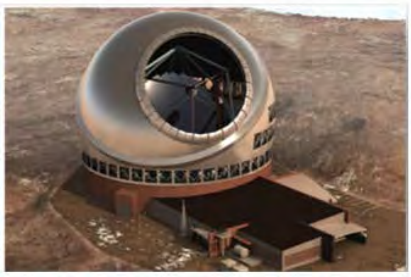
System-Wide Priorities for Astronomy in the University of California

A Report from the

UC Astronomy Task Force

30 July, 2011



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1 Executive Summary

The University of California (UC) Astronomy Task Force (ATF) was established to lead a community process culminating in a set of priorities for future system-wide investment in Astronomy & Astrophysics (A&A). Each UC campus with an A&A program (all but Merced & San Francisco), as well as the UC-run national labs had representation on the ATF. To broadly canvass the UC community for input, the ATF created a web-based Survey, held two town-hall meetings, requested written comments, and held multiple campus-level faculty meetings. Additional information was obtained from presentations from key administrative individuals.

Key Findings

UC has a vibrant and world-class A&A program, overseeing arguably the most prolific ground-based telescopes in the world. Over the last two decades, UC members have driven many of the most profound and fundamental contributions of our time, including discoveries of the accelerating universe, planetary systems around Sun-like stars, the anisotropy of the cosmic microwave background, and the supermassive black hole at the Galactic Center. Members of the UC A&A community have also made major technological breakthroughs, most notably, the segmented mirror design of the Keck telescope, which has been widely emulated, and the development of key elements of the Keck laser guide star adaptive optics system. These achievements, and many others, have led to significant rewritings of textbooks, have been featured as "Science Result of the Year" by science-wide publications, and have led to numerous awards and honors for UC faculty. These success stories are frequently the highlights of documentaries shown around the world, providing great visibility for UC's leadership and excellence as well as playing a significant role in the science education of the general public.

Currently, UC is operating shared telescopes at the Keck and Lick Observatories, and it is these shared facilities which have played the central role in UC's preeminence in A&A and the growth of departments across the system. Access to these outstanding facilities has attracted and retained top faculty and students to both large and small UC campuses. Significantly, there has been beneficial impact for those who directly use such facilities as well as for those whose work indirectly profits from the synergies and intellectual vibrancy that these facilities bring. Retention of technological expertise, collaborations with the UC-run national labs, and system-wide investment in a large multi-campus research unit (UCO) for instrument development and centralized operations, has promoted a highly engaged and innovative astronomical community.

For more than a decade, UC has played a central and leading role in the Thirty Meter Telescope (TMT) project, now in the early-construction phase. Technologically, TMT gains major heritage from the Keck Observatory in both telescope design and instrumentation, with UC faculty serving as the Project Scientist (Jerry Nelson, UCSC) and Principal Investigators of two of the three first-light instruments (James Larkin, UCLA; Rebecca Bernstein UCSC). Politically, UCSB Chancellor Henry Yang has served as chair of the TMT Board for the past four years, working tirelessly on critical issues such as the site and the partnerships. Financially, UC has received major philanthropic gifts for the TMT from the Moore Foundation. These gifts are notable within UC both for their size to a single scientific project and their support of a UC system-wide activity, as opposed to a campus-specific one.

Formally, the UC investments in A&A are separated into three funding lines due to differing partnerships for UCO, Keck Observatory and TMT, but these investments are highly coupled and leveraged off one another in a successful and productive way.

With its large ground-based optical and infrared telescopes, UC will leverage future, high-priority national observatories by enabling key follow-up observations such as faint-object spectroscopy or high angular resolution imaging. Similar to the Keck Observatory's complementary role to the Hubble Space Telescope over the past 15 years, the TMT complements planned national facilities including ALMA, LSST and JWST.

The survey of the UC A&A community clearly identifies the following prioritized ranking of facilities for UC system-wide investment (and associated percentage support):

1. The Thirty Meter Telescope (TMT) Project (90%)
2. Keck Observatory (89%)
3. UC Instrumentation Labs (70%)
4. Lick Observatory (40%)

Other proposed investments included LSST, the Large Synoptic Survey Telescope (20%), a system-wide facility for astrophysical computations (16%), and a radio astronomy facility (10%).

Prioritized Investment Recommendations

1. ***Ensure the long-term success of UC leadership within the TMT project.*** UC should continue to play a leadership role in the development of TMT's telescope design and instrument suite by investing in the technical expertise and UC laboratories. UC should commit to shifting $6.5 M/yr in 2018 from Keck operations to TMT operations when Caltech is contractually obliged to pick up that portion of Keck operations. This represents UC's contribution to TMT operations for a 15—18% share, leaving UC's share in Keck unchanged.

2. ***Keep the Keck Observatory at the cutting-edge of 10-m class telescopes and maintain UC's current share of the telescopes.*** UC should continue the contractually obliged funding of Keck operations. It should design and construct new instruments and new adaptive optics systems for the Keck Observatory. This requires UC to keep its instrumentation labs strong (at UCSC and UCLA) and to pursue, with its Keck partners, sources of additional funding.

3. ***Strengthen support for development and construction of instrumentation and adaptive optics.*** UC facilities, instruments, and personnel are vital to UC's leadership in both Keck and TMT and to the success of these observatories. UC should focus system-wide funding on labs capable of building next generation AO and instrumentation. It should also identify ways to mitigate risk for TMT and advance science at Keck.

4. ***Continue funding Lick Observatory at current levels, while exploring new funding models.***

In addition to the facilities above, we recommend creating a UC Astronomy and Astrophysics Council. This new body will improve the UC A&A community's ability to examine, optimize, and advocate for, the system-wide investments that UC makes in this field.

2 UC System-Wide Investment in Astronomy

2.1 Current Status

The University of California (UC) enjoys world-class standing in Astronomy & Astrophysics. Much of UC's strength in this field stems from visionary, system-wide investments in the design, construction and operation of large-scale optical/infrared (OIR) telescopes that are open to members of every UC campus and the UC-run national laboratories. While many fields of astronomy and astrophysics are pursued throughout the UC system, the large shared facilities are primarily OIR telescopes.

Currently, UC has two fully operational OIR facilities – the Keck and Lick Observatories. The W. M. Keck Observatory located on the summit of Mauna Kea, Hawai'i, houses twin ten-meter telescopes, the largest scientifically productive OIR telescopes in the world, which became operational in 1993 and 1996. This premier facility is run by UC, Caltech, and NASA. Within this consortium, UC has played a clear leadership role from inception. UC astronomers were responsible for the novel design of the Keck telescope optics, the development of key aspects of the Keck Laser Guide Star Adaptive Optics (AO) system, as well as the design and construction of more than half of the instrumentation at Keck Observatory. Lick Observatory, which is located on Mt Hamilton, California, is solely owned and operated by UC. The largest telescope on this site is the Shane 3-m reflector. When it was built in 1959, it was the second largest telescope in the world. Today, it offers UC astronomers and their graduate students a venue for large systematic surveys, as well as a site to develop innovative instrumentation and AO systems and concepts. UC's ongoing investment in these observatories and their operational centers is about $20M per year.

Over the last two decades, these shared OIR facilities have enabled numerous profound scientific achievements, such as the discoveries of the accelerating universe, planets outside our solar system, and the massive black hole at the center of our Galaxy, to name only a few results. Many of these discoveries have been labeled as "science result of the year" by Nature or Science magazine and have led to significant rewriting of textbooks. Almost any week of the year, one of these topics gets featured in documentaries that are shown all around the world, greatly boosting the visibility of the University of California and playing a significant role in the science education of the general public, a fundamental goal of the UC system.

UC is also one of the founding partners in the proposed Thirty Meter Telescope (TMT) Project. The completed design phase for TMT has resulted in a telescope and instrumentation suite that has strong heritage from Keck. Over the last ten years, UC has contributed numerous leadership roles within the TMT project, with UC faculty serving as Project Scientist, Chair of the Board, and Principal Investigators of IRIS and MOBIE, two of the three first-light instruments, and service on science steering committees. Participation in the TMT project has been enabled through generous gifts to UC from the Moore Foundation, which includes $25M for the now complete design phase and $100M for the current construction phase.

Investing in cutting-edge, large-scale, shared facilities is clearly at the core of UC's international success in A&A. It is access to unique facilities that has allowed UC to attract top faculty and students, raising the stature of all campuses across multiple sub-fields. While twenty years ago

only four UC campuses (UCB, UCLA, UCSC, UCSD) hosted substantial astronomy groups of international standing, the tremendous growth of astronomy and astrophysics faculty throughout the UC system has led to a blossoming of significant groups at Santa Barbara, Davis, Riverside and Irvine; Merced & San Francisco are the only two campuses without astronomy programs. With special access to a premiere facility like the Keck Observatory, UC astronomers have the opportunity to carry out unique work and become highly distinguished. In the National Academy of Sciences (NAS), which is composed primarily of older faculty, UC astronomers currently make up >20% of all UC NAS members and >20% of all NAS astronomy members. At the younger end of the spectrum, UC astronomy faculty makes up 25% of all recipients of the prestigious Packard Fellowships within astronomy. Numerous awards and honors have been bestowed on UC astronomers, including AAS Russell, Warner, MacArthur, and Pierce prizes, Sloan Fellowships, and numerous Kavli, Gruber, and Shaw prizes. Clearly, UC's system-wide investment in shared optical/infrared (OIR) observatories has resulted in great scientific success.

The University of California Observatories (UCO) is a multi-campus research unit, funded from the UC Office of the President (UCOP), and charged with operating Lick Observatory, developing instrumentation for both Keck and Lick, managing the time allocation committees and supporting future developments of OIR facilities such as the TMT. The headquarters of UCO are located on the UC Santa Cruz campus where there are multiple laboratories for the development and support of optical instrumentation. UCO also provides partial support for the Infrared Laboratory located at UCLA. A key feature of UCO is the investment in faculty and research staff with the technical expertise to innovate and pioneer new OIR facilities and instruments. UCO accounts for about $7.5M of the $20M investment that UCOP makes to shared astronomical facilities, with the balance going to Keck operations.

2.2 The UC Astronomy Task Force

The University of California's Astronomy Task Force (ATF) was established by Vice President for Research and Graduate Studies, Steven Beckwith, to advise on prioritization of funding and investment in UC A&A within the UC system, as input to the external committee that is charged with a review of UCO to be carried out in August 2011 (see Figure 1). Members of the task force were appointed from all UC campuses with Astronomy & Astrophysics programs (all but Merced [newest campus] and San Francisco [Medicine only]), and from the UC run national Labs (the Lawrence Berkeley Lab and the Lawrence Livermore lab). Initially, larger programs (Berkeley, Los Angeles, and Santa Cruz) were represented by two members, and the smaller programs and the national labs each had a single representative. After the first face-to-face meeting, one of the two co-chairs resigned as co-chair to minimize his conflict of interest as PI of a facility that was being discussed, but remained on the committee. In addition, two new members, both theorists, were added to increase the diversity of expertise and viewpoints, thus bringing the number of committee members up to 14.

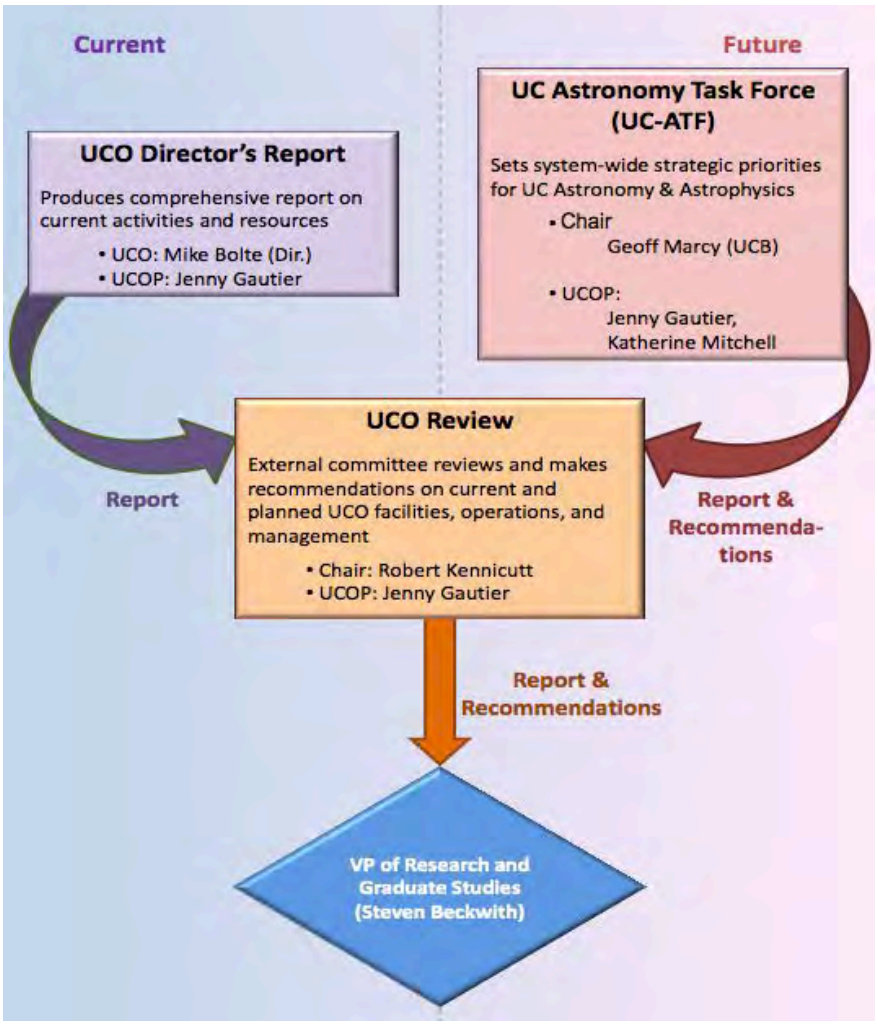

Figure 1. The role of the UC Astronomy Task Force. This committee of UC astronomers was charged with creating a prioritization for future UC system-wide investments in Astronomy & Astrophysics, as input to the UCO review committee, which is composed of experts external to the UC community.

Over a six month period beginning February 2011, the UC Astronomy Task Force (ATF) carried out the committee's charges to identify current and future priorities for UC system-wide investment in astronomy. While the full responsibilities of the ATF committee are given in the first section of the Appendix (Appendix A), the four specific charges are highlighted here:

Charges to the Task Force:

1. Lead a system-wide planning effort, through one or more workshops, with broad input from the UC Astronomy & Astrophysics community. The effort should prioritize both current and future infrastructure needs to create science and education opportunities for UC.

2. Assemble a short list of the anticipated major new investments needed to support these prioritized opportunities and shared facilities in the next decade. Include estimates of the costs, both capital investment and ongoing operations, to the extent possible today.

3. Produce a report on the recommendations for the highest priority investments in facilities, operations, and other activities, with a broad astrophysics perspective on what will best serve the ten-campus UC system for research and education in June 2011.

4. Propose a mechanism for ongoing assessment of future priorities by the full UC astrophysics community and for continuing accountability to the Office of the President.

