Maximizing *Kepler* science return per telemetered pixel: Searching the habitable zones of the brightest stars

A white paper submitted in response to the *Kepler* Project Office *Call for White Papers: Soliciting Community Input for Alternate Science Investigations for the Kepler Spacecraft*[1] released 2013 August 02.

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1. Executive Summary

primary recommendation: In Paper I (Hogg et al.) we propose image modeling techniques to maintain 10-ppm-level precision photometry even with only two working reaction

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[1] http://keplergo.arc.nasa.gov/docs/Kepler-2wheels-call-1.pdf

wheels. While these results are relevant to many scientific goals for the repurposed mission, we advocate for a change of strategy; namely, **observing bright stars continuously in "low-torque" fields across the ecliptic plane.** There are considerable benefits of such a strategy.

- The first scienfitic goal[2] of *Kepler* is to **determine the frequency of terrestrial and larger planets in or near the habitable zone of a wide variety of spectral types of stars**. Not only does this recommendation not detract from this strategy, it may provide the best chance to answer this question moving forward.

- By limiting ourselves to bright stars, the *Kepler* long cadence integrations of 29.4 minutes can be shortened, allowing for more sensitive observations of transit timing and transit duration variations. These stars will be later observed by TESS, but only for 30 days; there will not be enough transits observed to detect variations due to planet-planet interactions. Therefore, by observing bright stars that can be followed up by TESS, this will enable dynamical studies that could not be undertaken with either telescope alone.

- Similarly, shorter integrations may allow for asteroseismological studies of more stars. Many asteroseismological targets have been subgiant or giant stars, for which the period of oscillations are long enough so that they can be observed in long cadence data (Chaplin Ann Rev. 2013) By decreasing the integration time, solar-type oscillations can be observed on less massive stars. On these stars, asteroseismological signals are smaller, but by focusing on bright stars we expect the signals to still be observable.

This white paper is organized as follows. In §2, we outline our target selection and observing strategies. In §3, we project the expected number of planets detected by this strategy. In §HZ, we explain how this strategy will enable completion of the primary scientific goal of the *Kepler* mission. §5 and §6 outline the dynamical and asteroseismological "bonus science" that can be accomplished, the former especially in a synergistic manner with TESS.

2. Target Selection

Simulations suggest pointing errors from a two wheel *Kepler* will be minimized by pointing in the ecliptic plane, where the torque exerted on the telescope by solar pressure is

[2]http://kepler.nasa.gov/science/about/scientificgoals/

approximately zero. Such areas are expected to be stable for approximately six months, so that the expected drift is negligible over a 30 minute or shorter integration. We propose to observe fields in the ecliptic plane for this reason. To avoid the Earth crossing the field of view, it is recommended the telescope point only in the direction opposite motion, meaning each field is stable and observable for only three months. **Fortunately, the ecliptic plane is ideal for the *Kepler* telescope**. Recall the *Kepler* field is situated 8-18 degrees out of the galactic plane. This location provides a compromise between having a sufficent quantity of $K_p < 16$ stars to observe and a lack of crowding in the telescope's 4 arcsecond pixels. The ecliptic plane and galactic plane cross twice, at RA of approximately 7 and 19. It is therefore possible to choose four fields, each separated by approximately 6 hours in RA, that are both on the ecliptic plane and approximately the same distance from the galactic plane as the *Kepler* field. These are located near RA of 3, 9, 15, and 21.

In this paper, we do not attempt to choose specific fields, but instead simply show that there are sufficent observable stars such that our proposed observations are feasible. In part, this is because as Hogg et al. discuss, our image modeling techniques may be more successful when the drift is larger. With degraded pointing and additional drift, the diversity of stars that touch different combinations of pixels is increased. More simulations are required to determine the optimal positioning of the telescope with respect to the ecliptic so that the drift is large enough to maximize our abilities to model pixel sensitivities but small enough that the stars stay within their apertures. Fortunately, it is quite simple to select four fields that are both near the ecliptic and well separated such that each can be observed for approximately three months.

We recommend shorter integration times than the long cadence observations, as we discuss more fully below. As a result, fewer targets are available for observations than have been previously observed. We aim for approximately thirty thousand targets per field, with preference given to brighter stars. Here, "brighter" is intentionally left as an ambiguous term. If our goal is to detect Earth-sized planets, then M dwarfs are allowed to be fainter than G dwarfs because of their deeper transit signal.

