Kepler's Unparalleled Exploration of the Time Dimension

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Abstract

We show that the *Kepler* spacecraft in two–reaction wheel mode of operation is very well suited for the study of eclipsing binary star systems. Continued observations of the *Kepler* field will provide the most enduring and long-term valuable science. It will enable the discovery and characterization of eclipsing binaries with periods greater than 1 year – these are the most important, yet least understood binaries for habitable-zone planet background considerations. The continued mission will also enable the investigation of hierarchical multiple systems (discovered through eclipse timing variations), and provide drastically improved orbital parameters for circumbinary planetary systems.

1. Introduction and Motivation

The spectacular success of the *Kepler* is a result of the Mission's four pillars:
1. Ultra high-precision photometry (∼30 ppm for 12.5 mag in 6.5 hours)
2. Simultaneous observations of very many stars (∼170,000 stars)
3. Nearly continuous coverage (∼90% duty cycle on the same stars)
4. Very long duration (∼4 years exploration of the 4th dimension)

The high precision is an obvious signature of *Kepler*, but the other three aspects are equally important. Without them, the mission could not have been successful.

The original *Kepler* Mission's goal is to determine the frequency and characteristics of exoplanets by surveying a large number of stars and searching for planetary transits. Short period planetary and eclipsing binary (EB) systems are easy to detect since their transit and eclipse events are frequent. But for the more interesting longer-period systems, e.g., planets near the habitable zone, transits and eclipses are infrequent. These orbital periods are on the order of hundreds of days for an Earth+Sun-like system. A few-year mission will not be able to detect a meaningful number of such events. A single transit/eclipse event is not very useful; a minimum of two are required to even estimate the period. Three events is considered a minimum for candidacy (unless part of a multi-object system), but 4 or more are needed to begin to untangle some of the complexities of the orbit, like eccentricity and precession. For planets or stars with orbital periods of a year or longer, this demands more than the current 4 years of data to carry out a full investigation.

There are numerous long-period *Kepler* Objects of Interest (KOIs) and EBs for which we have only a few eclipse events. *Kepler* was able to discover these objects because of its unique many–star and "long–look" observing strategy. As we show below, *we can capitalize on Kepler's fantastic scientific legacy by continuing the Mission.* Regrettably we cannot continue the hunt for Earth-size planets around Sun-like stars, but we can continue the search for Earth-size planets around small stars, for larger planets (in particular, those in the habitable zone), and for EBs where even the degraded Kepler photometry can provide ample signal. With only 2 functioning reaction wheels, *Kepler*'s guiding is not stable enough to allow ultra-precision capability. But, *Kepler* has not lost the other 3 pillars of what made it great, provided it remains pointed at the same field.

If *Kepler*'s reaction wheels did function, there would be no question that the best place to point the telescope would be its original field. And, if a new hypothetical *Kepler* telescope were to be launched, it would take 4 years just to catch up to where the original mission left off — showing how exceptionally valuable the temporal baseline is. Larger and more sensitive missions can and will be launched. But those will not allow detecting long-period systems, for which there is no substitute for temporal information. Assuming the mission can continue for up to 2 more years, pointing to any other field(s) will gain no more than 2 years of data, of poorer quality than the already existing 4 years of *Kepler* data. Keeping *Kepler* on the original field gives a total of 6+ years of information — reaching sensitivity in the temporal dimension that simply cannot be achieved with any current or planned missions. Six years of nearly continuous observations of the same stars would create a legacy that would last for generations.

2. Science Drivers and Goals

2.1 Eclipsing Binary Stars

Binary stars are a natural outcome of star formation, and indeed, for stars $\geq 1M_\odot$, binaries are not the exception but the rule (Raghavan 2010, Kraus 2011). Eclipsing binary stars are a very special subset of binaries and are the cornerstone of stellar astrophysics: their unique geometry allows us to directly measure key stellar parameters – radii, masses, temperatures, and luminosities. We can measure the masses and radii to a few percent (Andersen 1991; Torres et al. 2010), and with *Kepler* data, down to 1% or better (e.g. Bass et al. 2012). An ensemble of systems enables further modeling that then yields the statistical relations that are used to calibrate stars across the H-R diagram (Harmanec 1988), determine accurate distances (Guinan et al. 1998), and study a range of intrinsic phenomena such as pulsations, spots, accretion disks, etc. (Olah 2007). Nearly every topic in astronomy benefits from a better calibration of stellar physics, and *Kepler* is enabling a factor of 10x better determination of masses, radii, temperatures and luminosities. Moreover, our interpretation of exoplanet transits is intrinsically limited by our characterization of the host star.