To carry out this work, the ATF held four in-person meetings (April 22 [Irvine], May 13 [Oakland], June 9 [Los Angeles], June 16 [San Francisco airport]), two town-hall meetings, and several teleconferences. The ATF's work fell into the following three well-defined phases:

1. The initial phase focused on gathering community input, with a significant fraction of the time spent on the design, execution, and analysis of a survey of the community; additional input came from town-hall meetings (April 22 [Irvine, ½ day] & May 13[Oakland, ½ day] and formal written input from the community.

2. To follow up on the initial findings, the ATF went through an interview phase during which facilities identified as highest priority were investigated using presentations and Q&A sessions with invited guests. At the May 13 meeting, the ATF received a two-hour presentation from Michael Bolte, the director of UCO. The discussion included the UCO budget, UCO activities, and the vital role in instrumentation played by UCO staff and faculty. Also discussed was the interface between UCO and other institutions, notably Keck and TMT. In another meeting (held June 9), the ATF received a two-hour presentation from Henry Yang, Chancellor of UCSB and Chair of the TMT Board, and Gary Sanders, the TMT Project Manager.

3. Last, the ATF wrapped up with a final prioritization and report writing phase.

Along the way, subcommittees were established in a half-dozen different categories, including analysis of the system-wide survey, the Keck Observatory, the TMT Observatory, other options for shared facilities, governance, and instrumentation. A very large number of email and telephone exchanges occurred among committee and subcommittee members.

While strategic planning across all of Astronomy & Astrophysics has not been a standard practice in previous reviews of UCO, which was formed to support OIR astronomy, the process has been a rewarding activity, and a reminder of the tremendous leadership that UC has played in A&A, thanks to a unity of purpose and the creation of large-scale, innovative, *shared* facilities.

This document describes the outcomes of the ATF's. Section 3 reports on charge #1 and describes the process and results of acquiring input from the UC A&A community. Section 4 covers charge #2 and details the final prioritization. Section 5 addresses charge #4 and proposes

mechanisms for assessment of and accountability for UC's system-wide investment in Astronomy & Astrophysics. This report itself satisfies charge #3.

3 UC System-Wide Community Input

3.1 Survey of UC Astronomers and Astrophysicists

To begin its work the UC-ATF conducted a major survey (the Survey) of UC astronomers and astrophysicists to provide input into the priority-setting activity. The process and results are summarized in this section, while the full text of the Survey can be found in Appendix B. We invited a large set of UC faculty and researchers carrying out a broad range of astronomy and astrophysics research to participate in the survey; the total pool of 255 survey recipients constituted a very wide net, as only 123 of them were members of the American Astronomical Society. Based on the detailed and thoughtful responses to what was a lengthy survey, the 91 respondents are clearly heavily invested in the future of UC astronomy. The rate of response was significant throughout the system as illustrated graphically in Figure 2, and most respondents (88%) have a senior position and/or tenure in their departments.

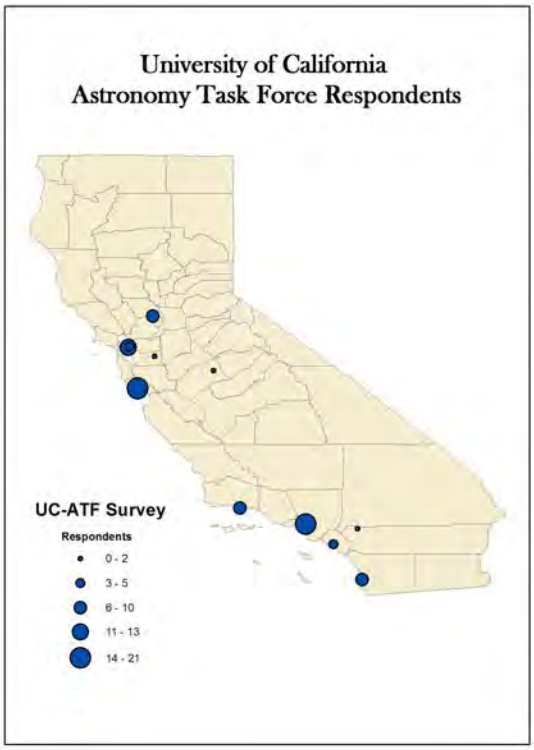

Figure 2: The distribution of where the 91 survey respondents work. Input was received from scientists on all UC campuses with Astronomy and Astrophysics programs (i.e., all but Merced and San Francisco) plus the UC-managed Lawrence Berkeley National Laboratory (LBNL) and Lawrence Livermore National Laboratory (LLNL).

3.1.1 Community Facility and Infrastructure Priorities

The Survey was designed to differentiate between scientific priorities and facility or infrastructure priorities. The questions were open-ended, not multiple choice, so that

respondents conjured answers creatively, not by suggestion. Significantly, 90% of respondents indicated that *both* the Thirty Meter Telescope (TMT) and the Keck Observatory should be UC's top facility priorities over the *next* decade. Over 70% of survey respondents also supported Optical and Infrared (OIR) instrumentation and infrastructure for TMT and Keck as a top priority (see Figure 3). While there was a range of specificity and direction of differentiation concerning OIR instrumentation and infrastructure, respondents in that category generally indicated the UCSC Optical Shops, UCLA's Infrared Lab, Adaptive Optics development and the UCO/UCSC operations facility, as the key priorities. Over 40% of respondents also supported continued investment in Lick/Mt. Hamilton facilities as one of their top priorities. The Large Synoptic Survey Telescope (LSST), a new national facility for which the PI (Tyson) is a professor at UC Davis, received 20% support, roughly half of which was associated with the opportunity for UC to follow-up LSST targets-of-opportunity with Keck and/or TMT. High performance computing facilities (16%) and new, shared radio astronomy facilities (10%) were also listed as possible facility and infrastructure priorities.

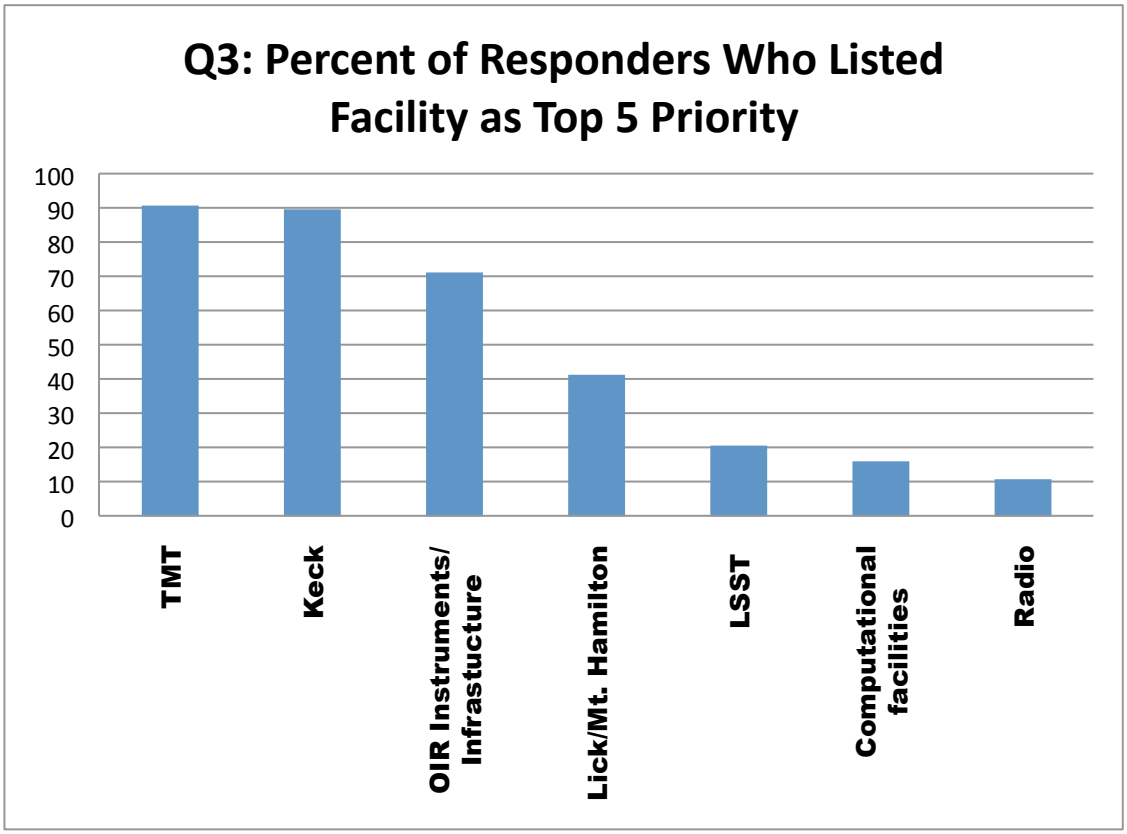

Figure 3. The percentages of responses for entries of the top 5 facilities for UC system-wide investment based on science priorities. The majority of survey respondents identify TMT, Keck, and Optical/Infrared Instrumentation and Infrastructure for Keck and TMT as priorities for UC system-wide investment.

Figure 4 shows the distribution of priority rankings for each facility identified as a "Top 5" facility for UC system-wide investment by more than 10% of Survey respondents in Question 2

(Figure 3). Again, examination of the placements from the Survey shows that TMT and Keck were ranked in a virtual tie for top priority for UC funding.

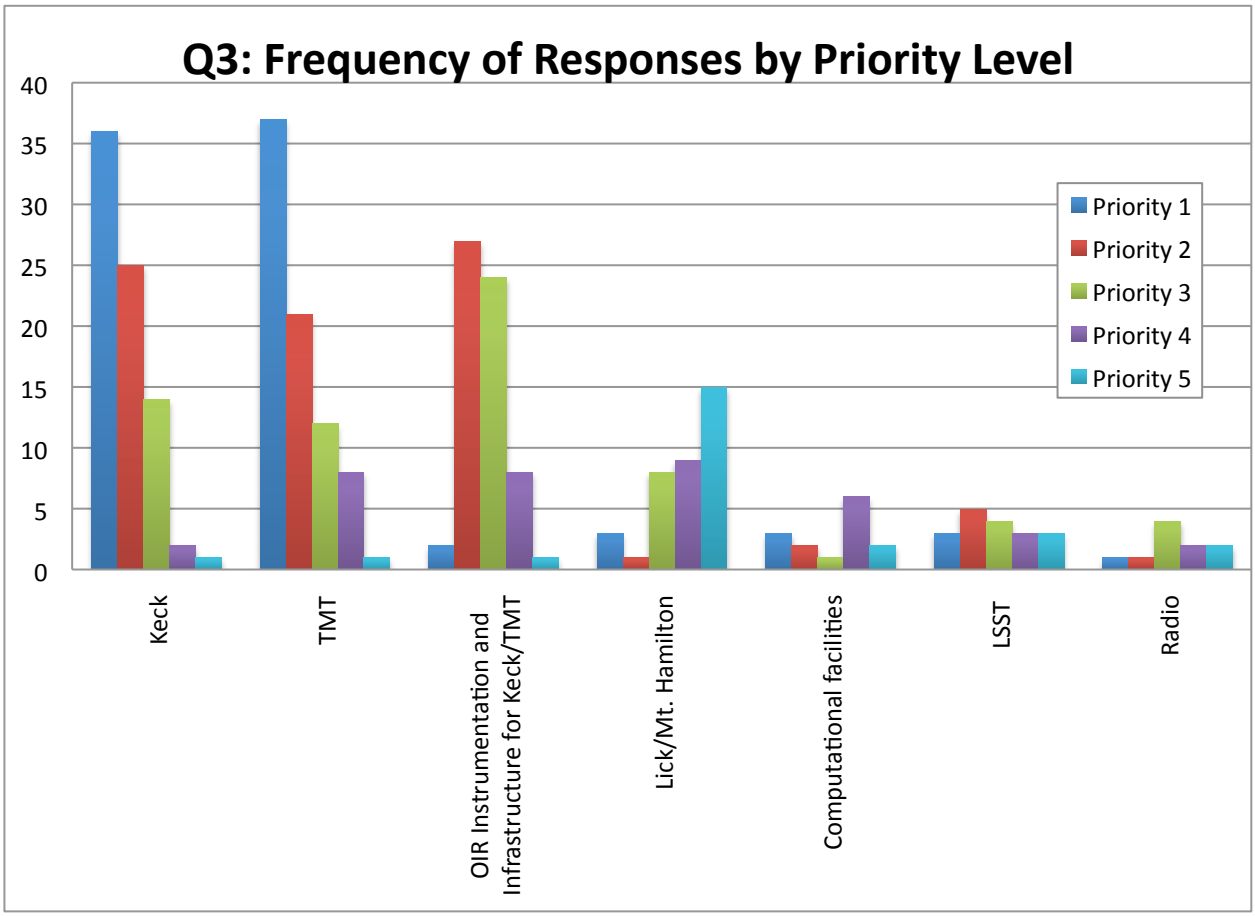

Figure 4. Distribution of priority rankings for each facility identified as a "Top 5" facility for UC system-wide investment by more than 10% of Survey respondents in Question 2 (see Figure 3). TMT and Keck are most often ranked as top priorities. Optical/Infrared Instrumentation and Infrastructure for Keck/TMT are most often listed as a second or third priority, and Lick Observatory has the next highest ranking.

When asked a second question about community priorities for future investment in shared facilities assuming that the funding for UC astronomy remains at current levels (no growth), the numbers were very similar to before (see Figure 5). Over 90% of respondents indicated that Keck and TMT were the most important assets to retain given budget constraints, with nearly 70% also supporting OIR instrumentation and infrastructure and over 40% naming the Mt. Hamilton/Lick Observatory as prioritized facilities. No other facilities received a greater than 10% response rate. Keck, TMT and OIR instrumentation were consistently mentioned as the top three priorities in the Survey.

