OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** long-term

Validating Habitable and Rocky Planets with AO Imaging

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Abstract of Scientific Justification

M dwarfs offer the best near-term prospects for finding and characterizing rocky, Earth-sized, and/or habitable planets. We are executing a large-scale collaboration to use K2, the updated Kepler mission, to find ∼500 small planets around M dwarfs, including dozens of potentially habitable systems and useful JWST targets. We request 1 night each with LBT/LMIRCam and MagAO for adaptive optics imaging to eliminate false positives and begin validating K2's M dwarf planetary systems. Eventually, our program will **measure the occurrence rate of habitable rocky planets around low-mass stars, optimize low-mass target selection for TESS, and find a few good targets for early-science JWST atmospheric characterization.**

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	LBT	f/9	LMIRCam	*	*	1	bright	Mar–Mar	Feb–Apr	yes	yes
2	MAG1	f/16	MagAO	*	*	1	bright	Jun–Jun	Mar–Jun	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: Our LBT run should be in February–April 2015 to allow observations of candidate planetary systems in Fields 0 and 1 at reasonable airmass. Our MagAO run must be after mid-March to ensure we have adequate time to find candidates in the Field 2 data release (scheduled for mid-February). A MagAO run during June would increase our flexibility by allowing us to observe targets in any of Fields 1, 2, or 3.

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A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	Kepler2, Field 0	06:33:10	+21:35:00	LBT-AO; Feb–Apr
2	Kepler2, Field 1	11:35:50	+01:25:00	LBT-AO or MagAO; Feb–Jun
3	Kepler2, Field 2	16:24:30	-22:27:00	MagAO; Mar–Jul
4	Kepler2, Field 3	22:26:40	-11:06:00	MagAO; Jun–Jul
5	TARGET NOTE:			Target identification is underway; see Fig. 2

Approval for Instrument Use from PI: Proposal prepared after consultation w/AO-instrument leads Phil Hinz (LMIRCam) and Laird Close (MagAO).

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Introduction

Surveys for new planets demonstrate that small, low-mass planets are common around FGK stars and planets occur with increasing frequency toward longer-period orbits (Howard et al., 2010, 2012). *Kepler* measured the frequency of transiting Earth-sized planets in Earthlike orbits to be 5–20% (Petigura et al., 2013a). Such Earth-analogue planets are of considerable interest for their ability to support life, assessing their habitability must wait for a Darwin/TPF-class mission. **M dwarfs offer a shortcut to habitable, rocky planets**. Compared to Sunlike stars, planets around M dwarfs are easier to find, they occur more frequently, and their atmospheres are easier to study. Planets transiting M dwarfs offer the best opportunity to study habitability and constrain models of rocky planet assembly and migration (Swift et al., 2013; Hansen, 2014) and of planetary atmospheres (Kaltenegger et al., 2011; Rodler & López-Morales, 2014). However, few confirmed transiting planets are known around M dwarfs, and the occurrence frequency of planets around M dwarfs is poorly constrained because *Kepler* targeted only 3900 M dwarfs (Dressing & Charbonneau 2013).

We are using **K2**, the continuing mission of NASA's *Kepler* spacecraft, to target ∼60,000 M dwarfs over ∼ten $12^\circ \times 12^\circ$ fields. By estimating K2's photometric precision (Howell et al., 2014) and the occurrence rates of planets around M dwarfs (Dressing & Charbonneau, 2013; Berta et al., 2013), we estimate that with K2 we will find ~ 500 M dwarf planets (see Fig. 1). Because the habitable zone lies at smaller semimajor axis around M dwarfs than around Sunlike stars, habitable planets orbiting M dwarfs are more likely to transit. K2's 80-day campaigns are ideally suited to find large numbers of small and habitable planets around M dwarfs: 20-30 will be found in their stars' habitable zones. In addition, 10–20 of K2's M-dwarf planets will orbit stars bright enough for atmospheric characterization via JWST transmission spectroscopy (Kaltenegger & Traub, 2009; Batalha et al., 2013). The first K2 data files were released on Sep. 8, and by the following day our team was already producing calibrated light curves and identifying possible planet candidates (see Fig. 2, *left*).

