

# The W. M. Keck Observatory: A Private/Public Partnership Enabling Frontier Astrophysical Advances in the Coming Decade

Contact Author:

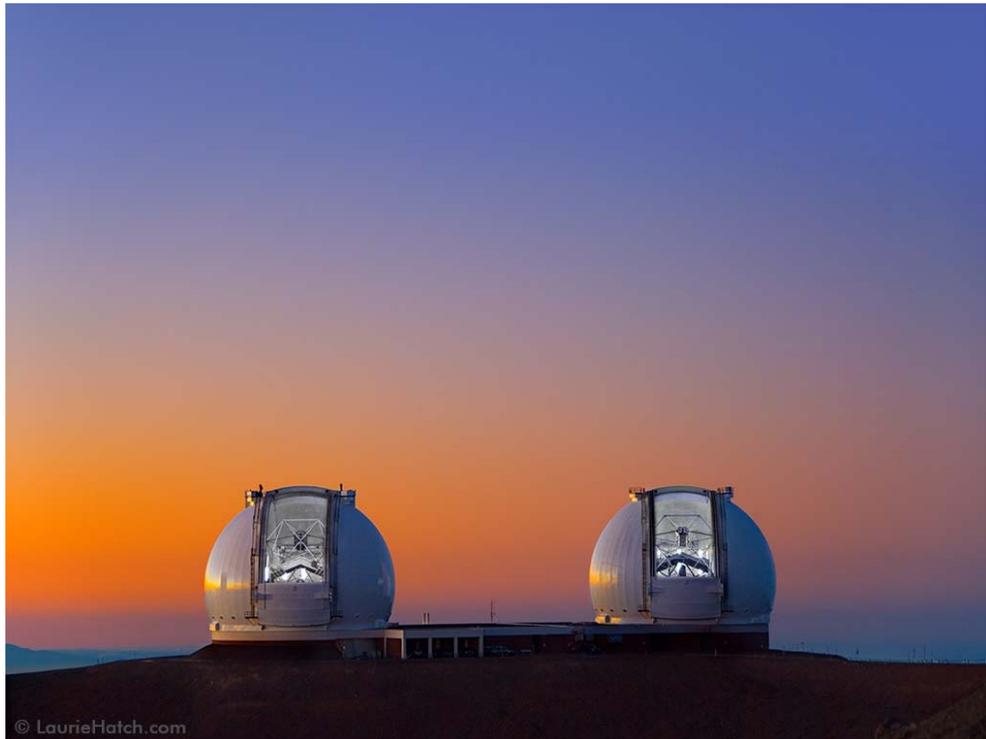
Taft Armandroff, W. M. Keck Observatory  
[tarmandroff@keck.hawaii.edu](mailto:tarmandroff@keck.hawaii.edu); 808-881-3855

Co-authors:

Sean Adkins<sup>1</sup>, Rachel Akeson<sup>3</sup>, Joshua Bloom<sup>4</sup>, Michael Bolte<sup>6</sup>, Judy Cohen<sup>2</sup>, Alison Coil<sup>7</sup>,  
Harland Epps<sup>6</sup>, Robert Goodrich<sup>1</sup>, Shri Kulkarni<sup>2</sup>, Hilton Lewis<sup>1</sup>, Chris Martin<sup>2</sup>,  
J. Xavier Prochaska<sup>6</sup>, Michael Rich<sup>5</sup>, Tom Soifer<sup>2</sup>, Peter Wizinowich<sup>1</sup>, Julien Willez<sup>1</sup>

<sup>1</sup>W. M. Keck Observatory  
<sup>2</sup>California Institute of Technology  
<sup>3</sup>NASA Exoplanet Science Institute  
<sup>4</sup>University of California Berkeley  
<sup>5</sup>University of California Los Angeles  
<sup>6</sup>University of California Santa Cruz  
<sup>7</sup>University of California San Diego

**Activity Submission in Response to the Astro2010 Programs Subcommittee  
Request for Information**



## **I. Summary**

The W. M. Keck Observatory (WMKO) operates twin 10-meter optical/infrared telescopes on the excellent site of Mauna Kea. 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 a sophisticated natural and laser guide star adaptive optics system and related instrumentation. The Observatory also operates the only large-aperture infrared interferometer in the U.S.

For the past 15 years, the W. M. Keck Observatory 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 support for on-going operations and new developments, and the scientific partnership between the private users and the general community observers that participate through NASA and NSF/TSIP observing time opportunities. The value of Keck as a community resource is demonstrated by TSIP observing time oversubscriptions of factors of 6 to 8 [March 2009 NOAO Newsletter]. NOAO's recent ALTAIR Report demonstrates that at least a quarter of U.S. community peer-reviewed access to large telescope observing is provided by Keck Observatory.

Keck is a versatile, efficient, high-impact general-purpose observatory. Its success relies on these closely knit factors: a clear strategic direction, an extraordinary operations staff, a creative, enthusiastic, involved, and broadening user community, and a suite of efficient, state-of-the-art instruments that keep the observatory at the cutting edge.

It is our intention to sustain Keck as one of the crown jewels of U.S. astronomy in the coming decade. We advocate modest increases in the funding of programs for new instrument development that will be highly leveraged by the existing Keck infrastructure and private funds. Federal program(s) of investment in new instrument development from which Keck could competitively secure roughly \$6M per year, to be combined with private donations, would enable Keck Observatory's continuing role as a key contributor to frontier U.S. astronomical research results.

## **II. Key Science Goals**

The W. M. Keck Observatory engages in an on-going scientific strategic planning process in order to capitalize on current opportunities for leadership in U.S. astronomy. A recent outcome of this process was to update the Keck Strategic Mission, summarized as follows:

- High angular resolution astrophysics
- Faint object, high-precision and highly-multiplexed spectroscopy from UV to K-band.
- Flexibility to exploit emerging opportunities
- Highly efficient operations
- Training the future leaders of the field

Keck has led the world in **high angular resolution astronomy**. Its pioneering Adaptive Optics system is mapping stellar orbits around the Milky Way's central massive black hole and has recently brought us the extraordinary first images of extrasolar planets. Keck will maintain its leadership role with the Keck Interferometer/ASTRA system (currently in development), with on-going updates to the existing Keck Adaptive Optics system, and with the Next Generation Adaptive Optics System, discussed in a companion Response to the PPP RFI (Wizinowich et al. 2009).