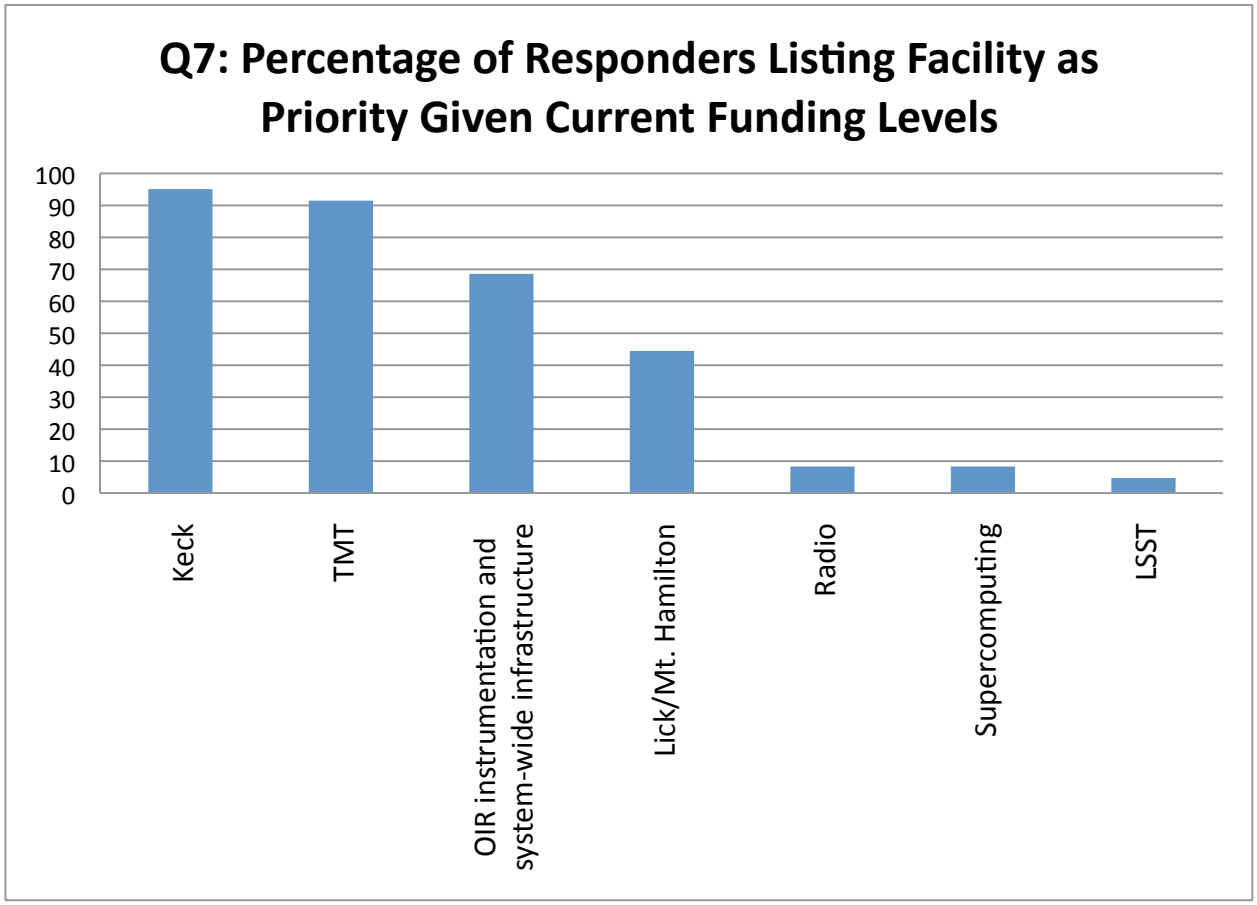

Figure 5. The percentages of responses for future investment in shared facilities, if the investment in UC Astronomy & Astrophysics were not to change. The responses rates are quite similar to Question #3, which is the science-driven version of this question.

3.1.2 Community Scientific Priorities

When asked about science priorities, Survey respondents listed a wide variety of areas deserving scientific focus within UC over the next decade. This reflects the breadth of excellence of the multi-campus astrophysics research effort. Many respondents also mentioned facilities as science priorities, but the Survey review committee focused on astronomical scientific priorities only for this question. Over 75% of question respondents listed priorities in the Galaxy Evolution and Exoplanets categories, and nearly 70% of respondents listed Cosmology as a major scientific priority for UC (Figure 6). Other categories listed as scientific priorities included, Supermassive Black Holes (46%) and Star and Planetary Formation (31%).

3.1.3 Achievements

The Survey also asked recipients to list the major scientific and technical achievements contributing to the University of California's excellence in Astronomy and Astrophysics, and to name the factors enabling these achievements. Many responses were very specific at the project

level, which led the Survey review committee to split the scientific and technical achievements and normalize each accordingly. (Specific factors enabling each achievement are listed below in parenthesis.)

Within the scientific achievement category, over 80% of respondents mentioned the discovery of exoplanets (Mt. Hamilton/Lick and Keck; radial velocity and direct imaging with AO) as a UC scientific achievement. This was followed by the discovery and study of the Milky Way's central black hole and its environs (Keck and AO) and by the discovery of the acceleration of the universe (Keck, spectroscopy, leveraging other facilities), which were each cited by approximately 60% of respondents who listed at least one scientific achievement. Studies of galaxy evolution and formation enabled by faint object spectroscopy at Keck (for example the DEEP2 redshift survey) were mentioned by 33% of respondents. Respondents made it clear that the results recognized as scientific achievements, shown in Figure 6, were enabled by UC's shared OIR facilities and infrastructure (Keck telescopes, Keck instruments, Adaptive Optics and Mt. Hamilton/Lick).

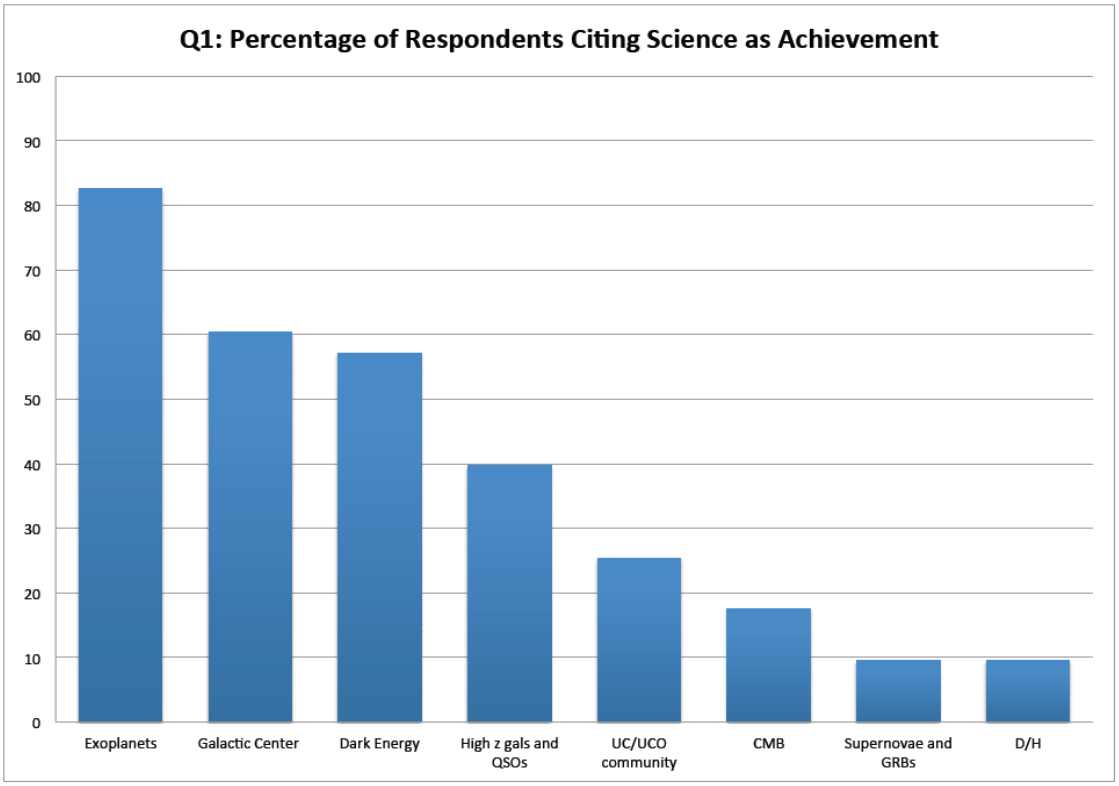

Figure 6. The percentage of survey responses for top science achievements that have contributed to UC's excellence in Astronomy & Astrophysics. The most well recognized results are those that were enabled by UC's investment in large-scale, innovative shared facilities and instrumentation.

Respondents also indicated a strong sense of pride in, and ownership of, the UC astronomical community's technical achievements, with 73 respondents listing at least one technical achievement (see Figure 7). Of these respondents, 96% cited the Keck Telescopes as a technical achievement (UC system-wide support of large-scale innovative projects; connection with

Lawrence Livermore and Lawrence Berkeley Labs; UC faculty with technical expertise), 81% mentioned Adaptive Optics (connection with labs), and 55% listed general instrumentation (strong on-campus labs). About 40% of respondents mentioned the general support by the UC system for groundbreaking and innovative projects, exemplified by the Keck telescopes. Respondents made it clear that the results recognized as technical achievements were enabled by more general factors such as people at UC, system-wide support for astronomy because of UCO and Keck operations, association with national labs and with the UCSC and UCLA labs, which appear as both achievements and enablers, as well as the existence of UCO as a vital operational center.

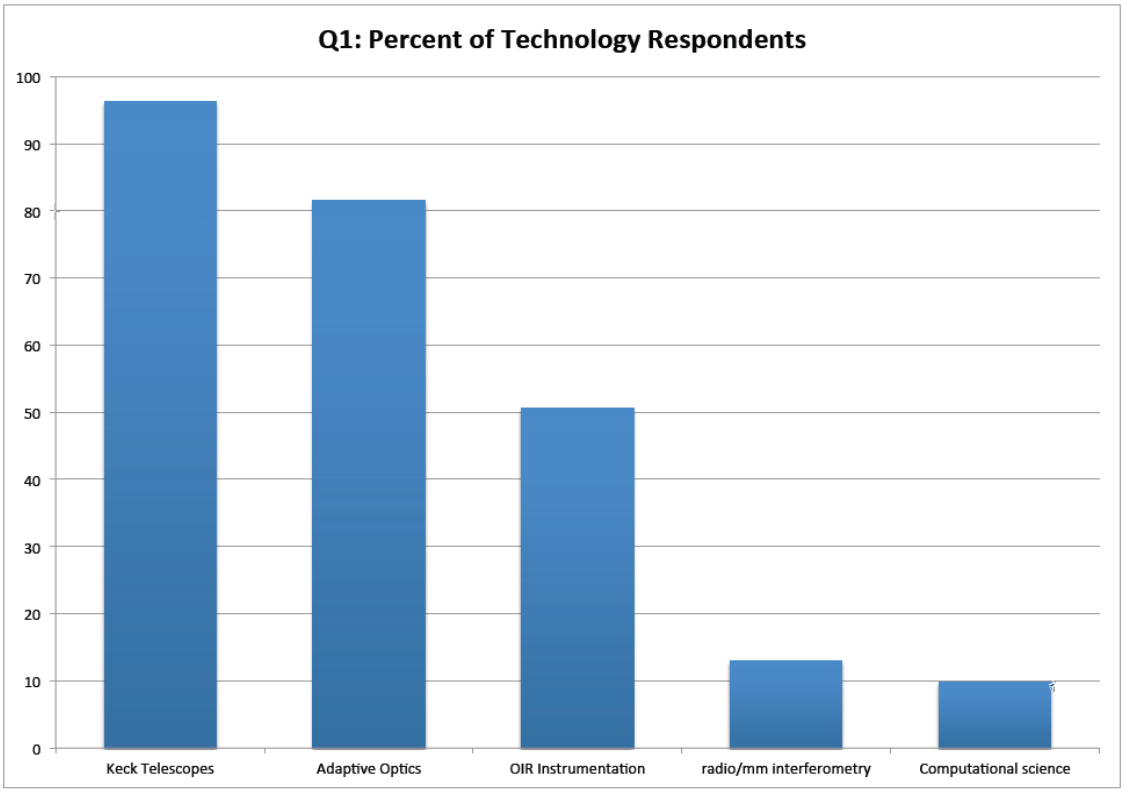

Figure 7. The percentage of responses for top technical achievements that contribute to UC's excellence in Astronomy & Astrophysics. The most well recognized results are those that were enabled by people at UC, or by system-wide support for astronomy (Keck, UCO).

While a wide variety of factors enabled both the scientific and technical achievements, over 60% of respondents cited some interplay between the intellectual environment, shared facilities and technological leadership, and thus considered this system-wide combination (sometimes called the "power of ten" effect) as a major factor contributing to UC's achievements in astronomy and astrophysics. This was a clear message from the Survey.

3.2 Additional Community Input: Town Hall Meetings and a Community Letter

At two of the in-person meetings, the community at large was invited to participate in a workshop, enabling them to hear about the deliberations, ask questions, and engage in discussions. Both meetings were well attended with over 50 people participating in this process. The ATF specifically solicited ideas about potential UC shared facilities that had, perhaps, not been adequately represented to date. Ideas discussed included radio astronomy, x-ray, gamma-ray, and particle astrophysics. The LSST, BOSS, ALMA, and other federally funded major facilities, as well as large-scale computing and theory were also considered. Opportunities for public outreach, especially at Lick Observatory/Mt. Hamilton, and concepts for multi-campus classes, such as the successful Adaptive Optics summer-school graduate course implemented by Claire Max using videoconferencing, were also discussed.

With the release of the Survey results, additional written input was solicited from the UC community. This solicitation yielded one major letter from a large segment of the UC astronomical community. *The letter elaborated on the role of system-wide investment in astronomy (as opposed to campus-specific investment) and was signed by over 60 UC Astronomers & Astrophysicists, a much broader base of astronomers than in the UC-ATF committee*. The letter largely supported the results of the Survey in its articulation of the highest priorities for shared, system-wide facilities, notably the value of Keck, TMT, Lick, engaged instrumentation personnel and well-established labs. Appendix C contains the full text of this letter.

3.3 Summary of Community Priorities for UC System-Wide Investments

In summary, the system-wide Survey of astronomers and astrophysicists revealed four major categories for future investment which the ATF (and the community) have prioritized as:

- Pursuit and continued leadership of the TMT Observatory (90% support)
- Continued funding of the Keck Observatory (89% support)
- Instrumentation labs and staff, at UCLA (infrared) and UCSC (optical) (70% support)
- Continued funding of Lick Observatory/Mt. Hamilton, but with exploration of new funding models (40% support)

These four items represent a prioritized list of how precious UC funds should be allocated. More details are given in the next section.

4 Findings for High Priority Facilities

4.1 The TMT and its Role in the UC System

Over 25 years ago the University of California took the visionary step to invest heavily in astronomy in the form of the twin 10-m Keck telescopes with their unique segmented-mirror design. As a result, the UC now hosts one of the strongest astronomy communities in the world.

To build on this strength for the future decades, and to assure continuity of the leadership UC enjoys today, a new anticipatory and ambitious strategic roadmap is required. From the unambiguous results of the ATF Survey, the proposed Thirty Meter Telescope (TMT) is at the heart of this plan. Scientifically, it is easy to see why the UC community has endorsed this project. The TMT will address many of the key issues facing astrophysics in the coming decades, including exploration of:

- The end of the "dark ages" when the first sources of light and the first heavy elements in the universe formed.
- The growth of galaxies and large-scale structure in the young universe, including the era in which most of the stars were formed.
- Super-massive black holes throughout cosmic time.
- Formation and characterization of extra-solar planets, their parent stars, and the solar systems in which they reside.

As has often been the case for previous large projects in astronomy (HST & Keck), many of the most outstanding discoveries will not be among those thought of at the time the telescope was designed. It is for that reason that TMT has been designed as a versatile, general-purpose observatory.

