

KEPLER 2.0: A SEARCH FOR SMALL PLANETS AROUND SMALL STARS

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Abstract

We propose to continue and extend the *Kepler Mission's* exoplanet survey by observing 8 to 12 fields in the Ecliptic plane for 2 to 3 months each over the next two years. *Kepler* is optimized for precise photometry and stable long-duration observations of many thousands of targets. By taking advantage of the pointing stability available for ecliptic plane fields we can retain much of the precision and stability. Continuing the exoplanet survey but concentrating on small cool stars will allow *Kepler 2.0* to meet several key science goals: to determine the habitable zone planet occurrence rate for cool stars, to identify a number of planets orbiting bright small stars amenable for characterization with JWST, to link the planet statistics of the prime mission with those of the TESS survey of nearby stars, to help quantify the background false-positive rate in the TESS results, to enhance TESS target selection by identifying giants in the TESS input catalog, and to identify planets for long-baseline TTV follow-up by TESS. By continuing observations in a manner very similar to the *Kepler* prime mission, *Kepler 2.0* will provide the most technically feasible and lowest-cost way to leverage the experience of the engineering, operations, and analysis teams, as well as the data processing pipeline, in order to provide light curves, planet candidates, and diagnostic products for tens of thousands of cool stars.

I Introduction

The phenomenal success of the *Kepler Mission* has revolutionized the field of extrasolar planets. During its 4 years of operations *Kepler* has yielded a host of firsts in exoplanet science: the first indisputably rocky exoplanet (Kepler-10b, Batalha, et al. 2010), the first Earth-size planets (Kepler-20e -f, Fressin, et al. 2012), the first habitable zone planets in a system (Kepler-62e, -f, Borucki, et al. 2013), the smallest planet (Kepler-37b, Barclay, et al. 2013), and the first circumbinary planet (Kepler-16, Doyle, et al. 2011). More significant than the individual findings have been the statistical results from *Kepler*. *Kepler* has shown that small planets are common in the Galaxy, habitable zone planets are common, and planetary systems are common. The recent release of results from the first three years of *Kepler* data has uncovered more than 3,500 “Kepler Objects of Interest,” or KOIs that have been dispositioned as planet candidates³. The ongoing analysis of the full four years of data promises to yield many more smaller and cooler planets, as the *Kepler* pipeline is refined to reduce instrument artifacts and uncover the smallest transit signals.

With the recent failure of the second of *Kepler's* four reaction wheels the science community and the public have been disheartened to learn that collection of exoplanet science data may have come to an end. Fortunately, the recent reports from Ball Aerospace and Technologies Corporation (BATC; described in the supporting material for this call for White Papers), suggest that this need not be the case. Although *Kepler* cannot continue its sensitive exoplanet survey in

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³ See KOI list at the NASA Exoplanet Archive: <http://exoplanetarchive.ipac.caltech.edu/>

its historical field-of-view, there are regions of the sky where *Kepler* can point with sufficient precision and stability to allow for a new sensitive exoplanet survey that can:

- (1) fill in holes in the prime mission target list by greatly increasing the number of cool small stars surveyed and better determine the frequency of small planets around cool stars,
- (2) tie the statistics of planet frequency among Galactic disk stars of *Kepler*'s prime mission survey to those of the nearest stars that will come from the upcoming Transiting Exoplanet Survey Satellite (TESS), and
- (3) identify a number of transiting planets around bright nearby cool stars that will be amenable for atmospheric characterization by NASA's upcoming flagship James Webb Space Telescope (JWST) mission.

We are proposing that *Kepler* continue its exoplanet survey by observing cool M and K dwarfs in the ecliptic plane. By observing 8 to 12 fields for two to three months each over the course of two years, *Kepler 2.0* can discover 60 habitable zone planets around cool stars including ~20 planets around stars brighter than 12th magnitude, ideal candidates for JWST follow-up.

