

The Value of the Keck Observatory to NASA and Its Scientific Community

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1 Executive Summary

Over the last 13 years, NASA and its astrophysics and planetary science communities have greatly benefited from access to the Keck Observatory, the world's largest optical/infrared telescopes. Studies using NASA Keck time have ranged from observations of the closest solar system bodies to discoveries of many of the known extrasolar planets. Observations at Keck have supported spaceflight missions to Mercury and the technology development of the James Webb Space Telescope. Access to Keck for the NASA community is an extremely cost effective method for NASA to meet its strategic goals and we encourage NASA to continue its long-term partnership with the Keck Observatory.

2 The Keck Observatory

The two 10-meter telescopes of the Keck Observatory are the world's largest optical and infrared telescopes and are located on Mauna Kea, one of the world's premier sites for astronomy. With their suite of highly sensitive instrumentation, time on the Keck telescopes is one of the most sought after resources in astronomical and planetary science research.

The Keck Observatory was made possible through grants from the W.M. Keck Foundation and the Observatory is operated by the California Association for Research in Astronomy, whose Board of Directors includes representatives from the California Institute of Technology and the University of California.

3 NASA/Keck partnership

NASA has been a partner in the Keck Observatory since 1996 and allocates its 1/6 share of the observing time on Keck I and Keck II to both strategic projects and investigations competitively selected by a time allocation committee. In this white paper, we summarize the usage of this valuable resource by the NASA community, particularly focusing on the strategic use of time to support NASA missions.

3.1 Community use of NASA Keck time

Usage of NASA's time on the Keck telescopes is open to the entire US astronomical community. From the second semester of 1996 to the first semester of 2009, there have been a total of 113 different principal investigators and 322 co-investigators representing 122 institutions.

From 1996 to 2008, the use of NASA Keck time was allocated to support the following areas:

- Detection of extrasolar planets
- Origin and nature of planetary systems

- Investigations of our own solar system
- Direct mission support

In 2009, NASA Headquarters added all Cosmic Origins science including stars, star formation, galaxies/AGN, and galaxy formation to the list approved science topics

4 NASA Keck Science Results

Numerous US astronomers have used NASA Keck time to obtain science results that are very important for achieving NASA science goals and/or supporting NASA missions. A few notable results in the fields of solar system studies, extrasolar planets, and origins of planetary systems (the NASA Keck science areas for most of the past decade) are now highlighted. A bibliography of over 120 NASA/Keck papers can be found at <http://nexsci.caltech.edu/missions/KeckSolicitation/bibliography.shtml>.

4.1 Extrasolar planets

NASA Keck time has been used to discover dozens of extrasolar planets, including ones with masses less than that of Neptune. This includes the discovery and characterization of several multi-planet systems and the discovery that the orbits of planets are generally coplanar with the rotation of their stars. The projected angle between the spin axes of the star and the orbital plane of its planets has now been measured in 12 systems and is found to be aligned to within a few degrees except for one system (hosting the XO 3 planet) that is misaligned by 37 degrees! About half of these systems, including the discrepant XO 3 one, were measured using NASA Keck time (e.g. Winn et al., 2007, ApJ, 665, 167). NASA Keck observations also produced the discovery that M star planets are likely to be low mass and have produced precise mass measurements of transit-discovered planets. NASA Keck long-term monitoring is now producing true Jupiter analogs like HD 154345b (Wright et al. 2008, ApJL, 683, 63).

NASA Keck usage has also been critical for understanding extrasolar planets when combined with data from other NASA facilities. For example, the low mass planet GJ 436b was discovered and its mass was measured to be 22 Earth masses using NASA Keck time (Butler et al. 2004, ApJ, 617, 580). It was later found to transit, and photometry with Spitzer measured the radius of this planet very precisely to be 4.2 Earth radii. This combination of mass and radius is consistent with the planet having a dense refractory core, a large fraction of water ice, and a thin H/He envelope. The detailed analysis of the structure of this very low mass planet (the second lowest mass transiting planet to date) would have been impossible without the Keck telescope, and JWST transit spectra will reveal even more information about it.