**Faint object, high-precision and highly-multiplexed spectroscopy** with Keck has led to many major discoveries, including the vast majority of extrasolar planets discovered via reflex motion, the cosmological nature of gamma-ray bursts, and deep views into the processes of galaxy formation in the young universe. In the next decade we propose to provide new spectroscopic imaging capabilities that can discover and map IGM emission (Keck Cosmic Web Imager, KCWI), higher precision and more sensitive optical and near-IR spectroscopic capabilities that will stretch the boundaries of planet-finding and enhance synergies with upcoming IR and radio facilities, and enhanced capabilities for moderate and high resolution multi-object spectroscopy that will push the frontier of galactic archaeology and support the extensive follow-up demands of synoptic survey missions.

Keck's **flexibility to exploit emerging opportunities** has paid off in countless ways in the last 15 years. Keck users were very quick to leverage SDSS (e.g.  $z > 6$  QSOs), HST ( $z \sim 3$  galaxies), Scuba ( $z \sim 2$  sub-mm galaxies), and soon will pursue Kepler follow-up. In the next decade we anticipate a number of new survey missions (Kepler, WISE, Pan-STARRS, GAIA, NuStar, LSST, JDEM) and facilities (HST/SM4, JWST, ALMA, EVLA) that will benefit from present and targeted future Keck capabilities. Modest investments in observing flexibility will support the growing profile and potential science impact of Time Domain Astrophysics. Keck continues to provide a platform for testing new instrumental technology and observational techniques that greatly benefit the community at large and dovetail with plans for GSMT. We anticipate that Keck's role toward the end of the next decade will evolve, and that its flexibility, innovation, and survey power will remain unique strengths far beyond 2020.

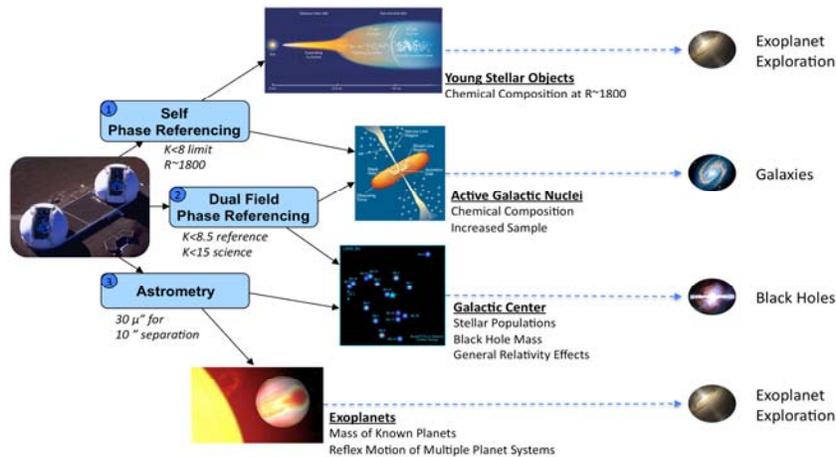
We have closely coupled the Keck Scientific Strategic Planning process to the community-wide conversation enabled by the Astro2010 survey because Keck is a national resource for astronomical leadership. To this end we have reviewed *all* of the 334 white papers submitted to the Science Frontier Panels to determine the role of existing and future Keck capabilities in advancing the field of astrophysics over the next decade. Fully 143 of these papers discuss science that would benefit from capabilities available now at Keck or planned for the next decade, with many that explicitly reference this need. Of these papers, 47 would benefit from improved high angular resolution provided by ASTRA and NGAO, 67 discuss needs for new capability in faint object, high precision, and/or multi-object OIR spectroscopy that we are planning or contemplating, and 15 discuss applications in time-domain astronomy that would be facilitated by a more flexible Observatory.

The remainder of this document discusses the scientific opportunities, technical basis, cost and schedule for initiatives to enable Keck Observatory's continued service as a crucial tool for the U.S. community to perform world-leading research. The details of implementation and relative priorities of these projects may evolve over the coming decade as the scientific state of the field matures. What will not change is the need for instrumentation renewal and continued investment to maintain Keck Observatory as a national resource for astronomical leadership.

## Science Enabled by New Capabilities in Very High Angular Resolution Astronomy

### Phase Referencing and Astrometric Science with the Keck Interferometer

The NASA-funded Keck Interferometer is being further developed with NSF MRI funds to extend its capabilities to a much broader range of science by providing higher spectral resolution, a significantly fainter limiting magnitude and a narrow-field astrometry mode. The following four science cases are the drivers for this ASTrometric and phase-Referencing Astronomy (ASTRA) project which relate to the new ASTRA observing modes (Figure 1).



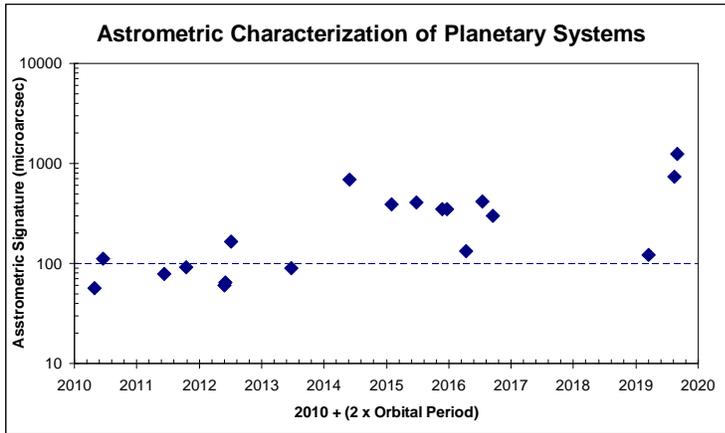
**Figure 1.** The ASTRA operating modes (self phase referencing, dual field phase referencing and astrometry) and the science cases for which they are being developed.

**Terrestrial planet forming region of proto-planetary disks.** By increasing the near-infrared spectral resolution of the interferometer, it becomes possible to study the chemical composition and the planet formation mechanisms in young stellar objects. ASTRA has provided an  $R \sim 1800$  spectral resolution mode in the K-band that is operational and is being used for science (higher resolutions are possible for future upgrades).

**Milliarcsecond-scale unification of Active Galactic Nuclei.** The planned  $\sim 5$  magnitudes improvement in the sensitivity of the interferometer will increase the size of the sample of observable AGNs. A more systematic study of the role of the torus in the unification of AGNs will become possible on a representative sample.

