Astro2020 Science White Paper

The End of Galaxy Surveys

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

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Abstract:

Over the course of the next decade, optical and near infrared (NIR) sky surveys will reach increasing depths over much of the sky. Here, we examine the long term 'end game' of this progression. We advocate for defining a path to **end the era of galaxy surveys** by making the definitive measurements of the galaxy population in the optical/NIR, thereby creating a map of galaxies (and their associated dark matter) throughout the entire visible universe, from the dawn of the first galaxies a mere 500 million years after the Big Bang to the present day, more than 13 billion years hence. We advocate for studies that would define the (spatially unresolved) spectroscopic and (resolved) photometric measurement and survey capabilities needed to answer all current and anticipated questions relating to the large-scale structure (LSS) of the universe and the evolution of galaxies and their dark matter halos as probed by statistical measurements of galaxies. We also identify some of the technologies that would need to be developed to make this ambitious goal tractable over the next few decades.

I. Measuring All of the Galaxies

In the coming decade, *WFIRST*, *Euclid*, and LSST will measure the shapes and low-resolution spectra of ~2 billion galaxies. Although impressive, this represents only ~1% of the galaxies in the ~140 billion galaxies in the visible universe, as scaled up from observations of the Hubble Ultra Deep Field (HUDF), depending on how one defines a galaxy[1]. Additionally, *JWST* will give us the first views of the dawn of galaxies through its deep, needle-point field of view. These observations will lead to profound and transformative discoveries in astrophysics and cosmology, but will not exhaust all of the information content potential in deep galaxy optical/NIR imaging and spectroscopy. Here, we advocate for a study of the optical/NIR surveys and corresponding instrumentation advances that would be needed to bring the era of large optical/NIR surveys to its *conclusion*, in the sense that there would be no additional useful information about large scale structure (LSS) and the bulk properties of galaxies and the dark matter halos they reside in to be gained from further imaging or unresolved spectroscopy at these wavelengths. Put simply, we propose to study what it would take to essentially exhaust the information content of galaxy surveys. Other white papers may propose what the *next* galaxy survey is; we seek to understand what the last galaxy survey might be.

Making maps of the universe is a long-standing driver for cosmology. Over the past half century, CMB experiments (COBE→WMAP→*Planck*) have measured the temperature fluctuations of the residual radiation from the Big Bang to increasingly high precision over the entire sky. With *Planck*, essentially all the statistical information about the early universe that can be extracted from maps of the primary temperature fluctuations imprinted on the CMB 300,000 years after the Big Bang has been extracted. CMB cosmology from temperature fluctuations has thus been brought to a formal conclusion: while there is still significant information to be extracted from the CMB (e.g. from polarization), the era of CMB experiments motivated by temperature measurements of primary anisotropies is over. **In this paper we propose a path for the 2020s that would see the full formulation and justification of a multi-decade program that would, by analogy, culminate by extracting essentially all the information there is from the positions, shapes, and optical/near infrared unresolved spectra of galaxies in the universe.** As with the end of the era of CMB temperature maps, this would bring to a logical close this modern era of galaxy survey measurements and produce a data set with wide ranging applicability to a huge array of astrophysical and cosmological questions.

Surveys conducted with wide-area telescopes in the optical/NIR have proven to be the most efficient means for both measuring the photometry and redshifts of galaxies. Redshift surveys have increased in scale by a factor of 10 every 10 years, with planned projects expected to deliver ~30 million galaxies in the 2020s (see Figure 1). While we acknowledge that observations in other wavelengths using different technology will play a key part in unlocking the secrets of the universe in the coming decades, in this paper we consider those questions of galaxy evolution and cosmology which can be answered via spatially unresolved spectroscopy and broad-band photometry in the optical/NIR. We choose these measurements given that only a small fraction of the visible universe has currently been mapped in these properties and that many current scientific questions can be addressed via these measurements. Below, we outline a few scientific goals that

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[1] If one includes the smallest early progenitors of current galaxies (the second of our tiered surveys described below) and satellite galaxies (the third of our tiered surveys) the number of ‘galaxies’ could be many more than the ~140 billion number used here.

would help drive a survey strategy and the technology path that would enable it; however, we fully expect that the data sets derived from implementing this would have wide and far reaching applicability, just as is expected for the data from the aforementioned survey missions.