4.2 Uranus and its rings

The planet Uranus was aligned with Earth in the summer of 2007 so that its ring system crossed our line of sight. This rare event occurs only during Uranus equinoxes, once every 42 years. High-resolution NASA Keck adaptive optics (AO) observations before, during, and after the crossing revealed significant new information about the planet's atmosphere and ring system. Figure 1 shows the rings before (2004 and 2006) and during (2007) the ring plane crossing. Keck data showed that dust permeates the ring system, but

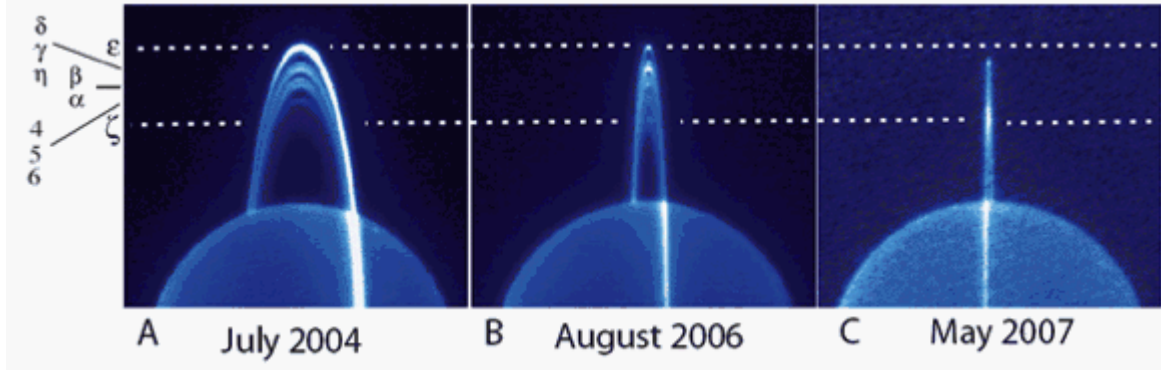


Figure 1: Keck near-IR AO images of the Uranus ring plane crossing (de Pater et al., 2007, *Science*, 317, 1888)

the dust is *not* correlated with known narrow rings or with embedded dust belts imaged by Voyager. Optically thick rings like ϵ disappear due to inter-particle shadowing during the crossing, while optically thin rings like ζ brighten. This combination of unique illumination changes and Keck capabilities produced information on ring particles and densities that were impossible to obtain any other way.

NASA Keck AO observations of the equinox of Uranus have produced other unique science as well. Observations before and through the 2007 equinox revealed the beginning of a reversal in band structure in the planet's atmosphere. The oldest cloud feature (discovered by Voyager) in the planet's atmosphere (Southern hemisphere) also changed structure suddenly near equinox, and new, discrete clouds were observed to form for the first time in that hemisphere (Sromovksy et al., 2007, *Icarus*, 192, 558; Hammel et al., 2005, *Science*, 312, 5770). Keck AO observations also determined that the 2 new faint outer rings of Uranus are strongly colored; one is very red and one is very blue. The rings were discovered by HST in 2006, but high sensitivity near-IR Keck AO observations were needed to determine their colors (de Pater, et al. 2006). Even JWST will not have the spatial resolution of Keck in the near-IR, so Keck AO images will likely be very important for the foreseeable future.

