Renewing Small Telescopes for Astronomical Research

Report of the Committee for Renewing Small Telescopes for Astronomical Research
December 2007

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Acknowledgements: We are grateful to NOAO staff David Sprayberry, who served as liaison with NOAO for technical information, and Letizia Stanghellini Ron Probst, Jay Elias, and the NOAO Working Groups on the renewal of small and mid-size telescopes, for their assistance in our quest for information. Richard Binzel, chair of the AAD Division of Planetary Science, convened a special working group to assist us with the definition of the science case for planetary sciences and Faith Villas assisted with the final preparation of the planetary science case. Rachel Akeson and Steve Ridgway provided a useful summary of facilities and needs for interferometry. Johannes Andersen attended our final meeting to brief the Committee on the status of European initiatives for small and mid-size telescopes. Mia Hartman's assistance in organizing our meetings is especially appreciated.

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[1] The Renewing Small Telescopes for Astronomical Research Committee was formed in May, 2007 by Todd Boroson, Interim Director of the National Optical Astronomy Observatory, at the request of the National Science Foundation Division of Astronomical Sciences. NOAO is managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

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Executive Summary, Findings, and Recommendations

The ReSTAR Committee was convened by NOAO in response to the Report of the Senior Review of the NSF Division of Astronomical Sciences, to consider the system of telescopes available to the U.S. community in a comprehensive way, such that the suite of large, moderate, and small aperture telescopes can work together to achieve the scientific goals of the community. The charge to the ReSTAR Committee was to focus on telescopes in the range 1 to 6 meters, and to create a blueprint for developing a system of small and mid-sized telescopes, including the specific instrumentation and operational capabilities that will enable front-line science with such telescopes and maximize their scientific productivity. With the assistance of the community through an online survey, a representative subset of the important observational research to be carried out on small and mid-size telescopes was identified and the instrumental and operational capabilities needed for the science were characterized.

The ReSTAR Committee endorses the following findings and recommendations.

Findings

1. *The science to be done with small and mid-size telescopes remains compelling and competitive in the era of big telescopes. Small and mid-size telescopes continue to produce innovative science in themselves, and to provide precursor and followup observations that enhance the scientific productivity of larger telescopes. Small and mid-size telescopes also enable scientific investigations that are not possible on larger telescopes. (Section III.J)*

2. *Specific instrumental capabilities on small and mid-size telescopes stand out as being essential to the progress of a wide range of research topics: optical spectroscopy at both high and low spectral resolution, and near-infrared spectroscopy at both high and low spectral resolution, optical imaging, and near-infrared imaging. The need for significant amounts of observing time with these capabilities dictates that such instrumentation should be available on national facilities. Moreover, the instrumentation available on small and mid-size telescopes at national facilities should be competitive with the best instruments available elsewhere. State-of-the-art instruments are important at all apertures. (Section IV.A)*

3. *Small and mid-size telescopes contribute additionally to the discipline through their training and education functions and as test beds for innovative new instrumentation and techniques. (Section V)*

4. *A system of small and mid-size telescopes comprising federal facilities and public access to non-federal facilities will provide a cost effective mechanism to meet the needs of the discipline for observations and also provide a more diverse set of instrumental capabilities and operations modes than can be offered through federal facilities alone. (Section VI)*

5. *NOAO, on behalf of the community, is the appropriate organization to select and negotiate with non-federal observatories participating in the ReSTAR System of small and mid-size telescopes, in cooperation with the NSF. (Section VI)*

Recommendations

1. *The continued operation of small and mid-size telescopes at the national observatories should be based primarily on the value of science produced, and publicly available time on telescopes in the ReSTAR system should be awarded on the basis of competitive review and scientific merit. (Section VI)*

2. *The number of nights needed in the system of small and mid-size telescopes can be estimated in several ways. Various approaches involving conservative assumptions consistently suggest that the equivalent of at least eight 2- to 4-m class telescopes should be available to the community for classically scheduled PI and survey programs. Telescopes in the ReSTAR System should include a mix of smaller apertures and the mix should evolve toward larger apertures over time as funding permits. (Section IV.E)*

3. *Oversubscription factors on current facilities should be monitored as new instrument capabilities come online to evaluate the ongoing need for new facilities. For key major instrument capabilities identified for the system, oversubscription factors should not exceed a factor of two for extended periods. If oversubscription factors regularly exceed two, new facilities should be considered. (Section IV.E)*

4. *In establishing the ReSTAR System, priority for funding should be provided first to assure that telescopes in the system are functioning in a safe, reliable, and efficient manner, and then that competitive instrumentation and associated software are available. Next, adding three or four 2- to 4- meter class telescopes to the system, both new and existing, and specialized time domain facilities should receive priority. (Section VI)*

5. *The specialization of both federal and non-federal 2-4 meter class telescopes should be encouraged. Specialization will provide a more limited set of observing capabilities on each telescope but should preserve a breadth of capability across the ReSTAR System. Thus, total costs for instrumentation and operation of small and mid-size telescopes could be reduced. (Section VII-A)*

6. *Additional instrumental capabilities utilized more selectively for a smaller range of science programs should be accessible for public use preferentially on non-federal facilities. (Section VI)*

7. *Access to a global network of telescopes for time-domain investigations should be made publicly available. The global network should include multiple 1-m telescope spaced around the globe for photometric monitoring and a small number of 2-m telescopes for spectroscopic monitoring. These telescopes may also contribute to*

other PI science programs that can be carried out in queue mode. Such a network should be developed in collaboration with non-federal partners. (Section IV-B)

8. *We recommend further investment in remote observing to allow greater flexibility in telescope scheduling that will enable new observing modes. Options like short programs, snapshot modes, and some synoptic observations may be possible through more flexible scheduling. The implementation of observing scripts on small and mid-size telescopes would also permit a limited use of "queue" observations carried out by classically scheduled observers. The implementation of observing templates will improve efficiency for both classical and remote observers. (Section IV.C)*

9. *Non-federal facilities contributing to the pool of publicly available time should meet standards of efficiency, reliability, performance, documentation, usability, and data quality that will allow investigators to obtain data with the same assurance of success that they expect at federal facilities. Non-federal facilities should be supported to achieve these levels of user services if such facilities participate in the System. (Section IV.D)*

10. *All facilities participating in the system of small and mid-size telescopes, including both national facilities and non-federal telescopes, should provide data that can be reduced using standard systems and the data should be made publicly available after an appropriate proprietary period. Pipeline reduction of data is encouraged, if appropriate. (Section IV.D)*

11. *We recommend that NOAO maintain a database of current capabilities on publicly accessible telescopes. This database should be easily accessed in electronic form and provide sufficient information for proposal development. (Section IV.D)*

12. *The role of AO on small and mid-size telescopes should be considered in the development of the next AO roadmap by ACCORD and NOAO. (Section IV.A)*

13. *Access to O/IR interferometry should also be publicly available, and the System should provide a funding support structure to enhance the efficiency and user base commensurate with the promise of recent advances in interferometric techniques and results. In the short term, partnership with existing or developing facilities is encouraged. (Section IV.B)*

14. *The ReSTAR System of national access to federal and non-federal telescopes will evolve with time as it responds to changing scientific priorities and opportunities. A mechanism for regularly monitoring the success of the ReSTAR System and for reviewing the capabilities offered by the system through community oversight must be put in place. (Section VII.B)*

I. INTRODUCTION

The ReSTAR Committee was convened by NOAO in response to the Report of the Senior Review of the NSF Division of Astronomical Sciences, to consider the system of telescopes available to the U.S. community in a comprehensive way, such that the suite of large, moderate, and small aperture telescopes can work together to achieve the scientific goals of the community. The Senior Review report provides guidance on the key aspects of our charge: to identify the first-rank science that can and should be done with telescopes of small and moderate aperture, to work with the community to establish the scientific case for these telescopes, and to define what capabilities are needed to carry out first-rank science with them. Our recommendations address both community needs in the next few years, and in the era of GSMT, JWST, ALMA, Pan-STARRS, and LSST in the next decade. We consider not only the renewal of existing telescopes, both federal and non-federal[2], but also the need for new telescopes, new instrumentation, and new operating modes.

The Senior Review noted three compelling reasons for continued support of small and mid-size telescopes: exciting and durable science, student training, and instrumentation development, and argued that resources should be allocated on the basis of competitive peer review rather than on the basis of access. The current status of many telescopes leaves much to be desired, and relatively small application of funds could allow more effective use of these telescopes for excellent science.

The charge of the committee is to determine the instrumental and operational capabilities needed by the U.S. community on ground-based optical/infrared (O/IR) telescopes less than 6.5 meters in diameter, based on the recommendations of the Senior Review (section 5.2.2.2). The list of capabilities should flow from community scientific aspirations and should represent all areas of astronomical research, O/IR wavelengths, and types of observation, though the committee should roughly prioritize and/or establish a sequence to keep the size of the total suite and the complexity of the System realistic.

In addition, if a known facility can provide the needed capability or can be argued to be the best place to deploy such a capability, the committee should present that information. In particular, we are to identify those capabilities that are most appropriate for NOAO telescopes or NOAO sites. With support from a NOAO technical group, we are also to establish a rough but consistent costing for the capabilities that do not currently exist.

As a point of reference, it is appropriate to enumerate the current federal facilities in the aperture range from 2-4 meters that are available for public access. These currently total some 4.2 equivalent telescopes, including 80% of the Blanco 4-m at CTIO, 30% of the SOAR 4.1-m telescope at Cerro Pachon, 70% of the Mayall 4-m at Kitt Peak, 40% of the WIYN 3.5-m telescope at Kitt Peak, 100% of the 2.1-m telescope at Kitt Peak, and 100%

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[2] Federal observatories include current NOAO facilities and the IRTF. Non-federal observatories include private and state-supported observatories such as the DuPont Telescope operated by the Observatories of the Carnegie Institution of Washington or McDonald Observatory operated by the University of Texas.

of the IRTF on Mauna Kea. This corrresponds to roughly 1200 publicly available telescope nights per year.

In the time period 2011-2016, the Dark Energy Survey will receive 30% of the time on the Blanco, leaving 60% for public access (10% is awarded to the host country, Chile), but current agreements with other institutions for time on the Blanco and Mayall will have expired. Thus, in the period from 2011-2016, the publicly available time will likely total 4.3 equivalent 2-4 meter telescopes.

The ReSTAR report is to be used as input to subsequent discussions with the NSF and with the operators of non-federal small and mid-sized telescopes for the establishment of the ReSTAR system of community access to small and mid-size telescopes. The goal of this subsequent discussion is to develop a national program that creates the optimized suite of capabilities, provides appropriate access to them by the entire community, and supports them at an adequate level.

Telescopes can be considered most effectively in three groups, those with apertures larger than six meters, those in the range from two to six meters, and those smaller than two meters. Telescopes larger than six meters are served by the TSIP program and face different issues than do the mid-sized telescopes. Telescopes with apertures smaller than two meters face a different set of challenges and probably would benefit from a different structural solution for community access than for the mid-size telescopes.

Our charge is to create a blueprint for developing a system of small and mid-sized telescopes, including the specific capabilities that will enable front-line science with such telescopes and maximize their scientific productivity. In this context, the term System will refer to the full suite of observing capabilities of all apertures available for public access, and the ReSTAR System is specifically those facilities with apertures 1-6 meters. Our blueprint should include reliable cost estimates for improving telescopes, building new instruments, and operating telescopes to support the general community. In some respects, our blueprint should also be a roadmap, defining how the ReSTAR System might evolve as LSST, ALMA, JWST, Pan-STARRS, and GSMT begin to affect the way science is being done.

Our charge includes defining not only instrumental capabilities but also operational modes that will enable front line science with small and mid-size telescopes. Operational modes that will enlarge the scientific opportunities in the next 10 years include time-domain scheduling, a rapid response capability, a queue observing mode, and remote observing for classically scheduled observational programs. Effective utilization of new operating modes and the availability of massive new surveys and survey facilities will drive the need for cultural changes in how astronomers use telescopes. Small and mid-sized telescopes will play an important role in preparing the community to take best advantage of the resources becoming available in the next decade. The potential benefit for the community in developing a system of effective and competitive small and mid-size telescopes is large. Such a system can provide multi-wavelength access and access to the time domain, as well as make more effective use of scarce instrumentation resources by avoiding duplication on many telescopes. Access to more specialized instrumentation by the wider community may also be facilitated through a system approach.

The Committee's work progressed through four meetings during 2007: May 14-15 in Tucson at NOAO, July 30-31 at the NSF in Arlington, VA, October 15-16 in Chicago, and December 17-18, Tucson (NOAO). Summaries of those meetings are available on the ReSTAR website (www.noao.edu/system/restar). The purpose of the first meeting was to refine our goals, review the literature, identify major science themes, and plan for community input. Our second meeting focused on the science to be done with small and mid-size telescopes, using input from our community survey and other sources. Our third meeting identified key instrumental and operational capabilities needed to fulfill the community's ambitious science goals on small and mid-size telescopes. Our fourth meeting was devoted to finalizing this report.

II. LISTENING TO THE COMMUNITY

Beginning its deliberations, the Committee reviewed the current state of ground-based, O/IR facilities and capabilities, including the literature on the science and productivity of small and mid-sized telescopes in the past decade, a summary of NOAO user statistics for small and mid-sized telescopes and of existing collaborations between NOAO and community groups, and a report on the TSIP program. Concerning the literature on the science and scientific productivity of small and mid-size telescopes, the Committee found little guidance concerning the role of such telescopes in the coming decade when Pan-STARRS, ALMA, LSST, JWST, and perhaps GMST will dominate the astronomical landscape. It is clear from the literature, however, that small and mid-size telescopes continue to be both scientifically productive and cost effective.

NOAO provided an analysis of recent requests for and allocations of telescope time on small and mid-size telescopes at NOAO, including the number of requests received, the number scheduled, oversubscription factors, the length of observing runs, and the instrumentation most frequently requested. The most requested instrumental capabilities are optical imaging, optical low resolution spectroscopy, infrared imaging, and optical high resolution spectroscopy. These account for 93% of the requests, with the remainder of the requests divided among many different capabilities.

Recognizing the importance of broad participation by the U.S. astronomical community in the development of a blueprint for a system of small and mid-size telescopes, the ReSTAR committee, assisted by NOAO, developed a website to gather community input and comments. ReSTAR pursued several mechanisms to solicit community input. The online survey requested information on scientific programs to be carried out on small and mid-size telescopes, apertures needed, and instrumental and operational capabilities required to carry out the science. Respondents were also asked to consider how the availability of new facilities such as ALMA, LSST, JWST, GSMT, and Pan-STARRS would impact the scientific programs to be carried out on small and mid-size telescopes.

Community input was solicited in the following ways.

- The community was informed about the website through an AAS email announcement, an NOAO email announcement, an NOAO Newsletter article, and a handout at the AAS meeting in Honolulu.
- We emailed requests to department chairs encouraging faculty discussions and offering to visit institutions that are willing to host regional discussions about the formation of a system for small and mid-sized telescopes. No institutions accepted our offer to visit.
- Each member of the Committee directly contacted a dozen or more colleagues to solicit input personally, particularly in the form of sciences cases for telescopes of small and mid-sized apertures.

Nearly 160 online survey forms were received through the ReSTAR website, and the responses are summarized here. Note that numerical results from the survey may be biased by selection effects. The responses received still represent less than 5% of the ground-based, O/IR community and the responses should not be considered to be representative. In particular, respondents who have stopped using public access facilities may be under-represented.

Respondents were first asked to identify the area to which research most closely related. The number of responses is given in parentheses below, and many identified with research in more than one area.

- Stellar physics (59)
- Structure and evolution of galaxies including stellar populations (50)
- Star formation and the interstellar medium (47)
- Cosmology, including the distance scale, supernovae, dark matter, and dark energy (32)
- Extra-solar planets (31)
- Accretion, high energy processes, AGN, and black holes (27)
- The Solar System (22)

Additional scientific areas identified include astrochemistry, gamma-ray bursts, massive stars, astrometry, time-domain astronomy, planetary nebulae, globular clusters, old stellar populations in the Milky Way Galaxy, binary Stars, fundamental calibrations, and nebular physics, many of which overlap with the categories above.

When asked to rank which capabilities would be needed to carry out research on small and mid-size telescopes during the next five years (2008-12) and beyond 2012, respondents placed highest priority on wide field, broad band, optical imaging, both now and in the future. Moderate and high resolution optical spectroscopy was also given high priority, as was infrared imaging. The full list is given below, with the rankings indicated in parentheses for the two time periods.

Wide field, broad band, optical imaging	(1, 1)
Moderate resolution optical spectroscopy (1,000<R<10,000)	(2, 2)
High resolution optical spectroscopy (10,000<R<50,000)	(5, 3)
High spatial resolution imaging in the infrared	(7, 4)
1-5 micron infrared imaging	(3, 5)
Wide field, narrow band, optical imaging	(6, 6)
1-5 micron infrared spectroscopy (R<20,000)	(4, 7)
1-5 micron infrared spectroscopy (R>20,000)	(10, 8)
Low resolution optical spectroscopy (100<R<1,000)	(8, 9)
Very high resolution optical spectroscopy (R>50,000)	(9, 10)
Mid-Infrared (8-13 micron) spectroscopy	(12, 11)
Mid-infrared (8-13 micron) imaging	(11, 12)

Other instrumental capabilities noted by respondents were integral field or wide field multi-object spectroscopy (all bandpasses) (8 respondents); high spatial resolution imaging in the visible (6 respondents); polarimetry and spectropolarimetry (6 respondents); optical/NIR interferometry (3 respondents); narrow field, broad-band optical imaging (2 respondents); IR or mid-IR spectroscopy, including high resolution mid-IR spectroscopy (R>30k) (2 respondents); wide field, broad band, NIR imaging; and an LSST-type facility for brighter stars (V<13).

Respondents also considered operational modes needed to carry out science programs on small and mid-size telescopes, indicating how time should be offered to the community. The responses were relatively well balanced among various operational modes.

Classically scheduled PI programs:	25.1%
Service or queue observing modes:	23.2%
Classically scheduled PI programs/remote observing:	20.9%
Time domain observing modes:	16.5%
Large, community-based survey projects:	14.4%

Several important points and a diversity of viewpoints emerged from the survey responses.

- The diversity of science proposed by respondents is impressive.
- Many respondents noted that research on transient phenomena is becoming increasingly important and described research programs of interest.
- Some respondents argued that publicly accessible facilities need to work at a high level of reliability while others felt that access was more important than reliability and that some unreliability might even be beneficial in providing a learning environment for students.
- For some, access to processed data was important, while others felt that the availability of pipeline processed data would lead people away from an adequate understanding of the limits of data. Others noted that the goal is for users, including students, to understand their data, but that goal does not necessarily mean astronomers must be present at telescopes themselves.

- Respondents also differed on the issue of building new facilities vs. refurbishing older ones. Some argued that building new, high-tech telescopes meeting modern performance specifications may be less expensive that trying to bring older facilities up to similar specifications, while others felt that modernizing older facilities is to be preferred.

The survey suggested that many astronomers remain primarily concerned with what's needed now to conduct their own research programs, but have not yet identified how their research needs and goals will change as new facilities such as Pan-STARRS and LSST become available. Many were skeptical about LSST, and many expect to continue with large, wide-field surveys even in the Pan-STARRS and LSST era. These perspectives will likely change over the next few years, but the ReSTAR survey does indicate that community education will be an ongoing need. Our survey is a good starting point, but the responses do not clearly define what the system should be in the long term.

Many respondents stressed that observing experience for students remains essential, both to attract undergraduates into the field and to provide training for graduate students. Others felt that the system for national access was not the appropriate place for training students, and that university facilities should be used for training. For example, some suggested that students can be trained to handle data at relatively low cost, using 14" telescopes and small CCDs. But at least some students also need to learn to solve more complex problems. Large projects need scientists, engineers, and managers who can understand very complex instrumentation and data systems.

Input was also provided by the group of directors of non-federal observatories (the AURA Coordinating Council of Observatory Research Directors, ACCORD) through liaison members George Jacoby and Suzanne Hawley. They stressed that the system must include four major components - telescopes, instruments, astronomers, and software. Further, the observatory directors stressed that operations costs, particularly the cost of supporting public-access visitors to non-federal facilities, must be included in our planning as well as the number of nights needed.

The diversity of capability desired by the community is extraordinary, and will likely never be achieved without extraordinary resources. While economies of scale may help to increase access beyond what is currently available, it is unrealistic to expect that all desired capabilities can be made available to the community through public access. Our system of small and midsize telescopes should, however, be responsive to those capabilities in highest demand and with the broadest and most compelling scientific rationale. The response of the system to the community's needs must be dynamic, providing for the greatest good, but not necessarily providing something for everyone.

III. OPTIMIZING THE SCIENCE

The science case for small and mid-size telescopes serves as the "design reference mission" for developing a system of such telescopes. While the science case cannot cover all science that the community will want to carry out on small and mid-size telescopes, it should fill parameter space so that the needed capabilities can be well specified and reliably costed. While we must also understand that a science case written in 2007 may not accurately forecast the science to be done in 2014, we need to assure that the community has the capability to carry out the scientific investigations of the next decade.

Small and moderate aperture telescopes contribute in many ways to the health of astronomy and the astronomical community. Examples of these contributions include:

- PI science programs
- Large surveys
- Education and training
- Technology development
- Infrastructure for supporting instrument building groups
- Allowing those without access to non-federal facilities to compete on a level playing field for publicly available time on large telescopes
- Time domain science programs, including those that require telescopes spaced longitudinally for long time coverage
- Calibration of data from larger, ground-based telescopes and from space telescopes.
- Programs requiring multi-wavelength and/or multi-technique observations

How the important science themes for small and mid-sized telescopes will change between now and 2016 must also be explored. By 2016, Pan-STARRS, LSST, ALMA, and JWST may be in operation and GSMT may also be operating, and all will be factors in defining important observational programs for ground-based, O/IR telescopes of all apertures.

Many surveys, either underway or planned, will also impact the use of small and mid-size aperture telescopes in the next decade, including UKIDDS (UK Infrared Deep Sky Survey), VISTA, the UKIRT Hemisphere Survey, the CFHT Legacy Survey, the Dark Energy Survey, and many more. Followup observations on small and mid-sized telescopes will continue to leverage the scientific productivity of these large surveys. Specialized optical imaging (e.g. narrow band filters or high spatial resolution), deep and wide field infrared imaging, and moderate and high resolution optical and infrared spectroscopy will continue to be important capabilities. The impact of large surveys will not be limited to followup observations but will also affect traditional observing programs as well, likely increasing sample sizes and providing ancillary data to support ground-based programs.

While is it not possible to consider and evaluate all of the potential science that will be done on small and mid-size telescopes in the next decade, ReSTAR focused on seven specific areas that will help to define the characteristics needed for an effective system that can be used for a wide range of research programs. Those seven areas are studies of solar system objects; exoplanets; star formation and the interstellar medium; stellar astrophysics; black holes, neutron stars and white dwarfs, including accretion physics; the structure and evolution of galaxies; and cosmology, including and large scale structure, dark matter and dark energy. In the following sections, we will consider each of these areas in some detail to understand the context of the research, the questions the community aims to answer, and the facilities, instrumentation, and modes of operation that will enable progress in these fields. Much of the science presented is drawn from our community survey and its purpose is to illustrate the role and promise of small and mid-sized telescopes, rather than provide a comprehensive overview.

A. The Solar System

Solar system astronomers engage in observational investigations ranging from directed studies of individual objects (e.g. planetary satellites) to surveys revealing the large-scale structure of the solar system (e.g. Kuiper belt) and inventorying potential hazards to civilization (near-Earth objects). Solar system astronomy can be conducted by day (e.g. bright planets in the infrared or radio; transits of the Sun; solar eclipses) or by night. In the nighttime sky, solar system astronomers pursue the greatest extremes in dynamic range of measured flux, for example, from the Moon and Venus to Kuiper belt objects at the limit of detection. Solar system astronomers often push the physical limits of telescope systems to pursue critical measurements at inescapable low elongations from the Sun and low altitudes above the horizon (e.g. comets at perihelion; the planet Mercury). The ability of a telescope to track at non-sidereal rates is absolutely essential for nearly all facets of planetary astronomy and a requirement for any telescope to be regularly engaged in solar system science. To further illustrate the required capabilities in the wavelength and time domains, several specific science themes can be described.

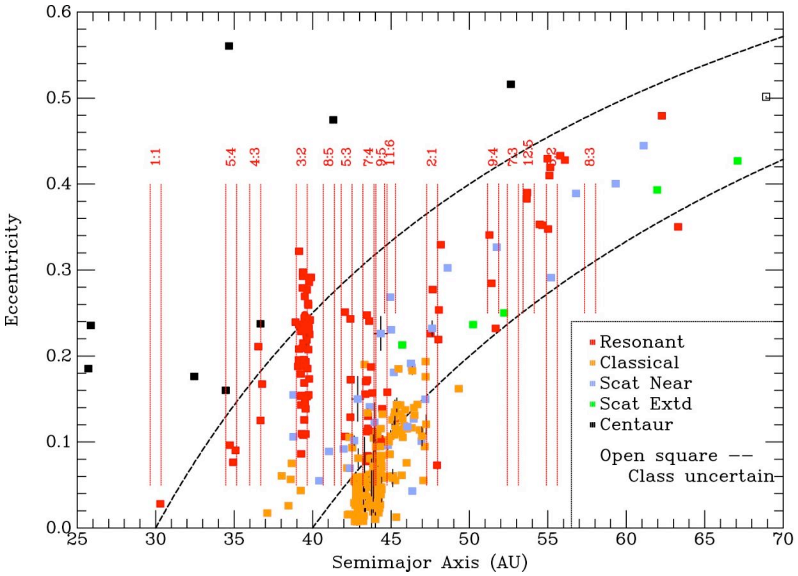

Figure III.A.1: Orbital eccentricity vs. semi-major axis for KBOs with well-known orbits (Wasserman, private communication, using data from Millis et al., 2002).

