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Enabling an Exozodiacal Dust Survey
with an L-band Single-Aperture Rotating-Baseline Nuller

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The detection and characterization of exozodiacal disks around nearby stars is one of NASA’s top priorities, as the exozodi level is critical to determining mission parameters needed by exoplanet imaging missions aiming at terrestrial exoplanets. Nulling interferometry has been the technology of choice in this regard, but the nulling landscape has evolved markedly over the past decade. Observationally, the KIN survey has concluded, while the more sensitive LBTI survey is just beginning. However, in both of these 10 µm surveys, the amount of accessible information is limited. To increase our knowledge of exozodiacal disks, one obvious tack is to detect the disks in a different passband, as this would allow significantly more accurate source modeling. Based also on technical issues, we propose L-band nulling observations of the KIN/LBTI exozodi samples with a simple, low-cost L-band nulling interferometer, using a single Keck telescope aperture.

We begin from the simple observation that a nulling baseline across a Keck aperture, of order 7.5 m, would halve the length of the LBTI’s 15 m baseline. Thus, halving the observing wavelength at Keck would provide the same angular resolution as the LBTI. Going even somewhat shorter, i.e., to L band, then provides a higher angular resolution at Keck, which is in fact also needed because one would expect the hotter dust emitting at L-band to be somewhat closer to the star. Thus, an L-band nulling interferometer across a single Keck aperture would be an excellent scientific complement to the LBTI, as these two systems together would probe dust at two wavelengths & spatial scales, thus enabling much better definition of source characteristics.

Moreover, because of several factors, the needed instrumentation can be developed and deployed very quickly, and at very low cost. First, the use of the long L-band behind the Keck AO system means that the Strehl ratio is sufficiently high that the AO system itself will act as the fringe tracker, as already demonstrated at even shorter wavelengths on the Palomar Fiber Nuller. Second, in a single-aperture common-mode configuration, the π phase flip can be carried out trivially, with, e.g., crossed half-wave plates. Moreover, the beamcombiner optics are also fairly trivial: as demonstrated at Palomar, all that is needed is a single mode fiber! Third, single mode L-band fibers are now readily available, being inexpensive, off-the-shelf items from, e.g., Thorlabs now! Thus, the nulling optics can be provided as a small number of drop-in components in the existing AO bench. Fourth, L-band camera capabilities are already available at Keck, both in NIRC2 and in the Keck Interferometer L-band camera. Fifth, over the past few years, we have invented a new, high-accuracy statistical null measurement technique that obviates the need to stabilize at the null fringe. Instead, modeling of the null depth fluctuation histogram is used to extract the null, without bothering to stabilize the null to better than a tenth of a wavelength. This level of stabilization (<400 nm) is already provided for free by the AO system. With this approach, null depth accuracies close to \(10^{-4}\) are regularly obtained at Palomar. Sixth, the nulling baseline can be rotated with the Keck pupil rotator, as we already did earlier in a test experiment at Keck, in which we detected a binary with a rotating baseline. Thus, an L-band nulling interferometer comparable and complementary to the LBTI can be obtained using the existing Keck AO system, existing L-band camera, and a few drop-in optical
elements in the AO bench, and a commercial single-mode fiber, allowing rapid progress in the exozodi issue. We note that without a second wavelength or baseline, it will remain very difficult to locate dust relative to the habitable zone unambiguously.

Finally, we note that such a nuller could also be useful for other measurements, such as of protostellar disk structure, and the detection of very close-in brown dwarfs. Moreover, such an instrument will be an excellent pathfinder for a future nuller on the TMT, which can be a very powerful instrument. Indeed, with a 25 m baseline on the TMT, an H or K band nuller can directly observe and take spectra of hot Jupiters at separations of a few mas! However, to be ready for such an eventual instrument, it is vital to continue to develop nulling interferometry techniques. Indeed, as mentioned above, over the past decade several revolutions have occurred in nulling interferometry, including the fiber beam combiner, the use of a rotating baseline nuller within a single large telescope aperture, and the statistical approach to null depth measurement that has obviated the need for fine scale stabilization. However, we note that such novel approaches are not invented in a vacuum. Specifically, to eventually be able to make use of an even more advanced nuller on the TMT or in space, the nulling techniques need to continue to be developed in the interim. Luckily, the exozodi project described here combines a scientific measurement goal of great interest to NASA, with a technological approach that is very amenable to rapid, low-cost implementation, while potentially opening the door to further innovation as well.
A new high-precision spectrograph for Keck

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August, 2014

Rationale

• Because of its size, site, and support, Keck remains the premier optical/IR observatory.
• Among the many achievements of the Keck Observatory, the work related to exoplanets has to rank among the most notable, and especially so to NASA.
• Keck exoplanet work has involved a number of capabilities, but HIRES has been the workhorse. HIRES is now more than 20 years old. It still performs well, but a new generation of exoplanet science fed by TESS, PLATO, etc. require both better performance (in RV precision) and better sensitivity (as M dwarfs with transiting planets are found).
• Space offers unique advantages for particular kinds of studies, but ground-based RV work is an absolutely essential component of the search for planets and planetary systems like ours; without it the mass of the planet is left unknown. Without that mass we do not know if we’ve found an Earth analog, and with the mass we learn density, a more interesting aspect of exoplanets than was suspected until Kepler stars were studied.
• There is also the need to characterize in detail the stars that host planets so we understand their context.