It is possible to maintain stable pointing for such a relatively long duration due to the symmetry of the *Kepler* spacecraft and the orientations of the remaining viable reaction wheels. *Kepler* can be pointed stably for up to three months at a single field-of-view (FOV) in the ecliptic plane. In this orientation, with the Sun in *Kepler*'s X-Y plane (see Figure 1), the torque from the Sun is primarily about the Z-axis and can be compensated for by the reaction wheels without the use of thrusters for attitude control. Pointing precision is limited by the precision of the guidance corrections from the star trackers (~1 arcsec precision). Importantly, the ecliptic plane orientation offers the potential of using the fine guidance sensors on the focal plane for pointing control, which would restore the pointing precision to near prime mission levels, greatly improving photometric precision. Pointing duration on a given field is limited by Sun-avoidance and power requirements to about $\pm 45^\circ$ about the normal to the solar arrays, or about 90 days of orbital motion. In this mode, "resaturation," or spinning up, of the two reaction wheels is required every 3 to 4 days in order to allow them to continue to absorb momentum from the solar torque. This resaturation is done using thrusters and allows for small pointing corrections to put the Sun back in the X-Y plane and to reset the boresight RA & Declination.

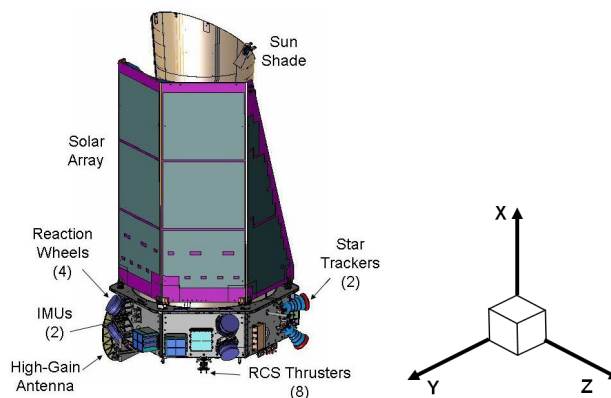


Figure 1: The *Kepler* spacecraft and photometer showing the orientation of the coordinate axes. The X-axis is aligned with the boresight, the Y-axis is out of the center line of the solar panels, and the Z-axis is opposite the high-gain antenna. With *Kepler* oriented such that the Sun is in the X-Y plane, the solar torques are around the Z-axis and can be balanced by the two remaining viable reaction wheels.

Pointing drift about the boresight (X-axis), which cannot be corrected by the two wheels, occurs as the Sun moves out of the X-Y plane. Therefore, slight pointing errors will result in

uncompensated roll about the boresight. Modeling by BATC indicates that with an initial pointing error such that the Sun is 20 arcsec out of the X-Y plane, the boresight roll over 4 days will be ~ 120 arcsec, corresponding to ~ 12 arcsec, or 3 pixels, at the edge of the focal plane (see Call supplemental materials). Experience with the star trackers indicates that pointing repeatability of ~ 20 arcsec is achievable with calibration, especially in the benign thermal conditions of staring observations in the ecliptic plane. With 1 arcsec pointing precision and ~ 3 pixel maximum image drift based on BATC modeling, we can expect photometric precision to be dominated by image motion coupled with inter- and intra-pixel variability.

We have carried out preliminary simulations of *Kepler* data using the predicted pointing jitter and drift and find that simple analysis can recover $\frac{1}{2}$ hour precision of 500 parts per million (ppm) at $K_p=12.5$ without compensating for motion in the flux time series – a step that is critical in achieving the full precision from *Kepler's* prime mission data– so we expect to be able to realize a significant improvement in precision after regressing out image motion. However, even with this conservative estimate of precision, we can still expect to detect small planets around M dwarf stars, since the transit of a $1 R_{\oplus}$ planet around an M0 is 220 ppm, 550 ppm around an M3, and 2,100 ppm around an M5 star. A $1.5 R_{\oplus}$ super-earth would show a 490 ppm transit around an M0 and a 1,200 ppm transit around an M3. The signal-to-noise ratio grows as the square root of the number of transits, so we gain a factor of ~ 2 in SNR for the short-period M-dwarf habitable zone (HZ) orbits. We detail the predicted planet yields for our ecliptic plane fields under different estimates of achieved precision below.

In addition to the spacecraft being capable of continuing a sensitive transit survey in the ecliptic plane, the *Kepler* operations team and data analysis pipeline are capable of taking maximum advantage of such observations with minimal costs. Because our proposed mission is very similar to the prime mission, routine operations will be largely unchanged from the prime mission, once calibration of the two-wheel spacecraft is completed. Additionally, since the data gathered will be similar to a quarter of prime mission data, we will be able to run the existing analysis pipeline – from calibration through Data Validation of transit candidates, with only minimal modifications to allow for new fields-of-view. By using the existing pipeline, we will produce all of the archive products: calibrated pixels, light curves, threshold crossing events (TCE), and data validation products, to which the community is accustomed.

