

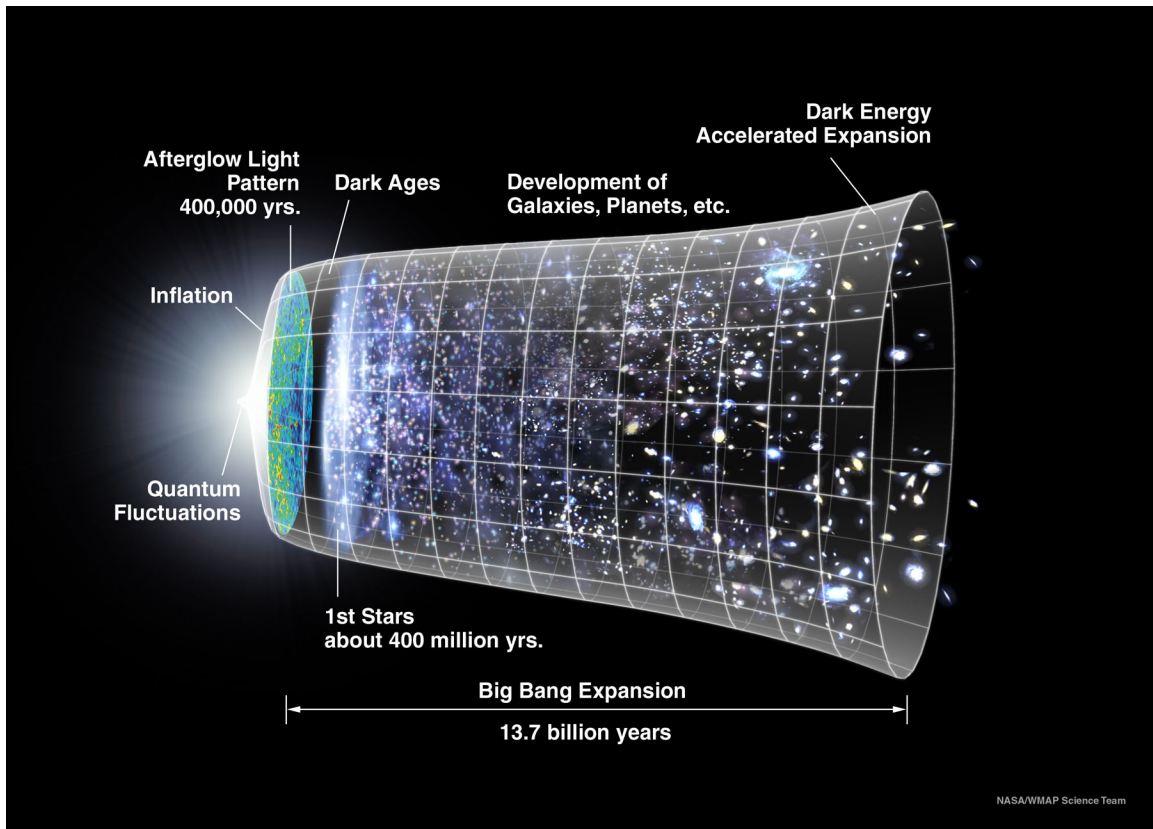
Great Surveys of the Universe

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Schematic timeline of cosmology, courtesy WMAP/GSFC.

GREAT SURVEYS OF THE UNIVERSE

1 Motivation

Looking ahead to the next decade and imagining the landscape of astronomy in 2020, it is clear that astronomical surveys, large and small, plus extensive follow-up projects, will be a great engine of progress in our profession. Surveys have long had a critical role in astronomy, and in the coming decades will be even more central as we probe deeper into the Universe. In fact, one might call the next two decades the “*Era of Great Surveys*”. This next generation of surveys will probe a huge range of astronomical objects and phenomena including planets, stars, gas, galaxies, background radiation, dark matter, dark energy, degenerate matter compact objects, black holes, magnetic fields, cosmic ray particles, neutrinos, gravity waves, and exotica (particles, topological defects, etc.).