Needed capabilities

• The highest possible throughput for both the optical and near-IR regimes is critical to achieve success. To get to the needed precision every photon must be used.
• The needed precision implies a well-stabilized spectrograph with high demands on its ability to be calibrated. The spectrograph must be very efficient in terms of use of all available useful photons.
• This need suggests a double instrument with both optical and near-IR arms. One may be better suited to detecting an Earth around a solar-type star, while the other would be favored for cooler stars.
• A fiber-fed device seems like a good choice, particularly to feed a stabilized device, but more innovative designs should be sought.
• AO capabilities are improving and extending toward the optical, due especially to work at Keck, and AO combined with a spectrograph of this kind could be vital for achieving the desired sensitivity.

Comments

• All of the above suggests that a new spectrograph meeting these requirements could be one of the most complex, demanding, and costly astronomical instruments ever built. At the same time, HIRES has dominated Keck usage, and so it is very likely that this new instrument would deliver world-class science over a number of years and so be fully cost-effective once its amortization is taken into account. In other words, a replacement for HIRES is effectively self-amortizing.
• NASA should consider providing the primary funding for this instrument because it will address NASA’s highest-level science goals. The initial need is for a study to define specific capabilities and requirements.
Keck observatory investigations into the giant planets of our solar system

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The gaseous planets within our solar system represent a unique class of astronomical target, as spatially resolvable objects whose atmosphere and aurorae can lead to dramatic variability on timescales as short as minutes and as long as centuries. In addition, these are worlds that have, and will continue to be, visited by NASA driven space missions. Over the last two decades, our understanding of these planets has increased dramatically. For Jupiter and Saturn, this comes as a result of both the space missions Galileo and Cassini, respectively, as well as a wealth of ground-based astronomy, both in support of these space missions and independently. For Uranus and Neptune, following the departure of Voyager from Neptune in 1989, our significant scientific advances come entirely from Earth-based astronomy.

Infrared studies of these planets consistently produce high impact scientific returns, published in journals like Nature and Science. While some of these results have been produced using smaller telescopes, over the past decade Keck has proven itself as a unique platform for the study of these planets. The large aperture that Keck provides is essential in resolving mid-infrared morphology (e.g. using LWR - Orton et al., Science 2004). This aperture is also key in measuring the weak auroral emissions from Saturn, Uranus and Neptune and has lead ground-breaking research into the non-auroral ionosphere at Saturn (e.g. using NIRSpec – O’Donoghue et al., Nature 2013).

Keck has also played a leading role in providing direct mission support to the Cassini mission, in particular providing a ground-truth to Cassini VIMS observations of Saturn’s aurorae, and as a major component in the Cassini Spring Auroral Campaign in 2013. These observations were highlighted by Keck in a ‘Live from the Keck Telescope’ webcast, providing a ground-truth to VIMS observations and showing significant scientific returns, with six papers already published or in publication from the broader Keck-Cassini support programme.

In the coming decade, the study of gaseous planets promises to continue to provide a wealth of scientific returns. The Cassini Grand Finale will, between 2016-2017 provide highly inclined, close in orbits of Saturn, before the spacecraft crashes into the planet. These orbits will provide unique new views of the aurora of the planet, with very detailed high-resolution imaging and in-situ measurements of the current systems and sounding of the top of the atmosphere. Keck is perfectly placed to provide direct mission support for these observations, providing a combination of short timescale measurements from Keck’s large aperture, and higher spectral resolutions and broad-scale morphology from the NIRSpec instrument, that will prove key in understanding these detailed Cassini observations.

At Jupiter, the Juno mission, which will orbit the planet over the poles between 2016-2017, will provide an equally unprecedented view of the aurora, and deeper atmospheric polar vortices. Again, Keck promises to provide an essential ground-truth of great importance, allowing a view of the entire aurora, and measurements of temperatures and ion winds in the upper atmosphere, as the JIRAM and UVS instruments on Juno observe thin slivers of the aurora at incredible resolution.

Past space missions, such as Voyager, have shown the importance of ground-based observations to provide continued mission support long after the mission itself has ended, enabling us to follow longer term changes in the planet, as well as continuing to reveal new science. These advances will continue, not only for Jupiter and Saturn, but also for Uranus and Neptune. These ice giants have seen significant new scientific discoveries within the past decade, with renewed interest driving calls for a new mission to one of these planets, leading to recent proposals for space missions to both NASA and ESA. Ground-based observations from Keck could prove key in aiding the planning for such missions, through better understanding of the upper atmosphere conditions, needed to provide limitations to any aerobraking maneuvers used in calculating mission designs.

However, despite these major scientific advances, over this past decade, we have also seen developments in instrumentation at both Keck, and in particular at Keck’s leading rival telescopes, resulting in a significant reduction in the range of useful instrumentation available to study the giant planets. From the perspective of giant planet tropospheres and stratospheres, the absence of any mid-infrared instrumentation from world-class observatories is becoming problematic. COMICS is on Subaru is only available a few days
a year; VISIR on VLT and MIRSI on the IRTF are currently both offline; and CanariCAM on Grantecan remains untested. Gemini retired TRECS and MICHELLE a few years ago, and Keck lost LWS over a decade ago. The community is now crying out for new and readily-available imaging and spectroscopic instrumentation at wavelengths longer than M band, out into the mid-infrared.

The situation for auroral studies is better, but has faced similar problems recently. While mid-spectral-resolution instrumentation remains well represented in the L-band, high resolution instruments are moving away from larger spectral slits: the ‘upgrade’ of CRIRES on VLT has seen it removed for the foreseeable future, returning with a 10’’ slit, the new iCSHELL instrument, replacing CSHELL on IRTF sees a similar reduction in slit length, so that within the next two years, Keck’s NIRSpec instrument will be the only instrument in the world capable of measuring Saturn entire diameter, or Jupiter’s entire auroral region, at >20,000 spectral resolution. The loss of NSFcam2 on IRTF, due to instrument failure, means we no longer have a near-IR imager with a tunable wavelength, so that we must rely on the few remaining imagers that have specific auroral filters, such as the imaging mode on SpeX/IRTF, which are not ideal.