In short, an exoplanet survey mission in the ecliptic plane offers the highest science return from a spacecraft that was optimized for finding transiting planets in long strings of stable data. It is the best, lowest risk, lowest cost, way to take advantage of the *Kepler* spacecraft, the operations team, who have been operating the spacecraft in a similar manner for four years, and the Science Office (SO) and Science Operations Center (SOC) teams, who have been analyzing and interpreting *Kepler* results for years, and who have the most complete knowledge of the nuances, limitations, and strengths of the *Kepler* data. By continuing and expanding the exoplanet survey, we will provide the best science return from *Kepler*, directly supporting major goals of NASA's Science Mission Directorate, the Astrophysics Decadal Survey *New Worlds, New Horizons in Astronomy and Astrophysics*, and NASA's 30-year Astrophysics Roadmap.

II Scientific Approach and Goals

The major scientific contributions from *Kepler* in both exoplanets and stellar physics have been due primarily to the remarkable photometric precision and the nearly continuous nature of the observations. In spite of its reaction wheel failures, *Kepler* can still carry out an observation campaign with sufficient precision, cadence, and duration to answer several important scientific questions and to help pave the way for NASA's long term goals in Astrophysics to search for

Earth-like planets and to answer the question “are we alone?”⁴ We propose to take advantage of the opportunity offered by the orientation of the spacecraft when observing in the ecliptic plane to continue and expand *Kepler*’s exoplanet mission by searching for planets around small stars in 8 to 12 ecliptic plane fields over the course of two years. This small planet survey directly addresses key recommendations of the 2010 Decadal Survey: *New Worlds, New Horizons in Astronomy and Astrophysics*, in particular the discovery of nearby habitable planets as a first vital step in the search for life around other stars (Decadal Survey 2010). This survey and the likelihood of finding small planets around stars bright enough for JWST follow-up directly address portions of NASA’s 30-year Astrophysics Roadmap. Finding nearby transiting planets that can be characterized by JWST is identified as a key near term (within 15 years) step along the road towards probing the atmospheres of HZ terrestrial exoplanets (15 to 30 years) and eventually mapping the surfaces of HZ planets (beyond 30 years; Koveliotou 2013). Details of the proposed observing approach are given in section III. Here we present expected results from a conservative simulation of *Kepler*’s performance in the ecliptic plane.

Expected Planet Yield

The planet yield expected from the ecliptic fields can be estimated to first order by scaling the expected yield from TESS, which is expected to find ~500 Earths and super-Earths⁵. There are 30 distinct *Kepler* FOVs around the ecliptic plane, providing approximately 30/400 of the sky. Thus, we would expect to discover on order of 30 Earths and super-Earths, approximately one per FOV, assuming we observed all 30 for one month each, as TESS will. However, since *Kepler 2.0* can observe deeper and up to 3 times longer than the typical TESS observation, this calculation is conservative.

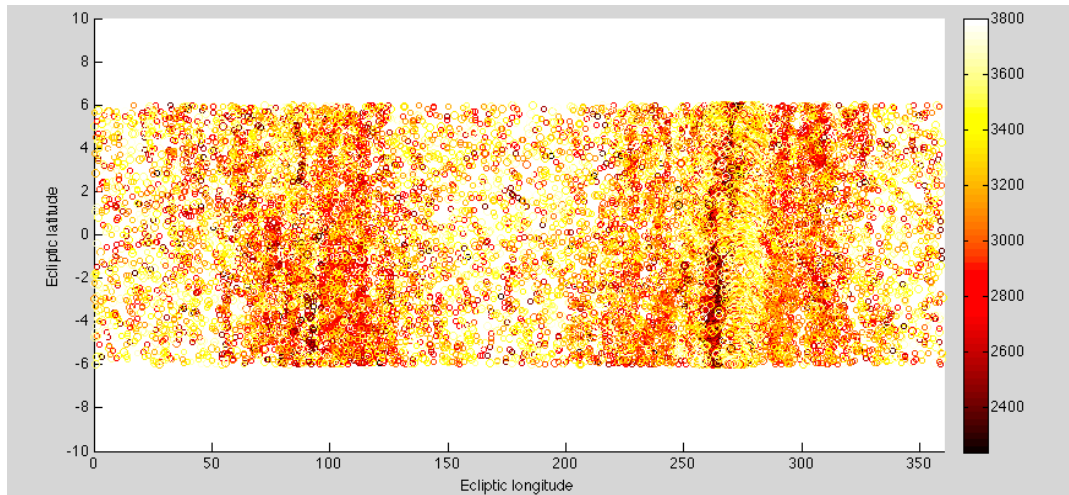


Figure 2: M-dwarf stars from the TESS input catalog within ± 6 degrees of the ecliptic plane. The color scale indicates the effective temperature and the marker size is proportional to brightness. There are 60,000 M-dwarfs down to 18th magnitude, or ~2,000 per *Kepler* FOV. Clearly, the regions of the ecliptic

