos. They determined that an M^* galaxy today corresponds to $M^* \sim 5 \times 10^{10} M_{\odot}$ at $z = 1.2$. In Figure 1.1 we show the predicted i -band magnitude of an M^* galaxy (where $M^* = 5 \times 10^{10} M_{\odot}$ at $z=0.2$ using the mass function of Muzzin et al. 2013) with different SFHs. Such a galaxy with a passively evolving SFH and $z_{\text{form}} = 2$ has $i = 23.7$ at $z = 1.2$. Using the BigBOSS exposure time calculator and the signal-to-noise dependent redshift success from BOSS, we find that an exposure time of 4 hours results in a signal-to-noise of 3-4 per resolution element redward of the 4000 Å break. This is the absolute minimum S/N of any galaxy in our survey as all other galaxies will be brighter, have a longer exposure time, or be at lower redshift.

Another S/N constraint comes from the necessity of extracting astrophysics (mean stellar content and age, star formation rate, ionization, metallicity, velocity dispersions, etc.) from the spectra. This requires accurate modeling of the continuum as well as decomposing absorption and emission lines (e.g. Rudnick et al. 2000; Moustakas et al. 2011). This will not be possible for individual galaxies but the parameters for an ensemble of galaxies can be determined by jointly modeling their spectra (Shu et al. 2012). We can evaluate the information in the spectra of a sample of galaxies via the S/N in the composite spectrum (or “stack”). Composite spectra with the S/N necessary to decompose absorption and emission lines are attainable in 30 hours of exposure on our faintest galaxies ($i = 23.7$ passive galaxies), or equivalently 8 galaxies with 4 hour exposures each.

Galaxy selection: We will pre-select our galaxies in a way that as closely as possible resembles mass selection. The WISE all sky survey (Wright et al. 2010) will allow us to detect $M^* = 5 \times 10^{10} M_{\odot}$ galaxies at $z = 1.2$ by their rest-frame NIR light (see Figure 1.2).

The survey size: We require spectra of enough galaxies to populate the full range of parameter space. A baseline estimate results from considering the following properties and bin sizes: Stellar mass (5 bins), gas-phase metallicity (3 bins), halo mass (from clustering; 5 bins), velocity dispersion (4 bins), SFR (3 bins), and luminosity weighted stellar age (3 bins). While optimizing the number of galaxies per bin requires a full simulation including a clustering analysis we can make an estimate of the survey size by requiring 30 galaxies per bin. This results in 81,000 objects per redshift bin. If we assume 5 redshift bins of $dz = 0.2$ each then the total survey will contain 4×10^5 galaxies with spectroscopic observations. The number of bins above is based on the precision with which the different parameters can be measured given the expected data.

A more realistic accounting of the galaxies, and hence signal-to-noise, per bin must take into account that galaxies are distributed unevenly throughout parameter space, with many more galaxies at low mass than at high and with galaxies following well-defined

relations in, e.g. SFR-stellar mass and stellar mass-metallicity. In practice this will result in more galaxies/higher S/N in the regions of parameter space where most galaxies lie. The numbers we quote here are therefore only indicative of the S/N that will be realized by the survey.

To determine the area of the survey we integrated the redshift-dependent stellar mass functions from Muzzin et al. (2013) at $M^* = 5 \times 10^{10} M_{\odot}$ to determine volume and area necessary to obtain 81,000 galaxies in each redshift bin.

These are plotted in Figure 1.3 and Figure 1.4. They demonstrate that the proposed survey will sample a substantial fraction of an SDSS-like volume (0.06-0.14 Gpc³) at every redshift and will be 1-2 orders of magnitude larger than the biggest current galaxy evolution spectroscopic surveys. As an additional qualifier, the PRIMUS survey uses extremely low-resolution spectroscopy and in general the spectra are not useful to determine quantities such as velocity dispersion or luminosity-weighted stellar age. Photometric samples with precise redshifts can offer larger numbers or area, but the Muzzin et al. (2013) sample is drawn from the UltraVISTA survey of the COSMOS field and contains 42,000 galaxies over the whole range $0.5 < z < 1$ with only photometric redshifts. The state-of-the-art UltraVISTA survey (or *any* survey based primarily on photometric redshifts) is sufficient for studying the stellar mass evolution in two bins of galaxy star formation activity but is inadequate for studying more complicated parameter dependencies and contains no spectroscopic information.

Survey strategy: An example survey strategy involves splitting the volume into two components in a tiered wedding cake format with a “wide” 100 square degree survey conducted for galaxies at $0.3 < z < 0.7$ and a “deep” 55 square degree survey inscribed within the wide one for galaxies at $0.7 < z < 1.2$. As part of targeting, galaxies will be placed into broad redshift bins using photometric redshifts. To insure observability all year round and to mitigate cosmic variance the survey would be split into five disjoint fields, with each field having a survey strategy similar to that shown in Figure 1.5. The linear dimensions of each disjoint area are shown in Figure 1.6. Each BigBOSS pointing is 173 Mpc across at $z = 1$ and 100 Mpc at $z = 0.5$. The clustering scale (r_0) for clusters is ~ 28 Mpc (Papovich 2008) and so the proposed survey would span $4r_0$ for clusters in each pointing. Because $r_0 = 11.4$ Mpc for $\log(M^*) = 11.1$ galaxies at $z = 1$ (Wake et al. 2011), a the survey will probe $> 10 r_0$ for massive galaxies.

The surface density of targets at $0.3 < z < 1.2$ in the “deep” fields is 36,400 galaxies per a single seven square degree BigBOSS pointing. Assuming that we can only place 60% of the fibers on unique sources we will need 12 fiber configurations to target every observable sample galaxy within a single BigBOSS field of view. The targeting efficiency is based off of the fiber placement simulations of the main survey (80% efficiency) combined with an extra 20% of the fibers dedicated to much deeper observations of a subset of galaxies to enable astrophysically useful spectra at the faintest levels and to calibrate the ensemble modeling proposed. In the “wide” fields the surface density of galaxies with $0.3 < z < 0.7$ is 10,400 per BigBOSS field of view, which will require 4 fiber configurations. Assuming that 50% of the pointings target both “wide” and

“deep” fields results in 4 hours (12 config. \times 10 pointings + 4 config. \times 10 pointings) = **640 hours or 70 clear nights or 110 nights accounting for weather.**

Advantages of an early start: One potentially interesting mode for this survey could be as part of an extensive commissioning run for the main cosmology survey. By targeting significantly deeper than the main survey and doing so for a magnitude limited (as opposed to color-selected) sample, this program would serve to provide much needed redshift templates in advance of the main survey and would test many aspects of redshift completeness, targeting selection, etc.

This dataset would have a very large legacy value, comparable to the SDSS, where the spectroscopic survey has yielded an incalculably large amount of science.

Performing this survey before the start of the BAO component would have a clear advantage to the community, as it will enable galaxy evolution science to be commenced at the beginning of survey rather than at the end or drizzled out over the course of the project. This will maximize community engagement and short-term return on NSF investment. Making such a survey completely public would have significant impact and benefit for the community, which is losing access to 4-m nights.

Requirements Summary:

- Total Number of spectroscopic redshifts: 4×10^5 galaxies
- Redshift range: $0.3 < z < 1.3$
- Total Area: 100 square degrees at $0.3 < z < 0.7$ and 55 square degrees at $0.7 < z < 1.3$
- Minimum S/N for individual galaxies: 3-4 per resolution element
- Time to reach minimum S/N: 4 hours
- Typical S/N in stack: 22 per resolution element
- Target surface density: 1.4 deg^{-2}
- Total number of Dark/Gray nights: 110

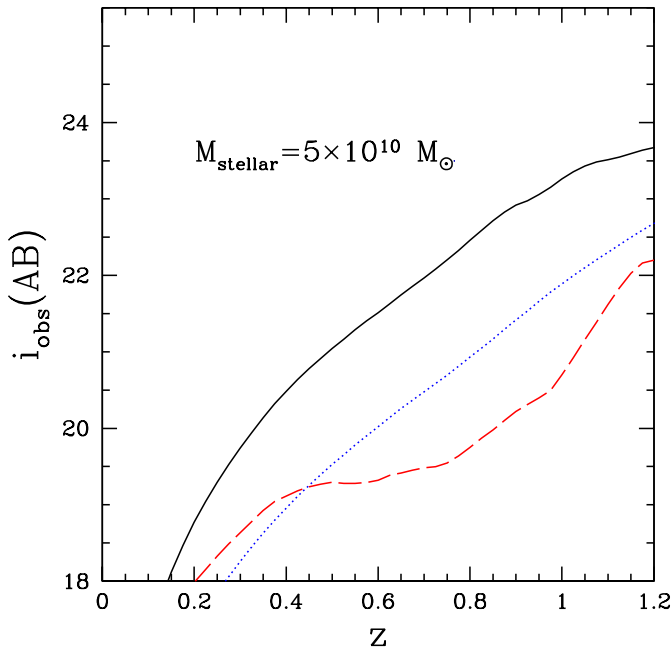


Figure 1.1. The observed i -band magnitude for an $M^* = 5 \times 10^{10} M_{\odot}$ galaxy with one of three star formation histories. Solid: Simple stellar population (SSP) formed at $z = 2$; dashed: an SSP formed at $z = 1.3$; dotted: an exponentially declining model with $\tau = 6$ Gyr and $z_{\text{start}} = 2$.

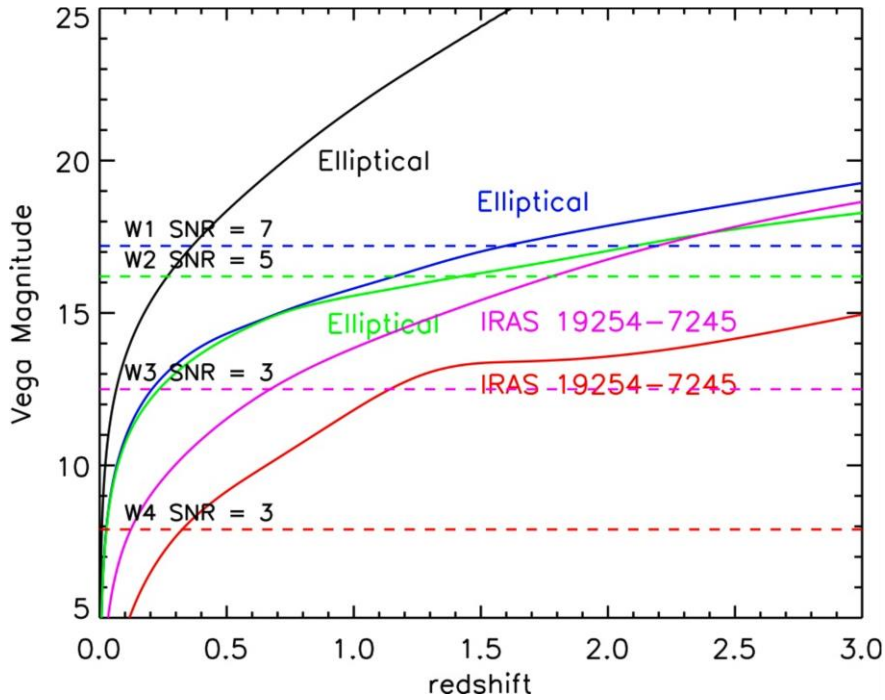


Figure 1.2. Adapted from Yan et al. (2013). The blue and green lines show the 7- and 5-sigma detection limits for a $z = 0 M^*$ Elliptical with no evolution as seen in the WISE W1 and W2 bands. A $z = 1.2$ passively evolving galaxies with $M^*/2$ will be detectable by WISE at $z < 1.2$.