The astronomical infrared community as a whole sees an exciting series of advances in the telescopes and instrumentation available in the coming decade. The launch of JWST and first light from three >24m telescopes is likely to have occurred in the next ten years. However, unfortunately, the mis-direction away from instrumentation that can produce headline scientific returns from the gaseous planets appears to be continuing into the future.

The Hubble Space Telescope has proven itself an essential tool in understanding the auroral emissions from Jupiter, Saturn and Uranus. With the inevitable end of that mission approaching, JWST has been heralded as an advanced replacement. However, there are significant limitations to using JWST on solar system objects. The imaging filters on NIRCam/JWST are not able to isolate auroral emissions from the background of reflected sunlight. NIRSPEC/JWST has a field-of-view smaller than the diameter of Uranus, limiting its use for Jupiter and Saturn. Using MIRI/JWST, it is likely that both Jupiter and Saturn will be saturated on the instrument and so no observations will be made of these planets, and the limited aperture will produce lower quality images than have previously been taken at Keck. A similar picture emerges in proposed instrumentation from the new >24m class of telescopes, with instrument design driven by extragalactic needs. Most infrared instrumentation for these telescopes have a similarly small field-of-view, leading to the need for complex mosaicking to cover the giant planets, problematic given the short temporal variability often observed on these targets.

In short, it remains more important than ever that Keck continues to provide, and perhaps extends, its suite of instruments that provide broad views of the planets within our solar system. As such, the primary requirements of the community are to continue to provide:

- Specific NASA mission support programs (and perhaps extend this to other space agencies)
- Instruments with wide fields-of-view (20-60’’), such as NIRC and NSFCam

Current planetary observations at Keck could be significantly improved logistically through:

- The ability to ask for time on an hourly basis, as support observations for space missions often occur when half or full nights involve significant time when the target planet is not observable.
- Producing new procedures for off-axis guiding and AO correction on moons, as well as the development of observing macros, so that complex observing patterns can be produced and run easily.

We believe that significant new advances could be made by Keck though the design of new instrumentation specifically with planetary studies in mind. The most significant instrumental improvements that Keck could make in the coming decade include:

- Imaging and spectroscopy in the mid-infrared
- Higher spectral resolutions, essential to measuring the atmospheric and auroral winds at Jupiter, Saturn and Uranus and wider slits widths (up to 4’’) to allow emission line imaging
- Allowing AO in the L-band window, combined with auroral specific filters (such as the Connerney H_3+ filters at IRTF) would provide a replacement for HST images of Jupiter’s aurora, while spectral AO observations would garner a wealth of new scientific returns
- An imager with a tunable CVF, to allow planetary images at multiple wavelength specific windows in gas giant atmospheres, to allow access to different layers within the planet’s atmosphere.
White Paper Submitted In Response to the NASA Solicitation for Input To The Keck Strategic Planning Meeting (2014).

The Keck Observatory Archive (KOA): Back to the Future

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The First Ten Years
The Keck Observatory Archive (KOA; http://koa.ipac.caltech.edu) is celebrating 10 years of operations this summer. Funded by NASA, KOA is collaboration between the NASA Exoplanet Science Institute (NExScI) and the W. M. Keck Observatory to operate an archive of data acquired with all ten Keck instruments, and serve them in compliance with the archive’s Data Access Policy. KOA has recently completed the ingestion of observations acquired with all Observatory instruments, going as far back as the instrument commissioning phases in most cases. Altogether, the archive contains 15,000 program nights (35 TB) of raw (level 0) data collected over the 20-year lifetime of the Observatory. Seventy percent of these data, from seven instruments, are now public; this will rise to >85% in the next year with the release of data from the remaining instruments. These data have been validated and organized for optimal scientific exploitation, and in the cases of HIRES, NIRC2, LWS, and OSIRIS, served with enhanced (level 1) browse products, created by KOA, to aid in understanding the science content.

KOA represents an extraordinarily rich resource for enabling scientific investigations not otherwise possible. Many of these directly address the three strategic science objectives of the NASA Astrophysics Division: probing the origin and destiny of the Universe; exploring the origin and evolution of stars, galaxies and planets; and discovering extra-solar planets and exploring whether they harbor life. Examples include using Ovi as a probe of the circum-galactic medium to study the evolution of QSOs¹, temporal monitoring of exoplanet orbital phases, follow-up observations of planets with long-period orbits that require a large time baseline, and a comprehensive planetary census that requires a statistically significant and complete sample of stars. The science value of KOA is reflected in the growth of citations to KOA in peer-reviewed papers. There have been 69 citations to date, including 22 in 2014.

The Next Ten Years
The most important new activity for KOA will be to work closely with support astronomers and instrument developers to deliver automated pipelines for all instruments, and to use them to support quick-look reductions at the telescope and to serve reduced, possibly publishable-quality data from the archive.

¹ The Keck Observatory Database of Ionized Absorbers toward QSOs (KODIAQ), a NASA funded archival research program.
Automated pipeline development will proceed side-by-side with archive operations. Thus, KOA will archive all nightly data, support the commissioning of new instruments by ensuring they deliver fully self-describing data sets, develop new functionality in response to users’ changing needs, make the archive interoperable with other archives, and serve new products as created at the Observatory, such as AO point-spread reconstructions. We will convene an archive Users’ Group to guide the priorities for new archive services.