II. Galaxy Regimes

For the purposes of considering the “end-game” of optical/NIR galaxy imaging and spectroscopic surveys, we consider two complementary survey strategies: all-sky and deep/narrow. This informs the observational strategies and technological capabilities needed to study phenomena over scales from individual galaxies to the whole sky.

A. Large-Scale Measurements of Cosmic Structure and A Census of Ultra-Faint Dwarfs in the Local Universe (All Sky)

Cosmic Structure: Precise measurements of distances secure 3D positions and an appropriate imaging resolution secures accurate galaxy shapes. By having this information for *all* accessible galaxies to a faint magnitude limit, we can trace the evolution of the cosmological structure across all environments and all masses of self-bound galaxy or galaxy-cluster dark matter “halos.” There is at least as much unexplored cosmological information in the large-scale structure as that from current galaxy surveys, according to our best understanding of general relativity and the initial conditions of the universe. This is especially true for under-dense regions of the universe, which are limited by the paucity of bright tracers of the underlying matter distribution. The scientific prizes in mapping and interpreting such a broad dynamic range of structures include tests of dynamical dark energy and corresponding extensions to the standard models of particle physics and gravitation, cosmic inflation scenarios for seeding density perturbations, primordial black hole populations, neutrino mass hierarchies, and the particle nature of dark matter. These prizes may only be won with a complete accounting of structure formation and with measurements of large-scale density perturbation modes within our horizon up to the cosmic variance limit.

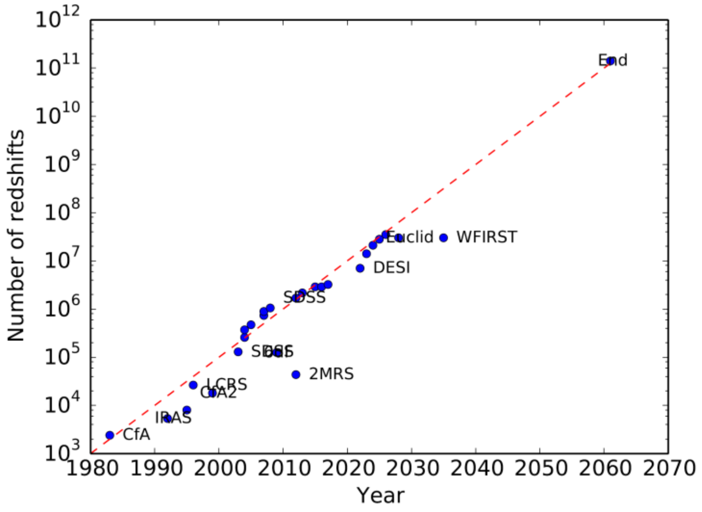

Figure 1: Spectroscopic redshifts as a function of year. The number goes up be a factor of 10 every decade.

For this tier, we envision covering the entire extragalactic sky at depths and resolutions that would allow galaxies to some (to be defined) magnitude limit to have shapes and (at least) photometric redshifts and possibly spectra to be measured. Figure 1 shows that several decades of experience indicate we may be on track to measure 140 billion spectra by the 2060s, a reasonable timescale for a goal this ambitious. We advocate for a limited scope research program in the near future that would calculate the magnitude limit needed in order to exhaust the information content of galaxy shapes for LSS measurements. While it is by no means clear that the best path forward for cosmology and LSS beyond DESI/Euclid/WFIRST/LSST is more galaxies, more depth, or more area, we do advocate for a deeper understanding of how much information could be achieved by these methods and what surveys characteristic would be needed to acquire it.

Local Universe: A second science objective of an all-sky survey consists of a comprehensive census and structural characterization of so-called ultra-faint satellites of galaxies out to more than 100 million parsecs, to distances where universal expansion overcomes our local neighborhood's self-gravitating properties. Information about the reionization mechanisms, as well as other aspects of galaxy formation is encoded in the cutoff mass below which dark matter halos no longer host galaxies. Further, these ultra-faint dwarfs are dark matter dominated, making them the ideal candidates measuring signatures of the microscopic nature of dark matter. While such studies are underway for the Milky Way itself, a detailed study of these satellites in a large fraction of the local universe will provide us with a statistically significant sample with respect to both the actual ultra-faint satellites, as well as host properties. Again, the fraction of the local universe that needs to be probed in order to close out these lines of study is an open but tractable question. An all sky survey as proposed here may have a depth and resolution driven by this science goal rather than LSS. Moreover, telescopes with extreme sensitivity to low-surface brightness objects may be more demanding from what is needed for LSS studies.