2.2 Binary Science Goals for an Extended Mission in the Kepler Field

We argue that continued monitoring of the *Kepler* field will provide the highest impact science for a continued mission in two-reaction wheel mode – which we refer to as *"Kepler II"*. In particular, it will allow the following unique achievements.

2.2.1 The discovery and characterization of EBs with $P > 1$ year: *Kepler* has been incredibly fruitful for the study of binary stars; the *Kepler* Eclipsing Binary Star Catalogs I, II, and III (Prša, et al. 2010, Slawson et al. 2011; Kirk et al. 2013) are major deliverables of the *Kepler* Mission. However, the investigation remains incomplete: the longer-period EBs are under-represented if not outright missing. Long-period binary systems are far more numerous in the sky: the field distribution is log-normal, peaking at ~ 50 AU (Raghavan 2010). However, the eclipsing ones are observationally rare, due to the precise alignment needed between the observer and the binary orbital plane. In the current *Kepler* EB Catalog there are 989 systems with periods between 0.001 and 0.01 years, 848 systems between 0.01–0.1 years, 255 between 0.1–1.0 years, but only 14 between 1.0–10 years. There are many more long-period systems awaiting discovery in the *Kepler* field if only we keep looking.

The discovery of long-period systems is invaluable for several reasons. First, long-period EBs are crucial for *Kepler*'s primary mission goal of determining η Earth: these long-period eclipsing systems are the most important for estimating the occurrence rate of background EBs for determining the false-positive KOIs of habitable planets. Second, long period systems are particularly well suited for benchmarking stellar properties; one obtains all of the stellar parameters without the added complications of tidal interactions. Even though radial velocity (RV) surveys can partially characterize these systems, the precision of the stellar and orbital parameters will be far superior for systems that eclipse. And of course, eclipses provide radii, while RVs do not.

More broadly, a large sample of longer-period EBs can help resolve important unanswered questions in binary formation theory. Even with the torrent of new data, close binaries still present challenges to theories of binary formation (Artymowicz & Lubow 1996, Bate 2000, Tohline 2002). There is no single mechanism that can explain the range of observed systems. The existence of planets in these systems further restricts formation pathways by setting a very stringent timescale on the host system's orbital evolution to small periods. While RV surveys can and do discover binaries in this period range, the light curves observable with *Kepler* will allow us to measure the radii and stellar spin periods (via starspots), and also make best use of the Rossiter-McLaughlin (R-M) effect. The R-M effect provides the relative angle between the stellar angular momentum and the orbital angular momentum. Thus these data can uniquely distinguish between migration-based and dynamically-driven models for close binary formation.

2.2.2 The discovery and characterization of hierarchical multiple systems: Stellar and substellar tertiaries in binary systems are observed either directly (by detecting tertiary eclipse/transit events in the *Kepler* light curve) or indirectly (from eclipse timing variations). By modeling eclipse shapes and dynamical aspects simultaneously – via the method called photodynamical modeling – the precision of derived fundamental parameters of the system can reach an astounding $\sim$0.2% in radius and $\sim$0.5% in mass (Carter el al. 2011, Doyle et al. 2011), an order of magnitude better than what we can obtain from eclipsing binaries alone (Torres et al. 2010). Thus multiple star systems are truly superior for stellar and orbital parameter calibration.