What is the distribution and nature of the Kuiper Belt Objects?

Studies of the chemical and physical nature of Kuiper Belt Objects form a bridge between the structure and dust edge of our solar system's disk and stellar astrophysics. The population of KBOs can be divided into three dynamical classes: Resonant objects, whose orbital periods are commensurate with Neptune's orbit; Classical KBOs, whose orbits have been undisturbed since solar system formation; and Scattered objects and Centaurs that have dynamically interacted with Neptune. Two competing theories about the evolution of the objects in the solar system can be tested through the study of KBOs. The generally accepted theory is that most solar system objects formed in situ, followed by moderate perturbations in location and the Late Heavy Bombardment in the inner solar system caused by gravitational interactions of Jupiter and the Sun. Recent theories, however, suggest that KBOs were drawn into the main solar system by the planetary migration of Jupiter and Saturn. Study of the dynamic and compositional characteristics of the KBOs will test these theories. Observational programs include population surveys, dynamical studies, light curves, and spectroscopic studies of the surfaces and atmospheres of the larger objects. The instrumental capabilities needed include wide field (2 degree FOV), 4-m class telescopes in both hemispheres (with sufficient follow-up cadence to define orbits for discovered objects), as well as photometric and spectroscopic capabilities in the visible and infrared at limiting magnitudes >21.

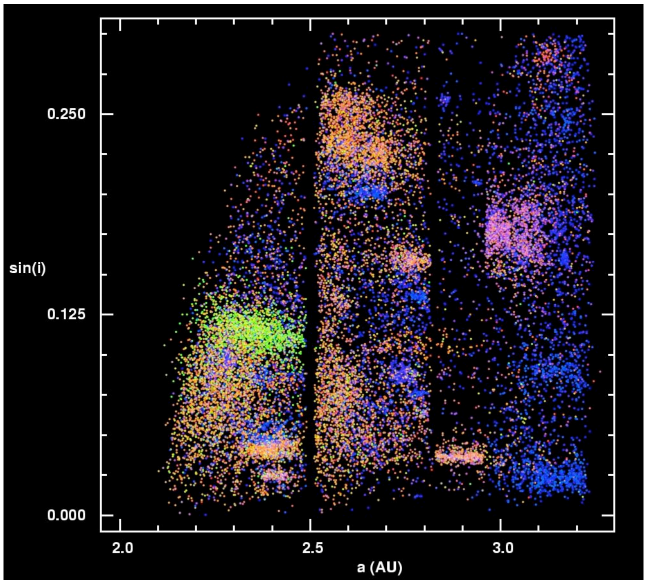

Figure III.A.2: The colors of main-belt asteroids observed as part of SDSS. The asteroid families stand out. New families have been identified, and some cluster ages have been determined. (Juric et al., 2002.)

What are the physics of collisions and what is the history of collisions of asteroids?

The discovery of asteroids has snowballed: Twenty years ago, 5000 asteroids were known. Today, well-known orbits exist for ~160,000 asteroids. Overall, the characterization of the asteroid population lags behind the discovery rate. About a third of the asteroids in the main belt fall into orbital families. SDSS data showed that these orbital families were also segregated into color families (Juric et al. 2002). These families have been formed over the history of the solar system as a result of collisions between asteroids. The families decay because of perturbations from Jupiter and grinding down by continuing asteroid collisions. The size and velocity distribution of the family members probe the break-up and re-assembly process. For example, the larger members of the Karin family formed by gravitation aggregation of smaller bodies formed in the break-up (Michel et al. 2003).

Recently, the family that was the probable source of the K/T impactor was identified as being centered on the asteroid Baptistina (Bottke et al. 2007). The discovery and characterization of the near-Earth asteroid (NEA) population is important to the assessment of the impact of an NEA with the earth as a hazard to humankind. A limited time window of usually a few days is available to characterize small NEAs, and telescopes must be able to track at non-sidereal rates and very quickly. Broad-band, wide-field imaging with a 3-day cadence is critical for discovery and characterization. Similar telescope systems to KBO searches and characterization are effective for asteroid studies.

What do comets and asteroids tell us about the early solar system?

Asteroids are small remnants of early solar system materials, not churned by the surface processes to which planets are subjected. Their physical characteristics vary with heliocentric distance, and, as such, represent probes into the distribution and processing of material during early solar system formation.

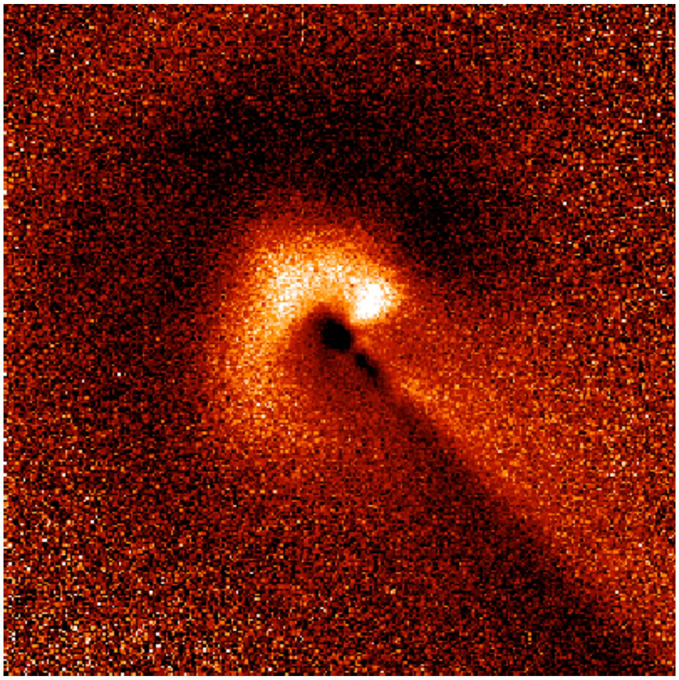

Figure III.A.3: Comet Hyakutake dust jets (Schleicher & Woodney, 2003) from the Lowell 1.1-meter telescope. The orientation and location of outgassing in comets addresses the strong difference in dust and gas release before and after perihelion.

The known population of comets beyond 3-7 AU has increased as a result of the extensive near-Earth object searches. About 30 comets per year at these distances are bright enough for spectroscopic studies with a 4-m telescope. These objects present opportunities to study the physical effects of solar heating at large heliocentric distances and near perihelion. Distant comets also represent a population of primitive solar system objects not yet significantly altered by solar passage. Comets also represent a potential mechanism for delivery of volatiles to the early inner solar system. In addition to broadband wide field imaging, narrowband imaging through specialized filters for 2-D information is required, as well as long slit spectroscopy. High-resolution spectroscopy requires 4-m class telescopes to delineate the detailed and complex chemistry of cometary comae.

What are the processes in planetary atmospheres?

Clues to the dynamical processes operating in the atmospheres of the giant planets require long-term monitoring to provide synoptic meteorology. The current chemistry, as well as orbit-dependent changes in gas composition with time (e.g. methane on Pluto), also require long-term monitoring. These observations extend to some of the larger Jovian and Saturnian satellites such as Titan or Europa, where conditions exist that could be conducive to the existence of life. This work requires high-dispersion IR spectroscopy on 4-m class telescopes.

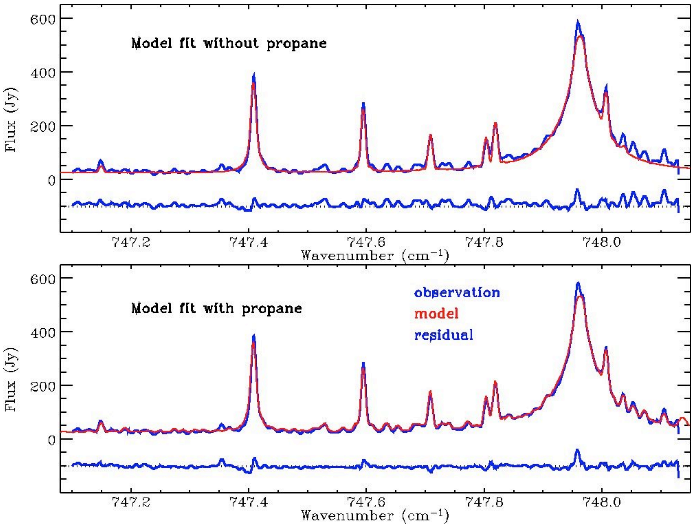

Figure III.A.4: First detection and measurement of propane in Titan's atmosphere, using the echelle spectrograph on the IRTF (Roe et al. 2003). Propane is one of the major hydrocarbon products of the photochemistry in Titan's atmosphere and should also be one of the most abundant hydrocarbons on Titan's surface.

What are the dynamical histories of outer planets and satellites?

Studies of outer planets and satellites are centered on their dynamical history, including the discovery of satellites, observing ring plane crossings, and seasonal effects such as the changes in Pluto's atmosphere (e.g. state of methane on Pluto) with its seasonal cycle of 250 earth years governed by changes in Pluto's heliocentric distance. Support for space probe missions to the outer planets such as providing a context for spacecraft flybys is also in demand. Small telescopes also play a crucial role in basic astrometry, tracking new objects, determining orbits, and improving orbital elements. This work requires optical through mid-IR imaging and spectroscopy capability on 2- to 4-m telescopes. Support for such work by Division 1 (Fundamental Astronomy) of the IAU is particularly noted.

Summary of Solar System Science

The exploration of the nearest celestial objects to the Earth is one of the strengths of small and mid-sized telescopes. In many cases, the improvements needed in the facilities are not an increase in aperture size, but reliable non-sidereal tracking, flexible scheduling, including synoptic and time-critical observations, and the availability of capabilities in both the northern and southern hemispheres.

Capabilities for Solar System Science:

- **Non-sidereal tracking**
- Narrow-field broadband imaging in the optical through mid-IR
- Narrow-field low-resolution spectroscopy in the optical through mid-IR
- Narrow-field high-resolution spectroscopy in the optical through mid-IR
- Wide-field broadband optical imaging

B. Exoplanets

Within the exoplanet field, a number of basic/fundamental science questions remain unanswered. Small- to mid-range aperture telescopes and instrumentation are required for significant contributions. Discovery of exoplanet systems requires time-domain capabilities: high precision radial velocity time-series spanning weeks to decades and the photometric monitoring of large numbers of stars for microlensing and transit events. The characterization of many exoplanets may be achieved from the ground using 4m or smaller telescopes through high precision transit measurements (in both amplitude and time). When combined with information about their host stars (composition, radius, etc.) from spectroscopy and, in some cases, interferometry, one can begin to approach fundamental questions such as:

- What is range of planetary system architectures?
- What is the origin of hot Jupiters?
- How are the compositions/structures of hot Jupiters different from their Solar System counterparts?
- How do planets and planetary systems form?

What are the architectures of planetary systems?

It is through radial velocity techniques that the bulk (about 90%) of the known exoplanets have been discovered, and most of these (roughly 75%) on telescopes of 4-m aperture or less (May 2007 compilation by D. Naef, ESO). Doppler detection of a host star's reflex motion allows the determination of star-planet distances, minimum masses, and eccentricities. In dozens of cases, the radial velocity time series has revealed the presence of multiple planets. Beyond this, radial velocity measurements are the primary mechanism by which transiting exoplanet candidates are confirmed. The spectroscopic data collected in the process can also be used to determine the properties of the host stars themselves.

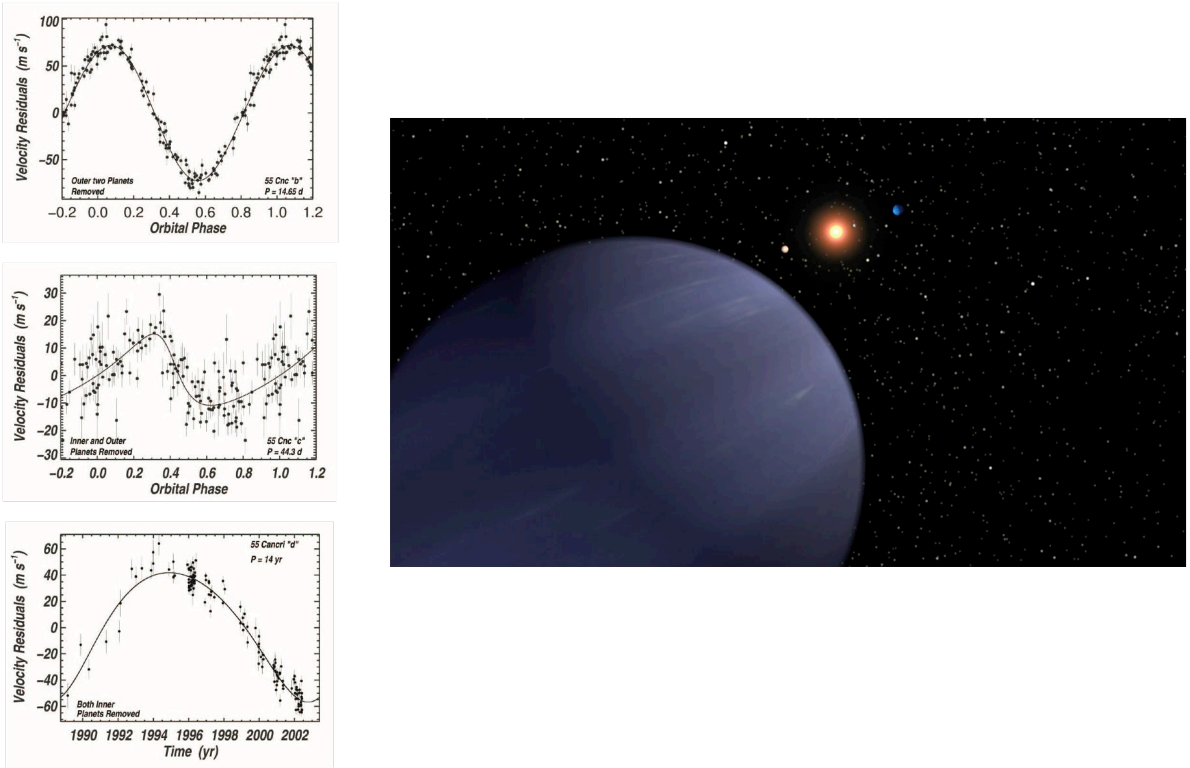

*Figure III.B.1: Left, Keplerian orbital fits to the velocities for 55 Cnc from the Lick/Shane 3-m telescope assuming a three-planet system (Marcy et al. 2002). Four more years of data from Lick coupled with seventy Keck spectra have demonstrated that this is likely at least a five planet system, with the fourth being a 45*M_{Earth} *planet in the habitable zone (Fisher et al. 2007). Right, an artist's impression of what the fourth planet might look like (NASA/JPL-Caltech).*

The current state of the art in velocity precision of about 1 m/s (or slightly better) is often achieved in visible light with HARPS, Keck-HIRES, AAT-UCLES, etc. This capability has allowed the detection of planets with masses as low as Msin(i) = 5 M_{Earth} (albeit around GL 581, a red dwarf). Of course the majority of exoplanet discoveries via radial velocities have been of considerably more massive planets. But even today's sample of over two hundred fifty planets points to a surprising variety of apparently distinct giants (ultra-hot Jupiters, hot Jupiters, and eccentric giants), none of which were predicted before discovery. Currently, the eccentric giants form the largest group, although it is unclear whether their eccentricities are the result of orbital interactions, or mechanisms operating in the protoplanetary disks.

Perhaps even more exciting is that the high precision radial velocity searches have now been operating for more than a decade (and in some cases almost two). Thus they currently have sensitivities to giant exoplanets with orbital periods of about 5 years, i.e., they are beginning to enter the realm of the "long period" giants similar to those found in our Solar System. An excellent example of the fruits of these long-term investments is shown in Figure III.B.1. As the time baseline for these studies continues to grow, giants in ever longer orbits will be uncovered. We also expect that evidence for multiple planets unresolved in the current velocity time-series data will be uncovered. As we enter a parameter space comparable to the Solar System, we begin to address important questions regarding the distribution of planetary system architectures at sizes comparable to our own. Critical among the questions that can be addressed is the role of migration of giant planets, which in turn can play a pivotal part in determining the rates of terrestrial planets in the habitable zones of stars. These giant planets at large radii will also the likely be the targets of the first imaging attempts, which will open an era of exoplanets as more the simply point masses.

To date, most searches have been undertaken at visible wavelengths using echelle spectrographs and velocity standards such iodine cells. In the future, new technologies such as robotic spectrographic telescopes and dispersed fixed-delay interferometers promise to increase efficiency with regard to both throughput and multiplexing (e.g., fiber feeds). It is, however, unclear how much additional velocity sensitivity may be gained in the visible, regardless of technique. At some level, the technique is limited by the atmospheric jitter of the host stars. This in turn limits the lower limit of masses detectable from the ground around sun-like stars.

Significant progress can be made in the near-IR, where lower mass stars are brighter. In the search for Earth-mass planets, the M-dwarf regime has the advantages of larger induced reflex motions for a given planetary mass, a habitable zone at shorter periods, and less photospheric "jitter" (among younger stars). This, combined with a higher space density towards lower masses has raised the priority of near-IR Doppler searches in the community.

Key to the success of Doppler searches are: a) stable, efficient high-resolution spectrographs in both the visible and near-IR, and b) the maintenance of long-term programs (to detect long period planets and characterize perturbations in the orbits of already detected short period planets). Such time-domain studies, on time scales from days to decades, are ideally suited to modest aperture facilities.

What are the properties of hot Jupiters?

Transits (Figure III.B.2) offer an opportunity to gather considerable information about an exoplanet with a modest investment in aperture. Immediate outcomes of such observations include orbital inclination and an estimate of the exoplanet's size and semi-major axis relative to the host star. When combined with mass estimates from radial velocity observations (in addition to confirming a transit) and information about the star itself from high resolution spectra, physical size and basic composition may also be inferred from the resulting density (see Figure III.B.3). A recent example of the application of these techniques is TrES-4, discovered through the Trans-atlantic Exoplanet Survey (TrES) with the 4-***inch*** (yes, inch!) Lowell Observatory Planet Search Survey Telescope and the 4-***inch*** Sleuth telescope at Palomar Observatory. Follow up photometry was obtained using the Whipple Observatory 1.2-m and Lowell 0.8-m telescopes (see Figure III.B.2). When combined with Keck/HIRES radial velocities and stellar models, the mass of the planet was determined to be 80% that of Jupiter yet 1.7 times the radius, *i.e.,* the largest known exoplanet as well as the least dense (at 0.2 g/cm^3).

Rather than relying on models for stellar properties like size, Baines et al. (2007) used the CHARA optical/IR interferometric array to measure the angular diameter of HD 189733 - a star hosting a transiting exoplanet. When combined with the *Hipparcos* parallax, the actual radius of the star was determined, which then lead to the first direct measurement of an exoplanet's diameter. Another technique to determine fundamental stellar parameters provided using modest-aperture telescopes and time domain techniques– asteroseismology – is discussed in the stellar astrophysics section.

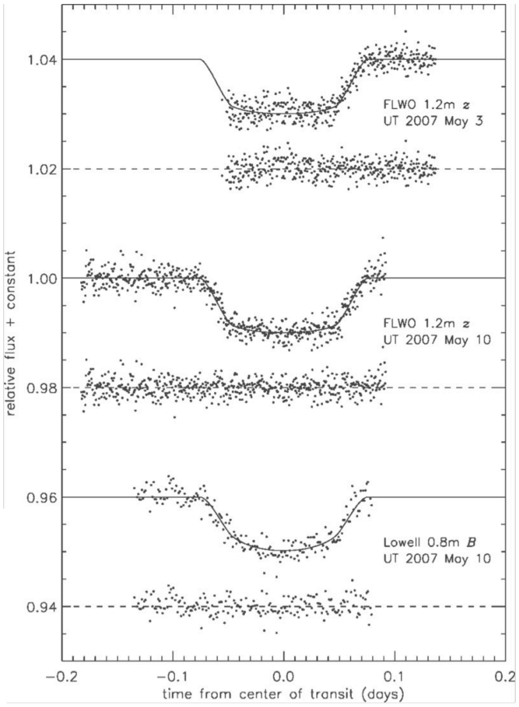

Figure III.B.2: Light curves of the transit of TrES-4 from 1-m class telescopes. These observations combined with Keck spectra of the host star lead to its classification as the largest and least dense known exoplanet. (Mandushev et al. 2007).

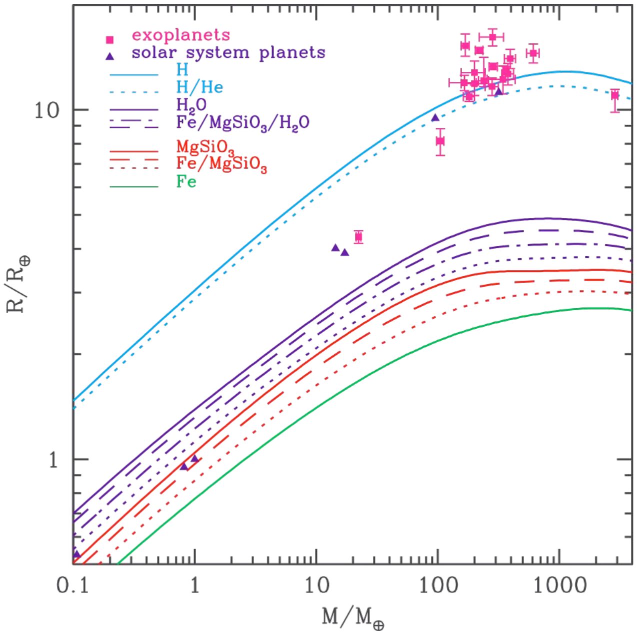

Figure III.B.3: Mass-radius relationships for solid planets are compared to results inferred from transit observations. Solid lines correspond to homogeneous planets, dashed to differentiated planets. See Seager et al. (2007), Figure 4, for details.

These and other transit observations of roughly twenty exoplanets have lead to the realization that while many giant exoplanets are similar to Jupiter in density, there are also a sizable number which are either too large or too small for their given masses which in turn raise questions about our models of the structure and evolution of giant planets.

Further information that can be extracted from transit observations includes the orientation of the orbit with rotation axis and the direction of revolution relative to the host star's rotation (via the Rossiter-McLaughlin effect, see Albrecht et al. 2007 for an application to V1143 Cyg using the 0.6-m CAT telescope at Lick). Transit timing variations can infer the presence of other planets to low masses (especially near resonances, see Agol et al. 2005). There is also the hope of detecting exoplanet atmospheres during transits, although it is likely at this point impossible from the ground.

We note a number of large scale searches are currently underway or planned for transiting exoplanets. One can expect these surveys to do the "heavy lifting" in the search for such systems. However, a good deal of science clearly relies on being able to accurately characterize the eclipses and the host stars once they have been found. For precision transit measurements, one requires moderate aperture telescopes (1-2 meter) with high-speed cameras and accurate local clocks. The expected duration of transits typical transits (a few hours) may warrant longitudinal coverage and such capabilities in both the northern and southern hemispheres would be useful.

For those low-amplitude transiting systems that will be found from space (i.e. by Kepler, to be launched in February 2009 as of this writing), characterization of their host stars will provide essential details for interpreting the transits and measuring the parameters of the planets. Since the Kepler targets are all relatively bright, this can be done with telescopes of moderate aperture.

What is the frequency of planets like those in our solar system?

Microlensing events take place when one star (the lens star) passes in front of another (the source star) and the gravitational well of the lens star magnifies the source star. Though the components are unresolved, the resulting brightening has a characteristic bell shaped curve. If an exoplanet is present around the lens star as well, this can cause significant and observable perturbations in the light curve shape (see Figure III.B.4). By identifying and following these light curve deviations with high cadence photometry, it is possible to extract the basic parameters of the lensing planet (mass and semi-major axis).

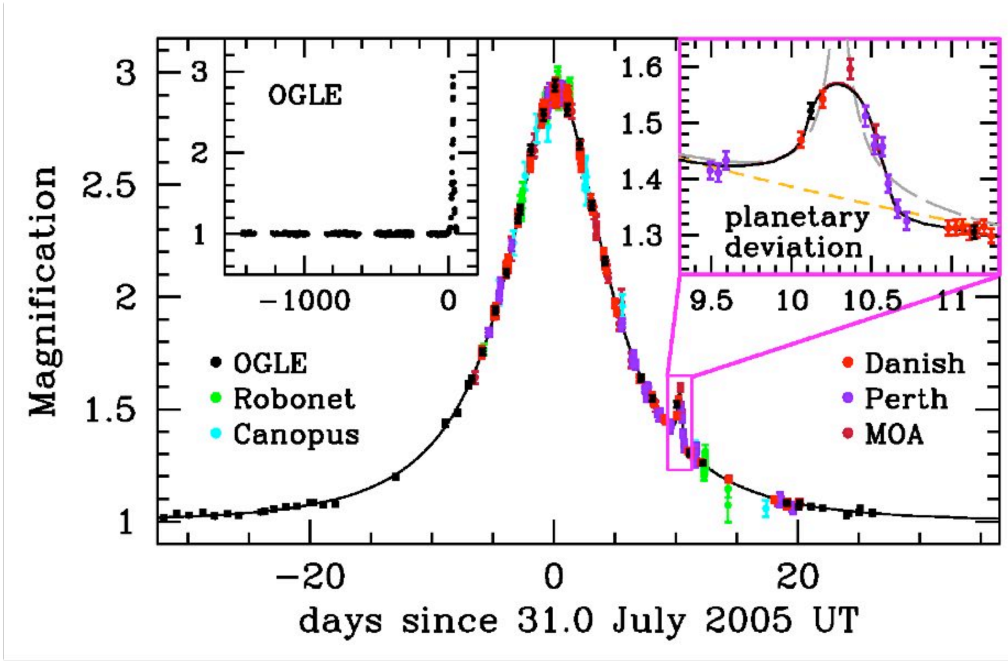

Figure III.B.4: The observed light curve of the OGLE-2005-BLG-390 event. The best fit modeling suggests a 5.5 M_{Earth} planetary companion at 2.6 AU from its host M-dwarf star. The data set consists of 650 data points collected with 1 to 2-m class telescopes (From Beaulieu et al. 2006).