4.3 Volatiles in the Solar System

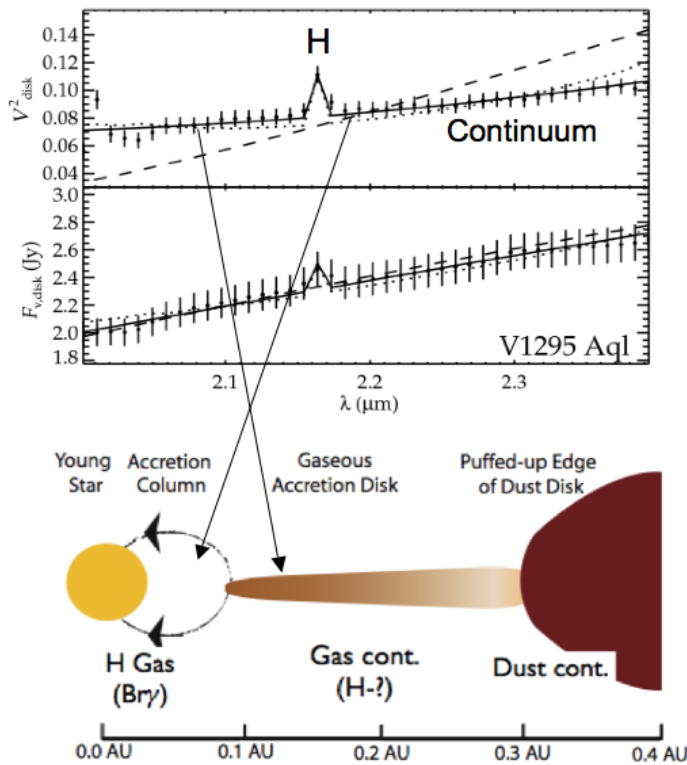
High-resolution spectra of comets obtained with NASA Keck time over the past decade have revealed that comets contain a multitude of volatile organic compounds. Observations coordinated with the Deep Impact mission revealed that comet Tempel-1 showed H_2O but not C_2H_6 in June 2005 before the impact, but the material ejected during the impact had a ratio of $\text{H}_2\text{O}:\text{C}_2\text{H}_6:\text{HCN}$ of 10000:5:2. This indicates that the ejected sub-surface material was more pristine, and the abundance ratios agree with those found in Oort cloud comets. This makes it likely that Tempel-1 and Oort cloud comets had a common place of origin in our Solar System's proto-planetary disk (Mumma et al. 2005, *Science*, 310, 270).

Mumma et al. (2009, *Science*, 323, 1041) have recently discovered spatially restricted methane on Mars. NASA Keck observations from 2006 were used to determine that the

methane seen in 2003 was nearly totally depleted, indicating that 50% of the methane is destroyed every 1.6 years on Mars. This indicates that the methane seen in 2003 must have been produced very close to that time, and Mars must currently have active geological or biological processes that create methane.

These measurements of volatiles on Mars and in comets were made with the Keck NIRSPEC near-infrared spectrograph. NIRSPEC is a truly unique instrument, there is no other instrument on the ground or in space that has its combination of spectral range, spectral resolution, and high sensitivity. It is also likely to remain unique for quite some time; for example the JWST spectrograph will have over 10 times less spectral resolution than NIRSPEC, inadequate for detecting the narrow and closely spaced molecular absorption lines of organics and other volatiles.

4.4 Young Stars and protoplanetary disks



The Keck Interferometer has produced much unique science. Eisner et al. (2007, *Nature*, 447, 562; 2009, *ApJ*, 692, 309) took advantage of its recently added spectroscopic capabilities to spatially resolve gaseous and continuum emission in the protoplanetary accretion disks around 15 young stars. Gas, including atomic hydrogen and sometimes water vapor, was found interior to the edge of the dust disk. Br gamma HI emission was generally found to be very compact, as predicted by magnetospheric accretion models. Interactions of this accreting gas with migrating planets may lead to short-period extrasolar planets like those detected around main-sequence stars. A schematic is shown in Figure 2.

Figure 2: Keck spectro-interferometric data resolves the dust and gas (solid line) continuum in the accretion disk of V1295 Aql and other young stars, but finds the HI gas to be generally unresolved (Eisner et al. 2009, 692, 309).

5 Strategic Use of Keck Time

NASA has dedicated a significant fraction of its Keck time to strategic projects. Here we discuss the past and ongoing strategic projects.

5.1 Mission support

Direct support of active and in-development NASA missions and support of NASA collaborations with other agency missions has been an important component of the NASA use of the Keck telescope. Here are some examples of that mission support.

