MRI: Development of a deployable tertiary mirror for the Keck I telescope

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2. PROJECT SUMMARY

Background: The 2010 Astronomy Decadal Survey noted the growing primacy of time-domain astronomy (TDA) as a central theme for some of the most challenging modern pursuits both past and future. The discovery of the accelerating universe, for example, made use of repeated imaging and spectroscopic observations of distant Type Ia supernovae. The treasure trove of discovery and physical insight into extrasolar planets required high-resolution synoptic spectroscopy. The characterization of the black hole at the center of the Milky Way required repeated adaptive optics imaging of the surrounding stars. All of these are great triumphs for US astronomers, enabled in large part by the Keck telescopes.

Time-domain observations will continue to serve as the backbone framework for 21st century astrophysics. Wide-field imaging at all wavelengths (radio, optical, γ-ray) demonstrates that the universe is highly dynamic, with variability on all time-scales. Of great interest are exploding stars, black hole mergers, eclipsing planets, gravitational microlensing events, and flaring sources, all of which stem from a diverse set of astrophysical processes. Central to resolving the astrophysics of these events is high-precision spectroscopy and imaging, ideally at high cadence. Such observations demand the use of large-aperture telescopes; but, while the most suitable instruments at a given time may exist for a telescope, unless those instruments can be rapidly deployed, the inherent inefficiency will weaken the scientific returns. Indeed, the growing demands for precious follow-up time using the world's largest telescopes conflicts with the classical approach of telescope allocation: one night, one instrument. Clearly, a more nimble approach that is receptive to the needs of the observing community is urgently required.

Proposed Activities: The aim of this proposal is to build a new tertiary mirror (M3) and its mount for the 10 m Keck I (K1) telescope at the W.M. Keck Observatory (WMKO). In contrast to the existing tertiary mirror and mount, the device will rapidly deploy and rotate the mirror to any of the instruments at the Nasmyth focus or, as desired, stow the mirror out of the light path to permit observations at the Cassegrain focus. In this manner, the K1 deployable tertiary mirror (K1DM3) will enable observations with any of the K1 instruments on any given night, and at any given time. This capability is critical to maximizing the science return in the TDA era. The K1DM3 device will be integrated within the K1 telescope control system and WMKO has committed to a new operations model that takes full advantage of this new capability.

Intellectual Merit: Bringing the routine use of K1DM3 to Keck will enable the effective and efficient study of time-critical Solar System events, the analysis of stellar atmospheres, the monitoring of stars orbiting the Galactic center, and the discovery of the most distant explosions in the universe. The astrophysical processes explored via these phenomena include the tidal disruption of compact objects, the explosion mechanisms of stars at all masses, gas accretion and planetary dynamics. The installation of K1DM3 will further position the WMKO community to play a leading role in follow-up observations of gravitational wave events.

Broader Impacts: The proposed device will enable PhD and postdoctoral research from throughout the WMKO community in this forefront area of time-domain astronomy. The two Keck telescopes are the most scientifically productive telescopes in the U.S. observing system. WMKO maintains scientific leadership for a large user community by innovating and deploying pioneering instrumentation and this proposal seeks to continue this tradition through development of a deployable tertiary that will enhance WMKO's ability to serve the U.S. community through NASA's partnership in WMKO and through the NSF/NOAO TSIP program, in addition to serving astronomers at the University of California (UC), the California Institute of Technology (CIT) and University of Hawaii (UH). The list of astronomers who made use of WMKO for their theses includes many of the emerging and mid-career leaders in U.S. astronomy. WMKO is currently providing many graduate students and post-docs direct access to the state-of-the-art instrumentation, adaptive optics capability, and the Keck Interferometer.

3. PROJECT DESCRIPTION

3.a. Instrument Location and Type

Instrument Location: The Keck I Telescope at the W. M. Keck Observatory (WMKO) on the summit of Mauna Kea, Hawaii.

Instrument Code: MRI-49.

3.b. Research Activities to be Enabled

3.b.1. Background

A major thrust of astronomy in the 21st century is to study, observationally and with theoretical inquiry, the variable night sky. This area is broadly referred to as time domain astronomy (TDA) and its high scientific priority was established by the Astro2010 report (National Research Council, 2010). Their highest recommendation for large telescope ground-based observing, for example, is to build the Large Synoptic Survey Telescope (LSST). In advance of that ambitious project, several projects are using wide-field cameras to image large areas of the sky at high cadence. This includes the NSF-sponsored Palomar Transient Factory (PTF) and the Pan-STARRS surveys which repeatedly image the full northern sky, finding hundreds of new transient phenomena on every clear night. These surveys are discovering *thousands* of supernovae, immense samples of asteroids and near-Earth objects, variable stars of diverse nature, flaring phenomena, and other exotic sources. These advances in TDA observing at optical wavelengths follow decades of TDA science performed at higher energies from space. Indeed, the first astronomical sources detected with γ−rays were themselves transient phenomena: the so-called γ−ray bursts (GRBs; Klebesadal et al., 1973). Satellites like *Swift* and *Fermi* monitor $\approx\pi$ steradians of the sky at any time, scanning for transient and variable high-energy events.

The focus of most previous and on-going TDA projects has been wide-field imaging of the sky in search of rare and new classes of events. In part, this is because the phenomena are relatively rare. To fully explore and exploit the astrophysics of newly discovered sources, however, one must obtain spectroscopy, at the highest resolution possible. And, despite the wavelength at which the event was detected, optical spectroscopy remains the most powerful and efficient passband to perform the spectroscopy. This is the primary role of large, ground-based observatories in TDA science. Recognizing their value, several 8 m-class observatories have established very effective observing strategies (generally at great expense) to perform such science. Both the Gemini and European Southern Observatories (ESO) designed their largest telescopes with systems that could rapidly feed any of the available foci. Furthermore, they have designed queue operations to enable rapid responses to targets-of-opportunity (ToOs) and programs that repeatedly observe a source for short intervals at high cadence. Successes of this model include time-resolved spectroscopy of varying absorption lines from a GRB afterglow on minute time-scales (Vreeswijk et al., 2007) and high-cadence monitoring of the Galactic center to recover high fidelity orbital parameters (e.g. Gillessen et al., 2011).

WMKO boasts twin 10 m telescopes, currently the largest aperture ground-based optical/IR telescopes on Earth. Over the course of the past ~20 years, we have successfully instrumented each telescope with high-throughput imagers and spectrometers spanning wavelengths from the atmospheric cutoff to several microns. The Keck I (K1) telescope hosts the Nasmyth mounted HIRES spectrograph (Vogt et al., 1994), one of the primary tools for obtaining high resolution visible wavelength spectra from TDA observations. K1 also hosts the Nasmyth mounted Keck I adaptive optics (AO) system which is receiving a laser guide star (LGS) upgrade and will soon host the near-IR integral field spectrograph OSIRIS (Larkin et al., 2006), a key tool for synoptic observations of the Galactic center. At Cassegrain K1 hosts both the LRIS multi-object visible wavelength spectrograph (Oke et al., 1995), and will soon be home to the near-IR multi-object spectrograph and imager MOSFIRE (McLean et al., 2010). Presently, K1 is highly sub-optimal for the emerging field of time domain astronomy; instrument scheduling follows classically-based observing programs (i.e., one PI astronomer and one instrument per night) and is further restricted by the requirement to remove and install the tertiary mirror module in order to switch between Nasmyth and Cassegrain focal stations. For ToOs, this often means a mismatch between the scientific need and the available instrument. Furthermore, it is essentially impossible to design an observing campaign to study a set of objects at high cadence (e.g., every night for several weeks). The K1 deployable tertiary (K1DM3) will directly address these failings. Its installation enables a tremendous set of observing programs with scientific impact ranging from cosmology (e.g., the reionization of the universe at z~7) to the Solar System.

3.b.2. Science Topics

3.b.2.1. Targets of Opportunity (ToOs)

There are a small but extremely valuable set of astrophysical phenomena that appear and then disappear on time-scales of hours to days. These transient events include the deaths of massive stars (GRBs), the flares from tidally disrupted stars, and the chirps of merging compact objects. These sources are random both in time and position on the sky and therefore require one to interrupt any planned observations to capture their fleeting light. Only with K1DM3 would one have the flexibility to match the proper instrumentation with the event and thereby fully reap the science. We now discuss a few examples.