To date, four detections of exoplanets via microlensing have been published - two Jupiter mass and two sub-Neptune mass planets (see Figure III.B.4 for an example of the later). This is primarily the result of two ground based microlensing surveys (OGLE, with a 1.3-m telescope at Las Campanas and MOA with a 1.8-m at the Mt. John Observatory in New Zealand, each monitoring more than 100 million stars) which provide notices of interesting events in near real time to two other groups who perform high precision high cadence follow-up photometry. At present these are the PLANET Consortium with five telescopes at four longitudes with apertures from 1.5 to 0.56-m) and the MicroFun Group with 16 telescopes from 2.4 to 0.35-m.

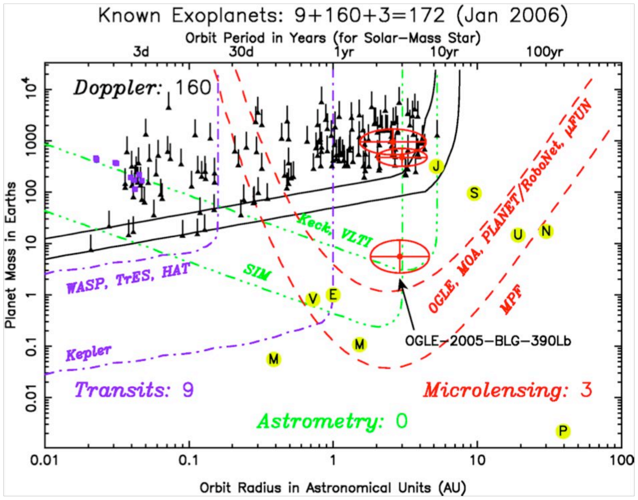

Figure III.B.5: Discovered exoplanets and detection limits for various techniques as function of mass m and orbital radius a or Period P (indicative): radial velocity (Doppler wobble), astrometry, eclipsing transits, and microlensing. The planets of our Solar system are indicated by letters (M-V-E-M-J-S-U-N-P). http://planet.iap.fr/OB05390.news.html.

Of particular importance, microlensing searches (and follow-ups of interesting events), allow the efficient exploration of a unique parameter space - including exoplanets of lower mass than can be detected through radial velocity searches and at larger distances from their host stars (see Figure III.B.5). Because of this it is expected that microlensing will play a critical role in future surveys of planetary architectures. Moreover, microlensing is also not limited to nearby stars and can be used to probe the planetary constituencies of a variety of populations. Unfortunately however, individual detections/exoplanets cannot be followed up because the lensing event does not repeat, though the lensing star may be resolved after a few years of patient waiting.

Summary of Exoplanet Science

Although only three examples are given here, the ReSTAR committee notes smaller (2-3m class) telescopes played a key role in the birth of this field. And although several space missions to search for and explore exoplanets have been proposed (and may well fly), small telescopes and the techniques noted above will continue to play a pivotal role in follow-up/verification as well as discovery. Indeed, as the field continues to grow and mature, the pressure on telescopes engaged in these activities will increase proportionally, especially for queue driven high resolution spectroscopy (for radial velocity programs in the O/IR) and time-domain/event triggered photometry (for transit searches/follow up and microlensing events).

Capabilities for Exoplanets:

- High-resolution optical and near-infrared spectroscopy
- Narrow-field optical imaging
- High-resolution optical and near-infrared imaging
- Interferometry

C. Star Formation and the ISM

A large number of studies in this area continue to be dominated by work on a relatively small subset of nearby (< 1 kpc) star forming regions in the Milky Way. Telescopes in the 2-4 meter range continue to make important contributions, as numerous important targets remain within reach of this aperture range. With more efficient instruments (e.g., higher spatial resolution and greater sensitivity), these telescopes are capable of reaching more distant star forming regions. The proposed Spitzer Warm Mission would have a major impact on follow-up studies of star forming regions with ground-based telescopes. The mission, if approved, would allow for large-scale surveys of ongoing star formation in many more molecular clouds than have been observed to date. It would also have angular resolution that is great enough to resolve groups and clusters of YSOs (Strom et al. 2007). More immediately UKIDSS, a successor to the 2MASS near-infrared sky survey using the 3.8-m UKIRT telescope will, upon its planned completion in 2012, result in a survey of 7500 square degrees of the Northern sky in JHK to a magnitude limit of K=18.3. Like sources detected in a Spitzer Warm Mission, UKIDSS sources will require follow-up spectroscopic and photometric observations, many of which can be undertaken with 4-m class telescopes. Representative questions able to be investigated with current and future instruments on 2-4 meter telescopes are listed below.

What is the mass distribution of stars?

An ongoing problem in the field of star formation remains an understanding of the mass distribution of stars (the Initial Mass Function, or IMF) and how it originates. Obtaining this understanding is crucial, since the nature of the IMF: 1) results from the basic physical processes that are responsible for all that makes up our observable universe; 2) represents the mechanisms by which the chemical elements are created; 3) represents processes responsible for the input of energy into the ISM; and 4) impacts the overall formation and evolution of galaxies (Bonnell, Larson & Zinnecker 2006). Yet, we still do not have a true understanding of the physics that gives rise to the distribution of stellar masses. Numerous observational studies continue in this research area, and they largely depend upon near-infrared (e.g., JHK and L-band) imaging studies of star forming regions, coupled with moderate resolution near-infrared spectroscopy in the 1-5 micron region for spectral classification.

The boundary between planetary physics and stellar physics, and the mechanisms responsible for the formation of the lowest mass stars in particular, are among current topics in star formation research. For example, a recent study of the stellar population in the Chamaeleon I star-forming region found that the IMF in Chamaeleon I reaches a maximum at a mass of 0.1-0.15 solar masses, while the IMF is essentially flat in the substellar regime, and shows no sign of reaching a minimum down to a completeness limit of 0.01 solar masses (Luhman 2006). Among the instruments used in that study was the Infrared Side Port Imager (ISPI) at the CTIO 4 m Blanco telescope. The major targets of many IMF studies continue to be nearby, requiring wide field imaging and multi-object spectroscopy capabilities. Telescopes in the 3-5 meter range will continue to be in demand.

What are the masses and radii of pre-main sequence stars?

Among the most fundamental properties of a star is its mass. Detached eclipsing binaries provide one of the best targets for measurement of fundamental stellar properties, particularly, masses and radii. Knowledge of these same fundamental properties are of great interest in the evolutionary state before a star reaches the main sequence, yet few fundamental determinations of masses and radii exist, particularly for low-mass stars. One example of the effort underway to address this issue is the “Monitor Project”, a high cadence, large-scale survey for eclipsing binary and transiting exoplanet systems in a number of young open star clusters, using 2-4 meter telescopes (Hodgkin et al. 2006). A recent discovery is that of a 0.26 ± 0.02 and 0.15 ± 0.01 solar mass pre-main-sequence eclipsing binary with a 5.3 day orbital period (Irwin et al. 2007). This discovery helps to fill an important region of the mass–radius parameter space. While follow-up spectroscopic observations with Gemini and the VLT were required, the discovery was made using the 2.5-m Isaac Newton Telescope and Wide Field Camera, with supporting photometric observations using 1-meter class telescopes.

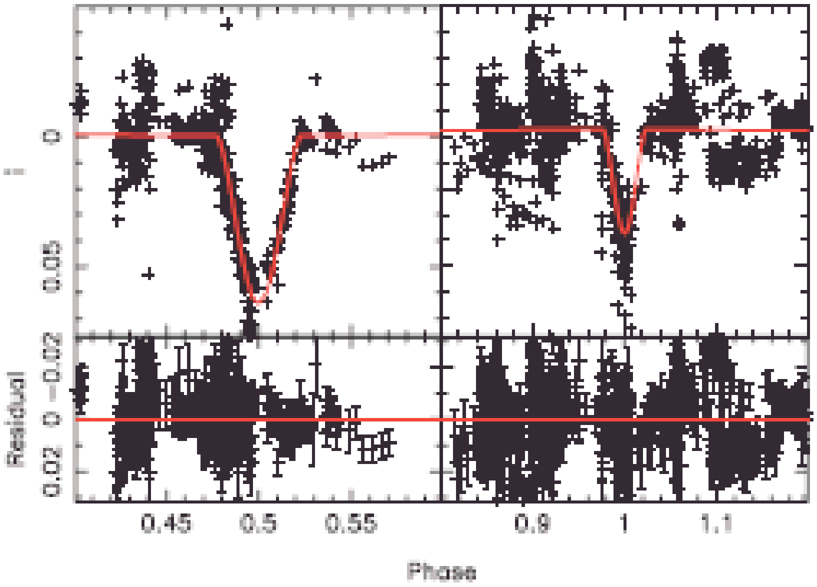

Figure III.C.1 - Phase folded combined i-band light curve, with phase 0 defined to be at mid-secondary eclipse. The upper panel shows the light curve, with the fit overlaid (solid line), and the lower panel shows the residuals (data - model). The panels show a magnified view of the regions around primary eclipse (left-handed panels) and secondary eclipse (right-handed panels). The scatter in the secondary eclipse is larger than the primary since this was only observed in the follow up observations and not in the INT/WFC survey photometry (which was of better photometric precision). (Irwin et al. 2007)

What is the predominant mode of star formation in molecular clouds?

A majority of stars form in clustered environments, but the degree of clustering varies. A major focus of star formation studies in recent years has been to ascertain the degree to which star formation occurs in dense clusters versus a more distributed mode. These studies have particular relevance in establishing how the properties of newly forming stars (e.g., disk stability and lifetime) are affected by clustering, and how the presence of high mass stars that are preferentially found in clusters affects star formation.

A recent near-infrared imaging survey of the Rosette Molecular Complex, adjacent to the famous Rosette Nebula (see Figure) determined that 60% of the young stars in the region, and 86% of the stars within the molecular cloud itself are contained in clusters, indicating that the majority of stars in this Rosette Complex formed in embedded clusters (Román-Zúñiga et al. 2007). The data were obtained with the Florida Multi Object Imaging Near-Infrared Grism Observational Spectrometer (FLAMINGOS) at the KPNO 2.1m telescope. Many studies of this type focus on relatively nearby star forming regions, and utilize capabilities that include NIR imaging and NIR/optical spectroscopy over wide areas, and telescopes in the 2-4 meter range will remain in demand.

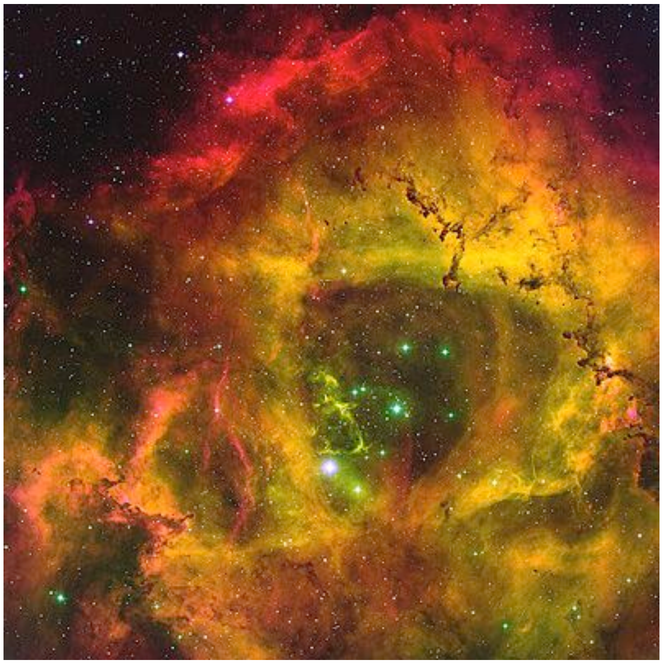

Figure III.C.2: KPNO 0.9-m image of the Rosette Nebula. Image credit: T. A. Rector/University of Alaska Anchorage, WIYN and NOAO/AURA/NSF

How do newly forming stars interact with their environments?

The interaction of outflows from young stellar objects (YSOs) with the surrounding medium gives rise to regions of shock-excited emission of light that (in the optical) are know as Herbig Haro (HH) objects. Although the existence of HH objects has been known for many years, a wide range of advanced studies in the general field of stellar outflows and jets are being undertaken. For example, how an outflow interacts with the surrounding molecular cloud, how radiation fields from nearby stars affect outflow physics, and which YSOs launch outflows (and for how long) are just some of the questions under active investigation.

For example, narrow-band imaging on the 4-m Mayall with the MOSAIC imagers revealed new, irradiated HH objects in the Pelican Nebula (Bally & Reipurth 2003), demonstrating that vigorous star formation is still occurring in clouds that surround this evolved complex. Another narrow-band study focused on the 2.56 m Nordic Optical Telescope and the 3.58 m NTT of B335, an isolated cloud containing one of the best examples of a Class 0 source (the earliest evolutionary phase of star formation) (Gålfalk & Olofsson 2007). Along with discovering new HH objects and infrared H_2 knots, they were able to make a proper motion map of the flow activity to investigate physical properties in the cloud through shock models. Another example of multi-epoch, "time domain" research in star formation is a study by McGroarty, et al. (2007), using the 2.5-m Isaac Newton Telescope and Wide Field Camera, that reinforces the notion that proper motions are among the best means to conclusively determine the driver of an outflow.

Observational capabilities that allow for multi-epoch observations, and include near-infrared and optical narrow-band imaging over wide areas, are needed to connect jets and outflows with their YSO drivers. NIR spectroscopy, and high angular resolution narrow-band NIR imaging are required to better understand jet physics. Telescopes in the 2-4 meter range will remain workhorse instruments in these studies.

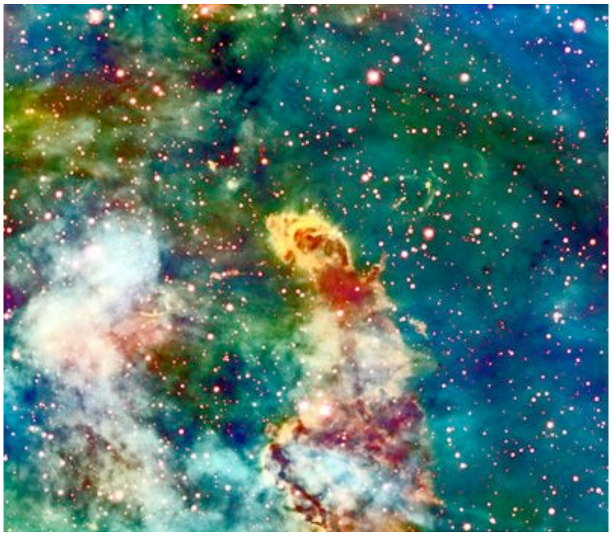

Figure III.C.3: This image from the Blanco 4-meter telescope was used to discover an extremely large outflow in the Carina Nebula, known as Herbig-Haro 666 (HH 666). Ionized gas squirts out along the polar axis of the hidden young star in this jet-like outflow at speeds up to 500,000 mph (Smith, Bally & Brooks 2004).

Image credit: Nathan Smith and John Bally (University of Colorado) and NOAO/AURA/NSF

How do circumstellar disks evolve?

Observational evidence has revealed that most young stars are surrounded by circumstellar disks that are remnants of the star formation process itself. How a circumstellar disk transitions to a stellar/planetary system is perhaps one of the most interesting (and exciting) areas of star formation research. This multidisciplinary area of star formation study, in particular, bridges the fields of stellar and planetary astronomy.

Understanding the interaction of gas and dust dynamics is vital if we are to understand the mechanisms and timescales involved in solar system formation.

Many young brown dwarfs exhibit infrared excess from disks and emission lines related to accretion, similar to classical T Tauri stars. Using the Hubble Space Telescope, the CTIO 4-m Blanco Telescope, and Spitzer, Luhman et al. (2005) identified a very low mass (~8 M_J), free-floating brown dwarf with a disk. Similarly, using ESO's VLT and 3.6-m NTT telescopes, Jayawardhana & Ivanov (2006) obtained optical spectra of isolated planetary mass candidates in the Chamaeleon II, Lupus I, and Ophiuchus star-forming regions, and found that four objects with masses between ~5-15 M_J were surrounded by "circumsubstellar" disks.

Optically thick, edge-on disks are prime targets for spatially resolved observations in the visible or infrared. Using adaptive optics polarimetry with the Lick Observatory 3-m Shane telescope, and subsequent observations with Keck, Perrin et al. (2006) found a disk around the Herbig Ae star in the PDS 144 binary system, providing the first intermediate-mass analog of HK Tau and similar T Tauri stars.

Understanding the role that circumstellar disks play in the formation of high mass stars is also of interest. For example, using Spitzer IRAC and 1.8-meter Lowell Observatory NIR data, a recent study (Currie et al. 2007) concluded that disks around high mass stars disperse within ~10^7 yr. Conversely, the idea that methanol masers exist in circumstellar disks around massive stars has been tested by NIR imaging surveys. De Buizer (2003), using narrow-band imaging with OSIRIS on the 4-m Blanco telescope, found that the sources had H_2 emission, originating from outflows, that was predominantly parallel to the maser distribution, arguing against a disk location for the masers.

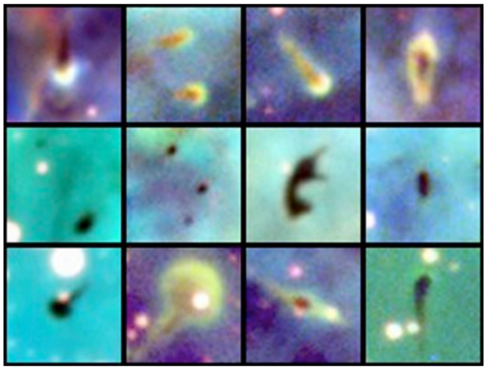

Figure III.C.4: "Proplyds" harboring disks of gas and dust that could one day form planetary systems. This group in the Carina nebula (NGC 3372), imaged with the CTIO Blanco 4-m telescope, is the first large population of these objects to have been found outside of the Orion Nebula.

Image credit: Nathan Smith, John Bally, Jacob Thiel, Jon Morse U.Colorado / CTIO / NOAO / AURA / NSF

Ground-based telescopes in the 3-5 meter range are inherently needed for these types of studies, on their own and in support of large-aperture and/or space-based programs.

How do newly forming stars interact with their circumstellar disks?

The interface between the a circumstellar disk and a YSO is an intensely interesting region that defines how stellar masses grow, how a YSO regulates its angular momentum, and the physics responsible for outbursts, jets and outflows.

The regulation of angular momentum is a key process in the evolution of newly forming stars. For solar-mass stars, the rotational evolution is mainly determined by the magnetic interaction with a circumstellar disk, and angular momentum loss through stellar winds. For very low mass stars and brown dwarfs, which are likely to be fully convective, major differences in rotation and activity are to be expected, since fully convective objects may not host a solar-type dynamo (Eislöffel & Scholz 2007). Small to moderate size telescopes have played a huge role in these studies, primarily through photometric determination of stellar/pre-stellar rotation rates, but also by means of follow-up observations. Just a few examples of these studies: include: 1) a multiyear photometric study of IC 348 using the Van Vleck Observatory 0.6-m telescope (Cohen et al. 2004); 2) a rotational and variability study of a large sample of PMS stars in NGC2264 using the Wide Field Imager on the 2.2 m telescope on La Silla (Lamm et al. 2004); 3) M-, N-, and Q-band observations with the 3.8-m UKIRT telescope, together with published rotation rates from photometric monitoring, to probe a region in T Tauri circumstellar dust disks from a few stellar radii through the terrestrial planet zone (Kundurthy et al. 2006); and 4) a study the presence of disks around brown dwarfs in the Taurus cloud, using Spitzer, 2MASS and optical photometric data from telescopes including the3.6-m CFHT (Guieu et al. 2007).

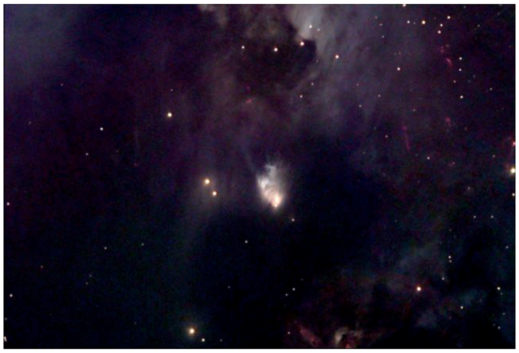

Figure III.C.5: McNeil's Nebula from http://www.noao.edu/outreach/aop/observers/mcneil.html Image credit: Adam Block/NOAO/AURA/NSF

The 2004 outburst of the young star V1647 Ori, associated with "McNeil's Nebula", offered a rare opportunity to study the outburst of a low-mass pre-main-sequence star. V1647 Ori appears to be a deeply embedded low-mass pre-main-sequence star, surrounded by a disk, with the outburst having been caused by increased accretion with an accompanying stellar wind (Acosta-Pulido et al. 2007). Among the many post-outburst studies include: 1) optical photometric monitoring, using the SMARTS[3] facilities at Cerro Tololo (Walter et al. 2004); 2) NIR photometric and low-resolution

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[3] SMARTS, the Small and Moderate Aperture Research Telescope System, is a consortium of universities and research institutions that operate the small telescopes at Cerro Tololo under contract with AURA

optical spectroscopic monitoring observations using 2.0-m and 1.2-m telescopes (e.g., Oja et al. 2006); and 3) NIR spectroscopy using SpeX on the 3.0-m IRTF (Vacca et al. 2004) and NIR spectra obtained with Keck and the 3.0-m IRTF (Gibb et al. 2006), to look for and characterize disk properties.

Summary of Star Formation and ISM Science

The need for wide-field images of Galactic star-forming regions, both in narrow and wide bandpasses, fits well with the capabilities of 4-meter telescopes. The clustering of YSOs and their relative brightness makes them ideal targets as well for multi-slit observations on mid-sized telescopes. While upcoming surveys will provide some of the required near-infrared imaging, the need for narrow-band observations as well as spectroscopy will continue to be strong. The impact of many of the optical surveys (i.e., LSST and PanSTARRS) may be smaller in this field of study, because the ugriz filters are not designed for star formation work, because many of these regions are heavily extincted, and because pipeline reductions of these very crowded fields with variable extinction may be unreliable. Progress in this field will continue to rely on telescopes like those in the ReSTAR system.

Capabilities for Star Formation and ISM Science:

- Narrow-band (i.e., specialized filter) wide-field optical imaging
- Narrow-band wide-field near-infrared imaging
- Low to moderate resolution near-infrared multi-object spectroscopy (R~3000)
- High spatial resolution narrow-field optical and NIR imaging
- Interferometry
- Wide-Field broad-band optical imaging

D. Stellar Astrophysics

Stellar astrophysics can benefit enormously from investing in small and midsized telescopes. For many fields of study within stellar astronomy, interesting and important stars are bright enough to observe with reasonable exposure times on 1-5 meter telescopes. In many cases, such as broadband imaging searches for variability, large telescopes lead to saturation and unusable results. Also, stars with interesting kinematic or photometric properties are often widely spaced on the sky; therefore the need is for additional time on smaller apertures to observe single objects, rather than observing the faintest objects in a single field. Time-domain explorations of stellar variation, caused by pulsations, unstable mass transfer, etc. require multiple coordinated observing sites for which small telescopes are much more readily available and efficient. We highlight some of the specific contributions of small and midsized telescopes to crucial questions of stellar structure, evolution and nucleosynthesis.

What are the fundamental properties of stars?

For all celestial objects, we want the answers to certain fundamental questions: how large is it? How massive? How luminous? How hot? How old? The answers to these questions are crucial for understanding the inner structure of stars and how they work, and for interpreting stellar populations from star clusters to galaxies.

The Sun has long been the only resolved star that we could study. However, the power of optical interferometry has permitted the imaging of the surfaces of other stars. These images provide direct measurements of the radius of the star, the size of the equatorial bulge and the amount of limb and gravitational darkening. Observations via interferometry have exposed unsuspected weaknesses in the abilities of theories of stellar structure and stellar atmospheres to reproduce the observations (i.e., Figure III.D.1) (Monnier, et al. 2007)

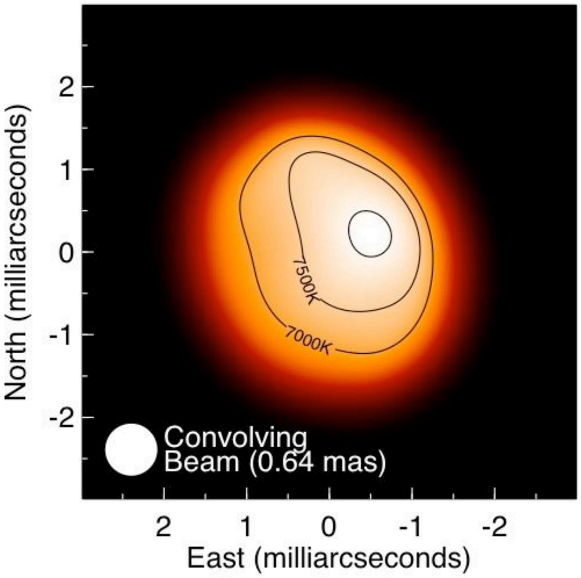

Figure III.D.1: The surface of Altair imaged with the CHARA interferometer. Altair is a rapidly rotating star, which leads to R_{pole}/R_{eq}=0.82. The image confirms qualitatively the idea that rapid rotation affects gravity darkening, but the magnitude of the effect disagrees with theory. This indicates that there is important physics (such as differential rotation, convection or opacity effects) not included in the models.
Credit: Science/John Monnier

Other recent advances from interferometry include measurement of the radii of M stars (Berger et al. 2006), calibration of Cepheid distances (Merand, et al 2005) and study of the structure of the atmosphere of Mira stars (e.g. Millan-Gabet, R. et al 2005). The number of bright stars that have been studied by interferometry so far is quite small, while the number of targets is larger and will only increase when the upgrades to the current and planned interferometers are considered.