- **Galileo:** Thermal characterization of white ovals on Jupiter in conjunction with Galileo flyby (PI: Orton).
- **MUSES-C (Japan):** Obtain visible spectra of asteroid in support of sample return mission (PI: Binzel).
- **Deep Impact:** Determination of nucleus size through multi-wavelength observations of comet 9P/Tempel 1 for mission design (PI: A'Hearn).
- **Cassini:** Measurement of Titan's wind velocity and direction to support the Huygen's probe entry into the atmosphere (PI: Griffith). Imaging Titan's atmosphere in conjunction with the Cassini flyby (PI: Young). Near-infrared imaging of Saturn's atmosphere in conjunction with Saturn flyby (PI: Baines).
- **JWST:** Demonstration of dispersed Hartmann sensing on the Keck telescope to validate the baseline approach for coarse phasing on JWST (PI: Ohara).
- **SIM:** Radial-velocity observations of potential narrow-angle reference stars to identify those with unsuitable astrometric motion (PI: Shao).
- **New Horizons:** Orbital determination of potential Kuiper Belt flyby targets (PI: Spencer).
- **EPOXI:** Characterization of comet 85P/Boethin to facilitate interpretation of *in situ* spacecraft observations (PI: DiSanti).
- **Messenger:** Observations of Mercury's atmosphere in support of flyby (PI: Bida).
- **CoRoT (France):** Observations to confirm planetary nature of transit events (see Section 5.6).
- **LCROSS:** Observations of material ejected in impact with lunar polar region (PI: Wooden).
- **Kepler:** Observations to confirm planetary nature of transit detections (see Section 5.7; PI: Borucki).

5.2 Interferometer development

After joining the Keck partnership, NASA began the Keck Interferometer (KI) project to join the two 10-meter Keck telescopes as a long-baseline infrared interferometer with an 85-m baseline. The on-sky engineering time to complete the technical development and characterization of KI came both from observatory engineering time, as for all new instruments, and from the NASA allocation, as the interferometer is a particularly complex instrument. The integration and characterization of the visibility science and the nulling instruments took place from 2001 to 2007. After these interferometry modes became available, they were opened to the entire Keck community, with operations fully funded by NASA.

5.3 TPF Keck preparatory science

In 2005, NASA issued a one-time, supplementary call for Terrestrial Planet Finder (TPF) preparatory science. In preparation for the TPF mission, detailed knowledge is required of the incidence of extrasolar planets down to lowest possible masses and of the properties of possible TPF target stars. To facilitate this goal, NASA acquired an additional 10 nights of Keck 1 observing time (in addition to NASA's regular Keck 1 time allocation) and allocated this time to the radial velocity search for extrasolar planets using HIRES (High Resolution Echelle Spectrometer), with the specific objective of detecting planets in the mass range $\geq 10\text{-}20 M_{\text{Earth}}$ in short period orbits. The primary scientific goal of this effort was to develop a better understanding of the incidence of such planets, possibly large rocky "super Earths" or small ice- or gas-giants, around mature main sequence stars with spectral types F, G, or K. This time was allocated to a team led by W. Cochran (University of Texas) and the nights were allocated in semester 2005B. These data are now available to the entire community via the Keck Observatory Archive (KOA).

5.4 Frequency of Earth-like planets (η_{Earth})

A second strategic project to probe even lower masses and longer orbits for the frequency of potentially habitable planets was begun in 2007. Estimates for η_{Earth} (the frequency of Earth-like planets) for nearby stars range from 0.05 – 0.5. A high value η_{Earth} would enable a smaller TPF mission at lower cost to study the nearest stars, while a small value would require a more expensive TPF mission to study more distant stars. Investigators were solicited to address η_{Earth} through extrasolar planet detections that approach the mass and orbital characteristics of habitable planets, for example by detection of super-Earths ($\sim 10 M_{\text{Earth}}$) in habitable zone orbits, or by detection of planets of near Earth mass ($\sim 5 M_{\text{Earth}}$) in orbits smaller than habitable zone orbits. Statistical results of such searches can be linked to the value of η_{Earth} through theoretical modeling of planetary system formation, while actual detections provide characterization of specific nearby exosystems, and can approach "proof of existence" of candidate terrestrial and potentially habitable planets. This program was scheduled to cover 4 semesters, allowing the discovery of much longer period planets.