Two other "extremely large telescopes" (ELTs) are being designed: the European-ELT and another US telescope, the Giant Magellan Telescope (GMT). These projects have strong funding and momentum. Both the E-ELT and the GMT are direct competitors for the TMT. However, both of these telescopes will be located in the Southern Hemisphere (Chile), whereas TMT is to be built in Hawai'i giving it access to the entire northern sky. It is exciting to imagine a world in 2020 in which UC and its Pacific partnership would have a northern hemisphere 30m telescope.

4.1.1 TMT: UC Technology Development

In addition to a strong research faculty, UC also contains a rich base of technical expertise in the design, development and operation of major OIR astronomical facilities. This factor cannot be overstated. TMT's optics, its control systems, and two of its three first-light instruments are being designed by UC scientists. Albeit with 492 segments instead of 36, TMT derives significant heritage from the Keck experience which has served UC brilliantly for over 15 years. The segmented mirror concept has now been emulated in other telescopes such as the GTC, HET and SALT. Many of the faculty and staff involved in the development and exploitation of the Keck Observatory are now engaged in TMT work. As the Survey shows, UC astronomers recognize the value of investing in technical expertise and our own state-of-the-art shared facilities.

4.1.2 UC Leadership and Funding of the TMT

Building on its leadership in the Keck telescope design, the University of California has been an essential intellectual, technical, and political force driving the development of the TMT in partnership with Caltech. With funding from the Moore Foundation, UC faculty members are

engaged as the designers of TMT's segmented-mirror and accompanying control system[1], and of two of its three first-light instruments. Numerous UC faculty members have contributed very substantially to the "science cases" which drive the observatory's design. And UC administrative leaders are playing pivotal roles in building and cementing the new international partnerships with Canada, China, India, and Japan that will enable the TMT to be built.

The Gordon and Betty Moore Foundation has given UC $125M, of which $25M supported UC's effort in the design phase (completed) and $100M is for UC's share of the TMT's capital costs. This is a generous gift that is analogous to that made by the Keck Foundation to Caltech for its (36%) participation in the Keck Observatory, guaranteeing Caltech access to Keck for the first 20 years, while UC paid for all of the operation costs over this same period to cover its share (36%). UC is very fortunate in the TMT project to have the benefit of a philanthropic gift guaranteeing UC access (15-18%) to the TMT without having to assume a disproportionate share of the operations costs as was done in the Keck era.

Nonetheless, UC will have to pay its share of TMT operations costs. UCO Director Bolte has presented a plan for accomplishing this requirement. In 2018 and beyond, there will be a sharp (50%) decrease in UC's contractual contribution to the operation of the Keck Observatory, but without loss of share, when Caltech begins covering its share of Keck operations. These funds can be redirected to TMT. The TMT partnership agreements, currently under negotiation, would limit UC's liability for potential cost over-runs. *Thus, the TMT funding model for UC currently provides extant funds for both capital costs (Moore Foundation gift) and operations (coming from Keck operations savings in 2018) that do not further impact the UC System, its campuses, nor taxpayers*. This UC funding model corresponds to a 15—18% share of TMT.

4.1.3 The Science Case for the TMT

The full science case for a diffraction-limited 30-meter telescope operating from the near-ultraviolet to the mid-infrared has been expounded elsewhere and a detailed analysis of this extraordinary science is beyond the scope of the UC-ATF review. From the results of our internal survey, TMT is deemed an essential tool for UC astronomers to address the premiere questions in astronomy over the next 50 years. To provide only the minimum of context for this UC report and for our recommendations, we have extracted the following from TMT documents.

<u>When did the first galaxies form and how did they evolve?</u>

Observations of the first stars and galaxies to form in the universe (Figure 8) are beyond the reach of present telescopes, but with TMT they will begin to reveal themselves. With current telescopes we see galaxies interacting dynamically, gradually regularizing their shapes, and forming stars. TMT will be able to observe galaxies as they assemble themselves from separate irregular pieces into the orderly structures we see today. During the early history of the universe most atoms and molecules actually are found outside of galaxies. Intergalactic space is filled with a tenuous gas that provides "fuel" for forming galaxies, and is a repository for material

[1] Prof. Jerry Nelson was recently recognized with the Kavli Prize for "pioneering the development of a new generation of large optical telescopes with innovations such as precise reflecting mirrors and more sophisticated shaping." See http://news.ucsc.edu/2011/06/kavli-obama.html

expelled by galaxies. By observing the effect that intergalactic gas has on the spectra of the most distant objects, TMT will reveal the extent to which galaxies alter the physical state of the intergalactic gas: their sphere of influence, mass outflows, ionization effects, and deposition of mechanical energy.

Many UC astronomers work in this general field. Recently, UC astronomers discovered the highest redshift galaxy found to date and confirmed its redshift using a sensitive Keck spectrograph, a tantalizing reminder that TMT will be an even more powerful tool to study high redshift galaxies.

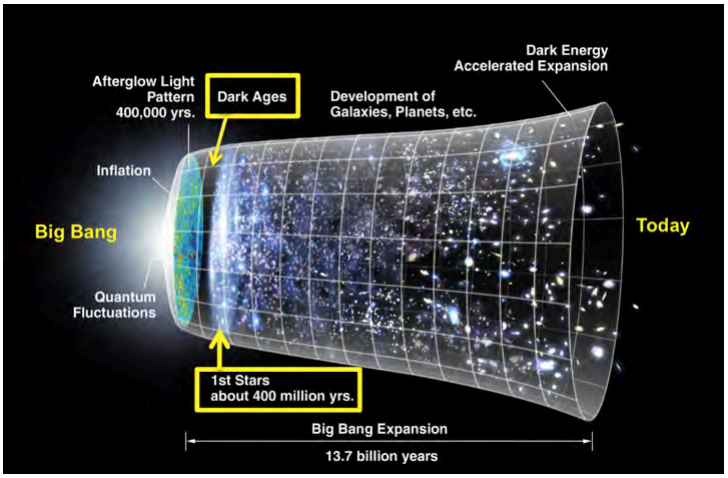

Figure 8. A schematic diagram showing the history of the universe. For hundreds of million years after the Big Bang, the universe was dark. TMT will be able to detect and characterize many of the first long-lived galaxies, which formed about 400 million years after the Big Bang. Credit: NASA WMAP Science Team.

What is the relationship between black holes and galaxies?

There is overwhelming evidence that black holes with as much as a billion times the mass of the Sun occupy the centers of large galaxies. However, we do not know when or how these super-massive black holes formed, or how they fit into the overall picture of galaxy formation and evolution. TMT will enable the next giant leap in super-massive black hole physics, comparable in magnitude to the one that followed the launch of the Hubble Space Telescope. Researchers using TMT will study the demography of super-massive black holes as a function of environment, and extend their reach to lower black hole masses and higher redshift galaxies in order to understand the correlation between black hole and host-galaxy properties. The best-studied super-massive black hole will remain the one in the center of our own Milky Way Galaxy, whose properties are revealed by watching the stars in very close orbits around the black hole (Figure 9) using infrared light. The significantly higher depth and better resolution of TMT observations will test the predictions of General Relativity close to an object with a million times the mass of the Sun, as well as provide tests of black hole growth models.

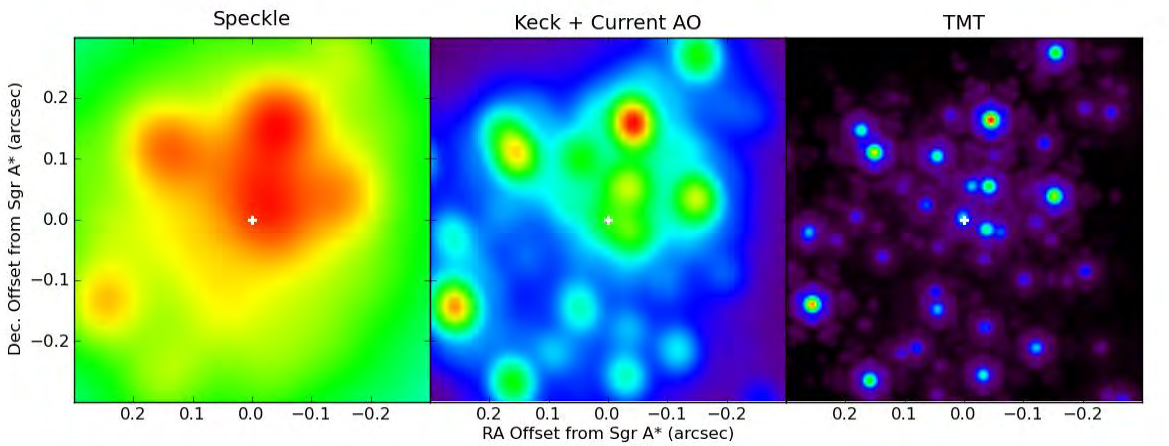

Figure 9. Three views of the region surrounding the million-solar-mass black hole at the center of our Milky Way Galaxy. Left: Keck Observatory "speckle image" without adaptive optics correction. Middle: Keck Observatory image with laser guide star AO correction. Right: Predicted image using TMT laser guide star adaptive optics. Credit: Andrea Ghez (UCLA) using data from the Keck Observatory.

In Figure 9, the individual stars are orbiting at speeds as high as ~1600 km/sec around the central black hole. Measuring their detailed orbital motions provides a test of General Relativity, and reveals the profile of matter and dark matter in the core of the Galaxy.

How do stars and planets form?

We know that stars form within dense clouds of molecular gas, by complex physical processes. What determines when these huge clouds form stars? What determines the masses of these stars? What fraction of newborn stars has a planetary system? The greatly increased spatial resolution and flux sensitivity of TMT will allow individual young stars to be resolved, even in crowded fields, within a wide range of stellar environments in our own and nearby galaxies. TMT will have the sensitivity to allow spectroscopic analysis of star-forming cores, to diagnose the structure and kinematics of gas as it falls onto the new stars, and to observe jets and winds launched from the inner regions of forming star-disk systems. High-contrast imaging capabilities will allow TMT to record disks around young stars. When these disks have significant gaps caused by orbiting planets as illustrated in Figure 10, we will be witnessing planetary systems in formation.

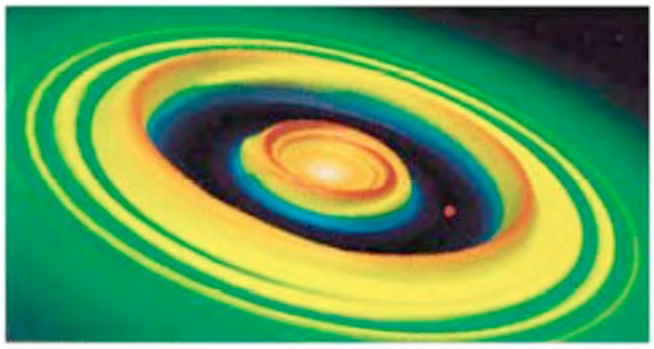

Figure 10. Computer simulation showing the dynamical effects of a newly formed gas-giant planet (red dot within the dark ring) on a disk of gas and dust surrounding a young star. The planet's gravity opens up a gap, or dark ring, of very low density. The spectrum from such a ring+gap will show characteristic features that TMT can measure, revealing the width of the gap and the mass of the planet. Credit: TMT Detailed Science Case report.

What is the nature and origin of extra-solar planets?

Almost all of the ~550 exoplanets detected to date are gas giants like Jupiter and Neptune. They were found because their large mass noticeably perturbs the motion of their host star. Surprisingly, many are found very close to their parent star. Because the higher temperatures there would prevent such planets from forming *in situ*, they must have migrated inward after forming at greater distances. A large fraction of the known exoplanets was discovered by measuring the reflex motions of their parent stars. A high-resolution spectrograph on TMT will expand the number of host stars accessible to this type of detection by a factor of 30 by allowing a greater volume of space to be explored. In addition, TMT's higher sensitivity will allow lower-mass stars, such as M stars, the most common stars in the galaxy, to be observed. These lower-mass stars are more strongly affected by planetary gravitational perturbations, so lower-mass planets can be detected. TMT will be able to detect Earth-mass planets orbiting in the habitable zone of M stars (the habitable zone is the region surrounding the star where a planet would have a temperature conducive to the formation of life). TMT's proposed Planet-Finder Imager will perform a complementary role, by imaging the outer regions of exo-solar systems.

4.1.4 TMT as a Discovery Engine

In retrospect, the most important discoveries of the Keck telescopes (extrasolar planets, the acceleration of the universe due to dark energy, the black hole at the center of the Milky Way) were not anticipated when the telescopes were built. That is why TMT has been designed as a general-purpose observatory rather than for a specific purpose. As has been the case for every previous increase in capability of this magnitude, it is very likely that the scientific impact of TMT will go far beyond what we envision today, and TMT will enable discoveries that we do not anticipate. Those discoveries may well be the most important ones.

4.1.5 TMT and LSST

By making a “movie” of a large area of the sky during the 2020s, the Large Synoptic Survey Telescope (LSST) will be a transformative tool to discover and characterize the time domain (a relatively unexplored phase space gaining tremendous interest in our community). Every night, this number-one ranked national facility will broadcast alerts worldwide for perhaps a million faint events (exploding stars, moving objects, *the unknown*). Two things will be required to reap

the full scientific harvest of this new view of our universe: (1) innovative data analysis to sift through these events characterizing the truly intriguing ones, and (2) access to powerful 10—30m telescopes to obtain spectra of those objects. With Keck and TMT, UC would be able to follow-up with spectroscopy and AO imaging the most interesting objects identified by LSST.

With its latitude at +19 degrees, the TMT will be well positioned to observe half of the LSST sky (despite the fact that LSST will be in the southern hemisphere). Studies of the history of galaxy formation with TMT, especially at large redshift, will aid LSST's precision tests of cosmology, illuminating the physics of dark energy. LSST and TMT will certainly also study, in tandem, gamma-ray bursts, supernovae, their rates, and the galaxies responsible for re-ionization of the universe. LSST and TMT make an excellent complementary pair.

Viewing Keck and TMT as precious resources, great scientific returns may derive from following up the vast numbers of LSST discoveries. As such, there is motivation to build a UC-wide shared computational and algorithmic facility and framework for the characterization and classification of the million LSST alerts per night. We note event classification itself is not a data deliverable of LSST. Professors Bloom and Tyson in the UC system have begun organizing such an "LSST Characterization Center" for pipeline event classification, drawing on expertise in computer science, statistics and astronomy across UC campuses. We encourage further discussion of this possibility.

4.1.6 Funding Model for TMT

One of the charges to the ATF was to understand the funding model for large investments to the extent possible. The current capital cost estimate for TMT is $1.152B in 2011 dollars. The Task Force heard directly from the TMT Project Manager that the TMT has had a series of extensive and invasive cost reviews and we were able to examine the detailed plans and methodology being used. The most recent of these reviews with published material was a four-day review in January 2011 by a 20-person international team of experts in the construction of large ground-based facilities, optics, and observatories. The review committee concluded that "the TMT team is first-rate," that "the management tools and processes are excellent and are what is needed for a project of this size," and that "the base cost estimate is justified (within 5%)." The cost estimate quoted above has adjusted the cost upwards to take this additional 5% into account.