Asteroseismology provides another technique of probing stellar structure. With adequate time-series data (either photometry or radial velocity), comparison with theoretical models can yield detailed stellar parameters (for example, masses, radii, rotation rates, and ages) with high precision. For some pulsators, the observed frequencies can reveal subsurface structure such as compositional stratification and internal differential rotation. Asteroseismology has been used to study stars ranging from the main sequence through white dwarfs. Recently, for example, the mass, temperature, gravity, metallicity, and helium abundance, all to much higher precision than possible with other techniques, have been determined for α Centauri (Bouchy & Carrier 2002). The data were time-series measurements of radial velocities, which yielded *p*-mode frequencies that were then fit with seismic models.

Among more evolved stars, the success in white dwarf seismology is notable. Pulsating white dwarfs give us a chance to measure their mass to high precision. Many white dwarfs have had their internal structure decoded, with measurements of the thickness of their hydrogen and helium layers, providing important constraints on pre-white dwarf evolution and giving an observational demonstration of diffusion in stars. Measurement of the secular period change in these stars has helped calibrate white dwarf cooling curves (and therefore theoretical white dwarf luminosity functions) and placed important limits on the rate of neutrino emission from stars. Recently, timings of pulsations of one of the sdB stars, using observations from 1-3 m class telescopes, provided the key to the discovery of the first exoplanet that has survived the red giant phase (and core helium flash) of its host star (Silvotti et al. 2007). This technique has just barely begun to be exploited for stars beyond the Sun.

The flight of GAIA will provide accurate (<5% error) distances to an immense number (26 million) of bright stars (V<15), offering another opportunity to improve our understanding of stellar structure. While the information from GAIA will be crucial, it will be by no means complete, and we anticipate that interesting subclasses (for example subdwarf stars and variable stars, such as eclipsing binaries and ellipsoidal variables) will require subsequent observations on 1-4 meter class telescopes before their properties can be fully elucidated.

What are the properties of planet-harboring stars?

One of the most dynamic and rapidly growing areas of astronomy has been the discovery and study of exoplanet systems. Clearly, to understand the structure and formation of planetary system, we need to know the properties of their host stars as well. One fundamental example of this is the higher average metallicity of systems with planets (i.e. Figure III.D.2) (Laughlin 2001; Gonzalez et al. 2001).

Planets and planetary material should interact with the stars in various ways, such as polluting the stellar atmosphere with fresh metals (e.g. Ecuvillon et al 2006) and perhaps inducing chromospheric activity in the star (Shkolnik et al, 2003). To study such effects, different observing techniques than those used in the discovery of the system are needed. In particular, wide wavelength coverage, as well as high spectral resolution, is required to observe a sufficient number of lines of the diagnostic element. At least several hundred planets with V<14 are anticipated to be found with the upcoming surveys, such as the Kepler mission, now slated for launch in early 2009. Since there are only about 3500 stars with high-resolution abundance analysis and over 2 million stars in the Tycho (V< 12) catalog, very few planet-harboring stars already have the necessary data. These are ideal targets for studying with small and mid-sized telescopes.

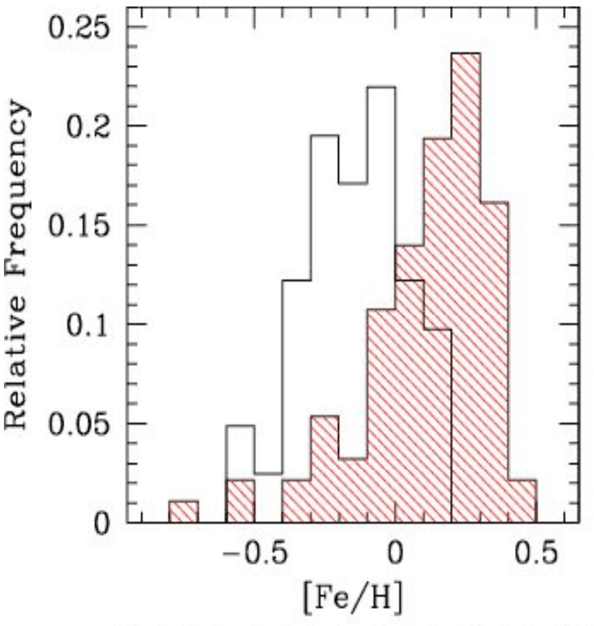

Figure III.D.2: Histogram comparing the metallicities of stars with planets (red histogram) with a volume-limited comparison sample (white histogram). The stars harboring planets are more metal-rich on average than the comparison sample. This work was done using a large number of telescopes, with the majority in the 1-4 meter class. (Santos, et al. 2004)

What are the origins of the elements?

While we know that that stars are responsible for the formation of the elements heavier than helium, this broad statement hides our ignorance of the actual processes and sites at work at different stages of stellar evolution. Some critical questions include:

- What, besides Fe, do Type Ia SNe produce? Is this metallicity-dependent?
- Where are the nucleosynthesis sites of elements that are observed in gas-phase at high redshift such as Zn?
- What polluted the most iron-poor stars? (e.g. Figure III.D.3)
- Where is the site of the rapid neutron-capture process?

The three main observational strategies are observations of the nucleosynthesis in situ (on the surfaces of AGB stars, Wolf-Rayet stars and stars heavily polluted by AGB stars), the detection of correlations between elements, and the measurement of abundance ratios in systems with different star formation histories. Recent examples for each technique include the proof that Pop II AGB stars produce fluorine (Schuler et al. 2007), the discovery of weak r-process and the main universal r-process (e.g. McWilliam et al. 1995), and the dependence of Mn production on the metallicity of the SN (e.g. Feltzing et al. 2007). Each of these was either exclusively or in part done on small to midsize telescopes.

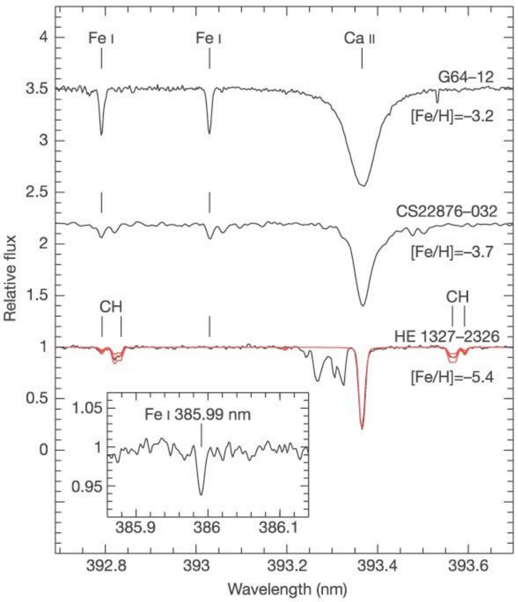

Figure III.D.3: The spectrum of the most iron-poor star, HE 1327-2326, compared with other metal-poor stars. Note the extreme over-enhancement of C, seen in the CH lines. This pattern is also seen in the two next most iron-poor stars. The source of this pollution is unknown, but the abundance ratios of this star are directly connected to the PopIII object that polluted it. This is a bright star, V=13.5 mag,; the anomalies were discovered with Blanco 4-m data. (Frebel, et al. 2005)

How was the stellar component of the Milky Way assembled?

As we establish the types of stars that manufacture different elements, we can use that information to interpret the evolution of components of the Milky Way, nearby galaxies, and, with less detail, higher redshift galaxies and gas. The most prominent example is the [α/Fe] ratios of galaxies, where the start of Fe contributions from Type Ia SN causes the ratio of elements produced only in Type II SN (e.g. O) with respect to Fe to drop (Figure III.D.4). This technique is most effective when kinematics can be used to isolate interesting stellar populations (e.g., Bensby et al. 2004). The RAVE and GAIA surveys will provide radial velocities, [Ca/H] and, in the case of GAIA, proper motions, producing a rich target list of bright stars belonging to different parts of the Galaxy. It is clear from looking at the halo, the disk, the bulge, the globular clusters, and the dwarf spheroidals that element ratios, including Mn, Cu, Zn, Y and Ba vary depending on their environment (e.g. Venn et al. 2004). Therefore, we can "fingerprint" the origin of stars by measuring the abundances of many elements from high-resolution optical or near-infrared spectrographs (Freeman & Bland-Hawthorn 2002).

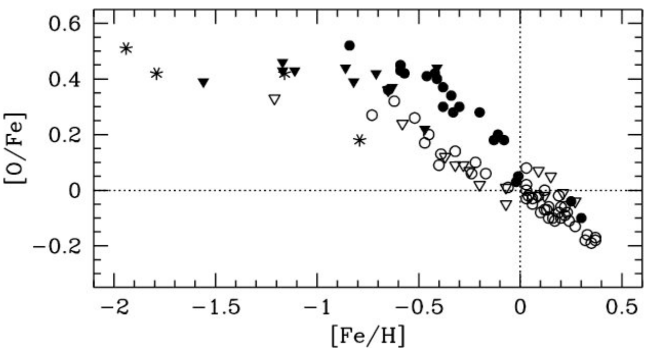

Figure III.D.4: [O/Fe] in thin disk (open symbols) and thick disk (filled symbols) stars. These kinematically selected stars show that the thick disk had more intensive star formation at the beginning, so it reached higher [Fe/H] values before Type Ia pollution began. This work was done on the La Silla 3.6 meter telescope. (Bensby et al. 2004)

What is the nature of objects at the extremes of the mass function?

A number of imaging and proper motion surveys, both past and present, have found interesting candidates for the lowest mass brown dwarfs. However, low-resolution spectra are needed to verify the identifications, calculate parameters, and fulfill the scientific aims of the surveys, such as determining the mass function of brown dwarfs (Figure III.D.5). The number of targets will only increase with the arrival of WISE all—sky imaging in the IR and PanSTARRS and LSST imaging in the optical, as well as GAIA. The brighter of these will be accessible to low-resolution optical and NIR spectroscopy on 4-meter class telescopes.

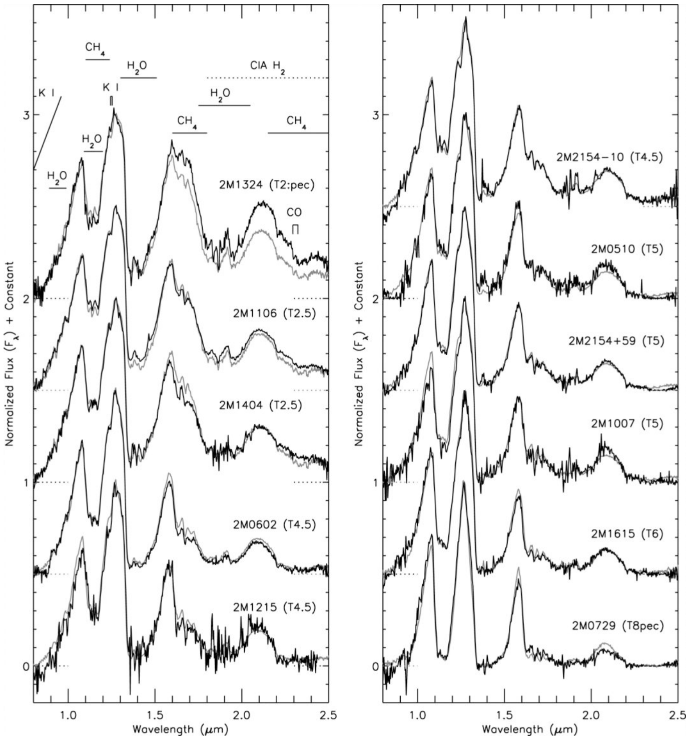

Figure III.D.5: Near-infrared spectra from the IRTF of 11 newly discovered nearby T dwarfs. Nine of these T dwarfs are within 25 pc, adding to the census in the solar neighborhood and providing ideal candidates to study the presence of close-by companions.
(Looper, et al. 2007)

At the other end, the upper mass limit for stars is not known. This limit impacts our understanding of star formation, chemical evolution and the detectability of high-redshift SN. Eclipsing binaries are the best systems for determining masses. The discovery of such systems is frequently made on small telescopes, including the SMARTS telescopes, the OGLE telescopes and the Blanco 4-m. Depending on the brightness, the follow-up radial velocity measurements also fall within the capabilities of mid-sized telescopes can also be done. Because stars become increasingly rare as the mass increases, continued effort in this area, sparked by imaging campaigns such as OGLE, is required to pin down the ultimate mass limit for stars.

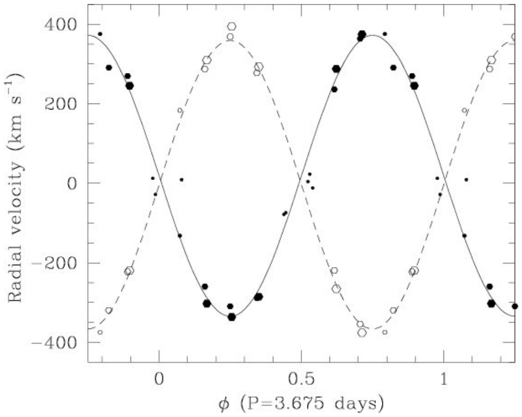

Figure III.D.6: The radial velocity measurements for the eclipsing binary system consisting of the two most massive stars known, approximately 80 solar masses apiece. These measurements were taken with the 3.5 NTT telescope at La Silla. (Rauw et al. 2004)

Summary of Stellar Science

We have mentioned just a few of the areas of stellar physics that benefit enormously from, or indeed require, the use of small and mid-sized telescopes. For many techniques, such as interferometry and asteroseismology, we have barely begun to study the accessible targets. Synoptic imaging and spectroscopy are vital for these techniques. For other areas, the coming years will see an explosion of information about the distances, kinematics, colors and variability of stars, as well as identification of stars with planets. To understand what these stars are telling us, need additional data, in particular spectroscopy, both optical and NIR and both low and high-dispersion.

Capabilities for Stellar Science:

- High-resolution narrow field optical (ideally to the atmospheric cutoff in the blue) spectroscopy
- High-resolution narrow field near-infrared spectroscopy
- Low-resolution optical and near-infrared spectroscopy, both single-slit and multi-slit
- Interferometry
- Narrow-field optical and near-infrared imaging

E. Compact Objects and Accretion Physics

Accreting compact objects result in some of the most spectacular phenomenology in the sky. Novae and supernovae, quasars and blazars, and many other explosive and highly energetic sources result from accretion onto black holes, neutron stars and white dwarfs. These sources divide naturally into two categories, namely accreting compact binaries (where “compact” refers to the nature of the accreting star) and AGN, which display accretion onto a supermassive black hole. While these two categories of sources differ by many orders of magnitude in their masses and scales, they display remarkably similar physical processes. Indeed, a strong argument for the existence of black holes is that it is hard to imagine any other kind of object whose physical characteristics remain similar when scaled in mass by eight orders of magnitude.

Much of the astronomical community's huge investment in high-energy astrophysics, including orbiting X-ray and gamma-ray observatories and ground-based air shower arrays, is motivated by studying accretion onto compact objects and the wide variety of phenomena so produced. But it has become clear that this is a truly multiwavelength endeavor – many crucial constraints can only be provided by optical and infrared observations. Small and mid-sized telescopes play a critically important role in such studies, and relatively modest instrumentation, thoughtfully created and operated, will be crucial to exploiting the multi-billion dollar investment in high-energy astrophysics. It should also be noted that many of the scientists at the forefront of exploring these issues work at NASA research labs and other institutions that do not have a tradition of private access to ground-based telescopes. Thus an appropriate set of publicly available facilities is particularly important in this area.

While individual objects and phenomena can spawn whole subfields in this area, two general overarching science goals can be identified. One is to understand the physical processes of accretion. Accretion physics is of course important in other areas of astronomy, notably star formation, but it is on display in an unusually pure and often spectacular way when the accretor is a compact object. The other primary goal is to understand the distribution, demographics, and evolution of compact binaries and AGN. Below we discuss the importance and current status of each of these broad questions, and the ways in which small and mid-sized ground-based optical/IR telescope are crucial to improving our understanding of these issues.

What are the physical processes that govern the inflow and outflow of material onto compact objects?

The fundamental observable characteristic of accreting compact objects is dramatic variability on many timescales – hence the name "cataclysmic variables". The physical processes that govern accretion and changes in accretion are complex, and our understanding is still quite limited, but dramatic improvement is possible in the near future. Some of this growth will be fueled by new instruments at other wavelengths, but ground-based O/IR observations with small and mid-sized telescopes will play a crucial role.

One source of dramatic variability is thermonuclear explosions of accreted material, which result in novae (on white dwarfs) and X-ray bursts (on neutron stars). The absence of such explosions is one of the markers of accretion onto black holes, which lack a surface on which material can accumulate. Understanding the dynamics of expanding nova shells is of special importance, both for understanding the chemical enrichment of the interstellar medium, and because current evidence suggests that in many cases novae expel more material than they accrete, which would make it impossible for the accreting white dwarfs to cross the Chandrasekhar limit and become Type Ia supernovae. The key observations required are spectra taken over the many months following the nova event (e.g. Ederoclite et al. 2006). Since novae are optically intrinsically bright, and require flexible scheduling, such observations are ideal for smaller telescopes.

Another source of variability is change in the mass transfer rate and therefore in the accretion luminosity. This is thought to be the root cause of dwarf novae outbursts, and of the transient nature of many strong X-ray sources. In binary systems, these cycles are often attributed to the by now classic “Disk Instability Mechanism” (Bath & Pringle 1982; Cannizzo, Ghosh & Wheeler 1982), but recent detailed studies of a variety of object have suggested that other factors may be involved. Changes in the mass transfer rate appear to result in significant changes in accretion flow geometry (Remillard & McClintock 2006), from disks to radial flows such as ADAFs. Some geometries can reveal dramatic strong-field relativistic effects (Garcia et al. 2001), and in others jets and outflows may be ubiquitous (Fender, Belloni & Gallo 2004). Thus understanding the physics of accretion flows, and how they change with time, is of broad importance. The observational data required are coordinated multi-wavelength campaigns, since the outer accretion disk (dominant in optical and IR bandpasses) provides a boundary condition for the UV and X-ray emitting inner accretion flow, which in turn creates the conditions for radio-loud outflows. Since many of these sources, both galactic binaries and AGN, are optically quite bright, these are again ideal targets for smaller telescopes.

Variability is also a key to understanding the structure of AGN. Reverberation mapping (Blandford & McKee 1982) is an extremely powerful tool, but it requires multiwavelength monitoring and spectroscopy over periods of months to years. Monitoring strongly lensed quasars to search for time delays between the components is also a very powerful tool, providing information about the structure of the quasar and the lensing galaxy, and potentially about cosmology as well. In this case also, monitoring must be sustained over months and years. Recently considerable progress has been made using 1m-class telescopes optimized for such monitoring studies (see Figure III.E.1), but this only scratches the surface of what is possible as more appropriate sources are discovered.

A particular opportunity for coordinated O/IR/high-energy observations will be created by the upcoming launch of GLAST. GLAST will provide orders-of-magnitude better sensitivity to GeV gamma-rays than previous missions such as EGRET on CGRO. One particular focus of GLAST science will be blazars, dozens of which will be monitored continuously. The spectral energy distribution (SED) of blazars is dominated by two emission peaks, one in gamma-rays, and one in the optical/IR (Fossati et al. 1998). The basic emission mechanisms behind blazar SEDs are still subject of considerable dispute (Boettcher 2007 and references therein). Correlations and time lags between the two SED peaks provide particularly strong constraints on theories of these sources. The relationship of the optical emission lines to the continuum emission is also of considerable interest. Since the optical brightness of these sources ranges from V=10-17, they can be observed with small telescopes. However they vary dramatically on timescales of hours, so obtaining an equivalent O/IR data set to compare with the continuous GLAST coverage currently will require careful coordination across many sites, particularly if equivalent widths of the emission lines as well as broad-band photometry is to be obtained.

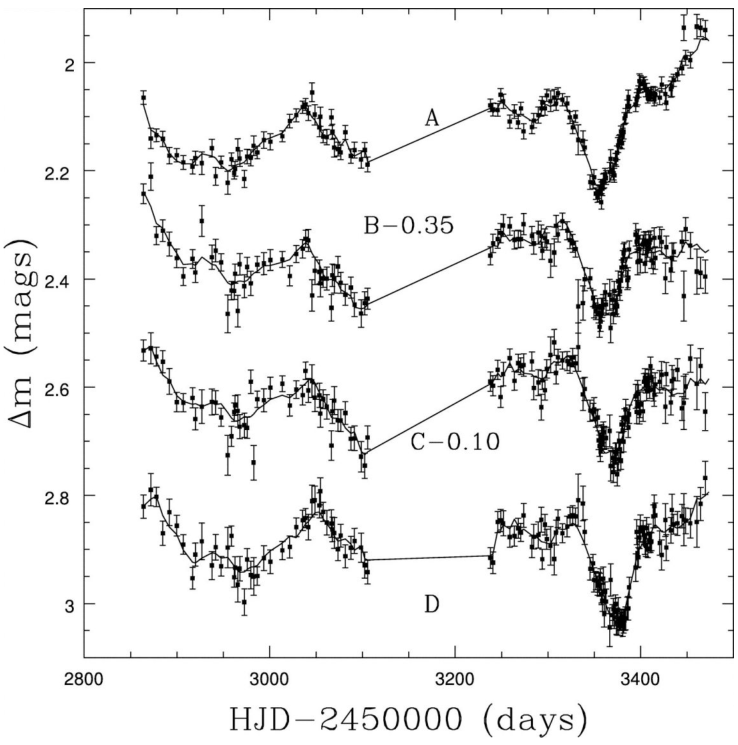

Figure III.E.1: Lightcurves of the components of the lensed quasar HE 043-1223 obtained with the SMARTS 1.3m queue-scheduled telescope. From Kochanek et al. (2006).

What are the demographics of accreting compact objects, and what are the evolutionary processes responsible for them?

Understanding the demographics of compact objects is a difficult task, as the selection effects governing their discovery are unusually complex. However it is crucial to try to sort them out. In the case of AGN, a detailed understanding of demographics and evolution is required to investigate the co-evolution of black holes and galaxies, and also to understand how AGN turn on and off. In the case of compact binary systems, demographics and evolution are interesting both for their own sake, and because of the importance of the end products of compact binary evolution. These end products include Type Ia supernovae, and mergers of compact objects, which are potentially observable sources of gravitational wave radiation and are thought to result in “short” gamma-ray bursts.

Considerable progress has been made recently in understanding AGN demographics through very deep moderate area (a few degrees) multiwavelength surveys, such as the GOODS collaboration (Giavalisco et al. 2004). By combining deep X-ray images with deep multi-color optical and IR photometry, many of the biases in discovering AGN can be understood and mitigated. The next steps will be to extend such surveys in area and depth, and to understand the distribution of the AGN in redshift. The latter will require deep multi-object spectroscopy for the brighter sources, and photometric redshifts for the fainter ones. As in the case of galaxy evolution, the need for photometric redshifts will drive surveys with a variety of intermediate and narrow band filters, which will require considerable time on moderate aperture telescopes. Understanding AGN will also require repeated surveys to study variability of these sources. Discovering AGN through their variability properties provides another cut through the discovery space. Determining the variability characteristics of appropriately chosen sample will be crucial for understanding the accretion processes, and the balance of black hole growth mechanisms between mergers and accretion.

The observational biases in discovering compact binaries are even more extreme, since they are generally identified by their outbursts. Binary black holes in particular are most often transient systems identified by their occasional huge X-ray outbursts. Estimates of the number of quiescent systems containing compact objects must therefore include assumptions about outburst frequency, which can vary by orders of magnitude. Searches for such systems in their quiescent state hold promise (Grindlay et al. 2005), and, as for AGN, require a combination of deep X-ray surveys and broad and narrow band optical/IR imaging, but in this case of the galactic plane.

Once they have been discovered, information about the orbital parameters of binary systems is required to fully understand their demographics and evolution (see Figure III.E.2)

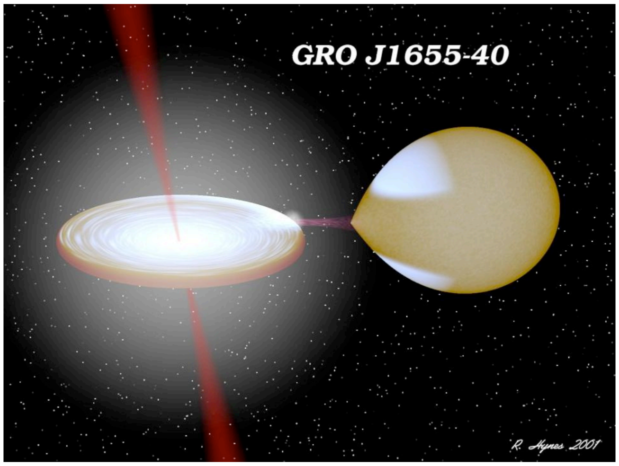

Figure III.E.2 (1655): Artist's conception of the black hole binary system GRO J1655-40 with binary parameters taken from the recent literature. Image created with BinSim, created by Rob Hynes.

The first, most critical parameter is the orbital period, which requires observations with time resolution much shorter than the orbital period, sustained over durations long compared to the period. Since crucial objects are spread over the sky, and the appropriate time cadence varies from object to object, this task is generally carried out on an object-by-object basis. To do this for large samples of objects thus requires substantial amounts of telescope time. Time resolved spectroscopy is particularly important, since it is required to determine radial velocity curves, which in turn determine the masses of the components. The mass of the compact object is particularly important, since if it is greater than the upper limit of stability of a neutron star (around 3 solar masses), the mass provides unambiguous evidence for the presence of a black hole in the system. Since the exposure times are limited to a fraction of the orbital period, which can be as short as a few hours, some of the fainter systems require observations with large telescopes. But since the duration of the relevant series of observations is determined by the orbital period, rather than by signal-to-noise considerations, it is particularly inefficient to use large telescopes for studies of these kinds when they are not needed. Thus telescopes equipped for time resolved photometry and spectroscopy across the full range of apertures is crucial.