**Masses and orbital inclination of known exoplanets.** The planned 50 to 100 micro-arcsecond astrometric capability, when combined with existing radial velocity measurements, will allow the mass and orbital inclinations of known planetary systems to be determined independently. Figure 2 is a plot of known radial velocity planets where the astrometric signature would be large enough to be measured with ASTRA and suitable reference stars have been identified (this sample will increase as more planets and reference stars are identified).

**High-order general relativistic effects in the Galactic Center.** Current adaptive optics observations have delivered accurate measurements of the orbits of the stars around the black hole at the center of our galaxy, yielding mass and distance measurements. With the increased astrometric accuracy (30 micro-arcseconds for this science case) the Keck Interferometer will enable the first measurements of high order general relativistic effects.



**Figure 2.** A sample of known exoplanets whose mass and inclination could be measured with the ASTRA-astrometry mode of the Keck Interferometer. An astrometric accuracy of 50  $\mu$ -arcsec will allow the interferometer to measure all of the targets in this plot. The targets are plotted in time versus the start of observations assuming that observations are needed over two times their period.

### ***Exoplanet Science Enabled by Precision Optical and Near IR Spectroscopy***

The development of the field of exoplanet studies has been truly explosive since the announcement of the first planet orbiting another star (51Peg). As of now, more than 320 exoplanets are known orbiting more than 275 stars. The vast majority of these planets have been discovered via the radial velocity technique, and Keck/HIRES has led the way.

Currently, the known planets range in mass from super-Jupiters to sub-Neptunes down to 10-15 Earth masses. The quest now has turned toward finding and characterizing earth-like planets in the “habitable zone.” Because the radial velocity semi-amplitude is proportional to  $m_{\text{planet}}/m_{\text{star}}$ , there is great advantage to searching around lower mass primary stars in order to find the earth-mass planets. For example, a 0.1  $M_{\text{sun}}$  late-M dwarf with an earth mass planet orbiting within its (luminosity dependent) habitable zone at 0.02 AU would exhibit 2 m/s reflex motion. Although this is within the velocity precision of the best of the optical high dispersion spectrographs employed for planet searches, the challenge is sensitivity. For stars later than M5 dwarfs, near IR spectrometers will be more efficient than optical spectrometers such as HIRES. Indeed, planets and planetary systems have been discovered around several M stars and the solar neighborhood is dominated by M stars, which outnumber AFGK stars within 10 pc by roughly 3:1 (and more at closer distances). A near IR instrument on Keck could survey over 1000 M dwarfs.

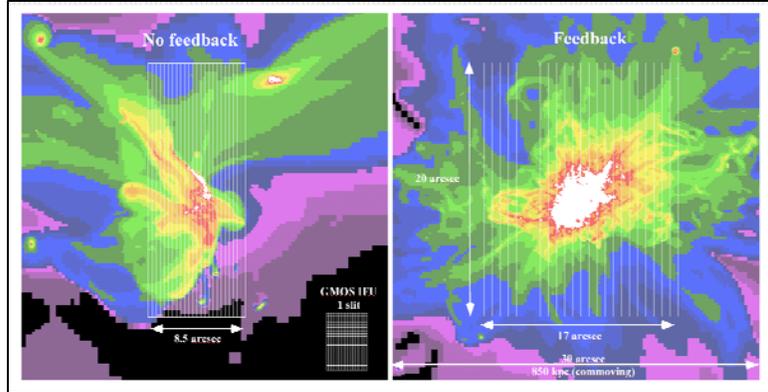
### ***Science Enabled by High Sensitivity, 2D Faint-Object Spectroscopy***

KCWI is designed to provide visible band, integral field spectroscopy (IFS) to Keck, with moderate to high spectral resolution, various field of view and image resolution formats, high efficiency, and excellent sky-subtraction. IFS at Keck will benefit from the excellent seeing, low sky background, large aperture, and high KCWI throughput, providing a world-leading capability that will enable the following science:

**Galaxy-IGM-Circum-Galactic Medium Co-evolution.** One of the forefront topics today is the connection between galaxies and the gas in their dark matter halos (Circum-Galactic Medium [CGM]) as well as with the IGM gas in the cosmic web. KCWI is optimal for detecting low surface brightness emission from redshifted Ly $\alpha$ , OVI, and CIV over the redshift range  $2 < z < 6$ . For example, the Ly $\alpha$  halos around Lyman Break Galaxies trace gas in dark matter halos which may be fueling star formation and galaxy formation, or represent material that has been

energized by galactic superwinds (Figure 3). Separating the different emission components, isolating the excitation mechanism for resonance line emission, dissecting Ly $\alpha$  radiative transfer, and separating foreground objects and companions require 2D spectral imaging with excellent sky subtraction, high sensitivity, good imaging resolution, and moderate ( $R \sim 3000$ ) spectral resolution.

**Figure 3.**—Simulation of Ly $\alpha$  ( $z \sim 2.5$ ) emission from CGM performed by Greg Bryan, with KCWI field of view. Color scale is logarithmic, with medium green corresponding to the 5 sigma sensitivity limit in  $5 \times 5 \text{ arcsec}^2$  emission regions for KCWI after 8 hours of integration (orange is 10 times higher intensity, blue ten times lower). LEFT: CGM with no feedback, narrow/fine IFU. RIGHT: CGM with feedback, medium field of view IFU (see Table 1).



**High  $z$  galaxy environments / assembly.** High redshift galaxies are likely to lie in complex, multi-component systems with fainter companions and extended stellar and gaseous features. KCWI will detect these fainter companions and measure relative velocities and other properties. 2D coverage permits summing light from extended components and producing the highest possible SNR spectra.

**AGN/QSO hosts/ionization/Circum-QSO Medium/QSO absorption lines.** Prior to and shortly after QSOs are born, the Circum-QSO medium (CQM) may be a fair representation of the typical QSO environment. In particular, the CQM, which will be illuminated by the QSO providing high SNR emission maps of the CGM around galaxies at  $2 < z < 6$ . Coupled with an occulting spot, it should be possible to explore QSO host galaxy, host environment, and intervening absorber galaxy properties.

**Metagalactic ionizing background** can be measured in principle at high redshift using Ly $\alpha$  fluorescence, and at low redshift using H $\alpha$  or H $\beta$  emission. Reaching the very low surface brightness required, and separating out other mechanisms for producing the emission is best accomplished with 2D spectral mapping designed to probe emission strengths  $< 0.1\text{-}1\%$  of sky.

