

Input to the NSF Astronomy Portfolio Review from W. M. Keck Observatory

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on behalf of Keck Observatory and its scientific community

1. Overview of W. M. Keck Observatory

The W. M. Keck Observatory (WMKO) operates twin 10-meter optical/infrared telescopes on the excellent site of Mauna Kea, renowned for its superb seeing, extremely dark skies, and excellent characteristics for infrared observations. The two telescopes feature a highly capable suite of advanced instrumentation for both optical and near-infrared wavelengths, including imagers, multi-object spectrographs, high-resolution spectrographs, and integral-field spectroscopy. WMKO has developed and operates sophisticated natural and laser guide star adaptive optics (AO) systems and related instrumentation on each telescope.

For the past 19 years, WMKO has played a leading role in U.S. astronomy and astrophysics. A key component of this success has been the highly effective partnership between private and public institutions (CARA, NASA, and NSF) that provide financial support for operations and new developments, and the scientific partnership between the private users and the community of observers that participate through NASA and NSF/NOAO's Telescope System Instrumentation Program (TSIP) observing time opportunities. Keck is a versatile, efficient, high-impact general-purpose observatory. Its success relies on these closely knit factors: a clear strategic direction, an extraordinary staff, a creative, enthusiastic, involved, and broadening user community, and a suite of efficient, state-of-the-art instruments.

Four objective metrics demonstrate Keck Observatory's scientific success:

- 1) In Dennis Crabtree's (2011, BAAS 43, 157.19) studies of observatory scientific productivity, WMKO consistently ranks highest in the number of papers per telescope per year of general-purpose ground-based observatories. For example in 2010, the two Keck telescopes produced 285 papers, or 142.5 papers per telescope per year. This dramatically exceeds all other U.S. facilities and also exceeds ESO's VLT.
- 2) In Crabtree's studies, WMKO also has the highest total impact per telescope of ground-based observatories, which takes into account not only publications but also citations.
- 3) WMKO dominates the emerging field of laser guide star adaptive optics (LGS-AO) science. Three quarters of all LGS-AO papers worldwide from 2004 through 2011 are based on WMKO data.
- 4) The large impact of the Keck telescopes on astronomy education is well illustrated by the 240 PhD theses produced using WMKO data from 1994 to early 2012.

It is our intention to sustain WMKO as one of the crown jewels of U.S. astronomy for the next ten years and beyond. We strongly believe that modest enhancements to federal programs for new instrument development as recommended by Astro2010 (e.g., Mid-Scale Innovation Program, TSIP and ATI), that will be highly leveraged by the existing WMKO hardware and future private funding, will dramatically enhance WMKO's already robust potential to meaningfully contribute to achieving the Astro2010 scientific objectives.

2. U.S. Community Participation in Keck Observatory

The partners in the operation of WMKO are Caltech, the University of California and NASA. The University of Hawaii participates in Keck observing by providing access to Mauna Kea. The allocation of observing time is divided among these institutions as follows: Caltech (36.5%), University of California (36.5%),

NASA (14.5%), and University of Hawaii (12.5%). Yale University participates in WMKO observing via a partnership with Caltech. The broad U.S. community gains peer-reviewed access to the Keck telescopes via the NASA partnership and through TSIP (approximately 24 nights per year). In a search of the WMKO observing database from 2008 to 2011, a total of 918 unique names were found with the following institutional breakdown: 615 UC/CIT/Yale, 154 UH, 198 NASA community, 118 NSF/NOAO community, 16 Gemini exchange, and 34 Subaru exchange. NOAO's ALTAIR committee noted in the context of 6.5-10 m telescopes that "of the open access time available to the entire US community, Gemini represents ~57%, the NASA Keck time represents ~25%, and NSF TSIP represents ~18%." Thus, WMKO represents a significant fraction of U.S. peer-reviewed public access to large telescopes.