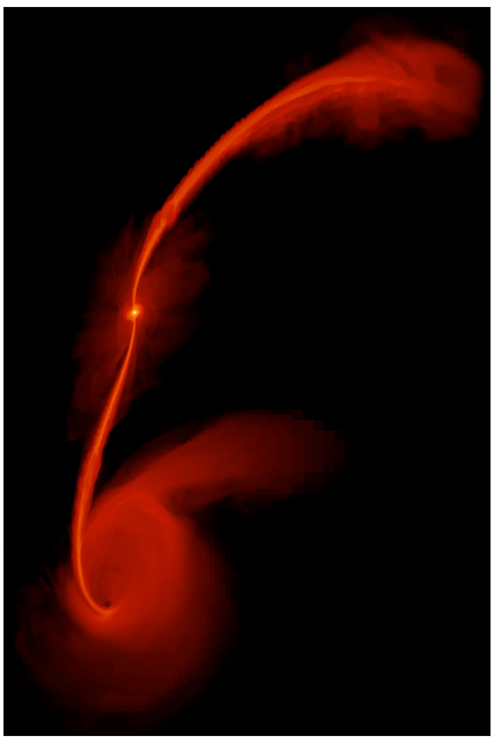

Figure 1: Disruption of a solar-mass star by a 10^6 M_{Sun} black hole where the star survives the encounter. In the tidal disruption of a star by a black hole, roughly half of the ejected stellar mass becomes bound and falls into the black hole, while the other half is ejected at high velocity. The emergent radiation may have a strong dependence on the structure and orientation of the accreted bound debris.

Tidal Disruption Flares: In the past few years, astronomers have detected probable flares arising from stars that were tidally disrupted by a massive black hole (MBH) at the center of nearby galaxies (Figure 1). In these events, the emission is dominated by the UV/optical light arising from the fallback accretion of the stellar bound debris. Ongoing optical and high-energy experiments and future radio observations are predicted to discover 10 to 100 such events per year, each fading on timescales of days to weeks. Follow-up observations with the suite of K1 instruments would precisely establish the position of the source and provide spectral diagnostics of the emission, which helps elucidate the demography of massive black holes in the local Universe. These observations test Einstein's theory in the strong field regime, to check whether space-time around such objects obeys the metrics of Scwarzschild and Kerr.

Gravitational Waves (GWs): If the merger described above had involved two MBH's, the primary emission would have been gravitational waves. Indeed, funded upgrades to the LIGO experiment should achieve sufficient sensitivity to provide direct detections of such events by the year 2018. Discovery and exploration of the electromagnetic (EM) counterparts to gravity wave events using K1DM3 is crucial on two fronts in that it will allow: 1) rapid spectroscopy on a number of EM candidates across a large (disconnected field) with little notice, and 2) efficient repeated observations of the most likely counterpart as it fades beyond detectability for other smaller aperture telescopes.

Including PI Prochaska and collaborator Bloom, we expect significant investment of Keck users in pursuing the GW-EM connection. Starting in 2015 (culminating with full sensitivity in 2018), GW events from the merger of stellar mass remnants are expected to be readily detectable by Advanced LIGO (funded by the NSF), and upgraded VIRGO, and the Japanese LCGT. At advanced sensitivities for a three detector LIGO-Virgo network, predicted "realistic" event rates range from several tens to hundreds of sources per year (Abadie et al. 2010). Because the localizations of such events will be poor (20-100 square degrees at 90% confidence; Fairhurst 2010), wide-field imaging surveys (e.g. PTF2, SkyMapper, LSST) will be used to identify potentially dozens of possible optical candidates and spectroscopic follow-up will be critical to confirm candidates.

Identifying the precise position via an EM counterpart is critical for breaking degeneracies inherent in the chirp signal (Nissanke et al. 2009) and understanding the nature of the progenitors/surroundings of the event. Importantly, since GW signatures encode luminosity distance but not redshift, an EM counterpart enables the use of such events as precision standard sirens (Schutz 1986, Holz et al. 2005, Dalal et al. 2006). Independent of the cosmological distance ladder and other systematics that plague traditional standard candles, the possibility of measuring H_0 to a few percent accuracy, with only an appeal that General Relativity correctly describes the GW emission and evolution, is a compelling impetus. Precisely *what* will be seen in the EM sector is not known for sure. GW event rates are informed by a potential connection to short-hard gamma-ray bursts (SHBs; see Bloom et al. 2006) which implies a coincident afterglow event. Such afterglows within the LIGO volume would be bright initially (R~18 mag for the first 10 minutes) but then fade rapidly as t^{-1} to t^{-2}.

Regardless of whether a NS-NS merger produces a SHB and irrespective of the binary's orientation, there are strong theoretical motivations to believe that a short-lived (peak of -14 mag after 1 day) event is inevitable. This should look like a mini-supernova at broadbrush but different in the timescales, color evolution, and spectral signatures (see Metzger et al. 2010 for a recent treatment). At a typical Advanced LIGO distance (250 Mpc), this means we expect an R~23 mag event at peak. There could also be a prompt signature (not associated with relativistic outflow producing a GRB) but the details of these signatures have not yet been explored. Obtaining a dense spectral sequence of such an event would be unprecedented, not only yielding insight into the origin of GW events but also a new vista on r-process nucleosynthesis.

GRBs: The most active area of ToO science is the study of gamma-ray bursts (GRBs). In addition to the brief emission of γ-rays that announce these events, the majority of GRBs exhibit afterglows of longer wavelength emission. In the optical (typically the rest-frame UV for the GRB), the afterglows have peak apparent magnitudes of ~16(20) mag for the long (short)-duration events at t ~10 min fading rapidly (Figure 2). It is critical, therefore, to observe these events during the same night that they are discovered.

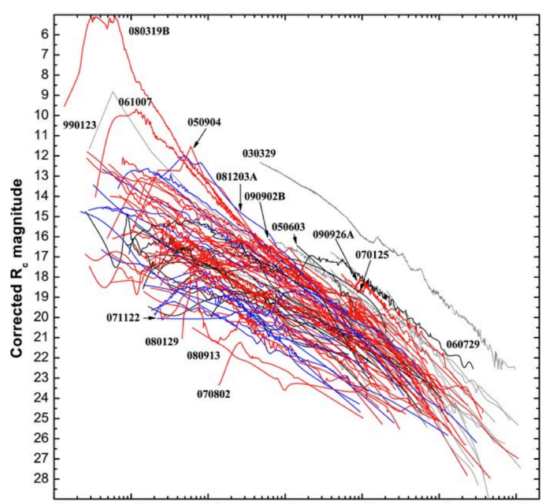

Figure 2: GRB light curves in the optical demonstrating the extreme brightness of these events and their rapid decay times (from Kann et al., 2011).

At WMKO, the primary ToO activity for GRBs is to obtain high-fidelity spectra of these afterglows. Indeed, the spectrum that first and firmly established that long-duration GRBs are extragalactic sources came from a Keck/LRIS spectrum (Metzger et al., 1997). Modern programs of GRBs pursue a wide range of scientific goals that include (i) constraining the physical properties of the gas within the high z, star-forming galaxies that host the events (e.g. Prochaska et al., 2007, 2008; Fynbo et al., 2009); (ii) analyzing the intergalactic medium in a complementary manner to traditional quasar spectroscopy (e.g. Prochter et al., 2006); (iii) exploring the epoch of reionization (the z>7 universe; Kawai et al., 2006; Tanvir et al., 2009); and (iv) establishing the energetics of the GRB population (e.g. Butler, Bloom, &

Poznanski 2010). For the short-duration GRBs, the community still awaits the first optical spectrum that would likely confirm their extragalactic nature and hopefully give fresh insight into their origin.

The principle gain of K1DM3 to GRB ToO observations would be to match the afterglow brightness and color with the appropriate instrumentation on K1. Ideally, one would observe V<18mag sources with Keck/HIRES to optimally resolve the many absorption lines associated with the GRB host galaxy. For sources at z>6 (or highly reddened events), near-IR spectroscopy is essential and MOSFIRE is the preferred instrument. Lastly, the faintest optical sources (R~23) demand the high throughput of LRIS. Experience over the past decade has shown that WMKO has missed out on several fundamental discoveries (e.g. the GRB at z = 8.2) due to a mismatch between the GRB properties and the night's instrumentation. With K1DM3, one would optimally match the properties of any ToO to the instrument suite, perform the ToO, and then quickly return to the original observing plan for that night.

Microlensed Stellar Spectroscopy: The OGLE and MOA surveys monitor more than 100 million stars in the Galactic bulge. Together they issue about 800 alerts for microlensing events a year. A small fraction of these (roughly 10 events/year) have maximum magnification (brightness amplification) factors in excess of 100, which boosts the brightness of a normal bulge dwarf into the range accessible to high dispersion observations with the Keck Telescopes. This offers us a new window into the Galactic bulge stellar population in which one trades the high magnification factors making the bulge stars temporarily much brighter against the difficulties of carrying out ToO observations.

These ToO programs provide very high S/N echelle spectra on sources that would otherwise be too faint for analysis (e.g. Cavallo et al., 2003; Johnson et al., 2007; Cohen et al., 2008). Efforts to date have focused on dwarf and subgiant stars of the Galactic bulge, with intriguing new results demonstrating (1) the abundance ratios of the bulge dwarfs follow closely those of the Galactic disk and (2) a surprising double-peaked metallicity distribution function, including an apparent correlation between metallicity and microlensing magnification (Cohen et al. 2010; Bensby et al. 2011).

Although the first measurements were made with HIRES on K1, the field is now dominated by the VLT owing to its well-established support of TDA observations. The installation of K1DM3 would bring Keck back into the fore-front of this research and our community would be poised to leverage upcoming high-cadence, wide-field imaging surveys. ToO programs could expand from analysis of Galactic bulge stars to stars throughout the Galaxy or even to other galaxies of the Local Group.