Why a Great Surveys Program? The term “Great Surveys” is intended both as a theme as well as a suite of projects. The inspiration is the “Great Observatories” program of NASA and the key space missions *Hubble Space Telescope* (HST), *Compton Gamma-Ray Observatory* (CGRO), *Chandra X-Ray Observatory* (CXO), and the *Spitzer Space Telescope* (SST). We are now enjoying the legacy of the Great Observatories in the tremendous advances that this program has brought to our field. In addition to the four highly visible centerpieces, we have also benefited from a broad and balanced portfolio of small, medium, and large-scale facilities based on ground, sub-orbital, and space platforms, with research in diverse areas ranging from observation and data analysis to modeling and theory.

This case for this decadal review is being framed in terms of “central questions” that are ripe for answering and “general areas where there is unusual discovery potential” that will define the scientific frontier of the next decade based on new scientific opportunities and compelling scientific themes. This Position Paper advocates the overarching theme of a true Survey of the Universe built up of a diverse range of “great surveys” and the exploitation of these surveys. A significant number of the proposed decadal activities and facilities are either explicitly Survey Telescopes or plan to devote significant amounts of time to survey science. Others, such as large aperture narrow field telescopes, are aimed at targeted detailed observations that are a necessary counterpoint or follow-up to surveys.

The Great Surveys Workshop: The Great Surveys of Astronomy Workshop was held 20–22 November 2008 in Santa Fe, NM and was sponsored by the LANL Institute for Advanced Study and Associated Universities Inc. (AUI). This meeting brought together the community to talk about common issues such as scientific goals, survey strategy, telescope and information technology, follow-up observations, coordination of Multi-wavelength resources, theoretical frameworks, simulations, data management, data products, and other cross-cutting problems or solutions. To summarize the spirit of the meeting: “This meeting will bring together the key workers in the field to exchange ideas, and identify areas of cooperation, complementarity, and coordination between surveys and with the greater astronomical community. The vision is for a future where a variety of surveys and follow-up programs are underway and flourishing.” Participants spanned wavelength, technique, research area, and primary funding agency. The agenda and talks can be found online at the conference web-

site ¹. There have been other workshops on similar subjects, e.g. the 2007 KICP Cosmic Cartography Conference².

Disclaimer: The points advanced in this paper are not unique, and to a large part they are due to discussions with the participants in the Great Surveys workshop as well as with others in the field. I do not do this subject sufficient justice here, and in particular I do not provide a proper set of references as it deserves and refer to only a small number of papers I know of or have co-authored myself. There are a number of superior white papers submitted to the Astro2010 science and profession panels. In fact, most the issues presented here are more fully discussed in a other position papers, e.g. [1, 2]. This paper makes use of the more open process for input to Astro2010 that sets this process apart from the previous ones, and to indulge myself in what can be characterized as a “manifesto” of sorts, and as an example of what might be presented by Astro2010 to those inside and outside astronomy on this topic.

2 Great Survey Science Goals

The science goals that motivate great surveys are the same goals that cross-cut all of astronomy and astrophysics. These are represented in the areas defined by the decadal Science Frontier Panels. See the excellent Science White Papers that were posted to these panels for a more complete view of these areas, as well as in reports in the past inter-decade period (e.g. [3, 4]). Some survey-related highlights:

Cosmology and Fundamental Physics: Over the past few decades, observational and theoretical advancements have led to a number of startling conclusions about the physical nature of our Universe, which are encapsulated in a “Standard Cosmological Model”. The cornerstone of this standard model is that the expansion rate of the Universe is currently accelerating (requiring an equation of state with negative pressure, or “Dark Energy”). Long-range gravitational forces are dominated by the Dark Sector: Dark Energy plus effectively collisionless “Dark Matter”.

Observationally, the key measurements are of the expansion history (through its integral, the cosmic distance scale), and growth rate of structure (which is controlled by the expansion history and the equation of state). Large surveys across the electromagnetic spectrum can be used as precision cosmological parameter probes. Great surveys can illuminate dark corners of cosmic time such as during the neutral era (from recombination to reionization), the radiation dominated era, the inflationary epoch, and possibly back towards the Planck time.