Detecting multiple systems is very challenging and thus it is no surprise that so many major discoveries are credited to *Kepler* – because of its long-term, uninterrupted observations of

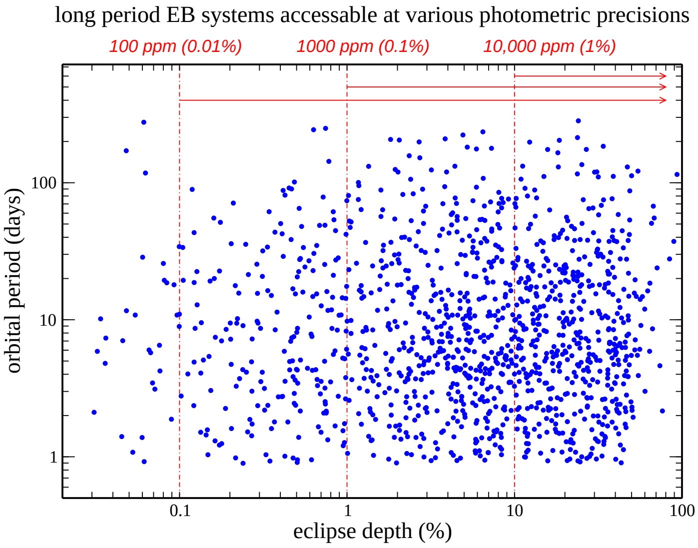

Figure 1: **EBs observable with *Kepler II*** — The orbital period for the longer-period *Kepler* EB sample is plotted versus the primary eclipse depth. *Assuming a threshold of S/N of >10 for being useful,* the dashed vertical lines show the photometric precision needed to measure the eclipses for various eclipse depths.

the same field. Temporal baseline is extremely important in this regard because tertiaries will always have comparatively long periods as required by dynamic stability of the system. In particular, 32 out of 111 short-period binaries that exhibit eclipse timing variations (ETVs) indicate a presence of a tertiary component with a period longer than 4 years (Conroy et al. 2013) meaning that a *third* of the sample lacks sufficient temporal coverage. For the longer-period EBs ($P \gtrsim 1$ day), the rate of triple-star systems is 27% (Orosz et al. 2013). Continued surveillance of the *Kepler* field, even at degraded photometric quality, is the only way to garner a statistically significant sample. Such a sample will also shed light onto formation theories by allowing for the study of changes in mass ratios and orbital properties with spectral type.

2.2.3 Improved parameters (orbital and mass) for circumbinary planetary systems: The degraded photometry of *Kepler* will likely prohibit the discovery of new transiting circumbinary planets if their depths are comparable to those in the current sample (aside from Kepler-16 whose primary transits would be easy to detect). Nevertheless the continued monitoring of the existing 14 systems will provide far better constraints on the planetary parameters. For many of the detected circumbinary planets, there are more degrees of freedom in the dynamical modeling than there are transits. We expect to be able to detect some predicted future transits, and the transit timing information will enable much better determination of the planet's orbit. Deviations from the predicted time may indicate the presence of non-eclipsing planets. In addition, longer-duration monitoring will allow us to become sensitive to planets at larger semi-major axes from their host stars – and these are predicted to be the giant planets (Pierens & Nelson 2008), and thus have ample transit depths for detection.

3. Feasibility and Expected Photometric Performance

3.1 Feasibility of Proposed Goals: To demonstrate the feasibility of our science goals, we consider the detectability of the current *Kepler* EB sample with a more noisy *Kepler II* mission. Because we are mainly concerned with the longer-period EBs in this White Paper,