More detailed calculations can be performed using the TESS sample input catalog, which contains approximately 17000 M stars ($T_{\text{eff}} < 3800$ K) brighter than $V=14.0$ and 4000 K5 and later K stars brighter than $V=14.0$ within ± 6 degrees of the ecliptic plane (the approximate diameter of *Kepler*’s FOV; see Figure 2). Given the short periods corresponding to the habitable zone for these small stars (~40 days at M0, and ~20 days at M3), the geometric probability of alignment is rather high, 15% to 20%. If such planets are common, we expect approximately

⁴ <http://science.nasa.gov/astrophysics/>

⁵ http://space.mit.edu/TESS/TESS/TESS_Overview.html

1500 to show transits, assuming conservatively that half the stars in the TESS sample catalog are dwarfs that have not evolved off of the main sequence.

The number of detections depends on the photometric precision actually achieved with the *Kepler* 2.0 observations. In order to estimate the precision that we might achieve, we have generated a series of model star images using the Target Aperture Definition (TAD) code from the *Kepler* pipeline and a model jitter power spectrum for an ecliptic plane FOV provided by BATC (see Figure 3). TAD provides a high-fidelity model of a *Kepler* image and includes all major instrument characteristics and noise terms (Bryson et al. 2010).

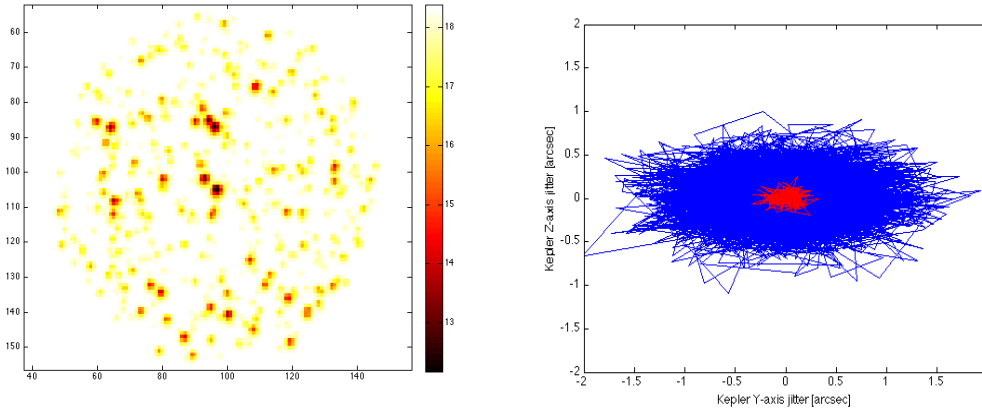


Figure 3: Model star image from channel 58 (left) and 4-day pointing time history realization generated using the BATC supplied pointing error power spectrum (right). The colorbar on the star image denotes the approximate Kepler magnitude. The brightest star at the center has $K_p=12.5$. The stars are drawn from the KIC. The pointing time history shows the 1-minute pointing error (blue) and the long cadence (30 minutes) average pointing error (red) from a BATC model of the ecliptic plane pointing using the star trackers and two reaction wheels. The 1-sigma 30-minute error is 0.12 arcsec in Y and 0.07 arcsec in Z, in contrast with the prime mission value of 0.003 arcsec when using the fine guidance sensors and full set of reaction wheels.

We generated 192 long cadence images, representing 4 days worth of normal data collection. From these images we collected simple aperture photometry on fourteen stars of varying magnitudes. We then calculated the $\frac{1}{2}$ -hour precision for these stars (see Figure 4). We achieved significant improvement in the precision of stars that were in crowded apertures by regressing out the 30-minute Y-axis and Z-axis pointing positions (red diamonds in Figure 4). While both the photometric analysis and the treatment of the motion were extremely simplistic, the resulting precision provides a conservative estimate of what we might expect for stars over a range of magnitudes. A simple linear fit to the motion-corrected precision versus magnitude (green line in Figure 4) was used to assign predicted precisions to the TESS catalog ecliptic plane stars for the purpose of estimating the planet yield.

