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# Keck Observations of Solar System Objects: Perspectives for Extremely Large Telescopes

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**Abstract** From differential tracking techniques, required for appulse observations of KBOs with Laser Guide Star Adaptive Optics (LGSAO), to developing methods for collecting spectra at the precise moment of a predicted impact, each Solar System observation conducted on a large telescope presents a unique set of challenges. We present operational details and some key science results from our science program, *adaptive optics observations of main belt asteroids and near earth objects*; as well as the technical and operational details of several Keck Solar System observations conducted by other teams: the impact of Shoemaker-Levy 9 on Jupiter, volcanoes on Io, the Deep Impact mission to Comet 9P/Tempel 1, and recent observations of Pluto's moons Nix and Hydra. For each of these observations, we draw from our Keck experience to predict what challenges may lie ahead when similar observations are conducted on next generation telescopes.

**Keywords** Keck · ELT

## 1 Introduction

In Sects. 2–5 we present a brief summary of four key Solar System observations carried out by other teams at Keck Observatory. Within each of these sections, we follow the summary with one or more details of the observation and a related perspective (set off in *italic type*) to be considered by future designers of Extremely Large Telescopes (ELT). Section 6 follows the same format, but, because it describes the work of the authors, we provide more depth and motivation for the Keck observations. In Sect. 7, we conclude with a viewpoint synthesized from the nine perspectives taken from Sects. 2 to 6.

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## 2 Shoemaker-Levy 9 (SL-9)

On July 16, 1994 (prior to implementation of adaptive optics), Keck I was used to capture near-infrared images as the 'R' fragment of comet SL-9 crashed into Jupiter. The initial upward velocity (approximately 8 km/s) of the ejecta plume, and its maximum altitude (approximately 1,300 km), were measured directly from those images (Graham et al. 1995). The observation demonstrated to the astronomical community that the newly commissioned Keck was operational and ready for science.

Weather played a critical role during the SL-9 observation. Conditions hovered within a grey area, between a humidity level likely to result in moisture on telescope optics, and a humidity level at which it would be safe to open.[1] In 1994, the time to open or close the Keck I dome shutter was approximately 10 min.[2] Thanks to the efforts of an experienced telescope driver, Keck was open during the R-fragment impact and data was captured without any adverse effect to telescope optics, but the dome opening and closing had to be perfectly timed within a fortuitous (but brief) let-up in the humidity. *Perspective for ELT* Provide a dome shutter system (and/or mirror cover) that can react quickly to changes in humidity or other factors.

To achieve the detector read-out speed required for time-resolved imaging at 2.3 microns, we had to modify the electronics firmware of the infrared camera. These modifications, coded and tested during the weeks immediately preceding the impact, introduced some risk to the success of the observation. In the end, the instrument performed flawlessly (Matthews and Soifer 1994). If, however, the capability for rapid read-out had been built-in prior to delivery, the risk imposed by these last minute changes would have been avoided. *Perspective for ELT* For ELT instruments, provide read-out modes for acquiring time-resolved data sets of solar system events.

## 3 Deep Impact

On July 4, 2005, Keck participated in a coordinated effort to observe, from multiple ground-based observatories, material excavated by a projectile impacting the surface of Comet 9P/Tempel 1 (Meech et al. 2005). Excellent results were obtained from Keck I spectra obtained with HIRES (Vogt et al. 1994), but here we focus on the technical aspects of the NIRSPEC (McLean et al. 1998) observations on Keck II. That observation resulted in fundamental theories suggesting a common origin for Oort Cloud comets (Mumma et al. 2005).

A near infrared slit-viewing camera (SCAM) gives NIRSPEC a significant edge over its competitors. For example, during the Deep Impact event, in parallel with the long exposures needed to obtain spectra, the intensity and shape of the ejecta were measured with SCAM.[3] But this was possible only when working at K.

SCAM is not sensitive beyond 2.5 microns. Plans for a SCAM detector sensitive out to 5 microns were de-scoped during the specification phase of the instrument. During Deep Impact, when the spectrometer was being used to collect M-band spectra, the comet was not visible on the slit. *Perspective for ELT* When features are de-scoped during design and

[1] The guidelines for opening require a two degree differential between dew point and outside temperature.