KOA has demonstrated the effectiveness of automating existing interactive data reduction packages (DRPs). This approach was used to develop level 1 pipelines for HIRES and OSIRIS. For HIRES KOA underwrote an adaptation of the *make* pipeline to process data obtained with the 3-CCD camera upgrade, and nearly 100 peer-reviewed papers have cited it. A similar approach was used for OSIRIS, NIRC2, and LWS. KOA is currently creating a Python-based pipeline for NIRSPEC, based on the REDSPEC reduction package.

We plan to use the same model to make level-1 products available for all the operating modes of all Keck instruments. Many data reduction tools have been made available for nearly all of the instruments (e.g., XIDL, packages by J. Prochaska). We are developing agreements with Dr. Prochaska (UCSC) and colleagues to automate their reduction packages, and are assessing levels-of-effort with a view to developing a delivery schedule. New instruments (such as NIRES) are required by Keck to be delivered with a DRP, and KOA will cooperate with developers to ensure that an automated pipeline will be archive-ready from the first day of operation.

Currently, most instruments use only a limited set of common keywords for data searches. The archive will develop a full keyword set for all instruments, enabling, among other features, a more sophisticated “calibration association” across all instruments. Calibration association associates specific calibration frames with specific science frames, making calibration of the science data more efficient and seamless, and is, to our knowledge, a capability unique to KOA.

**KOA in the Era of JWST, TESS, and WFIRST.**

In addition to archiving follow-up data for missions such as Kepler and Spitzer, KOA has supported NASA missions such as Deep Impact and Comet ISON by immediate public release of time-critical data obtained at Keck. It will support the immediate release of New Horizons data from Keck monitoring programs during its Pluto Encounter, and will continue to archive follow-up observations for missions such as JWST, WFIRST, and TESS, and will offer rapid dissemination of time-critical and important data sets under NASA’s direction. KOA’s capability to support time-critical data sets and survey data positions it to play a crucial role in distributing raw and reduced data from all such future projects, especially time-critical, immediate-release follow-up data from LSST, and preparation of observing programs for next-generation giant telescopes such as the TMT.
Keck Planet Imager

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Abstract

The advent of fast low-noise infrared cameras (IR-APD arrays), the rapid maturing of efficient wavefront sensing techniques (Pyramid/Zernike), as well as small inner working angle coronagraphs and associated low-order wavefront sensors opens new parameter spaces complementary to first and second-generation extreme adaptive optics (ExAO) systems designed decade(s) ago. Indeed, the search and characterization of planetary systems around M-dwarfs (the science case for future extremely large telescope planet finder instruments, such as PFI and PCS on TMT and the EELT, respectively) can be initiated now on a 10-meter class telescope. The Keck Planet Imager (KPI) is a low-cost upgrade of the current Keck AO, reusing Keck, Palomar, and JPL assets to explore this new scientifically compelling niche, while maturing system-level and critical components for future more ambitious ground- and space-based instrumentation.

1. What is KPI?

KPI consists of an upgrade of the current Keck AO system with an efficient infrared wavefront sensor (IR WFS) using the latest low-noise detector technologies, a high-order deformable mirror, and a state-of-the-art coronagraphic bench upstream of existing science instrument assets available at Keck and/or Palomar (infrared imagers and IFUs). An ExAO high contrast imaging facility optimized for faint red objects by means of IR WFSing can characterize exoplanets both around nearby young M stars and in the nearest star-formation regions, and enable ExAO performance towards the galactic center. IR WFS will provide the Keck Observatory with capabilities orthogonal to its competitors at a modest cost.

2. Science cases

Exoplanets around M-dwarfs. M dwarfs constitute the most promising reservoir to advance our understanding of planetary formation and evolution. Indeed, M dwarfs vastly outnumber all earlier-type stars together \cite{8}. Their abundance and low close binary fraction imply that they are common sites of planet formation. Close separations (< 1 AU) have been extensively probed by Doppler and transit surveys with the following results: the frequency of close-in giant planets (1 − 10\textit{M}\textsubscript{Jup}) is only 2.5 ± 0.9\%, consistent with core accretion plus migration models \cite{7}. On the other hand, Kepler indicates that Earth- to Neptune-sized planets might be as common as one per star \cite{19, 5, 13}.

The outskirts of young M-dwarf systems (10 − 100 AU) are being probed by first-generation direct imaging instruments, and preliminary results show that massive planets are rare: less than 10.6\% of M-dwarf systems surveyed harbor 1 − 13\textit{M}\textsubscript{Jup} giant planets in their outer regions \cite{2}. Disk instability does not seem to be a common mechanism of giant planet formation. The 1 − 10 AU parameter space is thus believed to be the El Dorado of planet formation. Across the entire range of sensitivity (10\textit{M}\textsubscript{⊕} − 10\textit{M}\textsubscript{Jup}), the occurrence rates measured by microlensing survey imply an average 1.6 ± 0.9 planets per star \cite{3}. Microlensing probes the full range of planetary masses in this region, but the masses and metallicities of the host stars are usually poorly constrained and so are of limited value for statistical studies. High contrast imaging with a good knowledge of the host star is therefore the perfect complement.

KPI will target this reservoir (Fig. 1) with the most advanced high contrast imaging techniques, imaging these planets down to unprecedented sensitivities, but also directly analyzing their emitted light with medium-resolution spectroscopy.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Age vs distance scatter plot of nearby active M stars visible from Keck, the basis for the proposed large-scale M-dwarf surveys of KPI (color rectangles).}
\end{figure}
Figure 2. Layout of KPI, with the new components in light blue, and use of current assets potentially available at JPL, Keck and Palomar. The ambient temperature coronagraphic bench allows easy access to subsystems such as the low-order wavefront sensor. Simultaneous use of the classical imager and IFU (a la SPHERE) is straightforward and advantageous but not required. The duality is excellent for wavelength coverage, sensitivity (imager has higher throughput) and FoV. The IFU can also provide natural means of measuring high-order wavefront aberrations in real-time thanks to wavelength diversity [21].