We request 1.0 night on LBT/LMIRCam and 1.0 night with MagAO to begin rejecting false positives (such as background eclipsing binaries) via medium-contrast imaging ($\Delta K \approx 7$ mag at 0.3"). Observations at **both facilities are necessary to permit AO imaging of K2 targets in the North and South** (see Target List). Eventually, our program will determine physical parameters to (1) refine measurements of **planet frequency as a function of stellar and planetary size, orbital period, and stellar type**; (2) directly inform **theories of planet formation and evolution around low-mass stars**; (3) find **new habitable planets**; and (4) maximize JWST's science return by revealing new **targets for atmospheric characterization** well before the launch of NASA's TESS mission.

Several types of non-planetary configurations can masquerade as true planetary systems, but the most common involve background eclipsing binaries. Kepler has huge pixels (4" on a side), so chance alignments often throw multiple unrelated stars into the same pixel. If an eclipsing binary is blended with a brighter foreground star, deep stellar eclipses are diluted to appear as shallow, transit-like events. For example, an Earth-sized planet transiting a mid-M dwarf has a transit depth of 10^{-3}, but this signal could be a solitary M dwarf and a $\sim 10^{-3}\times$ fainter eclipsing binary. A rough estimate is therefore that we must rule out targets $\sim 10^{-3}\times$ fainter than the host star (i.e., $\Delta K \approx 7.5$; see the Technical Remarks section).

To eliminate these and other false positives, we employ a "BLENDER" analysis (Torres et al., 2011; Fressin et al., 2011) to quantify the likelihood of a false positive by simulating a wide array of possible background eclipsing binary systems and comparing the frequency of plausible false positives to Galactic population models. **We have written our own BLENDER code** (see Fig. 2, *right*) to validate all Kepler & K2 M dwarf planets. Initial analyses such as those shown in Fig. 2 demonstrate that with LBT-AO and MagAO observations reaching a *K*-band contrast of $\sim 10^{-3}$ we can eliminate essentially all eclipsing-binary configurations and validate these systems as true transiting planets.

Similar AO surveys for the original *Kepler* sample (see Fig. 3; Adams et al., 2013; Law et al., 2014; Lillo-Box et al., 2014; Marcy et al., 2014) reveal previously-unknown contaminating stars for ∼20–30% of these systems. **AO observations are essential** to accurately validate K2's planet candidates (e.g., Schwamb et al. 2013's identification of Kepler-64 as a *quadruple* system with a transiting planet). This past experience with *Kepler* systems demonstrates that both angular resolution and sensitivity are essential in these efforts. For both reasons, these AO systems are the superlative instruments for high-resolution follow-up of these systems – **very few other AO systems on this Earth can efficiently reach the necessary contrast and inner working angle**. With 2 nights we will begin to validate the most interesting M dwarf systems. Eventually, our work will yield major improvements in our understanding of planetary formation, atmospheres, and habitability around low-mass stars. We will: (1) Find targets for atmospheric studies via JWST transmission spectroscopy; (2) Complement new RV surveys for planets around M dwarfs by measuring planet frequencies vs. planetary and stellar properties; (3) Directly inform theories of terrestrial planet formation and evolution around low-mass stars; (4) Dramatically increase the number of known M dwarf planetary systems; and (5) Constrain models of planetary interiors and atmospheres.

References

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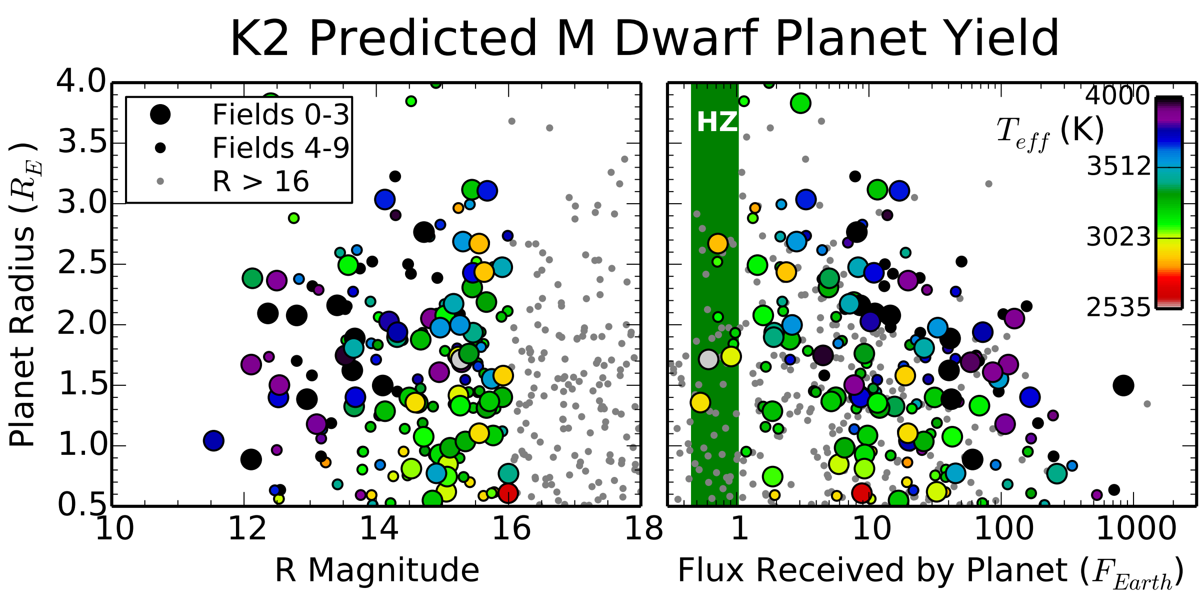