B. Early Universe Measurements (Narrow and Deep)

The observational strategy for the early universe (z~6-20) requires a different and complementary survey from the 'all-sky' component of our proposed end-game. The guiding principle here would be to define the combination of depth of and area such that the smallest early galaxies would be detected, while simultaneously covering an area that fully captures the LSS, statistics, and variety of environmental conditions relevant to early universe physics and the formation and evolution of galaxies and their dark matter halos. This leads to a need for substantially deeper photometric and spectroscopic surveys. Such surveys need cover a modest fraction of the sky because the volume probed at high redshift is sufficiently large over a much smaller area. We estimate the required area to be ~1-5% of the sky, with the caveat that a more detailed study is needed to pin down this number. We further advocate for spectroscopic measurements in this same 'deep survey' as described in the following section.

A dense, representative sample of the galaxy population reaching to z~9 would not completely solve all the outstanding puzzles in the formation and evolution of galaxies. However, large surveys like SDSS have, historically, had great impact on galaxy evolution. Galaxy populations change qualitatively in the early universe, and a similarly complete census at higher redshift should be expected to have a similarly transformative impact. In particular, the Last Survey would:

- determine the distribution and evolution of vital statistics such as galaxy sizes, luminosities, morphologies, and masses
- determine the star formation rate over cosmic time
- map the relative influence of feedback from AGN and star formation
- fix the connection between galaxies and dark matter
- map the environmental dependence of galaxy properties
- constrain the metal enrichment history of stars, the IGM, and the CGM
- measure the buildup of dust over cosmic time
- constrain the growth of supermassive black holes in the centers of galaxies

III. Summary of the Science Drivers

As outlined above, creating a map of the galaxies in the entire visible universe will likely settle fundamental problems in cosmology (like the nature of the dark matter and dark energy that make up 95% of the universe) and galaxy evolution (like the origin of stars and heavy elements). While even a complete map may not fully resolve these problems, it will exhaust galaxy shapes and unresolved spectroscopy (in the optical and NIR) as a source of information; *future studies* *would have to find fundamentally new ways to probe these questions*. We advocate for fleshing out the aforementioned complementary strawman surveys to accomplish the goal of creating a complete map of the mass in the universe. The first survey measures the whole sky to retrieve mass density information (via weak lensing measurements of galaxy shapes) for a large fraction of the universe and detailed information about dwarf galaxies in a representative fraction of the local universe. If the progression in Figure 1 proves unfeasible to sustain and true spectra are not universally available, each galaxy would need a photo-z. These distances would ideally be calibrated with a huge and representative spectroscopic redshift sample either through cross-correlation analysis or direct calibration. Therefore, there would be a minimal spectroscopic component of this program in addition to deep broad-band imaging. For a representative fraction estimated to be 1-5% of the sky, we advocate for the acquisition of higher-resolution spectra and high-resolution morphologies to return additional chemical or dynamical information of the measured galaxies.

IV. Building on a Previous Study

In August, 2018 some of the authors of this paper participated in a one-day JPL "A-Team[2]" study to assess the feasibility of "measuring all the galaxies," and exploring what that in fact means! The first take-away was that the concept needed to be better defined, starting with establishing what is the smallest collection of stars that constitutes a "galaxy." Furthermore, some of the sky is obscured by our own Milky Way and thus all galaxies are not accessible to observation. Thus, we have shifted the focus here to define the path to the end of the era of galaxies being studies as probes of the structure and content of the universe. This A-Team study gave us confidence that there is a technical path toward making these measurements. We are of course helped by a peculiarity of General Relativity whereby the angular sizes of galaxies do not continue to shrink as we observe them farther away; rather, they asymptotically reach a minimum size that can be resolved with reasonable sized apertures. However, to collect the photons needed for the ambitious surveys outlined above in a ~5-year mission lifetime, we estimated that we would need either a ~60m aperture space telescope, or a fleet of a dozen 4+m-class space telescopes, each with focal planes that measure in *square meters* instead of square centimeters, and with trillions of pixels. Of course, having serviceable space telescopes with lifetimes measured in decades would relax some of the collecting area requirements. Another challenge lies with how to multiplex the necessary spectroscopy of tens of thousands of objects. Getting the data back to Earth (and processing it) were also identified as challenges. A further challenge is that the telescopes would need to be efficient survey instruments, whereas large space telescopes (e.g. JWST) generally require large amounts of fuel and time to perform a traditional step-and-stare style survey. These ambitious objectives would entail the need to develop fundamentally new technology and techniques for the space telescopes and their deployment.