The planet yield model calculates the transit alignment probability and signal detection probability for a planet of a given size at an orbital distance defined by either the incident flux level relative to that at Earth (S_{eff}), or the planet's equilibrium temperature. As we are primarily interested in small habitable zone planets, we ran several cases for varying levels of incident flux at the model planet: $S_{eff} = 1.0, 1.1, 1.75$ times the Solar flux at the Earth. These values correspond roughly to the moist greenhouse, ocean evaporation, and early-Venus empirical habitable zone inner limits respectively (Kopparapu, et al. 2013). The planet yield per ecliptic plane FOV are given in Table 1. These numbers assume one such planet per star. While the average number of planets per cool star is an open question that *Kepler* 2.0 will help to answer, preliminary estimates of the occurrence rate of small planets based on *Kepler* prime mission data range from 0.5 to 0.87

planets per star (Kopparapu 2013, Dressing & Charbonneau 2013), so the numbers in Table 1 might be scaled by 0.5. With this 50% occurrence rate and a 50% reduction from assuming that half of the TESS catalog stars are evolved giants by observing 8 fields over 2 years, we could expect 6 $1.0 R_{\oplus}$ planets, 16 $1.25 R_{\oplus}$ planets, and nearly 30 $1.5 R_{\oplus}$ planets at the inner edge of the HZ. We would expect nearly 60 $1.5 R_{\oplus}$ planets at $T_{eq} \geq 400K$.

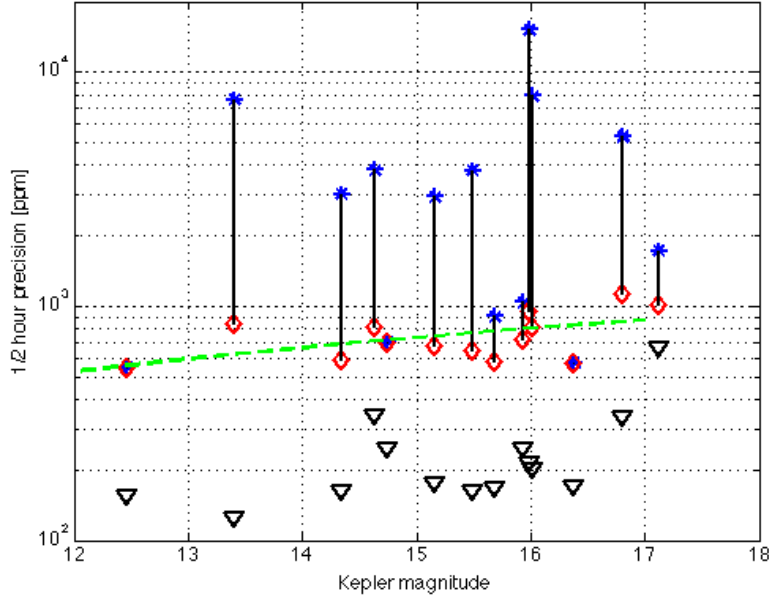


Figure 4: Photometric precision for 14 model stars using a BATC supplied jitter model. The raw precision is indicated by blue *’s, the precision obtained after regressing out the Y-axis and Z-axis 30-minute pointing errors is indicated by the red diamonds. Note the order of magnitude improvement in some of the stars with crowded apertures. The black triangles indicate a theoretical minimum noise consisting of shot noise from the star and background flux and read noise appropriate for the long cadence apertures. The green line is a simple linear fit to the motion-corrected precision versus magnitude and was used to assign predicted precision to TESS catalog stars for the purpose of estimating the planet yield.

Table 1: Predicted number of HZ planets per Ecliptic plane FOV in 3 months of observations. Observations average 6,300 dwarf stars with $T_{eff} < 6000 K$ per field. The numbers assume one such planet per star and that all stars are main sequence dwarfs. Eight such fields could be observed in 24 months.