Figure 1: Expected planet yield from K2, showing planet radii vs. R magnitude (for AO guide stars; left) and vs. planet irradiation (right). Large circles indicate targets expected from K2 Fields 0, 1, 2, & 3; we estimate ∼75 targets with $R < 16$. With 2 nights **we will validate the candidate planets of the most interesting ∼40 systems.**

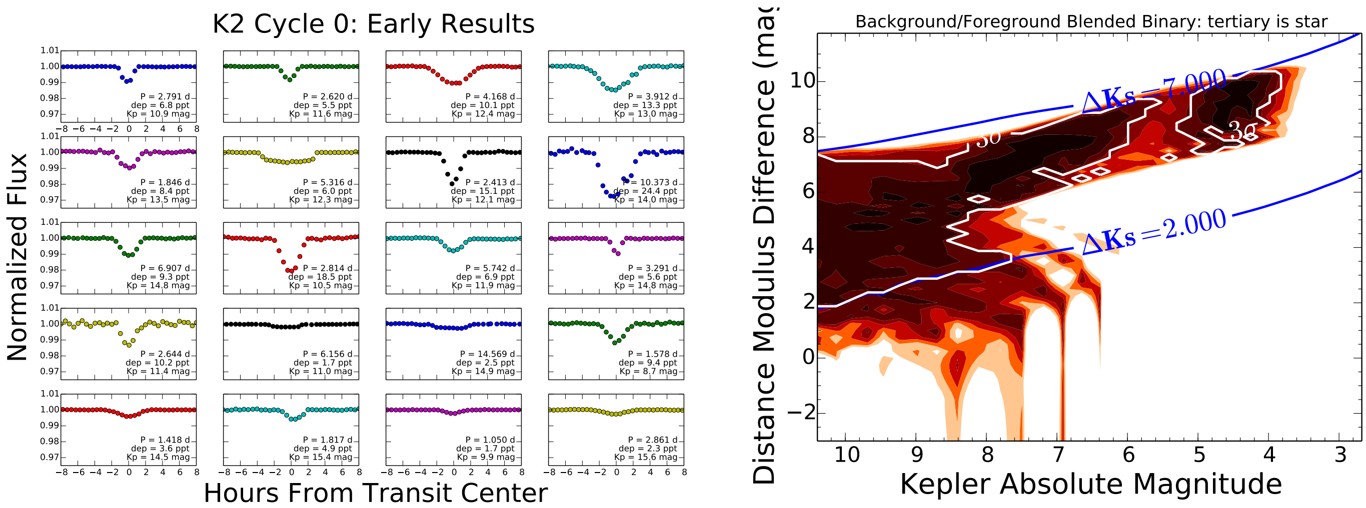

Figure 2: **Left:** Some *preliminary* K2 candidate planet light curves, extracted by our team from K2 Cycle 0 data in just 2 weeks. We continue to fine-tune and improve our photometry & transit-search pipeline, only recently adapted for K2. **Right:** Our `BLENDER` analysis of a representative M dwarf candidate. Dark areas (enclosed in the white contour) represent possible false-positive background eclipsing binaries. AO imaging reaching $\Delta K \approx 7$ mag (indicated by the upper, solid blue line) will rule out most false positives and (with light-curve diagnostics) will **robustly validate such systems as true transiting planets.**