3. Keck Observatory's Planned Contributions to Astro2010 Scientific Goals

The scientific opportunities and goals identified by the Astro2010 process are highly aligned with WMKO's current and future observing capabilities. WMKO is poised to be a vital contributor to meeting the Astro2010 scientific goals. We list below many of the Astro2010 science themes and the related planned achievements from WMKO:

- ***What are the flows of matter and energy in the circumgalactic medium?:*** One of the forefront topics today is the connection between galaxies and the gas in their dark matter halos as well as with the intergalactic medium (IGM) gas. The Keck Cosmic Web Imager (KCWI), an integral-field spectrograph designed for Keck II, is optimal for detecting low surface brightness emission from redshifted Ly α as well as resonance lines of OVI 1033 Å, CIV 1550 Å over the redshift range $2 < z(\text{Ly}\alpha) < 6$. Ly α halos have now been detected (Steidel et al., 2011, ApJ 736, 160) around Lyman Break Galaxies, which may trace gas in dark matter halos that is either fueling star formation and galaxy formation via inflows, or shocked / outflowing gas that has been energized by galactic superwinds. Separating the different emission components, isolating the excitation mechanism for resonance line emission (scattering, recombination, shocks), and removing compact sources requires 2D spectral imaging with excellent sky subtraction, the highest possible sensitivity, good imaging resolution, and moderate ($R \sim 3000$) spectral resolution to separate components at different velocities and to resolve velocity structure produced by bulk motions and radiative transfer in the resonance line.
- ***How do baryons cycle in and out of galaxies and what do they do while they are there?:*** As with the previous question, we expect the planned instrument KCWI on Keck II to contribute deeply via integral-field spectroscopic studies.
- ***What is the fossil record of galaxy assembly and evolution from the first stars to the present?:*** Detailed studies of nearby galaxies provide vital clues about their formation and evolutionary history. Andromeda and the Milky Way have long been cornerstones for identifying substructure, detailed reconstruction of recent collision events, and using dwarf satellites as tracers and building blocks of larger galaxies. WMKO's DEIMOS instrument has contributed powerfully to our understanding of the fossil record in M31 (e.g. Guhathakurta et al. 2006, AJ, 131, 2497) and the Milky Way dwarf spheroidals (e.g., Kirby et al. 2011, ApJ, 727, 79). WMKO plans to upgrade DEIMOS with new, more sensitive CCDs to make it even more capable for studies of the fossil record.
- ***How do black holes grow, radiate and influence their surroundings?:*** Diffraction-limited near-IR imaging of the central few arcseconds of the Galaxy with the Keck telescopes over the past 17 years has led to widespread acceptance that a 4-million solar mass black hole is located there (e.g., Ghez et al. 2008, ApJ 689, 1044). The modest accretion flow onto the black hole has been detected and its dramatic variability monitored (e.g., Hornstein et al. 2007, ApJ 667, 900). Precision studies of the

stellar orbits around the black hole have been, and will continue to be, the key to this investigation, in terms of both the proper motions and the radial velocities of the stars. Keck's planned Next Generation Adaptive Optics (NGAO) System will improve the Strehl ratio of the images of the Galactic Center and will increase the stability and knowledge of the point spread function over the field. This will dramatically improve the precision of the astrometry and thus the orbits. It will also increase the number of observable stars and lessen their confusion with other sources.