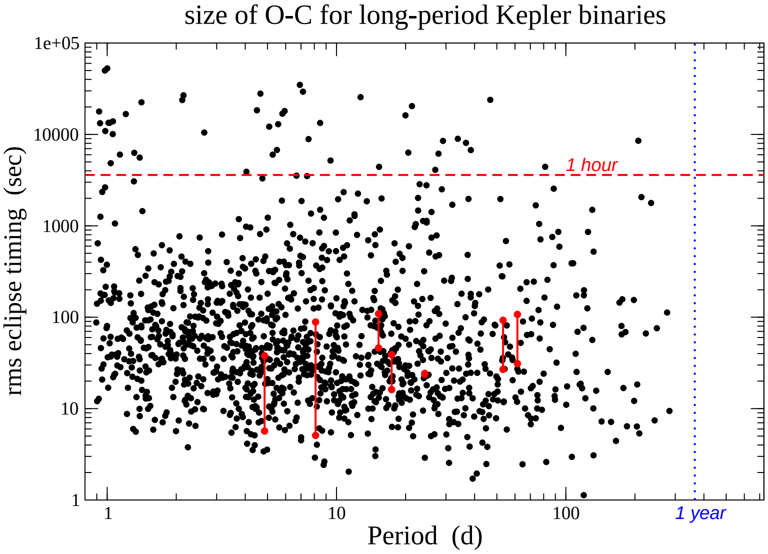

Figure 2: **O-C vs P** — The orbital period of a binary star will normally be constant, yielding an O-C curve that is zero aside from noise. But if a third body perturbs the binary, the O-C will have systematic patterns and the rms of the O-C will be large. The upper portion of this figure shows those EBs with exceptionally large O-C variations, due to a third (or more) star. The right-hand portion of the figure is empty, showing the lack of long-period EBs. The red points connected with a vertical line show the current rms timing variations (lower points) and the expected rms for a *Kepler II* mission (upper points).

we make use of the Orosz, et al. (2013) sample of EBs with $P \gtrsim 0.8$ days, but note that this is mildly incomplete due to on-going work: there are 24 systems with $P > 1$ yr not yet analyzed in addition to the sample of 1250 EBs shown in Figures 1–4.

Figure 1 shows the orbital period of the longer-period EB sample plotted against the primary eclipse depth. If we require the eclipse depth to be 10x larger than the short-term photometric noise, the dashed red vertical lines show the photometric precision needed to measure the eclipses times as a function of the eclipse depth. Points to the right of the dashed lines are measurable with the precision marked along the top of the figure. For example, if the eclipse depth is 1%, a photometric precision of 0.1% is required. Because the eclipses are so deep (median depth is 6.6%), analysis of many, if not most, of the sample is possible even with significantly degraded photometric precision. Even if only 1% precision is available, that leaves 509 EBs accessible to continued analysis in the *Kepler II* mission, or $\sim$ 40% of the long-period EB sample.

Figure 2 shows the rms deviations of the primary eclipse times from a linear ephemeris (i.e. the O-C amplitude) versus the binary period. The median period of the Orosz et al. (2013) sample is 7.13 days. Several important features are illustrated: (i) The median O-C rms is only 46.4 sec; by contrast, the points at the top of the figure have huge eclipse timing variations ($>$ 1 hour). These are not due to poor measurements; they are real variations that are caused by a third star perturbing the binary orbit. As noted above, these $\sim$ 50 systems are prime targets for an extended mission in the *Kepler* field. (ii) These huge timing variations are so large that timing precision of even hundreds of seconds would still be more

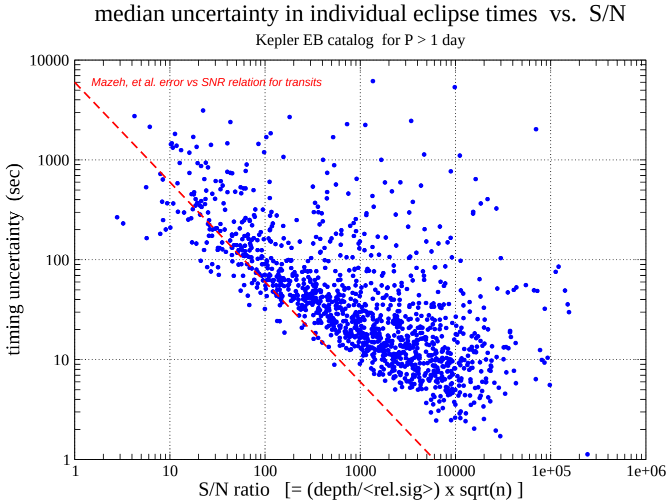

Figure 3: **Eclipse Timing Uncertainty** — The precision with which we measure eclipse times is shown as a function of the signal-to-noise ratio. The SNR spans almost a factor of 10^5, and the median precision is < 30 sec. A large number of EBs have such high SNR that a degradation of even a factor of 50x in photometric precision will still allow timing precision to better than 100 sec.

than adequate to help measure the properties of the third star. (iii) The right-hand part of the figure is sparse – these are where the longest-period binaries would reside, and where we would gain the most from continuing in the original *Kepler* field. Shorter surveys would simply re-populate the shorter-period part of the figure. (iv) The red points connected with a vertical line illustrate how the timing precision degrades (moves up) with the expected *Kepler II* photometric performance (based on simulations described below). In some cases, the degradation is completely negligible. In other cases it is a factor of ~ 20 worse. For many cases, the timing is still excellent and sufficient for investigations of third body dynamics.