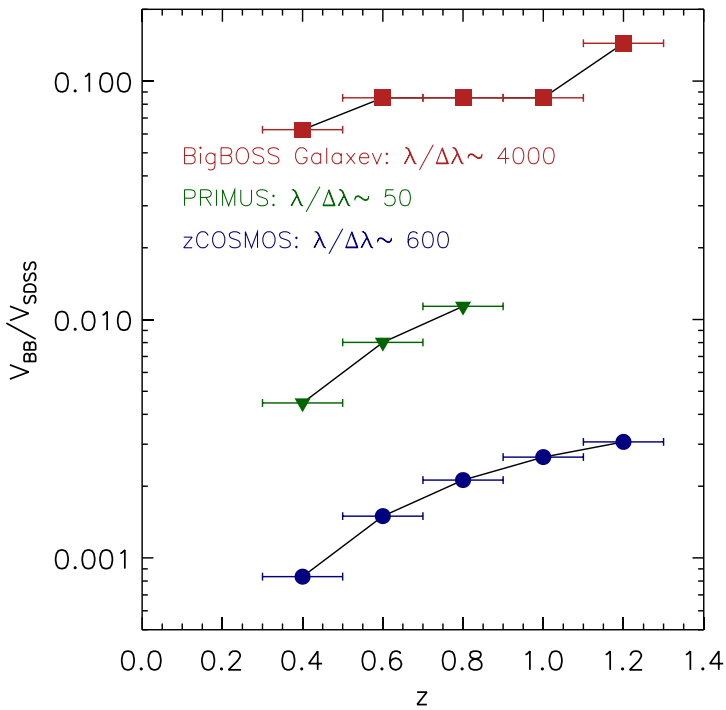


Figure 1.3. The co-moving volume needed to contain 81,000 galaxies in each redshift bin, computed by integrated the evolving stellar mass function at $M^* > 5 \times 10^{10} M_\odot$. The volume is compared to the entire SDSS volume at $z < 0.2$ and shows that the proposed survey will contain 5 – 10% of the SDSS volume in each of 5 redshift slices. For comparison the two next largest existing spectroscopic surveys are shown along with their spectral resolution. Neither of these surveys are selected by a good stellar mass proxy, the PRIMUS data are too low resolution for astrophysically useful spectra, and the volumes are 1-2 orders of magnitude below the proposed survey.

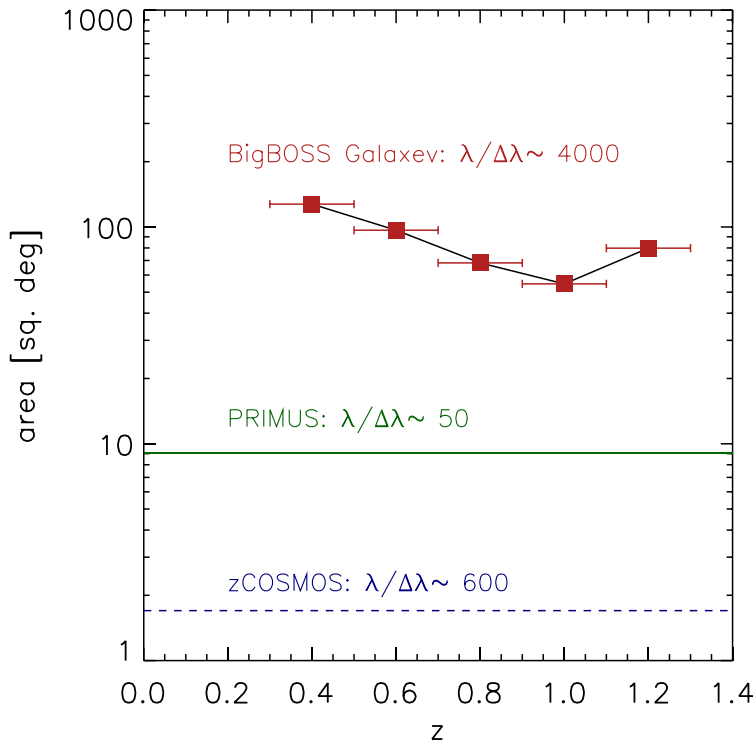


Figure 1.4. The area needed for our planned survey, compared to the area of PRIMUS and zCOSMOS. This area is derived directly from the required volumes shown in Figure 3. Our proposed strategy splits this into two segments, a “wide” segment of 100 square degrees at $0.3 < z < 0.7$ and a “deep” segment of 55 square degrees at $0.7 < z < 1.2$ that is contained within the wide segment.

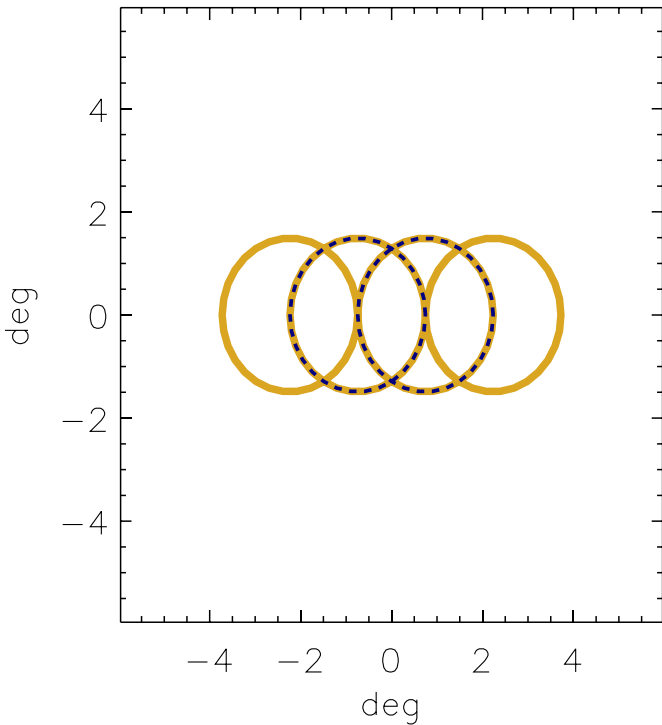


Figure 1.5. A proposed layout for one of our survey fields, assuming that the total area of the survey is split over five disjoint areas. The solid circles indicate the wide survey footprint and the dashed circles the deep survey footprint. The exact number of pointings required to cover the desired area depends on the necessary overlap of pointings and the number of disjoint fields.

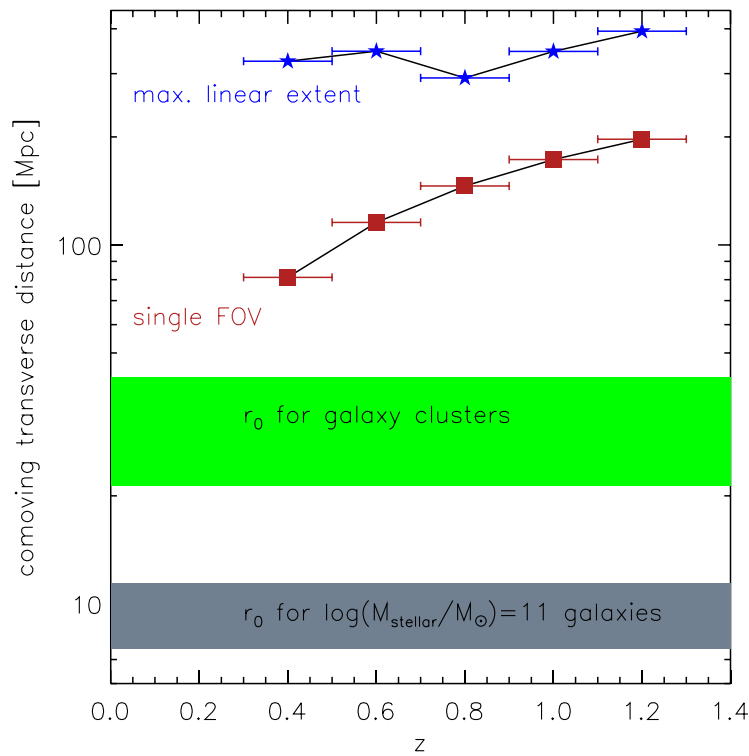


Figure 1.6. An example of the transverse scales probed by the survey and their relation to the clustering scale length of various populations. The lower curve is for a single BigBOSS pointing ($D=3$ deg.) and constitutes a strict lower limit. The upper curve is for the number of contiguous non-overlapping fields needed to probe one-fifth of the survey area at each redshift and could increase or decrease depending on the exact survey strategy. At all redshifts the proposed survey will sample many relevant scale lengths for all interesting populations.

2. Studying the Intergalactic Diffuse Medium with BigBOSS

Brice Ménard, Casey Papovich, J. X. Prochaska, & Gregory H. Rudnick

Introduction

The majority of baryons in our universe exist within a diffuse medium outside of stars and galaxies. The dominant reservoir is the intergalactic medium (IGM), which is responsible for the well-known Lyman-alpha forest absorption observed in the spectra of quasi-stellar objects (QSOs). The IGM is a low-density, photoionized gas, which covers an enormously dynamic range of structure and physics traced by diffuse media. Combined with the interstellar media (ISM) within galaxies, the scientific significance of the IGM and ISM touches nearly all astrophysical endeavors. This includes cosmology, galaxy formation, star-formation, stellar/AGN formation and feedback, and even fundamental physics (temporal variations in the fundamental constants; the neutrino mass). Many of the science questions developed by the 2010 Decadal Survey may be addressed through studies of these gaseous media. Ironically, despite the near ubiquity of diffuse IGM, its low density and generally low enrichment level imply very weak emission from radiative processes (e.g. 21cm, H α , Ly α , etc.). The IGM gas is very rarely detected in emission and therefore is most commonly probed in absorption in the light from background sources. Therefore, spectroscopic observations are required. Furthermore, the majority of line-diagnostics of this gas have energies of several eV or greater implying rest-wavelengths in the far-UV.

One of the main survey samples for BigBOSS is spectroscopy of more than a million $z \sim 3$ QSOs with the explicit goal of measuring a BAO signal from cross-correlation analysis of the IGM/Ly α forest. The BigBOSS Key Project intends to take single-exposure (~ 20 min) spectra of every QSO candidate in their footprint. For the brightest sources ($r < 20$), this should provide a sufficient spectrum for traditional IGM absorption line analysis. Given the enormity of the sample, BigBOSS will provide a quantum leap in surveys of the diffuse media compared to previous surveys (SDSS, BOSS), and the data gathered in the Key Project will provide a tremendous community dataset for work on the diffuse media over an enormous range of cosmic lookback time, $z = 0.3 - 5$. Here we discuss the scientific value of this dataset, and discuss surveys available with community access to BigBOSS to maximize the scientific value of this dataset. The main requirements for this science are (1) to push to the bluest wavelengths possible (e.g. below 3700 Å) which increases redshift coverage, survey path, and provides access to a greater number of UV transitions; and (2) to provide high precision spectrophotometry, especially relative fluxing.

Regarding the community access through BigBOSS, we predict that the majority of science on the diffuse medium will be pursued through allocation of community fibers. This is because it will prove difficult to use the full instrument (i.e. 5000 fibers across 7 square degrees) for science focused on diffuse media, which generally requires at least modest S/N continuum spectra of very distant sources. The usage of community fibers

would allow observations of rare but interesting sources (e.g. highly reddened QSOs), sources avoided by the Key Project, and unique configurations (e.g. pairs of projected objects). In the following sections, we present a series of design reference missions. These are meant to be illustrative of the potential to study diffuse media with community access, i.e. beyond the major datasets that the BigBOSS project would generate during its Key Project. Casual readers may wish to study the Table and the concluding summary at the end of this section.

The Cosmic Distribution of Baryon Gas

Studying the evolution of the IGM across cosmic time improves our understanding of the radiative and chemical enrichment history of galaxies, and improves our understanding of cosmology through measurements by mapping Lyman-alpha absorbers along $\sim 100\text{-}400$ Mpc/h of QSO sightlines (e.g., McDonald et al. 2006, ApJS, 163, 80; Busca et al. 2013, arXiv:1211.2616v2). Indeed, a primary goal of the BigBOSS Key Project is to analyze the IGM at $z \sim 3$ to measure a BAO signal in the IGM through the Lyman-alpha forest of QSOs.

Extending the definition of the IGM to all low density ($n_H \sim 1 \text{ cm}^{-3}$) material in all states includes several other vital phases of baryons in the Universe beyond the Lyman-alpha forest component of the IGM. On the next largest scales after the IGM ($> \text{a few Mpc}$), there is the intracluster medium (ICM), the virialized and X-ray emitting medium that surrounds galaxies in massive clusters. An evaluation of the luminosity, temperature, entropy, and metal enrichment in the ICM will establish the mass of the system and bears on the nature of galactic feedback.