	$R_p = 1.0 R_{\oplus}$	$1.25 R_{\oplus}$	$1.5 R_{\oplus}$	$2.0 R_{\oplus}$	$2.5 R_{\oplus}$
Flux = $1.0 F_{\oplus}$	1.7	5.4	9.4	18	23
Flux = $1.1 F_{\oplus}$	1.8	5.8	10	19	24
Flux = $1.75 F_{\oplus}$	2.8	8.2	14	25	31
$T_{eq} = 400K$	7.1	18	28	49	57

The planet yield numbers presented here are conservative as they are a strong function of precision. If we can lower the photometric noise to 0.66 times the levels used for this model, we would expect to increase the yield of $1.0 R_{\oplus}$ planets from 5 to 15 at the inner edge of the HZ. We are confident that by taking advantage of the sophisticated systematic error corrections available with the *Kepler* analysis pipeline we can realize such an improvement in photometric noise.

Because of the long duration on an ecliptic FOV and the low roll rate, it could be possible to define fine guidance sensor (FGS) targets in the same manner as the prime mission, allowing for the possibility of using the FGS in the attitude control loop. Guiding with the FGS would restore the pointing precision to near that of the prime mission, resulting in photometric precision comparable to what was achieved then, ~ 30 ppm at 12th magnitude over 6 hours. While it is not certain that the FGS can be used, we advocate testing this possibility due to the great increase in photometric precision and thus in the subsequent science output that would result.

Scientific Goals

The proposed *Kepler 2.0* mission has several complementary science goals that are well aligned with the goals of NASA. Such a mission can provide valuable input to two high-profile missions scheduled to launch in the next 5 years: TESS and JWST.

Synergies with the TESS Mission

Observing fields in the ecliptic plane to search for small planets transiting small M- and K-type stars offers multiple synergies with the TESS Mission, slated for launch no earlier than 2017 or 2018. TESS is an all-sky transit survey that will spend 27 days on each FOV in order to tile the entire sky. The TESS team expects to detect at least 300 Earths and super-Earths over the two-year mission and at least 1000 planets in total. The ecliptic FOV mission proposed here will reduce the technical risk of carrying out the TESS mission, as well as enhance the science return from TESS in several ways.

First, this proposed ecliptic FOV mission will discover planetary objects that are similar to those we expect TESS to discover orbiting the same stars that TESS will observe in 5 or so years. Thus, the planets discovered by *Kepler 2.0* will furnish a list of planetary systems for TESS that will complement the planets TESS discovers transiting these same stars as it is unlikely both TESS and Kepler will observe the same transiting planets, except for those with periods short enough to have multiple transits in the ~ 1 month of TESS observations. Moreover, the follow-up and characterization teams for TESS, which are just now spinning up with the selection of TESS by the Explorer Program this year, can use these *Kepler 2.0* objects to "cut their teeth on" well in advance of the TESS Mission. Thus, the TESS team can develop and refine their follow-up strategies and procedures well before TESS flies and will be ready to perform their job for TESS when the time comes. Given that the planet candidates identified in the TESS data set will occur on a monthly basis, it will be important for the team to have efficient strategies in place to manage their resources to keep up with the torrent of potential transiting planets.

Second, the TESS Science Processing Operations Center (SPOC) will be located at NASA Ames Research Center and is being developed based on the *Kepler* SOC codebase and architecture. The *Kepler 2.0* data will be similar to that expected from TESS and thus, will provide a similar data set that can be used to help reduce risk in retooling the *Kepler* SOC to support TESS, which has some key differences from *Kepler* in the conditioning of the data and the shorter periods of the transiting planets to be detected.

The *Kepler 2.0* observations will enhance the science return from TESS by helping to mitigate the risk to TESS posed by background eclipsing binaries and background planets since a *Kepler* pixel covers 1/25 the sky area of a TESS pixel (4 arcsec per pixel as opposed to 20 arcsec per pixel for TESS). These observations will also allow us to look somewhat deeper than TESS and if we elect to observe for longer than one month in some of the fields, *Kepler 2.0* can help determine the robustness with which transiting planets can be recovered with only one or two transits, and therefore help to maximize the discoveries possible with TESS.

The *Kepler 2.0* results will tie together the exoplanet statistics from the *Kepler* prime mission, which observed relatively faint Galactic disk stars, with those from TESS, which will observe

brighter Solar neighborhood stars. The overlap of 8 to 12 FOVs –approximately 1000 square degrees– will allow for a direct comparison of the completeness, reliability, and biases of the two surveys, resulting in a better understanding of the frequency and distribution of exoplanets. *Kepler 2.0* observations will improve TESS target selection for the overlapping fields by pre-detecting the giants due to their oscillations and activity at the millimag level. Additionally, the planet detections from *Kepler 2.0* will provide a long 5-year baseline for detecting transit timing variations (TTV) in the TESS data. Such TTVs will enable the detection of non-transiting planets in those systems that would not otherwise be detectable in the TESS 1-month observations.

