ENSURING KECK IS READY TO REALIZE THE WEALTH OF TRANSIENT SCIENCE COMING IN THE NEXT DECADES

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ABSTRACT

The landscape for astronomy will undergo significant changes in the next 10-15 years. With ambitious NASA missions and at least one extremely large telescope, Keck will be able to have an important scientific advantage in this landscape. Notably, Keck will provide deep spectroscopy across a broad wavelength range on a frequent and regular basis. Transient objects, such as the time varying cores of active galactic nuclei, supernovae, tidal disruption events, kilonovae, or fast radio bursts, will all need spectra over a broad wavelength range at moderate resolutions. What Keck offers is the ability to observe these targets on a 10m telescope night after night, a critical component to understand the time evolution of time-varying objects. This white paper provides a list of required improvements to Keck Observatory that will allow the Observatory to stay at the forefront of the field. The key components are 1) stable, high throughput spectrometers that can acquire data across a broad wavelength range, 2) the ability to switch rapidly between instruments during a night, 3) the operational ability to support frequent, regular observations, 4) the ability to rapidly acquire new targets, and 5) the highest image quality possible to ensure the most efficient collection of light. With K1DM3, Keck I already has the technical capability to quickly switch between different instruments, but the facility will need to ensure that this is matched with the operational ability to rapidly switch between programs. Planned upgrades to existing spectrometers and ground-layer adaptive optics (GLAO) using adaptive secondary mirror will provide the stable spectrometers with excellent image quality. With these capabilities in place, Keck will not only rapidly follow-up new discoveries but watch them evolve over time.

1. THE SCIENCE NEED

By the year 2035, the Rubin observatory will have been producing tens of millions of transient object alerts for more than a decade. As the initial survey will be in its final years, it will have a highly tuned algorithm for finding the most interesting and unusual objects. At the same time, CMB-S4 will be detecting time-varying objects in the millimeter range, including afterglows from the events that normally yield gamma-ray bursts. Numerous interferometric arrays will be operating to detect and rapidly localize fast radio bursts. LISA is planned to be launched in 2034, and the IceCube-Gen2 will have been working for another decade. All of this points to a collection of observatories that span a large range in energy and physics which will produce detections of some of the most astrophysically extreme events in the universe. Rapid follow-up imaging will be available across a wide variety of facilities beyond the Rubin Observatory, potentially including the Keck Wide-Field Imager. What will be a unique challenge will be obtaining high-quality spectra of these objects.

All three extremely large telescopes (ELTs) plan on having moderate field of view, single order spectrometers at first light. At the same time these three facilities are planned to come online, many 8-10 m telescopes will have equivalent instruments that are 35 years old, assuming they have not decommissioned them entirely. The question becomes, what will be the strategy for acquiring the data needed to dissect these events. In the case of supernova, for example, the evolution of the spectra provide clues about the surrounding medium, evidence for nearby companions, details about the symmetry of the explosion mechanism, and indications about the progenitor. Thus, a single spectrum from one of the ELTs for such an event will not be sufficient.

As an example, consider the case of SN 2008D[3]. This was a moderately bright and nearby supernova that showed a shock breakout, clear evidence of the interior event bursting through the surface of the star. Of the 30 spectra, some of the key data are the early observations which show rapid evolution in the near-UV, and those spectra were taken with a variety of 8-10 m facilities such as the MMT, GMOS and DEIMOS on Keck II. During the normal evolution of the object, a vast array of spectra were acquired from telescopes ranging in size from 2 to 6.5 m. Then, critically, SN 2008D was observed with Keck I LRIS several months later. These late-time data show evidence of asymmetries in the ejecta, providing a complete picture of non-spherical nature of the event. This was a bright supernova, discovered with the KAIT 0.75m telescope at Lick Observatory, yet spectra from 8-10m telescopes were critical for understanding the evolution of the object. SN 2008D is not an one-off object. Overall, LRIS is currently on the Keck I telescope for $\sim$100 nights a year. Roughly $\sim$40% of the science exposures made with LRIS are made with a long slit[4]. This shows the importance of single object spectroscopy of rare objects for one of the most scientifically productive instruments at Keck.

Future facilities will be finding new and fascinating objects at much fainter magnitudes. The Rubin Observatory has 80 times the collecting area as the KAIT. How will the community observe the discoveries from these facilities, especially

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[3] Modjaz *et al.* 2009, ApJ, 702, 226.
[4] 42% of LRISB and 43% of LRIS red exposures that are >300 seconds long and on sky are taken through a long slit. This is based on the publicly available LRIS FITS header keywords provided by KOA on February 22, 2021. This is roughly 4300 hours of total exposures since LRISB was installed.

as they rapidly evolve in time? The ELTs will obviously take spectra, but will they be able to take spectra quickly, night after night over the course of months, as required to truly understand the unique discoveries that are awaiting us?