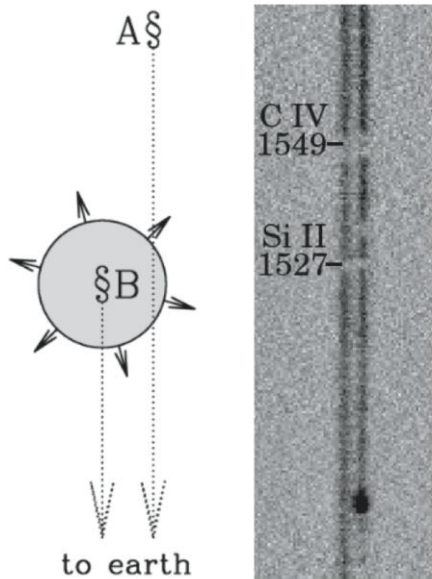


Figure 2.1. Associated absorption from the CGM of galaxy “B”, which is located along the line of sight to source “A” located at higher redshift (Adelberger et al. 2005, ApJ, 629, 636).

On somewhat smaller scales ($< 1 \text{ Mpc}$), individual galaxies harbor gaseous halos: a diffuse, enriched, and multi-phase medium that is also referred to as the circumgalactic medium (CGM). In our own Galaxy, the CGM is manifest as the high velocity clouds that are believed to move through an even more diffuse and more highly ionized medium

(traced by O VI gas). The CGM provides a substantial reservoir of gas from current and future star-formation and, as importantly, offers the fossil record of mechanical and material feedback from galaxies, which includes stellar winds, supernovae explosions, AGN activity, tidal stripping, all of which contribute energy, momentum, metals and dust to the CGM.

On the smallest scales (<100 kpc) galaxies contain an ambient interstellar medium, traced in particular by the warm neutral medium in our Galaxy. This gas, likely the dominant phase of baryons in lower mass galaxies, does not actively participate in star-formation but is almost certainly the fuel for future stars. Similar to the CGM, the ambient ISM records past activity within the galaxy. Furthermore, it traces the gravitational potential on kpc scales as well as turbulent motions generated by star-formation and/or AGN activity. In the parlance of QSO absorption line studies, the ambient ISM is traced by the damped Lyman-alpha systems.

Tracing Outflows, Enrichment and Spatial Extent of the CGM of $z \sim 0.5$ galaxies

In the last few years, analyses of spectra of $0 < z < 1$ star-forming galaxies have revealed that the systems drive outflows of cold, metal-enriched material as traced by Mg II, Fe II, and NaD absorption (Rupke et al. 2005, ApJS, 160, 115; Weiner et al. 2009, ApJ, 692, 187; Rubin et al. 2010, ApJ, 719, 1503). The average velocities of this outflowing material are a few hundred km/s, sufficient (in principle) to drive the ISM gas from the star-forming disk but largely insufficient to escape the galaxies' dark matter potential. Current constraints on the extent, energetics, total mass, and ultimate fate of this material are very poor. For example, the SDSS could not target galaxy-galaxy or galaxy-QSOs within about 60 arcseconds because of fiber collisions. This limited studies with SDSS to projected distances of 300 kpc at $z > 0.5$. SDSS did not allow measures of projected pairs (or the galaxy-gas correlation) on smaller scales. Furthermore, at $z \sim 0.5$, when the average SFR has declined significantly from its cosmological peak, existing galaxy samples are quite sparse. Key considerations, such as the characteristics of outflows with SFR, galaxy morphology, stellar mass, spectral type, etc. have not yet been explored. In turn, the impact of these outflows on the future SFH of the galaxies remains an open and critical question. Similarly, the connections between these ISM outflows and the CGM and (perhaps) the IGM are largely unknown.

With community fibers from the BigBOSS survey, we would have the opportunity to explore outflows in star-forming galaxies over the redshift range $0 < z < 1.4$ while simultaneously constraining the spatial extent of the CGM surrounding the systems. This can lead to measurements of the galaxy-gas and galaxy-dust correlation functions on a wide range of circumgalactic scales. These are fundamental quantities that we need to understand the large-scale distribution of baryons and metals, both for the central galaxies of dark matter halos (the so-called 1-halo term) and the interplay between central and satellite galaxies in the same halo (the so-called 2-halo term).

An experimental design to study outflows and the CGM could be as follows. Using community fibers or follow-up observations, one targets thousands of galaxies within the

BigBOSS survey area that lie within ~ 300 kpc of $z < 2$ QSOs that were previously observed (e.g., by the SDSS or BOSS surveys) where the galaxies' redshifts are less than the QSO. We require galaxy spectra of sufficient S/N to establish the galaxy's redshift and to contribute to a composite spectrum. These composite spectra¹ would yield constraints on gas outflowing from and/or inflowing into the galaxies (on average) through absorption line analysis of the Mg II ($\lambda 2796, 2803\text{\AA}$), Fe II ($\lambda 2374, 2382, 2586, 2600\text{\AA}$), Ca HK, and Na D transitions. In parallel, analysis of the existing QSO spectra would provide a map of the MgII/FeII/CaII/NaI gas in the CGM surrounding these galaxies. Again, this would be a statistical analysis, which would yield a map of the material with impact parameter as a function of galaxy characteristics (see, e.g., Zhu & Ménard 2013 for such an analysis of CaII with SDSS). The observations would provide a census of the integrated CGM enrichment, modulated by subsequent infall.

Technically, this project has several key requirements. First, one must be able to efficiently select galaxies (particularly star-forming galaxies) with redshifts $0 < z < 1.4$ to $r \sim 23.5$ mag, and this is likely feasible using the BigBOSS targeting procedures (for example, SDSS-type photometry already enables the efficient selection of blue, star-forming galaxies, e.g., Comparat et al. 2012). Second, this project requires spectral coverage to $\lambda < 4000$ \AA with good sensitivity (e.g., Fe II 2382 at $z = 0.5$ lies at $\lambda = 3570$ \AA). This is essential to trace the gas outflows (and/or inflows) in absorption. Third, the analysis could rely on composite spectra generated from stacking low S/N data from thousands of galaxies¹. The results will be sensitive to errors in relative spectrophotometry and sky subtraction. High precision, absolute flux calibration is not essential, but data with significant systematic error is prohibitive (e.g. small scale wiggles or inaccurate zero-levels).

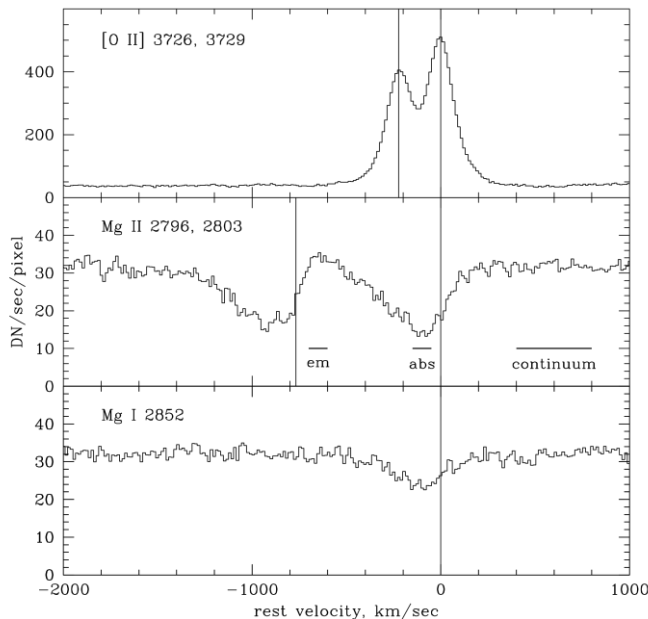


Figure 2.2. Outflows seen in absorption in Mg II and Mg I. The systemic velocity, measured from [OII], is indicated by vertical lines (Weiner et al. 2009, ApJ, 692, 187).

¹ Very few (if any) of the galaxy spectra would have the data quality to examine outflows directly. A separate program could be carried out that targets fewer galaxies with repeated exposures to increase S/N of individual galaxies.

Revealing Rare Pairs with BigBOSS

The primary survey of BigBOSS is designed to optimize the number of pairs of objects on large scales, whereas there is a large range of additional galaxy science that requires small-scaling sampling of galaxies on the sky. One such example is the study of galaxy evolution using close pairs of galaxies.

At present, only a handful of close pairs of extragalactic sources have been studied. This includes a few projected galaxy-galaxy pairs (e.g. Rubin et al. 2010), a small sample of projected QSO pairs (Hennawi & Prochaska 2013, ApJ, 766, 58), and physical galaxy pairs (e.g., Ellison et al. 2007, AJ, 135, 1877). The projected pairs allow studies of the nature of the IGM on the smallest scales, and allow one to examine the CGM of galaxies at all redshifts including those hosting bright AGN.

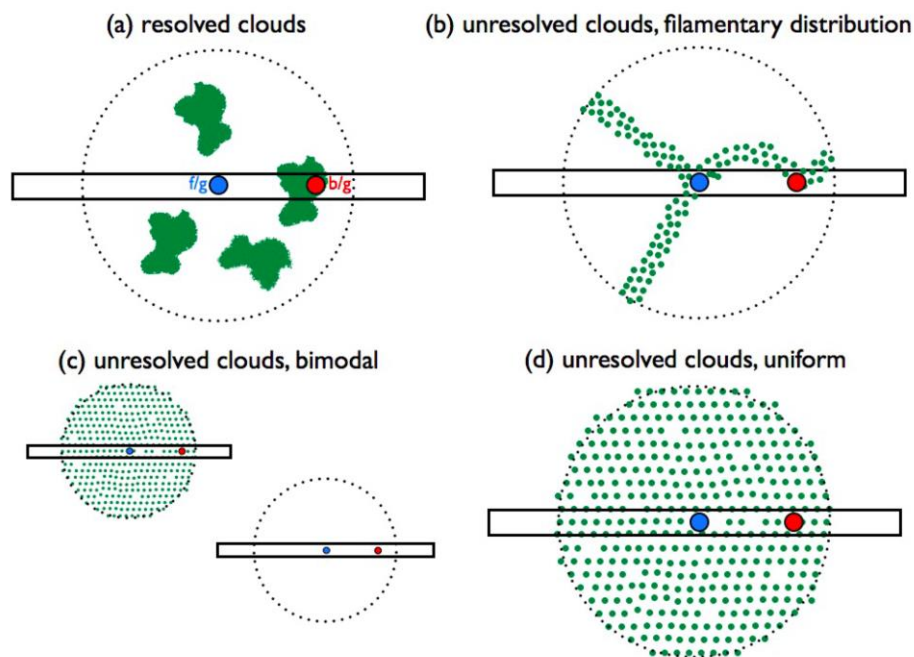


Figure 2.3. Scenarios illustrating how “rare pairs” can probe the spatial distribution of gas in galaxy/quasar halos (Hennawi & Prochaska 2013, ApJ, 766, 58). (a) Large resolved clouds are located at random positions in the quasar CGM. (b) Clouds are spatially unresolved, but gas resides in large resolved filamentary complexes that cover a fraction of the quasar halo. (c) Clouds are unresolved, and only some quasars have cool gas complexes. (d) Unresolved clouds are distributed uniformly in the quasar halo.

Community Access to BigBOSS allows for a large increase in the sample of rare pairs. The design of such an experiment is relatively straightforward. BigBOSS fibers are limited by collisions to only 15 arcsecs, and therefore community-placed fibers would probe projected physical pairs on scales down to ~ 100 kpc. Studies of such objects would open a new window on spectroscopic small-scale galaxy-gas correlations and provide an

estimate of the gas distribution in galaxy halos. One wishes to generate a large sample ($\sim 10^4$) of pair configurations with impact parameters of < 100 kpc (within 15 arcsec) for sources having $0 < z < 1.4$. Such close projected pairs are sufficiently rare that community fibers from BigBOSS must be used. For this project, an efficient approach would be to target sources with small projected distances to any previously known source over this redshift range. These will be dominated by QSOs and LRGs (with known redshifts) from the SDSS and BOSS surveys. The target pool will be dominated by faint galaxies, with $\sim 10 - 30$ candidates per BigBOSS field-of-view. Depending on the science emphasis, one may give highest preference to these rare pairs.

Regarding requirements for the BigBOSS observations, the primary consideration is to achieve a precise and accurate redshift for the target such that it may be associated with metal absorption in the spectrum of the neighbor (background) galaxy/QSO. Of course, the nominal design of the BigBOSS instrument is very well suited to this goal. The key consideration would be whether to request multiple exposures of the faintest targets to improve the S/N and therefore the redshift determinations.

Because of fiber collisions, the nominal survey design for BigBOSS would limit the team from targeting any projected pairs separated by less than 15 arcsec as part of the Key Project (i.e. where they intend to observe the source, i.e., QSOs, during each visit to the tile), although multiple passes of BigBOSS over the same field could target such projected pairs. A community access program (either the use of community fibers or independent targeting with BigBOSS) could target specifically sources in close projection to the Key Project targets.