Both the depth and sophistication of the TMT budgeting process are extraordinary. Bottom up costing and contingencies have been painstakingly developed and extensively reviewed. Contingency levels remain at the comfortably high end for the current stage of project completion, as measured relative to other major ground-based facilities.

It is anticipated that the TMT will have 6 partners: UC and Caltech (in equal shares), Canada, China, Japan, and India. The US National Science Foundation may join at a later date. Wording for the official partnership agreements is currently being negotiated.

UC and Caltech's shares of observing nights will each be approximately 15—18%, in return for supplying $300M of capital costs. As already stated, the lion's share of UC and Caltech's contributions to the capital costs of TMT will come from grants and gifts by the Gordon and Betty Moore Foundation.

The language in the Moore Foundation's $200M commitment to TMT says that UC and Caltech are each also "expected" to bring in matching funds of $50M from other private donations. UCSB Chancellor Henry Yang (as chair of the TMT Board) and Caltech President Jean-Luc Chameau have agreed that they will undertake this fundraising project together over the next 5.5 years. The ATF applauds this approach. The TMT Board, the UC Chancellors, the Caltech President, and the Moore Foundation would take the lead, once a fundraising plan is in place with the Moore Foundation at the end of 2012. The ATF notes that UCOP need not be involved in this fundraising effort (unless it wants to be) and we do not see UCOP as being asked to contribute a capital share of this $50M.

The current best estimate for UC's share of TMT operating costs is $6.5M/year. As indicated previously, in 2018 the partnership agreement with Caltech for operating the two Keck telescopes will enter a new phase. UC's share of the operational cost will decrease by a factor of two, freeing up $6.5M/year in Keck operating costs. If these funds are apportioned to pay UC's share of the TMT operating costs, no additional funds from UCOP will be needed for TMT operations.

If it were to turn out that the operating costs are somewhat higher than $6.5M/year, UC has several options. Those include, but are not limited to, reducing the UC share of TMT time, or raising the needed funds by selling Keck time for $100K/night as Caltech is doing today, finding partners or a new funding source to reduce and divert the investment in Lick Observatory. The exact details of possible trades are premature to consider at this point. Should the necessity for such a trade arise, it should be reviewed by a representative body of UC astronomers and astrophysicists, notably the UC A&A governance Council suggested in Section 6 in this report, to ensure maximal benefit to UC.

It will be a mistake if UC does not take full advantage of the $125M gift from the Moore Foundation or fails to use it efficiently and constructively. This would jeopardize future fund raising efforts and would send a wrong message to potential donors.

4.1.7 Strong UC Community Support for a Flagship Scientific Facility

From the System-wide survey and the unsolicited letter from UC astronomers, the TMT garners enormously strong support throughout the system. The articulated reasons for this support include:

1. The TMT represents the greatest aspirations of the UC astronomy and astrophysics community, founded on a world-renowned research and teaching faculty that has benefitted from the tremendous opportunities afforded by leadership and access at Lick Observatory (starting in 1888) and Keck Observatory (starting in 1993).
2. The TMT will be a recruiting and retention tool for the very best astronomy faculty and graduate students for the next 50 years.
3. A 15—18% fractional share in TMT telescope time will make the TMT a highly effective tool for UC astronomers, allowing them to leverage that access to strongly compete at other major facilities (e.g., ALMA, JWST, LSST).
4. There is strong and enthusiastic community support for the TMT project within UC. In a

survey poll of the UC astronomy and astrophysics community, TMT was the facility receiving the most "Priority 1" votes, followed closely by the Keck Observatory.

5. A new giant segmented-mirror telescope (GSMT) was the number one priority of the optical/infrared sub-panel of the recent Astro2010 Decadal Survey of Astronomy and Astrophysics, conducted by the National Academies of Science on behalf of the federal funding bodies for science, and a GSMT was ranked third among *all* ground-based national priorities by the main Astro2010 panel.

4.1.8 TMT People, Leadership, and Management

UC astronomers played a crucial early role in the intellectual and technical development of the TMT, starting more than a decade ago. In particular, the design of the TMT is credited to UCSC Prof. Jerry Nelson. Today, the lion's share of the TMT development work occurs within California (both at UC and Caltech). UC astronomers have substantial leadership roles in two of the three "first light" instruments, implying that a significant share of UC construction costs will be reinvested within California.

Chancellor Yang, as TMT Board Chair, has represented the project and UC interests extraordinarily well, working to foster new international collaborations with Japan, India, China, and Canada and working diligently and respectfully with partners in Hawai'i (the TMT site). His acumen with appropriate political channels in Washington has served the project well, as have his strong connections with private funding sources.

UCO Director Mike Bolte serves on the TMT Board. Director Bolte plays a crucial role in representing UC interests with TMT, in helping to shape new international partnerships, and in assuring that the observatory will meet the scientific needs of UC faculty.

The TMT project has a world premier project manger in Gary Sanders, the previous project manager of the LIGO project (which was a similar scale project as the TMT, brought in on time and on budget). He has been a leader for decades in state of the art project management, establishing the best practices used today by many other billion-dollar scale projects.

4.2 The Keck Observatory and its Role in UC

Located on the summit of Mauna Kea in Hawaii, the twin 10-meter Keck Telescopes are the leading general-purpose ground-based optical/infrared telescopes in the world. The observatory's eighteen-year legacy of exploration includes the detection of extra-solar planets, the discovery of dark energy, the proof of a supermassive black hole at the center of our Galaxy, all paradigm-shifting breakthroughs and both led by UC scientists. Access to these transformative telescopes has propelled the whole UC system into international leadership in observational OIR astronomy. Keck will remain the premier UC astronomical facility for at least the next decade and will enable forefront discoveries in astronomy and astrophysics for the foreseeable future.

Figure 11. The 36 segments of the Keck II primary mirror.

The University of California has played a leadership role in Keck Observatory since its inception. Made possible by a unique mirror design by Jerry Nelson (UC Santa Cruz) that allows 36 hexagonal segments to operate together as a single coherent mirror (Figure 11), science operations began in 1993 (for Keck I) and 1996 (for Keck II). In 1996,

the National Aeronautics and Space Administration (NASA) joined as a one-sixth partner in the Observatory. Both telescopes were funded via a gift to Caltech (by the W. M. Keck foundation) and UC is currently making up its share by paying operating costs ($12.5M per year in 2011). The time-share partnership in Keck is currently 36% UC, 36% Caltech, 18% NASA, and 10% University of Hawai'i.

The power of Keck stems not only from its aperture size but also from its suite of nine state-of-the-art observing instruments. As discussed in Section 4.3, the UC has been a leader in building and maintaining these instruments, thus sustaining the preeminence of Keck in the face of competing telescopes with similar collecting area. The Keck Observatory is also a world leader in the field of Adaptive Optics (AO), the technology that removes distortions caused by turbulence in Earth's atmosphere and provides image clarity exceeding that of the Hubble Space Telescope (HST) at the same (infrared) observing wavelength. Taken together, the telescopes and instruments of Keck Observatory place it among the most respected facilities in astrophysics. The over-subscription of nationally competed Keck time is similar to that of HST, even though HST awards come with associated research funding, while Keck awards do not.

It is no accident that UC astronomers have been at the forefront of exploration. Not only do UC researchers have access to Keck, but also this access has attracted some of the most ambitious and talented researchers in the world to our campuses. This combination of tools and talent is among the lasting legacies of the UC investment in the Keck Observatory.

Given the preeminence of Keck within the current astronomical landscape, the rationale for UC's current investment is solid. Moreover, ongoing involvement in Keck will be important as the era of the Thirty-Meter Telescope approaches. UC scientists will use Keck to prepare for the TMT, for example, by continuing the development of advanced AO technologies, which will be essential for the TMT to reach its full scientific potential. Even after the TMT era, into the 2020's and beyond, the twin Kecks will remain workhorse telescopes for UC astronomers. Keck will cull samples to identify the most essential objects for follow-up with precious TMT time. With investment in relatively wide-field spectroscopy, Keck could play a central role in its own right in elucidating the astrophysics of LSST-discovered transient objects (as described above).

While the funding model for normal operations of the Keck Observatory is sound (with contributions currently from UC and NASA), the model for new instrumentation is in some difficulty. The Keck Observatory has been funding new instruments through four funding streams, namely NSF MRI and NSF ATI grants, from TSIP in exchange for telescope time to the NSF, and from private donors. All four of these streams seem to be weakening, along with the economy. The Keck Observatory is finding it difficult to fund new instruments that today typically cost $8-15M. Thus, there is a need for pursuing alternative funding models for Keck instrumentation. These models may include more funds contributed from the Keck partners, selling more Keck nights, a more vigorous private development effort by the UC system on behalf of Keck (this currently doesn't happen at all) and by other Keck partners. There is a clear need for the UC system to establish a development effort on behalf of its system-wide shared research facilities. Thus, we recommend that a system-wide fund-raising effort be pursued for Keck instrumentation and that Caltech be engaged to do the same.

4.3 Instrumentation, Adaptive Optics, and UCO

One clear outcome of the Survey was the overwhelming support throughout UC's astronomy and astrophysics community for high-quality, state-of-the-art instrumentation, adaptive optics, and technical facilities. UC astronomers clearly articulated the fact that it is not only access to the biggest telescopes on the best observing sites, but also equipping those facilities with the most efficient and sensitive astronomical cameras and spectrographs as well as a successful adaptive optics system, that has enabled UC astronomers to make revolutionary discoveries and establish a world-leading position. UC's leadership role in the Keck and TMT partnerships is generated by the strength of its technical expertise in telescope design, adaptive optics, detector systems, optical and infrared instrumentation and software.

UC Santa Cruz, the headquarters of the University of California Observatories (UCO), and UCLA's Infrared lab provide centralized support for the development of optical and infrared instruments, respectively. This concentration of technical expertise and infrastructure has made it possible for these labs to assemble teams of skilled and experienced technical staff, and to build on the institutional memory from previous projects to enable successive generations of more scientifically capable and ambitious instruments. See Figure 12. Facilities at UCSC are directly supported by UCO and involve a significant number of faculty and staff. It is there that Kavli prize-winner Jerry Nelson, inventor of the segmented-mirror concept, is based and it is there that much of the innovation in telescope design has occurred. UCSC astronomer Claire Max pioneered and continues to lead development of adaptive optics through facilities like the Moore Adaptive Optics Lab and the NSF Center for Adaptive Optics. Indeed, a Next Generation Adaptive Optics facility at the Keck Observatory is a major goal for the upcoming decade, to produce better resolution and to achieve near diffraction-limited images at optical wavelengths (R and I-band). Optical design work is carried out by Harland Epps for instruments at Keck and telescopes around the world. UCSC constructed three instruments for Keck, namely HIRES, ESI and DEIMOS (Steve Vogt, Joe Miller, Sandy Faber). The era of building Keck instruments came to a (temporary) halt with the completion of DEIMOS in 2002, nine years ago. The newly proposed Next Generation Adaptive Optics system for Keck is an excellent candidate for UCO to make substantial contributions to the next Keck project.

The Infrared Lab at UCLA is a much smaller unit established mostly with internal resources (non-UCO) about 20 years ago by Ian McLean and Eric Becklin, who are now joined by James Larkin and Michael Fitzgerald. Today it receives UCO support at the level of $300K/yr (4% of the UCO budget) but is otherwise largely self-sustaining through contracts and grants. Despite this very modest 4% of UCO funds, most of the currently operational infrared instruments on the Keck telescopes (NIRSPEC, NIRC2, and OSIRIS) were built either entirely or in part at the UCLA IR Lab. NIRC2 was a joint project with Caltech in which the IR detector system was contributed by UCLA.

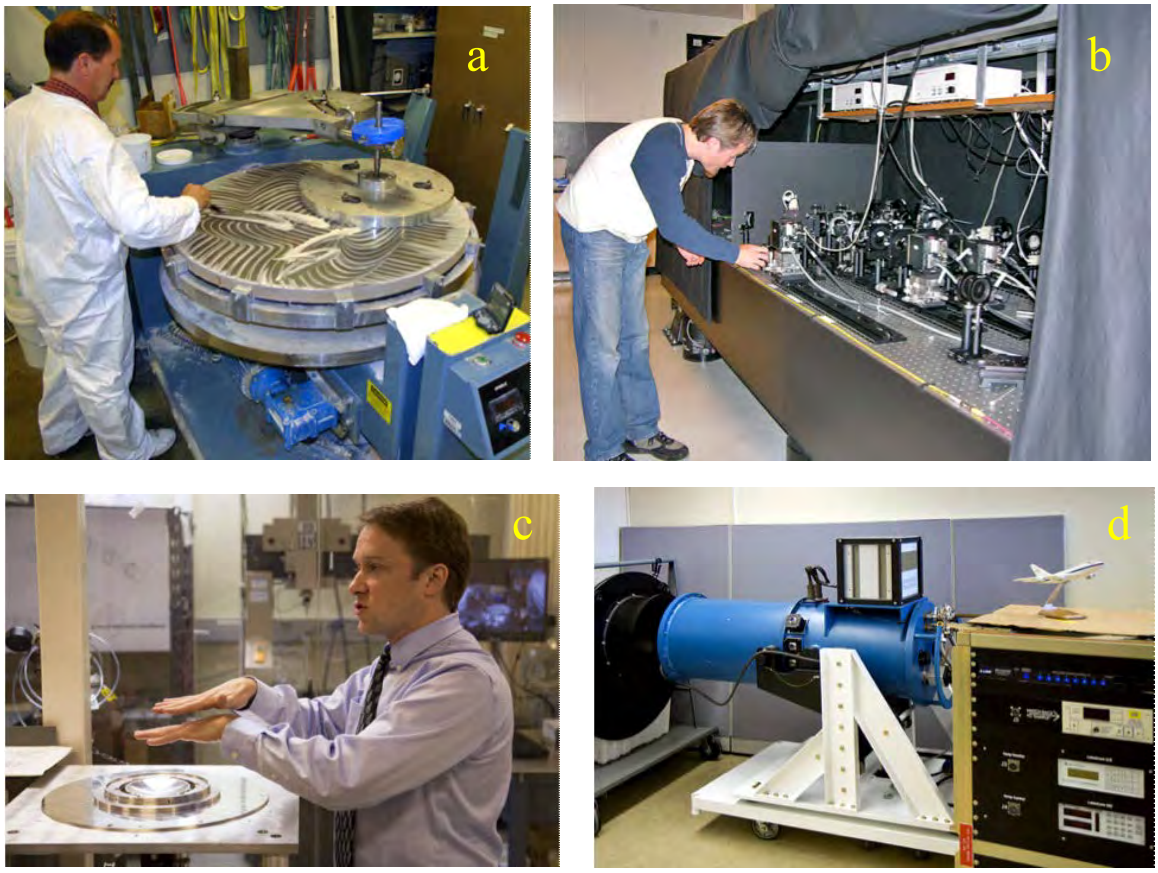

Figure 12. a) UCO optical shops. Brian Dupraw working on a test segment for TMT's primary mirror. B) UCSC's Laboratory for Adaptive Optics. Grad student Luke Johnson working on the MCAO testbed which can simulate AO on a 30-m telescope. c) UCLA IR Lab professor James Larkin leading a tour on the occasion of the Lab's 20th anniversary. d) UCLA IR Lab: the FLITECAM infrared camera built for NASA's Stratospheric Observatory for Infrared Astronomy.