Planets around Bright Stars

Finding small planets around bright nearby cool stars in the *Kepler 2.0* survey would be a great boon for the study of exoplanets as they would be ideal candidates for atmospheric characterization studies by JWST. Such discoveries would provide several years of advance notice for thorough ground-based characterization of these targets and their planets. The characterization of exoplanet atmospheres is one of the key steps towards reaching one of the goals of NASA’s 30-year Roadmap: “Are we alone?” Indeed, the near-future portion of the Roadmap specifically calls out the need to find nearby transiting planets and characterize them with JWST (Kouveliotou 2013). One of the prime goals of TESS is to provide a set of exoplanet targets for JWST characterization; indeed an all-sky survey is needed to ensure a reasonable number of such targets are detected. However, the launch of TESS is currently scheduled to precede that of JWST by a year or less, so while the detections of TESS will provide a vital target list, they will not have the advantage of the ground-based characterization available for the *Kepler 2.0* discoveries.

Table 2: Maximum distance in parsec for JWST-NIRspec characterization and number of predicted Kepler 2.0 cool star planets. The distances are the furthest at which an exoplanet transiting a cool star would have a detectable atmosphere at 15σ . The numbers in the second sub-column are the total numbers of planets of each type predicted by our planet yield model for 8 FOVs in the ecliptic plane, assuming each star has such a planet. The first number results from our conservative precision estimate from the model image data (see above) and the second number in [brackets] is that predicted if we achieve a factor of 0.66 reduction in photometric noise.

	T _{eq} = 400 K		T _{eq} = 1000K	
1 M _⊙ H-rich	d _{max} = 10 pc	0 [0]	d _{max} = 40 pc	2 [4]
4 M _⊙ H-rich	d _{max} = 14 pc	1 [1]	d _{max} = 43 pc	6 [8]
10 M _⊙ H-poor	-not detectable by JWST		d _{max} = 26 pc	10 [18]

We can estimate the potential number of planets that might be amenable to characterization with JWST-NIRspec from 1 to 5 microns using the recent sensitivity study Batalha & Kalirai (2013). Their maximum distances for detecting transiting exoplanet atmosphere under several conditions are summarized in Table 2. Hydrogen-rich exoplanets are much more detectable due to their large atmospheric scale heights. Also shown in Table 2 are our expected numbers of detections of planets around M-dwarfs (T_{eff} < 3800K) within these distances using our current predicted photometric precision and a model with a 0.66 reduction in noise. While we expect only one 400K planet around a sufficiently bright star in 8 FOVs, we expect a number of hotter 1000 K planets from 1 to 10 M_⊙ around bright stars amenable to JWST characterization, even in the case of the H-poor atmosphere. Of course, an effort should be made to identify the FOVs that have the greatest number of bright (V<12) M-stars to enhance the science return and increase the value of the follow-up and characterization efforts.

Guest Observer & Participating Scientist Opportunities

Our proposed mission offers a significant increase in the opportunities for Guest Observers and/or Participating Scientists over the prime mission. Because of the concentration on cool stars, *Kepler 2.0* will be using only a small fraction of the total quota of target definitions and pixels. Based on the TESS input catalog, the ecliptic plane fields average only about 6,300 stars with $T_{\text{eff}} < 6000$ K. Fields nearer to the Galactic plane will have more stars, but still nowhere near the target/pixel limits even as *Kepler's* downlink rate decreases. This leaves many tens of thousands of targets, or even large patches of the sky available for Guest Observer/Participating Scientist science.