In addition to furthering the program just described, the redshift determination of any foreground galaxy would allow one to examine the systematic effects of metal-line contamination in the BAO signal. Specifically, one could mask the data at the wavelengths of expected strong metal- line absorption (e.g. MgII) and empirically assess this systematic effect.

Mapping Dust Reddening around Local Galaxies

The diffuse medium of the CGM exhibits hydrogen and metal absorption on scales of tens to several hundred kpc (e.g., Steidel et al. 2010, ApJ, 717, 289). This includes faint and bright galaxies of all spectral types (e.g. Prochaska et al. 2011). The gas exists in a multi-phase medium, with the cooler material traced by low-ion absorption (H I, Mg II) and the higher ionization states probed by high-ion absorption (C IV, O VI).

There is now strong evidence that this medium also carries dust: the average reddening of Mg II absorbers is modest but non-negligible. Ménard et al. (2010) have shown that QSO sightlines that lie within several tens kpc of $z \sim 0.3$ galaxies are redder than the average. Indeed, in galaxies about 1/3 of all metals by mass are in the solid phase (Weingartner & Draine 2001, ApJ, 548, 296), and apparently, the mechanism(s) that transport metals from galaxies to the CGM also carry along dust grains (the possibility that dust is formed in situ being remote).

The experiments described above for assessing dust in the CGM of low- z galaxies are statistical. To date, no individual galaxy has been demonstrated to have large amounts of dust in their CGM on scales of ~ 100 kpc. The pioneering analysis of Zaritsky (1994, AJ, 108, 1619) measured reddening of background galaxies in the halos of two galaxies, showing the presence of dust to ~ 60 kpc in each, albeit with weak statistical significance (consistent with Nelson, Zaritsky, & Cutri 1998, AJ, 115, 2273). With Community Access to BigBOSS, one could perform a modern variation on these experiments over a sample of nearby galaxies. The primary goal would be to map the extinction in the extended disk and CGM of these present-day galaxies to infer the integrated expulsion of dust (and by inference metals).

Community access with BigBOSS would also permit a study of extinction in the CGM. A possible survey would target nearby galaxies with a virial radius of ~ 1 degree. The BigBOSS field-of-view would then cover the entire CGM and also a region beyond that could serve as the control. One would then measure differential reddening throughout the field. A similar study has been recently carried out for the Galaxy using red-and-dead galaxies drawn from SDSS (Peek & Graves 2010, ApJ, 791, 415). Furthermore, combined with studies of the CGM and rare pairs above, it will be possible to study the galaxy-dust correlation function both for individual galaxies in halos (the 1-halo term) and the transition to multiple galaxies in halos (centrals and satellites, the 2-halo term). A Community survey could also target galaxies as well as faint QSOs throughout the field. Furthermore an assessment of Galactic reddening (and its variations) would be made through analysis of stars in the field.

A program to study the dust and gas (Na I) distribution surrounding nearby galaxies could obtain spectra of 500-1000 background $R\sim 21$ galaxies with S/N $\sim 12-15$ per resolution element in 3 hours per pointing. A study of 10 nearby galaxies would require a total of 30 hours. Ideally, one would couple the spectrophotometry with high-precision, wide-field images of each field.

Summary

SDSS has provided us with fantastic results on the galaxy-mass correlation function through galaxy-galaxy lensing measurements. Community access to BigBOSS can provide another fantastic set of constraints on the galaxy-gas and galaxy-dust correlation functions through absorption and reddening measurements. Such a new opportunity will allow the astronomical community to study the large-scale distribution of metals in both the gaseous and solid phases and significantly advance our understanding of galaxy formation and evolution.

The table below summarizes the key aspects and requirements of several of such Community Access programs using BigBOSS. Some of the most original research on the diffuse IGM, CGM, and ISM with the SDSS dataset has been derived from community use of the SDSS spectroscopic dataset. These analyses have often used composite spectra, in concert with photometric analysis. This has included stacking in the absorber

frame to assess dust in the CGM and ambient ISM (Peek & Graves 2010), and gravitational lensing by the host galaxies. It has also involved stacking in the source frame to assess galactic-scale outflows (Chen et al. 2010, AJ, 140, 445), and to place novel constraints on the mean opacity of the IGM (Prochaska et al. 2009, ApJ, 705, 113). The combination of the BigBOSS Key Project, availability of community fibers in the Key Project, and community access for additional surveys will provide the next leap forward in the field of diffuse media science.

Summary Table for Diffuse Medium Science with BigBOSS Community Access

	0 < z < 1.4 CGM	projected pairs	extinction mapping	BigBOSS main survey
observing mode	community fibers	community fibers or community access	community access	archival from Key Project dataset
Targets	r < 23.5, star-forming galaxies at z~0.5	r < 24 mag source with 5" of known z > 0.5 source	QSOs and red galaxies; Galactic Stars	QSOs
wavelength coverage	< 3700 Å	wide as possible	wide as possible	< 3700 Å
spectral resolution	R > 2000	any	any	R > 2000
spectro-photometry	relative	any	Absolute	relative, but absolute useful for some science

3. BigBOSS Galactic Archaeology Survey

Verne Smith, Connie Rockosi, Carles Badenes, Tim Beers, Jennifer Johnson, & Catherine Pilachowski

Galactic Archaeology as a Window into the Formation and Evolution of Galaxies

Observational efforts to understand the formation and evolution of galaxies, as well as other large-scale structures in the universe have followed two different, but complementary paths in recent years. One path is to study faint galaxies at large redshifts to characterize their early phases of evolution. The galaxy evolution survey discussed in **Section 2** is an example of this type of approach. Another path is to survey the stellar populations of nearby galaxies to probe their star formation and chemical evolution over cosmic time; this is called “near-field cosmology”. These different observational approaches yield complementary data; large-scale global galactic properties of young galaxies at *high-redshift*, and high spatial, kinematical, and chemical information of ancient stars in the *local universe*.

The highest information density about galactic evolution, for the specific case of a large, barred spiral, resides in the stars of the Milky Way. Encoded in the spatial distributions, kinematics, and chemistry of the various distinct stellar populations is the assembly history of the Milky Way, which then provides strong constraints on the formation and evolution of our Galaxy. The process of recreating the assembly history of a galaxy by identifying recognizable stellar population remnants has been referred to as “Galactic Archaeology”.

Recent Galactic surveys and observations, along with galaxy evolution models, point to evolution that has occurred in a much more complicated scenario than the sequential “top down” evolution of halo to thick disk to thin disk. The Milky Way, and presumably other large galaxies, has evolved in a non-continuous manner, resulting in an array of constituent stellar populations with distinctly different spatial, dynamical, and chemical properties that have been witness to a complex evolutionary history. While many theories or models can explain the overall large-scale features of the Milky Way, many important questions remain.

- What fraction of stars in the Milky Way’s halo, disk and bulge are accreted in merger events?
- What are the star formation and chemical evolution histories of progenitor systems accreted by the Milky Way? How do those properties correlate with the mass and accretion time of the progenitor systems as inferred by the kinematic and spatial information in the leftover debris from the accretion events?
- What role to cosmological mergers and interactions play in shaping the structure and star formation history of the disk and its evolution via secular processes?

Progress toward these questions has been limited, in part, by our ability to characterize the properties (position, velocity, chemical abundance, and age) of large numbers of stars spanning a significant fraction of stellar populations.

Because these required quantities can all be estimated spectroscopically, massive spectroscopic surveys of stellar populations in our Galaxy will be the next major advance in our understanding of the history the Galaxy. This advance is analogous to the advent of wide-field imaging surveys a decade ago and one with the same transformational potential: imaging surveys have established the presence of substructure in the disk and halo of our Galaxy and M31.

Previous spectroscopic campaigns have been designed to probe the stellar population of known substructure. In addition, sparse, exploratory surveys have examined representative stellar samples spread over the Galaxy. BigBOSS will enable spectroscopic surveys that cover larger area to higher completeness and greater depth than previously possible. With this qualitatively new information about the stellar populations in our Galaxy, we can address questions such as those listed above.

The Promise of Chemical Abundance Studies

Variations within element abundance patterns observed across a variety of stellar populations reflect the relative contributions in nucleosynthetic yields from previous generations of stars, which are formed as a result of star formation histories, either within the Milky Way itself, or within galaxies that were eventually incorporated into the Milky Way. The eventual mix of chemical elements that emerges from the combination of stellar evolution, nucleosynthesis, and stellar death is dictated by the mass distributions of stars that formed to produce and eject enriched gas, which then mixed with the ambient interstellar medium (ISM) to form subsequent stellar generations. As a specific example, supernovae are major sites of nucleosynthesis. Both Type II (massive-star progenitor) and Type Ia (lower-mass binary-star progenitor) supernovae (SN) contribute Fe to the ISM, but α -elements (such as O, Mg, Si, Ca, or Ti) originate mostly from SN II, while each SN Ia event produces considerably more Fe than each SN II event. Consequently, the chemical abundance ratios of $[\alpha/\text{Fe}]$ (measured as $[\text{x}/\text{Fe}] = \log(\text{N}_\text{x}/\text{N}_\text{H})_\text{star} - \log(\text{N}_\text{x}/\text{N}_\text{H})_\text{Sun}$) changes over time in a stellar population, with this ratio typically expected to decrease over times $\tau > 1$ Gyr, as SN Ia take longer to evolve and begin to contribute significantly their Fe to the ISM. The $[\alpha/\text{Fe}]$ - $[\text{Fe}/\text{H}]$ distribution is thus used to gauge the star formation rate (SFR), or star formation history (SFH) in a stellar population. The value of $[\text{Fe}/\text{H}]$ at which $[\alpha/\text{Fe}]$ begins to decline is a measure of the star formation efficiency (or specific SFRs) within a distinct population.

Different types of galactic environments, with different SFHs, should thus result in different values of $[\text{Fe}/\text{H}]$ at which $[\alpha/\text{Fe}]$ begins to decrease. This effect has been observed in some of the small, nearby Local Group dwarf galaxies, such as the Magellanic Clouds or dwarf spheroidals. Figure 3.1 shows such a difference, relative to

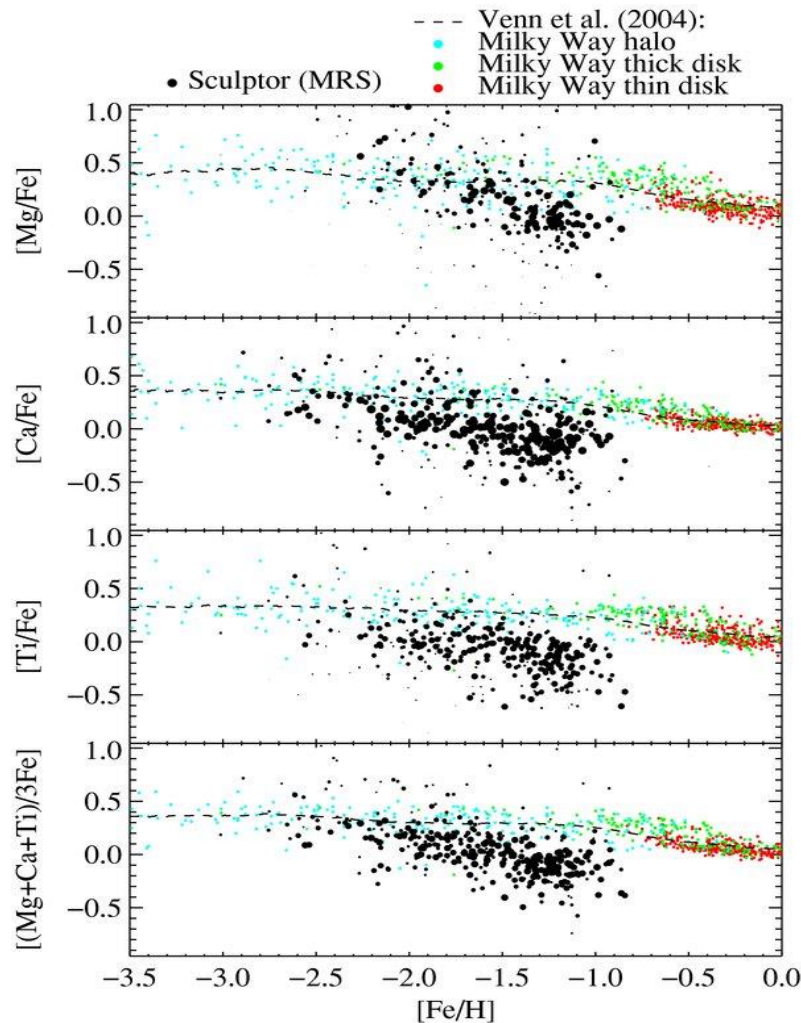


Figure 3.1: Abundance results from Kirby et al. (2009), with the black points showing his medium-resolution, multi-element abundances for the Sculptor dwarf spheroidal galaxy. The y-axes illustrate the behavior of various α -elements versus metallicity, as $[\text{Fe}/\text{H}]$. The colored points show different components of the Milky Way, all based on rather small (<100 - 200) samples of stars. The differing types of chemical evolution in $[\alpha/\text{Fe}]$ as a function of increasing overall metallicity is clear, with Sculptor characterized by smaller relative contributions from SN II relative to SN Ia over its chemical evolutionary history. Such abundance differences can be used to detect and characterize stellar populations.