UCLA is also working with Caltech on a nearly finished and very ambitious Keck instrument, MOSFIRE. This huge vacuum-cryogenic instrument will be the first multi-object spectrograph for infrared astronomy at Keck Observatory. The UCLA IR Lab also provides infrared instrumentation support for Lick Observatory, for NASA's SOFIA mission and for the Gemini Planet Imager. Both the UCSC and UCLA centralized facilities regularly team with scientists on other campuses to develop specifications and science projects for new instruments, and both work in close collaboration with the national labs (LLNL, LBL) and with Caltech and Keck Observatory in the Keck partnership. Thus, with the two most recent major Keck instruments, OSIRIS and MOSFIRE, the UCLA IR Lab is making major contributions to the Keck community, benefitting not only the UC system astronomers but also all other Keck users as well. Again, this is a remarkable record during the past decade, but with only 4% of the UCO annual funds this lab is vulnerable.

The centralized UC labs just mentioned are leading two of the three first-light TMT instruments, IRIS at UCLA and MOBIE at UCSC, and the third instrument is a clone of Keck's MOSFIRE. UC leadership of these projects will create a close connection between UC astronomers and the early scientific capabilities of the TMT, ensuring and enhancing the scientific value of this powerful new facility for the entire UC community.

One of the major factors in UC's success in instrumentation, including adaptive optics and even telescope design itself, is that it has fostered faculty who are willing and able to lead large technically-challenging projects. It is the astronomy faculty members who conceive and design new instruments to provide world-leading observational capabilities that can address forefront questions in astronomy. Their ongoing and daily engagement with technical personnel, contractors, funding agencies and the observatory, along with the expectation that they carry out their own research programs, provides the crucial driving force for maintaining progress towards a successful outcome. Those faculty members also train students and engage their UC colleagues to ensure that the investment in new facilities can be applied to the broad range of scientific interests represented in the UC community. The creation of a community that encourages and supports this faculty is a major achievement, enabled by the system-wide support of astronomy and astrophysics at the centralized labs under the UCO umbrella. The need for technically engaged and scientifically active faculty to lead future instrumentation projects will continue in the TMT era, regardless of the balance between in-house, international and industry partnerships employed in these projects.

Moreover, high-quality technical staff at the UCO plays a key role in maintaining and improving the performance of existing instruments and of the observatories in general, especially the Keck Observatory. Innovations are varied and far-reaching, including novel high-throughput coatings on both mirrors and transmission optics, optimizing the clocking and voltage shaping of CCD read-outs, new multi-object masking techniques, new cryogenic, multi-object slit mechanisms, and even high-speed remote observing at nearly every campus. It is this multi-dimensional instrumentation work that permits the extraordinary success of the UC telescope facilities and ensures that these shared facilities continue to be responsive to the needs of the UC astronomy community. The strong engagement of both faculty and technical staff is crucial to the success of our observatories.

As highlighted by the respondents to the Survey, the instrumentation work supported by UCO remains vital to the science that UC astronomers do at the Keck Observatory. This work includes maintaining and improving detectors, optics, and telescope system software. The importance of infrared instrumentation for the TMT and for current and future Keck instruments was widely recognized by the community, as was the success of UCLA's Infrared Lab. We therefore recommend increased funding from UCO for the UCLA IR Lab to enable it to provide greater support for both deployed and future instruments.

Finally, UCO faculty and staff have historically taken it as their job to watch over the existing instruments. *This sub-set of UCO faculty and staff are vital and even critical to the functioning of the Keck Observatory*. Thus, we recommend that this operational support for Keck continue without any diminishment. We further recommend that this support be made more transparent in the UCO budget so that advisory committees will be able to offer more useful recommendations.

4.4 Lick Observatory at Mount Hamilton

Lick Observatory at Mt. Hamilton (Figure 13) is a widely-used shared facility, broadly supported by the community as shown in the results of the UC-ATF survey. Lick Observatory carries out superb research programs with a specialty in time domain observations over days, months, and years and the value of these facilities per dollar is excellent. Access to Mt. Hamilton also offers students a hands-on education in observational techniques ranging from precision spectroscopy to adaptive optics, and it performs excellent outreach to the public, as described below. Looking to the future, we recommend that UCO consider developing additional funding models for Mt. Hamilton. In particular, it may be an important resource for engaging our partners in the TMT.

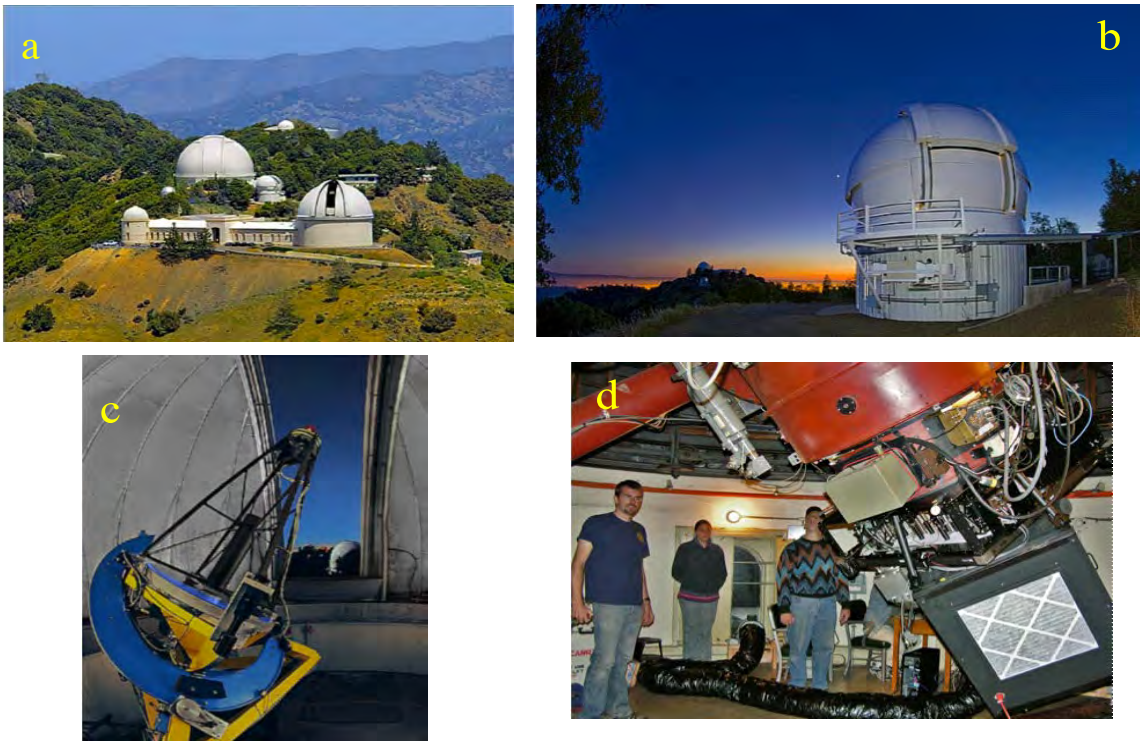

Figure 13. a) Summit of Mt. Hamilton. Shane 3-m telescope dome is at center. b) Dome of new Automated Planet Finder telescope. c) KAIT telescope. d) Nickel telescope with Villages adaptive optics system (lower right).

Although the Lick telescopes are modest in size and the seeing is only good (0.8-1.5 arcsec), but not great, these telescopes offer excellent instruments and a temporally strategic allocation of nights. Three projects exemplify the continued value of Lick Observatory in this regard.

The 3-meter Shane telescope has been carrying out a 20-year survey for Exoplanets by the Doppler technique. Indeed, the Shane 3-meter discovered 9 of the first 10 exoplanets discovered around main sequence stars. This telescope also discovered the first multi-planet system (around Upsilon Andromedae) offering the first evidence that exoplanets were astrophysically similar to our own Solar System. Long-term acquisition of precise Doppler measurements continues to

reveal exoplanets of longer orbital periods, now out to periods of 20 years. Thus, the continuous, stable, temporal sampling of Doppler measurements from Lick Observatory offers a unique, unmatched contribution to exoplanet science.

Another outstanding example of ongoing important contributions at Lick Observatory is the supernova search led by Alex Filippenko using the dedicated KAIT robotic telescope facility, an important element in UC's high profile work on the accelerating expansion of the universe and on dark energy.

Yet another example of unusual capabilities at Mt. Hamilton is the long-term Lick AGN Monitoring Program on the Shane 3m telescope to carry out reverberation mapping of the supermassive black hole environments in host galaxies. This program was conducted by a team of UC Astronomers led by Aaron Barth at UC Irvine. The initial time allocation to the project was a block of 64 nights in Spring, 2008, a large allocation made possible by the coherent collaboration and time-allocation of the Lick Observatory. Studies of time-dependent AGN phenomena in galaxies is increasingly recognized as a crucial diagnostic of this phase of galaxy formation and feedback mechanisms. This significant investment in telescope time, allocated in a non-traditional way in contiguous blocks of nights to a large team, was possible thanks to the flexibilty enabled by UC's ownership of the Mt. Hamilton facilities.

Lick Observatory also supports the Nickel 1-meter telescope which is used mostly in direct imaging mode with an optical CCD mutli-filter system, from near UV to Z band at 1 micron. This telescope is often operated with remote observing facilities from the campuses, sparing the observers the trip to Mt. Hamilton. Common applications involve time domain monitoring of supernovae, measuring exoplanet transits, AGN monitoring, and an optical SETI search. The subscription rate averages 80%, with heavy use during dark time. The Nickel telescope also hosts the Villages MEMS-based adaptive optics system which is providing the proof-of-principle for "Multi-Object Adaptive Optics," a new appraoch to AO with a wide field-of-regard.

A new telescope has just been built at Lick Observatory, the "Automated Planet Finder" (APF). This robotic telescope and its spectrometer are being commissioned during the summer and fall of this year (2011). It is funded and designed explicitly for precise Doppler measurements of bright stars (Vmag < 10) with the primary goal of detecting low mass planets around nearby stars by the Doppler method. The telescope and dome were built by EOS as an integrated unit, with the echelle spectrometer built in the UCO shops in Santa Cruz. This telescope is designed to be entirely robotic, measuring Doppler shifts automatically each night by a prescription designated by UC astronomers. It will be the first robotic, Doppler exoplanet finder in the world, with a goal of finding nearly Earth-size planets around nearby stars, unlike the Kepler satellite which surveys for planets around stars that are typically 1 kiloparcsec away.

Access to Mt. Hamilton is an important component of graduate and undergraduate education at UC. Graduate students have the opportunity to be the Principle Investigator on proposals that use these facilities. The process of seeing a project through from brainstorming the idea to writing the successful proposal to final publication is an important aspect of graduate mentoring enabled by UC's investment in Mt. Hamilton. Remote operation of the telescopes from the individual UC campuses opens up the possibility of using these facilities for undergraduate research as well.

The Mt. Hamilton facility has also played a crucial role in the success of UCO instrumentation as a technology and development platform. The most outstanding recent example is the adaptive optics (AO) system on the 3m Shane telescope. Natural Guide Star (NGS) observing was commissioned in 1999, and Laser Guide Star (LGS) science began in 2000. This was the first LGS adaptive optics systems available to a general astronomical user community. The Shane AO system has a successful publication record on its own. In addition, the real-world information about the technical performance enabled the assembly of an experienced community of AO observers which was crucial for the success of the Keck adaptive optics system. This cycle of development is continuing with an NSF-MRI funded project to upgrade the Shane AO sytem to use deformable mirror and other new technology developed at the Center for Adaptive Optics, an NSF-STC centered at UC Santa Cruz from 1999-2009.

Mt. Hamilton operates with a budget of roughly $1.8M/yr, with its funding coming from and managed by UCO. This is a usage of UCO funds that directly benefits the faculty, graduate students, and undergraduate students in the UC system. With its unique research and education niches, especially in time domain research and student hands-on access, and its role in instrument development, the return per dollar spent on Lick Observatory is widely considered to be an extraordinarily good value.

In the longer term, however, as the Thirty Meter Telescope project moves forward, we recommend that UCO develop additional funding models for Mt. Hamilton to save money. One option, which could also address the need for the UC A&A community to strengthen its working relationship and collaborations with the TMT partner institutions, might be to move toward a business model where our TMT partners are also partners in the operation of Mt. Hamilton. Another option is to pursue a consortium of partners that use and pay for the operations. Any such cost savings should go toward funding instruments for Keck and TMT so vitally needed.

5 Final Prioritized Recommendations for UC Investment in System-Wide Shared Facilities

5.1 Recommendation #1: TMT

Based on the extraordinary scientific opportunities, broad community support, major financial commitment from the Moore Foundation on behalf of UC, and the strength of the TMT project from a technical and management perspective, the ATF makes the following multi-faceted recommendations:

1. UC administration and Chancellors should vigorously pursue UC's partnership and leadership in the TMT project, a premier international scientific endeavor that will have worldwide impact for the next half-century.

2. Chancellors should continue to engage campus astrophysicists and Vice Chancellors for Research in helping to drive TMT development and partnerships. These people can be strong advocates in articulating the TMT case with private funding organizations and with the people of California.

3. As the international partnership agreements solidify over the next few years, UCOP and the UC President should pursue contractual obligations concerning organizational, fiducial, and financial burdens that ensure that the California taxpayers are sheltered from financial risk, while allowing UC to maintain strong leadership in the operations and conduct of science with the TMT. The ATF has learned that current drafts of these agreements already place such risks solely within the TMT Corporation, not obligating California taxpayers to be responsible for cost overruns.

4. As part of the partnership agreements, it is likely that TMT operations funding will need to be contractually obligated within a few years. The current draft partnerships agreement calls for a UC contribution of $6.5M/yr for TMT operations. *The $6.5M/yr currently obligated to Keck operations (half of the total obligation) should be shifted to fund the UC fraction of TMT operations when the Keck obligation completes in 2018.*

5. We recommend continued support for the UC lead in TMT instrumentation.

6. We recommend establishing an office of TMT outreach at UCO, with the aim of promoting TMT, public awareness about it, and private funding for the support of it.

5.2 Recommendation #2: Keck Observatory

Keck will remain the premier UC astronomical facility for the next decade and will enable forefront discoveries in astronomy and astrophysics for the foreseeable future. *Our second recommendation is that UC maintains its current share of the Keck Telescopes.*

However, we further recommend that increased funding be sought for the operations and instrumentation, and for the adaptive optics budgets of the Keck observatory. Declining federal dollars require more funding from UC and its other partners in the Keck Observatory. We recommend that UC, and its new Astrophysics Council (see Section 6.2), explore models that bring additional funds to instrument development and maintenance. Models to consider might include making more Keck telescope nights available for purchase by federal agencies and by the larger astronomical community. We similarly recommend greater access to the Keck telescopes for the larger astronomical community, to build support for Keck and prepare relationships for TMT's future. We applaud the recent inclusion of NOAO (through the TSIP program), Yale, and Swinburne. If economic times improve, we recommend that UC contribute more funds, along with its partners, toward the operations and instrument budgets of the Keck Observatory. This may require a slight renegotiation of telescope share commensurate with contributions.