Figure 3 shows the median uncertainties in the measured eclipse times versus the signal-to-noise ratio (SNR). As before, these are for the longer-period EBs that have a detached or semi-detached morphology. Because the eclipse signal is so strong for these data (the median SNR is ~ 1200), the median uncertainty in a measurement of an individual eclipse time is only 28.9 sec, which is roughly a factor of 20 better than the median uncertainty in planetary transit times. The expected trend, based purely on random-noise statistics, is illustrated by the dashed line representing the transit-timing uncertainty relation from Mazeh et al. (2013): $\sigma_{TT} = 100/\mathrm{SNR}$ (minutes). Scatter off this line is likely due to intrinsic stellar noise (starspots, pulsation, etc.). At very high SNR, the data deviate significantly from the expected line, suggesting the onset of a noise floor, perhaps caused by the 30-min cadence binning. This would imply that for these cases, as the SNR degrades due to poorer photometry, the loss in timing precision is not as steep as expected. This is born out in the simulations discussed below.

The same data can be plotted versus *Kepler* magnitude, as shown in Figure 4. The sample has a median brightness of Kp = 13.96 mag. Note that the median timing precision is not a strong function of Kp: the precision is relatively flat out to 16th magnitude. This means that as the noise increases, the precision of the eclipse timing does not rise nearly as quickly as naively expected. While the timing uncertainty is not insensitive to the photometric noise, the expected degradation is not important for the higher-SNR cases or for the cases with large eclipse timing variations.

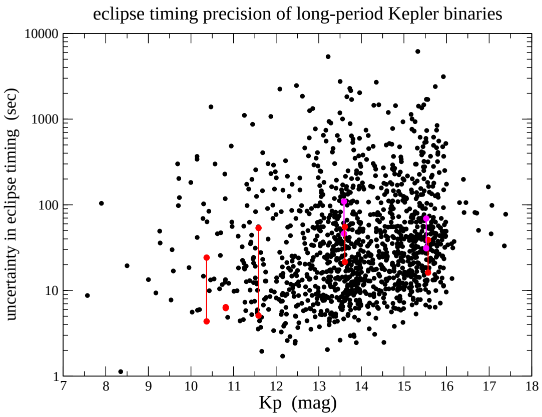

Figure 4: **Eclipse Timing precision** — The median uncertainty of individual eclipse timing measurements is shown versus the Kepler magnitude of the star. Seven test cases are shown in red, illustrating the expected change in timing precision due to the anticipated photometric degradation in the *Kepler II* mission.

Finally, it is important to recall that much of the *Kepler* mission's success has been due to the significant catalog preparation that preceded the mission, i.e., the KIC (Latham et al. 2005, Brown et al. 2011, and later Pinsonneault et al. 2012), plus extensive follow-up observations (KFOP). By retaining the *Kepler* field, we can build on: (1) all available auxiliary data already at hand, (2) all *Kepler* observations from the first 4 years of the mission that are of unique photometric precision, and (3) the ongoing effort by the Community Follow-up Program (CFOP) to acquire follow-up observations.

3.2 Simulated Expected Performance: While the expected photometric performance of *Kepler II* when pointed at the original *Kepler* field is not known, a *rough* estimate can be made. Fortunately, even a rough estimate is sufficient to demonstrate that observations of eclipsing binaries will yield scientifically valuable information.