Milky Way stars, in the dwarf spheroidal galaxy Sculptor; this figure is from Kirby et al. (2009) and the abundances were derived from modest resolution spectra ($R=6000$), which are not much higher than what is planned for BigBOSS in the red. Kirby plots some of the individual α -element values, $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, and $[\text{Ti}/\text{Fe}]$, versus $[\text{Fe}/\text{H}]$ for Sculptor, along with Milky Way halo, and thick and thin disk stars. The values of $[\alpha/\text{Fe}]$ in Sculptor are declining at significantly lower metallicities than are seen in the general populations of the Galaxy. This demonstrates that, not only has Sculptor not cycled gas through star formation as quickly and efficiently as the Milky Way, but the details of this sort of SFH leave chemical fingerprints in the stellar populations that result from such a history. This is the principal of “chemical tagging”.

In addition to the α -elements, other information about the enrichment of the ISM may be obtained from other families of elements, such as the odd-Z elements Na or Al, that are produced by C- and Ne-burning in massive stars. These particular elements tend to have metallicity-dependent yields (i.e., their abundance depends on the metallicity of the supernova source progenitor) and thus, they provide more information on SFHs, such as enrichment time-scales and the relative importance of outflow or infall. The BigBOSS spectra with $R=5000$ in the red are of high enough resolution to also study additional types of elements, such as the s-process species Sr or Ba, whose chemical evolution is dominated by asymptotic giant branch (AGB) stars.

BigBOSS will provide spectra for an unprecedented number of stars that can be used to map chemical abundances produced by an array of nucleosynthesis sites and use these results in chemical tagging. The abundance patterns will probe for stellar substructure across large volumes of the Milky Way.

Massive Spectroscopic Surveys as a Key Tool in Galactic Archaeology

As discussed above, it is through spectroscopy that the key parameters defining the pedigree of a star can be determined, such as radial velocity, effective temperature (T_{eff}), surface gravity (usually parameterized as $\log g$), chemical abundance distribution, and approximate age. With an estimate of distance to the star, its Galactic location is set and this spatial position, along with the other characteristics derived from the spectra provide the necessary information to place this star within a Galactic population census. Repeat this process millions of times, over a broad range of positions in the Milky Way, and a richly textured, multi-parameter map can be constructed from which a detailed history of our Galaxy can be drawn.

Current photometric plus relatively small spectroscopic surveys are just beginning to provide hints of a rich stellar population substructure that permeates the Milky Way. Figure 3.2 provides a broad-brush view of known substructure by showing the locations and extents of distinct stellar streams. Such currently detected stellar substructure is just the “tip of the iceberg” awaiting substantially larger and deeper surveys.

Table 3.1 summarizes some characteristics of the most well-studied stellar structures identified in Figure 2, such as the size or extent over the sky, the distance from the Sun or general Galactic location, as well as the approximate number of stellar spectra collected to date on these systems. The takeaway points from this table, along with the graphical view from Figure 2, are that these substructures are ubiquitous and cover the sky, as well as being typically quite large, in the sense of spanning broad angular areas. The other noteworthy item is that the amount of spectroscopic data obtained to date, which is used to characterize the substructure, is not terribly large.

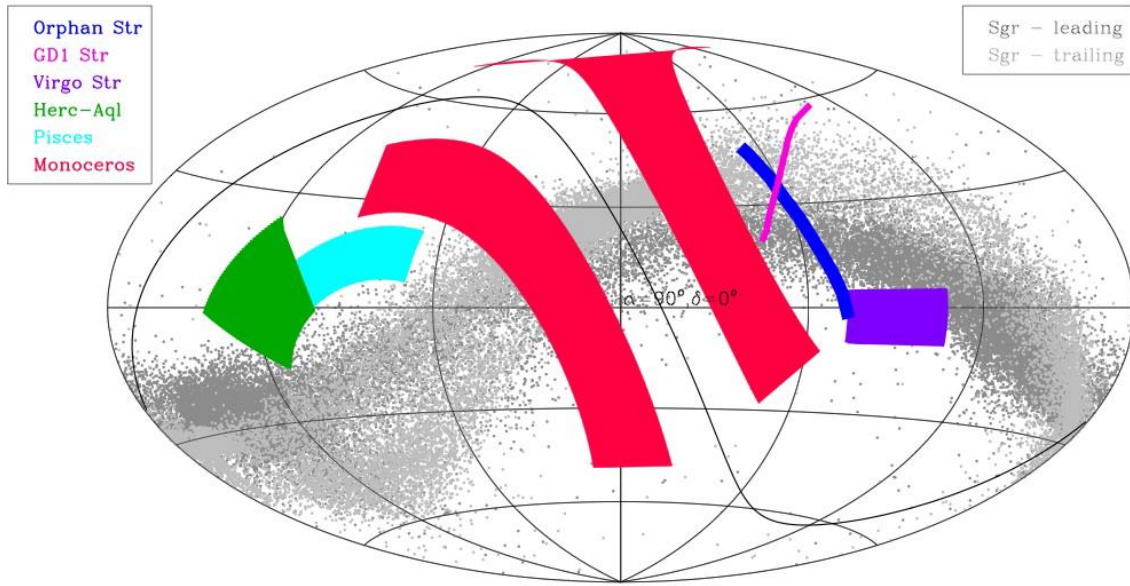


Figure 3.2: Known photometrically-detected substructure plotted in equatorial coordinates, centered on RA=6hr. Streams from the Sagittarius dwarf galaxy are shown with the leading and trailing arms (Laws & Majewski 2010) plotted as shades of grey. Besides Sagittarius, known structures now include the Monoceros ring structure, the Virgo overdensity/stream, the Hercules-Aquila Cloud, Pisces, along with the Orphan and GD1 Stream.

Based on the properties of Galactic stellar substructure probed so far, an efficient way to best characterize the number, size, and physical characteristics of underlying stellar streams is to maximize area, the number of stars studied, and the depth of the survey. The following discussion of a Mayall/BigBOSS Galactic archaeology survey demonstrates the potential to meet all three of these criteria to a higher degree than any currently planned surveys.

Table 3.1: Known Galactic Stellar Substructure

System	Sky Extent	Location	# Stellar Spectra
Sagittarius	All over sky	Throughout halo	~few hundred
Virgo	750-1000 sq-deg	Distance ~12-20 kpc	~100-150
Monoceros	Longitude 60-300 deg	Anti-center, “thick disk”?	~500
Hercules-Aquila	Stripe 82	16-28 kpc	~1800 RVs

The BigBOSS Galactic Archaeology Survey

Magnitude limits: The premise of the survey is to exploit three premier strengths of BigBOSS on the Mayall: a large aperture allowing observations to faint magnitudes, a 3-degree wide field-of-view providing the ability to cover large areas on the sky, and a massively multi-plexed 5000-fiber spectrograph. The survey presented here is anchored on 4x1200 second visits per field in order to achieve signal-to-noise (S/N) spectra of 25-30 per resolution element for the faintest targets. The requisite S/N limits depend on the types of target stars, which are divided into three groups depending on T_{eff} .

For cooler stars, such as those on the red giant branch (RGB) with $T_{\text{eff}} < 5000\text{K}$ (where typical metal-rich clump giants have $T_{\text{eff}} \sim 4700\text{-}4900\text{K}$), Kirby et al. (2009) have used moderate resolution spectra ($R=6,000$) in the $\lambda 6300\text{-}9000\text{\AA}$ region to derive stellar parameters and abundances for the elements Fe, Mg, Ca, and Ti. With a $S/N \sim 25$ in this spectral region, stars could be observed to as faint as $r = 18$ in any moon conditions with BigBOSS on the Mayall. If dark-time could also be used, the magnitude limit for 4x1200 second visits would drop to $r = 19$.

Stars having intermediate values of $T_{\text{eff}} \sim 5000\text{-}6000\text{K}$, such as main-sequence turn-off (MSTO) will ideally use combinations of lines spanning both blue and red regions of the spectrum. A conservative estimate is that a $S/N \sim 25$ should be sought at 4000\AA (e.g., Ca II $\lambda 3934\text{\AA}$ or Sr II $\lambda 4077\text{\AA}$), which then leads to a magnitude limit for all lunar conditions of $r = 17$ and $r = 18.5$ in dark time. Testing would be done to optimize the amount of information that could be gained from the red spectral lines ($> 6500\text{\AA}$) over more specific effective temperature regimes, as this would allow the survey to reach $r = 18$ in all lunar conditions and to $r = 19$ in dark time.

For warmer stars, $T_{\text{eff}} > 6000\text{K}$, such as very metal-poor MSTO stars, stronger lines at bluer wavelengths are necessary for deriving abundances in the metal-poor stars. A goal of $S/N \sim 25$ per \AA as blue as 4000\AA would allow stars as faint as $g = 17.5$ (relevant for the flux at 4000\AA) to be observed over all moon phase. Dark time would allow observations to $g = 19$.

Target density: Straightforward estimates indicate that 1% of stars in an old population are on the RGB with $T_{\text{eff}} < 5000\text{K}$ (Kirby's temperature range), with about 3.5 mag between that point on the RGB and the tip. This works out to an absolute magnitude range in r of $M_r \sim 1$ to -2.5 . Observing to $r = 18$, at $M_r = 1$ yields a distance of 25 kpc. At $M_r = -2.5$ the distance is 125 kpc.

The luminosity function suggests that there will be 43 RGB stars with $T < 5000$ per 7 sq. degree BigBOSS pointing. There are also about 20 red clump or blue horizontal branch (BHB) stars to $g = 18$.

At the MSTO, $M_r = 4$, at a faint magnitude limit of $g = 17$ is a distance of 5 kpc. Counting stars in the SDSS photometry (bright limit of about 15th magnitude in g and r), there are 3800 targets per 7 sq. degree field to $g = 18.5$, $|b| > 40$ degrees, $-0.25 <$

$g-r < 0.75$. That red limit is about $T_{\text{eff}} = 4700$ K; the MSTO is at $(g-r) \sim 0.2$. Between $30 < |b| < 40$ degrees there are almost 7000 stars per 7 sq. degree field at those same color and magnitude limits. The survey could easily fill, or almost fill the fibers across large fractions of the sky; however, room could be made for other programs as well.

The layout of SDSS plates was such that the 7 sq. degree field covered 5 unique sq. degrees (with overlap). If this strategy were adopted, with filled areas (no holes), then 4x 1200 sec. exposures per field, would result, on average, in observing 5 fields per night, or between 25 and 35 unique sq. degrees.

Need for a Large, Contiguous Survey Area: There are no large area, filled spectroscopic surveys of the Galaxy to the depth and completeness possible with BigBOSS, and such a survey would provide a qualitatively different view of the stellar populations of our Galaxy.

The availability of wide-field, homogeneous imaging data revealed features in the halo and disk of our Galaxy and M31 not seen in older wide-field photographic and pencil-beam digital imaging data. We have limited spectroscopic data from follow-up of the detections of substructure from the imaging surveys, and surveys like APOGEE and SEGUE are pencil-beam spectroscopic surveys that explore the Galaxy with representative but sparse sampling. These surveys provide information about existing substructure and have been used to identify new radial velocity substructure, but it is not possible to “connect the dots” and get a complete picture of the kinematic distribution of stars in the halo and disk. To do that requires a filled survey over a large, contiguous area.

In addition to the need for a contiguous survey area, it is also critical that the survey not be dominated by a single, large substructural feature in the thick disk or halo. Because these features can be many tens of degrees long (e.g., the Sgr tidal tails), a fair sample of the halo requires a patch with a diameter several times that characteristic size. That argues for a patch of order 100 degrees on a side, for a survey area of at least 10,000 square degrees.