A single team, lead by G. Marcy (UC Berkeley) was selected and received 35 nights over 4 semesters in 2007 and 2008. During this time period, the team conducted a survey of 230 nearby G, K and M dwarfs, also including observing time provided by team members from the UC allocation. As of early 2009, 75% of the sample had over 20 observations and 75% have at least 1 high-cadence observing run. The team is following up many low-mass candidates. An example detection from this program is a $9.3 M_{\text{Earth}}$ ($M \sin i$) planet around the K0 star HD 7924b (Figure 3; Howard et al., 2009, ApJ, in press).

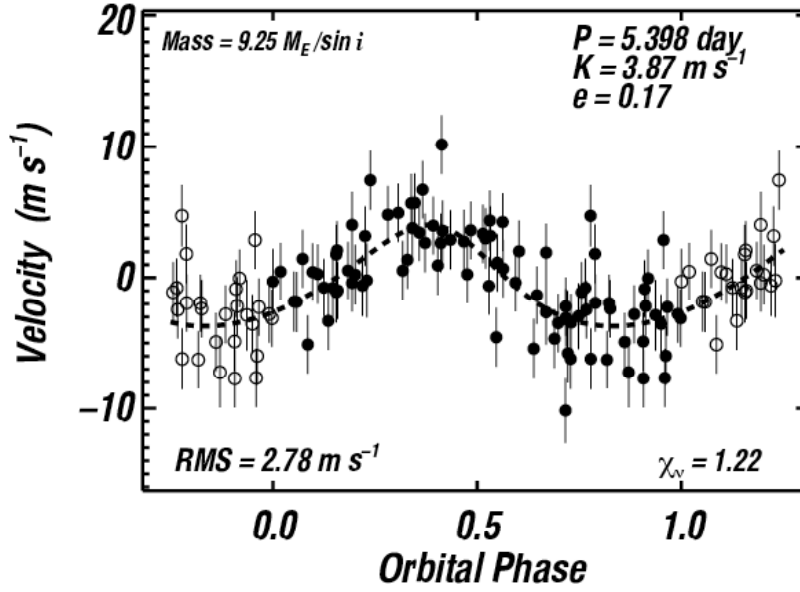


Figure 3: Single-planet Keplerian model for the radial velocities of HD7924, as measured by Keck-HIRES. The dashed line shows the best-fit Keplerian orbital solution representing a $9.26 M_{\text{Earth}}$ (minimum mass) planet in a 5.398 d orbit. Filled circles represent phased and binned radial velocities, while the open circles show the same velocities wrapped one orbital phase. The error bars show the quadrature sum of measurement uncertainties and 2.13 m s^{-1} jitter. Figure from Howard et al (2009, *ApJ*, in press).

5.5 Exo-zodiacal Dust Survey

In 2008, NASA solicited proposals for Key Science teams to use the Keck Interferometer Nuller (KIN) to study exo-zodiacal dust around main sequence stars. The proposals were requested to address two fundamental questions:

1. What are the physical and evolutionary properties of exo-zodiacal disks, with a particular focus on studying warm ($\sim 300 \text{ K}$) material located in regions analogous to the zodiacal dust and asteroid belt of our solar system? Is material found within 1 AU by KIN a continuation of material seen at longer wavelengths by Spitzer? Are there excesses from hot material not previously identified in Spitzer surveys due to limitations on absolute photometric accuracy, and whose presence is hinted at by shorter-wavelength interferometric observations?
2. What is the level of warm ($\sim 300 \text{ K}$) material in the exo-zodiacal disks around specific nearby main sequence stars, which will be the prime targets for future planet finding missions such as TPF and Darwin. Studies at Spitzer sensitivity levels reveal that approximately 1% of main sequence stars show an excess at ~ 10 microns. How does this number increase with improved sensitivity? Is there a population of very small, hot dust grains ($> 500 \text{ K}$) that might have been missed by Spitzer's photometric or spectroscopic observations?

Three teams were selected to observe a total of 45 objects during 2008 and NASA allocated 32 nights of KI time for this Key Project. The observational phase of this

project was completed in January 2009 with observations of 42 targets at a sensitivity level equivalent to the mid-infrared emission of a few hundred times that of our own solar system.

The Exoplanet Task Force strongly endorsed the need for a significant amount of precision Doppler capability and the HIRES instrument at Keck is currently the only such instrument that is open to the entire US community. In addition to the intrinsic scientific interest of the results, these three extrasolar planet related studies (TPF preparatory, η_{Earth} , and exo-zodiacal dust) are critical for planning NASA's future exoplanet missions.