Summary of Science for Compact Objects and Accretion Physics

Observations of compact objects range from studying nearby neutron star or black halo binaries to studying massive black holes in luminous quasars at the edge of the Universe. This wide variety of targets requires a variety of observing techniques, including many that are well-suited to the ReSTAR system, especially monitoring the behavior of variable sources on a variety of cadences, both spectroscopically and photometrically, and synchronizing observations for multi-wavelength studies. As new space-based and ground-based facilities (JWST and LSST, for example) become available, the presence of a flexible system of 2-4 meter telescopes will be needed to provide the crucial data unavailable through these sources.

Capabilities for Science for Compact Objects and Accretion Physics:

- Narrow-field broadband imaging, both optical and near-infrared
- Narrow-field, narrow-band imaging
- Low/moderate resolution optical (and some near-infrared) spectroscopy

F. The Structure and Evolution of Galaxies

Over the past several decades, work with modest-sized telescopes has produced a revolution in our understanding of galaxy formation and evolution. For example, we have learned that mergers have played a far more important role in the formation and evolution of galaxies than previously imagined. We have found that galaxies lose material through winds, polluting intergalactic space and acting as a feedback to internal processes in disks. We have discovered robust trends between average gas densities and star formation rates, between galactic mass and metallicity, and between galactic mass and star formation histories. Yet, we still do not understand some of the fundamental processes that drive the evolution of galaxies. Studies of nearby galaxies provide the best opportunity for sensitive, high-resolution studies of ongoing galactic processes, while studies of galaxies at increasing redshift provide a longer timeline over which to judge the effects of galaxy evolution. Here we identify five basic questions in galaxy evolution that confront us. Some of the work that is needed on nearby galaxies must be done laboriously star by star, and some on large-scale properties of statistically significant samples of galaxies. But both types of studies require lots of time with excellent instruments on modest-sized telescopes to answer these questions.

How do external and internal influences shape galaxies along the Hubble sequence?

It is becoming increasingly clear from recent work that the morphological evolution of galaxies is determined by both external and internal processes. The importance of galaxy interactions has become clearer in the last decade, and it is now the working assumption that mergers play a central role in building galaxies, central bulges, and the supermassive black holes in the centers of galaxies. But at the same time we are beginning to understand the degree to which feedback from local star formation and mass inflow can also drive the evolution of galaxy structure from within. To what extent do internal processes in galaxies define their ultimate structure, and to what extent will the effects of internal processes be overwritten by galaxy interactions?

Progress on the theoretical side has accelerated over the last decade, expanding upon the small number of early studies (Toomre & Toomre 1972, Toomre 1977, Barnes 1988, 1992). A number of powerful numerical simulations, in which the effects of gas dissipation and star formation are included, give quantitative predictions of the effects of galaxy merging as well as a variety of internal processes (e.g. Barnes & Hernquist 1996; Mihos & Hernquist 1994, 1996; Naab & Burkert 2003; Hopkins et al. 2006b; Robertson et al. 2006; Hopkins et al. 2007). These models can be compared with measurements of various photometric and kinematic diagnostics and guide their interpretation (e.g. Kormendy & Bender 1996, Genzel et al. 2001, Dasyra et al. 2006, Rothberg & Joseph 2006a,b).

Thus, the study of galaxy evolution is poised to delve into a careful, quantitative study of these effects. This is what we need:

1. A survey of large samples of galaxies with a variety of narrow band and spectroscopic techniques in order to characterize gas abundances and stellar populations in different environments as well as detailed kinematics to distinguish the different processing effects in galaxies.
2. A complete survey of all tidal features in the Local Group (see, for example, Figure 111.F.1).
3. Comprehensive, wide-field studies of nearby galaxies outside the Local Group to search for structures created by interactions or large-scale galaxy winds from starburst events (see, for example, Figure III.F.3). And,
4. Narrow-band and spectroscopic followup of more distant galaxies discovered in large-scale surveys in order to characterize the region of relevant parameter space being spanned by a particular galaxy population.

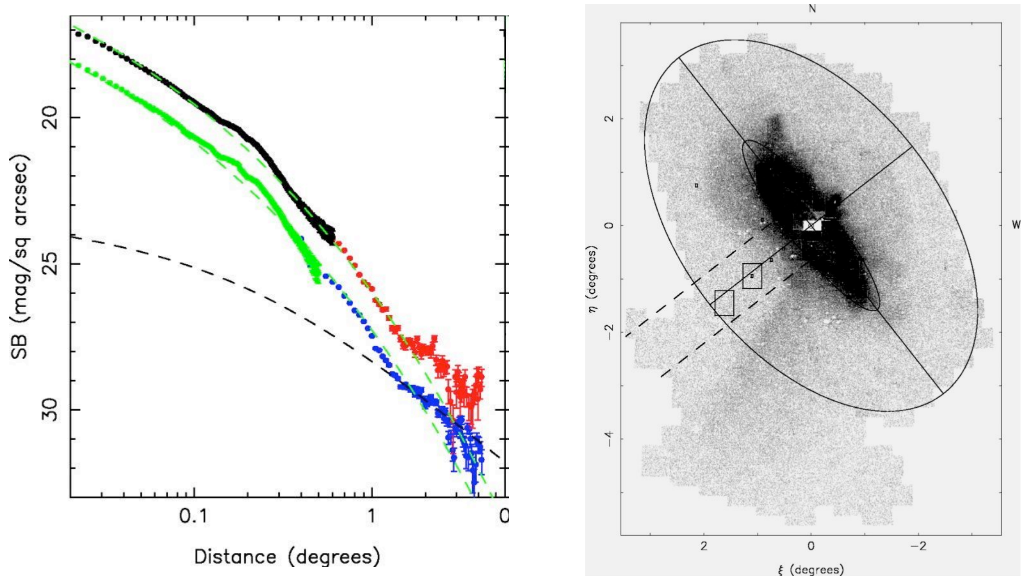

Figure III.F.1: INT 2.5 m imaging. Star counts coupled with surface photometry of the extreme outer disk of M31 have revealed morphological relics of a complex formation history that has included absorption of dwarf satellites (Irwin et al. 2005).

Kinematic information is particularly valuable in understanding the dynamical effects occurring in galaxies, both from interactions and from internal processes. Full velocity fields are more straightforward to acquire at centimeter or millimeter wavelengths, but the resulting spatial resolution is lower than what can be achieved in the optical. However, long-slit spectroscopic surveys of merging galaxies to date have been rather small. Highly efficient, flexible spectroscopic instruments are necessary to make possible a more complete sampling of the kinematics in galaxies over a wide range of interaction and star forming histories. Therefore, a significant advance in the study of galaxy dynamics would be permitted by the installation of a small number of IFUs on telescopes in both hemispheres. These would enable detailed kinematic studies of statistically significant sample sizes for the study of different stages of interaction. Spectroscopic and IFU studies will also be able to disentangle the kinematic signatures of different populations within a single galaxy.

What conditions lead to nuclear activity in galaxies?

Mergers of gas-rich galaxies not only play a major role in the morphological evolution of galaxies, but also in the nuclear activity galaxies experience in the course of this evolution (e.g. Joseph & Wright 1985, Sanders et al. 1988, Genzel et al. 1998). We are now aware that galaxies periodically go through active phases in which the nuclei "light up" to ~100 times their normal luminosity. For nearly 25 years there has been an on-going debate about the relative importance of starbursts and AGN in powering these high luminosity phases (Heckman et al. 1983). However there is increasing evidence of a starburst-AGN connection since detailed studies are beginning to reveal the co-existence of both AGNs and starbursts in the same objects. That is, both processes are triggered by the gas inflow driven to the center of the merger by the dynamics of the interaction (e.g. Hopkins et al. 2006b).

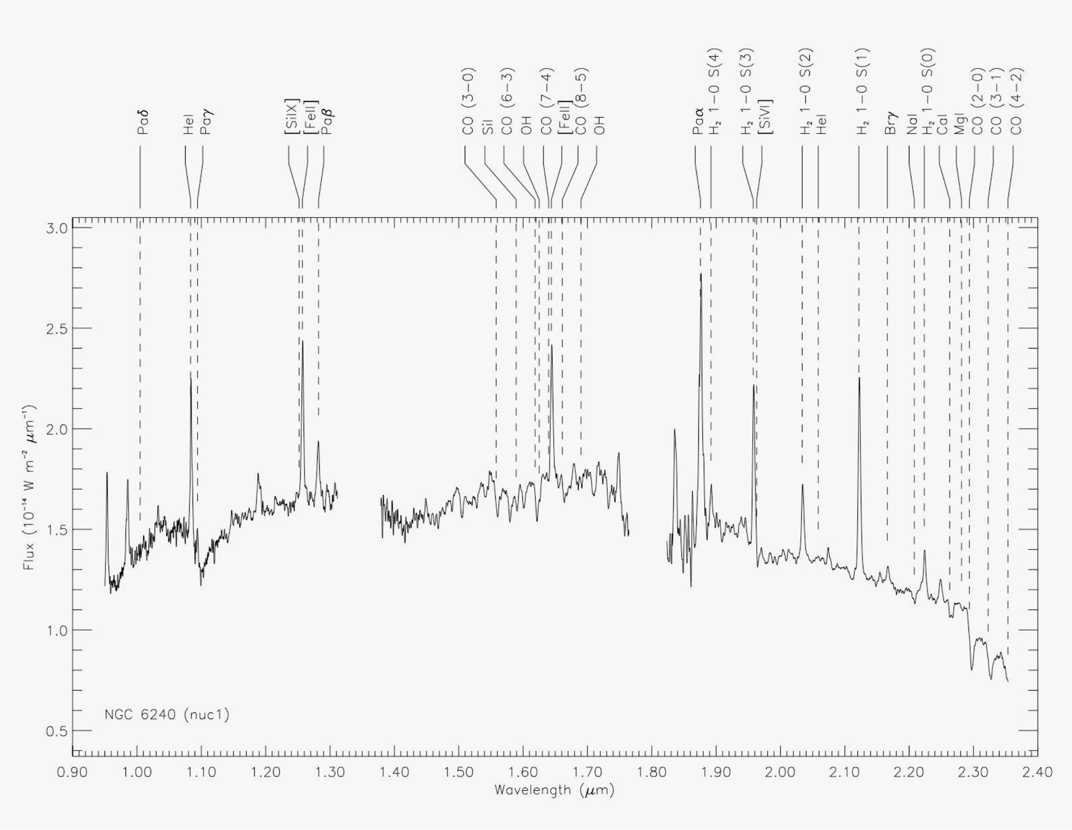

Figure III.F.2: IRTF 3 m with SpeX. A near-IR spectrum of one of the two nuclei of NGC 6240 showing the variety of atomic and molecular diagnostic features useful in understanding starbursts and AGNs in galaxy nuclei.

However, we know relatively little about the sequence of events associated with these processes or their lifetimes. For example, the inflow may first trigger accretion onto a dormant supermassive black hole and the resulting AGN outflows compress the surrounding interstellar medium and trigger a burst of star formation. Or it may be that the inflow stimulates a burst of star formation and outflows from the red giant phase of the stars formed in the starburst drive gas deep into the center of the merger to turn on an AGN. Confirming and elucidating the details of these processes are problems well-suited to medium-aperture telescopes since one needs to study samples of galaxies at relatively low redshifts to get the spatial resolution needed to discriminate AGN and starburst activity. While optical imaging and spectroscopy are important, both processes are buried in dust: the AGNs are surrounded by torii of dust and the starbursts are buried in the cocoons of dusts associated with star formation. Thus, it is infrared imaging and spectroscopy (see, for example, Figure 2) that will provide the most insight, since the extinction is much reduced (extinction at K-band is one-tenth that in the visible).

While the installation of WFC3 on HST in 2008 may provide a premier facility for optical and NIR imaging of AGN environments, infrared IFU spectroscopy on small- to mid-sized telescopes will be the *sine qua non* for detailed examination of the physics involved in the nuclear activity of galaxies.

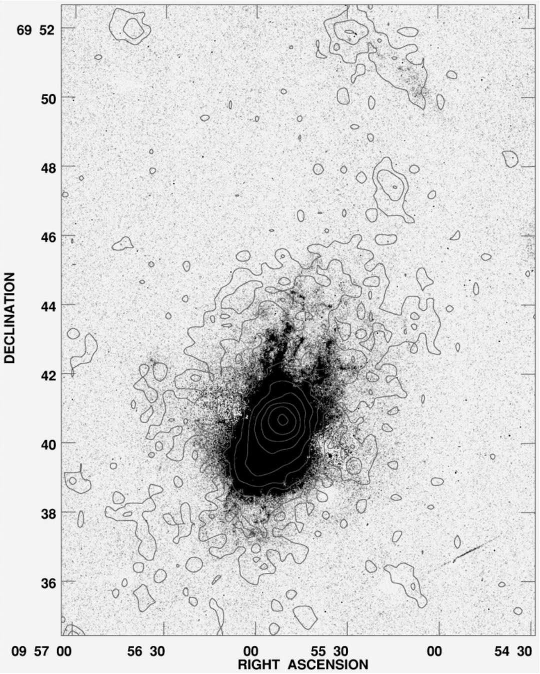

Figure III.F.3: KPNO 0.9 m narrow-band imaging. Hα (gray) and X-ray (contours) emission along the minor axis of M82 show gas being lost in the superwind of a starburst (Lehnert et al. 1999).

What are the star formation histories, enrichment histories, and star formation drivers along the Hubble sequence?

The Hubble sequence exhibits a wide variety in star formation histories (SFHs) and star formation rates (SFRs), which are correlated with the mass of the galaxy, its gas content, and the environment in which it resides. At one extreme of the Hubble sequence are red, passively evolving, bulge-dominated galaxies with old stellar populations and little current star formation. These massive galaxies formed their stars in a short burst at $z > 2$ (Kauffmann et al. 2003), and are more predominant in cluster cores. At the other extreme are blue, disk-dominated galaxies with strong young stellar populations that have had more extended star formation histories. These systems are more representative of field galaxies. This variation in star formation rates and histories along the Hubble sequence is a manifestation of ``downsizing" (Cowie et al. 1995; e.g., Homeier et al. 2006), in which smaller and smaller galaxies dominate the star-forming universe over time. Downsizing may also be responsible for the correlation between galactic mass in stars and metallicity (Tremonti et al. 2004). Downsizing has been attributed to AGN (e.g., Bower et al. 2006; Hopkins et al. 2006a) and supernova feedback (e.g., Dekel & Birnboim 2006; Menci et al. 2005; Kajisawa & Yamada 2006). But, what actually quenches star formation in some galaxies and allows it to continue in others is uncertain. Study of the star formation processes in nearby galaxies can clarify the quenching phenomena, and thus, put crucial constraints on models of star formation at high z.

The feedback from star formation and AGNs may have played a substantial role in quenching star formation and/or depleting galaxies of gas, and could explain the difference between the mass function predicted by ΛCDM models and the luminosity function observed for galaxies and the metallicity trend of galaxies (e.g., Scannapieco et al. 2005). The role of feedback, however, has not been fully quantified on observational grounds, and recent works reach almost opposite conclusions in regard to the importance of stellar feedback (Martin 2005; Grimes et al. 2006). Understanding stellar and AGN feedback is thus critical for understanding galaxy evolution. Much of the complexity in understanding feedback comes from observational limitations; a full census of feedback in galaxies requires the combination of many data at many different wavelengths (Veilleux et al. 2005), including wide-field narrow band imaging (from the ground) coupled with X-ray observations to obtain a full census of the shocks and hot gas produced by feedback, and integral field spectroscopy to provide kinematical information on the displaced cool and warm gas.

Furthermore, as one moves towards later galaxy types, the ratio of present SFR to the past average shows increased scatter (Lee 2006). Presumably this reflects environmental and internal feedback mechanisms, but we really do not understand why or how.
One of the crucial missing links in our knowledge of star formation and galaxy evolution is an understanding of the interplay between the SFR in galaxies and the underlying properties of the interstellar medium (Kennicutt et al. 2007). While the Kennicutt-Schmidt law (Kennicutt 1998, Schmidt 1959) shows a tight correlation between the average SFR per unit area and the mean surface density of cold gas, we do not understand the physical mechanisms that generate such a relation (e.g. Elmegreen 2002).

Clearly, we do not understand the basic large-scale drivers of star formation in galaxies, the feedback of star formation to the interstellar medium (see, for example, Figure III.F.3) and further star formation, and its efficiency as a function of metallicity and environment. Only nearby galaxies have the spatial scale necessary to dissect these internal processes. And, the large range of star formation histories and conditions in nearby galaxies (Grebel 2006) means that suitably instrumented moderate aperture telescopes can access many different galactic environments with relatively bright flux levels.

What are the star formation and growth processes in outer stellar disks?

The outer edges of galaxies present an extreme environment for star formation and other processes. The standard model for star formation in disks predicts a precipitous end to star formation where the average gas density drops below a critical threshold (Toomre 1964). Yet, stars are found even to a surface brightness level of $\mu_V = 31$ mag/arcsec^2 (e.g. Irwin et al. 2005), and stellar disks continue to decline as far out as they have been measured (e.g. Pohlen et al. 2002). Furthermore, recent satellite ultraviolet imaging has revealed UV-bright stellar complexes in the far outer disks of spirals, well beyond the extent of HII regions (e.g. Thilker et al. 2005). And star-forming regions have been discovered that lie 20--35 kpc from the nearby spiral, blurring our concept of the transition from galaxy to intergalactic material (e.g., Ferguson et al. 1998, Werk et al. 2007). So, how do stars form at gas densities that are, on average, a few percent of the critical threshold in outer disks (Schaye 2004)?

In addition, in many systems we also see a complex stellar surface brightness profile in the outer disk: the profile abruptly changes slope, dropping more steeply in the outer galaxy. These double-exponential surface brightness profiles are seen in the outer parts of spirals (Pohlen et al. 2002; Kregel & van der Kruit 2004), about 1/3 of a sample of disks at large z (Pérez 2004), and in about 1/4 of a large survey of dwarf galaxies (Hunter & Elmegreen 2006). The bend in the stellar surface brightness, and hence stellar density, profile implies a change in the cloud/star formation process at that radius. What is the nature of that change (Elmegreen & Hunter 2006)?

We can address these questions with star-by-star observations of Local Group galaxies (see, for example, Figure III.F.4) and integrated observations of more distant systems on 3--4 m class telescopes. Deep wide-field broad-band imaging is necessary to quantify the level of star formation that has taken place over the past Gyr, to characterize the bulk star formation histories in outer disks, and to look for morphological peculiarities that indicate external dynamical processes at work. Imaging in the ultraviolet is important, as it contributes an important lever-arm on the youngest component of stellar populations. High resolution spectroscopy of individual stars yields elemental abundances that provides information on the chemical enrichment history of a galaxy.

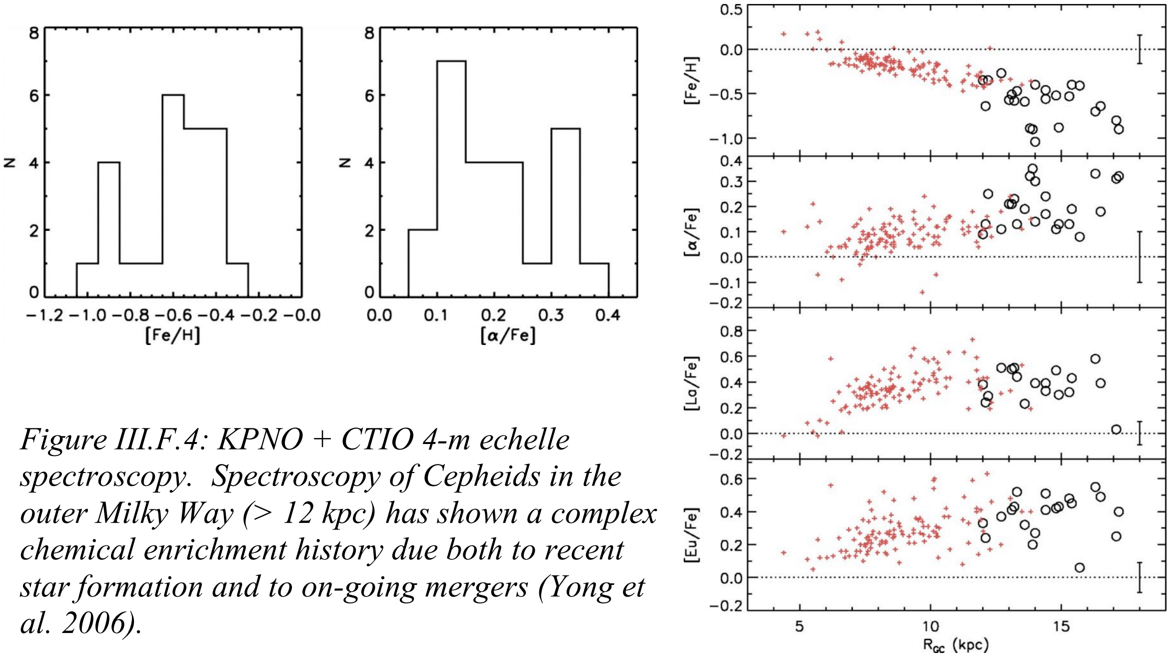

Figure III.F.4: KPNO + CTIO 4-m echelle spectroscopy. Spectroscopy of Cepheids in the outer Milky Way (> 12 kpc) has shown a complex chemical enrichment history due both to recent star formation and to on-going mergers (Yong et al. 2006).

Comprehensive work on these issues using midsized telescopes, combined with high-resolution studies of outer disk regions with HST, can be used to assess predictions from ΛCDM theory that disks should grow from the inside out (e.g. White & Frenk 1991, Mo et al.1998, Muñoz-Mateos et al. 2007). Are star formation histories in outer disks consistent with this picture?

What are the structures and mass distributions of galaxies and how have they evolved with time?

In popular cosmological models, dwarf galaxies are the product of the Big Bang and the building blocks of giant galaxies. Furthermore, spiral galaxies in the HST Ultra-Deep Field, which lie between z = 1 and 2, have half the disk scale lengths of local spirals, making them like local dwarfs in size (Elmegreen et al. 2005). Thus, the structures of giant galaxies, and perhaps of dwarfs as well, have undergone considerable evolution over the age of the universe. But, what is the intrinsic structure of galaxies, and how have they arrived at the point we see them today?

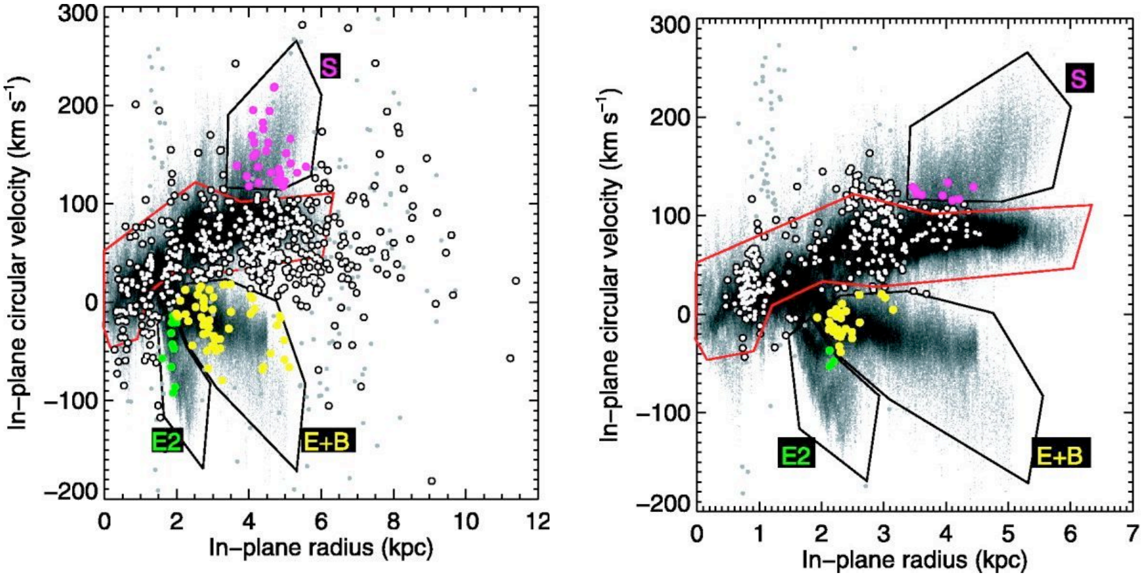

Figure III.F.5: UK and CTIO Curtis Schmidts, broad-band imaging; duPont 2.5 m and CTIO 4 m MOS medium resolution optical spectroscopy. Kinematics of individual carbon stars (left) and red supergiants (right) compared to HI (gray) in the Large Magellanic Cloud reveal the tidal heating of the stellar disk (Olsen & Massey 2007).

Small telescopes have a long history of examining the stellar structure and mass distributions of galaxies, and the observational techniques are diverse. A recent example comes from a study of the kinematics of individual carbon stars and red supergiants in the Large Magellanic Cloud, which revealed the tidal heating of the LMC stellar disk (Olsen & Massey 2007, see Figure III.F.5). Recently, stellar absorption lines have been used to begin determining the intrinsic shape of dwarf galaxies through large-scale stellar kinematics (Hunter et al. 2005). Wide-field broad-band imaging on 2-4 m telescopes are needed for star counts and stellar population studies of the Milky Way and nearest galaxies and for integrated surface photometry of more distant objects. Medium resolution (to R ~ 10000) optical long-slit and multi-object spectroscopy and high resolution (to R ~ 50000) optical long-slit spectroscopy on 4-m telescopes are required for kinematic studies, including stellar velocity dispersions.