A baseline survey of 12,500 square degrees would require 500 nights to complete. Most of the large, photometrically-detected substructure in the SDSS is many hundreds of square degrees, so smaller programs to map those known features, requiring several tens of nights, could also be included. The product of the survey would be spectra of well over 10^7 stars, covering the broad range of Galactic stellar populations. The combination of numbers of stars, numbers of chemical elemental abundances, and radial velocities will provide the most exquisite map of substructure in the populations of the Milky Way—a true Galactic census.

Relation to Gaia and Other Galactic Stellar Surveys

The planned space mission Gaia (current launch in October 2013) will have a major impact on understanding the structure of the Milky Way. Gaia is an ambitious cornerstone ESA mission which will measure positions to unprecedented accuracies for

$\sim 10^9$ Milky Way stars (20 μ arcsec at $V = 15$, to 200 μ arcsec at $V = 20$). In addition to its astrometric mission, Gaia will also obtain spectra ($R \sim 11,000$) in a 200 \AA region centered on the Ca II infrared (IR) triplet, near $\lambda 8500 \text{\AA}$, that will be used for determining radial velocities and stellar abundances for a few elements.

Because Gaia will not measure spectra for stars fainter than $V \sim 16-17$ (i.e., almost 90% of the Gaia sample), this leaves a large “spectroscopic gap” in the potential scientific return from Gaia. This gap will be filled partially by the currently running VLT/FLAMES large program called “The Gaia-ESO Public Spectroscopic Survey”, which will use 300 nights over 5 years and focus on the $V > 17$ targets. This large chunk of 8-m time will still “only” cover 100,000 stars in the southern hemisphere.

Table 3.2. Comparison to Other Galactic Stellar Surveys

Survey	Telescope + Instrument	Wavelength	Resolution	Targets	Survey Period
BigBOSS Galactic Archaeology Survey	4-m Mayall + 5000-fiber BigBOSS instrument	3600 – 9800 \AA	3000 – 4800	$> 10^7$ stars, to $r \sim 18$ or 19	
Gaia-ESO Public spectroscopic survey	VLT + FLAMES/GIRAFFE/UVES	Optical	20,000 + some at 50,000	10^5 stars, mostly $r \sim 17-18$	Jan 2012-
APOGEE	SDSS 2.5-m + 300-fiber spectrograph	1.5 – 1.7 micron	22,000	10^5 stars, $H < 14$	Summer 2011 – Sept 2014
HERMES-GALAH	AAT 3.9-m + 400-fiber spectrograph	Optical to 7900 \AA	28,000	10^6 stars, $V < 14$	From 2013 for 5 years
RAVE	1.2-m UK Schmidt + 150-fiber spectrograph	CaII IR triplet region (8410 – 8795 \AA)	7500	400,000 stars, $I = 9-13$	Completed
SEGUE	SDSS 2.5-m + multi-fiber spectrograph	3900 – 9000 \AA	1800	240,000 stars, $14 < g < 20$	Completed
LAMOST	Meridian ~ 5 -m + 4000-fiber spectrograph	3900 – 9000 \AA	1000-5000	$V < 20$	Pilot survey begun in 2011

There is also an ESO proposal to use the VISTA 4-m with a “BigBOSS-like” multi-object fiber spectrograph to do a much larger Gaia follow-up, which is called 4MOST (4-m Multi-Object Spectroscopic Telescope; 1600 fibers at $R=5000$ and 800 fibers at $R=25,000$). 4MOST is in competition with another project called MOONS (Multi-object Optical and Near-infrared Spectrograph), with a downselect between these two set for May 2013. (MOONS would be for the VLT, have $R=20,000$ and cover the wavelength range from 5000 \AA or 8000 \AA out to 1.8 μ m.)

Compared to other Galactic stellar surveys (Table 3.2), the BigBOSS Galactic Archaeology Survey represents an increase of an order of magnitude or more in the sample size.

Summary

A design reference mission for Galactic archaeology using BigBOSS on the Mayall would have the capability to complement, as well as massively extend, many aspects of any planned surveys over the coming decade.

Relative to other current or planned surveys, some strengths of a BigBOSS + Mayall survey are:

- A multiplex capability of 5000 fibers provides the capability to do much larger surveys of over 10^7 stars covering a number of chemical elements and radial velocities to accuracies of ~ 5 km/s.
- The combination of spectral resolution with the 4-m aperture, provides the capability to go as faint as any of the other surveys, or exceed most of them (it can reach the limit of the Gaia catalogue, whereas Gaia-ESO and HERMES cannot).
- BigBOSS will come on-line in 2018 and can take advantage of Gaia distances in its target selection. The stellar types to be targeted could be easily tuned if required. Clump giants could be surveyed to distances of ~ 100 kpc.
- As a deep survey, it will probe the largest distances and realize the full 6D + chemistry from Gaia, taste the Galactic potential over the greatest range, as well as provide the largest-scale view of kinematic substructures
- With $R=5000$ spectroscopy, the chemistry will not just be overall metallicity plus an average $[\alpha/\text{Fe}]$, but will include a number of individual elements covering a range of nucleosynthesis origins, such as Na, Mg, Al, Si, Ca, Ti, Fe, Ni, Sr, or Ba. It might be possible to measure close to the number of elements being studied in the RAVE dataset ($R=7500$).
- The capability to find the largest numbers of spectroscopically confirmed very metal-poor stars.
- If ESA 4MOST is approved, BigBOSS provides complementarity such that all-sky surveys utilizing the Gaia results would be possible.

4. Exploring the Time Domain with BigBOSS

Carles Badenes & Joan Najita

Introduction

Time resolved spectroscopy is the next frontier in observational astrophysics. The Sloan Digital Sky Survey (SDSS) initiated the era of large imaging and spectroscopic surveys, and several ongoing projects like the Palomar Transient Factory (PTF) and Pan-STARRS are exploiting the rich phenomenology of time variability using large imaging cameras, but the spectroscopic time domain remains relatively unexplored. Community access to the unique capabilities of BigBOSS will open new areas of discovery in time domain astronomy that can spawn both large surveys and small PI-led projects on a wide range of scientific topics. Some examples include reverberation mapping and the feeding habits of supermassive black holes at the centers of galaxies, the magnetic activity of stars within our own Milky Way (**Section 5**), and the search for binary companions to these stars, which has a direct impact on their ability to harbor planets that can support life.

Time resolved spectroscopy studies address a wide range of scientific topics, including several of the key priorities outlined in the most recent Decadal Survey. The massively multiplexed, wide-field BigBOSS spectrograph is uniquely poised to make significant contributions in this field. A monitoring campaign of bright active galaxies on timescales ranging from months to years, for example, can be used to unveil the population of binary supermassive black holes predicted by theory (Valtonen et al. 2008), and also to characterize the details of accretion and outflow in these systems, which have a direct impact on galaxy formation through an ill-understood feedback mechanism (Fabian 2012). In the field stellar astrophysics, the capabilities of BigBOSS have the potential to revolutionize our knowledge of chromospheric activity (Kruse et al. 2010) and stellar multiplicity (Benjamin et al. 2012, Badenes & Maoz 2012), which are key inputs to a comprehensive study of the capacity of stellar systems to host and maintain life.

4.1 Stellar Binaries

Here we will use stellar multiplicity to illustrate the potential of time domain spectroscopy in the context of a large Galactic structure survey with BigBOSS. One possible strategy, which would have a low impact on the survey itself, would be to split the total exposure time into sub-exposures, as was done for SDSS (Stoughton et al. 2002). This kind of survey would allow the detection of compact binaries, such as double white dwarf binaries and detached compact object-main sequence binaries, with periods of minutes to hours and radial velocity (RV) semi-amplitudes of several hundred km/s (Badenes et al. 2009, Kilic et al. 2012). These systems are among the strongest known gravitational wave sources, and could be the progenitors of Type Ia SNe, X-ray binaries, and other exotica. Beyond the value of the discovery of individual systems, the statistical analysis of large samples of sparsely sampled RV curves can be used to measure fundamental parameters like the merger rate of Galactic white dwarfs (Badenes & Maoz

2012), and constrain the underlying properties (binary fraction and separation distribution) of the corresponding binary population (Maoz et al. 2012).

More ambitious studies are possible if the time-resolved dimension of the survey is planned carefully. The target period range will be determined by the accuracy of the RV measurements, the number of exposures and the time lag between consecutive exposures.

An example is shown in Figure 4.1. By introducing a time lag of five hours between the first and last exposure for a large enough number of fibers, BigBOSS would be able to characterize the poorly-constrained population of short period binaries for main-sequence solar-like stars in the field. These binaries are the progenitors of future interacting binaries (CVs, X-ray binaries, Type Ia SNe, novae, etc.). This could be done for a subset of the fibers devoted to a large Galactic survey, or as a separate project. Even longer temporal baselines could be envisioned as a joint time-resolved survey that combines stellar and extragalactic targets (e.g., AGN) to be executed during bright time. These studies would be able to provide invaluable inputs to binary population synthesis codes that model interacting binaries, and they would be crucial to determine the number of stellar systems with habitable planets in stable orbits (Cuntz 2013).

For spectra with $S/N \sim 10$ (so that RVs can be measured with an error of ~ 10 km/s; e.g., Yanny et al. 2009), our Monte Carlo simulations indicate that sample sizes of a few hundred thousand stars (i.e., smaller than the entire SEGUE survey in SDSS) should yield interesting constraints on binary fractions and period distributions. For temporal baselines of a few hours (which is feasible in dedicated observing nights during bright time), several hundreds of binaries should be detected, enough to explore the dependence of the basic multiplicity parameters on factors like stellar metallicity and disk/halo membership.

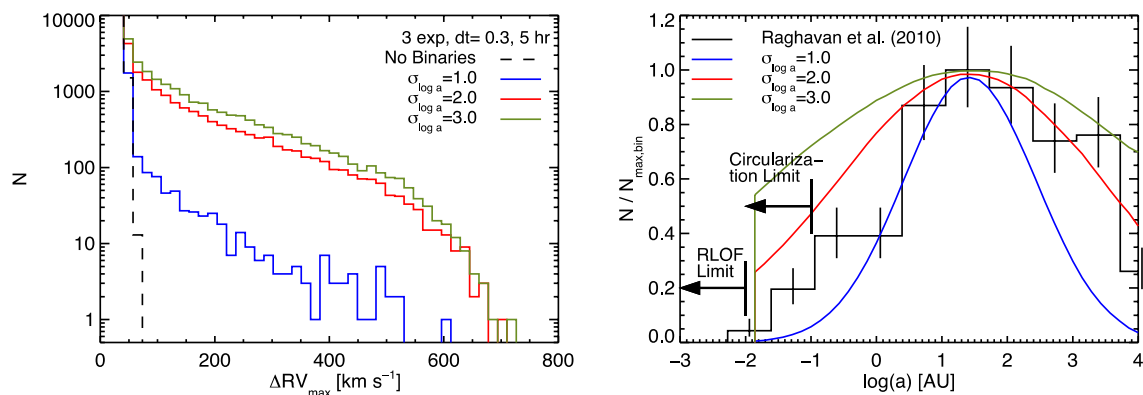


Figure 4.1: Left: simulated histograms of ΔRV_{\max} (the maximum RV shift between exposures of the same fiber) for a BigBOSS survey of 1 million fibers and a RV error of 10 km/s, three exposures per fiber, and a time lag of five hours. The underlying binary population has been drawn from a lognormal distribution with a peak of 1.5 in $\log a$ and different values of $\sigma_{\log a}$ (the standard deviation of the RV error distribution, assumed to be Gaussian), indicated in the plots. Right: the distribution of separations for solar-like main sequence stars in the volume-limited sample of Raghavan et al. (2010), together with the separation distributions used in the simulated

histograms to the left. The limits for orbital circularization and Roche Lobe Overflow are indicated by arrows.

4.2 Binary Black Holes

Time domain spectroscopy would also enable other frontier science, such as the search for and study of binary black holes. Short-period binary supermassive black holes appear to be an inevitable prediction of the hierarchical paradigm for galactic evolution (Milosavljevic et al. 2002). The detection and characterization of this population of objects would allow us to fill in one key missing piece in this paradigm - the so called 'final parsec problem'. The capabilities of BigBOSS are ideally suited for a comprehensive survey of broad emission line quasars already observed by SDSS in order to achieve the ~ 10 yr baselines and multiple epochs necessary to unambiguously detect RV shifts in orbits with the expected periods and semiamplitudes (a few hundred years and several thousand km/s for $\sim 10^8 M_{\text{sun}}$ black holes; Eracleous et al. 2012).