Galaxies Across Cosmic Time: Galaxies are the “atoms” of the large scale structure of the Universe, aggregated into the molecular Cosmic Web of clusters and filaments yet retaining identity until merging or dissipating in encounters. We are now discovering the life cycles of galaxies, and a frontier for the coming decade is to peer into the mysterious process of the formation of the first objects.

We also have the opportunity to discover the physiology of galaxies, and understand the inner workings of the “sub-atomic” constituents: the stars, gas, dust, magnetic fields, high-energy particles, black holes, and dark matter.

¹<http://t8web.lanl.gov/people/salman/grsurveys>

²<http://cosmicmaps.uchicago.edu>

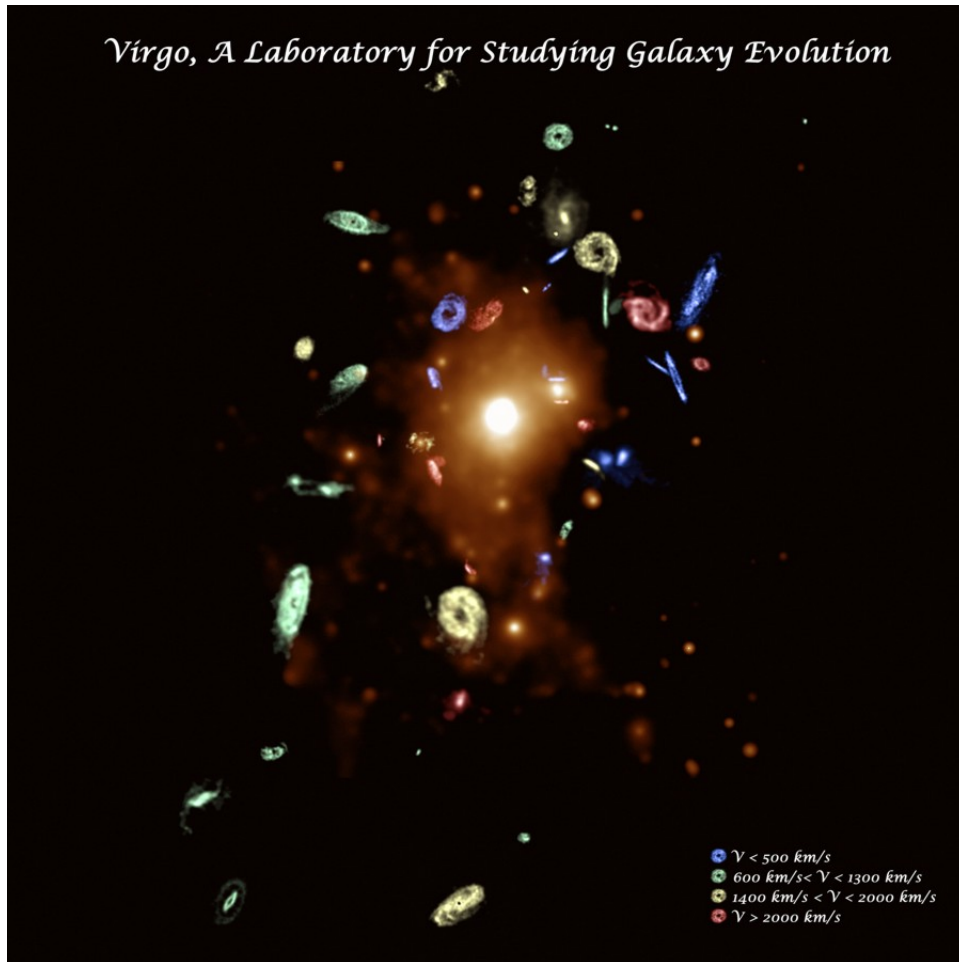


Figure 1: A small-scale Survey of the Virgo Cluster of galaxies. X-ray image from ROSAT overlaid with VLA HI images of galaxies (HI image scale magnified by 10x). This is but one minor example of combining surveys to form a panchromatic view of the sky. Image courtesy of NRAO/AUI and Chung et al., Columbia University.