Summary of Science for the Structure and Evolution of Galaxies

Small and mid-sized telescopes have made fundamental and wide-ranging contributions to the study of the structure and evolution of galaxies. With a diversity of capabilities available on these telescopes the properties of galaxies can be probed in interesting and appropriate ways. We expect that observers using small and mid-size telescopes, with adequate amounts of telescope time and modern instrumentation, can continue to address fundamental questions in extragalactic astronomy. Observations with large facilities such as ALMA, JWST, LSST and the GSMTs will complement these studies and fuel additional focused studies on small and mid-sized telescopes.

Capabilities for Science for the Structure and Evolution of Galaxies

- Narrow-field low-resolution (R~1000-2000) optical (to 3600 A) and near-IR spectroscopy
- Integral Field Units
- Wide-field broad-band optical and near-IR imaging
- Wide-field narrow-band optical and near-IR imaging
- Medium resolution (to R ~ 10000) optical long-slit and multi-object spectroscopy
- High resolution (to R ~ 50000) optical long-slit spectroscopy

G. Cosmology, Dark Matter, and Dark Energy

The field of observational cosmology has changed dramatically in the past 15-20 years. Whereas the field then was dominated by the pursuit of the Hubble constant plus redshift surveys and the mapping of large-scale structure in the local universe, it has pushed outward dramatically to much higher redshift in recent years. Many of the key science questions being addressed today were not even on the horizon 20 years ago (e.g., dark energy, gamma-ray bursts (GRBs)), while others were simply intractable given the observational facilities of the day (e.g., the nature of the earliest galaxies). Other key problems, such as the formation and evolution of large-scale structures and the nature and distribution of dark matter have become mature fields of study where modern programs are achieving results scarcely dreamed of just two decades earlier.

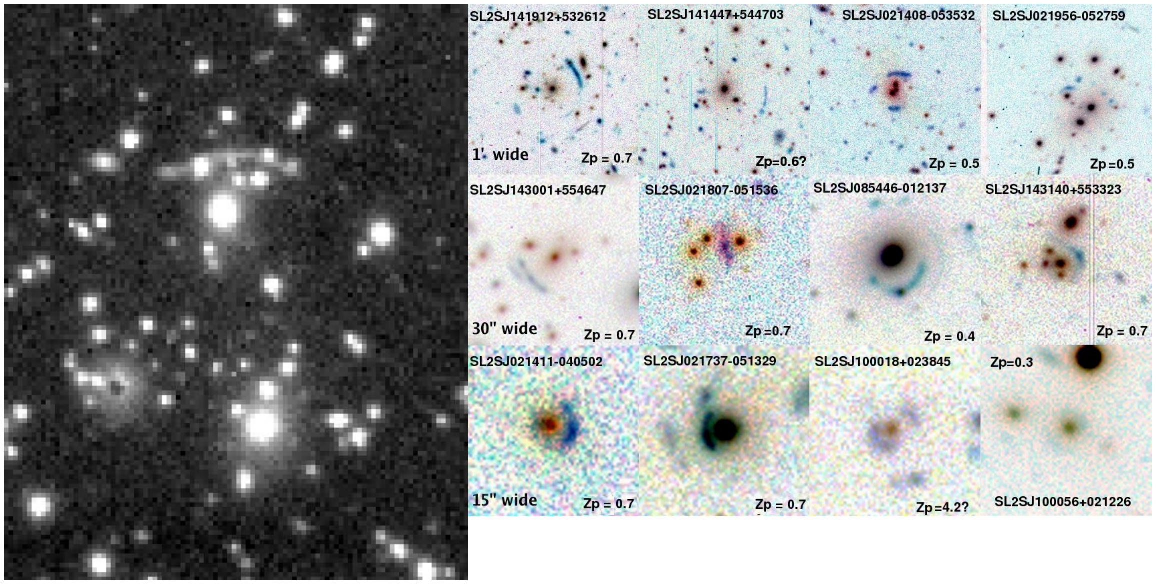

Figure III.G.1: Strong lenses discovered with the 3.6-meter CFHT. The left panel shows the first gravitational arc reported (Soucail et al. 1987) and the right shows a collection of new gravitational lenses discovered in the CFHT Legacy Survey. Image Credit: Canada-France-Hawaii Telescope Corporation

A tremendous amount of cutting-edge science is being done using telescopes of 2 to 6 meters in diameter, especially in combination with data from space-based observatories such as Chandra or HST, and ground-based telescopes in the 6-10 meter class. Examples include the characterization of the distant galaxy population by near-infrared imaging (e.g. Wang et al. 2006, Conselice et al. 2007)., studies of the distribution of dark matter by weak lensing (e.g. Bacon et al. 2000; Mahdavi et al. 2007), strong lensing (e.g. Soucail et al. 1987 and Figure III.G.1) and velocity dispersions (e.g. Douglas et al. 2007), photometric and spectroscopic identification of the highest redshift objects such as quasars (Fan et al. 2001; Willott et al 2007) and Lyman-break galaxies (Steidel & Hamilton 1992) and the discovery of dark energy by observations of high-redshift SNe. (Riess, et al 1998; Perlmutter et al. 1999). Here we list examples of questions in cosmology that are being answered using small and medium-sized ground-based telescopes.

What is the size of the Universe?

One key area in modern cosmology is the studies of supernovae to measure the cosmological parameters. Much of the work to discover SNe and to monitor their light curves has occurred and will continue to occur on 2-4 meter telescopes. While larger telescopes are needed to observe SNe at high redshifts, much crucial work remains to be done to continue to refine the SNe distance scale. This work is well suited for medium-sized telescopes. Once discovered, the SNe must be observed spectroscopically in order to determine their types. This can be done effectively for all but the faintest sources using 4-6 meter telescopes. For example, LSST is predicted to observe 30,000 Type Ia SNe at redshifts below 0.3 per year. If sufficient numbers of these can be followed up with multi-band photometry and spectroscopy, additional details of Type Ia light curves may be understood, leading to a decrease in the systematic errors and the scatter associated with this method. With the bright limit on LSST and the lack of spectroscopic capabilities, these studies will require additional telescope resources, such as the ReSTAR system.

What powers gamma-ray bursts?

An important growth area in the field is the discovery and subsequent follow-up study of GRBs. The current generation of high-energy satellites is producing unprecedented numbers of new detections. There is much demand for quick target-of-opportunity optical and NIR follow-up to detect the optical after glows associated with the GRBs. Many of the brighter after glows are accessible to medium-sized telescopes, particularly during the very early-time stages of the burst. Clearly, observational agility is at a premium here, but all that is needed is a 2-4 meter telescope with a narrow field CCD. By studying GRB afterglows, we can learn about the geometry of the jet, its interaction with the surrounding material and the association between GRBs and SNe (Figure III.G.2).

It is worth noting that the science to be done here is largely synoptic monitoring (in the case of the SNe light curves) and target-of-opportunity observations (in the case of the GRBs), two observing modes not regularly associated with observational cosmology. Further, the planned all-sky synoptic monitoring programs (PanSTARRS and LSST) will be only moderately effective for the SNe light curve work (due to the expected cadence of the surveys) and will be useless for the GRB after glows.

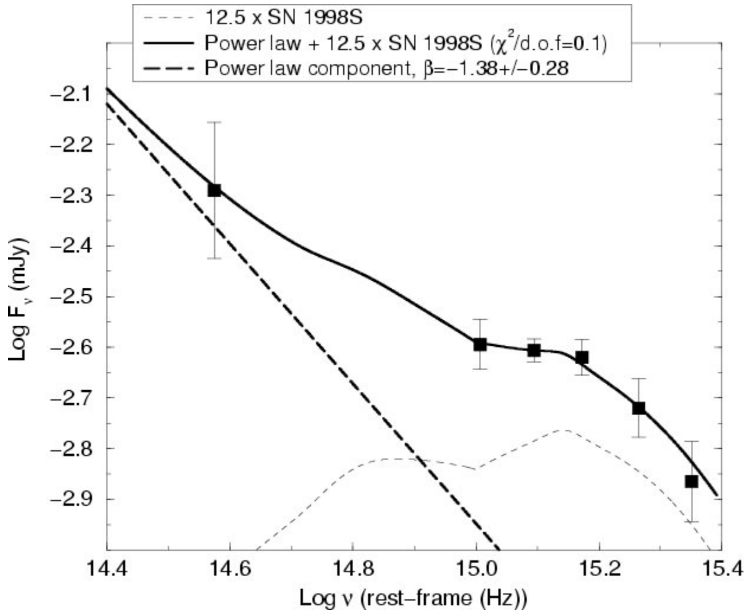

Figure III.G.2: The light curve for GRB 020305. The best fit comes from combining a power-law with a Type Ic SN, although both a low-redshift and a high-redshift SN provided reasonable fits to the data. Observations were taken in part on the 2.5-meter Nordic Optical Telescope and the 3.5-meter NTT. (Gorosabel et al. 2005)

What are the properties of galaxies at high-redshift?

While this field of study has been dominated by deep, small-area surveys carried out with large telescopes, improvement in instrumentation is making possible a number of survey methods that can take advantage of 4-meter class telescopes. For example, wide-field optical imagers equipped with narrow-band filters have the sensitivity to detect star-forming galaxies via the Ly-α line out to z ~ 6. The use of wide-field NIR detectors and suitable narrow-band filters could push these studies to even higher redshifts and ultimately probe the era of re-ionization. Such studies would provide fundamental information on the star-formation properties of galaxies at the earliest stages of their development, yet can be achieved on modest-sized telescopes. These same surveys will also be sensitive to other strong emission lines like Hα and [O III] at different lookback times, providing a complementary but simultaneous measure of the star-formation characteristics of galaxies at a range of epochs.

The advent of new wide-field NIR imagers (e.g., NEWFIRM on the NOAO 4 meter telescopes) will also allow for a wide-range of exciting survey science. One proposed project will use intermediate-width filters to measure accurate photometric redshifts for early-type galaxies out to redshifts of ~3 or more. The key to all of these deep surveys is wide-field coverage and access to an array of filters (both narrow- and intermediate-band) to target specific parts of the galaxian population.

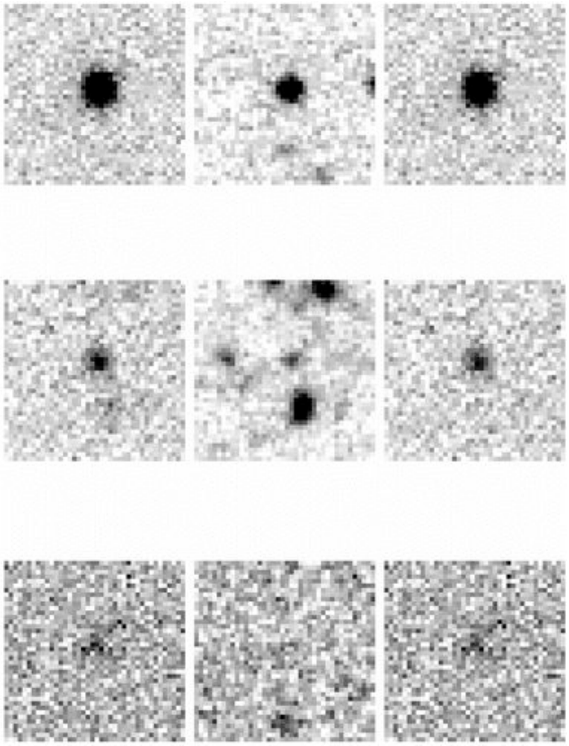

Figure III.G.3: Observations of Lyman-α emitters at z~3.1, taken with the Blanco-4m. The leftmost panel shows the image taken through a narrow-band filter at 5000A. The center panel shows the field in the broadband B+V filters, while the rightmost shows the difference. The Ly-α emitters appear as detected sources in the subtracted images. (Gronwall, et al. 2007)

What is the distribution of luminous and dark matter?

While huge strides have been made in establishing the details of the large-scale distribution of galaxies in the past two decades (e.g., CfA redshift surveys, Sloan Digital Sky Survey, 2dF survey) there is still a need for additional, specialized spectroscopic surveys for redshifts. Examples include focused studies around QSOs which possess nearby examples of Ly-α forest lines in their UV spectra. Establishing a connection between specific absorption lines and galaxies near the line-of-sight to the QSO will help us to understand the nature of absorbers responsible for the Ly-α forest lines seen at high redshift. This type of work can be accomplished with modest-sized telescopes equipped with high-throughput, low-resolution spectrographs.

Another area that falls under the heading of large-scale structure research is using velocity-independent distance measurements (e.g., Tully-Fisher, D_n-σ, surface-brightness fluctuations) to map out the distribution of galaxies. This allows for the measurement of peculiar velocities and ultimately the ability to measure the large-scale distribution of dark matter. Such studies require detailed broad-band imaging of the target galaxies which can be carried out using relatively modest apertures (~2 meters). While LSST will eventually provide suitable imaging data for much of the sky, the ability to observe individual galaxies for obtaining deep, multi-color surface photometry will likely remain a common need for the foreseeable future. Also required (for TF and D_n-σ programs) is some measure of the galaxian velocity field (e.g., rotation velocity for TF). This can be done effectively using moderate-sized telescopes equipped with high-throughput single-slit spectrographs.

The densest regions of the galaxian distribution, galaxy clusters, remains an active area of research. Studies in nearby clusters (e.g., Virgo, Coma) probe the details of galaxian evolution in the cluster environment, addressing issues such as gas striping, galaxy harassment and the build-up of clusters with time. Much work can be done using 2-4 meter telescopes (both imaging and spectroscopy). The study of more distant clusters (e.g., $z \sim 0.5$) provides a direct comparison with nearby ones in order to assess the evolution of both the clusters (i.e., rate of build-up with time) and their population of galaxies. At redshifts around $z \sim 1$, the focus is mainly on the detection of the earliest clusters. Here deep, wide-field imaging with good spatial resolution on 4-6 meter telescopes is required.

The distribution of dark matter on all scales continues to be an important and active area of research. We have already alluded to peculiar velocity studies that provide a measurement of the dark matter distribution on the largest scales (tens of Mpc) through the measurement of bulk streaming motions. On the scales of galaxy clusters (few Mpc and smaller), the measurement of velocity dispersions and strong gravitational lensing are important probes of the dark matter that are accessible to moderate-sized telescopes. High throughput multi-object spectroscopy (over a range of angular scales) is the preferred mode of observation for cluster work.

On the scales of individual galaxies, a wide range of instrumentation provides important information on the velocity fields and dark matter content. Traditional use of long slit spectroscopy to study spiral disk galaxies is still popular. Modern work on elliptical galaxies is employing wide-field multi-fiber spectrographs to measure the velocities of individual globular clusters and planetary nebulae, hence allowing the dark matter content to be probed over much larger radii than is possible with traditional long-slit observations of the galaxy light. This work can be done using 4-6 meter telescopes (although larger telescopes offer obvious advantages). An emerging area of importance is the measurement of velocity fields in galaxies at large redshifts ($z \sim 1$). This is an important probe of the evolution of dark matter content and mass-to-light ratios in a cosmic epoch when galaxy assembly was still active. Current observational schemes here employ either narrow slits or densely-spaced integral field units (IFUs), both used in conjunction with adaptive optics. This work can be accomplished on 4-6 meter class telescopes.

Summary of Science for Cosmology, Dark Matter, and Dark Energy

The field of observational cosmology, like most fields in astronomy, benefits from access to a wide range of telescope apertures and instrumentation. While much current work is being carried out on 8-10 meter telescopes, important programs can still be accomplished with 2-6 meter apertures. An excellent example is the Dark Energy Survey, which will utilize 30% of the time on the CTIO 4 meter for five years, and will image ~5000 square degrees to faint limiting magnitudes in four filters. This major program will be completed entirely on a single 4 meter telescope with a relatively modest investment in time (relative to the science gains). The arrival of new surveys and new facilities (ALMA, LSST, PanSTARRS, JWST) will impact the science that will be done on the ReSTAR system. A growing need will be access to narrow- and intermediate-band imaging, particularly in the NIR. Current and future wide-field imagers will need to provide access to a variety of large (and expensive) filters to truly take advantage of the capabilities of these wonderful new instruments (e.g., NEWFIRM, ODI, DECam). On the spectroscopic side, all standard modes of observation are expected to be needed, from single-slit to multi-object (fibers for wide fields and slitlets for smaller fields) to IFUs. Most spectroscopic work will be at low and intermediate resolutions (1000-5000), although some work (e.g., QSO absorption line studies) will require high resolutions as well.

Capabilities for Science of Cosmology, Dark Matter and Dark Energy:

- Narrow-field optical and NIR imaging
- Wide-field, low-resolution, multi-object spectroscopy
- Wide-field optical and NIR imaging, including narrow- and intermediate-band
- Integral field units

H. Survey Science

Astronomy is undergoing a transition to a new era in which there are major surveys both from ground-based and from space-based observatories. These surveys cover much of the sky at wavelengths across the electro-magnetic spectrum from x-ray to radio wavelengths. Some are in progress or largely completed, such as the ROSAT All-Sky X-Ray Survey, the ASCA and XMM x-ray surveys, the SDSS, COSMOS, and CFHT Legacy Survey in the visible, the 2MASS and UKIRT Deep Infrared Sky Survey (UKIDSS) in the infrared, and the NVSS, ALFALFA, FIRST, and Cambridge surveys in the radio. These surveys are producing massive databases that, taken together, provide an enormous virtual observatory of data for astrophysical research. Moreover, there are major new facilities in progress, such as the Pan-STARRS all-sky survey in the north, or planned, such as the LSST visible and VISTA infrared all-sky surveys in the south. We expect small and mid-size telescopes will continue to play an important role in carrying out surveys in the future.

The increasing availability of such databases is already beginning to change the way many astronomers do their research. No doubt some kinds of traditional uses of small and medium-aperture telescopes, particularly for photometry of non-variable sources, will no longer be as common as they have been in the recent past. However, it is clear that analysis of these databases will raise many new astrophysical questions, and they will provide target lists for more focused investigations. Therefore, we expect that the era of large surveys will increase rather than eliminate the demand for small and mid-sized telescopes. While there may be somewhat less demand for photometry, there will be a much increased demand for optical and infrared spectroscopy at a variety of spectral resolutions and imaging in other bandpasses in order to characterize sources and understand the astrophysics.

Ongoing surveys providing data on transient events are already taking astronomy into the time-domain regime. The LINEAR survey to search for "killer asteroids" is one example, and the Beppo-SAX survey for gamma-ray bursters is another. The Pan-STARRS 1 survey, which will begin in a few months, will provide for the first time an astronomical survey in the time-domain over 3π steradians of the sky. The transient object detections are expected to be made public very quickly and these data will include objects such as moving objects in the solar system, variable stars, active galaxies, after-glows of gamma-ray bursters, and supernovae. These will demand rapid follow-up with small and mid-size telescopes to produce the astrophysical interpretation of these different classes of time-varying objects and events.

I. Time Domain Science

Introductory teaching in astronomy often stresses the extreme age and expanse of our Universe by pointing out that, over a human lifetime, the changes in celestial objects are virtually immeasurable because they are so slow. Difficult ideas to convey to the public include the fact that the "fixed stars" change their relative positions on millennial time scales, stars live for billions of years as main sequence stars, and so on. This extremely slow secular change is an accepted paradigm in most of astronomy, but we are now living in a time when sensitive and stable instruments allow us to measure changes in objects over manageable time scales ranging from seconds to centuries.

Other sections of the ReSTAR science case *Optimizing the Science* discuss applications of "time domain science" in various subfields of astronomy. These range from photometric and spectroscopic monitoring classical variable stars of many classes (i.e. Cepheids, eclipsing binaries, cataclysmic variables, etc.), asteroseismology (shorter time-scale measures of small changes in brightness or spectral line profile / velocities), exoplanet discovery and monitoring, solar system measures of small object rotation or motion, transient follow-up of gamma-ray bursts and extragalactic supernovae.

Traditional observing modes may not be adequate to sample these time-variable phenomena. In addition to selecting optimal modes (i.e. spectral coverage, resolution, spatial coverage, relative vs. absolute photometry, etc.) time-domain work must adequately sample the time scales (and phases) of interest. Certain targets can be sufficiently monitored regularly from a single site, while others require more continuous monitoring and therefore need multi-site coverage to eliminate diurnal aliases.
A fundamental issue in some aspects of time-domain observation is that the mode involves looking at a single, relatively bright target continuously ("treetop to treetop") for several nights – a serious departure from normal "asynchronous" observations. Other time-domain targets are time-critical – with specific phenomena occurring periodically but predictably, while still others require "instant response" with specific instrumental configurations. And while LSST and Pan-STARRS will provide time domain data, the cadences will not be appropriate for many variable phenomena (and the bright limit for LSST will be ~V=18.) When one considers the inevitable competition among target-of-opportunity, coordinated observations, long-term monitoring, dense monitoring and very rapid time variability programs on the same facility, it is clear that additional care must be taken in developing the technical infrastructure and operational model for a facility that is to support time domain astronomy.

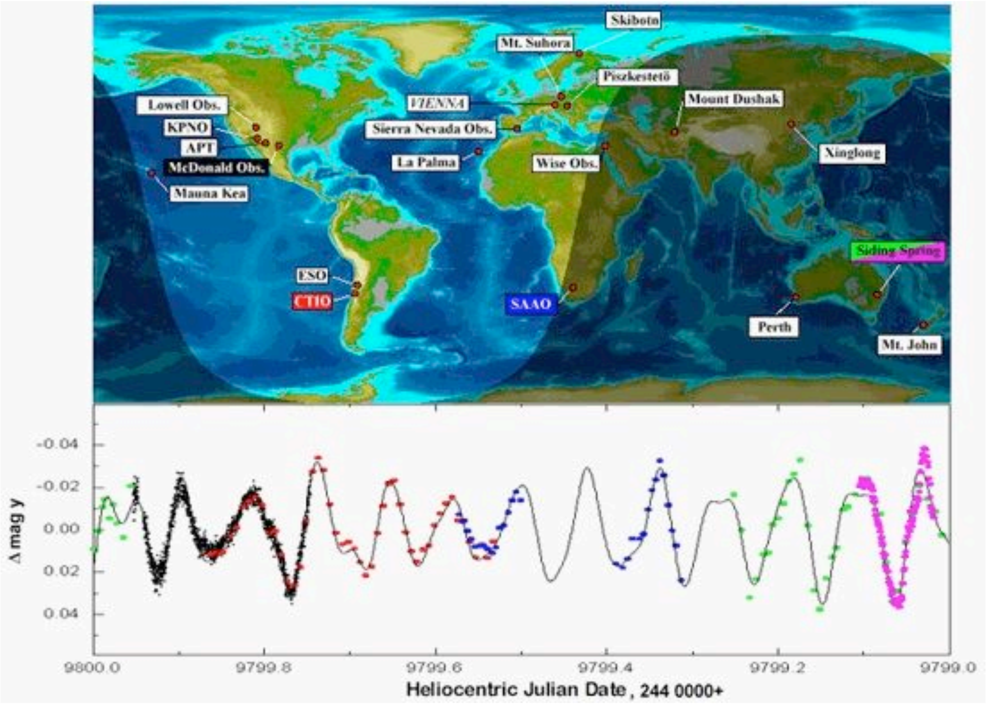

Fig. III.I.1.: The Delta Scuti Network (DSN): http://www.univie.ac.at/tops/dsn/intro.html

For rapid time-series photometry with CCDs, an essential instrumental feature is rapid readout so as to maximize the duty cycle during a continuous observation. Many CCD cameras have relatively long readout times, compromising the S/N of time series data. In particular, for rapid variations characteristic of white dwarfs, pulsating sdB stars, solar-like pulsators, and flickering in CVs, integration times of 5 – 20 seconds are required. CCD readout times in excess of a few seconds have unacceptable overhead.

The instrumental and observational capabilities needed to carry out various forms of time domain science effectively include

- Photometry on 1-2 meter class telescopes and spectroscopy on 2-5 meter class telescopes.
- Multiple sites for continuous coverage and to allow competing cadences.
- High speed (but not necessarily continuous) photometry.
- Real-time scheduling coordination.
- Uniform instrumentation among telescopes and sites.
- A rapid user-friendly data reduction pipeline.

Networked observations with dense coverage and/or high duty cycle

Examples of time-domain studies are quite numerous – the most successful examples are those that were developed to answer specific science questions. As an example, consider the study of pulsating white dwarf stars. The nature of these targets is that they are multi-periodic pulsating variable stars, with periods on the order of minutes, but with beat frequencies on the order of a day or more. Thus, to fully resolve their pulsation spectra, diurnal aliases often prevent unambiguous determination of the underlying pulsation spectrum. To solve this problem, the Whole Earth Telescope (WET) network was developed by Ed Nather and Don Winget. The WET is a network of small (1-2m) telescopes with functionally uniform photometers (initially, multi-channel photoelectric photometers; now, thinned, back-illuminated CCD photometers) distributed in longitude around the globe. With, typically, 10-15 participating sites, simultaneous observing time is obtained through the normal proposal channels peculiar to each site, by local astronomers, with the science goals described including the collaborative nature of the project. Each observing campaign (generally lasting two weeks) is coordinated from a central headquarters (staffed by participating astronomers 24/7) to allow multiple targets and therefore exploit longitude redundancies. Other similar networks are in operation (such as the delta Scuti network) to enable collaborative observations and obtain high duty cycle, dense time coverage of variable stars that require that mode of time-domain coverage.

The networks mentioned above concentrate on time-series photometry, and make efficient use of telescopes in the 1-2 meter class. However, RV studies of solar-like oscillations in main sequence stars, other studies of rapid pulsators, extrasolar planet searches, and RV studies of close binaries require larger telescopes (and generally brighter targets) to obtain sufficient signal-to-noise in individual observations. For those that require dense sampling and high duty cycle, geographically distributed networks of such facilities are essential.