References:

- Badenes & Maoz 2012, ApJ 749, L11
- Benjamin et al. 2012, ApJ 744, 119
- Cuntz, 2013, arXiv:1303.6645
- Eracleous et al. 2012, ApJS 201, 23
- Fabian 2012, ARA&A, 50, 455
- Kilic et al. 2012, ApJ 751, 141
- Kruse et al. 2010, ApJ 722, 1352
- Maoz, Badenes & Bickerton 2012, ApJ 751, 143
- Milosavljevic et al. 2002, MNRAS, 331, L51
- Raghavan et al. 2010, ApJS 190, 1
- Valtonen et al. 2008, Nature 452, 851

4.3 Cost-free Supernova Surveys

Supernovae are critical probes for mapping out the cosmos, and they are also important in understanding the origin of the heavy elements in the Universe. Despite their astrophysical importance, several fundamental issues about supernovae remain unknown. These include the progenitor population(s) and the explosion mechanism of Type Ia supernovae. These issues can be addressed by studying supernovae in low redshift galaxies ($z < 0.2$) and measuring supernova rates and delay time distributions as a function of galaxy type.

Any large-scale galaxy evolution survey that obtains enough spectra with moderate to high S/N can be mined to identify the galaxies that are hosting SNe when the data are collected, resulting in a virtually cost-free SN survey. This has the crucial advantage that it provides the SN discovery, plus a spectrum of both the SN and the host galaxy at the same time, so that SN rates and delay time distributions can be calculated without the need for additional observations. An illustration of this approach is the recent study of Graur & Maoz (2013) which found 90 Type Ia SNe among 700,000 galaxy spectra in SDSS, and used these identifications to derive values for the Type Ia SN rate and delay time distribution, obtaining one of the more accurate data points at low redshift available today (Figure 4.2).

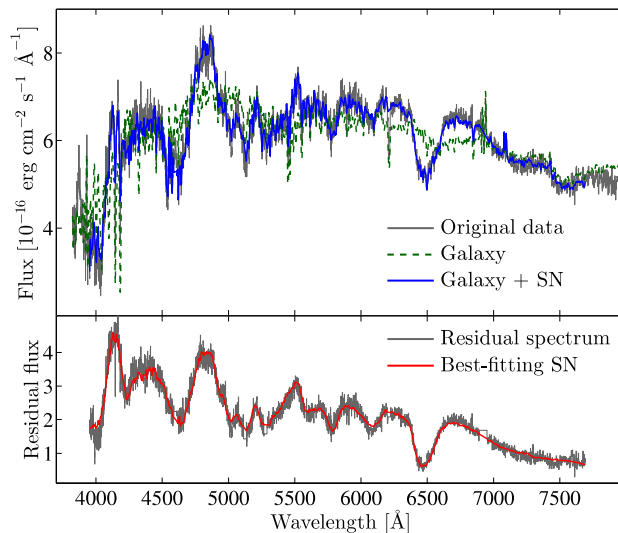


Figure 4.2: A SN Ia discovered in the SDSS galaxy spectrum 0424-51893-355 (plate-MJD-fiber) at $z = 0.054$. Top: the original galaxy spectrum (grey) is fit with a galaxy model (dashed green) composed of ten eigenspectra, resulting in $\chi^2_r = 7.6$. When fit with both eigenspectra and transient templates (solid blue), a SN Ia template produces $\chi^2_r = 1.1$. Bottom: residual spectrum (grey) produced by subtracting the galaxy model from the original data. The best-fitting SN Ia template is shown in red. Figure from Graur & Maoz 2013.

BigBOSS would open a much larger discovery space for this kind of cost-free SN survey, and probe SN rates and delay time distributions in different redshift regimes, which could only be achieved by traditional SN surveys by setting up a SN discovery and follow-up program at a considerable cost in resources. One approach would be to target nearby

galaxies with the several million “community fibers” that will be available in the BigBOSS Key Project survey. The Key Project integration times (15 minutes for emission line galaxies; 30 minutes for luminous red galaxies; http://bigboss.lbl.gov/CH_3.html) are well matched to the required integration times. A sample size that is 5-10 times that of the Graur & Maoz (2013) study would yield ~500-1000 Type Ia SNe, which would allow us to study progenitor demographics as a function of galaxy type.

4.4 Reverberation Mapping

Central supermassive black holes occur commonly as an outcome of the formation of massive galaxies. Moreover, the correlation between black hole and stellar bulge masses suggest that galaxies acquire their stellar and central black hole masses in a coordinated way. Detailed studies of AGN, which are powered by gravitational accretion onto supermassive black holes, allow us to explore how and when black holes achieve their masses, the origin of the relation between black hole and stellar bulge masses, and the nature of accretion and outflow processes in the vicinity of the AGN (e.g., the broad line region; BLR).

The measurement of black hole masses and the kinematics of BLR gas plays a central role in addressing these questions. While the BLR subtends small angular sizes (microarcsecond scales even in nearby AGN), the structure and kinematics of this region can be studied by observing the response of the broad emission lines to changes in the nuclear continuum, i.e., using reverberation mapping. By monitoring AGN spectra on timescales of months, we can measure the time delay between variations in the continuum and emission lines. Interpreting the time delay as the light-travel time between the continuum source and the BLR, we can infer the distance R of the line-emitting gas from the central source, which can be used to infer the black hole mass:

$$M_{\text{BH}} = f R \Delta V^2 / G$$

Much of the reverberation mapping work to date has focused on obtaining the average time delay (integrated over the line), which allows us to infer the mean distance of the emitting gas from the continuum source given an assumed value of the “ f ” factor. These studies demonstrate the diagnostic power of this approach and the potential for future, more extensive and more detailed, studies.

The reverberation mapping samples that have been studied to date are small (~50 systems), heterogeneous, and not representative of the general quasar/AGN population. The current samples emphasize low redshift ($z < 0.3$) and poorly sample high luminosity quasars (see review by Shen 2013/arxiv:1302.2643). This limitation makes it problematic to use relations calibrated with current samples to characterize high redshift or high luminosity QSOs. Future studies that sample a more representative range of AGN over a wider range in redshift would therefore be extremely useful in characterizing central black holes in AGN, their evolution, and their environment.

Another concern is the poorly understood structure and dynamics of the BLR, which limits the accuracy of black hole mass measurements. Physical caveats of this kind are believed to introduce systematic biases of a factor of a few, although current samples are too small to explore the diversity in BLR structure (Shen 2013; arxiv:1302.2643). The current observational frontier in this regard is to measure the time lag as a function of velocity (the “velocity delay map”), which describes how the BLR responds to a delta-function outburst (as a function of velocity and time-delay) and thereby probes the BLR geometry and kinematics. It also allows us to infer, rather than assume, the “ f ” factor and thereby reduces the systematic error in black hole mass measurements.

Numerical simulations illustrate how velocity delay maps can be recovered from high signal-to-noise (~ 100 ; continuum and line variations are a few percent), moderate resolution spectroscopic observations ($R > 500$; Peterson & Horne 2004, astro-ph/0407538). Current work suggests that some BLRs are dominated by rotational motion, while others show signatures of infalling or outflowing gas (e.g., Bentz et al. 2010, ApJ, 720, L46; Grier et al. 2012, ApJ, 764, 47).

A Community Science Project

A survey of large numbers of QSOs and AGN could be carried out using community fibers and/or archival observations of the BigBOSS Key Project calibration fields. These could target known AGN or those discovered by the BigBOSS Key Project. Velocity delay maps could be constructed for bright targets with high s/n spectra. Time lags could be measured for fainter targets with lower s/n spectra. Because calibration data will be obtained over the lifetime of the Key Project (5 years), these observations would sample the long timescales needed to study the properties of high luminosity systems, which have larger BLRs. Weekly observations would probe the properties of lower luminosity systems.

Selecting targets in fields that have been studied spectroscopically and for which multiwavelength data are available would allow the reverberation mapping results to be connected with spectral energy distributions, host galaxy morphologies (from high angular resolution imaging, e.g., HST), and other AGN properties. The BigBOSS Key Project calibration fields fulfill these criteria (e.g., the NOAO Deep Wide-field Survey, the COSMOS field). Each calibration field (~ 7 square degrees) would contain numerous AGN. For example, in the 9 square degree NDWFS Bootes field, the AGES survey measured redshifts for 4764 quasars and galaxies with AGN signatures (Kochanek et al. 2012). AGN were selected as radio, X-ray, IRAC mid-IR, and MIPS 24 μm sources to a limiting magnitude of $I \sim 22.5$ for point sources. Of this sample, 2926, 1718, 605, 119, and 13 were found to be above redshifts of 0.5, 1, 2, 3, and 4, respectively (Kochanek et al. 2012).

Regular monitoring of the calibration fields with the appropriate cadence would yield black hole masses and BLR geometries and kinematics for an unprecedented number of

QSOs over a wide range in redshift. While accompanying broad-band continuum monitoring is normally required, the combination of the targeting imaging and the precise calibration of the BigBOSS instrument will allow simultaneous monitoring of the continuum, line fluxes, and line widths from purely spectroscopic data.

5. Stellar Activity and Planetary Systems

Jennifer Johnson and Joan Najita (with thanks to Marc Pinsonneault, Travis Metcalfe, Savita Mathur, Sarah Schmidt, and Rafael Garcia)

Summary

Studies of stellar activity have the potential to address fundamental questions about the nature of stars and exoplanets. As described below, characterizing stellar activity (as a function of time and stellar mass) lends unique insight into the *nature of stellar dynamos* and provides a *cosmic context for the eleven-year activity cycle of our Sun* (Sections 5.1, 5.3). Because stellar activity introduces radial velocity jitter and photometric variability, characterizing stellar activity levels (time average and its range of variation) improves current observational estimates of the *frequency of exoplanets*. Our understanding of stellar activity (both time average and short-term flaring behavior) and its associated UV radiation also impacts directly on our understanding of the *habitability of planetary systems* (Section 5.2). Because stellar activity may be enhanced in stars with close-in giant planets, studying the stellar activity of such stars may also provide a unique opportunity to investigate the *magnetic fields of exoplanets* (Section 5.4). Finally, as one of the few available *age indicators for field stars on the main-sequence*, calibrating stellar activity as a function of stellar age facilitates a host of other astrophysical investigations (Section 5.1). We describe below example studies that make use of the highly multiplexed spectroscopic capability of BigBOSS to probe activity in large samples of stars in the **time-domain**.

Background

At birth, cool stars (FGK) stars have dynamic, active atmospheres, marked by a large number of starspots, chromospheric and coronal emission. There are strong observed correlations between observational diagnostics of activity and stellar color, rotation, and age. These correlations reflect the origin of stellar activity in the interaction of convection, rotation, and magnetism. The observed pattern of stellar activity therefore serves both as a diagnostic of stellar physics and a marker of stellar mean properties, such as mass and age. For example, activity is an age diagnostic because it is related to rotation, which in turn declines with age as stars lose angular momentum in magnetized winds. There is also important information in the mass dependence, typically parameterized by the Rossby number (a ratio of rotation period to convective overturn timescale.) There should be a transition between solar-like stars with radiative cores and an interface dynamo and fully convective M dwarfs, where a turbulent dynamo is required to generate the magnetic field; but any signature in the activity data is subtle if present at all. As the Maunder minimum in the solar cycle dramatically indicates, the activity of stars is not constant even over short timescales. Understanding the activity of stars is therefore crucial for understanding the evolution of the dynamo and its connection with rotation and convection. More practically, this understanding is important for knowing the fraction of stars around which planets can be detected in transit surveys and as an age indicator for field stars.

An R~2000-4000 spectroscopic survey of tens of thousands stars for CaII H&K and H α emission lines would address a variety of astrophysical questions. Some questions require long-term monitoring of a smaller sample, while others require snapshot data for a larger sample. Spectroscopic measurements of emission in the cores of strong lines have been shown to be robust measurements of activity in stars, and have been used for ground-breaking studies of activity/age/rotation (e.g. Mamajek & Hillenbrand 2008 ApJ, 687, 1264; West et al. 2008). They are noticeably easier than photometric variability measurements of activity and less susceptible to systematic effects such as inclination.