3.b.2.2. Cadence Observing

Traditional scheduling of time at WMKO is in increments of one-half to a whole night on each of the telescopes. For the standard allocation of a given PI, this implies only a handful of opportunities to observe a given object each year. However, for some sources there is tremendous scientific value in taking a series of observations across a short time-scale (days to months). Such high cadence observations are nearly impossible with K1, in part because classically scheduled observing demands that the instruments are changed weekly.

Galactic Center (GC): In 2018, the brightest star (SO-2) known to orbit the $\sim 10^6$ solar mass MBH at the Galactic center will reach pericenter. During the few months when the star swings around the MBH, it will offer a tremendous opportunity to empirically constrain properties of the black hole and our galaxy (e.g. our Sun's distance to the center), and to test GR in a unique portion of parameter space. At that time, OSIRIS on K1 will be the premier instrument to perform the experiment; using K1DM3 astronomers could observe the GC every clear night during the passage.

Exoplanet research: Extrasolar planets present another class of extremely exciting opportunities for the K1DM3. Of particular importance are high-resolution spectroscopic observations taken during the rare, precisely timed transits of eccentric long-period planets. By measuring the so-called Rossiter-McLaughlin effect (Figure 3), one can infer the projected degree of misalignment between the planetary orbital angular momentum vector and the spin pole of the star -- information that provides vital clues to these systems' intriguing dynamical histories. Furthermore, there are a number of key multiple-planet systems (such as those orbiting the nearby M-dwarfs Gliese 436, Gliese 581, and Gliese 876) whose characterization and orbital phase coverage can be dramatically improved by Doppler velocity measurements obtained at optimal, pre-determined, and highly specific times. With K1DM3, the HIRES spectrograph on Keck can be made available for these critical measurements when the need arises.

The WMKO planet-hunting teams also suffer from serious aliasing problems caused by the lunar synodic frequency, which makes it particularly difficult to pin down periods near 1 month or integral multiples of a month. These periods are especially important as they are similar to the periods of potentially habitable planets in habitable zone orbits around M-type stars. There are several exciting (unpublished) systems whose orbits beat awkwardly with the synodic lunar period, making it difficult to achieve complete phase coverage. With occasional access to phases at other times of the lunar month, it would be straightforward to confirm these orbits, and with much less overall Keck observing time. A simple 10 minute observation a few times/year at times other than bright of the moon would suffice.

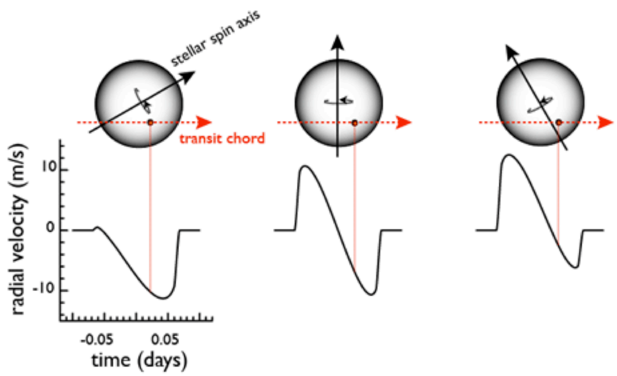

Figure 3: Schematic diagram that illustrates the Rossiter-McLaughlin (RM) effect. RM observations during planetary transits are currently generating a great deal of excitement in the exoplanet community because they give unique information regarding the dynamical configuration of the star-planet system. Precise scheduling of the HIRES spectrograph is required in order to obtain these measurements.

Finally, even for candidates with non-aliased, low-eccentricity orbits, it would be a great benefit to spot-check the predicted orbits when particularly interesting or low-mass solutions emerge. With occasional access to 10 or 20 minutes/night, one could select the highest priority, most promising cases and quickly verify their nascent orbital solutions. If confirmed, then regularly scheduled time can be efficiently used to constrain the solution with increased observing cadence. If not, the star could be dropped in priority until a better solution arose. In short, "cadence" observations with K1DM3 would enable the detection of fascinating new planets with orbits that challenge traditional scheduling and greatly improve the efficiency of detection and follow-up analysis.

Monitoring Variability in SNe Spectroscopy: Despite the remarkable progress made to date in utilizing SNe Ia to constrain the cosmological model of the Universe, there is still no single satisfactory theory for their progenitor systems. SNe Ia are thought to arise via the thermonuclear explosion of a CO white dwarf (WD) which approaches the Chandrasekhar mass limit as it accretes material in a binary system. But the accretion mechanism is as unclear as the nature of the explosion (Livio 1999; Hillebrandt et al. 2000). The merging of two WDs may better reproduce the observed SN~Ia rates (Pakmor et al. 2010; Fink et al. 2010), but apparently some SNe Ia explode with masses significantly above the Chandrasekhar limit (Howell et al. 2006; Silverman et al. 2011). Quite possibly there are several routes to the production of a SN Ia event. Understanding the various channels and their dependence on the local environment is key not only to our physical understanding of stellar evolution, but also to our confidence in calibrating the use of SNe Ia in cosmology.

Even in the case of the SN2011fe, the most nearby SN Ia in decades, the progenitor system of these explosions continue to elude detection, despite sensitive, multi-color pre-explosion images from HST (Li et al., 2011). Instead, future progress appears to require an indirect approach, in particular by studying how the supernova interacts with the circumstellar environment. High-resolution optical spectroscopy of several recent nearby SNe Ia has revealed variability in the absorption profile of the Na D line, likely due to photoionization (and subsequent decay) of material ejected from the companion star via a wind (Patat et al. 2007, Simon et al. 2009). Based on the relatively low expansion velocity (coupled with the lack of X-ray and radio detections), these authors inferred that the companion star must be a red giant to account for the dense circumstellar environment.

Such high-resolution studies, however, have only been reported for a small handful of SNe~Ia, and most were selected in large part due to their high line-of-sight extinction. A proper survey would examine a large sample (~ 20) of nearby SNe Ia, including SNe~Ia from many different environments (ellipticals vs. spirals, extinguished vs. nonextinguished, intrinsically bright vs. faint). At present, the single dominant factor limiting our progress is the lack of regularly available access to HIRES. Ideally one would obtain spectra on a ~ weekly basis but the current operation leaves large (several week) gaps in coverage when the variability evolution is expected to be strongest. Installation of K1DM3 would enable an optimized experiment.

3.b.2.3. Flexible Observing (and Scheduling)

Time-Critical Observations: There is already a diverse set of programs being carried out at WMKO that are time-critical, i.e. require observations on a specific night, often to the precise minute. These include imaging and spectra of `once-in-a-lifetime' Solar system events (de Pater et al., 2008) as well as programs coordinated with coeval observations from ground and space (Eckart et al., 2009). With K1DM3, these time-critical events could be captured on any night with any K1 instrument.

High-Elevation Targets: There are a number of valuable targets and fields that lie just at the edge of WMKO's grasp, e.g. the Galactic Bulge, GOODS-S. Because these can be viewed for only a few hours per night, programs that study them are either artificially expanded to include other targets or share the nights with other teams. Again, K1DM3 would provide additional flexibility to schedule and perform such observations throughout each semester.

Optimizing to Observing Conditions: Another common usage of K1DM3 would be to maximize observing efficiency by matching programs to the current observing conditions. WMKO would not transition toward a full-queue scheduling -- there is neither the funding nor sufficient community interest -- but we would establish a poor weather/seeing queue that observers could turn to on challenging nights (e.g. RV spectroscopy of bright stars with HIRES). By the same token, one could schedule AO observations that took advantage of the most stable nights with high-quality seeing. These are only some of the logistical 'use cases' -- coherent and cost-effective strategies will be generated by WMKO and its partners to make best use of this added capability.

3.b.3. Personnel

The WMKO community includes a large and growing number of astronomers with expertise in TDA science. Indeed, our researchers are recognized as the first to spectroscopically confirm the extragalactic origin of GRBs (Metzger et al., 1997), as the leaders in Type Ia SNe spectroscopy (Perlmutter et al., 1997), as the pioneers of cadence observing from RV measurements of exoplanets (Butler et al., 2006), and as at the forefront in monitoring stars at the Galactic Center (Ghez et al., 2008). Our community also includes the PI's of all the funded, ground-based TDA imaging programs (PTF, Pan-STARRS, LSST). We will engage the community, in part, through a Science Advisory Team as described in Section 3.e.

As a facility device for WMKO, the K1DM3 will be available to all observers who access the telescope. The only limitation will be the operations model that WMKO will have to support its usage (e.g. LGS AO observations may not be available on every night).