**Planetary systems in star forming regions (SFR).** Sky coverage with an IR WFS is typically 50% higher than in the visible [4], but in obscured areas such as SFR, the gain is much more dramatic. The population of young stars in Taurus, 140 pc away, is dominated by M stars and very late K stars [6], making IR WFS essential for these very red stars. Indeed, an R-band WFS sensitivity rolloff at $R \approx 10$ currently provides access to only a handful of T Tauri stars, while an H-band sensitivity rolloff at $H \approx 10$ mags would enable high contrast on a hundred young stars in Taurus alone. Thus, IR WFSing can enable high contrast imaging studies of extrasolar planetary systems (both disk + protoplanets) in their infancy.

**Galactic center (GC).** IR WFS has proven to be very robust to study the GC with VLT-NACO: IRS 7 ($H = 9.3, K = 6.5$) is only 6” North of SgrA+. An IR WFS ExAO would boost the Strehl ratio (SR) by a factor of a few compared to current LGS assisted observations (10 – 30% SR at K), therefore enhancing SNR, enabling shorter wavelengths, and thus improving resolution and astrometric precision (reduced confusion).

### 3. Technical case

Powerhouse second-generation AO systems such as SPHERE and GPI were designed 10 years ago. The technological landscape has considerably evolved since then, in particular in wavefront sensing, coronagraphic, and detector technologies. Specifically, we propose to supplement the current Keck AO system with an IR WFS using a state-of-the-art fast, low-readnoise detector.

**Phased low-cost implementation.** The new proposed instrument can reuse current assets available at JPL, Palomar and Keck, and give valuable pieces of equipment a second life (Fig. 2). New developments are kept at a minimum, and focussed on key areas, such as efficient wavefront sensing techniques (Pyramid/Zernike wavefront sensor), and low-noise infrared cameras (IR-APD, MKIDS), which are highly strategic to future TMT instrumentation.

**Complementarity/synergy with other (space-based) facilities.** KPI, with its IWA of $\approx 25 – 50$ mas at J-band, will complement JWST nicely at very small angles (the IWA of NIRCAM and MIRI will be 5-10 times larger). KPI benefits from recent advances in coronagraphy, wavefront control (e.g., ACAD[14]) and low-order wavefront sensing techniques developed for space-based coronagraph projects such as WFIRST-AFTA, EXO-C, and ATLAST, while providing a platform for demonstrating and optimizing these techniques in an operational environment. Specifically, the vector vortex coronagraph (VVC) has demonstrated $\approx 10^{-3}$ raw contrast at $2\lambda/D$ on the high contrast imaging testbed [16]. Moreover, a pupil plane low-order wavefront sensor (LOWFS) on a VVC on SCoExAO at Subaru has recently demonstrated closed loop $\approx 10^{-3}\lambda/D$ tip-tilt and focus retrieval accuracy on-sky [17].

**Pathfinder to TMT’s planet finder.** An ExAO high contrast imager at Keck will bridge the gap between Keck first-generation AO and PFI [10]. It will allow demonstrating critical component-level and system-level aspects, gain operational experience on segmented telescopes (Keck provides the most credible pathfinder for ExAO on the highly-segmented TMT), and enable formidable, unique science, which will vet the most promising targets for TMT follow-ups.

### 4. Yield estimates

To demonstrate the superiority of KPI over current high contrast imaging capabilities (even second generation instrument in the regime of faint NGS in the visible, i.e. low-mass stars), we ran simulations to estimate the yield of a putative 3-year survey, assuming roughly 50 nights per year.

**Sample.** We started from the Bright M Dwarf All-Sky Catalog - MDFWARFASC - [9], did a first cut of objects only visible from Keck, retained active M-stars only (either X-ray, FUV, or NUV detections). Ages for active M stars were derived using 2 complementary methods, based on their activity lifetime and decay [20, 18]. This produced the sample shown in Fig. 1.
then arbitrarily did a cut a 20 pc (=1 AU with KPI’s 50 mas IWA), and 2 Gyr yielding a sample of 569 relatively young M-stars with spectral types ranging from M0 to M7.

**Instrument performance.** To represent current AO performance on M-stars, we used the median contrast curves published in Ref. [2] ($\Delta \text{mag} \simeq 2.5, 4.4, 9.8$ at 0",1",0",2",0",5", respectively). We emphasize that for typical M-star $R_m$ mitudes, 2nd-generation AO with visible SH WFS do not significantly deliver better performance than first generation AO instruments (e.g. SPHERE, with its EMCCD starts to be photon-starved at $R > 11$; GPI at $R > 9$).

A tentative error budget (R. Dekany) shows that KPI’s efficient low-noise IR (Pyramid) WFS provides optimal ExAO-like performance for $J < 10$, which is by chance the cutoff J magnitude of our MDWARFASC sample. To anchor our post-processed contrast estimates to reality as best as we can, we used the validated performance estimator of SPHERE, scaled and transposed the results to KPI yielding on average $\Delta \text{mag} \simeq 12.7, 13.8, 14.5, 15$ at $0".05, 0".1, 0".2, 0".5$, respectively. We also assumed improved performance at the IWA of 50 mas, corresponding to $2\lambda /D$ at J. Indeed, an aggressive, but realistic IWA requires using a proven small-IWA coronagraph such as the vector vortex [11, 15]. To ensure the best contrast at the IWA, the vortex needs to be matched with a low-order wavefront sensor (LOWFS), as has been demonstrated at Subaru [17].