**Reionization HII Regions.** Models predict that during the epoch of reionization ( $z > 6$ ) growing HII regions should be detectable by extremely faint and highly extended (many arcmin) Ly $\alpha$  emission, detectable by KCWI to a redshift of  $z \sim 7.2$ . This is a pioneering but challenging observation that cannot be performed by any other facility.

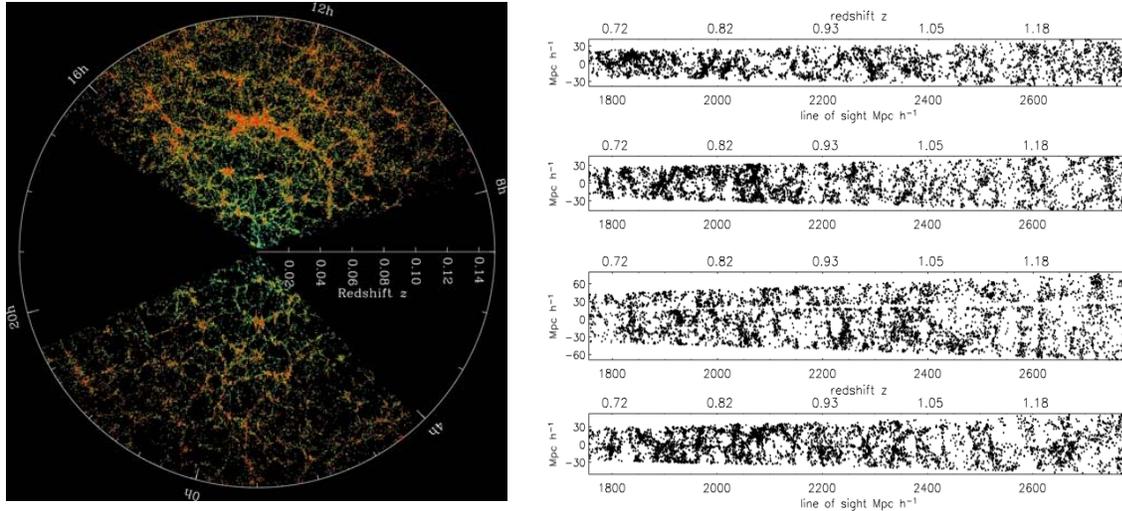
**Intracluster Light** has been detected in many nearby clusters, and is believed produced by stars stripped from their galaxies as the groups and cluster assemble, as well as by stars formed during the interactions in tidal streams. KCWI would provide kinematic maps and line-index diagnostics that could provide stellar age and metallicity information crucial to unraveling these stellar relics.

**Strong lens systems** are complex, 2D systems that could be analyzed in detail using KCWI spectral images, which would provide information about the lensing galaxy (redshift, velocity dispersion, mass, stellar populations) and lensed galaxy (stellar populations, star formation rate, age, metallicity, etc.).

**Galaxy stellar kinematics and populations.** KCWI could extend kinematic and stellar population measurements to the unexplored low surface brightness regions in the outskirts of galaxies, probing relic structures with long dynamical times and memories of their assembly history, and probing kinematics in dark matter dominated dwarfs.

*Science Enabled by New Capabilities in Wide-Field Spectroscopy*

Keck observatory is exploring new initiatives to expand its wide-field spectroscopic capabilities at both low and moderate resolution with these science areas in mind:



**The formation and evolution of galaxies at  $z\sim 1$ :** As pioneering surveys of nearby galaxies demonstrated, redshifts remove the effects of projection, reveal the cosmic web, and allow conversion of observed fluxes and sizes to physical rest-frame quantities. Whereas the local galaxy population ( $z < 0.1$ ) is now well surveyed (SDSS, 2dF), the leading projects at  $z\sim 1$  (e.g. Keck/DEEP2) remain limited by cosmic variance because of their small survey volumes. Because galaxy properties correlate with large-scale structure, one must map much wider areas of the sky at  $z=1$  and beyond to construct a coherent picture of galaxy evolution, to understand the interplay of star formation, stellar mass build-up, accretion through mergers, feedback from stars and AGN, and the effects of environment over cosmic time. Such efforts demand a low-dispersion, highly efficient spectrograph multiplexed for 1000 targets across at least 1/10 sq.deg.

**Local Group dwarf Spheroidals:** Surveys of the kinematics and chemical abundances of low luminosity dwarf spheroidal satellites address critical questions on the nature of dark matter and the nature of early galaxy formation: Are the recently discovered low luminosity dwarfs the last remnants of the primordial population that perhaps formed prior to reionization? Is their detailed chemistry different from the field halo and the more luminous dwarfs? Although many new systems are certain to be discovered (via PANSTARRS, LSST), no instrument exists on current telescopes to undertake a major program of spectroscopy on hundreds of stars per galaxy.

**Galactic bulge:** We would be capable of obtaining high resolution spectra of bulge dwarfs, which are faint ( $R\sim 18-19$ ) and crowded. This capability would substantially enhance current research with microlensed bulge dwarfs (a high fraction of which are metal-rich) which are rare and occur in random fields across the bulge. With a multi-object spectrometer, one could obtain spectra for  $\sim 50$  bulge dwarfs in several fields. These stars may be selected to have proper

motion measurements from *HST*, making it possible to explore correlations between kinematics and composition. One could even select for stars that have candidate transiting planets offering the possibility of measuring planetary masses and properties across a wide swath of the Galaxy.

**Extragalactic globular clusters:** With moderate-to-high resolution multiplexing spectroscopy of extragalactic globular clusters, integrated light chemical abundances of globular clusters can be measured in galaxies ranging from M31 to the brightest objects in the Virgo Cluster. Metal-poor globular clusters are essentially the only way to study the chemical abundances of stellar halos in the 10-m telescope era. With similar data but at lower signal-to-noise, velocity dispersions and thence mass-to-light ratios can be measured of large samples of extragalactic globular clusters. These data explore the relationship between dwarf nuclei and ultra-compact dwarf galaxies. A straw-man spectrograph covering  $\sim 0.1$  sq. deg could obtain radial velocities for 1500--2000 globular clusters in M87 in a few nights, allowing an extraordinarily accurate profile of the mass and anisotropy, independent of other data.