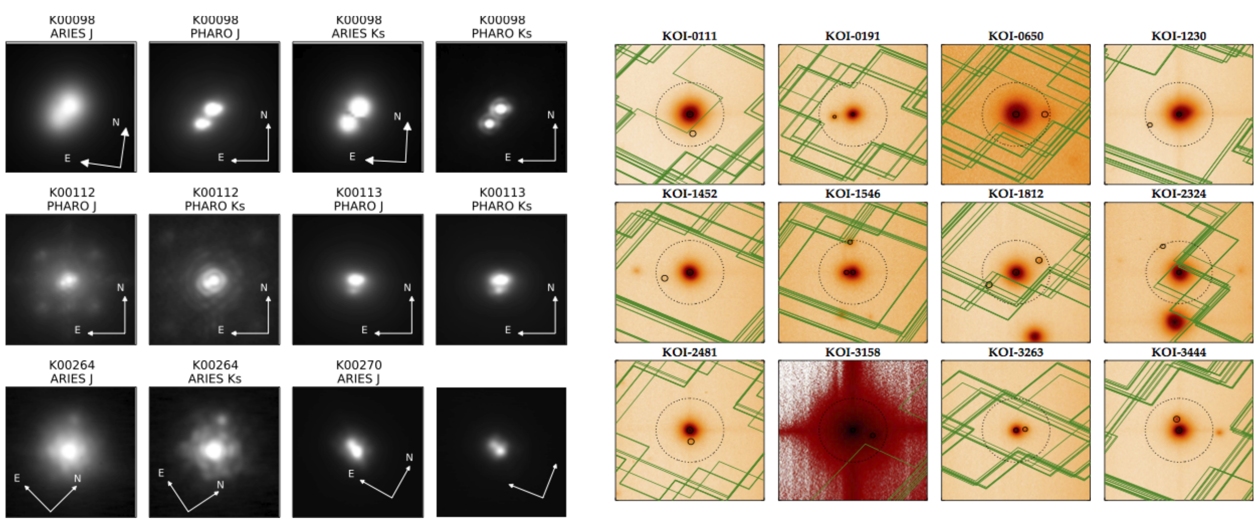

Figure 3: Example candidate-vetting of *Kepler* planet candidates via high-resolution imaging (Adams et al., 2013; Lillo-Box et al., 2014). In these efforts, ∼20% of the FGK targets contained at least one companion within 2 arcsec, indicating blended photometry and a higher likelihood of false positives rather than true planetary systems. Note that this figure is just an example: we will observe entirely new systems that have no previous AO observations.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Our program consists of LBT/LMIRCam and MagAO observations using our K2 M dwarf targets as natural guide stars (NGS). Our observing approach is standard for NGS AO imaging of moderate-to-faint targets, but the combination of **observing efficiency, contrast, and inner working angle make these the superlative instruments for our program**. At LBT we observe in *K* band to strike the optimal balance between Strehl ratio (which boosts the S/N of faint objects), reasonable background flux, and access to faint sources with red colors. Although we would achieve narrower FWHMs at *J* band, with our faint NGS targets **the *K* band maximizes our sensitivity**. Observing at *K* also maximizes the color contrast between our red M dwarf targets and any nearby, hotter stars blended with our targets. However, at Magellan (where the AO system works better) we observe in *H* band to achieve comparable spatial resolution and sensitivity in both data sets (50 mas).

The LBT and Magellan AO systems can lock onto stars as faint as $R \sim 15-16$ mag, and Fig. 1 demonstrates that our M dwarf targets will have a brightness range of $R = 12 - 16$ mag. Fig. 2 shows that to eliminate most false positives we must reach contrast levels of $\Delta K \approx 7$ mag ($\sim 10^{-3}$); LBT and Magellan achieve this at just $\lesssim$0.3" (Esposito et al., 2013; Morzinski et al., 2014; Schlieder et al., 2014). Since our M dwarf targets have typical colors of $R - K \approx 3.5$ mag, **we will detect objects as faint as $K < 19.5$ mag.** We will observe the fainter targets in the best seeing conditions, to allow observation of the full range of target magnitudes.

Sensitivity estimates indicate that we would need only $\sim$10 min of integration to detect a $K = 19.5$ mag target with a $R = 15$ mag NGS (cf. Morzinski et al., 2014), but our true sensitivity is lower since we are working at narrow separations where the background is dominated by speckle noise from the host star's PSF. With overheads for slewing, acquisition, dithering, and detector readouts, past experience with these AO systems indicate that we should expect to achieve a cadence of $\lesssim$30 min per target, or ~ 10 **targets per half-night**.