The Galactic Neighborhood: Our corner of the Universe is in many ways a microcosm of the whole, the understanding of which underpins our view of the macrocosm. The Local Group is the archetype of galaxy groups and thus of galaxy clustering, with the Virgo (e.g. Figure 1) and Coma clusters our nearest examples of larger structures. We now have the possibility of conducting a nearly complete census of our neighborhood across the electromagnetic spectrum. In addition, we can observe phenomena in other nearby galaxies that have heretofore been seen only in our Milky Way.

Galactic structure studies have been revolutionized by new survey techniques including microlensing searches, 21-cm neutral hydrogen mapping, and through astrometry. Significant advances in these areas are still to be made through new facilities and surveys.

Stars and Stellar Evolution: Stellar astronomy has also benefited from large surveys, particu-

larly those targeted at microlensing searches and from the Sloan Digital Sky Survey (SDSS)³. Studies of the endpoints of stellar evolution — planetary nebulae, supernova remnants, white dwarfs, neutron stars, black holes — have made great advances. New phenomena and classes of “galactic” objects, such as Soft Gamma-ray Repeaters and magnetars, have been discovered based on survey missions and follow-up.

Future surveys will enable the more detailed studies necessary to build the next generation of theoretical models of stars and stellar structure. New phenomena, filling gaps in our mapping of the timelines of stellar evolution, await discovery. And finally, more complete surveys of stars in our own galaxy will shed light on our own Sun and its future.

Planetary Systems and Star Formation: Charting the sites of star formation in our galaxy and surveying for planetary systems is a high priority goal for the coming decade. The recent explosion in exo-planetary research and discoveries strengthens the case for the ubiquity of other solar systems and other Earths. We are tantalizingly close to being able to truly search for other life-supporting environments in our Galaxy, and an ambitious exo-planetary survey and study program is planned for the coming decade.

Besides being the ultimate genesis of planetary system formation and thus likely that of life, the process of star formation also greatly impacts astrophysical systems on all scales, including the cosmological. For example, the process of star formation related “feedback” into galaxy formation and the intergalactic medium is a fundamental ingredient in models of the massive clusters of galaxies that form the backbone of the cosmic web. Yet truly predictive star formation models elude us, and are key projects for the next decade. Great surveys provide the observational support necessary for the construction of these theories.

Cross-cutting Science: In addition to the categories highlighted in the Decadal Survey Science Frontier Panels, there are cross-cutting areas that drive and derive from Great Surveys:

- Things that “burst in the night”: Transients and Time Domain

Synoptic surveys on the new generation of telescopes are opening the time domain. This was pioneered for example by gamma-ray burst studies and microlensing searches. In the optical/infrared bands PANSTARRS and LSST are exemplary synoptic survey projects, while the ATA at radio wavelengths is leading the way. New capabilities ranging from transient burst and quasi-periodic emission detection, variability monitoring, and moving object identification and tracking experiments will lead to new and compelling discoveries.

- Extreme Objects and Physics

By obtaining extremely large survey samples, studies to find and characterize rare phenomena will be enabled. These in turn will test the extremes of physics and astrophysics. New classes of stellar remnants and black holes, and new stages in galaxy, stellar and planetary system evolution, await.

- New Windows on the Universe

It is growing harder in astrophysics to open truly new “windows” in observational space, with most advances pushing the current boundaries instead. However, we are on the verge of the start of the first gravitational wave astronomical observations. Due to the highly omni-directional response of the detectors, gravity-wave observatories

³<http://www.sdss.org/>

will conduct surveys by necessity. Targets will be teased out of the data stream. It may also be that in the coming decade we see the fruition of other non-electromagnetic observational experiments such as dark matter searches and more advanced particle and neutrino telescopes.

- New Frontiers and Exploration of the Unknown

Great Surveys and follow up observations will open frontiers in time, distance, and wavelength which will result in new discoveries. Although it is difficult to categorize the quest for new phenomena in the context of key questions or experiments, the exploratory nature of science is at the heart of what observational astronomy is all about, and why it is compelling to the public as well as to the profession.