### *Time-Domain Astrophysics Enabled by a Flexible Observatory*

Keck Observatory, by virtue of its user community, aperture size, and instrument suite has been a leader in time-domain astrophysics (TDA) discoveries, with, for example, the 1) first inference of dark energy with photometry and spectroscopy of supernovae, 2) measurement of the orbits of stars around Sgr A\*, providing the location and mass of the black hole at the center of the Galaxy, 3) leading in the discovery of exoplanets, 4) discovery of Dysommia, a moon with common proper motion with Eris, the largest dwarf planet, 5) discovery of the cosmological nature of gamma-ray bursts, 6) discovery of the largest volcanic eruption in the Solar System on Io and the first spectrum of an Io eruption. With other 8–10m class telescopes on-line, many of which are queue-scheduled and some with rapid instrument switching capability, it is clear that Keck is facing increased competition and is in serious danger of ceding important scientific ground without improving its time-domain capabilities. For instance, Next Generation Imaging Surveys (NGISs), such as Pan-STARRS and LSST, will soon routinely produce hundreds to thousands of transients per night. The phase space for new discoveries is enormous and Keck must position itself to capitalize on the “needles in a haystack.” In addition, there are several representative TDA science areas of broad interest to our community:

**Black Hole Tidal Disruption Events:** These should be found by NGISs by the dozens in the next few years, offering a new window on black hole growth in the distant universe. Keck observations could provide crucial spectroscopic confirmation, redshifts, and monitoring of emission-line diagnostics and variability over timescales of weeks to months.

**Progenitors of Supernovae:** High-resolution imaging of SN progenitor sites enable the correct selection of the progenitor from among the stars in the pre-explosion SN images. After decades of effort, only seven SN progenitors have so far been detected. The use of Keck LGS-AO represents a promising direction for such studies.

**Gamma-Ray Bursts as Probes:** As bright lighthouses, GRB afterglows for hours can outshine the brightest quasars in the sky. Systematic programs could use GRBs to understand the nature of damped Ly $\alpha$  systems, ISM and molecular clouds in distant galaxies, and non-continuum features extragalactic extinction curves. GRB afterglows are also providing probes of the early universe (into the Epoch of Reionization), before the assembly of supermassive black holes capable of producing bright quasars. In this respect, rapid access to low- to moderate-resolution IR spectroscopic capabilities with Keck must be cultivated.

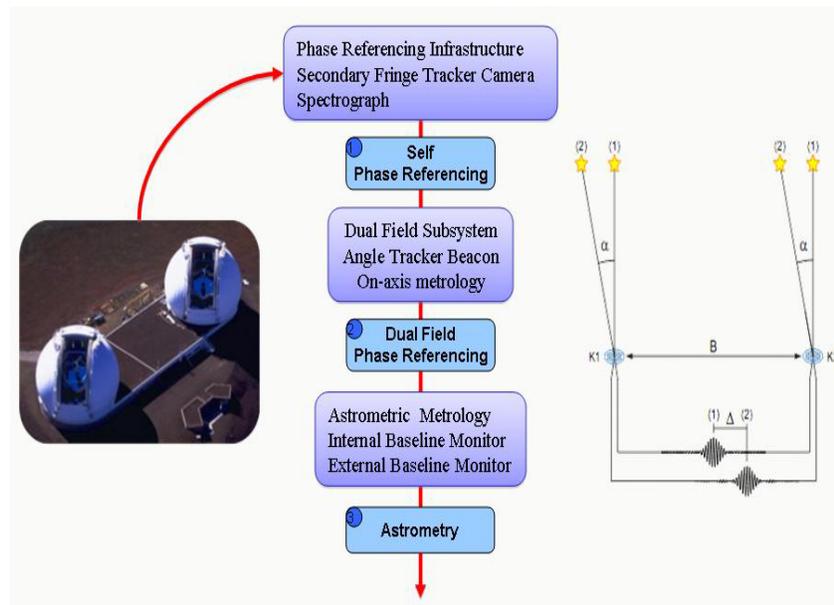
### III. Technical Overview

#### *New Capabilities in Very High Angular Resolution Astronomy*

#### **Keck Interferometer ASTRA Phase Referencing and Astrometry**

The technical steps in the development of the Keck Interferometer for phase referencing and astrometry is shown conceptually in Figure 4. The existing Keck Interferometer provides a powerful operational facility on which to build the new science capabilities. The three observing modes are described in the following bullets:

- **Self phase referencing** has been scientifically demonstrated and is operational. This mode provides  $R \sim 1800$  spectral resolution of science targets currently as faint as  $K \sim 7$ . In self phase referencing, like adaptive optics (AO), some of the light from the science object is used to measure and control the wavefront (in this case the phase or piston between the two telescopes). A beamsplitter is used to divide the science objects light and to send the light through separate interferometer delay lines to two fringe tracker cameras. The science integration time on one of these delay lines and cameras can be set to  $\sim 1$  sec versus the 200 Hz update rate required for fringe tracking.
- **Dual field phase referencing** does the same as self phase referencing but using two separate targets (or fields), one for science and one for phase referencing, separated by up to  $30''$  in order to increase the limiting magnitude of the interferometer from  $K \sim 10$  to  $K \sim 15$  science targets. Since much more of the path is now non-common path additional metrology systems are required for both phase and angle (i.e., tip-tilt) tracking. In order to not be limited by the limiting magnitude of the AO systems it is also necessary to have laser guide star (LGS) AO systems on both telescopes (the Keck II LGS AO system has been operational since 2004 and the Keck I LGS AO system will be operational in 2010).
- **The astrometry measurement** is shown schematically on the right side of Figure 4. A differential phase measurement ( $\Delta$ ) between the two targets is turned into a measurement of the angular separation  $\alpha = \Delta/B$  where  $B$  is the baseline between the two telescopes. Another level of metrology must be added along with systems to accurately measure the stability of the baseline between the two telescopes in order to achieve the required  $30 \mu\text{arcsec}$  accuracy. This mode is planned to be ready for science observations in 2010.



**Figure 4. Development of the Keck Interferometer (KI) for phase referencing and astrometric science.** The text boxes list the major components required to be added to move from the existing KI (left image) to self phase referencing, then to dual field phase referencing and finally to astrometry. The schematic at right shows how a phase difference measurement ( $\Delta$ ) is used to obtain the angular separation ( $\alpha$ ) between two stars based on the baseline distance ( $B$ ) between the two Keck telescopes.