5.3 Recommendation #3: UCO System-Wide Instrumentation

Maintain UC support for the labs, staff, and faculty that are directly involved in the innovation and operations of the UC system-wide telescopes, adaptive optics and instrumentation. Focus UC system-wide funding beyond Keck operations and TMT on labs capable of building next generation AO and instrumentation for UC system-wide telescopes.

This recommendation includes continued support for the established laboratories at UCSC and increased UCO support to strengthen the infrared instrumentation effort at UCLA. UCO's support for the adaptive optics laboratory and experts at UCSC will be key to Keck's continued competitiveness in this growing field. Strong technical expertise is vital for UC's involvement in

the TMT, and has been and will continue to be a major enabler for the science achievements of the entire UC astronomy community. Furthermore, UC should identify ways to simultaneously mitigate risk for TMT and advance science at Keck.

5.4 Recommendation #4: Lick Observatory at Mount Hamilton

Maintain funding for the telescopes on Mt. Hamilton at current levels, as its role in time domain research, in graduate and undergraduate education, and in outreach are all unique roles in UC astronomy. We recommend new funding models be explored, including possible new partners, selling of nights, and attention to management.

6 Governance of UC Astrophysics

6.1 Motivation

The existence of shared facilities has been a powerful unifying factor for UC astronomy and astrophysics. Directly, and through its role in the operations and support of the Keck Telescopes for the benefit of all UC astronomers, UCO has been a very successful multi-campus research unit. UCO has provided support for innovative research and technical development. In addition, UCO has demonstrated leadership throughout the Keck era and into the TMT era. During the last two decades this unity of purpose and vision has led to significant intellectual growth in astronomy and astrophysics across the UC system. The investment of UCOP funding in system-wide research facilities has been essential in stimulating this development. One consequence of this evolution however, is that there is a rich pool of talent at every campus and there has not yet been evolution of the shared governance structure to enable UCO to take full advantage of the "power of ten." Strengthening representation, participation, collaboration, and communication between UCO and the user community will be valuable in order to continue to exploit the unrivaled economy of scale of the UC-system. This goal is strongly supported by the community: 35/49 (71%) of the responses to the governance question of the survey (Q8) recommended improving system-wide representation, participation, collaboration, and communication. A stronger governance structure will also improve the power of advocacy of the UC astronomy and astrophysics community.

A further increase in complexity of the challenges faced by the UCO structure and management is expected in the next decade, if the TMT project goes forward as recommended by this Task Force. Deployment of TMT will add a formidable tool to system-wide astronomy ensuring it will stay at the forefront for decades to come. Maximizing the scientific potential of TMT however, will require a structure that strengthens UCO's ties with individual campuses, with UCOP, and with our domestic and international partners. As a result of improved representation and shared governance, UCO will become an even stronger voice speaking on behalf of the entire UC astronomy and astrophysics community.

In the longer term, the broader UC astronomy and astrophysics community needs a system-wide structure capable of identifying scientific priorities and opportunities that may arise across the entire discipline, recognizing and aiming to leverage the human and technological investment and leadership in OIR astronomy.

6.2 Proposed Governance Structure

The ATF suggests a two-level governance structure that would help strengthen the UC astronomy and astrophysics system-wide effort, meeting the goals outlined above: improve representation, participation, collaboration, and communication as well as coordination between the observatories with UC participation. The proposed new structure provides a mechanism for ongoing assessment of future priorities by the full UC astrophysics community and for continuing accountability to the Office of the President as requested by point 4 of the charge to the ATF.

Both committees are concerned with optimizing the current system-wide investment in OIR astronomy through UCO. The first is a newly-created UC Astronomy and Astrophysics Council, and the second is a UCO Users Committee. The latter is an evolution of the existing UCO Advisory Committee. After considering many options, the ATF identified one possible implementation of this structure. We are eager to discuss options and details of the shared governance structure with the VP-ORGS, the Review Committee, and the UC Academic Council, and promote investment of UC money in system-wide priorities that have been identified by the UC astrophysics community.

1) **UC Astronomy and Astrophysics Council**.
   This is a new oversight and advocacy committee that oversees shared astrophysics facilities in the UC system, currently Mt. Hamilton, Keck, and TMT. Members on this Council will engage each campus chancellor, the UCO director, and ensure campus representation. The actual bylaws will establish membership, constructed by an ad hoc assembly of this UC ATF in Fall 2011. The council will report to UCOP. The charge of the Council consists of:
   a. Overseeing major strategic decisions by approving yearly budgets, annual reports submitted by the UCO director, long-term plans. The Council is not involved in day-to-day or month-by-month management of astrophysics facilities or UCO.
   b. Overseeing senior appointments. The Council approves searches for senior positions requested by the UCO Director. The UCO Director conducts the search assisted by a search committee that includes representation of the UC Council. The UC Council approves the candidate identified by the Director and the search committee.
   c. Working with the UCO director to ensure that the management structure is sufficient and adequate to fulfill the mission of UCO.
   d. Strengthening the mandate of the UCO director as a representative of UC by approving the UC position on major strategic decisions such as those discussed by the Keck and TMT consortia.
   e. Harmonizing the UC voice across observatories by working with the director to ensure coordination and regular communications between UC representatives to the Keck Science Steering Committee, the TMT Scientific Advisory Committee,

the UC Astronomy and Astrophysics Strategic Planning Committee (described below, see item i), and UCO.

f. Establishing a direct connection between UCO and the campuses by holding regular meetings between the representatives and their chancellors.
g. Creating a direct communication channel between UCO and UCOP by providing yearly reports to UCOP.
h. Serving as a strong voice of advocacy on behalf of UCO priorities.
i. *Appointing an ad-hoc committee, the UC Astronomy and Astrophysics Strategic Planning Committee to examine the broad range of astrophysics efforts in the UC system*. This committee will engage the broad UC astrophysics community by such activities as workshops, white papers, regular polls about scientific and programmatic issues, and other UC activities in the broadest range of fields that leverage existing shared facilities in the UC system. This ad-hoc committee convenes as needed, normally every five years. Its findings are summarized in a written report submitted to the UC Astronomy and Astrophysics Council.

2) **UCO Users Committee**.

This committee replaces the current UCO Advisory Committee. It is appointed by the UCO director, in consultation with the campus department chairs, and includes representatives from each campus with an OIR astronomy and astrophysics effort. It reports to the director of UCO. The committee meets at least twice a year, or as requested by the UCO director. The charge to the committee consists of:

a. Advising UCO management on the operations and use of UCO telescopes and instruments.
b. Improving communications between UCO directorate and users by holding regular meetings at each campus between representatives and users. This role would be considerably more vigorous than has been played by the UCOAC in the recent past, returning to a role that was prevalent in past decades.
c. Organizing regular UC-wide scientific workshops on subjects of current topical interest, including the Keck Science Meeting when hosted by UC.
d. Advising the director on policy issues involving the allocation of telescope time.
e. Discussing and advising on policy issues impacting Mt Hamilton, Keck, and TMT. This would include both issues brought to their attention by the Director, and those originating within the committee itself. The committee would be responsible for ensuring a dialogue with all UC astronomy campuses on policy issues as they arise.

6.3 UCO: Annual Reports and Strategic Plans

UCO shall provide UCOP and the UC Astronomy and Astrophysics Council with a detailed annual report, including budget specifics describing the use of funds during the previous year. UCO will also provide a suggested long-range strategic plan, outlining the major priorities of the upcoming year and decade. This annual report should be approved by the new UC Astronomy and Astrophysics Council (described above) that reports to UCOP.

Appendices

A. Full Charge to UC Task Force on Investment Priorities for Astronomy (UCATF)

Final Version: 1 February 2011

Background:

The University of California supports research and education in astronomy through investments in large facilities from the Office of the President that are shared among scientists at each campus within the UC system. The present investment is approximately $20M/yr, including $12.6M/yr support for the Keck Observatory and $7.5M/yr for the UC Observatories (UCO), comprised of the shared facilities at Lick Observatory on Mt. Hamilton and staff and laboratories on the UC Santa Cruz campus. UCO is a Multicampus Research Unit (MRU) subject to the recommendations from the UC Academic Council and the UC President that all MRUs be weighed against new proposals to receive continued support. The funding for Keck satisfies UC's commitment to a contract that expires in 2018.

UC is also participating in a design study for a thirty-meter telescope to succeed the ten-meter Keck telescopes. Faculty at different campuses are involved in other large projects that could serve the entire UC community as part of the multi-campus program. These new projects may need to compete with the current systemwide funding to become viable at a time UC's resources are shrinking. To maintain the current level of support for observatory infrastructure as a multi-campus resource, the astronomers within the ten campus UC system will need to create a clear set of priorities for investment in shared infrastructure for the next decade. This review offers an opportunity for the University of California to maintain and enhance its preeminence in astrophysics at an exciting time for the field by prioritizing and optimizing its resources.

Purpose of the task force:

The Vice President for Research and Graduate Studies is establishing a task force to lead a system-wide process to set priorities for investment in astronomy and astrophysics. The task force is requested to identify potential areas of future investment in astronomy and to recommend a list of priorities for shared research infrastructure in consultation with the UC astronomy and astrophysics (A&A) community. As part of its process, the task force should convene at least one meeting or workshop with wide participation from all UC scientists doing research in astronomy and astrophysics. The workshop should aim to achieve broad consensus on the major astronomy opportunities and priorities for investment in the decade 2011-2020.

The task force should produce a draft report in June 2011 for circulation and comment. A final report should be submitted within two months of publication of the draft. The report should broadly treat the amount of support needed to sustain its recommendations at different levels while recognizing that many of the future costs are just rough estimates at this time.

Charge to the task force:

1. Lead a system-wide planning effort, through one or more workshops, with broad input from the UC astronomy & astrophysics community. The effort should prioritize both current and future infrastructure needs for creating future science and education opportunities for UC.

2. Assemble a short list of the anticipated major new investments needed to support these prioritized opportunities and shared facilities in the next decade. Include estimates of the costs, both capital investment and ongoing operations, to the extent possible today.

3. Produce a report on the recommendations for the highest priority investments in facilities, operations, and other activities, with a broad astrophysics perspective on what will best serve the ten-campus UC system for research and education in June 2011.

4. Propose a mechanism for ongoing assessment of future priorities by the full UC astrophysics community and for continuing accountability to the Office of the President.

B. UC ATF Community Survey Questions

Below, the text of the survey question is provided as captured in an email reminder that went out to the UC Astronomy & Astrophysics community on March 9 2011.

UC Astronomy and Astrophysics Community Survey Questions
Responses due by Friday, April 8

Please provide your brief thoughts on the following:

1. What do you consider to be the top five science or technical achievements that contribute to UC's excellence in astronomy & astrophysics today? What has enabled each of these achievements to happen at UC?
[You will have one line to fill in for each achievement. For each achievement, you will also have a 50 word box to discuss what has enabled it.]

Future Science Directions and Needs for the UC Community

2. What do you consider to be the top five science priorities in UC astrophysics systemwide? In your answer, please consider programs and directions for the overall UC system on the 2020 time scale and beyond. Please also consider how to best leverage current system-wide UC investments and take into account Federal priorities such as those recommended by the Decadal Survey

For each priority, please provide any additional comments, including the type of UC systemwide resources required, in the web form.
[You will have one line to fill in for each science priority. For each priority, you will also have a 50 word box for further comments.]

3. In light of the science priorities you described in question 2, please give us your priorities for facilities and infrastructure that are most important for UC to support as systemwide resources. These priorities may include existing facilities, such as the Lick and Keck observatories and campus laboratories and centers, and facilities under development, such as TMT or other projects.

Please consider, in your response, the context and scale of your suggested priorities in the light of existing and future national and international facilities, the role of UC in the project, and UC access to the facilities. In setting your rankings, please evaluate the impact for one or more science priorities listed above, as well as the contribution to UC astronomy capability systemwide. Please also consider the ability to enhance the UC educational mission as well as the investment of time and money required.
[You will have one line to fill in for each facility/infrastructure priority.]

Current UC Systemwide Resources

4. The UC currently has several resources available to the UC A&A community. Next to each resource listed below, please check the box indicating whether you or members of your research group have used it directly in the past five years.

For each resource, please also rate its importance to the UC A&A community (Very Important--High—Medium—Low—Not Important) considering each aspect of the UC Mission (Education, Research, Public Outreach). Please elaborate or clarify with any comments.
[The resources/facilities listed are Lick Observatory, Keck Observatory, the UCO/UCSC labs, the UCLA IR lab, and Remote Observing Terminals. In addition, there is a field that you may fill in for a systemwide resource not mentioned above. For each resource/facility you have a 50 word box for any additional comments.]

Current Campus Specific Resources

5. What has your campus contributed to UC systemwide A&A shared capability?
[You will have a 50 word box for your answer.]

6. What campus-specific resources exist within the UC system that might be a useful shared facility?
[You will have a 50 word box for your answer.]

Investments in Future UC facilities

7. If the funding for UC astronomy remains at its current level, what are your priorities for future investment in shared facilities (e.g. Keck, TMT, Lick, UCO, and other future systemwide resources not mentioned in this survey)?
[You will have a 50 word box for your answer.]

UC A&A Program Planning and Community

8. Give us specific suggestions you may have regarding UC A&A governance structure and All-UC meetings.
[You will have a 50 word box for your answer.]

9. What suggestions do you have for UC systemwide astronomy meetings or workshops (beyond the annual Keck Science Meeting) that would enhance intercampus collaboration and increase the scientific productivity of the UC astronomical community?
[You will have a 50 word box for your answer.]

[The last section of the survey asks several demographic questions including your campus, your title, and any other non-UC facilities you may use for your research.]

Link to Survey:
http://fs19.formsite.com/UCOP/form1/index.html

C. Community Letter to UC Task Force on Investment Priorities for Astronomy

The Astronomy Task Force (ATF) received the following letter from the community on June 6 2011.

Members of the UC Task Force on Astronomy & Astrophysics,

You have been tasked with establishing UC-wide priorities for Astronomy & Astrophysics (A&A), in parallel with an ongoing review of the University of California Observatories (UCO). To further aid your effort, we provide the following letter which summarizes the principal views of the undersigned.

Our consensus view is that a UC-wide MRU is fundamental to the long-term success of A&A research and education at UC. Specifically, UC's current and future world leadership in A&A derives from our direct and private access on all UC campuses to the world's greatest ground-based observational facilities – Keck, Lick, and the future TMT. Our university-wide ownership, technical participation, and governance in these facilities provide a unique competitive advantage that produces premier scientific excellence, has built the world's top observational and theoretical faculty for research and scientific education, and exemplifies the enormous value of UC-wide shared resources. Furthermore, it enables us to stake primary roles in nearly all other A&A projects and astrophysical facilities, and has helped secure substantial funding from private, state, and federal sources. Originally the domain of a handful of UC campuses, the expansion of the UCO facilities[1] into a UC-wide system has stimulated the growth of A&A excellence and faculty participation throughout the entire UC system.