5.1 How active are stars? Is the solar neighborhood representative? What is the length of the activity cycle?

The Mount Wilson survey of 1296 stars and other smaller such surveys of solar-type stars found trends between activity and mass and activity and age. However, these surveys are confined to nearby, bright stars and stellar clusters (e.g. Duncan et al. 1991, Mamajek & Hillenbrand 2008) Therefore the range of stellar parameters, such as metallicity, which is important for affecting the depth of the convection zone, is small. With missions such as Gaia providing metallicities and kinematic information for stars brighter than V=17, interesting subpopulations can be identified for activity follow-up.

Another important question is the length of the stellar activity cycle for different stellar masses, including the question whether all stars have a steady cycle, how common Maunder minimum periods are and if there are equivalent periods of high activity. Most current investigations are like that of Lubin et al. (2012, ApJL, 747, 32), based on small samples (e.g. 500 stars) confined in stellar mass/age/metallicity parameter space and based on single observations.

The largest sample of stars studied for activity is the ~50,000 M dwarfs observed spectroscopically by SDSS (e.g. West et al. 2008). By examining the H-alpha fluxes, they determined age-activity relations for a wide range of M spectral types. However, each M dwarf is observed only once, so all information is gained statistically, with proxies such as scale height used for age and metallicity.

The expected history of stellar activity as a function of stellar type is tied to the question of the detectability of planets. High levels of stellar activity make it more difficult to detect planets by transits or radial velocity studies (e.g. Bailey et al. 2012 ApJ, 749, 16, Mazeh et al. 2013, ApJS, submitted). The transit timing variations thought to be detected around WASP 10-b and to indicate the presence of another planet (Maciejewski et al.) were shown by Barros et al. 2013 (MNRAS 430, 3032) to likely be the result of stellar activity instead. Therefore, a more complete knowledge of stellar activity, both theoretical and observational, will permit the correct evaluation of the frequency of planets around stars based on their detectability and the improvement in future transit studies by allowing more precise targeting across the HR diagram.

5.2 How does activity affect the habitability of planets?

Planetary habitable zones vary with spectral type, and are quite close to the parent star for M dwarfs. High levels of UV flux, associated with high levels of stellar activity including flares, can seriously impact the actual habitability of these planets (e.g. Heath et al. 1999). UV flux and flares are both associated with youth (< 1 Gyr) in M dwarfs (Hilton et al., AJ, 140, 1402). It is important to know if flaring is associated with high H-alpha emission, so that we can know from a single spectra if a planet in the habitable zone is safe from large amounts of UV radiation and to assess the statistics of habitability. To date, there has been no large-scale follow-up of flaring stars to identify their “normal” levels of H α activity. Such a spectroscopic follow-up of photometrically identified stars (e.g. Walkowicz et al. 2011) would be very valuable.

In addition, the association of age and UV activity was done statistically on the basis of height above the plane. To detect the frequency of real outliers in this relation, individual ages are needed, such as those provided by rotation periods and H α measures. Such a check could detect abnormally high activity periods among old, normally quiescent M dwarfs, proving that flare stars are not always young, and be important for assessing the long-term habitability of M dwarfs.

Finally, calculations of the climates of exoplanets have become increasingly complex and better reflect the actual habitability of planets. Kopparapu et al. (2013, ApJ, 765, 131) recently updated models for planets including the entire spectral energy distribution (SED) for stars and advocated using actual stellar incident flux rather than equilibrium temperature to correctly assess the temperatures of planets. However, they used stellar atmosphere model calculations, which do not have any chromospheric emission present, despite its effect on the star’s SED. An empirical measurement of activity is therefore globally important for understanding planetary atmospheres.

5.3 How are rotation and activity connected?

Since at least Kraft (1967, ApJ, 150, 551), high rotation has been known to be connected to high activity in general. Many specifics, however, are unknown, such as how likely it is for a star to be a highly-active slow rotator or an inactive rapid rotator. Independent measurement of surface rotation from photometric monitoring of starspot movement could confirm that active M dwarfs without spectral line-broadening are the result of an inclination effect (Browning et al. 2010, AJ, 139, 504).

For late M dwarfs, the connection between rotation and activity appears to break down, based on a sample of 14 stars (West, et al. 2009, ApJ, 693, 1283), which must be explained by any explanation for the source of activity in M stars. In another example, Reiners & Giampapa (2009) argue that high levels of activity seen in two M67 stars, despite their relatively old ages, are the result of rapid rotation rather than large excursions away from “normal” activity. A large sample of stars with both rotation and activity measures will explore this correlation for solar type stars and cooler and identify the fraction and types of stars for which rotation and activity are not correlated. In

addition the importance and threshold for rotation-induced activity will be identified and used as input for dynamo models.

5.4 How are planets and activity connected?

There is tantalizing evidence that planets have an impact on stellar activity. Models for such influence depend on the magnetic field of the planet; indeed the appearance of stellar activity is the only current way to examine the magnetic fields of hot Jupiters (e.g., Lanza 2008, *A&A*, 487, 1163). The existence of a planetary magnetic field can provide insight into the internal composition of the planet. For example, Jupiter's magnetic field is generated by currents in its outer core of liquid metallic hydrogen.

Krejcová & Budaj (2012 *A&A* 540 82) found that the activity parameter $\log R'_{\text{HK}}$ had a broader range for stars with close-in planets. For cooler stars, close-in planets were associated with higher activity levels in a statistically significant manner. However, their sample size was ~ 200 stars in snapshot mode and other studies have not found similar results. This situation could be clarified with longer term monitoring and an increase in sample size.

Very high-quality data for a few nearby stars have shown a more direct connection between hot Jupiter and star: the period of stellar activity variations, as measured by the CaII H&K lines, is tied to the period of the planet (e.g. Shkolnik et al. 2003, 2005, 2008). These results suggest that a magnetized close-in giant planet can induce activity on the surface of its host star. The signals are quite small in the systems in which a connection is found. However the dissipated power is expected to be a function of the magnetic field strengths of both the star and planet (Lanza 2009), so an extensive survey of planet-hosting stars could reveal cases of a much stronger impact on stellar activity. The results of such a survey would provide excellent data for our understanding of planet and stellar magnetic interactions, particularly in light of the recent advances in understanding stellar magnetic fields from polarimetry (e.g., Reiners, 2012, *Living Reviews Of Solar Physics*, 8, 1)

In summary, stellar activity studies have been limited in sample size, target coverage, or both. None of the current missions will be able to measure activity spectroscopically, either because they are photometric or because their limited spectroscopic range does not cover H-alpha and CaII H&K (e.g. Gaia). Spectroscopic information is highly desirable in addition to photometric observations of variability because it is sensitive to lower levels of activity and can be obtained for large samples of stars using a single spectrum taken in snapshot mode. For example, the Sun has measurable CaII emission in the Mount Wilson survey (Baliunas et al. 1995, *ApJ*, 438, 269) although it is a very inactive star by photometric standards.

Proposed Survey

The BigBOSS resolution and sensitivity is sufficient to determine activity in cooler stars at a similar level to the Mount Wilson survey. Therefore, we will be able to determine

quantities such as S and $\log R'_{\text{HK}}$ (Noyes et al. 1984) that have been successful in measuring stellar activity (e.g. Duncan et al. 1991, *ApJS*, 76, 383; Metcalfe et al. 2007)

While many fields are possibilities, we single out looking at activity in the *Kepler* field because it will have the largest sample of

- Extremely precise lightcurves for stars. Understanding these data requires understanding the frequency and magnitude of activity. Such light curves have also been used to detect flaring stars (e.g. Walkowicz et al. 2011) for analyzing questions about planet habitability.
- Transiting planets, including ~500 hot Jupiters (Santerne et al. 2012).
- Rotation periods based on sunspot effects on the lightcurves. Periods for some M dwarfs (McQuillan et al. 2013) and solar-like stars (e.g. Garcia et al. 2012, *ASPC*, 462, 133) have already been determined and the sample size is growing steadily.
- Asteroseismic measurements of stellar structure, such as depth of convection zone, interior rotation, and age in a sample of ~500 solar-like stars. Correlations between these observations and observed amounts of chromospheric emission, for both active and inactive stars, will provide new information on the properties that are important for the operation of the solar dynamo (e.g. Karoff et al. 2009, *MNRAS*, 399, 914, Hekker & Garcia, 2012, *AN*, 333, 1022).

Therefore, we will know an impressive amount about many stars in the *Kepler* field, including rotation period, occurrence of white-light flares, composition, age, kinematics, as well as the more basic temperature and gravity. In special cases, we will have extraordinary views of the interiors of stars thanks to asteroseismology. These data provide an incredible physical backdrop to understand stellar activity and flaring.

Presently there is no attempt to get spectroscopic measures of activity, notably the CaH&K line and H α for these stars. The *Kepler* satellite observes such a large number of stars by observing a large field of view. The 105 square degrees from which *Kepler* draws its targets makes many traditional multi-object spectrographs ineffective. The 7 square degree field of view of BigBOSS matches well with the individual *Kepler* tiles; therefore ~20 BigBOSS fields can cover the entire *Kepler* field.

The target density in many cases is well-matched to the number of fibers available on BigBOSS. For example, with ~90,000 solar-type stars targeted (Batalha et al. 2011), there are ~800 targets per square degree.

Optimistically, ~20,000 of these solar-type stars will have rotation ages, but at least a few thousand will definitely, along with several hundred stars with asteroseismic information.

Magnitudes for these stars targeted by *Kepler* reach $g \sim 16$ mag, although there is an emphasis on brighter stars to enable radial velocity follow-up and to detect asteroseismic

oscillations. (e.g., Batalha et al. 2011). The BigBOSS exposure time calculator estimates that a G2V star at $g \sim 16$ mag would reach $S/N=100$ per pixel at 3900Å in 4.5 hours for grey time and 13.5 hours for full moon. A S/N of 100 at this resolution is the quality of data used for CaH&K observations (e.g. Metcalfe et al. 2007) and is superior to the data for the H α surveys from the SDSS group (e.g. West et al. 2008). We note that $S/N > 100$ throughout the spectra will also result in spectra that can be used for measuring stellar properties, such as metallicity, temperature and gravity. This is important because the information from Gaia about stellar parameters and metallicities decreases rapidly in accuracy for stars below $V=12$. Therefore using the experience of the SEGUE survey, for example, to determine the characteristics of the fainter stars will be very important (e.g. Lee et al. 2008).

One possible scheme is a 20-night (in total time) campaign per year in grey time to get a snapshot of most of the stars monitored by *Kepler*, observing an average of 1 field per night under conditions between grey and full moon. With these data, we could answer several of the questions posed above. We could investigate if the flare stars identified in the *Kepler* field are correlated with large amounts of H α emission and develop a more appropriate SED for planet atmosphere modeling. We can consider the connection between rotation and activity across the H-R diagram, including identifying slow rotators that are active, determining if the correlation depends on composition, and identifying the spectral types where rotation and activity are not correlated. We could compare the activity in stars with a variety of solar systems, including systems with and without hot Jupiters, to investigate the connection between stellar activity and the nature of the surrounding solar systems.

For the questions that require long-term monitoring, we can begin a time series investigation by spacing out the above observations over the course of 1-2 months in ~ 1 hour observations. We could then continue long-term monitoring of fewer stars, focusing on the bright stars in a more limited number of fields in bright time. These data would continue the exploration of planet habitability by assessing the cycles of stellar activity and the excursions to high (and low) activity levels. Such data are also important for understanding the stellar dynamo and in placing the Sun's activity in the context of the broader range of stellar activity.

These observations could be used to identify the systems with the strongest evidence for star-planet magnetic interaction. These systems could be monitored with BigBOSS and handed off to other facilities for intensive follow up. To assess the variability on a variety of timescales, both closely-spaced observations, as well as observations covering ~ 10 years would be appropriate. Thus over 10 years, this would be a 200 night program.

The longer term monitoring campaign would likely not use all the fibers. Remaining fibers could be used to measure radial velocities and stellar parameters for $V \sim 17-18$ stars in the *Kepler* field to complement the parallaxes and, more particularly, the proper motions of Gaia. We could also observe some of the 40 million stars in the field that have not been observed by *Kepler* for additional stellar activity information. An example would be observing relatively bright M dwarfs, as the sample in *Kepler* is not extensive,

and long-term spectroscopic monitoring of H α in bright M dwarfs has not yet been done. An expanded sample of these would, therefore, provide new insights into the nature of the source of the activity in these fully convective stars.