3 Realizing Great Surveys

It will take more than a position paper to realize a Great Surveys program and to make this theme more than cosmetic. There are many challenges facing astronomy and astrophysics in the coming decades. Though these are framed in terms of surveys, they have more general significance, and will be found in any number of Decadal white papers, position papers, and project proposals. In particular, see [2] for more on data processing and analysis issues. I do not claim any particular insight here!

3.1 Ingredients in a Great Surveys Program

Survey Infrastructure: The hardware and software needed to carry out and process a large survey is substantial, and particularly on the information technology side is becoming increasingly complex. Large surveys must be well-planned and well-managed. Even though much of the value comes from use of the published products by persons outside the original collaboration (and is thus off the ledger), the public survey approach necessarily adds requirements on the survey sophistication, for example in tight quality control. This must be designed and built in from the start.

Data Products: The ultimate payoff in survey science is in the form of the raw (e.g. time-ordered) data and the processed survey Data Products such as images and object catalogs. This is what the general astronomical community will be expected to use. Assurance of the quality of these products is paramount (see below). Modern archives and data releases for programs and missions such as SDSS, HST, CXO, and SST have led the way in setting the standards for what products users should have access to.

Data Tools: The utility of publicly accessible data products is also dependent on the quality and usability of tools that can turn the data into science. Most areas of astronomy have one or more standard data reduction packages or suites of applications that make use of generic environments (e.g. Python, IDL, Matlab, Mathematica). Significant effort is going into next generation data reduction, visualization, access and analysis tools within projects. In many cases common standards and multi-use software packages would improve the ability of casual multi-wavelength astronomical users to make use of survey data. National initiatives facilitating the development of cross-cutting tools be an effective way to unify common

efforts, though this should be balanced against scope creep and added complexity that often occurs with large software projects.

Universal Access: The ultimate payoff in survey science comes from enabling astronomers that would not otherwise be able to use and contribute as part of the survey team. Publicly available data on a short but reasonable timescale after observation is the necessary first step. SDSS was spectacularly successful in tapping the wider community for value-added science beyond that of the core survey group. Future surveys have even greater potential for nearly universal astronomical utility. Once data is public, there needs to be a way for astronomers to use it. The establishment of the national and international Virtual Observatory (VO) projects⁴ this past decade was a step towards enabling the widest possible use of data resources. For Great Surveys, VO applications will need to have even wider application, yet have much deeper visibility into the actual survey data in order to maximize the quality and efficiency of its performance.

Opportunity for Innovation: It may not be apparent that surveys are engines for innovation, but the success of a Great Surveys program will hinge on our ability to spur and in turn incorporate novel developments by the community. Unlike first generation surveys based on physical media (plates and prints), such as the pioneering Palomar Observatory Sky Survey (POSS), and even early digital surveys and catalogs, modern sky surveys such as SDSS have reached a level of data richness and sophistication where new approaches to data mining and analysis can have a huge impact on survey utility. The extremely large data rates and volumes from future surveys will necessitate advances in processing and analysis, both within the survey pipeline infrastructure and in user-oriented post-processing. It will be critical to invite this opportunity and to build the survey to maximize its richness and to facilitate innovation.

Great Surveys Need Great Theories: The interplay between theory, modeling, observation, and data analysis is what allows us to make scientific progress in a classical sense. For example, in many areas we have been able to build a paradigm or “standard model” that is a synthesis of the knowledge in the field. Advances in our capability to carry out detailed simulations of astrophysical processes and cosmological volumes has revolutionized the field. The products of these simulations are datasets in their own right, and many observers and theorists have made use of these resources.

In the coming decade, progress must be made in a number of areas of theory and modeling. This case is made more directly in a number of other position papers and in numerous science white papers, e.g. [5, 6, 7] to cite only a few. Key issues include:

- Analytic and Semi-Analytic Modeling for Precision Cosmology

To a large extent, the measure of our “understanding” of astrophysics and cosmology lies in our ability to construct analytic theories of the Universe that capture key aspects of the physics that can apply to the observations. In more phenomenological cases, such as deriving observable functions (e.g. mass functions, luminosity functions, population counts) semi-analytic models can capture the salient features of the theory. A vibrant and adequately supported theoretical community is required for a Great Surveys (or any other) program to have meaning.