Currently, the UCO MRU stands as the premier example of the collective strength of UC as a single institution. To continue UC's position as the top institution in A&A requires that we not only maintain but extend our investment in the greatest facilities by participating in the TMT. There is strong and renewed competition from Europe (ESO) and institutions throughout the United States that are heavily funding A&A research and education. To keep our premier position in the field – and the faculty that led us here – we depend on system-wide funding to maintain access as well as scientific and technical leadership within the world's key A&A projects.

Scientific Excellence: For over a century UC astronomers have led research in A&A, and we maintain this role today because of our shared resources. The recently completed 2010–2020 Decadal Survey of our field has set the highest scientific priorities for future exploration as dark matter, dark energy, black holes, planets, and reionization. UC astronomers, primarily through their use of UCO facilities, have provided scientific leadership in each of these areas. A few prominent examples include exoplanet discovery (Keck/HIRES, Lick 3-m/Hamilton), the accelerating universe (Keck/LRIS, Lick/KAIT, Lick 3-m/Kast), measurement of the D/H abundance ratio (Keck/HIRES, Lick 3-m/Kast), first glimpses of the reionization epoch (Keck/ESI), high-precision studies of the Galactic center (Keck/AO), and new mass measurements of extragalactic black holes (Lick 3-m/Kast). Pushing these scientific frontiers demands the most powerful telescope+instrument capabilities on the planet, with supporting efforts on smaller aperture facilities. The ownership and access to UC Observatories (Lick, Keck, and next TMT) is essential to our continued scientific success.

[1]Throughout this letter we use the term "UCO facilities" broadly to refer to Lick, Keck, and the UCO labs and infrastructure at UCSC and UCLA.

1

There are several (imperfect yet still useful) metrics that one can use to gauge UC's scientific excellence in A&A. Regarding publications, in the interval of 1996–2005, which spans the first 10 years of the twin Keck operations, UC-wide publications and citations dwarf those of any other single institution.[2] The UC faculty, as a whole, transcend any other institution on the planet. On a similar note, the Keck Observatory has been the most cited ground-based observatory for over 15 years.[3] We further emphasize that the oversubscription for NOAO-awarded time at Keck nearly meets that of *HST* even without the concomitant research funds. These accomplishments result from the combination of the greatest astronomical facilities with a premier faculty.

The Premier Faculty in Astronomy & Astrophysics: UC has, for over a century, had a world-class faculty in astronomical research; presently, UC boasts the highest number of A&A faculty in the National Academy of Sciences. Over the past decade, the growth in faculty throughout UC has been especially astonishing, with nearly twice as many active astronomers at UC than only 15 years ago. There is now a first-class group or department in A&A at eight UC campuses (all except Merced and UCSF) and strong A&A participation at each UC-managed laboratory. All of these groups can link their growth to the catalyst of UCO facilities.

The successes of our youngest generation of faculty cannot be overstated. UC now boasts the highest membership of Sloan and Packard Fellows, as well as the highest number of AAS Warner and Pierce Prize recipients. UC has not built this faculty with salary and benefits, nor with local campus resources. This premier faculty has followed from UC's century-long commitment to providing private access to the greatest astronomical facilities.

Although this letter focuses primarily on UCO facilities and its impact on observational A&A at UC, we emphasize that the success of our experimentally-oriented faculty has inspired and promoted the hiring, retention, and scientific successes of our theoretically-inclined faculty. Indeed, many of these prominent theorists have served as PI on projects with UCO facilities, a testament to their terrific science return. Throughout the UC system, there is an excellent synergy between observational programs and theoretical inquiry. Such collaboration is central to the advance of science in A&A and is critical to identifying the next frontiers and the facilities to address them.

We also stress that our faculty has provided UC with greater diversity within the physical sciences. In the UC Departments of Physics and Astronomy, where only $\sim$ 10% of the faculty are women, nearly half of the female faculty perform their primary research in A&A. In addition to their outstanding scientific achievements, these faculty serve as mentors and inspiration for women in PhD programs and at the undergraduate level. This connection is essential to encouraging women to enter under-represented fields.

Lastly, we note that our success in A&A has strongly influenced the hiring of new

[2]Based on an ISI Web of Knowledge search of A&A journals, following Kinney (2008; astro-ph/0811.0311). A UC-wide search that included 8 campuses, LANL, and LLNL revealed 7518 publications for 351,785 citations with an h-index of 206.

[3]Restricting to general-facility observatories.

faculty in Physics (e.g., high-energy astrophysics, cosmology), Engineering, Statistics, and Planetary/Earth-Marine science departments throughout UC. These activities have generated excellent synergy amongst faculty on individual campuses and throughout the system.

Shared Resources and the Power of UC's Multi-Campus Structure: Despite operating under the umbrella of a single university, the UC campuses have very rarely taken advantage of this system (the "Power of Ten"). Within the MRU framework, A&A has been uniquely successful in showing the university how to profit from its multi-campus structure. The UCO MRU, as a system-wide set of facilities, has enabled eight of the campuses to develop first-class programs in A&A without requiring each individual campus to identify, raise, and develop the funding and infrastructure for astronomical research and education. This has saved tremendous costs on start-up, lab space, and facilities. Consider as an alternative a scenario where each campus was required to independently assess and satisfy their efforts within A&A. This would have great inefficiency, and only a handful of campuses could maintain a successful program. A&A has received very little campus-specific infrastructure from UC; the UCO MRU represents nearly the entire state investment.

For decades, UCO has served as a prime example of the synergistic power of shared resources across the full system. In the challenging financial climate that pervades UC, A&A should strive to further leverage these shared resources and identify new innovations to maximize their return (e.g., through additional multi-campus research, teaching, etc.). Administrative and cultural imagination and ingenuity are going to be required for the university to prosper in this era. A multi-campus pathway may be of great value for many other programs, in addition to astronomy.

Education: Aside from agriculture, California's success in the global economy stems from technological innovation. To this end, California needs a workforce that is highly trained in science and technology. UC has and must continue to play the leading role in this effort.

At the heart of scientific education are math and physics. Astronomy is well recognized as a major entry point, a "hook," into the physical sciences and engineering; we regularly capture the public attention with discoveries of new planets and views from the edge of the cosmos. In turn, A&A engages students of all ages in the scientific endeavor. For undergraduates, our classes inspire students of all interests and backgrounds, from physics majors to aspiring artists. Importantly, an increasing fraction of these students are drawn from traditionally under-represented populations in the sciences.

A direct outcome of UC's excellence in A&A is a first-class faculty for education in the sciences. These faculty touch many thousands of students each year in the physical sciences with courses that combine elements of statistics, physics, mathematics, and the scientific method. The success of astronomy courses in undergraduate education extends well beyond training the next scientists and engineers of California. Our mission is also to educate the broader citizenship in science, such that they can make informed decisions on the future of our state and nation. A&A, with its visceral connection, offers one of the few opportunities to achieve this goal.

Leverage in Other Facilities: The last two decades have witnessed tremendous growth in A&A observational and computational capability. Many new facilities have broad community access and participation (e.g., *HST*, SDSS, NCSA). Private access to UCO facilities has empowered UC astronomers to establish leadership in nearly every one of these projects. In turn, we have reaped the scientific successes of these instruments and have established scientific priorities within the projects.[4] By a similar token, UC astronomers have leveraged their access to UCO facilities to gain membership within otherwise closed experiments (e.g., Kepler, WISE).

The prospects for further leveraging UCO facilities are strong in the coming decade. The planned public *JWST* and LSST projects, for example, will be greatly enhanced by follow-up studies at Keck and the TMT. Similarly, research in ALMA will provide a critical complement to the deep, high angular-resolution capabilities in the near-IR of Keck and TMT. It is our private access and involvement within UCO facilities which greatly enhances our roles within these community-wide, public opportunities.

Success with Obtaining Federal and Private Resources: A critical measure, at least within administrative circles, of UC research funding is the "financial return" from that investment. At the individual faculty level, this is primarily measured by the funding obtained in grants for basic research. The UC faculty have been extremely successful in this endeavor at NSF and NASA, in very large part due to our secured access to UCO facilities. In contrast to many of our competitors, our position within UC enables research that cannot or would not be accomplished by other groups. Currently, there are nearly 100 unique PIs that access UCO facilities each year; we estimate that they generate many tens of millions USD per year in federal grants to fund this research.

At the level of individual campuses, UC has been awarded two NSF science centers dedicated to A&A (the Center for Particle Astrophysics at UCB, and the Center for Adaptive Optics at UCSC) and maintain a $\sim 1/3$ share in the NSF/KITP center at UCSB. In addition, various departments have played major roles in the design and development of new instrumentation for projects ranging from the *HST*/FOS camera at UCSD to the fabrication of the GPI instrument for Gemini.

Lastly, the UCO facilities remain a great attraction and a unique opportunity for the private fundraising of scientific research and education. Each of our UCO facilities has been built with a major capital donation, and we have had continued success with instrumentation.

Training the Next Generation of Outstanding Astronomers: Access to UCO facilities is a major attraction for PhD students into A&A at UC and for the hiring of postdoctoral researchers. These students and postdocs are critical to the research activities of the faculty, and they enhance all aspects of A&A science and teaching at UC.

At the same time, the UC faculty have had enormous success in the training of the next generation of leaders in A&A. A major aspect of this process follows from access

[4] A prime example is the spectroscopic analysis of $z \approx 6$ quasars which were discovered from the SDSS but which required the light-gathering power of Keck to realize the science.

to UCO facilities and to participation within the instrument projects that support these facilities. At Lick Observatory, PhD students and postdocs develop and lead their own programs of research. These experiences are critical to identify new areas for exploration and to design the experiments to address them. Indeed, many of the undersigned boast one or more degrees from UC physics and astronomy departments.

Instrumentation: A major role in UC's success within A&A has been its active participation in the development of preeminent instrumentation for the UCO facilities, both through the UCO labs and at individual campuses. This includes, among many other examples, the NIRSPEC, HIRES, ESI, DEIMOS, and OSIRIS imaging spectrographs for Keck, decades of instrumentation for Lick Observatory, the design and installation of the world's first laser and AO systems, and active participation in the first-light instrumentation for the TMT (MOBIE, IRIS). These activities have helped UC to recruit and develop faculty with first-class talent in instrumentation. Analogous to the relationship between theorists and observers, maintaining a set of instrumentalists is critical to overall success in A&A research and education. These faculty have been intimately engaged within the UCO facilities while enabling the broader faculty to access the greatest instrument suite for their science. These efforts are also essential to training the next generation of instrument builders needed by the entire community.

Furthermore, this rare and highly-demanded expertise has provided faculty funding and scientific collaboration beyond the UCO facilities. A recent example is the GPI instrument for the Gemini observatory, which leverages our expertise in near-IR instrumentation to pursue a cutting-edge project in exoplanet science.

Investing in the Future (TMT): As emphasized throughout this letter, UC's access and involvement in the shared UCO facilities has been essential to our great success. Continuing funding for astrophysics is one of the best choices UC can make, in order to maintain our highly competitive advantage. We advocate for continued access to Keck, as well as continued Lick operations of the most useful facilities (3-m Shane, KAIT, the new Automatic Planet Finder, perhaps the Nickel 1-m telescope). We also strongly advocate continued participation and leadership within the TMT project. This facility, the highest-ranked project by the ground-based optical telescope committee of the 2010 US Decadal Survey, will define the leading edge of new astronomical research. It builds directly on our vast experience and leadership in large-aperture telescopes and will enable UC faculty to perform forefront research into the next several decades. Furthermore, the terrificy synergy that the TMT will have with planned US-wide projects (e.g., LSST, *JWST*), will allow UC faculty to lead major efforts leveraging these new facilities.

As with Keck, an investment in the TMT benefits the entire UC system, not just a handful of individual faculty. An assumed share of $\sim 20\%$ in the TMT will require and inspire UC-wide collaboration to maximize our scientific return. The TMT represents the obvious and crucial evolution of the UCO MRU. Without UC participation, there is enormous risk that our younger faculty will leave UC and new recruitment will greatly suffer. UC would no longer have the top A&A faculty in the world and would lose one of the gems of the UC system.

Lastly, we emphasize that access alone to the TMT would be insufficient. We must

maintain scientific and technical leadership within the project to properly guide its development and success. We have a wealth of scientific and technical expertise which is already engaged within TMT. Recognizing that our role was essential, the Moore Foundation demanded that UC be a major partner in the project before agreeing to fund it.

In closing, we remark that while each of us has our own perspectives and unique scientific interests within A&A, this letter reflects our general consensus on the current success and future role for a UC-wide MRU in A&A. Our outstanding achievement in A&A has served as the prominent example of the power of UC as a single institution when resources are shared and leveraged across all of the campuses. In these respects, UCO is unlike all other MRUs at UC.

Regarding cost, we emphasize that the cost per active faculty member is comparable to the funds required to support experimental research in other departments of the physical sciences. The UCO facilities are our laboratories; we depend on such centralized resources to perform our research, and thus we require the support of UCOP. This is a truly unique situation within UC. Furthermore, we note that the contribution per campus ($\sim$ 2 million dollars annually) pales even in comparison to the tens of millions of dollars being invested by single public and private institutions throughout the US (e.g., Utah, Texas, Chicago, Yale). Their recent aggressive investment in A&A is in direct reaction to our successes with UCO facilities and also reflects a dissatisfaction with the nationally funded facilities (e.g., NOAO, Gemini).

To date, the targeted, focused funding of UCO facilities has worked extraordinarily well. We must continue this investment by maintaining access to and participation in Keck and by identifying new research (e.g., APF and long-term programs like LAMP for the 3-m Shane telescope) and educational opportunities for Lick, while forging new initiatives. A leading role in TMT is vital to our future success and will re-establish UC as the flagship for A&A education and research.

Sincerely,

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Rebecca Bernstein (UCSC)
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Gillian Wilson (UCR)
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Stan Woosley (UCSC)

D. ACRONYMS

A&A Astronomy and Astrophysics

ALMA Atacama Large Millimeter Array

APF Automated Planet Finder telescope at Lick Observatory

ATF Astronomy Task Force

AO Adaptive Optics

E-ELT European Extremely Large Telescope

GMT Giant Magellan Telescope

IRIS TMT instrument: Infrared Imaging Spectrometer

JWST James Webb Space Telescope

LSST Large Synoptic Survey Telescope: http://www.lsst.org

MOBIE TMT instrument: Multi-Object Broadband Infrared Echelette

NAS National Academy of Sciences

OIR Optical and Infrared wavelengths

TMT Thirty Meter Telescope

UC University of California

UC-ATF University of California Astronomy Task Force

UCO University of California Observatories (Multi-campus research unit)

UCLA University of California at Los Angeles

UCSB University of California at Santa Barbara

UCSC University of California at Santa Cruz

WFOS TMT instrument: Wide Field Optical Spectrometer