We follow the successful examples of past AO campaigns to validate *Kepler* target stars (e.g., Crepp et al. 2012b; Adams et al., 2013; Marcy et al., 2014), by obtaining multiple exposures at each of several dither positions in position-angle mode and using the finest plate scale available (to minimize the per-pixel background flux at the closest inner working angles). We will calibrate the data using standard techniques: sky-subtraction, flat-fielding, frame registration, and co-addition.

At Magellan, we use the Clio2 camera in narrow-field mode to provide 16 mas pix^{-1} pixels, providing an 8$\times$16" field of view. At LBT, we use LMIRCam with 11 mas pix^{-1} pixels, providing a 21$\times$21" field of view. In both cases the instruments' fields of view are far larger than *Kepler*'s 4" pixels and so are ideal for our purposes. Nearby stars located beyond the AO FOV will be identified via Pan-STARRS photometry (PI Crossfield has collaborating-scientist affiliation with Pan-STARRS). We will achieve some limited sensitivity to stars within our AO inner working angle via standard *Kepler* light curve diagnostics such as difference imaging and centroid tracking (cf. Bryson et al., 2013).

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

Program Overview & Time Awarded

PI Crossfield is leading this research effort, and Steward resources will play an integral role in characterizing K2 targets stars and validating new planet candidates. We have built a large, international collaboration to study the K2 M dwarf planet sample. We propose targets to K2 to ensure an optimal M dwarf sample, and we have submitted successful target proposals for Cycles 0, 1, & 2. Our team has developed the necessary software to rapidly calibrate the K2 data frames and search for transit candidates (cf. Fig. 2). Ground-based spectroscopy and **adaptive optics will identify false positives, classify target stars, and validate planets**. We have a **Large ESO Program (70 nights over the next 4 semesters)** for followup spectroscopy of target systems to provide precise stellar and planetary parameters. A global synthesis of all K2 M dwarf data will measure the global occurrence rate of planets around M dwarfs, including the frequency of habitable rocky planets.

Target Selection

To find targets, we use our own photometric pipeline (an improved version of Vanderburg & Johnson's 2014 algorithm) and the `TERRA` transit search pipeline (Petigura et al., 2013b,a). Fig. 2 demonstrates that **we are already finding preliminary candidate planets** in Field 0. Because this is a highly competitive field, our target list does not included coordinates of individual objects. Data for Fields 1, 2, and 3 will be released before (or during) semester 2015A. In the intervening time we continue to refine our pipeline, improve the quality of our lightcurves, and increase the number of transit-like detections suitable for AO followup.

A Large, Multi-Facility AO Program

The AO component alone is a large program, and **no single facility can validate our entire M dwarf sample.** We are requesting additional AO observations to supplement Steward AO. These data will come from LBT's German time allocation (**German-time LBT-AO observations are scheduled for Dec 2014**; PI Th. Henning), and from Keck (proposals submitted to both UC and NASA). Our yield simulations (see Fig. 1) estimate $\sim$75 bright M dwarf candidates with $R < 16$ mag, since K2 will have observed four fields by the middle of 2015A. By observing $\sim$10 targets per half-night, we therefore need 4 full nights of AO in 2015B (assuming good weather!). We request 2 nights in this proposal.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). **(up to one page)***

At present (Sep 2014), we have 70 nights of medium-dispersion spectroscopy at the ESO NTT 3.5m (PI Crossfield) and 1 night of LBT-AO through Germany's allocation (PI Henning). We have proposed for additional supporting observations at Keck (see "Summary of Time Requested and Awarded," above.)

PI Crossfield has been awarded time on numerous large telescopes resulting in high-impact publications. Among many others, these include the high-dispersion NIR Keck/NIRSPEC observations of sub-Neptune GJ 1214b, which are directly relevant to this proposal (Crossfield et al. 2011); high-dispersion NIR VLT/CRIRES Doppler Imaging of the nearby brown dwarf Luhman 16B (Crossfield et al. 2014, *Nature*); and medium-resolution Keck/MOSFIRE spectroscopy of the transiting hot Neptune GJ 3470b (Crossfield et al. 2013). He also advised two UA undergraduates during their use of UA's small-aperture telescopes (Biddle, Pearson, Crossfield, et al., 2014).