3.b.4. Results from Prior NSF MRI Support

PI Prochaska has not received prior support from the NSF/MRI program. Over the past 5 years, the NSF funding most relevant to this proposal is the NSF CAREER award (AST-0548180) titled "Enriching the Universe". This 5 year grant, which funded PhD students and postdoctoral researchers, has led to the publication of nearly 100 refereed papers including abundance work related to GRB afterglow spectroscopy. Co-PI Nelson, Co-PI Armandroff, and Faculty Associate Bolte have not served as PI or Co-PI on any NSF/MRI project in the past 5 years. Faculty Associate Rockosi is co-PI on a Major Research Instrumentation (MRI) grant (AST-0923585) for an upgrade to the adaptive optics (AO) system on the Shane 3m telescope. The project is on track to install the upgraded science instrument with the rest of the new AO system in early 2013.

3.c. Description of the Research Instrumentation and Needs

3.c.1. Conceptual Design

Motivated by the observational demands of TDA science, we have investigated the design and operation of a new tertiary mirror system on K1 that would permit observations at any of the foci on any given night and at any time. From this investigation we have developed the following top-level requirements:

1. The new tertiary mirror must be sufficiently large to satisfy the field of view (FOV) requirement for each of the existing and planned instruments at the Nasmyth platform of K1. It must have a high reflectance from 300-2500nm.
2. Errors in the tertiary surface and its placement must not contribute to measurable image degradation.
3. When stowed, the device must not vignette the FOV of any existing or planned Cassegrain instrument for K1.
4. The device must be able to rotate the tertiary to any of Nasmyth foci in under 5 minutes.
5. The device must be able to be fully deployed/stowed in under 5 minutes.

The first two requirements constrain the dimensions and support structure of the tertiary mirror. Requirement 3 restricts the placement and dimensions of the full device while the last two requirements drive the mechanical design of the mount and deployment mechanism.

3.c.1.1. Design and Support of the Tertiary Mirror

Geometry of the tertiary: The existing and planned instruments at the Nasmyth foci of K1 include the HIRES spectrometer (Vogt et al., 1994) and the OSIRIS instrument (Larkin et al., 2005). Of these, HIRES requires the largest FOV, dominated by the MAGIQ guider system. The current design needs approximately a 4' FOV; to be conservative we will meet the requirement of a 5' FOV as even this field implies a relatively modest mirror. The tertiary mirror has the shape of the intersection of a cone with a plane: an ellipse. The center of the ellipse does not intersect the optical axis of the telescope, but is somewhat offset. We calculate that a 5' FOV requires a mirror with major axis a = 0.4406 m and minor axis b = 0.3112 m.

Support of the tertiary: The tertiary needs to be supported adequately against gravity. One pathway would be a whiffletree for the axial support and a central diaphragm for the lateral support. This is analogous to the support philosophy used for the full-sized Keck tertiary. The current, full-sized Keck tertiary (providing a 20' FOV) is an ellipse with major and minor diameters of 1.439 x 1.068 m with a thickness of 0.125 m and is axially supported by an 18-point whiffletree system.

We discuss briefly the axial support and the resulting thickness of the tertiary. The optic is elliptical, so it has four equal quadrants. Since we want to support the mirror axially in a kinematic fashion, there are three axial constraints. Thus the simplest support system for a thin and relatively flexible tertiary will be a 12-point support system. Figure 4 shows the axial support locations and interconnections to carry the load down to three points. Not shown is the lateral support system which could be a single diaphragm in the midplane of the mirror that would carry in plane loads and provide the three in-plane constraints. The axial support system would provide the other three constraints. We expect that the axial and lateral loads will be connected at the three defining points indicated in the figure by red dots.

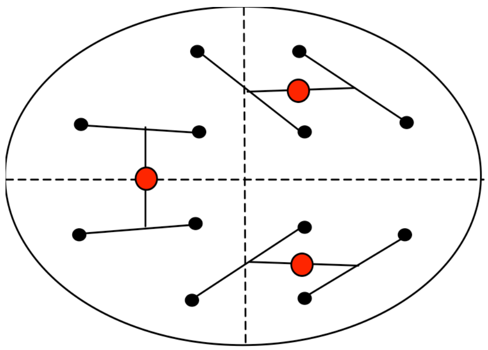

Figure 4: This cartoon shows approximately the locations of a 12 point axial support system and how they might be combined with whiffletrees to three location points that would form the attachment locations to the outside world.

We can estimate the gravity deflections of such a 12 point support as a function of the thickness of the mirror. This can be done relatively easily using "analytic" expressions. The minimum rms gravity deflections of a mirror on an N point support are given by $\sigma_N = \gamma_N$ (q/D) $(A/N)^2$ where σ is the rms surface error under full axial gravity loading, q is the gravity load/area, D is the "bending", and A is the mirror area. Taking N=12 and assuing the properties for Zerodur glass, we derive $\sigma_{12} = 4.09\text{x}10^{-11} (\pi ab/h)^2$. For the dimensions required to provide a 5' FOV for M3 and with h = 0.050 m, we get $\sigma_{12} = 3.03\text{x}10^{-9}$ m, and the mirror has a mass M = 54.5 kg.

In practice we need to find the optimum support point locations and forces in order to actually achieve this performance. Towards this goal we have done a preliminary finite element analysis (FEA) of this elliptical flat plate. For simplicity we modeled it as a shell, so the run time was negligible, allowing us to visually inspect the results and modify the inputs. We varied the positions of the support points (6 parameters) and forced the vertical deflections to be zero at these points. We minimized the peak to valley deflections and found a minimum of about $20\text{x}10^{-9}$ m, quite consistent with the estimated rms of $3.03\text{x}10^{-9}$ m. The map of the achieved surface deflections is shown in Figure 5. More generally, one can use FEA to vary the 8 independent parameters (6 positions and 2 force ratios) to minimize the surface error.

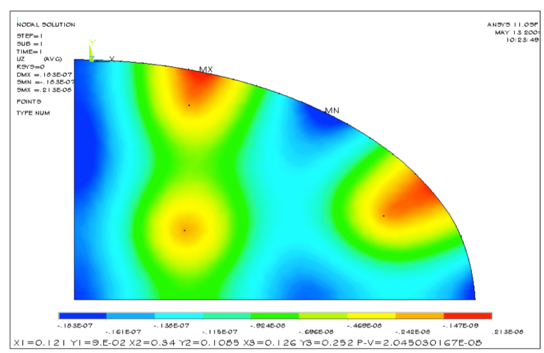

Figure 5: This color contour map shows the deflections of the FEA model for full gravity load perpendicular to the surface with a 12 point axial support. The support locations are indicated by the three small black dots. At these locations the vertical deflections were constrained to be zero. The peak to valley deflection is about 20 nm.

Image Blur: The geometric image blur follows from the slope errors on the tertiary, not the rms surface errors. More support points will reduce the deflections, but increase the spatial frequency of the undulations. Since the tertiary is close to the final focal plane, the slope errors have a smaller impact than if they arose on the primary mirror, by the ratio of the distances to the focal plane. If we assume the surface errors are sinusoidal, then the peak slope error is given approximately by $s_{max} = 2\sqrt{2}\pi\sigma\sqrt{(N/A)}$. The image diameter is four times the slope, scaled by the distance to the focal plane. So the 100% enclosed energy diameter for the Keck geometry is given by $\theta_{100} = 4s_{max}(6.5\text{m}/150\text{m})$. Continuing with the above example, we obtain $s_{max} = 1.42\text{x}10^{-7}$ radians $\theta_{100} = 2.46\text{x}10^{-8}$ radians = 0.005 arcsec.

We conclude from this that the surface deflections are sufficiently small, and resulting geometric image blur is negligible. An M3 with this surface quality is sufficiently good for both adaptive optics and seeing limited astronomy. Such a mirror is straightforward to fabricate, polish, and coat (in the UCO lab).

3.c.1.2. The Mount

K1DM3 Mechanical design concept: As described in the top-level requirements, the mount for the tertiary must be designed to rotate rapidly to any of the Nasmyth foci. Furthermore, it must be positionable to a tolerance of XX radians to preclude image degradation. Our conceptual design (Figure 6) envisions a "tub" which mounts the tertiary and deployment system. The tertiary mirror and deployment system is mounted on a custom bearing with inner diameter of 1.10 m and outer diameter of 1.23 m. A bearing meeting our requirements requires custom design and fabrication. In principle this is a source of great risk to the project. To address this key risk we identified in the fall of 2011 two vendors who will commit to its fabrication at a reasonable cost. Quotations from these vendors are included in the supplementary documents of this proposal.

The bearing carrying the tertiary mirror and deployment system is caused to rotate by a servo motor and encoder system that drives a ring gear mounted on the bearing.

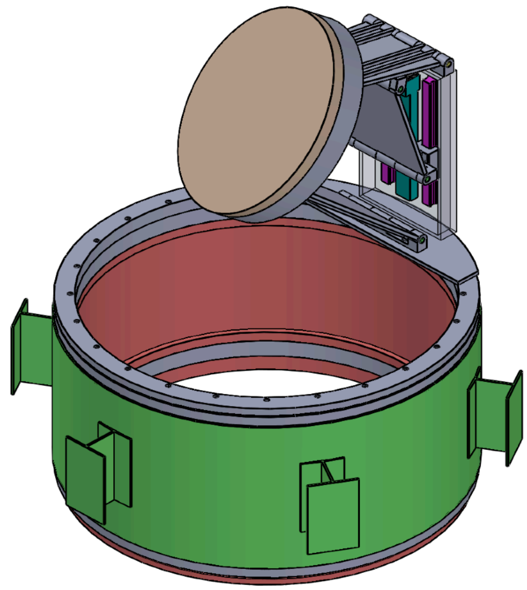

Figure 6: The K1DM3 "tub" which serves as the mount for the deployable tertiary. Aside from the custom bearing, all parts shown are standard, off-the-shelf items.