5.6 CoRoT

The CoRoT telescope was launched on Dec 27, 2006, and stares at a small number of fields for periods of 30-150 days looking for planets transiting their host stars. It is expected that up to hundreds to thousand of the stars monitored by CoRoT will show evidence for transits of planets with radii between the radius of Jupiter and a few earth radii. However, significant follow-up work is required first to validate these events as being due to planetary transits and not to other astrophysical phenomena such as eclipsing binary systems and ultimately to characterize such planetary properties such as mass.

Starting in 2009, NASA solicited proposals for follow-up observations of CoRoT transit candidates. These proposals must have a PI based at a US institution and must include participation from the CoRoT team. These proposals may request up to 15 nights per semester for up to 4 semesters. In return for its contribution of Keck time, CoRoT has agreed that the selected US investigators will become "CoRoT Associated Scientists", and cooperate with CoRoT Co-Is or other Associated Scientists on the selected program. As CoRoT Associated Scientists, US investigators will participate fully in the preparation and publication of scientific papers incorporating data from CoRoT and the Keck telescopes.

It is expected that Keck observations in the following areas will be of primary importance in the overall CoRoT program:

1. Characterization of the parent stars
2. Validation of planetary nature of transit signals
3. Observation of secondary transits in the infrared.

For the first call, a team led by M. Endl (U. Texas) was selected and new teams may apply in each semester of this call.

5.7 Kepler

NASA launched the Kepler mission on March 6, 2009. The scientific objective of Kepler is to explore the structure and diversity of planetary systems. This is achieved by surveying a large sample of stars to:

1. Determine the percentage of terrestrial and larger planets there are in or near the habitable zone of a wide variety of stars;
2. Determine the distribution of sizes and shapes of the orbits of these planets;

3. Estimate how many planets there are in multiple-star systems;
4. Determine the variety of orbit sizes and planet reflectivities, sizes, masses and densities of short-period giant planets;
5. Identify additional members of each discovered planetary system using other techniques; and
6. Determine the properties of those stars that harbor planetary systems.

NASA is allocating a portion of its Keck time to the Kepler Science Team to make follow-up observations of planet candidates from the Kepler mission. The Science Team will use other observing resources to screen candidates before they are observed at Keck. Given the average distance and magnitude of stars in the Kepler field, Keck is the only US facility presently available with the sensitivity to confirm the planetary nature of the Kepler transit detections and the Keck support of Kepler will continue throughout the mission lifetime.

5.8 Future Strategic Use

Many of the missions currently in the planning or development process at NASA will also benefit from access to the capabilities of the Keck Observatory. The Pluto-Kuiper Belt Explorer (New Horizons), launched in 2006, has already benefited from Keck observations for target selection. Other missions such as Juno and the Venus In-Situ Explorer could support flybys with Keck observations as has been done very successfully over the last 13 years.

The WISE survey mission will utilize Keck time for follow-up spectroscopy of brown-dwarf candidates and other discoveries. The optical and high-resolution capabilities of Keck will complement the studies undertaken by JWST and will impact all areas of NASA scientific interest, from extrasolar planets to the formation of early galaxies.

A vibrant instrumentation program and continued infrastructure support are necessary to keep Keck at the cutting edge of ground-based astronomy. The long-term plans at Keck include development of a Next Generation Adaptive Optics (NGAO) system, which will benefit many science areas, including Solar System studies and direct imaging surveys for extrasolar planets. Additional instrumentation upgrades of direct strategic relevance to NASA include enhancement of the optical precision radial velocity capability and development of precision radial velocities in the near-infrared. To obtain these goals, funding at levels necessary to produce second-generation instruments at 10-m class telescopes must be made available. We urge NASA to work with the NSF and the Keck community to develop funding for the necessary instrumentation.

6 Recommendations

Access to Keck for the NASA community is an extremely cost effective method for NASA to meet its strategic goals and provide support to the scientific and technical progress of its space missions. We strongly encourage NASA to continue its long-term partnership with the Keck Observatory.