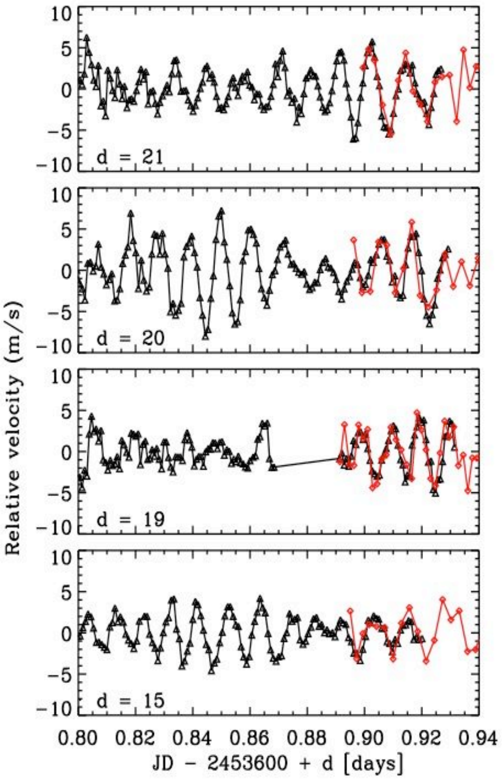

Figure III.I.2.: Radial velocity time series in the subgiant star beta Hydri caused by non-radial oscillations (from Bedding et al. 2007). The black curve shows data from HARPS on the ESO 3.6m; the red curve shows data from UCLES on the 3.9m AAT.

Advantages of these networks include benefits on the scientific front, as well as in the human resources area. A successful campaign can produce very high quality data at relatively low cost. In doing so, wide participation fosters the development of large, international science collaborations. Because of the importance of involving observers at all longitudes, these projects encourage development of science programs, and observing capabilities, in developing nations. Disadvantages include the limited number of targets that can be observed in a given time, the large personnel overhead in organizing and operating the network, and non-uniformities in instrumentation.

Time-domain studies of large numbers of targets / rich fields

Time-domain observations of large numbers of stars in searches for microlensing (in galactic structure studies as well as exoplanets) and planetary transits are more automated than the single-target networked observations. These efforts also seek relatively high cadence, and high duty-cycle, but on longer time scales than most asteroseismic network observations. Many such efforts are partially or fully automated. Clearly, this direction will be transformed in the era of LSST, but brighter ensembles of targets remain of interest and will need continued study even then.

Rapid response / time critical / target of opportunity (ToO) capabilities

The two techniques described above can be accommodated, to some degree, in existing user-class facilities through normal scheduling systems, since the phenomena being studied are usually continuous and of modest duration. Similar considerations exist for predictable events such as eclipsing binary phase studies, solar-system events including stellar occultations, and seasonal phenomena on planets in our solar system.

There are many cases where rapid response to unpredictable events is required, such as optical follow-up of gamma-ray bursts, extragalactic (and, hopefully, galactic) supernovae, nova outbursts, comet flare-ups, NEO post-discovery tracking, etc. Such rapid response observations cover the entire range of observing capabilities used in asynchronous observing. The ability to make rapid-response observations is largely a logistical capability that needs to be present in all facilities, but can and should be an anticipated occurrence during execution of standard programs. ToOs are difficult to schedule on ordinary classical user-mode telescopes, and work best with a background monitoring program.

Monitoring

The high cadence, high duty cycle time-domain science represents one extreme – the other is represented by occasional (but persistent) monitoring of known objects. For variable star studies, light curve generation can be a low cadence, low duty cycle process when the (known) periods are longer than several days. Monitoring accreting binaries to provide alerts to outbursts also falls into the category of low-cadence, but persistent, revisits. Examples in extragalactic astronomy include AGN reverberation monitoring, following-up extragalactic supernovae, and strong microlensing events.

For the rapid pulsators, monthly and seasonal revisits are required to monitor pulsational phase in the search for binary companions or for secular period change measurements. In this case, assuming the light curve has been fully resolved by earlier network observations, the follow-up observations to obtain (O-C) timing can be achieved from a single site, usually in a relatively short run.

For these monitoring projects, scheduling repeated visits for up to several years presents a challenge to the current scheduling modes, but should be considered as an essential element in a time-domain sensitive observing System. To show the breadth of science areas, time scales, and cadences that should be considered, we summarize a number of time domain targets in the following table.

Object/Science	**Sampling Time**	**Time Span**	**Comment**	**Challenge**	**Instr.**	**ToO / Time Critical**
Asteroseismology						
White Dwarfs & sdB stars	10 sec	1 week	continuous	high	phot	
Long-term monitoring of WD and sdB stars	10 sec	5-10 years	1 wk / yr	high	phot	
Solar-like	30 sec	1 week	continuous	high	RV	
B stars	1 hour	1 week	continuous	low	RV phot	
B stars, fine structure	1 hour	year	monitoring	low	RV / phot	
Extrasolar Planets						
RV search/char.	1 hour	years	nightly monitor	high	RV	
Transits						
ingress / egress	10 s	hour	continuous	high	phot	Y
timing	10 s	years	monitoring	high	phot	Y
searching	10 s	weeks	multi-target	high	phot	
Microlensing planet event(s)	minutes	days	continuous	low	phot	Y
Classical Variables						
CVs /XRBs-orbital	minutes	hours	continuous	low	phot spec RV	Y

Object/Science	Sampling Time	Time Span	Comment	Challenge	Instr.	ToO / Time Critical
CVs /XRBs – transient / outburst	hour-days	weeks-months	monitoring	low	phot	Y
Cepheid	daily	months	monitoring	low	phot spec	
Mira / LPV	daily	weeks	monitoring	low	phot spec	
Eclipsing Binaries	minutes	hours – days	continuous, monitoring	low	phot spec RV	Y
Transients						
GRB	seconds-minutes	days	continuous	low	phot spec	Y
Microlensing	days	months	monitoring	low	phot	Y
Solar System						
Small body rotation	minutes	hours	continuous	high	phot	
Transients	hours?	weeks?	continuous	low	phot spec	Y
NEO	seconds	days	monitoring	low	phot	Y
Extragalactic						
AGN reverb.	days	years	monitoring	low	spect	
Grav. lensing	days	months - years	monitoring	low	phot	
Supernova search & monitoring	days	months		low	phot spect	
Blazars (w/ GLAST , VERITAS)	minutes	years	coord. w/ continuous gamma obs.			

J. Summary of Conclusions from the Science Case

The science programs that are described in this section illustrate the incredible breadth and scope of the research that can be done on modest-aperture telescopes. Many of the specific cases presented in this report have been culled from programs described by members of the community in response to the ReSTAR request for input. As such, they represent examples of real programs that are either currently being proposed or planned for the near-future. Hence, these science cases for small and medium-sized telescopes are not made on past successes, but rather on real needs in the community.

Two main themes emerge from the science programs presented. First and foremost is the clear picture of the important science that can and will be carried out on modest-sized telescopes. While it is sometimes the case that "bigger is better" when it comes to astronomical observing, the realities of limited resources and facilities demand that not all observations will take place on the largest telescopes. Furthermore, the increased flexibility, agility, amount of telescope time, and sometimes instrumentation of smaller telescopes often make them the *preferred* mode for carrying out many programs. As we have shown in the preceding sections, the specific science programs we have highlighted are compelling and fundamental.

Another theme that emerges is the general need for a fairly standard suite of telescopes and instruments across the diverse subfields of astronomy. The observational capabilities required to carry out the forefront research in cosmology, extragalactic, Galactic, stellar, and planetary astronomy are, to first order, similar. The need for spectroscopy, both low and high resolution, is fairly ubiquitous in all of the science cases. Likewise, the capability for both optical and NIR imaging is a common need. While the *details* of the requirements may vary somewhat between the science cases, the overall sense is that a uniform suite of high quality, workhorse instruments will go a long way toward satisfying the bulk of the need of the user community. With proper planning and organization, perhaps highlighted by the sharing of instruments (or access) between telescopes, substantial economies of scale can be realized.

In summary, the US community continues to require access to a dependable suite of well-instrumented telescopes with a full range of apertures. While there continues to be a clear and pressing need for larger telescopes, small and mid-size telescopes remain an essential component of the overall system both in terms of providing support as well as enabling new science not otherwise possible. The committee feels strongly that continued access to such telescopes through a peer-reviewed process is essential for the continued health and growth of the field. Hence, we propose our first and perhaps most fundamental recommendation:

Finding: The science to be done with small and mid-size telescopes remains compelling and competitive in the era of big telescopes. Small and mid-size telescopes continue to produce innovative science in themselves, and to provide precursor and followup observations that enhance the scientific productivity of larger telescopes. Small and *mid-size telescopes also enable scientific investigations that are not possible on larger telescopes.*

IV. CAPABILITIES OF THE SYSTEM

In defining the capabilities of a system of small and mid-size telescopes, we must consider all the aspects that contribute to the effectiveness and productivity for carrying out the science, including instrumentation, specialized facilities, observing modes, community support, and access to observing time of appropriate aperture.

A. Instrumentation

The science cases outlined above, as well as the responses to the community survey, suggest specific instrumentation that should be widely available on telescopes in the small to mid-aperture system. These capabilities include the following:

- Both optical and infrared spectroscopy spanning a range of resolutions from $10^3 < R < 10^5$ will be needed to carry out high-priority science programs in several fields.
- Both wide field and high spatial resolution O/IR imaging will remain essential capabilities that must be included in the system to carry out high-priority science programs in several fields. Particularly important will be filters not used in all-sky surveys, including narrow band filters.
- Additional instrumental capabilities including optical multi-object spectroscopy over large (> 0.5 degree) fields of view, optical and IR multi-object spectroscopy over limited fields of view with integral field units, and mid-IR imaging and low or moderate dispersion spectroscopy are needed for science programs spanning several fields.
- Other capabilities needed for a more limited range of scientific applications include polarimetry and spectropolarimetry.

We emphasize that spectroscopy should receive the highest priority for new instrumentation, since instrumentation for imaging is in a somewhat better state. New cameras coming on line in the next few years include the Dark Energy Camera on the Blanco 4-m and the One Degree Imager on WIYN. One additional imaging instrument that would help complete the suite of imagers is a copy of the IR imager NEWFIRM to provide that capability simultaneously in both hemispheres.

Finding: Specific instrumental capabilities on small and mid-size telescopes stand out as being essential to the progress of a wide range of research topics: optical spectroscopy at both high and low spectral resolution, and near-infrared spectroscopy at both high and low spectral resolution, optical imaging, and near-infrared imaging. The need for significant amounts of observing time with these capabilities dictates that such instrumentation should be available on national facilities. Moreover, the instrumentation available on small and mid-size telescopes at national facilities should be competitive *with the best instruments available elsewhere. State-of-the-art instruments are important at all apertures.*

Since the public accessibility of data obtained through the ReSTAR system will enhance the productivity of such telescopes, archiving is an issue that needs to be addressed by the system. Standards for telescope control systems, software, and instrument control, and data reduction will also be essential to achieve the desired scientific productivity.

The committee emphasized the importance of the connection between the science and the specific capabilities that should be provided through ReSTAR. The management of the system should be dynamic, and changes to the capabilities offered should be driven by oversubscription rates.

David Sprayberry of NOAO provided very rough order-of-magnitude cost estimates for instruments, facilities, and operational models that the committee identified as important for the system. (Details of cost estimates are available in the online meeting notes for October, 2007.) The estimates are based on varying standards for costs, specifically for the deliverables (documentation, software, interface controls, commissioning, integration and test), and for the level of complexity and robustness of an instrument or facility. The main cost drivers for instruments are field of view and level of complexity. Operations drivers include reconfiguration time, expendables, and maintenance costs. For telescopes, site is the most significant cost driver.

Costs for optical spectrographs for 4-m telescopes are typically \$2-3M when full costs are accounted, including scientist salaries, benefits, overhead, integration, testing, commissioning, documentation, and software. Clones/exact copies of existing instruments may be substantially less, in the range of \$1M.

High resolution, infrared echelle spectrographs are somewhat more expensive, with costs up to \$4-5M for dual beam spectrometers covering the 1-2 micron and 2.5-5 micron windows simultaneously.

Wide field (~30 arc min) IR imagers are yet more, with costs of order \$7M. The cost to clone NOAO's NEWFIRM IR imager would be about \$4.75M. This is based on \$2.7M in non-recurring engineering costs and \$2M for four detectors. The design would only work for the Mayall or Blanco 4-m telescopes. Designs for wider fields would be substantially more, ~\$10M.

Adaptive Optics: In a programmatic sense, major gains in performance may be achieved for small and mid-size telescopes through investments in AO. The limiting brightness for natural guide stars is independent of telescope aperture at around 12th magnitude, and the price for laser beacons is coming within reach. AO systems for 4-m class telescopes are less complicated than for larger telescopes and require fewer elements, with costs in the range from \$3-4M. Turnkey natural guide star systems are available for 2-3m class telescopes. AO systems may provide ground layer correction to work into visible wavelengths for moderate field, deep imaging, and simple tip-tilt systems do well on small telescopes. For example, the gain on WIYN using the WIYN Tip-Tile Module is 0.1" to 0.15". The gain from no correction to tip-tilt to full AO needs to be investigated for 4-m telescopes. Orthogonal transfer arrays (OTAs) may be a cost effective alternative to tip-tilt for imaging. Applications for IR spectroscopy and with IFUs may gain the most, but costs may lead to the conclusion that investigators may be better off making observations requiring full AO on 8-m class telescopes.

ACCORD has undertaken to rewrite the adaptive optics roadmap, and the NSF is considering changing the mechanisms for supporting AO development. It is an appropriate time to consider the role that adaptive optics should play on moderate-sized telescopes in a public access system.

Recommendation: The role of AO on small and mid-size telescopes should be considered in the development of the next AO roadmap by ACCORD and NOAO.

B. Specialized Facilities

Survey Facilities: Few would argue with the scientific productivity of the Sloan Digital Sky Survey, carried out on a 2.5-m telescope or the 2-Micron All Sky Survey, carried out on a pair of 1.3-m telescopes. These surveys were conducted on highly specialized private telescopes built by groups and consortia who, with federal support, released the survey data to the community. Their successes demonstrated how small and mid-size telescopes can be used effectively for large survey programs, and substantial time on such telescopes can be dedicated to specific scientific programs. The Pan-STARRS time domain survey that will provide publicly available data on transient phenomena and that will commence in a few months is yet another example of a specialized survey facility. Similar dedicated survey projects using small and mid-size telescope will likely emerge and be conducted in a similar way.

Another model is the Dark Energy Survey, being developed as a partnership between NOAO and other institutions using the Blanco 4-m telescope at Cerro Tololo. The Dark Energy Survey will utilize 30% of the time on the Blanco from 2011 to 2016, and will, in return, provide the Gigapixel-class Dark Energy Camera for public use on the telescope. Other such "public-private" partnerships could emerge in the future, either utilizing existing facilities or building new ones.

Small and mid-size telescopes contribute important science when specialized for and used in survey or campaign mode. The ReSTAR system can and should include such specialized facilities, and public participation in major survey projects conducted on small and mid-size telescopes is encouraged, particularly when the projects are supported with federal funds.

Specialized System for Time Domain Science: A global system of one and two meter class telescopes would assist greatly in the development of time domain astronomy. One meter class telescopes should be equipped for optical imaging and two meter class telescopes should offer efficient imaging spectrographs with moderate (and, if feasible, with high spectral resolution) spectrographs and small FOV IR imagers (5-10', since most targets will be single objects). Starting with relatively small apertures will allow for the implementation of a global time domain facility and development of methodology and demand for time domain observations at reasonable cost. Many of the phenomena to be studied are accessible with small and mid-size telescopes, and some events saturate on telescopes with larger apertures. The competitive nature of access to larger facilities also makes scheduling time domain observations problematic.

We envision a network of six to ten 1-m telescopes spaced in longitude around the globe for photometric monitoring, and a network of four 2-m telescopes for spectroscopic monitoring. The denser longitudinal coverage of the 1-m telescopes will minimize gaps in time series data due to weather. The GONG project at NSO, with six telescopes around the globe, is frequently able to maintain greater than 90% time coverage for solar oscillations. Constraints on data for nighttime targets can be very different. Experience with the Whole Earth Telescope and Delta Scuti networks shows that redundancy in longitude can significantly increase the realized duty cycle. In addition, access to targets in the Northern and Southern hemispheres requires longitude redundancy. Given this, six telescopes is probably the minimum for an effective global network. The 2-m, spectroscopic telescopes will not be able to maintain unbroken time coverage, but will be sufficient for much of the proposed science.

The cost of telescopes in a global network of 2-m telescopes for spectroscopy operated for time domain science would be about $8-10M each. Spectrographs similar to the Goodman spectrograph built for SOAR would be $0.6-1.1M each. Small field (5' FOV) NIR imaging cameras would cost about $0.7-1.2M each. The total cost per telescope with instruments in the network $10-15M per copy. Costs for site development could be as much as 100% of the telescope cost, and would be less for developed sites.

The cost of operating a time-domain network of telescopes will depend on the operations model adopted. Intensive scheduling, queue, and service modes require highly trained staff. Robotic telescopes may be an option, but maintenance will still be expensive. Operations may be more cost effective for global network built from the ground up than for a network built from an upgraded mix of older facilities with different initial states and non-standard optical configurations.

The Las Cumbres Observatory is a good example of a network of telescopes being developed for time domain observations, and Las Cumbres is interested in providing community access to their facilities, including a spectroscopic capability. Opportunities for synergy to develop a robust capability for time-domain science with Las Cumbres should be explored.

Recommendation: Access to a global network of telescopes for time-domain investigations should be made publicly available. The global network should include multiple 1-m telescope spaced around the globe for photometric monitoring and a small number of 2-m telescopes for spectroscopic monitoring. These telescopes may also *contribute to other PI science programs that can be carried out in queue mode. Such a network should be developed in collaboration with non-federal partners.*

Interferometry: The optical/IR interferometry community, led by Rachel Akeson and Steve Ridgway, prepared a report concerning the role of interferometry on small and mid-size telescopes in the context of a new system of public access telescopes. Interferometry is a capability to which the community has no formal public access at this time, but advances in interferometry now allow application of the technique to a variety of interesting scientific programs, including:

- Fundamental stellar physics - basic driver: masses, radii, rotation (via shape), oscillations, binary interactions
- Stellar atmospheres, deep convection, limb darkening, multi-component atmospheres
- Dust formation and mass loss
- Young stars and planetary systems
- AGN: size of the broad line regions of accretion disks

Providing community access to interferometry depends on building a user community beyond the current facility users. Observations might be accomplished by queue/service observing, and thus have a modest impact on staffing of existing interferometers. Funding models for interferometry need further discussion. It may be possible to create a URO-like system, or to modify the TSIP programs to accommodate interferometry. Interferometers are funded by different agencies, including NASA, NSF, and DOD, with some state funding, as well.

Recommendation: Access to O/IR interferometry should also be publicly available, and the System should provide a funding support structure to enhance the efficiency and user base commensurate with the promise of recent advances in interferometric techniques and results. In the short term, partnership with existing or developing facilities is encouraged.

Other Specialized Facilities: Additional, specialized new facilities to meet particular scientific needs were also discussed, including a southern clone of the IRTF and a "baby" LSST to provide a similar cadence for monitoring the full sky, but with a brighter saturation limit. Costs for new facilities are more uncertain than costs for instruments. Scaling laws do not provide reliable estimates, and site is a critical cost driver. Annual operating costs should be figured at 10% of the construction cost, unless a convincing argument can be made for a lower figure.

A science case for a southern clone of the IRTF could be made for a site that would provide significant gain in performance over Gemini South for some observations. Potential higher altitude sites include Tolanchar (undeveloped, ~4500m, dry, good seeing, part of AURA reserve) and Chajnantor (development planned, ~5600m; Cornell/Caltech submillimeter telescope). The cost of a southern infrared telescope comparable to the IRTF would be about $25M, not including instruments, site infrastructure, or site permissions. At high altitude, site costs could easily equal or exceed telescope costs. Estimates for operations costs and instruments must also be added.

A science case might also be developed for a 1.5-m LSST clone for ongoing, all-sky monitoring for transient sources that will be saturated on LSST. Since the bright limit for LSST will be roughly V=18, and many transient events are brighter than that limit, a smaller aperture, wide-field imaging telescope slaved to the cadence of LSST would be useful for covering the sky to follow bright transients. A cost model based on a simple scaling of LSST MREFC proposal for a facility co-located with LSST would be about ~$3M for a 1-m telescope and ~$6M for a 2-m telescope. The LSST project already includes an additional 1.5-m telescope for calibration. The science case would need to factor in the contribution of Pan-STARRS in the north and justify, on the basis of science, why a facility might be needed in the south. The need for an LSST companion in the south can be assessed after Pan-STARRS has been in operation for a year.

The cost of a camera for a baby LSST would also be significant. A 1-1.5 Gigapixel camera may be sufficient, rather than a 3.2 Gigapixel camera. In that case, the cost of the camera would be similar to the Dark Energy Camera or the WIYN ODI camera ($7-10M). Much of the infrastructure for the site, operations, and the data pipeline could be shared with LSST (software, pipeline, etc.), especially if the telescope were co-located with LSST. Costs might be comparable to Pan-STARRS in the north.

The ReSTAR System should also include some mechanism for access to very small telescopes for some science programs. Examples include the determination of parallaxes for Cepheids observed with HST, studies of hot-Jupiter transits, and development of standard photometric systems, where apertures in the range of 0.4-0.6 meters are needed. The science pursued on most of the telescopes in this aperture range today is dominated by time domain observations.

C. Operations Modes

The science to be carried out with small and mid-size telescopes will benefit from the implementation of a variety of observing modes, with an appropriate balance among classical, queue, and service observing. The availability of classically scheduled observing time is particularly important for training students, for the development and commissioning of new instrumentation, and for the execution of science programs requiring significant interaction.

Service and queue observing would greatly benefit certain types of projects, such as target-of-opportunity, “snapshot”, and time-domain programs. For example, the WIYN 2-hour queue program operated by NOAO during the previous decade allowed observers to obtain limited data sets or test observations. (Regrettably, the queue was discontinued not due to lack of community interest, but rather because of staffing shortages.) The SMARTS consortium is currently operating several 1-m class telescopes at CTIO in service mode, enabling synoptic programs as well as observations of large data sets over many semesters. Some time-domain science, particularly monitoring programs in which many different sparsely sampled targets must be followed for long durations, may require queues similar to that now active on the SMARTS 1.3m telescope.

Perhaps a hybrid between classical and service/queue observing is remote observing, which was identified as a priority by many respondents to the ReSTAR survey. Remote observing frees the observer from the time and expense of traveling to a telescope, yet still allows the bulk of the flexibility (changing objects, exposure times, observing strategies, etc.) possible with classical observing. While this mode is indeed becoming increasingly popular, it does place heavy demands on computing/communications infrastructure at both ends. However, for astronomers from smaller institutions with fewer resources, the availability of this mode may be required for the maintenance of a vibrant research project that can involve students in the earliest stages of their post-secondary careers.

With the above in mind, the ReSTAR committee encourages increasing opportunities for remote observing and, to a limited extent, queue observing. Increased opportunities for remote observing can benefit the science in a variety of ways at relatively low cost. Increased use of remote observing can, for example, allow greater flexibility in scheduling programs to accommodate special needs. On the other hand, operating telescopes in full queue mode remains expensive due to staffing to support queue operations. The scientific gains for queue observing on small and mid-size telescopes are modest compared to their cost, and implementation of queue observing is not recommended, except in special circumstances or for appropriate time domain science. An example of such special circumstances may be the One Degree Imager on WIYN, since it will be used for survey programs as well as for classical investigations.

Key to the optimal operation of the system is efficiency – with regard to both the equipment and the people using it. The committee therefore believes that the use of observing templates would be beneficial as it will allow some observers to arrive at the mountain with a better-defined observing plan and enable them to ensure that they have collected all required calibration data. More importantly, such templates could be used to implement a straightforward execution of target of opportunity or synoptic observations by any observer present at the telescope, with proper prior approval by the relevant TAC.

Recommendation: We recommend further investment in remote observing to allow greater flexibility in telescope scheduling that will enable new observing modes. Options like short programs, snapshot modes, and some synoptic observations may be possible through more flexible scheduling. The implementation of observing scripts on small and mid-size telescopes would also permit a limited use of "queue" observations carried out by classically scheduled observers. The implementation of observing templates will improve efficiency for both classical and remote observers.

What is the right balance of survey and large programs? The question of the right balance between classical programs and large or survey programs is difficult to answer, even in the abstract. The committee notes the current trend is toward more and more surveys and large programs. Accompanying this is an apparent shift among astronomers early in their careers who are becoming comfortable with significant fractions of available observing time devoted to large programs and surveys.

NOAO survey programs are limited to 20% of the total observing time, and NOAO tries to limit the fraction of time allocated to surveys and large programs in any calendar phase (e.g. not more that 20% of March/April dark time). Surveys are required to return to the community uniform data products through the NOAO archive and investigators must describe in their proposals how the work will be managed. A survey fraction of 20% can be problematic, however, when a substantial share of telescope time is committed to partnerships.

The current NRAO policy for large programs allows 25-50% of time on their facilities (VLA, VLBA, and GBT) to be allocated to large programs and surveys, with an additional constraint that no more than 50% of available observing time in a given LST range shall be allocated to large programs in a given proposal period (trimester). Proprietary time periods may be no longer than one year, and investigators proposing large programs must also provide data reduction and release plans.

The role of non-federal observatories in carrying out surveys through public access should also be considered. Arrangements for public access time on non-federal telescopes should continue over a long enough period of time that surveys can be carried out. The participation of non-federal observatories in the system should be designed to enhance collaboration of community members in major surveys carried out on those facilities. It may also be appropriate for non-federal observatories to provide access to survey products in return for public operations support.

D. Community Support

Providing system facility information to the community:

The most direct support that NOAO can provide to potential O/IR observers is a full accounting of available facilities, so that potential observers can make informed decisions about the feasibility of planned investigations and the most suitable instruments to support them. We recommend that NOAO compile and maintain a compendium of available instrument capabilities in electronic form. This database should be searchable by a range of relevant characteristics, including instrument type, effective resolution, wavelength range, and location. It should also provide ready, electronic access to all relevant documentation and observing planning tools available for each instrument. We recommend that the current CATCH[4] website include descriptions of instruments at all facilities participating in the ReSTAR system.