If our image modeling techniques are successful, then a field similar to the original *Kepler* field with respect to the galactic plane will contain a sufficent number of viable solar-type and smaller targets. To verify each field will contain enough stars, we simulate the population of the nearby galaxy with TRILEGAL (Girardi et al. 2002).

We first consider the current *Kepler* field. TRILEGAL is limited to fields of 10 square degrees. To combat this, we simulate three regions of 8 square degrees across the *Kepler* field orthogonal to the galactic plane. We then estimate the extinction in the galaxy by calibrating the extinction value at infinity using the values found in the extinction map created by Schlegel, Finkbeiner, and Davis (1998). We return the *Kepler* magnitude of each star in our field.

Fig. **??** shows the distribution of stars as a function of effective temperature and apparent magnitude. Ideally, stars in the lower left region of the figure would be chosen. The number of simulated stars found is comparable with the true number of observable stars in the *Kepler* field.

There are sufficent hypothetical fields near both the ecliptic and galactic planes to develop four similar fields from which 30,000 stars could each be selected. It is of considerable importance, however, that **if new fields are selected, they should be located a similar distance from the galactic plane**. We provide evidence in support of this claim in the form of Fig. **??**. This figure was developed in an identical manner to Fig. **??**, but the numbers correspond to the expected yield in a region of the sky far away from the galactic plane (0:00:00, +0:00:00, blue) and very close to the center of the galactic plane, pointing away from the galactic center (6:00:00, +23:30:00, red). Out of the galactic plane, solar-type stars are an order of magnitude less common; in it, these stars are a factor of two more common, meaning crowding (and background eclipsing binary false positives) would be even more a concern than in the original misison[3]. Therefore, if new fields are selected we strongly recommend selecting four fields near the ecliptic plane and approximately 15 degrees from the galactic plane.

3. Expected Planet Detections

To determine the number of planets we would expect to find with this new observing strategy, we consider the best source of information on transiting exoplanets, the *Kepler* list of planet candidates found on the NASA Exoplanet Archive[4]. The number of detections depends on the level of success of our image modeling efforts, which has not yet been precisely quantified. A *reasonable, conservative* estimate is that we can expect to detect planets larger than 3 Earth radii around Sun-like stars. Planet transit signals induced by these planets would be, of course, nine times deeper than the transit of an Earth analogue, and is detectable by eye in the current *Kepler* data.

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[3]This is not a problem for a future M dwarf mission: because the stars are intrinsically faint, most M dwarfs brighter than 16th magnitude are within 100 parsec and distributed approximately isotropically across the sky.

[4]http://exoplanetarchive.ipac.caltech.edu

By our mission design strategy, we would stare at each of four fields for one quarter of a year, or 93 days. To observe three transits of a planet, we would then be limited to planets with periods of 31 days or smaller. We search the Exoplanet Archive for objects that are listed as “candidates” with periods less than 31 days and transit depths larger than 756 parts per million, 9 times that of an Earth analogue. In the Q1-Q6 catalogue, there are 620 matches to these criteria (in the full catalogue, this number increases by less than 10 percent).

Since we propose to observe 120,000 stars, not the 190,000 observed in the primary mission, we scale this number and find we would expect to detect **392** candidate planets (after a similar amount of vetting for false positives to the current mission! We would expect to discard 165 false positives) with periods shorter than 31 days and radii larger than thrice Earth’s. If our image modeling is successful, these are conservative predictions. If we are able to detect objects twice the size of Earth, the number of expected candidates jumps to **749**. Moreover, this thought experiment assumes a one year new mission. If the remaining two reaction wheels encounter no problems, we would expect to be able to push our detections to longer periods. Moreover, we would be biased toward planets with approximately one year periods due to our unique observing cadence. The proposed cadence is both a blessing and a curse for finding planets in the so-called habitable zone, as we explain in the next section.

4. The Frequency of “Habitable-Zone” Planets

Goal 1 of the *Kepler* mission is the determine the frequency of terrestrial and larger planets in or near the habitable zone of a wide variety of spectral types of stars. For M dwarfs the habitable zone varies considerably by spectral type, but is always located at periods inside of 30 days (citation goes here). Thus, in a one-year mission we would expect to determine the frequency of M dwarf habitable systems. This number is presently poorly constrained due to the small number of M dwarfs observed in the primary mission; we hope this is given prime consideration in the future plans for the telescope.