- ***What were the first objects to light up the universe and when did they do it?:*** Probing the epoch of reionization remains one of the most challenging problems in cosmology today. Our understanding to date is based mainly on Cosmic Microwave Background polarization and absorption in the Lyman α forest for high- z QSOs. A recent WMKO contribution to this field employs the fall-off of Lyman α emitting galaxies with redshift (Schenker et al. 2012, ApJ 744, 179), as the Ly α line becomes more subject to resonant scattering in the increasingly neutral IGM. An important planned study with KCWI is to map emission from either the HI redshifted hyperfine transition or redshifted Ly α emission. This is because the size of reionized zones around ionization sources grows with time, and scales with the local over-density of the ionizing source. Emission mapping provides a direct measure of the size of reionization bubbles. Bubble size can be correlated with local source overdensity to connect radius to halo mass. The bivariate distribution of mean bubble size with halo mass and redshift will tightly constrain the history of its reionization sources. The line profile gives important information about the kinematics and temperature of the ionizing gas, constraining the ionization spectrum. MOSFIRE, as the first efficient multiplexed infrared spectrograph, will transform our ability to follow-up $z > 7$ candidates being delivered by HST.
- ***How diverse are planetary systems?:*** Keck is well known for its leadership role in the detection of exoplanets via precision radial velocities using its HIRES instrument. In addition, four planets have been imaged around HR8799 using the Keck II AO system and NIRC2 (Marois et al. 2010, Nature 468 1080), showing WMKO on the forefront of direct detection studies of exoplanets. To increase Keck's productivity of Doppler exoplanet studies, we propose to develop and deploy SHREK (Stable High-Resolution Echelle for Keck). SHREK is planned to be thermally, optically, and mechanically stable with time so that the optical path from the telescope focal plane, to the spectrometer pupil, to the final detected spectrum is extraordinarily constant, translating to 1 meter per second in velocity precision. SHREK will be fiber-fed, bench-mounted, and temperature and pressure controlled. We propose to conduct next-generation Doppler studies of exoplanets around nearby stars with SHREK. In addition, WMKO is increasing its capabilities for AO imaging studies of exoplanets. WMKO's NGAO system's unique combination of high-contrast near-IR imaging (K-band Strehl ratios of 80-90%) and large sky coverage will enable direct imaging searches for Jovian-mass planets around nearby young low-mass stars and brown dwarfs. NGAO will strongly differentiate exoplanet research at WMKO from all direct imaging searches planned for other large ground-based telescopes. By number, low-mass stars ($M \leq 0.5 M_{\text{Sun}}$) and brown dwarfs dominate any volume-limited sample, and thus these objects likely represent the most common hosts of planetary systems. Such cool, optically faint targets will be unobservable with specialized extreme AO systems (e.g., ESO's SPHERE) because their parent stars are not bright enough ($I > 11$ mag) to provide a high-order wavefront reference. But thousands of cool stars in the solar neighborhood can be targeted by NGAO because of its laser guide stars.
- ***Do habitable worlds exist around other stars and can we identify the telltale signs of life on an exoplanet?:*** As with the previous question, we expect the planned instrument SHREK to contribute mightily. The key science impetus stems from the exoplanet candidates discovered by the NASA *Kepler* mission. Because most of the *Kepler* targets are very faint (fainter than 14th mag) and the

Doppler shifts are small (most planets smaller than 3 Earth-masses), the 10-m Keck Telescope aperture is needed to collect enough light for precise Doppler work.

- ***How do circumstellar disks evolve and form planetary systems?:*** We expect WMKO's NGAO system to make significant contributions.
- ***Time-Domain Astronomy:*** WMKO aims to build a new tertiary mirror and its mount for the Keck I telescope to make its full observational capabilities available for time-sensitive scientific programs. Bringing this capability to WMKO will provide flexible access to the unique suite of instrumentation on Keck I: HIRES, the only echelle spectrograph on a large telescope available to the U.S. community in the northern hemisphere; LRIS, one of the world's most sensitive optical spectrometers; and MOSFIRE, soon the premier multi-slit infrared spectrograph in the northern hemisphere. This will enable the effective and efficient study of time-critical Solar System events, the analysis of stellar atmospheres, the monitoring of stars orbiting the Galactic Center, and the discovery of the most distant explosions in the universe. The astrophysical processes explored via these phenomena include the tidal disruption of compact objects, the explosion mechanisms of stars at all masses, gas accretion and planetary dynamics. The implementation of the deployable tertiary will position the U.S. community to play a leading role in follow-up observations of gravitational wave events.

4. Funding Issues and Opportunities

WMKO is a highly successful public-private partnership. The Observatory's construction was funded by a gift from the W. M. Keck Foundation to Caltech (\$140 million in 1985). The Keck Foundation also funded much of WMKO's world-leading AO systems. Five sixths of WMKO's operations funding is contributed by the University of California and one sixth by NASA. Funding for new instrumentation has been obtained through grants from NSF and NASA, and from donations by individuals and private foundations.

WMKO has participated consistently in TSIP since its inception. TSIP has provided essential funding for two WMKO instruments OSIRIS and MOSFIRE, and also funded the design of NGAO and KCWI. OSIRIS is an integral field spectrometer that provides diffraction-limited $R=3,900$ spectroscopy behind Keck AO. MOSFIRE is a near-infrared imaging spectrometer that will provide an imaging field of view of 6.8' in diameter and allow $R = 3,000$ spectroscopy with almost full band coverage in Y, J, H or K for 46 slits over a field of view of 6.1' x 3' (commissioning in spring 2012). NGAO is a transformational AO system that will deliver unprecedentedly high Strehl, angular resolution, and PSF stability from red-optical to near-infrared wavelengths, through the use of multiple laser guide stars, and excellent sky coverage through the use of AO-corrected near-infrared tip-tilt sensors. KCWI will provide visible band, integral field spectroscopy with moderate to high spectral resolution, high efficiency, and excellent sky subtraction. Both NGAO and KCWI have successfully passed their Preliminary Design Reviews.