The dominant source of additional noise in the *Kepler II* photometry will be caused by pixel-to-pixel variations in sensitivity in the CCD. Prior to the loss of the reaction wheels, the telescope guiding was very stable at sub-pixel levels. But without three reaction wheels, the guiding will drift by roughly 2 arcmin per day (=0.625 pix per 30-minute cadence), and consequently the 1% imperfections in flat fielding will be manifested in the light curves. We created a few simulated *Kepler II* light curves based on information made available by Ball Aerospace on 2013 Aug 20. Briefly, we degraded real *Kepler* light curves of eclipsing binaries using a noise model that includes the CCD flat field sensitivity variations. Due to the drift across pixels, the flat field noise is correlated across 2.5 hours, and this was simulated as a moving average (MA) process. A full description of the simulation is available at the Eclipsing Binary Catalog webpage: http://keplerebs.villanova.edu/includes/appendix.pdf. Using these simulated light curves, we measured the uncertainty on the eclipse times.

As noted in Figure 3, the precision with which we can measure eclipse times is not particularly well-determined from statistical considerations alone. Thus a handful of simulations were run to estimate the precision and degradation of our eclipse timing capability. The precision with which we can measure the eclipse times are shown as the red points in Figures 2 and 4. We selected seven systems that span a wide range of brightness, and six of those were not in any way special: they have typical eclipse depths and typical intrinsic and instrumental variability. The seventh case was a very high SNR circumbinary planet case. This example shows no significant degradation because its eclipse is nearly 50% deep.

Figure 5 shows samples of the light curves for two of the seven simulations we ran. These are the two *worse* cases in terms of absolute timing precision (110 sec for KID 10659313), and degradation in timing precision (factor of 17.4x worse for KID 10601579). The take-away message is that even with much worse photometric performance, the eclipse signal is so strong that eclipse timing can still be precisely measured for a large number of systems.

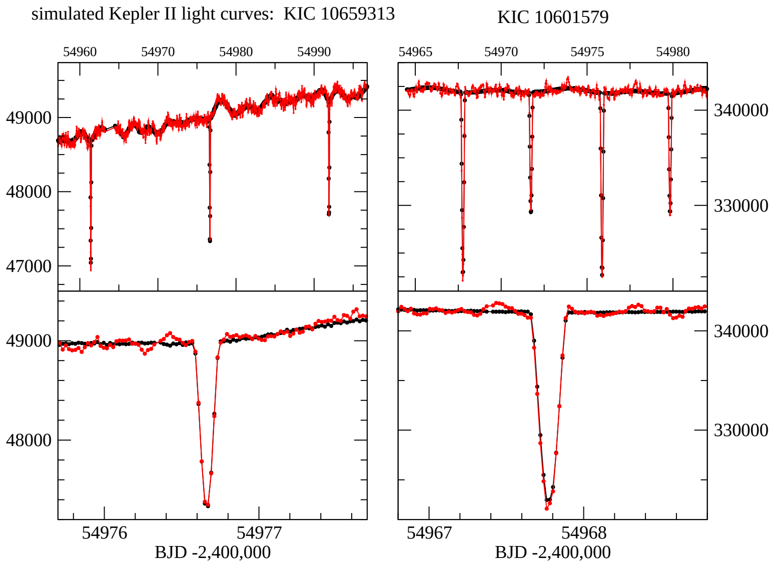

Figure 5: **Example light curve degradation** — *Upper panels:* Simulated light curves of two typical eclipsing binaries. Original data is in black, degraded data in red. The correlated noise due to the spacecraft drift is apparent. These two cases are the *worse* of our seven simulations. In the best cases, the noise is not visible on a scale that shows the full eclipse depth. *Lower panels:* Close-up of upper panels.