Instruments and equipment designed for the tertiary tower must travel on a two-rail system. All current designs rely on two pair of rollers, one set at either end of the structure. The tub provides some structural length to accommodate these rollers. The alternative (not yet considered) would be to have K1DM3 attached to an insertion device that is removed once the unit is connected to the kinematic mounts. If necessary two bearings spaced apart along the tub could be used to better resist the moment load of the tertiary. However, a single bearing meeting our requirements is capable of handling the moment loads on its own. The tub will also help protect the motors, encoders, and other related equipment.

Direct support of the mirror will employ uncoupled axial and lateral support systems. The design of these systems will be similar to the technology used on the primary segments and will also rely on recent studies for the support of the TMT tertiary mirror. In addition, experience gained from the recent work to address the issues of segment cracks at support locations will be leveraged as much as possible. The deployment system will consist of a linear actuator and a linkage system. Secondary actuators will also be used to lock the mirror in both deployed and stowed configurations. The deployed orientation needs to be as rigid as possible to ensure repeatability and stable imaging. The stowed position, although not as critical, needs similar reliability from an off-line and safety perspective.

Deployment system: The system is not yet fully vetted but is a great milestone in the conceptual design. It works as a single travel motion device without the need of any telescoping elements. It consists of a ball screw driven carriage that is guided by two linear bearings. The locking mechanism requires further design work. It may also consist of a linear stage. This will help to orient the deployed configuration for optimum stiffness and rigidity.

The mirror assembly will have a rigid third support attached which is presently conceived has an armature with a ball at its end. The deployment system will direct this ball to a socket fixed on the ring. A secondary actuator will then lock this connection to maintain rigidity. A similar arrangement will be employed for the stowed configuration as well although the same ball mirror assembly may not be involved due to its alignment with the primary linear drive.

Vignetting: The major advance of K1DM3 over the existing tertiary is the ability to permit both Nasmyth and Cassegrain observations on K1 in the same observing night. For Cassegrain instruments the tertiary mirror is stowed out of the light path, and for Nasmyth instruments the tertiary mirror is deployed and rotated to direct the light to one of the two Nasmyth focal stations.

Cassegrain instruments are mounted in rotator modules that allow the instrument to rotate about the telescope optical axis to compensate for the field rotation introduced by the altitude-azimuth mount of the

K1 telescope. This requires that the tertiary mirror be stowed out of the FOVs of these instruments and kept in a position that does not vignette their FOVs as they rotate about the optical axis. Presently there is one Cassegrain instrument for K1 (LRIS; Oke et al., 1995) and one planned for commissioning in 2012 (MOSFIRE; McLean et al., 2010).

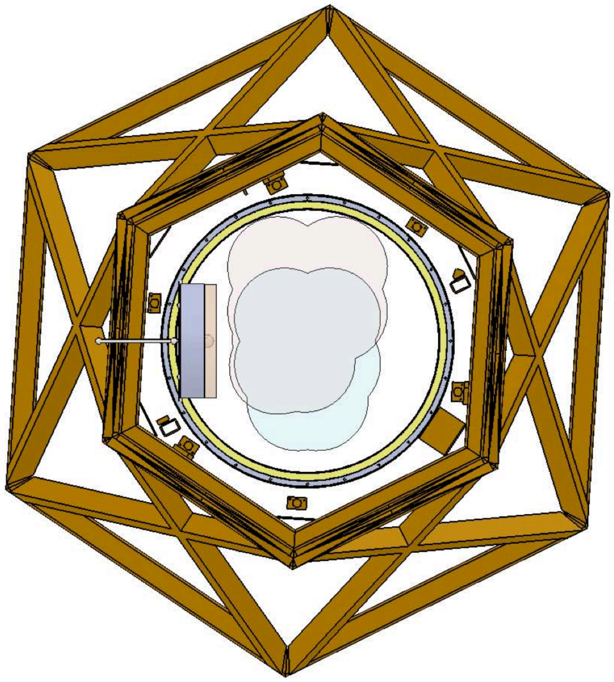

Figure 7: Top-view of K1DM3. FOV's for LRIS (pink) and MOSFIRE (blue) are indicated as estimated at the position of the top of the mount.

Figure 7 shows a top view of the tertiary tower and K1DM3 in its stowed position. Overplotted on the figure are estimated sizes for the unobstructed FOV's of LRIS and MOSFIRE at the top of the K1DM3 mount. These estimates have been informed by a full Zemax (optical design software) analysis using the existing "as-built" optical designs for K1, LRIS, MOSFIRE, and the atmospheric dispersion corrector (ADC) installed on K1. It is evident from the figure that MOSFIRE is easily avoided. Our Zemax analysis of the full system indicates that there is no vignetting of LRIS for elevation angles $\theta < 50°$ and that there is only ~1% vignetting at the extreme corners of the LRIS detector and for a subset of rotator angles at $\theta > 60°$. This is unlikely to ever impact scientific observations.

3.c.2. Development Plan

Work has been done previously to establish the basic modes of operation and the requirements, the space for the module and optics, and a concept design of the deployable tertiary mirror mechanisms including the rotation bearing. When funded the next phase will be the Preliminary Design (PD) that will finalize the overall design and fabricate and mount an envelope prototype on K1. Following the PD phase will be the Detailed Design (DD) phase in which the design will be completed and the fabrication drawings produced. At then end of the PD and DD phases a peer review will be conducted by WMKO. After the DD review, the Full Scale Development (FSD) phase will begin in which we will fabricate, integrate and test the K1DM3. Testing will include documentation of the compliance of the mechanism to the requirements. When testing is completed WMKO will conduct a pre-ship review. After that review, the K1MD3 will be shipped to WMKO, installed on K1, and commissioned over several nights on the sky.

3.d. Impact on Research and Training Infrastructure

3.d.1. Impact for the PI

Since 2003, the PI has been actively involved in PDA science with a focus on follow-up spectroscopy of GRBs (e.g. Prochaska et al. 2004, 2006, 2008, 2009). Over this time, he has mentored 2 PhD students, 2 undergraduates, and 1 postdoc on TDA research projects. The K1DM3 device would afford additional opportunities for students and postdocs within the Inter(stellar+galactic) Medium Program of Studies (IMPS) at UC Santa Cruz to pursue such research.

On the technical side, we would engage all researchers in the IMPS group with TDA interests to develop the operations model for K1DM3 at WMKO. Furthermore, we would include at least one PhD student and one postdoc in the testing and commissioning phases of the device. Experience in systems integration is of great value to astronomers that have an interest in serving as PI for a future instrument on large-aperture telescopes.

3.d.2. Community-wide Impact

The WMKO telescopes, instrumentation, and adaptive optics and interferometry systems have proven to be a powerful scientific research facility for the U.S. astronomical community and an excellent training ground for students and post-docs. The two Keck telescopes are the most scientifically productive telescopes in the U.S. observing system. For example, in 2010, 278 refereed publications were published based on data from the Keck telescopes[1], the highest number of papers per telescope among all ground-based O/IR telescopes. Via studies of the citation frequency of publications from various observatories, WMKO has also been shown to have the highest total scientific impact per telescope of all ground-based O/IR observatories as shown in Figure 8 (based on data from Crabtree, 2011). WMKO maintains scientific leadership for a large user community by innovating and deploying pioneering instrumentation and this proposal seeks to continue this tradition through the development of the K1DM3.

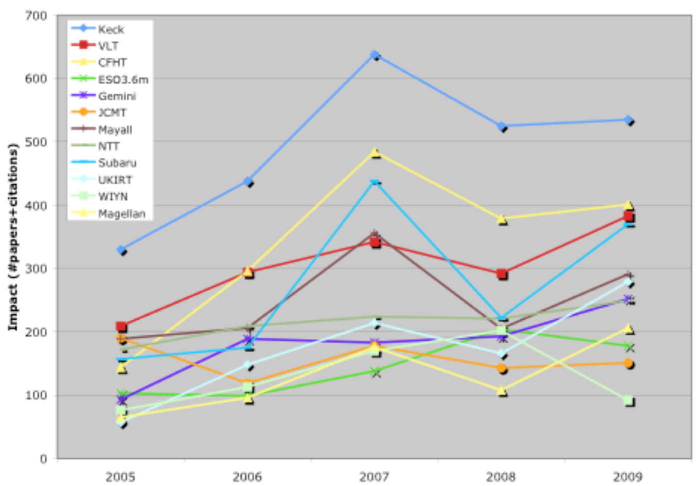

Figure 8: Total scientific impact per telescope for ground-based large telescope observatories.