As a strawman we consider 10m space telescopes, with a resolving power of 0.02''. This is sufficient to measure shapes of galaxies with $R_e > 1.25 * \text{FWHM}$ of the PSF, or $R_e > 0.06''$, which corresponds to a physical effective radius of 500 pc at z=3. We estimate galaxies of this size have mass $\sim10^7$-$10^8\ M_\odot$ at z~3, based on extrapolating the mass-size relation from, e.g., van der Wel et al. 2014 and examining the local universe relations in Lange et al. 2014 from the Galaxy and Mass Assembly (GAMA) survey. To reach this stellar mass limit at z~3 a depth comparable to the HUDF is required; at this point virtually all of the information at all scales that can be extracted from galaxy shapes would be exhausted to this redshift, corresponding to 85% of the history of the Universe. Of course, fully answering the question of what survey would exhaust the information

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[2] https://jplfoundry.jpl.nasa.gov/

content in galaxy images and spatially unresolved spectra would have to be the subject of serious study over the next decade.

V. Ambitious Telescope(s)

While this paper is motivated by the aforementioned science goals, we need to understand the technological leaps that will be necessary to achieve them. Measuring precise galaxy photometry, shape and redshifts from any individual galaxy can be done with any number of telescopes today. The challenge is to develop the technologies to do this cost-effectively on the full sky over the next several generations of telescopes. Ten meter class telescopes are more than sufficient in terms of resolving power (with adaptive optics on the ground) for the proposed studies, and it is likely that a combination of ground and space based assets will be needed to close out the era of galaxy surveys. We are advocating here for the technological leaps necessary for space telescopes to do this type of survey, with the caveat that some of this may be best done from the ground. Simply scaling up current ways of building space telescopes will not work for goals this ambitious. As an order-of-magnitude estimate of the photon-gathering power needed to achieve this goal, we use the HUDF as an example. For the all-sky survey we proposed, if we imagine HUDF depth over 30,000 square degrees, this will give us some estimate of the necessary survey characteristics. The caveat here is that the details of each survey would need to be worked out to greater precision in order to fully flesh out mission architectures and technology needs. The HUDF used of order 10^6 seconds on the 2.4m HST to acquire imaging across 8 optical and NIR bands over about 10 square arcminutes. If we want to complete a survey in ~10 years (a reasonable lifetime for a space telescope, but a requirement that could be relaxed with serviceable telescopes), and cover 30,000 square degrees of sky for the widest survey, this would mean we need to be several factors of 10^4 faster than Hubble at collecting photons. This would need to be accomplished via a combination of a (much) larger aperture telescope (or a constellation of telescopes) and much larger focal planes. A telescope with roughly 30 times the diameter of Hubble would give us a factor of ~1000, still requiring another factor of several 10s in increase in focal plane size. Alternatively, a 10m space telescope can match the HUDF depth in ~120 ksec. Assuming such a telescope could be built with a 1 deg^2 focal plane, a 30,000 deg^2 all-extragalactic-sky survey would require 110 years; a fleet of ~ten such telescopes could complete the survey in a little over 10 years. Thus, while amazingly ambitious in scope, such a complete mapping of the visible universe is not impossible!

Achieving the goal of ending galaxy surveys would require major advances in:

- In-space assembly of large structures and/or alternatively the cheap manufacture and launch of multiple 10m class space telescopes
- Extremely large focal planes (perhaps terapixels)
- Massively multiplexed spectroscopic instruments
- Telescopes that combine wide fields, large collecting areas, and fast survey speed
- Data downlink via optical communications
- Processing of extremely large data sets (with onboard processing perhaps alleviating other requirements)

VI. Summary

We advocate that in the 2020s, some thought be given to how we as a community might close out the era of optical/NIR galaxy surveys. The first task will be to define the information content available in then shapes, fluxes, and positions of all the galaxies in the universe. We must then calculate how deep, how wide, and with what spectral and angular resolution we must observe to capture that information. Finally, we need to set out a technology roadmap for the developments needed to make these measurements possible in the coming decades.

References

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