In return for TSIP funding, NOAO has gained time on the Keck telescopes to allocate to the broad community (typically 24 nights per year). Keck TSIP telescope nights have been the most heavily subscribed observing resource offered by the NOAO TAC (average oversubscription of 5.1 for Keck I and II reported in the ALTAIR Committee Report). NOAO's ALTAIR committee which investigated community access to large telescopes reported that "the access to the additional capabilities on the non-federal facilities that is afforded by TSIP and the NASA open access time on Keck is highly valued by the community."

Federal funding to WMKO is highly leveraged by private and state funding. All partners, including the broad U.S. community who gain access through NASA and TSIP, benefit from philanthropic gifts that have

enabled WMKO's powerful telescopes, innovative instrumentation, and world leading AO systems. For example, the MOSFIRE infrared multi-object spectrograph was funded equally by TSIP and philanthropy.

There is a shortage of funds to develop new instrumentation and AO systems for existing, productive observatories. WMKO needs to keep its instrumentation and AO systems competitive to address new scientific challenges. The ability of WMKO and other observatories to remain important discovery tools for the U.S. astronomy community depends on advancing the capabilities available to users via new and improved instrumentation. Funding a new instrument or AO system on an existing advanced telescope is very cost effective compared to designing and building a new facility. In order to address the need for new instrumentation and AO systems that meet the Astro2010 scientific objectives, the following are WMKO's priorities for implementing the Decadal Survey recommendations.

#1: Mid-Scale Innovation Program: Astro2010 recommended this program to “enable small to medium-scale experiments and facilities that advance forefront science...with costs ranging between the limits of the NSF Major Research Instrumentation and MREFC programs, \$4 million to \$135 million.” The Mid-Scale Innovation Program is particularly important for more ambitious instrumentation and AO development that exceeds the grant/funding levels of existing programs such as MRI and ATI. The ASTRO2010 report listed two future initiatives of great interest to WMKO and our user community as exemplars of what is possible with the Mid-Scale Innovation Program: “Next Generation Adaptive Optics Systems” and “Exoplanet Initiatives.” We are confident that funding from the Mid-Scale Innovation Program would have a transformative effect on WMKO's ability to address Astro2010 priorities. In particular, this program is the only practical route for WMKO to fabricate and deploy its NGAO system that would enable high-spatial-resolution imaging and spectroscopy of unprecedented detail and quality. NGAO is also a pathfinder for advanced AO techniques and prototype hardware for Extremely Large Telescopes.

#2 Telescope System Instrument Program (TSIP): Astro2010 stated “TSIP supports telescope instrumentation on privately operated telescopes in exchange for observing time. It is a vital component of the OIR system that was instituted following a recommendation of the 2001 decadal survey”. Astro2010 recognized that TSIP and the non-federal observatories have played a strong role in keeping the U.S. competitive in OIR astronomy despite greater government spending on OIR facilities in Europe. Astro2010 recommended for TSIP “an increment to \$5 million per year.” Given the support for TSIP from Astro2010 and ALTAIR, WMKO and our user community were dismayed that TSIP funding was eliminated from the NSF budget in FY2011 and beyond, eliminating the most important existing source of federal funding for developing instrumentation and AO systems that address key scientific questions. It also eliminates access to the Keck telescopes via the NOAO time allocation process. We urge the Portfolio Review Committee to investigate why TSIP, which was so strongly endorsed by community blue-ribbon panels, was eliminated when programs not endorsed by Astro2010 remain funded. We further recommend the reinstatement of TSIP or a TSIP-like program that embraces public-private partnerships as emphasized by Astro2010.

#3 Advanced Technologies and Instrumentation Program (ATI): Astro2010 recommended “increase this to \$15 million per year to accommodate key opportunities including, especially, advanced technology in adaptive optics development and radio instrumentation.” WMKO strongly endorses this Astro2010 recommendation. WMKO has benefitted from ATI to support development of our world leading AO systems. ATI is highly oversubscribed and is only one of two programs at NSF supporting astronomical instrumentation (the other is MRI). ATI is vital to advances in instrumentation that further Astro2010 goals.