[2] Following a 2006 upgrade to improve reliability, the time to open or close the Keck I dome shutter was reduced to approximately 7.5 min (Hess 2006)

[3] http://www.2.keck.hawaii.edu/science/deepimpact/deepImpactmovie.html

development, build in the hooks that will motivate and streamline a future instrument upgrade to restore those lost capabilities.

While guiding on a nearby star, the differential motion between that star and the comet varied slightly over time. Although we typically treat this differential as a constant rate, to boost the signal-to-noise for the Deep Impact observation, we manually varied the differential rate to better match the apparent motion.

This manual technique was possible thanks to Keck's 'open' architecture. If the Keck architecture had been 'closed', there would have been no recourse but to live with the linear rates. Keck software is 'open' in that it provides a well-defined keyword layer (Conrad and Lupton 1993). This keyword layer presents a consistent application programmer's interface (API) for software developers (Lupton and Conrad 1993) and, significant in this case, provides access to system parameters (like tracking rates) to scientists and astronomers so that they can better support unusual observing modes. *Perspective for ELT* Foresee as many tracking and guiding capabilities as possible (e.g., integrated access to ephemeris web services (Giorgini et al. 2001; Berthier et al. 2006), and implement those capabilities properly in a software base that is well-tested and kept under strict revision control. But, in addition, provide an open software architecture like the Keck keyword layer (Conrad and Lupton 1993), so that operational staff members can provide those tracking and guiding capabilities for which a need was not foreseen.

## 4 Volcanoes on Io

During December, 2001, adaptive optics (AO) images of Jupiter's large (diameter over 3,600 km) volcanic moon, Io, were taken with NIRC2.[4] Observations were spread across 10 nights to achieve full rotational coverage. The result was a complete cylindrical map of Io's surface taken at high angular resolution in three filters (Marchis et al. 2005). The nearly diffraction limited performance of the AO system revealed surface features to a resolution of 150, 240, and 300 km, at the observed wavelengths (2.3, 3.8, and 4.7 microns, respectively). This rendering, which included 26 (two previously unknown) volcanic regions, was then presented as a rotating sphere in both a movie and an interactive applet (Le Mignant et al. 2003).

More recently, spectroscopy with Keck is being used to detect $SO_2$ frost on the surface of Io, presented as two broad absorption features in reflectance spectra (Laver and de Pater 2008).

Keck observations of Io often require observing modes developed specifically for that purpose. For example, some programs that require observing Io in eclipse, also require differential tracking between Io and a moon which is still sunlit and can be used for AO correction. *Perspective for ELT* Be prepared to support observing modes that were not anticipated during specification and design. Enable teaming between the support staff that understand the details of the system and the observers that understand the details of the science.

[4] Near Infrared Camera 2 (P.I. Keith Matthews) fed by the Keck II AO system (http://www.2.keck.hawaii.edu/inst/nirc2/)

## 5 Nix and Hydra

The ability to use AO to detect faint satellites around Kuiper Belt Objects (KBO) was demonstrated famously for the mass determination of bigger-than-Pluto (136199) Eris when its moon was discovered with NIRC2/LGSAO on Keck II (Brown 2005). Following the discovery (Weaver et al. 2006), of the two new moons of Pluto, Nix and Hydra, Keck (among other large telescopes equipped with AO) was used to search for the moons, which should have been detectable. But poor observing conditions and high airmass prevented detection of these faint (23rd magnitude) satellites.[5]

Following a recent upgrade to the wave-front controller (WFC), Pluto images obtained with Keck AO "exceed the sharpness possible with Hubble Space Telescope" (University of Hawaii Astronomer Takes Sharpest Picture of Pluto System 2007). The upgrade provides a higher limiting magnitude (see Fig. 1) and better performance at shorter wavelengths. The star trails in the stack of images shown in Fig. 2, totaling 3,100 s and taken at H-band, are 35 mas wide. All three moons are visible in this image, and the new WFC makes this type of detection more routine.

Pluto's 3 moons may have formed from debris produced by a giant impact into Pluto itself (Ward and Canup 2006). Confirming a 3:2 resonance for Nix and Hydra, with respect to one another, stands as one method for testing this hypothesis (Tholen et al. 2008). Such precise orbit determinations require precise astrometry. To map and monitor geometric distortion within the instrument, we regularly image a grid of pinholes. To map and monitor the distortion contribution from AO and telescope, we regularly observe star clusters.