- Next Generation Models and Simulations

⁴<http://www.us-vo.org>

The process of extraction of model parameters from large surveys will require advanced simulation and modeling technologies to be effective. For example, the recent renaissance of cosmology and the progress towards precision cosmology has been sustained by innovations in methodology for the extraction of cosmological parameters from observations of the cosmic microwave background and large-scale structure in comparison with fast Boltzmann codes and N-body simulations. Increases in survey size coupled with tighter precision requirements for the next-generation of surveys will need simulations with larger numbers of cells or particles, greater accuracy, with greater efficiency. Besides cosmological simulations, the modeling of galaxy formation, star formation and stellar populations, and the genesis and properties of planetary systems are key areas for advance.

- Tools and Access

As with the processing of the survey data itself, the modeling and simulation of next generation surveys requires specialized tools and scientists to create and use them. Besides widely used standard codes (e.g. GADGET [8]), there is a healthy number of simulators who write their own codes, keeping the pace of innovation moving forward. On the other hand, some level of interoperability and intercomparison between codes is required for quality assurance (e.g. [9]).

3.2 Great Survey Challenges

In order to get maximum science return from our investment in facilities, science programs, and people, there are a number of cross-cutting issues that need to be addressed. See [1] for more detailed discussion. These topics include:

- Data Management and Optimal Processing for Large Surveys

One of the salient characteristics of the next generation Great Surveys is the tremendous data rates and volumes expected. Handling this data in the pipeline and early processing stages will be an extreme challenge.

- Accessibility and Distribution

Getting the rawer formats of the data out to the public is also difficult given the huge volumes. This will likely require partnerships with high-performance computing and data centers, as well as widely accessible VO tools.

- Data Mining and Science Extraction

Survey end-users (both internal and external) will need to dig through the data and extract model parameter constraints, calculate object counts and classifications, and measure statistics and/or detailed properties on data products. Again, astronomical data volumes present a challenge here, particularly for use by astronomers who might not have easy access to the top computational facilities.

- Interfacing Simulations/Models with Survey Data

As mentioned above, big surveys tend to require big simulations and extensive modeling, thus this aspect ends up inheriting the same issues as the data side.

- Common and Transportable Simulations

Again, as pointed out previously, some level of intercomparison between simulations is needed, as well as a mechanism to exchange data and simulation results.

- **Data Product Quality Assurance**

As both surveys and simulations become large and expensive, it becomes paramount to monitor and assure the quality of the data, its products, and the results of analysis. You may only be able to run the pipeline or simulation a few times (or once in pseudo-realtime) and thus there will be diminishing space for error tolerance. This is likely to be a non-trivial challenge for future surveys and modeling.

- **Survey Strategies and Maximizing Survey Complementarity**

There are many proposed survey and follow-up programs proposed for the coming decade. Although an attitude of “build the survey and users will come” has some merit, truly leveraging the diverse avenues of exploration into a reasonably coherent Great Surveys program will require some minimal level of coordination and exchange of ideas. Perhaps this can be done through informal workshops like the Great Surveys meeting, or perhaps more formal mechanisms are needed.

- **Multi-wavelength Follow-up Needs of the Great Surveys**

For every survey telescope, there needs to be some reasonable number of facilities capable of follow-up observations, e.g. to play the HST, CHANDRA, Keck, Gemini, Magellan and VLT (to name only a few) to SDSS. Adequate balance in the funding between surveys and exploitation is required. Generally, different telescopes are used for survey and follow-up, but in some cases (e.g. the SKA) the *same* instrument will do both the survey and exploitation, complicating the operational model for that facility.

3.3 Survey Sociology: It Takes a Community

An ambitious endeavor such as a Great Surveys program cannot happen in a vacuum. It is more than the sum of its telescopes, technology, and even its data products. Its success is primarily driven by the people that develop the design, build the infrastructure, create the technology, operate the survey, process and publish the data, use the products, turn it into science, and communicate the import and context to the public and to the next generation of young astronomers.