**5. Expected results and conclusions**

Projected results for our virtual survey with KPI are very compelling. With a relatively modest investment in hardware and telescope time, KPI will be able to probe a brand new parameter space left open by all other exoplanet detection techniques (Fig. 3). **One further striking outcome of KPI is that it could potentially detect reflected light from exo-Jupiters for the first time (Fig. 3, right),** if it also had good differential polarimetric capabilities (a la SPHERE-ZIMPOL [12]; implementable on the coronagraphic bench, see Fig. 1).

We have entered the golden age of high contrast imaging. Keck is the biggest, most sensitive telescope, in one of the best sites in the world. KPI will provide unique capabilities that will enable Keck to exploit very compelling science niches, such as the exploration of M-dwarf planetary systems. At the same time, KPI will demonstrate key technologies for TMT, also proof-testing years of developments at NASA, and optimizing systems in an operational scientifically productive framework. Finally, KPI can be quickly deployed, to be on time to follow-up TESS candidates, and be in sync with JWST.

**References**

Keck AO 3–5 μm Integral Field Spectroscopy
A focused, low cost instrument for Diagnosis of Exoplanets

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Adaptive optics has been demonstrated to achieve the contrast and resolution to detect planets at 3.5 μm with the Keck Telescope [Kraus and Ireland, 2012]. Despite widespread adoption of integral field spectrographs (IFS) for high contrast imaging (P1640, GPI, SPHERE), and the importance of 3-5 micron spectroscopy there are currently no high contrast IFS instruments operating at these wavelengths, and diffractive crosstalk with the IFS limits the efficacy of modifications to existing instruments, so a new instrument is required to efficiently implement well-sampled spaxels that are needed for high contrast imaging. A novel conceptual design for a diffraction limited 3-5 μm IFS with 2k×2k detector has been developed at Cornell that uses a 12 inch spherical primary mirror and a 2.5 inch Féry prism secondary. Although this brief white paper emphasizes exoplanets, there are many other science opportunities enabled by this instrument, such as active galactic nuclei, star formation and solar system bodies especially monitoring of Titan and Io. A high contrast IFS covering the atmospheric L and M windows will be a powerful instrument for planet detection and characterization that can be matured rapidly with this novel design.

High contrast imaging and non-redundant aperture masking at these wavelengths is especially relevant to NASA as this is the primary wavelength of the JWST aperture masking mode. The 2012 JWST Science Operations Design Reference Mission allocates 410 hours to aperture masking interferometry with NIRISS, which is 16% of the exoplanet science program, and 2.6% of the entire SODRM. JWST is not capable of spectroscopy in non-redundant aperture masking now that the TFI instrument has been removed. Spectroscopic aperture masking with a Keck instrument will be a powerful synergy with JWST, as a precursor instrument for demonstrating high contrast techniques, precursor surveys to eliminate low contrast binaries from JWST targets and as a spectroscopic complementary/follow-up instrument for discoveries made with GPI and JWST.

The cost of such an instrument is dominated by need for a large format detector array, but collaborators Judy Pipher and Bill Forrest at the University of Rochester have offered to commit a 2k×2k InSb ORION (JWST prototype) detector. Collaborator Dan Watson has offered to commit a cryogenic Fabry-Perot, that would enable high resolution imaging spectroscopy ($R \sim 4000$ vs $R \sim 100$). The simplicity of design and limited moving parts will lead to a rapid construction schedule (1-2 years). The low cost and external contributions in this instrument place a complete funding scenario within several grant opportunities. Without internal cryogenic AO, this instrument is within the envelope for the NASA and NSF grant programs, and

Figure 1: Left: the transitional disk around LkCa 15, as seen at a wavelength of 850 μm (Andrews et al. 2011). Right: Composite of two wavelengths (blue: $K'$ or $\lambda = 2.1$ μm red: $L'$ or $\lambda = 3.7$μm) reconstructed with Keck aperture masking of the central part of the cleared region. The location of the central star is marked with a white star. Most of the $L'$ flux comes from two peaks flanking a central $K'$ peak, which is interpreted to indicate inflow of accreting material, and shows that longer wavelengths are essential to understanding planet formation. From Kraus and Ireland [2012]
with cryogenic AO, suitable for an NSF/MRI proposal. With an IFS, higher performance non-redundant masks can be implemented due to lower bandwidth smearing, and better control of systematics through differential closure phase allows improved contrast. Without cryogenic AO, the sensitivity of an IFS on Keck will be comparable to that shown Figure 1, but with cryogenic AO, sensitivity can be improved by roughly one magnitude.

L and M bands have been disfavored by all other high contrast IFS projects for several reasons: longer wavelength cutoff detectors require colder operating temperature (e.g. 5 µm cutoff devices typically exclude LN2 cryostats); there is a more limited selection of transmissive optical materials; the high thermal background is greatly increased by the necessarily high emissivity of the large number of optical surfaces in a high performance AO system. However, these challenges are mitigated for an instrument focussed on 3-5 microns implemented with this design: we have a conceptual design that is all reflective except for the prism, for which a good material has been identified; at λ > 3µm, adaptive optics correction is greatly simplified, with r0 > 1 meter and t0 > 1 second. Therefore it is relatively straightforward to implement a cryogenic AO system inside the cryostat, requiring a DM with ~ 100 actuators and closed loop bandwidth ~ 1 Hz. Iris AO is a partner on the development of this instrument, and some testing of Iris AO deformable mirrors has been undertaken at Cornell. The use of segmented mirrors also allows the implementation of selectable aperture masks, and the low hysteresis and absolute calibration of Iris AO deformable mirrors enables the possibility of open-loop AO, further simplifying the instrument design. High performance AO systems require a large number of surfaces and necessarily high emissivity (≥ 50%). This instrument can be developed for use behind conventional Keck AO, or with a cryogenic AO system. The cryogenic AO need not be immediately implemented, as the fore-optics will necessarily have a fold mirror near a pupil, which can be sized to accommodate a MEMS DM as a future upgrade.