III Technical Approach

We propose to use *Kepler* in a manner as similar as possible to operations in the prime mission by conducting a staring mode survey in search of small transiting exoplanets. Given the limitations of two-wheel control, however, the best location for doing such a survey is no longer the *Kepler* prime mission FOV, rather it is a series of FOVs in the ecliptic plane. Because of the Solar torque, the symmetry of the spacecraft, photometer Sun-avoidance, and power limitations, we can stably observe a FOV in the ecliptic plane for up to 3 months at a time. We predict the best science return from observing a series of 8 to 12 FOVs for 2 to 3 months each over the course of two years. We will use the TESS input catalog as a starting point for selecting targets and will define apertures using the tools developed for the *Kepler* prime mission. We expect to observe on the order of 10,000 targets on any given FOV, a small fraction of the target/pixel resources available and so the remainder—the vast majority of the target/pixel resources—would be available for the science community. We propose to maintain the same 1 minute/30 minute short/long cadence observing sequences. Over the course of two years, we would observe between 80,000 and 120,000 targets, each with ~3 months of data, which is comparable to the amount of data from one quarter of *Kepler* prime mission observations (~3 months * 150,000 stars). Because of their similarity to *Kepler* prime mission observations, the *Kepler 2.0* observations can be analyzed in the existing pipeline with minimal modifications.

Advantages of Observing Fields in the Ecliptic

A preliminary analysis of the costs for retooling the Kepler SOC pipeline software for the purpose of collecting and processing data from a mission consisting of observing a sequence of ecliptic fields for 2-3 months each indicates that the software development costs are quite modest—about 22 person months of effort in total, which likely can be performed in a single 4 to 6-month software build cycle by ~50% of the current *Kepler* software development team. Similarities to the *Kepler* prime mission with respect to the likely data volume, and more importantly, the conditioning of the data for these new observations imply that operations costs should be comparable to those of the *Kepler* prime mission as well, with some increase in the short term as the team learns how to operate the spacecraft in this new mode. The retooled *Kepler* SOC pipeline will be fully capable of delivering all the current archival data products to the science community in the standard *Kepler* formats, including the calibrated pixel and flux time series products now archived to MAST, and perhaps more importantly, the Threshold Crossing Events and Data Validation reports currently archived to NExScI. The ability to reuse the existing pipeline significantly increases the likelihood that the analysis will be completed in a timely manner and that the science goals of the *Kepler 2.0* mission will be achieved.

While the allure of continuing observations in the current *Kepler* FOV is strong, there are significant technical barriers to getting precise photometric data there. The quality of data obtained for the *Kepler* FOV is likely to be significantly reduced compared to ecliptic FOVs due to the fact that the stars will be rotated to a new set of pixels every 24 to 48 hours as the orbital motion of the spacecraft requires a boresight rotation of 1° per day to keep the Sun in the spacecraft X-Y plane. Such a rotation will require new target tables daily and will lead to very

bright stars, currently relegated to the gaps between CCD modules, moving across the focal plane on timescales of days. The systematic errors due to the boresight drift and to the scattered light from bright sources will result in a more severe set of artifacts as well as reduced photometric precision compared to the case for an ecliptic plane FOV, where the location of the bright sources and their associated artifacts is relatively stable, permitting the *Kepler* SOC software to effectively identify and remove systematic errors to obtain sufficient photometric precision.

A software development cost analysis was also performed for the case of a two-wheel *Kepler* prime mission FOV with a resulting estimate of more than twice that of the ecliptic FOV case. The pixel and flux archival products would need to be significantly different than those of the prime mission, due to the necessity for a different target table each day or two of operations. Conducting a Transiting Planet Search (TPS) of the new data and generating of Data Validation (DV) reports we excluded from this cost estimate due to the complexity of conditioning the data and handling the changing target tables. In contrast, we expect to process ecliptic plane FOV data through the entire pipeline, including TPS and DV, as well as to archive those final products.

IV Summary: Kepler 2.0

We posit that the *Kepler 2.0* ecliptic plane two-wheel mission offers the best science return with the highest technical feasibility at the lowest cost for a number of reasons. We are proposing to continue operating *Kepler* in a manner as similar as possible to the prime mission. Such operations take advantage of the optimized design of the *Kepler* photometer and spacecraft. They allow the experienced operations team to continue in much the same manner as they have been, using most of the operations tools without modification. They allow the data analysis to continue using the team, pipeline, and analysis tools in order to produce and archive established products that will allow the science community to continue to reap the scientific rewards from *Kepler*. The primary differences from the *Kepler* prime mission are the changing FOV, and the shorter duration of observations on a given target set. The science output of such a mission is well aligned with both near-term and longer-term goals of NASA-Astrophysics, will keep *Kepler* at the forefront of exoplanet science for years to come, and will help to bridge the gap between the *Kepler* prime mission and the launch of TESS and JWST in 2017/2018.

V References

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