Upgrades like the next generation wave-front controller enable exciting new science. *Perspective for ELT* Provide an organizational structure in which development teams stay engaged and can work with the science support staff to commission upgrades.

Accurate astrometry is the limiting factor for several high-visibility AO programs at Keck. *Perspective for ELT* Whatever astrometry accuracy is provided for imagers, be prepared to push it beyond that limit through continued calibration and monitoring.

## 6 The Resolved Asteroid Program

Using AO systems on the world's largest telescopes (Keck, VLT, and Gemini), we measure precisely the size, shape, and pole orientation of asteroids. Accurate size leads to an improved albedo measurement which is key to understanding composition. Accurate size is also crucial for estimating volume and hence density when the mass is known (e.g., from existence of a satellite). For example, our discovery of a satellite around (41) Daphne (Conrad et al. 2008a; Merline et al. 2008a), together with a more accurate volume estimate, has resulted in the first measurement of that body's density.

On a typical night, for four or more resolved asteroids, we measure the long and short axes, as seen on the plane of the sky, at six or more epochs spanning a complete rotation. In addition to size and pole, our measurement gives us tri-axial-ellipsoid shape. But, increasingly, we see irregular shapes (see Fig. 3).

Knowledge of the shape can provide evidence of large impacts. For example, our analysis of a large facet on (511) Davida (Conrad et al. 2007) includes a statistical argument that impact by an approximately 8 km object is consistent and possible (see

[5] See http://www.boulder.swri.edu/plutonews/

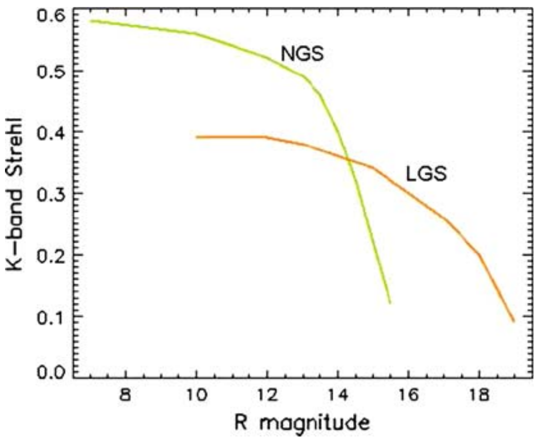


**Fig. 1** Strehl versus magnitude for the Keck next generation wave front controller. The *curves* labelled NGS and LGS indicate natural and laser guide star modes, respectively (van Dam et al. 2007)

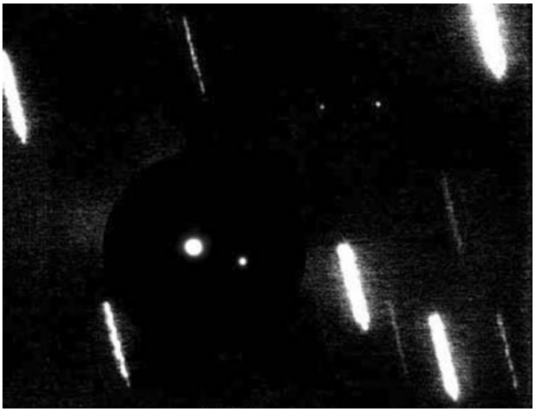

**Fig. 2** Stack of images totaling 3,100 s, taken with the Keck next generation wave front controller and NIRC2, of Pluto and its three moons (University of Hawaii Astronomer Takes Sharpest Picture of Pluto System 2007; Tholen et al. 2008)

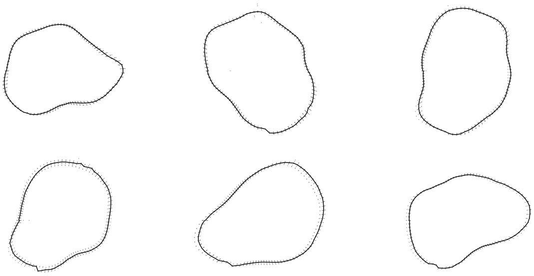

**Fig. 3** Contours of (41) Daphne determined from Keck AO images taken during March 2008, as it rotates (Conrad et al. 2008b)

Fig. 4). Response to impact, indicated by a body's shape, assists in determining composition and structure (Housen et al. 1999).