Figure 2: A selection of model planet spectra from Spiegel and Burrows [2012]. "cf" and "hy" denote cloud-free and hybrid clouds respectively in units of contrast relative to a sun-like star. "1s" and "3s" denote solar and 3× solar abundances respectively. All these models are within 5% of the same K band (2.2 micron) contrast, and are therefore indistinguishable by broad-band flux measurements alone. Spectroscopy is required to break the degeneracies between clouds, atmospheric abundances, mass and age. While there are some spectral discriminants at λ < 2.5 µm, the star-planet contrast is most favorable and the diagnostic information is richest in the atmospheric L window from 3.5-4.2 µm. Shown with purple bars are the spectral coverage ranges for existing/planned high contrast integral field spectrographs for large telescopes with high performance AO systems.
SHREK: Stable High Resolution Echelle for Keck

A white paper submitted to the Science Steering Committee for the 2014 W. M. Keck Observatory Strategic Planning Meeting

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Studies of Earth-size planets – including their detection, measurements of their properties, theories for their formation, and their habitability – constitute one of the most compelling and fertile directions in science. Recommendations to pursue research into Earth-size planets have come from New Worlds, New Horizons and the White House. Major impetus derives from the NASA Kepler Mission that identified over 400 planets smaller than twice the size of Earth.

However, the vast majority of these 400 Earth-size planets do not have a measured mass or bulk density, leaving unknown whether they are rocky planets or mini-neptunes with envelopes of gas. Also, their orbital eccentricities remain unknown, leaving unknown their variations in temperature, atmospheric chemistry, and hence habitability. The host stars are typically $V = 13$-$15$ mag, making the Keck Observatory the only facility able to carry out the needed high-resolution spectroscopy and Doppler studies of a statistically useful set of Earth-size planets.

Further studies of Earth-size planets are planned for the NASA Kepler/K2 mission (ongoing), and the NASA TESS mission (to be launched in 2017). Both surveys will find a few Earth-size planets around bright stars, with $V < 11$ mag, suitable for follow-up spectroscopy by 3-meter class telescopes. But the majority of the Earth-size planets found by those missions will orbit stars fainter than $V = 12$ mag, benefitting from the Keck aperture to keep exposure times modest for the needed $\sim 1$ meter/sec Doppler spectroscopy of a statistically robust samples of stars.

This white paper suggests that the Keck Observatory pursue the construction of a stable high-resolution echelle spectrometer designed specifically to measure Doppler shifts with an instrumental stability of 0.5 m/s, to measure masses, densities, and orbits of Earth-size planets in large, statistically useful numbers. We are developing the Stable High Resolution Echelle for Keck (SHREK) to meet these goals.

Figure 1 shows the value of Keck aperture for a stable, high-resolution spectrometer in the study of Earth-size planets. Figure 1 shows the properties of the host stars of the planets having sizes, $R_{pl} < 1.5 R_{\text{Earth}}$. Figure 1 shows known Earth-hosting stars from Kepler, but for TESS the host stars of Earth-size planets are simulated based on the TESS target list and planet-occurrence rates (P. Sullivan, in preparation). Some stellar hosts of Earth-size planets are brighter than $V = 11$ mag, for which the 3-4 meter class telescopes can do spectroscopy and Doppler work. But most are fainter than $V = 12$ mag, for which the aperture of Keck will be valuable in studying a statistically useful sample of over 100 Earth-size planets.

SHREK will also be vital for studying the over 500 known transiting, multi-planet systems that have host stars mostly with $V = 13$-$15$ mag. The study of these multi-planet systems will benefit from the aperture of Keck to allow time-sensitive, precise Doppler measurements, with exposures well under 1 hour, to measure the masses and orbital eccentricities of these dynamically important systems. Doppler measurements of planetary systems convey telltale information about the planet-planet interactions, resonances, eccentricity pumping, and dynamical instabilities that shape the architecture of planetary systems in general.
Fig. 1. The host stars of prospective rocky planets \((R_p < 1.5 \, R_{\text{Earth}})\) from the NASA Kepler (left) and TESS (right) missions, in a two-parameter space of Doppler amplitude and \(V\text{mag}\). For both missions, some Earth-size planets orbit bright stars, \(V < 11\) mag. But the majority of the Earth-size planets orbit fainter stars. SHREK on a 10-meter telescope enables planet masses, densities, and orbital eccentricities to be measured, directly determining if they are rocky with stable temperatures. SHREK will be sensitive to a statistically useful number of Earth-size planets by probing smaller Doppler amplitudes and fainter stars than HIRES or spectrometers on 3-meter class telescopes.

SHREK will strengthen the partnership between NASA and the Keck Observatory, with its ability to characterize the Earth-size planets emerging from Kepler, K2, TESS, and nearby stars that will be targets for WFIRST/AFTA, and certainly imaging/spectroscopic NASA missions to follow. SHREK will also provide masses and surface gravities needed to interpret the atmospheres of planets targeted for transmission spectroscopy by JWST.

Currently, several stable, high-resolution spectrometers exist, and four others are under construction, designed to achieve Doppler precision at the meter/sec level. All of these modern spectrometers avoid using iodine for Doppler calibration because the contamination of iodine lines forces the determination of both the instrumental profile and the wavelength scale locally at each wavelength for each exposure, costing precious photon-limited information. Also, a “template” spectrum must be de-convolved, a process that is ill-defined and imparts noise. In contrast, the iodine-free Doppler spectrometers have an optomechanical structure that has converged in design. Indeed, all such spectrometers have a remarkably similar design. These existing spectrometers serve 3-4 meter class telescopes, with ~7 times less light-collecting area than Keck. Doppler stability at the sub-meter/sec level requires optical and mechanical stability that has been demonstrated by fiber-scrambling and mechanical/thermal stability.