### ***Precision Optical and Near IR Spectroscopy***

As discussed above, mid-M dwarf stellar targets ( $\sim 0.2-0.5 M_{\text{sun}}$ ) observed in the near-infrared appear to be the sweet spot for the first detection of earth-mass planets. Innovative instruments on Keck will enable Keck to play a leading role in the search for earth-mass exoplanets orbiting low mass stars. One such example is an interferometric front-end instrument coupled to the Near Infrared Echelle Spectrometer (NIRES) currently in assembly. Such an instrument could achieve  $\sigma_v \sim 2-5$  m/s for H=10 late-type stars in a 5 min integration on the Keck telescope. There are more than 1000 M dwarfs brighter than  $V=12$ , and more than 2000 currently known M dwarfs later than M4V. A prototype for such instrumentation is currently under development and testing at the Palomar Observatory (TEDI). If successful, Keck will consider its implementation (NEDI) in the upcoming decade.

To date, the radial velocity technique at optical passbands has been by far the most successful approach to discovering new planets. And although other approaches are producing spectacular new results, precision radial velocity studies, in particular those with precision to  $<1$  m/sec, will continue to play a central role in extra-solar planet research for the foreseeable future. There are several opportunities for improving the Keck Observatory capabilities in this area:

- Build a new dedicated spectrometer optimized for precision Doppler measurements. A key improvement is to significantly increase the effective bandpass over which the measurements are made beyond the Iodine cell approach in HIRES.
- Build a fiber-based "scrambler" for the HIRES slit feed. The scrambler will ameliorate changes in pupil illumination due to imperfect centration of the star on the slit that is a limiting factor in velocity precision.
- Build a combination fiber scrambler and image slicer to either improve efficiency at the slit or to work with the same efficiency as now, but with higher spectral resolution.

### ***KCWI -- High Sensitivity, 2D Imaging Faint-Object Spectroscopy***

KCWI is an image slicer integral field spectrograph. The KCWI instrument configurations are detailed in Table 1 below. The instrument combines a reflective image slice (24 slices), several folding flats, a simple collimator, a dichroic that forms the two optimized optical channels (red and blue), and existing blue camera, a high QE  $e2v$  4k x 4k CCD optimized for blue QE for the blue channel and a new camera and deep depletion CCD for the red channel. Source/background shift-and-nod provides the required sensitivity and  $10^3-10^4:1$  background rejection to unambiguously detect low surface brightness emission against a complex sky spectrum. The spectrograph obtains a moderate to high spectral resolution, using high efficiency Volume Phase Holographic gratings.

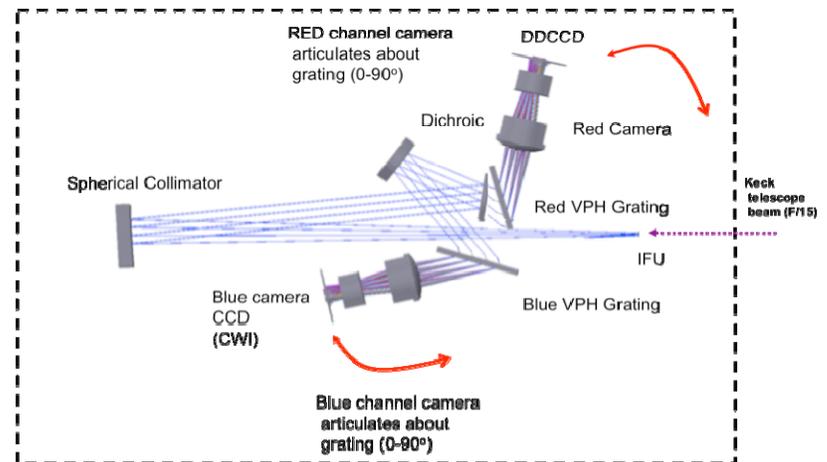


Figure 5. KCWI optical layout

**Table 1 –KCWI Instrument Configurations**

		Spatial Resolution			
		$\infty$ Dispersion	Dispersion (Slicer-width) Direction		
			Fine	Medium	Coarse
		0.3"	0.35"	0.7"	1.4"
<b>FOV</b>		20"x	8.4"	16.8"	34"
Spectral Resolution					
High	Instantaneous $\Delta\lambda/\lambda$	300Å /4000Å	R~20,000	R~10,000	R~5000
Medium	Instantaneous $\Delta\lambda/\lambda$	1000Å /4500Å	R~8400	R~4200	R~2100
Low	Instantaneous $\Delta\lambda/\lambda$	2500Å /5000Å	R~3600	R~1800	R~900

KCWI is designed to provide a wide range of capabilities, with emphasis on spatial sampling and spectral coverage. Spectral resolution, slicer width (image resolution in spectral direction) and bandpass are determined by the following simple relationship:  $R(\Delta\lambda/\lambda)\theta=500$ , where R is the spectral resolution ( $R= \lambda/\delta\lambda$ ),  $\Delta\lambda/\lambda$  is the fractional instantaneous wavelength coverage in one channel, and  $\theta$  is the slicer width in arcseconds (spaxel size in dispersion direction). The optical layout is shown in Figure 5. KCWI will provide 3 image slicer formats swapped into place in less than a minute. The multiple slicers would be designed to feed a fixed pupil mirror array, so that the resulting virtual slit is identical in the three cases except for slit width. KCWI will use Volume Phase Holographic (VPH) gratings, which provide very high efficiency when operated near the Bragg condition. For the higher dispersion/resolution gratings, the bandpass is modest but sufficient to cover line combinations such as Hb/[OIII] or Ha/[NII]/[SII]. The camera and grating are mounted on a rotating articulation unit that provides an arbitrary incidence angle to the grating ( $\alpha$ ) and exit angle to the camera/detector ( $\beta$ ). Full optical band coverage (3500 Å – 10,000 Å) would require 3 gratings on the blue side and three on the red side, assuming two simultaneous channels. Instrument throughput will exceed 25%.

**Technical Developments.** The principle technical developments are the large, high dispersion VPH gratings required for the highest resolution modes. The finer image slicer pushes the limits of slicer fabrication. KCWI will probably provide flexure compensation or an image derotator. DDCCDs are still considered developmental.

***New Capabilities in Wide-Field Spectroscopy***

**Keck observatory is considering several paths toward multi-object, moderate resolution optical spectroscopy over wide fields**, a capability that it currently cedes to many of the other 8 to 10m class telescopes (e.g. FLAMES, GIRAFFE/VLT; Hectoechelle/MMT). With one exception (MOE on Magellan), these are all wide-field, fiber-fed instruments. A high throughput multi-object echelle spectrograph on Keck would potentially enjoy a 1 mag or greater gain on these instruments, making it a unique facility.