Recommendation: We recommend that NOAO maintain a database of current capabilities on publicly accessible telescopes. This database should be easily accessed in electronic form and provide sufficient information for proposal development.

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[4] http://www.noao.edu/system/catch/

Setting standards for the ReSTAR system:
A publicly available telescope system should be subject to a high standard for system and data accessibility. Even first time users of ReSTAR facilities should be able to plan and execute observations, access their data, and produce scientifically useful data products with appropriate levels of user support.

The participation of non-federal observatories in the envisioned system should be evaluated using well-defined criteria for each stage of the data acquisition process. NOAO will be expected to develop guidelines on all relevant issues, including the following:

- Clearly identified instrument support personnel: each facility should have "experts" that can provide user support before, during, and after the observations are taken.
- Standardized observing preparation tools: these may include exposure time calculators and online user manuals.
- User-friendly telescope control software: the mechanism for directing observations should be simple and intelligible.
- Portable data formats: datasets should have standardized FITS headers and be readable in different data reduction and analysis packages (e.g., IRAF, IDL).
- Accessible data archives: observers should be able to access data electronically (with suitable proprietary periods).
- Universal data reduction software: packages needed to produce scientifically usable data should be tested to compile successfully on standard computing platforms.

NOAO should help to define sources of support to assist potential ReSTAR system facilities in developing the capabilities needed to satisfy the criteria set forth.

Recommendation: Non-federal facilities contributing to the pool of publicly available time should meet standards of efficiency, reliability, performance, documentation, usability, and data quality that will allow investigators to obtain data with the same assurance of success that they expect at federal facilities. Non-federal facilities should be supported to achieve these levels of user services if such facilities participate in the System.

In addition to telescopes and instruments that work well, observers need data reduction software. Specialized software that runs on limited platforms can be a barrier to the effective use of telescope time. To the extent possible, non-federal participants in the ReSTAR system should provide reduction software that makes use of widely used software systems, and image headers that allow use of standard software packages for data reduction. Data obtained by public-access observers at non-federal facilities should be publicly available either through NOAO or by other means, after an appropriate proprietary period.

Recommendation: All facilities participating in the system of small and mid-size telescopes, including both national facilities and non-federal telescopes, should provide data that can be reduced using standard systems and the data should be made publicly available after an appropriate proprietary period. Pipeline reduction of data is encouraged, if appropriate.

Balancing observer resources with system enhancements:
Observational astronomers continue to be concerned about acquiring the support necessary for all aspects of a successful project, including travel to telescopes, computational resources for data reduction and analysis, and publication costs. The committee acknowledges that this is a particular problem for observers from smaller institutions without dedicated facilities of their own. Therefore, the ReSTAR committee considered at some length whether support for investigators who are awarded time should be a high priority recommendation.

In an ideal world, NOAO would secure funds to support members of every observing project, but these costs mount rapidly. While about $0.05M per year currently goes to students to support dissertation observations, covering all travel costs at the level of one observer per run would add an estimated $0.4M to the annual budget, and the cost for NOAO to cover page charges for all papers resulting from NOAO observations would cost an estimated $0.7M per year. The cost of covering travel and page charges for one investigator per run is thus comparable to the cost of building a clone of the SOAR telescope's Goodman spectrograph per year. The cost of maintaining a full-up observing queue, including scheduling personnel and dedicated observers, for one telescope is also about $1M.

Given the tight budgets projected over the next few years, the committee felt the scientific return from new, state-of-the-art instruments benefit a wider range of users than the funding of all individual proposals in travel and page charges. National facilities should continue to support costs for students conducting observations for their dissertations, and may wish to consider providing a limited amount of travel or publication support for observers with special hardships. However, it would be more cost effective to make investments to enable remote observing or service observing than to fund the travel of all observers.

In consideration of those astronomers at institutions without broad observing support, we suggest that NOAO expend effort in implementing truly interactive remote observing experiences. Such experiences should be designed to allow an observer at their home institution to have the same kind of flexible, responsive observing experience they would have if they were on the mountaintop themselves. Providing the option for effective remote observing should also make it possible to develop a more flexible suite of observing modes, including programs significantly shorter than classical observing programs and synoptic observing programs.

E. How Many Telescopes, How Many Nights?

It is clear from community input that there is a significant and ongoing need for more publicly accessible telescope time. Respondents to the ReSTAR online survey identified observing programs for small and mid-size telescopes totaling more than 12,000 nights per year - nearly a factor of ten more observing time than is currently available on public access facilities. The Committee considered several approaches to make a somewhat more quantitative estimate of the telescope time the System should provide to accomplish the scientific goals discussed in Section III.

By way of context, the American Astronomical Society holds about 4,200 full members, and another 1,600 Associate and Junior members. One might subtract approximately 600 Emeritus members to get an estimate of roughly 5,000 working research astronomers. We can estimate that perhaps half of these, or 2500, will require optical or infrared ground-based observations for their research at least once a year. However, it is difficult to assess how many of these have access to private observing facilities and how many absolutely depend on public observatories. Of the 28 telescopes in the U.S. with apertures 2-m and larger, 80% are private. So, very roughly, if 20% of the 2500 astronomers needing O/IR facilities once per year need five nights per year on public facilities, they will need full-time access to about eight mid-sized telescopes. Clearly, this is a very rough estimate, since access to non-federal telescopes is not evenly distributed among astronomers, and astronomers with their own facilities also need access to additional capabilities not available on their own telescopes.

Another route to estimating the telescope time requirement for public facilities can be attempted by looking at proposal statistics to the present complement of public observing facilities. At NOAO there are about 2,000 unique, U.S.-based P.I.s and Co-Is proposing to use NOAO telescopes over a recent four-semester period, so the annual average is about 1,000 individual astronomers requesting observing time. If we assume applicants to the IRTF are a largely orthogonal set to this group, we can add another 200 astronomers for a grand total of 1,200. If the average observing program is about five nights annually, this comes to a total of about 6000 nights requested. We assume a success rate of perhaps 50% for winning observing time, and therefore arrive at an estimate of 3,000 nights of 2- to 4-m telescope time per annum. One might have available as many as 300 nights per year on a given telescope, after allowing for engineering, instrument commissioning and telescope upgrades, and so, again, we estimate a total of roughly eight-ten 2-4 meter telescopes are required for public access to U.S. optical and infrared astronomers.

A similar estimate of the number of telescope nights needed in the ReSTAR System is obtained by considering the 800 proposals received annually by NOAO, plus an additional 200 to the IRTF, half of which are awarded telescope time. This number is likely to rise substantially with new investment in a system of public access facilities. Providing a new, state of the art instruments on telescopes participating in ReSTAR will likely increase oversubscription rates to factors well above two. Low subscription rates on telescopes are due primarily to limited and aging instrumentation rather than to a lack of scientific value. The arrival of NEWFIRM at the Mayall 4-m telescope, for example, raised demand for this facility substantially. The Canada France Hawaii Telescope continues to be heavily oversubscribed because of the constant renewal of its instruments. Efficient RC spectrographs will increase oversubscription on NOAO's 4-m telescopes even though spectroscopy is not a new capability. As instrumentation improves, proposal pressure will increase, as will need for access to additional nights. While it is difficult to estimate how proposal pressure will increase with time as instrumentation is renewed, it is not unreasonable to expect that oversubscription rates will double over five years, leading to a need to double the available nights.

It is important to emphasize that, of the programs that received observing time on NOAO facilities over the past two years, *half of the PIs of these programs are from institutions which have no preferred access to non-public observatories larger than 3.5-m.*

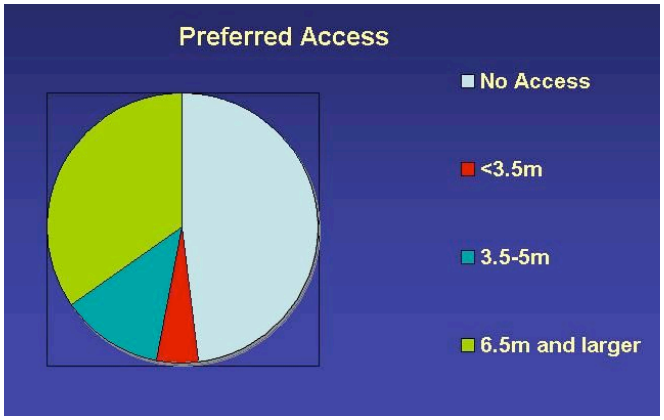

Fig. IV.E.1: Successful NOAO PIs from U.S. institutions over a four year period.

Another very important consideration for the number of nights required might be estimated based on the dissertation research of graduate students. Approximately 150 Ph.D. degrees are awarded in the U.S. each year in astronomy and astrophysics. NOAO supports about 50 unique proposals for dissertation research each year at KPNO, CTIO, Gemini, or through TSIP, and the IRTF supports another 5-10. These programs require about 10 nights per year per student. A typical student requires two years of dissertation observations. Thus, supporting dissertation observations requires at least 600 nights per year of telescope access. This suggests that two telescopes are required full-time just to support Ph.D. dissertation research.

The estimates above suggest that about eight 2- to 4-m telescopes in the ReSTAR System should satisfy the present requirements of the U.S. community with an over-subscription factor of two. As noted previously, the number of equivalent 2- to 4-m class telescopes currently available for public access is 4.2. The difference, nearly a factor of two, between the estimate above of the number of telescopes required and the number available, underscores the origin of the long-standing complaint from the community that those without access to private facilities are significantly under-served by the national observatories.

Recommendation: The number of nights needed in the system of small and mid-size telescopes can be estimated in several ways. Various approaches involving conservative assumptions consistently suggest that the equivalent of at least eight 2- to 4-m class telescopes should be available to the community for classically scheduled PI and survey programs. Telescopes in the ReSTAR System should include a mix of smaller apertures and the mix should evolve toward larger apertures over time as funding permits.

Additionally, the demand for telescope nights should be monitored, and facilities should be added to the ReSTAR system as demand increases, such that the oversubscription rate, averaged over all facilities, instruments, and lunar phases should not exceed a factor of two. Higher oversubscription rates for particular instrument capabilities should be interpreted as a need for access to more telescope nights with that capability.

Recommendation: Oversubscription factors on current facilities should be monitored as new instrument capabilities come online to evaluate the ongoing need for new facilities. For key major instrument capabilities identified for the system, oversubscription factors should not exceed a factor of two for extended periods. If oversubscription factors regularly exceed two, new facilities should be considered.

A common method for gaining access to non-federal facilities is through collaboration with those who have access. While this approach can ameliorate the problem to some extent, the Committee believes it is not an adequate solution. This solution obviously depends more on who an astronomer knows than on the merit of his or her scientific ideas. It obviously does not succeed if one has a program which competes with the scientific interests or which may challenge the conclusions of those who do have access to a given non-federal observatory. Such a solution does not serve the science at all well. However, the Committee strongly agrees that some capabilities needed for highly competitive science programs but which are not available on national facilities could be offered through public access to non-federal facilities.

V. TRAINING IN THE ReSTAR SYSTEM: OPTMIZING THE WORKFORCE

Development of human resources, including advanced training for students in observing and in instrumentation, must be integral parts of the System. In this area, small telescope science has a broad impact that is largely unrivaled. Greater hands-on opportunities differentiate a student’s experience at a small telescope from that gained when using a large telescope. For example, students observing on large telescopes do not typically have the opportunity to participate significantly in the technical operation of the instrument or the telescope – very often they are miles from the telescope during the observations. The development of students' engineering knowledge, as well as the problem solving experiences they gain from telescope and instrument operations in an observatory setting, are invaluable for ensuring the health of the field in the future.

Perhaps the most important skill for young astronomers to learn, particularly in ground-based astronomy environments where weather and technical problems greatly affect the quality of observations, is to teach students how to examine data critically. Seeing firsthand what conditions or problems affect the calibration of data, for example, and learning how a simple technical problem can preclude needed data from being obtained, are experiences that almost every observational astronomer has taken away from an observing run. On larger telescopes, queue scheduling, service observing, and, to a lesser extent, remote observing compromise this learning experience.

Additionally, because of the excitement that observing brings to recruitment efforts, observing at telescopes remains an important recruitment tool to attract excellent students into the field. Members of the committee can attest, through our first-hand experiences, to the importance of these experiences for the personal and professional growth of the future leaders of the field.

Finally, small telescopes play a major role as a test bed for new instrumentation, and the training of the next generation of instrumentalists. Very often smaller-scope prototype instruments are built as precursors for large-scale instruments; these prototypes are usually tested on, and often become workhorse instruments on, smaller telescopes. Young instrumentalists are likely to hone their skills building equipment for small telescopes. Additionally, access to smaller telescopes regularly plays a role in the development of instruments for our largest telescopes. Two recent examples include OSCIR (Observatory Spectrometer and Camera for the InfraRed) on Gemini North, but developed and tested on smaller telescopes, and FLAMINGOS (the Florida Multi-object Imaging Near-IR Grism Observational Spectrometer), which had its first runs on the Kitt Peak National Observatory 2.1-m and 4-m telescopes. The development of these instruments, using publicly available telescopes, helped to solidify the role of the University of Florida in instrumentation development for the astronomical community. The development of TEXES (Texas Echelon Cross Echelle Spectrograph), used on the McDonald Observatory 2.7 m and the NASA Infrared Telescope Facility 3-m telescopes and used on Gemini North, is another example of the value of small telescopes in instrumentation development and training.

Finding: Small and mid-size telescopes contribute additionally to the discipline through their training and education functions and as test beds for innovative new instrumentation and techniques.

VI. A BLUEPRINT FOR ReSTAR: REALIZING THE PUBLIC DIVIDEND

The ReSTAR System of small and mid-size telescopes should combine the best opportunities from both national facilities and non-federal facilities to provide telescope time to the astronomical community through peer-reviewed proposals. The system should include a range of apertures to match scientific needs, with emphasis on 2- to 4-m class telescopes, where scientific need is greatest. The current level of just over four such telescopes available for public access is sub-critical, and should be doubled over the next decade to eight equivalent telescopes in order to meet scientific need. The ReSTAR system should be expanded beyond current national facilities to provide telescope time for public access on non-federal facilities and, as appropriate, supplemented with new facilities. Non-federal observatories participating in the ReSTAR System should receive an appropriate level of federal support in return for their contribution to the ReSTAR System of public access.

There are certain over-arching principles that must guide public access to small and mid-sized telescopes at both federal and non-federal observatories. These principles assure that the ReSTAR System will be effective in providing the capabilities that the community needs in the near and long term. The principles address the capabilities that are made available at each site, the way in which telescope time is assigned, the quality and reliability of instrumentation and data products, the ability to reduce data, and the monitoring of the ReSTAR System components to ensure its quality and evolution. The principles identified by the ReSTAR committee are listed here.

Principles

- Access should be based on scientific merit through peer review, not by entitlement. Public access means that time is available through merit review and is not dependent on developing collaborations to gain access.
- The capabilities most in demand should be available on public-access telescopes.
- Capabilities in demand by relatively small numbers of users or for a limited scientific application may be best deployed on non-federal facilities.
- Competitive instrumentation is important for all apertures.
- The public access system of small and mid-size telescopes should emphasize reliability, standardization, and quality of data. Resources will be needed for non-federal facilities to achieve these standards. The balance between providing many nights of public access and the quality of services provided needs to be defined. The committee feels that telescopes contributing to the system should be held to a high standard.
- Software should be available and documented so that observers can reduce data, and data formats should be standardized such that observers can utilize the software of their choice for data reductions and analysis.
- A minimum set of deliverable data products processed through a pipeline, if appropriate, should be encouraged in agreements through which non-federal facilities participate in the ReSTAR System.
- Archives are an important component of a public access system, and providing usable archives of data is a higher priority than data pipelines.
- Procedures for assuring continued support for dissertations, once underway on public facilities, should be assured.
- Ongoing oversight of the ReSTAR System will be needed. The ReSTAR System must be allowed to evolve in a dynamic way as scientific needs change.
- The needs of the ReSTAR System should be considered in allocation of NSF funds to non-federal facilities for participation in the ReSTAR System.

Flowing from these principles, the ReSTAR Committee makes several specific recommendations to guide in the development of the ReSTAR System of public access. The success of the ReSTAR System will depend on not only on its scientific productivity, but also on the quality and significance of the science that is carried out on the telescopes of the System. Maintaining a high standard of peer review for programs scheduled through public access will assure that the science remains competitive, particularly when federal support for the breadth of astronomy is limited.

Recommendation: The continued operation of small and mid-size telescopes at the national observatories should be based primarily on the value of science produced, and publicly available time on telescopes in the ReSTAR system should be awarded on the basis of competitive review and scientific merit.

In building a new system for public access to telescopes, choices must be made. The community has many needs, and the ReSTAR System cannot fulfill all of them with the limited resources available. The Committee considered the priority of the various aspects of an effective community access system. In broad brush, access to adequately working telescopes should receive the highest priority. By working telescopes, the Committee includes not just image quality and reliable and efficient mechanical operation, but also telescopes equipped with control systems, including documentation, than enable efficient observing operations in support of user programs. Beyond working telescopes, the Committee identifies improved instrumentation, including software and documentation that facilities the full process from observations to analysis, as a high priority. The addition of new facilities to the ReSTAR System is the next highest priority. Several metrics suggest that a doubling the publicly available telescope nights is needed to meet scientific demand, especially as new facilities such as Pan-STARRS, LSST, ALMA, JWST, and GSMT come online and as surveys and specialized space missions yield a deluge of new science and new sources. A dedicated, time-domain network will be particularly important in the next decade to realize the science gains of these new facilities. Finally, as noted in separate recommendations, the implementation of adaptive optics with instruments available on telescopes in the ReSTAR system, as well as a mechanism for public access to interferometry, should be encouraged.

Recommendation: In establishing the ReSTAR System, priority for funding should be provided first to assure that telescopes in the system are functioning in a safe, reliable, and efficient manner, and then that competitive instrumentation and associated software are available. Next, adding three or four 2- to 4- meter class telescopes to the system, both new and existing, and specialized time domain facilities should receive priority. Finally, the potential of interferometric facilities and of adaptive optics for telescopes in the ReSTAR domain should also be exploited.

The advantage of establishing a ReSTAR system for public access to small and mid-size telescopes goes beyond increasing the number of telescope nights available to the community through a peer-reviewed system. ReSTAR offers the potential of community access to a wider array of instrumentation and to many excellent, state-of-the-art instruments available on non-federal telescopes. Specialized or unique instrumentation may be developed at any observatory, federal or non-federal, but no single observatory can afford to develop, operate, and maintain a suite of instruments needed to meet all of the diverse scientific requirements of the community.

Finding: A system of small and mid-size telescopes comprising federal facilities and public access to non-federal facilities will provide a cost effective mechanism to meet the needs of the discipline for observations and also provide a more diverse set of instrumental capabilities and operations modes than can be offered through federal facilities alone.

The ReSTAR committee notes, however, that the majority of the scientific programs identified for 2- to 4-m class telescopes can be carried out with only a few key capabilities in spectroscopy and imaging. It is not cost-effective for the national observatories to develop specialized instrumentation used for a limited number of programs, but rather should aim to provide those instruments needed for the widest range of scientific programs. More specialized capabilities should be provided for public access at non-federal observatories through the ReSTAR System.

Recommendation: Additional instrumental capabilities utilized more selectively for a smaller range of science programs should be accessible for public use preferentially on non-federal facilities.

Finally, the implementation of the ReSTAR System will require the leadership of NOAO, which can serve as a bridge between the astronomical community and the non-federal observatories. The establishment of the ReSTAR system will require both an in-depth knowledge of science, telescope operations, instrumentation, and community support needs and an ability to interact with the community and to represent that community in discussions with non-federal observatories. NOAO has a record of strong community support and the experience to know how to support that community.

Finding: NOAO, on behalf of the community, is the appropriate organization to select and negotiate with non-federal observatories participating in the ReSTAR System of small and mid-size telescopes, in cooperation with the NSF.

VII. ASTRONOMY WITHOUT BORDERS

A. Public-Private Partnership

The telescope and instrumental capabilities necessary to address the diverse science of the astronomical community are wide ranging. Thus, a breadth of capabilities with public access is necessary to satisfy these needs. But providing a full range of capabilities on each telescope would be prohibitively expensive. The construction of the ReSTAR System from both federal and non-federal facilities has the potential to provide the astronomical community with a more diverse set of tools than would be achieved by either alone. Further, if the ReSTAR System works as a true system without seams and to high standards, a full range of capabilities on every telescope is not necessary.

The ReSTAR committee acknowledges that specialization of capabilities on individual telescopes has the potential to reduce instrumentation and operating costs, and this should be encouraged. We feel that core capabilities must be available through the federal facilities that provide the bulk of the public access, but that some degree of specialization among federal and, particularly, among the non-federal facilities should be encouraged.

Recommendation: The specialization of both federal and non-federal 2-4 meter class telescopes should be encouraged. Specialization will provide a more limited set of observing capabilities on each telescope but should preserve a breadth of capability across the ReSTAR System. Thus, total costs for instrumentation and operation of small and mid-size telescopes could be reduced.

B. Maintaining the System

The ReSTAR System cannot be considered a static collection of telescopes, instruments and capabilities, but should rather be implemented as a dynamic entity that evolves and responds to the needs of the community in shorter timescales than those given by decadal surveys. Any system that meets the needs of astronomers today may not meet the needs 10 or 20 years from now; the ReSTAR System must evolve in response to changing priorities and opportunities. Continued community input will be needed, both to advise NOAO on implementation and to foster dialogue between NOAO, as the manager of the ReSTAR system, and the community. This will be especially important at the beginning of the implementation of the ReSTAR recommendations to monitor how the community is responding to the new capabilities and facilities being offered and to assure that community needs are being met. We therefore recommend a committee be formed for this specific purpose.

The committee would serve as an advisory panel to the NOAO Director and could meet on a yearly or semi-yearly basis. It should be composed of a variety of astronomers representing the different types of institutions and science areas that make use of the System. The members should serve for a few years in a staggered fashion, to ensure institutional memory is preserved but allowing it to evolve. The initial composition of the committee would benefit from maintaining a few of the original ReSTAR committee members.

The committee should seek input from the NOAO Users Committee and the NOAO staff involved with enabling access to non-federal facilities that are added to the ReSTAR system, and should foster an active dialog with the community. An ongoing “town meeting” at the winter and summer AAS meetings would enable input from a larger fraction of the community and would ensure that the user base remains engaged in conversation with NOAO.

Recommendation: The ReSTAR System of national access to federal and non-federal telescopes will evolve with time as it responds to changing scientific priorities and opportunities. A mechanism for regularly monitoring the success of the ReSTAR System *and for reviewing the capabilities offered by the system through community oversight must be put in place.*

C. Responding to the Future

The next decade will see the construction and early operations of ALMA, JWST, LSST and the GSMTs, as well as the true blossoming of the NVO. All of these will have profound effects on our field, and the system of small and mid-size telescopes will need to change as the field changes. This makes the oversight of the ReSTAR system even more important to assure that the System continues to evolve as the scientific needs evolve.

The policy of "open skies," that is, making U.S. national astronomy facilities available to proposers from any institution worldwide on the basis of merit and peer review, has served the discipline well. Science flourishes under an open sky, where the best ideas, independent of national origin, receive observing time. Historically, the fraction of observing time allocated by NOAO to proposals with non-U.S. principal investigators is less than 15%, although the proportion of investigators participating on proposals with U.S. PIs is higher - 36% of all investigators (PIs and Co-Is) applying for time and 30% of all investigators (PIs and Co-Is) awarded time are from outside the U.S. The open skies policy fosters collaboration and provides an avenue for U.S. investigators to access non-U.S. telescopes through those collaborations. The U.S. policy of open skies also leads some other countries to open their own facilities to proposals from U.S. investigators as PIs. Examples are Canada, which accepts proposals for the C.F.H.T in Hawaii, and the United Kingdom, which accepts proposals for UKIRT, for the AAO, and on telescopes on La Palma.

Although many nations do not yet follow an open skies policy, consideration of the need to specialize telescopes in the 2-6 meter range to reduce operations costs should lead to greater institutional collaboration across international boundaries, and can increase the number of telescopes participating in the ReSTAR System. Each telescope brings unique strengths in instrumental and operational capability, and adding international facilities to the system will benefit U.S. science. As the global astronomy community continues to grow and to pursue even more ambitious projects (such as ELTs), the opportunity may arise to collaborate with our international colleagues in the operation and maintenance of 2- to 4-m telescopes. NOAO and the NSF should start considering the administrative issues involved in such collaborations, so that the US community may take advantage of these opportunities on a timely basis when they arise. While such international partnerships may be difficult to arrange in the short term, in the longer term, over the next decade, the ReSTAR System should aim to grow in scope from national to international.

The European community, in particular, is currently facing similar issues to the ones presented in this report. Our European colleagues have prepared s a strong science case for small and mid-sized telescopes.[5] Some of these facilities perform exceptionally well, but funding limitations are leading to their neglect, closure, or privatization. As a result, opportunities for collaboration may arise that would benefit both European and US astronomy. These opportunities include, but are not limited to, balancing access to the northern and southern skies; instrument, detector, and software development; establishing standardized performance criteria for telescopes, instruments, or software; enhancing longitudinal coverage for a time domain network; and developing new sites. Most of the European 2-4 m class telescopes are under the control of individual nations, but initiatives are underway to bring some or all of them together under one umbrella organization. We recommend that NOAO consider international collaborations as a means to supplement or support the ReSTAR System, working with individual nations now, if appropriate, and a pan-European organization or other multi-national consortia, if such develop.

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[5] To view the ASTRONET science case, see http://www.eso.org/public/outreach/press-rel/pr-2007/Astronet_ScienceVision_lowres.pdf.

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