We envision SHREK to be a similar stable spectrometer for Keck Observatory. SHREK would be placed inside a vacuum chamber located inside a double-walled thermal enclosure held at constant temperature to within 0.001 C. This entire structure would be located in the highly stable beam-combining room that previously housed the Keck Interferometer. SHREK itself would have a two-element mosaic, R4 echelle grating, and a VPH cross disperser, and an optical camera \((\lambda = 440-590\, \text{nm})\) in an initial green channel. SHREK will be fed by optical fiber,
including a double-fiber scrambler composed of fibers with octagonal cross-section, feeding light from the Keck-2 telescope. The double-fiber scrambler stabilizes both the image and pupil motion (centroid) by a factor of 10,000, allowing employment of a three-slice image slicer to keep the size of SHREK the same as the similar spectrometers built for 3.5-meter telescopes. Figure 2 shows an optical ZEMAX point design for SHREK.

Fig. 2. Optical point design for SHREK. It is a standard white-pupil design and contains an R4 two-element mosaic, a double collimator, and VPH cross-disperser, and a CCD detector. SHREK is housed in a vacuum chamber, placed in a thermal enclosure held at ±0.001 C, and is fed by a double-fiber scrambler.

A detailed cost estimate (bottoms-up) shows the cost to be $5.5 million, including 30% contingency. This cost is the same as that of other similar spectrometers, i.e. Univ. Chicago and Penn State Univ. All benefit from the legacy knowledge drawn from the HARPS design.
Keck IR spectroscopy in the 2020s: NIRSPEC replacement thoughts
Tom Greene (NASA Ames) and Dan Jaffe (UT Austin)

High sensitivity and high-resolution spectroscopy have always been Keck strategic strengths, and this is likely to continue well into the future. The Keck community have already taken good advantage of studying objects discovered with smaller, wider field instruments, conducting deep or high resolution spectroscopic observations of objects found by Sloan, PTF, Pan-STARRS1, etc. This synergy is bound to continue in the 2020s and beyond: Keck has sufficient aperture to obtain high quality spectra of interesting objects discovered by Gaia, TESS, LSST, WFIRST, and other surveys.

Keck's IR spectroscopic capabilities must be upgraded to allow our users to take full advantage of this potential. NIRES will be a powerful addition, proving moderate resolution (R ~ 2500) spectra over 1 – 2.4 \( \mu \text{m} \) simultaneously. Higher spectral resolution (R ~ 25,000 or more) data will still be needed over 1 – 5 \( \mu \text{m} \) to study stars, exoplanets, solar system bodies, and other single objects. NIRSPEC currently fills this niche, but it is inefficient because its small detector (1k x 1k) records only a limited amount of spectral range simultaneously and its high read noise limits sensitivity (or increases exposure times). In the near term, its existing InSb detector should be replaced with a lower noise HgCdTe one as planned.

A new R ~ 25000 \( \lambda = 1 – 5 \mu \text{m} \) spectrograph with high sensitivity over large spectral range is needed to fully capitalize on Keck's potential in the 2020s. The VLT is upgrading its CRIRES instrument now to increase its instantaneous spectral coverage by an order of magnitude, and the TMT will not have a similar first generation instrument. Observing the entire H and K or L and M bands simultaneously will greatly speed observations and discoveries as well as enable new science by obtaining numerous atomic or molecular features simultaneously, allowing studies of gaseous excitation and abundances that are not currently possible. Greatly increased spectral range and sensitivity will also allow detection and characterization (compositions, rotation velocities) of new, smaller exoplanets by direct detection of their atmospheric features (e.g., Snellen group 2014). Such an instrument may also be useful in exoplanet detection via RV measurement if it is very stable (no moving parts) and is equipped with an IR laser comb or other accurate wavelength reference. High stability would also benefit spectro-astrometric studies (e.g., Pontoppidan et al. 2011).

The newest ground-based IR spectrographs provide lessons for a future Keck instrument. Figure 1 shows the optical layout of the IGRINS immersion grating spectrograph recently completed at McDonald Observatory (D. Jaffe, PI). This instrument observes the entire H and K bands simultaneously at R ~ 45000 with a 1” slit on the McDonald 2.7-m telescope. The Si immersion grating keeps the overall size small (25 mm collimated beam) and it has no moving parts, greatly helping stability and calibration. The grating also works efficiently in high orders, providing echellograms that fit efficiently on its two 2k x 2k HAWAII2RG HgCdTe detector arrays (one shown in Fig 2).

A Keck instrument using this technology could also be relatively compact; scaling to R=25,000 with a 0.7” slit on a 10-m telescope gives a collimated beam size of 36 mm, about ½ that of NIRSPEC. It may be possible to adopt a similar concept to the IGRINS concept for Keck by adding selectable dichroics and gratings to allow simultaneous observations of H+K or L+M bands. This would cover the entire \( \lambda = 1.5 – 5 \mu \text{m} \) region accessible from the ground in only 2 exposures. Unfortunately Si optics do not transmit at wavelengths \( \lambda < 1.2 \mu \text{m} \). R ~ 50,000 would be possible with a < 0.35 arcsec slit (GLAO regime), but 4k x 4k detectors may be required. Manufacturing an immersion grating with the required diameter and thickness is just beyond the current state of the art, but it may be feasible soon.
IGRINS spectral image of H-band night sky lines. You can drive a truck between them at $R=45000$.

Figure 1: Optical layout for IGRINS. All parts shown are within the cryogenic part of the instrument.