The science described above demands a spectral resolution of at least ~20000, with a slit size set such that at median seeing at Keck most of the light from a point source goes through the slit. It is critical to achieve a multiplexing of at least a factor of 20 while maintaining substantial wavelength coverage per object for abundance measurements on more chemical species or greater redshift coverage. Finally, a throughput exceeding 15% is needed to maintain an advantage over existing instrumentation at other observatories.

One approach to accomplish this is by **modifying the Low Resolution Imaging Spectrograph (LRIS)**, an existing optical spectrograph at Keck which already has a reasonably large field with

multi-object capability. This will provide a cost-effective way to rapidly bring online the desired new capability. The maximum spectral resolution of LRIS today is  $\sim 4500$  for a 1200 g/mm grating used with a 0.7 arcsec wide slit. Reducing the slit significantly from this is not feasible owing to the severe light loss it would incur. Harland Epps has identified an interesting configuration of dispersive elements which can increase the spectral dispersion without narrowing the slit nor increasing the beam size. We believe that Epps's new optical configuration can be implemented on the red side of LRIS, which is a double spectrograph with a red and blue side. The red side detector will be upgraded within a few months to have the best available CCD detectors with very low readout noise. The capability of obtaining multi-object high resolution spectroscopy could thus be added to the suite of observing modes available for a cost of less than  $\sim 1$  million dollars and could be completed within a year.

We have also begun exploring designs for a new facility instrument that would offer wide-field, multi-object spectroscopy at  $R \sim 20000$ . Considerable effort has been expended by a team led by Rebecca Bernstein on the design of a **moderate resolution multi-object instrument (MOBIE)** for the TMT. We would also explore whether this concept can reach the desired spectral resolution if scaled back for a 10-m telescope and how the cost would scale.

In terms of the wide-field ( $>0.1$  sq. deg.), low-dispersion instrumentation that would be ideal for galaxy and radial velocity surveys, Keck is challenged by its  $f/15$  secondary and the difficulty of locating instrumentation at the prime focus. Members of the GTC (a Keck clone) community are currently pursuing designs for a fiber-fed instrument at the Cassegrain focus. Keck may leverage these efforts to initiate its own development in the next decade.

### *Enhancing Capabilities in Infrared Spectroscopy*

**The WMKO Near InfraRed Echelle Spectrograph (NIRSPEC)** was commissioned in April 1999. NIRSPEC offers both a low ( $R \sim 2,000$ ) resolution mode and a cross-dispersed Echelle mode ( $R \sim 25,000$ ) over the wavelength range of 0.96 to 5.5  $\mu\text{m}$ . NIRSPEC has provided workhorse service, receiving approximately 100 observing nights per year. The continued development of infrared focal plane arrays offers the opportunity to upgrade NIRSPEC, an activity that would be responsive to requests from our observing community to improve the performance of the instrument in areas such as detector dark current and read noise, an improvement of particular interest for Echelle mode observations in the J, H, and K bands. Requests have also been made for improvements in spectral coverage in the K, L, and M bands, and a higher resolution mode, for example  $R \sim 60,000$ .

The most straightforward upgrade to NIRSPEC is to replace its current 1024 x 1024 pixel InSb science array with a 2048 x 2048 pixel 5  $\mu\text{m}$  cut-off H2RG (Teledyne Imaging Sensors Hawaii-2RG). The improvements possible in dark current and read noise are significant. The dark current of the H2RG is a factor of 70 times lower than the InSb array. Using Fowler sampling the H2RG has been shown to provide read noise of 5  $e^-$  rms compared to the 25 to 35  $e^-$  rms obtained from the InSb detector with 16 Fowler samples. The H2RG also offers a higher charge storage capacity and improved quantum efficiency, 80% is routinely demonstrated from 1 to 5  $\mu\text{m}$ . Using the existing camera optics the smaller pixel scale of the H2RG would increase the spectral sampling from 3 pixels (0.43" slit width) to 4.5 pixels but would not provide any additional spectral coverage. However, this improved sampling may be an asset to improving the precision of radial velocity measurements.

A second upgrade that would provide a significant benefit to observing efficiency would be to upgrade the instrument's slit viewing camera to a 5  $\mu\text{m}$  cut-off 1024 x 1024 H1RG. This would improve the sensitivity of the slit viewing camera for target centering and for slit guiding. The slit viewing camera optics would also need to be redesigned as the present refractive optical design is optimized for achromatic performance from 1 to 2.5  $\mu\text{m}$  and is unlikely to provide satisfactory performance at longer wavelengths. Both detectors would be controlled using the Teledyne SIDECAR ASIC to provide a high performance readout system to replace the current obsolete read out electronics which are a concern for continued spare parts and repair support.

Improving spectral coverage or providing increased spectral resolution in Echelle mode would require more extensive design changes, at a minimum the existing spectrograph camera optics (a three mirror anastigmat) would have to be replaced to take advantage of the area of the H2RG not illuminated by the existing camera. Higher resolution would require sacrificing the low resolution mode; an additional grating position is unlikely to be practical within the current constraints of the instrument's opto-mechanical layout. Both of these options would require more extensive design work to determine their feasibility.

### ***Time Domain Astronomy***

The W. M. Keck telescopes were not designed with time domain astronomy (TDA) explicitly in mind. With the growing interest and emphasis in TDA, the observatory is exploring new technical and institutional solutions to enhance TDA science at Keck.

Nights (or portions of a night) on the Keck telescopes are assigned 'classically' and the PI maintains full control over his/her assigned night. Although this approach to scheduling confers many benefits, it does create an impediment to efficient TDA observation, in comparison with queue scheduling models. Furthermore, current TDA policies are established individually by each partner and these do not allow for cross-institution observations. An example of the limitations this imposes to TDA science is as follows: if a TDA project were awarded by NASA for monitoring near-Earth asteroids with the NIRC2 camera, there is only a 0.7% probability that the observer could access NIRC2 on any given NASA night. With inter-institution cooperation, this would increase to 23%. Additional efficiency improvements may require further changes to Keck operations, including the possibility of some hybrid form of classical and queue scheduling under the direct control of the observer.

In tandem with advancing policy changes for TDA science, the observatory is exploring the possibility of making available on short notice, several instruments during the course of a night. Current practice is to guarantee availability of only the scheduled instruments on a given night (with some limited exceptions). It is feasible to expand this to make additional instruments available on timescales of  $\sim 15$ min. In some cases this is as simple as keeping instruments on standby. Other possible approaches being considered include fiber-fed instruments (though significant light loss may be a problem) and telescoping tertiary systems to redirect the light path. In the longer term, purpose-built systems containing multiple instruments could be constructed to allow rapid switch-over in support of TDA science.