The improved capability for TDA made available by the K1DM3 will increase the competitiveness of the U.S. observing community in this key field. Access to science observing time with the Keck telescopes is determined by time allocation committees (TACs) representing the institutions with direct interests in the Observatory: the California Institute of Technology (Caltech) and the University of California (UC) each with 35%, NASA with a 16.5% share and the University of Hawaii (UH) with a 12.5% share. Through participation in the NSF Telescope System Instrumentation Program, WMKO has made available 128 nights between 2006 and 2011 to the National Optical Astronomy Observatory (NOAO). In addition, exchanges with the Gemini Observatory over the last 5 years have totaled 32 nights. The NASA, NOAO, and Gemini time are directly available to the entire U.S. community. In a search of the WMKO observing database from 2008 to 2011, a total of 918 unique names were found with the following institutional breakdown: 615 UC/CIT/Yale, 154 UH, 198 NASA community, 118 NSF/NOAO community, 16 Gemini time exchange, 34 Subaru time exchange, and 24 WMKO staff. Keck telescope nights have been the most heavily subscribed observing time offered by the NOAO TAC (note the average oversubscription factor of 5.1 for Keck I and II reported in Table 2 of NOAO's ALTAIR Committee Report, Eisenstein et al., 2009, p. 6). In addition, TSIP users are reported to be very pleased with the instruments and user support at WMKO according to surveys conducted by TSIP staff. The report of the Second Community Workshop on the Ground-Based O/IR System (Alcock et al., 2004) states "Up to this point, most of the satisfied TSIP observers have used the Keck telescopes, where a good level of support is available" (p. C-2).

The recent ALTAIR survey to understand the needs of the U.S. community for observing resources on large telescopes stated "…the highest priority was for more open access time on non-federal facilities", and "The second priority for the more limited group of respondents with institutional access to large telescopes was for increased funding for instrumentation on non-federal facilities" (Eisenstein et al., 2009,

[1] http://www2.keck.hawaii.edu/library/2010.html

[2] http://www2.keck.hawaii.edu/library/theses.htm

p. 14) reflecting the demand for Keck telescope access among others. This proposal will enable continued access to WMKO by the broad U.S. community and the education and training benefits that arise naturally from this access. The impact of the Keck telescopes on astronomy education is well illustrated by the 225 PhD theses produced using Keck telescope data through 2010 (see Figure 9). The list of astronomers who made use of WMKO for their theses[2] includes many of the emerging and mid-career leaders in U.S. astronomy. WMKO is currently providing many graduate students and post-docs direct access to the state-of-the-art instrumentation, adaptive optics capability, and the Keck Interferometer.

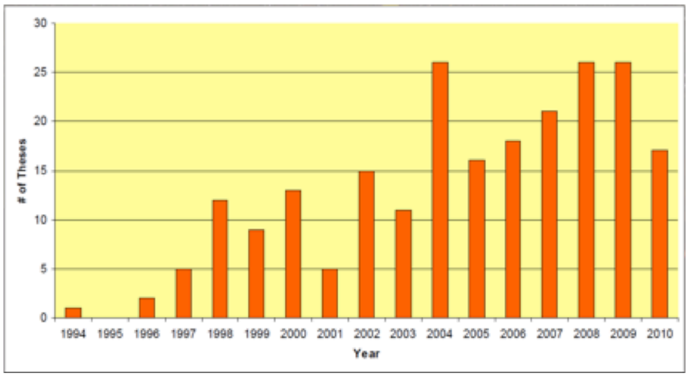

Figure 9: Number of PhD theses published annually based on Keck data.

WMKO's impact on educating technical people has also been high, with numerous students, post-docs, and young engineers involved in WMKO instrumentation and adaptive optics development and commissioning. On the local level WMKO offers many educational programs and services to residents, educators, and especially students.[3] Of special note is the Center for Adaptive Optics sponsored Akamai Observatory Internship Program in which WMKO has played a lead role.[4] WMKO personnel continue to participate in the Akamai short course and to mentor Hawaiian college students during their internships. Also of special significance, WMKO's monthly public astronomy lectures connect the Hawaii Island community with the astronomical research results from WMKO and continue to support a bond with the people of Hawaii.

3.e. Management Plan

The management process draws upon the extensive experience of the UCO/Lick Observatory in designing and fielding large instruments for astronomy, including several large instruments for the Keck telescopes (HIRES, DEIMOS, ESI). The project is following the Observatory's well established development process (Adkins, 2005) which defines the objectives, success criteria, and deliverable documentation for each project phase and the project uses the system of project monitoring and reporting in place at WMKO for the development of new instruments. Each month the K1DM3 project manager (David Cowley) will compose a report of recent activities and status of the project, including progress against schedule and actual expenditures versus budget in accord with WMKO's standard development project reporting format. Subawardees will report their progress to the K1DM3 project manager Regular project meetings are attended by all of the project participants. An agreed upon set of requirements will be used to control project scope, and the K1DM3 project manager will track schedule progress in comparison to a baseline saved in the Microsoft project plan for K1DM3 by regularly (at least monthly) updating the progress of each task. The schedule is then reviewed with the project team to highlight any areas where the rate of progress is a concern. When significant changes need to be made to address problems the schedule may be revised and a new baseline established. All major changes in the budget or schedule require review and approval by WMKO.

3.e.1. Project Plan and Schedule

2 http://www2.keck.hawaii.edu/library/theses.htm
3 http://keckobservatory.org/education
4 http://cfao.ucolick.org/EO/internships/akamai/akamaibigisland.php

The top level WBS for the K1DM3 project is shown in Figure 10. The third level of the WBS is shown for the PD, DD, and FSD phases. The K1DM3 project plan is based on this WBS. Effort levels for the work in the project plan were arrived at by expanding the top level WBS into underlying tasks, assigning appropriate personnel and estimating the required effort. Project personnel, including those budgeted in the subawards, were involved in developing the task lists and making the labor estimates. The Gantt chart for the K1DM3 Microsoft project is also shown in Figure 10. The planned start date is August 1, 2012 beginning with the PD phase (1.2). In this phase we will determine the optimum design approach and

WBS	Task Name	Duration	Work	Start	Finish
1	**Keck Deployable Tertiary**	**728.04 days**	**9,078 hrs**	**Wed 8/1/12**	**Mon 5/18/15**
1.1	**Reviews**	**415.54 days**	**440 hrs**	**Fri 9/27/13**	**Mon 5/4/15**
1.1.1	Prep for PDR	3.75 days	120 hrs	Fri 9/27/13	Thu 10/3/13
1.1.2	PDR	0 days	0 hrs	Thu 10/3/13	Thu 10/3/13
1.1.3	Prep for Full Scale Dev Review	5 days	160 hrs	Wed 5/21/14	Wed 5/28/14
1.1.4	SFDR	0 days	0 hrs	Wed 5/28/14	Wed 5/28/14
1.1.5	Prep for Pre-Ship Review	5 days	160 hrs	Thu 3/26/15	Thu 4/2/15
1.1.6	PSR	0 days	0 hrs	Thu 4/2/15	Thu 4/2/15
1.1.7	First Light	0 days	0 hrs	Mon 5/4/15	Mon 5/4/15
1.2	**Preliminary Design**	**302.5 days**	**2,512 hrs**	**Wed 8/1/12**	**Fri 9/27/13**
1.2.1	**Optics**	**103.43 days**	**28 hrs**	**Wed 8/1/12**	**Mon 12/24/12**
1.2.2	**Mechanical Design**	**302.5 days**	**2,284 hrs**	**Wed 8/1/12**	**Fri 9/27/13**
1.2.3	**electical design**	**115.71 days**	**60 hrs**	**Fri 11/2/12**	**Mon 4/15/13**
1.2.4	**Software**	**10 days**	**80 hrs**	**Fri 11/9/12**	**Fri 11/23/12**
1.2.5	**Coatings**	**7.5 days**	**60 hrs**	**Mon 12/24/12**	**Wed 1/2/13**
1.3	**Detailed Design**	**164.29 days**	**1,600 hrs**	**Thu 10/3/13**	**Wed 5/21/14**
1.3.1	**Optics**	**100 days**	**20 hrs**	**Thu 10/3/13**	**Thu 2/20/14**
1.3.2	**Mechanical**	**164.29 days**	**500 hrs**	**Thu 10/3/13**	**Wed 5/21/14**
1.3.3	**Tower**	**14.29 days**	**80 hrs**	**Fri 4/4/14**	**Thu 4/24/14**
1.3.4	**Strut and Drive**	**81.43 days**	**440 hrs**	**Mon 11/25/13**	**Tue 3/18/14**
1.3.5	**Baffling and Enclosure**	**7.14 days**	**40 hrs**	**Thu 4/24/14**	**Mon 5/5/14**
1.3.6	**Electrical**	**20 days**	**160 hrs**	**Tue 3/4/14**	**Tue 4/1/14**
1.3.7	**Coatings**	**5 days**	**40 hrs**	**Thu 10/3/13**	**Thu 10/10/13**
1.3.8	**Software**	**20 days**	**320 hrs**	**Tue 4/1/14**	**Tue 4/29/14**
1.4	**Full Scale Development**	**221.25 days**	**3,286 hrs**	**Wed 5/21/14**	**Thu 3/26/15**
1.4.1	**Optics**	**80 days**	**640 hrs**	**Wed 5/21/14**	**Wed 9/10/14**
1.4.2	**Mechanical**	**80 days**	**440 hrs**	**Wed 5/21/14**	**Wed 9/10/14**
1.4.3	**Tower**	**5 days**	**40 hrs**	**Wed 5/21/14**	**Wed 5/28/14**
1.4.4	**Ring gear and Drive**	**30 days**	**252 hrs**	**Wed 5/21/14**	**Wed 7/2/14**
1.4.5	**Struts and Drive**	**115 days**	**640 hrs**	**Wed 7/2/14**	**Wed 12/10/14**
1.4.6	**Baffling/enclosure**	**10 days**	**80 hrs**	**Wed 7/16/14**	**Wed 7/30/14**
1.4.7	**Electrical**	**41.25 days**	**170 hrs**	**Wed 5/21/14**	**Thu 7/17/14**
1.4.8	**Coatings**	**5 days**	**120 hrs**	**Wed 9/10/14**	**Wed 9/17/14**
1.4.9	**Intergration**	**46.25 days**	**760 hrs**	**Wed 9/17/14**	**Thu 11/20/14**
1.4.10	**Testing**	**90 days**	**144 hrs**	**Thu 11/20/14**	**Thu 3/26/15**
1.5	**Installation and Commissioning**	**31.25 days**	**340 hrs**	**Thu 4/2/15**	**Mon 5/18/15**
1.6	**Administration**	**650.97 days**	**900 hrs**	**Wed 8/1/12**	**Wed 1/28/15**