2. WHAT WILL THE FUTURE REQUIRE?

A future with multiple ELTs will still have a huge role for a high throughput, flexible observatory like Keck with two 10 m telescopes. The time evolution of active galactic nuclei, fast radio bursts, mm-wave transients, gravitational wave sources and all of the fascinating objects that will be discovered with optical domain data alone, will require facilities that have the ability to acquire data with a predictable cadence in a flexible manner. In order to be scientifically useful, the data will need to be of the highest quality possible.

2.1. *High-Throughput, Single-Order Spectrometers*

The core requirement is stable spectrometers with high throughput so that the observing time is used as efficiently as possible. High throughput is best done by using the Cassegrain focus, as that uses one fewer mirror, and the Cassegrain focus of Keck I has an atmospheric dispersion corrector. The natural spectrometers for characterizing these new discoveries will be LRIS and MOSFIRE. Both are the highest throughput in the optical and near-infrared passbands. In 2035, for single object spectroscopy, these will still be among the most important instruments. FOBOS will be excellent for this science because of its near-UV to near-IR passband and highly flexible observing architecture. It will never have the highest throughput, by design, and so will always be less likely to follow-up rare and unusual objects. LRIS, because of its age, has a throughput that will be only slightly higher than FOBOS. With modern dispersive elements and improved optics, however, LRIS could become much more efficient, more than 50% better than it is today.

2.2. *Stable Instruments*

Stability impacts the ability of the instrument to place a wavelength at a consistent location and, as the object moves across the input aperture, decreases the image quality. To use effectively a GLAO system, we require highly stable spectrometers in order to ensure that the image quality is as high as possible. There is also a secondary need. An unstable spectrometer means that calibrations must be acquired in as close configuration as possible to the one used for acquiring the data. This prevents having the data in a timely manner, or even interrupts science operations. This can prevent other facilities from having the data required to trigger additional follow-up. MOSFIRE and DEIMOS both show that, when correctly designed, a spectrometer can yield science quality data with calibrations taken at only the start of the night, but LRIS is clearly not sufficient to this requirement.

2.3. *Flexible Observing and Rapid Instrument Changes*

The need for a cadence follow-up system for Keck Observatory will be necessary to ensure that we achieve the maximum possible science results from the KPF and HISPEC instruments. This same kind of cadence system will be critical for the study of the vast number of transient objects coming from future facilities. Flexibility will mean that the Keck telescopes can be first on a target using a ToO, but a cadence program will mean that the Keck Observatory can take the second, third or fourth spectrum which, in the past, was critical for watching an object evolve. K1DM3 means that Keck I has the technical capabilities, but Keck Observatory will also need to implement the operational capabilities as well. For Keck II, FOBOS presents a wonderful opportunity. By design the instrument will be able to flexibly target a variety of sources in on-demand manner. Huge numbers of time-varying objects can be observed for demographic surveys on a nightly basis. This provides a practically unique resource for understanding the output of observatories such as Rubin and Roman.

2.4. *Rapid Acquisition*

Placing the target as quickly as possible on the input aperture obviously increases the efficiency of the observing program. This is a general need, as multi-slit programs can use this as well, and historically decreasing acquisition time has been a strength of Keck operational staff. What will be required to speed this up will be an accurate mapping between the position of stars in the acquisition / guide cameras and the input aperture of the instruments. Once again this will require stability in the instruments. Having the slit in effect move with respect to the guider, as happens with LRIS and possibly DEIMOS, prevents rapidly offsetting to the target.

2.5. *The Best Image Quality Possible*

Currently the telescope focus is measured a few times a night. Thus most of the data is not taken with the best quality images because measuring the telescope focus requires a significant amount of time. At minimum, wave front sensors that measure the correction required would eliminate the need for focus measurements. This will both decrease the time lost on instrument focus and, at the same time, ensure that the image quality is always the highest possible. However, multiple wave-front sensors along with a deformable secondary would vastly improve the seeing for Keck instruments, even in the visual pass-band. Ground-layer adaptive optics (GLAO), which will be discussed in a separate white paper, has the potential to effectively double the aperture of the Keck telescopes by halving the typical seeing in the red-optical and near-infrared. To observe the faint targets that will be detected by future facilities, we will need to make the Keck telescopes as "big" as we can, which GLAO has the potential to do. A number of technical requirements must be met. All of this must be robust and reliable every night or it will not meet the needs of the high cadence operational scenarios envisioned.

3. CONCLUSION

We have presented an outline of a set of capabilities that will ensure that the Keck Observatory's two 10 m telescopes will be powerful workhorses for transient science. Keck II has a planned, highly-efficient and flexible spectrometer in FOBOS that will enable large demographic studies of time-varying objects. Keck I is equipped with high throughput spectrometers and a flexible tertiary mirror to rapidly switch between instruments. LRIS, however, needs a significant upgrade to both increase its throughput and stability. Once its stability matches MOSFIRE, the two will provide an excellent pair for monitoring rare and unique objects night after night, especially when coupled with GLAO. Finally, the Observatory must embrace a new operational model for KPF and HISPEC that allows nightly cadence observations. Extending this for science driven programs to observe transients will only further increase the impact of Keck observations.