Keck has been a leader at developing efficient and fully featured remote control facilities to enable observation from sites distant from the telescopes. Indeed, 13% of observations are now done solely from sites at one of the partner institutions. Expanding this effort to support TDA science is a straightforward and natural outgrowth.

#### **IV. Activity Organization, Partnerships, and Current Status**

The partners in the operation of Keck Observatory 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 Hawai'i (12.5%). Yale University and the Swinburne University of Technology participate in Keck 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 the NSF/NOAO Telescope System Instrumentation Program (TSIP; approximately 24 nights per year). NOAO's recent ALTAIR committee report ([http://www.noao.edu/system/altair/files/ALTAIR\\_Report\\_Final.pdf](http://www.noao.edu/system/altair/files/ALTAIR_Report_Final.pdf)) noted in the context of 6.5-10 meter 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, Keck Observatory represents a significant fraction of U.S. peer-reviewed public access to large telescopes.

To measure the use of Keck Observatory by the broad U.S. community, we have studied the identities and institutional affiliations of principal investigators (PIs) and co-investigators (Co-Is) on Keck proposals from semester 2006A through 2009A. Principal investigators for WMKO observing programs were from 68 different institutions, 57 of which represent institutions not associated with Caltech, U.C., or U.H. Similarly, the co-investigators on observing programs came from 123 different institutions after excluding Caltech, U.C., and U.H. The total number of observing programs supported from semester 2006A through 2009A was 864. Of these, 238 programs (28%) did not have a Caltech, U.C., or U.H. PI. Similarly the NASA Keck programs from semesters 1996B through 2009A were conducted by 113 different PIs and 322 Co-Is at 122 institutions.

The 6.5 to 10 meter optical/infrared telescopes of today are the workhorses that will enable the scientific productivity of the optical/infrared community until the next generation of large telescopes (GSMT and LSST) are fully commissioned for science operations toward the end of the coming decade or perhaps in the subsequent decade. Even after the commissioning of GSMT, the 8-10 meter telescopes will play an important role for many years. Therefore, keeping the large telescopes in the U.S. observing system properly instrumented and taking advantage of advances in adaptive optics, detector, coating and other instrumentation technologies are crucial to the community's scientific productivity over the coming decade. The European Southern Observatory is currently spending at a dramatically higher level for instruments and adaptive optics systems on their Very Large Telescopes (VLT) than the sum of all spending in the U.S. system on comparable large telescopes.

Keck Observatory is a highly successful private-public partnership. The Observatory's initial construction was funded by two gifts from the W. M. Keck Foundation to Caltech, and NASA provided significant support through a cooperative agreement. The Keck Foundation also funded much of WMKO's world-leading adaptive optics 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 from grants from NSF and NASA, and also from donations by individuals and private foundations.

The NSF-funded ATI, MRI and TSIP programs are the primary federal funding vehicles for instrumentation for U.S. ground-based facilities. The amount of funding in the NSF programs is modest given the cost of state-of-the-art instruments for 8-10 meter telescopes. During calendar 2008, the average size of NSF-ATI awards was \$290,000, with the largest award being \$1.0 million. NSF MRI awards have a ceiling of \$2-4 million (and require 30% matching contribution). These funding levels are significantly below the costs for a typical new instrument for an 8-10 meter telescope of around \$10 million and \$60 million for a truly transformational capability.

This document has described several key scientific and technical initiatives that are envisioned by Keck Observatory as essential to maintaining and extending our high scientific productivity. In order for these initiatives to succeed, federal funding is essential. Recommendations for optimizing federal funding for the opportunities for scientific and technical advances possible with 8-10 meter telescopes in the U.S. system are contained in the Astro2010 State-of-the-Profession submissions “The Role of the W. M. Keck Observatory in U.S. Astronomy” and “Statement from ACCORD for ASTRO2010 Consideration.” In order for Keck Observatory to realize its full potential in serving the U.S. astronomy community and functioning as an essential element of the U.S. ground-based optical/infrared system, we recommend that:

- NSF increase the funding, to \$10M per year, for a TSIP or TSIP-like program, achieving the dual goals of funding instrumentation initiatives at independent observatories and making observing time available to the broad U.S. community;
- NSF make TSIP funding stable from year to year;
- NSF and NOAO implement additional financial incentive factors in TSIP in order to, for example, encourage the development of high-priority capabilities and long-term exchange arrangements;
- NSF increase the financial limits and allocations in the ATI and MRI programs to enable proposals for developing transformational instrumentation for 8-10 meter telescopes;
- Planning and funding of new transformational instrumentation in the U.S. community be developed through a competitive process open to all participants in the ground-based optical/IR system.

## V. Cost Estimates

The previous sections described a possible set of technical advances for Keck Observatory in the upcoming decade. Many of these are limited solely by funding, i.e. there is no significant technical risk preceding construction. Our greatest need, therefore, lies in a stable and sufficient funding profile to enable Keck to capitalize on scientific opportunities. Below we sketch a possible schedule of funding for several of the initiatives. This exercise serves as a rough estimate of our funding needs and the timing of such expenditures. The details of implementation and relative priorities of these projects may evolve over the coming decade as the scientific state of the field matures. What will not change is the need for instrumentation renewal and continued investment to maintain Keck Observatory as a national resource for astronomical leadership. We will seek both federal and private funds to fuel these initiatives, nominally half federal and half private.

**Table 2. Estimated Costs and Phasing of Initiatives**

Strategic Goal	Capability	Total \$M	Totals in \$M in 2 year intervals				
			FY10-11	FY12-13	FY14-15	FY16-17	FY18-19
High Angular Resolution	ASTRA operations	27	5 <sup>1</sup>	5	5	6	6
	NGAO	51.5	16	26.5	9		
Spectroscopy	KCWI	5	2.5	2.5			
	Optical Precision RV	21	1		4	8	8
	NIRSPEC upgrades	3.5	1	2.5			
	NEDI	2	1	1			
	LRIS higher-resolution MOS	1	1				
	Keck MOBIE	15		2	4	6	3
Flexibility	Instrument + Facility modifications	2	1	1			
<b>Total</b>		128	28.5	40.5	22	20	17

<sup>1</sup>Currently in NASA plan for FY10 only.