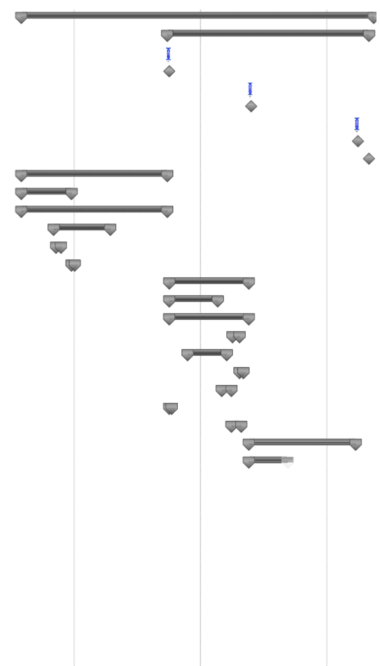

Figure 10: K1 Deployable Tertiary (K1DM3) project Gantt chart and WBS.

component selection for the deployable tertiary. We will design and fabricate a prototype of the tertiary tub with mounting points to the telescope, and test fit this prototype on the telescope. This will ensure compatibility of the K1DM3 envelope with the telescope and allow us to precisely determine the mounting point locations for the final structure. We estimate that 2,907 labor hours will be required to complete this phase. The related non-labor cost estimate is $20,000 for materials and parts, and $10,000 for shipping to and from WMKO.

In the DD Phase (1.3) we will complete the design and the engineering drawings. We also plan to order the substrate for the mirror and to order the ring bearing, as these are long lead-time items. We estimate there will be 1,928 labor hours required in this phase and that we will spend $60,000 on materials and parts, principally for the mirror blank and bearings. In the FSD phase (1.4) we will fabricate and test the structure and mechanisms. After a pre-ship review, we will deliver, install and commission K1DM3 on the Keck 1 telescope. We estimate that 4,201 labor hours will be required in this phase, and that we will spend $148,751 on materials, parts, supplies, and travel. The remainder of the project cost is for project management, costs incurred by WMKO for the design and implementation of the observatory interfaces for K1DM3, WMKO oversight of the project, and the design and pre-ship reviews.

3.e.1.1. Deliverables

The major project deliverables are listed in Table 1.

Table 1: K1DM3 major project deliverables

1. K1MD3 fully tested and ready to mount on the K1 telescope	2. Motion control system and all required interconnecting cables
3. Low-level control software	4. Storage cart (WMKO)
5. Project design reports	6. As-built assembly and fabrication drawings
7. Copies of purchase orders and manuals for all purchased parts	8. Spare parts, maintenance documentation, and a preventative maintenance schedule

3.e.2. Project Structure, Organization and Management

Management Structure: The PI, Professor J. Xavier Prochaska, will direct the project with technical support from Co-PI Professor Jerry Nelson and managerial support from Co-PI Taft Armandroff (WMKO). The PI's will be informed by a Science Advisory Team, chaired by Joshua Bloom (UCB), that will consider the scientific priorities of the WMKO community. Sean Adkins, Instrument Program Manager at WMKO, manages the development of all facility instrumentation. He will also ensure successful integration of K1DM3 with the K1 telescope and control systems. David Cowley, director of the Lick Optical Shops will serve as the project manager for the project. The organization chart for the project is shown in Figure 11.

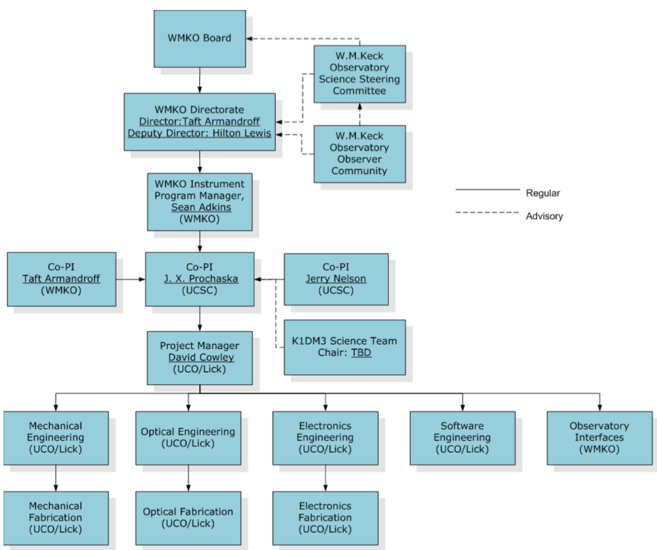

Figure 11: K1DM3 project organization chart

Personnel: Faculty associates Michael Bolte and Constance Rockosi oversee the UCO/Lick shops and will collaborate on the specifications for the K1DM3 and the commissioning plans. Andrew Phillips, the Coating Labs lead at UCO/Lick, and a researcher for the DEIMOS instrument project will lead activities related to optical design and coatings for K1DM3. Jerry Cabak will be the lead mechanical engineer for the project. He was the lead mechanical engineer for the Keck/LRIS detector upgrade and is involved in a wide range of design studies for the Thirty Meter Telescope project.

Other project staff at UCO will include additional mechanical engineering resources to ensure timely completion, an electrical designer for the motion control of K1DM3, instrument technicians for the fabrication and assembly, an optician to procure and test the mirror, and a software programmer to interface the motional control system within the WMKO software architecture. The UCO/Lick shops has considerable depth with 5 engineers, 4 electrical and mechanical technicians, and 4 machinists well trained in the art of instrument building. At WMKO, we will employ a mechanical engineer and design technician to interface K1DM3 to the tertiary tower and update the documentation, an electronics engineer, electronics technician and a software engineer to interface K1DM3 within the K1 control system, and a telescope engineer to ensure that K1DM3 performs as required and does not adversely affect other telescope operations.

3.e.3. Risk Assessment and Management

The significant risk areas for the K1DM3 project are summarized in Table 2. The project plan includes specific activities to mitigate these risks as discussed in the Table.

Category	Risk Area	Likelihood	Impact	Mitigation
Technical	Rotation bearing does not meet performance requirements	Medium	Major	Quotations from suppliers in hand. Expected bearing performance will be included in the analysis of K1DM3 performance in PD and DD phases. Analysis will be reviewed with bearing suppliers.
Technical	Uncertainty or errors in the as-built K1 tertiary tower.	High	Major	Build an envelope prototype and test fit in K1, perform precise metrology on tertiary tower and mounting points.
Technical	K1DM3 does not fit in K1 tertiary tower	High	Major	Build an envelope prototype and test fit in K1, perform precise metrology on tertiary tower and mounting points.
Technical	Mirror coating performance	Low	Medium	Mirror will be coated using a standard process. WMKO has facilities to strip and recoat the mirror after delivery if necessary.
Schedule	Bearing or mirror deliver delayed	Medium	Medium	Plan to procure these elements early in the DD phase. Quotes including delivery in hand for the bearing. Mirror similar to other fabrications with known timescales.
Budget	Cost of rotation bearing exceeds budget	Medium	Major	Quotes in hand from suppliers. Cost included in budget provides margin for increases as design of K1DM3 proceeds and bearing requirements are refined.