One of the surprises that I took away from the Great Surveys workshop was the extent of the passionate discussion of issues that had to do with the sociological and professional aspects of survey prosecution and use, rather than the more technical telescope and data problems. There were concerns about the perception of “survey scientists” in the wider and more traditional astronomy community, for the employment future of students and post-docs who work on survey programs, and for the assignment of credit in publications for contributions to surveys.

Some key issues:

Survey Science & Sociology: Surveys are going to play an even larger part of future astronomy than they do now, and the survey projects as well as our profession as a whole must come to grips with the sociological implications of this quiet revolution. There must be room for small groups and individuals as well as large groups to play visible and vital roles in surveys. Student education clearly must be part of Great Surveys (as it is now), and there

must be viable and interesting career paths for the students and professionals involved at all levels of survey work. Evolution of surveys from small teams to large collaborations is inevitable, and we must come to grips with this.

In addition, the advent of large survey projects and the availability of accessible survey data products has led to the appearance of new kinds of astronomers — “data wranglers”, survey scientists, analysis experts, software astronomers, etc. — that were a very small minority even 15 years ago. Since the proof is in the science, the acceptance of these new facets of the profession has been driven by the need and utility, but a perceived lack professional recognition still troubles the field.

Great Surveys Great Astronomy: It cannot be stressed too greatly that the ultimate goal in everything we do is to produce the highest quality, highest impact, most innovative, and most useful science possible with our people, projects, and facilities. It is for Great Astronomy that we do Great Surveys.

A relatively new aspect of surveys (in the SDSS age, as compared to the POSS era) is the development of efficient and usable mechanisms for the distribution of survey products and results to the astronomy community and to the public. The VO network was established to enable this on the widest scale possible, and one of the challenges of the coming decade will be to make the virtual observatory concept truly work or to find a different better paradigm. At the Great Surveys workshop there was some discussion on the approaches the surveys, super-computer and data centers, and VO might take for better partnerships and improvement.

Making the fruits of Great Surveys visible to the greater scientific community, to the public, to funding agencies, to politicians, and to other stakeholders is also of critical importance. This has always been a challenge, often requiring a different set of communication skill than those possessed by most astronomers and astrophysicists. The increasing emphasis on EPO in the profession highlights the need for increased support here. We are doing relatively well (compared to other basic science and mathematics fields, in my opinion) but there is clearly room and requirement for improvement.

Not Everything To Everyone: In this position paper, I advocate an umbrella of Great Surveys as a focal point for Astro2010. But clearly not everything is a survey, nor is everything an astrophysics experiment. There must be balance in our national astronomy program, and diversity at all levels should be encouraged. Even if the Great Surveys banner is dismissed, surveys will clearly be a large part of the picture and the issues highlighted here will need to be grappled with.

One of the most interesting discussions in the past few years on the sociology of the field was instigated by a paper on the “conflict” between experiment style astrophysics and more general observatory driven astronomy [10]. This discussion is even more relevant in the coming decade, as it will be challenging to maintain diversity of our program in the face of increasing project scope and cost and larger collaborations and project teams.

4 Conclusions

In this position paper, the concept of a Great Surveys meta-program was advanced, along with the presentation of a number of issues and challenges that astronomers face in the

coming decades. These are not new to the field (some even predate SDSS — gasp!) and are certainly better described in other white papers. The evolution of astronomy and astrophysics will continue regardless, and the growth of projects means that key programs and projects will continue to span decades in scale and scope. The Astro2010 panel has their work cut out for them to reconcile the diverse needs and wants of the community and to synthesize a compelling and coherent vision for the future!

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Another Disclaimer: The issues raised in this position paper owe a great deal to the excellent talks presented at the Great Surveys workshop, and to discussions between the participants. I apologize for not doing this justice and in particular for not referencing any of the talks (see the conference website). This is not meant as a proper conference summary, and should be considered as my own take on the subject. The views expressed here do not necessarily reflect those of my employer (NRAO) nor of the meeting participants.

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