Of those main belt asteroids (MBA) that can be resolved with today's 8–10 m telescopes, approximately 10 have satellites, which can be used to determine mass, and hence density. The density of a body allows us to make inferences about the composition and structure of the interior of the asteroid. We can also compare asteroids of the same or different classes to see if they might have the same or different composition/structure. This

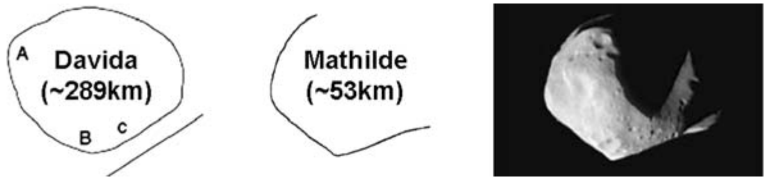


**Fig. 4** Contour of (511) Davida measured with Keck AO (*left*) and close-up image of (253) Mathilde taken by the NEAR spacecraft (*right*). The *center* sketch gives a contour of Mathilde to guide the eye in comparing the two results. The A and B promontories and c facet indicated for Davida are those assigned by the authors (Conrad et al. 2007). Object diameters are given in *parentheses*

**Fig. 5** Discovery image of a small moon of (41) Daphne (Conrad et al. 2008a; Merline et al. 2008a)

helps us infer a possible composition/structure for objects for which we do not have direct density measurements (because of no satellite).

In March 2008, we discovered a small satellite to Daphne at Keck (Conrad et al. 2008a; Merline et al. 2008a) (see Fig. 5). The unusually short period of the satellite (approximately 1.1 day), and the estimated size of the primary (239 $\times$ 183 $\times$ 153 km), lead to a density near 2.0 g/cc. This is significantly higher than most other large C-types with densities determined from the presence of a moon (Merline et al. 2002).

One of the peculiarities of this object is its highly irregular shape. Because of the surprising density result, and because we expect to derive an accurate volume from our data, we are placing special emphasis on our size and shape determinations. We plan to apply several methods of determining the volume, including: tri-axial ellipsoid fits, detailed shape modeling, and improving estimates by using existing light-curve information. For future 30-m telescopes (ELT), the number of objects that can be studied in this way will grow from approximately 10 to well over 100.

Most recently (Aug 8, 2008), we used Keck AO to image Near Earth Objects (NEO). These include a resolved near-Earth asteroid, 2004-XP14 (Busch et al. 2007), a binary NEO (see Fig. 6) (Merline et al. 2008b), and a faint NEO (188452) that required use of the laser. Tracking fast moving objects requires special attention to how the telescope and AO control systems "shake hands" to coordinate tip-tilt correction (E. Johansson et al., personal communication, 2004).

With triple the aperture, ELT MBA resolution will improve to 14 km (from approximately 42 km currently achievable with Keck). For NEOs, ELT will resolve to about 20 m on the surface, down from Keck's 60 m. *Perspective for ELT*: Be prepared to observe fast (up to one arcsecond/second) moving objects in all observing modes (including appulse and laser for faint objects).

With nine times the light gathering capacity, the number of objects that can be covered in survey programs (e.g., searching for asteroid satellites) will be overwhelmingly

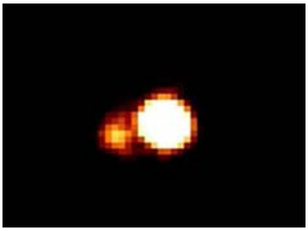

**Fig. 6** Binary NEO 1991VH imaged with Keck AO (Merline et al. 2008b)

dominated by slew and read-out time. *Perspective for ELT*: Minimize both to take advantage of increased aperture.

## 7 Conclusion

In the discussion above we have provided nine perspectives to be considered by the future designers of ELT. These nine fall into two broad categories: specific, technical suggestions, for example detector read-out speed to accommodate time-resolved photometry; and broad structural suggestions, for example, open software architecture and post-commissioning teaming for upgrades. Solar System specific features should not be dropped from requirements documents because they are, from the outset, seen as too difficult or expensive to implement. Keeping the requirements on the books will ease implementation down the road, after the crush of "first light" pressures has passed and the scientific staff settle down to conduct the fantastic Solar System research that will be enabled by telescopes with 9–16 times the collecting area and 3–4 times the angular resolution available from current-generation, large telescopes.

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