The true frequency of habitable zone planets is less constrained for solar-type stars. If our image modeling techniques are successful, such a strategy as the one proposed here will enable an estimate of this value in a multi-year extended mission. Because we return to the same field every year, we will be biased towards planets that transit once per year. Planets that transit exactly twice (or three, or N) times per year will also appear in our sample as habitable zone “imposters.” Such imposters can be accounted for in a statistical sense by an analysis of transit durations (which increase as a function of period), and for individual highly interesting systems by future space-based follow up. Therefore, we do not expect such "imposters" to be a significant hinderance.

For each field, because of our cadence, we expect to miss a significant fraction (approximately 75%) of the transiting habitable zone planets. This is an unavoidable effect from this observing strategy, but should not affect our results. Because *Kepler* would always be staring at one of the four proposed fields, it will always be on the lookout for some transiting, potentially habitable systems; this missed systems can be accounted for statistically.

5. Dynamics with *Kepler* and TESS

5.1. The Flatness of Transiting Exoplanetary Systems

Despite the tremendous success of *Kepler* at finding planets, questions remain as to the flatness of the exoplanetary systems uncovered. While the vast majority of transiting systems must have inclinations of a few degrees or fewer, it is unclear how flat is "flat." Moreover, in special cases we may expect inclined companions to transiting planets. For example, hot Jupiters may be formed by early dynamical interactions with a mutually inclined perturber, initially exchanging inclination for eccentricity and then circularizing through tidal effects. If this scenario is accurate, then we would expect inclined companions to slowly perturb transiting planets. As the inclination of a transiting planet changes, so does the chord the planet cuts across the face of its star. This also necessarily changes the duration of the planet transit, especially for large impact parameters when a small change in inclination significantly affects the length of the transit chord.

Due to its four year mission lifetime, *Kepler* is not optimal for observing these secular effects, which occur with timescales

$$\tau = \frac{M_\star}{M_p} P_{tr} \tag{1}$$

with $M_\star$ the mass of the host star, M_p the perturber's mass, and P_{tr} the period of the transiting planet. For a planet in a 10-day orbit perturbed by a $2M_J$ object, this cycle is approximately 14 years. However, a repurposed *Kepler* working in concert with TESS or a future TESS-like mission would be the ideal instrument for this study. *Kepler* will be able to measure the transit durations of large, warm transiting planets in a few fields in 2014. Moreover, with an increased cadence the precision of observations will be enhanced over the work currently accomplished in the *Kepler* field. Observing transits each year will enable a search for transit duration variations (TDVs). When these fields are revisited in 2018-2019 with TESS, we will immediately have at least a five year baseline to compare transit durations against. **This is a science objective that could not be carried out**

by TESS or *Kepler* alone. A search for TDVs will enable key outstanding questions about the architecture of exoplanetary systems to be answered; there are not any missions current or planned that will be able to study the flatness of exoplanetary systems as well as the combination of a repurposed *Kepler* and TESS Perhaps add in a line about apsidal precession? Exomoons?

5.2. Masses of Transiting Planets

An unexpected success of the *Kepler* mission has been the discovery of many systems with tightly-packed inner planets (hereafter STIPs, e.g. Boley and Ford 2013). Ten percent or more of stars appear to have planets a few Earth radii in size with periods smaller than 20 days. These systems appear to form around stars of a variety of spectral types, from Solar-type stars (Kepler-11, Lissauer et al. 2011) to mid M dwarfs. (Kepler-42, Muirhead et al. 2012). While their existence is unquestioned, their formation is uncertain. Boley & Ford (2013) propose *in-situ* formation via aerodynamic drift, while Cossou et al. (2013) and Swift et al. (2013) propose migration of planetary embryos. To better understand the formation and evolution of these systems, it is imperative to understand their mass (and thus density) distributions. The most effective method to determine masses of small transiting planets to date has been the characterization of transit timing variations (TTVs) (e.g. Fabrycky et al. 2012), the effects of gravitational perturbations between planets near each conjunction.