3.e.4. Dissemination of Results

The design and development of K1DM3 will be documented through the project's design reports and through publications in scientific and technical journals. Upon completion of the project the DD phase report and the results of on-sky commissioning will be available through the K1DM3 instrument web page at WMKO.

3.e.5. Operations Plan

Keck Observatory is a leader in scientific productivity with the highest number of refereed publications per telescope per year of any conventional ground-based observatory. A number of factors contribute to this high scientific productivity, including the excellent site characteristics of Mauna Kea, Keck Observatory's very capable instrumentation suite, and the light gathering power and image quality of the telescopes. Another key factor is the direct involvement of the astronomical investigators in carrying out their observations and their full engagement in real-time decision making. The current operations model at Keck allocates observing time in units of nights or half nights to proposers who are responsible for carrying out their observations with the assistance of Keck staff (typically a support astronomer and an observing assistant). The astronomers control their observations from either the remote control rooms at

Keck's Headquarters in Kamuela, Hawaii, or at remote observing facilities located at Caltech, each Campus of the University of California, Yale University and Swinburne University.

Keck Observatory will develop a new operational model for observing with the Keck I Telescope that will commence with the commissioning of K1DM3. We seek to retain the considerable advantage of direct involvement of community astronomers in taking the observations. Keck will engage the observer community in planning this new mode in a cost-effective way; Keck is known for cost-efficient operations among large-aperture observatories.

Our tentative plan for the new mode is to allocate the bulk of any night to a single program with a single instrument. A time block of monitoring or a single time-domain interrupt would be allowed on each observing night. We would allow the transition from the primary observing program to the monitoring or interrupt program and then the transition back to the original program. This restriction is intended to enable time domain astronomy, while minimizing the amount of the precious observing time lost to instrument reconfiguration. The limit to two observing programs per nights also assists with calibrations. The primary program would be allocated dome and sky calibrations in the afternoon/evening preceding observing while the secondary program would obtain intrusive calibrations in the morning following observing (some calibrations are possible with internal sources and can proceed in parallel with observing with another instrument). The two Nasmyth instruments and one Cassegrain instrument would be kept ready for observing on each night. With a monitoring program or an interrupt, one could enable the deployable tertiary to rapidly transition to the other instrument and begin observing. Our remote observing facilities on the mainland are a great asset in enabling the observers to carry out the secondary program. Laser-guide-star adaptive optics (LGS-AO) observing would only be allowed if the primary program is already LGS-AO. This is due to the need for specialized staff on duty and also Defense Department prior permission for laser propagation.

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6. Budget and Budget Justification

The UCO/Lick Observatory is submitting this proposal for the development of the K1 deployable tertiary mirror (K1DM3), a new tertiary mirror and its mount for the 10 m Keck I (K1) telescope at the W. M. Keck Observatory (WMKO). The project duration is 47 months with a planned start date of August 1, 2012 and a completion date of June 18, 2016. The total project cost is $2,453k. The amount requested from the NSF for the project is $1,717k. UCO/Lick and WMKO will contribute the balance of $736k, representing 30% of the total project cost. The cumulative budget for the K1DM3 project is shown in Figure 12. For this project WMKO will receive a sub-award from UCO/Lick. A statement by WMKO that the funds received from the NSF portion of this project are counted towards WMKO's limit of 3 MRI proposal submissions for the current solicitation is provided in the supplementary documents section of this proposal.

6.a. Budget Justification (the categories listed below are the categories in the detailed project budget)

a. *Senior Personnel*: the development of astronomical instrumentation is a highly specialized field, and the participation of the senior personnel listed here is essential for the success of this project. The salaries for senior personnel are based on each institution's standard fiscal year 2012 (FY12) labor rates with the addition of 3% inflation for subsequent years.

b. *Other Professionals*: the engineers and technicians required by this project represent the engineering skills needed to design and implement the upgrades. The salaries for the project staff included here are based on each institution's standard fiscal year 2012 labor rates with the addition of 3% inflation for subsequent years.

c. *Fringe Benefits*: the fringe benefits included are based on the standard Federal benefit rates at each of the participating institutions. The fringe benefits include employer taxes, retirement costs, and health and welfare insurance costs.

d. *Equipment*: the equipment purchases for this project consist of the envelope prototype for the K1DM3, and the major purchase over $5k per line item required for the construction of the K1DM3 and shipping of K1DM3 to WMKO. Quotes for the two major cost items, the rotation bearing and the tertiary mirror are included in the supplementary documents section of this proposal.

e. *Travel Costs*: domestic travel costs are included for travel by UCO/Lick staff to WMKO for the test fitting of the K1DM3 prototype and for travel to WMKO to install and commission K1DM3. Travel costs are also included in the UCO/Lick portion of the budget to support travel by invited peer reviewers to the project reviews. Travel costs are included for the WMKO instrument program manager to attend project meetings and project reviews.

f. *Participant Support Costs*: no participant support costs are included in this project budget.

g. *Other Direct Costs*: other direct costs consist of materials and supplies for the construction of the K1DM3 and "other" costs for the direct cost of 6 nights on the K1 telescope at a cost of $17,422 per night.

h. *Total Direct Costs*: the total direct costs represent the full project cost which consists of the sum of all of the above budget categories.

i. *Indirect Costs*: WMKO has a federally approved indirect cost rate of 65%. This is applied to a modified total direct cost base consisting of the total direct costs less capital equipment and subawards. The same formula was applied in subsequent years.

The Observatory's fiscal year begins on October 1 of each year, and the Observatory's operations are funded by the University of California and NASA. The cost sharing commitment will be supported by non-Federal funds and will be available at the start of each fiscal year.

6.b. Cost Sharing

The total cost share amount for this proposal is $736k, the cost share items, amounts, and funding sources are listed in the following Table.

Cost share item	**Amount**	**Source**
UCSC academic salaries and benefits	$ 221,298	UC non-Federal funds
UCSC VCR cash contribution	$ 96,000	UC non-Federal funds
Additional WMKO cost share	$ 163,697	WMKO non-Federal funds
WMKO salaries and benefits	$ 150,468	WMKO non-Federal funds
WMKO observing nights	$ 104,532	WMKO non-Federal funds
Total cost share identified	$ 735,787	

Table 3: K1DM3 cumulative project budget

UCO/Lick and WMKO are committed to providing a cost share of $736k for this proposal. to the NSF Major Research Instrumentation Program titled "MRI: Development of a deployable tertiary mirror for the Keck I telescope". UCO/Lick will provide a cost share of $317k over the duration of the project. WMKO will provide a cost share of $419k over the duration of the project. This cost sharing commitment is included in the UCO/Lick and WMKO budgets for fiscal years 2013 through 2015, consistent with the timeline and proposed yearly budgets submitted with this proposal.

Expenses	Notes	Person Months	Total Cost
Senior Personnel			
J. X. Prochaska, Principal Investigator		4.00	$ 48,184
Jerry Nelson, Co-Investigator		0.21	$ 4,874
Taft Armandroff, Co-Principal Investigator		1.80	$ 42,036
Mike Bolte, Faculty Associate		2.00	$ 30,674
Constance Rockosi, Faculty Associate		2.00	$ 18,550
Andrew Phillips, Optical Engineer		1.67	$ 13,649
			$ -
Total Senior Personnel			$ 157,967
Other Personnel			
Post Doctoral Associates			$ -
Other Professionals (Technician, Programmer, Etc.)		86.9	$ 1,363,542
Graduate Students			$ -
Undergraduate Students			$ -
Secretarial - Clerical (If Charged Directly)			$ -
Other			$ -
Total Salaries and Wages			$ 1,521,509
Fringe Benefits	1		$ 104,788
Total Salaries, Wages and Fringe Benefits			$ 1,626,297
Equipment			$ 30,000
Travel			
Domestic			$ 18,302
Foreign			$ -
Other Direct Costs			
Materials and Supplies			$ 275,236
Publication Costs/Documentation/Dissemination			$ -
Consultant Services			$ -
Computer Services			$ -
Subawards (Subcontracts)			$ -
Other	2		$ 104,532
Total Other Direct Costs			$ 379,768
Total Direct Costs			$ 2,054,367
Indirect Costs			
Modified Direct Total Cost (Base)	3		$ 496,970
Indirect cost rate	65%		
Indirect Costs	4		$ 398,256
Total Indirect Costs			$ 398,256
Total Direct and Indirect Costs			$ 2,452,623
Contingency			
Materials (Equipment, Materials and Supplies)	5		$ -
Labor (Total Salaries, Wages and Fringe Benefits)	5		$ -
Total Contingency			$ -
Total Cost including contingency			$ 2,452,623
Total Requested from NSF			$ 1,716,836
Cost Share Amount	6		$ 735,787

1. WMKO benefit rate 26.1%, UCO/Lick benefit rate variable
2. 6 WMKO nights at $17,422 per night before indirect cost
3. MTDC = total direct costs less equipment and subawards, plus $25K of each subaward
4. Indirect costs included for UCO/Lick and UCSC senior personnel
5. Contingency included in estimate, exact amount not disclosed
6. Cost share of 30% of total project costs

Figure 12: K1DM3 cumulative project budget