Far and away the most common type of TTV observed with *Kepler* is variations that occur on the timescale of planetary conjunctions for near-resonant systems (the ones described above). A mission that observes systems for approximately one month per year is suboptimal for detailed characterization of this type of TTV for specific systems. However, all hope is not lost. In the commonly observed case where both near-resonant planets transit, the period of the TTV signal is known and equal to the period of conjunctions, leaving the only free parameters the amplitude of the TTV signal and its phase. As the typical period of these conjunctions is 1-2 years, one quarter of observations is not enough to determine the masses of the transiting planets. However, return observations of these systems over multiple years with *Kepler* and eventually with TESS can enable a full cycle to be observed, allowing for masses to be estimated. Even when a full cycle can not be observed, strong upper limits can be placed on the masses of the planets from TTV nondetections.

Kepler was, fundamentally, a statistical mission. A study such as this will help us better understand the statistics of TTV systems. While we will likely not be able to characterize systems as well as can be presently accomplished (e.g. KOI-142, Nesvorny et al. 2013), statistical analyses that lack sufficent numbers of TTV systems will be able to be undertaken.

If the updated *Kepler* mission collects four pointings each of 30,000 stars, then of the 120,000 stars observed, 12,000 would be expected to host STIPs and approximately 600 of these systems would be expected to trasit. Adding numbers such as these to the current sample will allow a tremendous increase in our understanding of the properties of these systems and provide insight into their formation.

6. Other Benefits

In some ways, the proposed mission is similar to a mini-TESS. There are considerable benefits to such a strategy. Many have been outlined above; the potential to open up TESS to searching for TDVs and TTVs over 400 square degrees of the sky cannot be overstated. TESS will also have the ability to search for longer-period planets in these fields, when its data is combined with *Kepler* data. It is worth mentioning that this proposed survey will only cover one percent of the sky, and will thus not impinge on TESS' discovery space in any significant way. It is of our opinion that the benefits to observing these fields in the first half of this decade as a precursor to TESS only serves to enhance the future mission, as opposed to detracting from it.

Observing brighter stars at a higher cadence will allow asteroseismological studies of more stars than were observable with the completed *Kepler* mission. With decreasing stellar density, both the magnitude of the pulsations and their periods increase, making giants more appropriate asteroseismological targets. With brighter targets at a higher cadence, if carefully planned, we can open up these studies to stars nearer the main sequence. **Tom, this discussion is very superficial, perhaps because that is the best word to describe my knowledge of asteroseismology. Does Dan Huber want to add something here?**

An additional benefit to focusing on brighter stars is the increased ability for radial velocity (RV) followup. If our proposed obsering strategy is undertaken, there will be four new *Kepler* fields, two near a declination of +20 degrees and two near -20 degrees. These are ideally placed for follow up radial velocity work by existing telescopes in Hawaii and Chile, as well as future 30-meter class telescopes. The faintest stars in the *Kepler* field are too faint to be observed effeciently on existing telescopes, and with observing time as competitive as it will likely be on the proposed giant telescopes, this is unlikely to change. Therefore, a focus on brighter stars (perhaps $K_p < 15$ for solar-type stars) will enable more effecient and successful RV follow up.

Finally, and perhaps most significantly, such a mission will allow potentially interesting objects to be found before the launch of the James Webb Space Telescope (JWST). Scheduled to launch in ~~2011~~ ~~2015~~ 2018, JWST will be placed at the inaccessable L2 Lagrange point, making it necessarily a fixed-length mission. Moreover, by this time the *Spitzer* telescope will have drifted too far from Earth to still be scientifically useful. TESS is scheduled to launch at approximately the same time as JWST, but space telescopes do occassionally run into delays for various reasons[5]. If TESS were to be delayed, and JWST ran for only its nominal five year mission, it is conceivable that many of TESS' most interesting discoveries will occur at a time when there are no available infrared space facilities available for follow up work. Certainly, even if both telescopes proceed according to plan, time will be limited between publication of TESS' results and the end of the JWST mission. This proposal, which intends to find interesting transiting systems across the sky, will accomplish this feat well before the launch of JWST, allowing considerable time to plan observations with the future observatory before launch and assuring that JWST will have an abundance of planets to characterize.

7. Summary and Conclusions

Our strategy outlined here is one possible observing strategy. If our image modeling techniques are successful, we feel such a strategy provides a unique opportunity for the contributions of *Kepler* to continue unhindered for the next decade, through a combination of its observations and those planned in the future by TESS.

Blah blah blah *Anyone else want to contribute a writeup?*

8. Acknowledments

Blatant stealing of text from Hogg's paper goes here.

[5]see also: JWST