4. Observing Mode Details:

4.1 Focal plane mode: Target apertures are needed. These must be large enough to capture the drifting starlight. **4.2 Cadence and Integration times:** If possible, a shorter cadence is strongly desired: we get a stronger signal (less smearing by convolution) and less noise (better pixel-to-pixel systematic noise removal). A shorter cadence means better resolution of sharp ingress/egress eclipse features, thus better analysis. To balance cadence with sample size, 10 or 15 min cadence is desired. **4.3 Data storage needs:** Since far fewer stars than the original mission are proposed, the data storage will generally not be a problem. Even if *all* the KOIs and EBs were observed, this is only ∼6200 stars compared to the 170,000 currently observed. However, larger apertures are needed to accommodate the guiding drift. If the apertures are roughly 40 pixels long, then this very roughly takes 10x more memory. Then a 2x faster sampling (i.e. 15 min cadence) would result in the same data storage needs as the original mission, and allow all KOIs, EBs, and ∼1300 other targets to be observed. **4.4 Data Reduction:** While moving apertures are not needed, new aperture positions are required for every spacecraft roll (i.e. daily). Since large apertures are needed (or contiguous sets of smaller ones), and the star is drifting within the aperture, the standard *Kepler* pipeline will not work. However, this is not nearly as challenging as it sounds: it is just like ground-based aperture photometry where you have to keep track of the star's x,y pixel position throughout the night and have a "soft aperture" within which to sum the flux.

The GO pixel-level photometry tools are the crux of the code. What is needed is a way to track the optimal soft aperture as the star drifts. Simple centroiding (just like in IRAF) is a good starting point. **4.5 Target type:** Stellar point sources. **4.6 Duration:** Targets should be observed continuously, for as long as possible.

4.7 Highest Priority Eclipsing Binary Target List

- circumbinary planets: 14 systems
- long period EBs: 34 systems with P> 300 days
- large ETVs: 280 systems (long-P and depth-changing EBs)
- large ETVs: 32 systems (short-P EBs)
- triply-eclipsing systems: 10
- very low-mass EBs for precise M-R determination: 95 systems (Coughlin et al. 2011)

⟶ Bare minimum total number of EB systems: 465

4.8 Ground-based Eclipse Follow-up? No.

While observations from the ground are helpful for systems with short periods, there are very serious problems that makes such methods totally infeasible for the goals outlined in Section 2.2. Ground-based observing is interrupted by the diurnal cycle, seasons, and weather. Those effects introduce the well-known observing window function (von Braun, et al. 2009) which makes the discovery of long-period punctuated signals like transits and eclipses vanishingly small at periods much beyond one month. Furthermore, it is necessary to observe entire eclipses to characterize the systems described here. The longer the period, the longer the eclipse duration, and once the duration exceeds one night, it becomes exceptionally hard to get full-eclipse coverage for more than a very few systems (multi-site campaigns are needed which often have significant systematics, and are both expensive in telescope time and risky due to weather). Finally, the most interesting cases are the ones where whole eclipses are impossible to predict within 12 hours due to the perturbations caused by the third body. Multi-site campaigns of several nights in duration would be needed for just one eclipse. While it might be possible to devote such resources to a few objects, it is not feasible for a statistically significant set of such eclipsing systems.

5. Arguments For Pointing Along the Ecliptic

Strong arguments can be made for pointing *Kepler* at positions along the ecliptic; but a stronger argument has been made to remain in the original field. Nevertheless, for completeness we list some advantages of moving to a field along the ecliptic. 1) The most significant advantage is the much better guiding stability and hence better photometric precision. However, for studies of eclipsing binaries, this is not that great an advantage, since the eclipse depths are so large that even several millimag precision is very useful. 2) Likely to be far less engineering work required, both for spacecraft management and for on-ground data calibration. This maps directly into significant savings in time and cost. 3) Given that roughly 1.5% of all *Kepler* targets observed are EBs, we can expect hundreds to ∼2000 new EBs to be discovered. Some of these will be circumbinary planet hosts. The catalog of short-period EBs could conceivably be almost doubled. This would be impressive. 4) Several thousand new planet candidates will be identified; a great feat. 5) Discoveries of rare, exotic objects will be made. 6) Targeting a field that contains a well-studied open star cluster (e.g. the Hyades) would yield much better constraints on planet formation and evolution, since the planets would have the same age and composition. 7) With the ∼100-300 ppm precision expected if pointed along the ecliptic, asteroseismology of red-giant stars can be done, and more comparisons between asteroseismic- and EB–derived parameters can be made. Other variable stars will of course be found.

These are significant and exciting advantages, and it is abundantly clear that great science could be done if *Kepler* were pointed at fields in the ecliptic. However, we must keep in mind that statistically, the objects *on average* will be the same (the exceptions being the youthful cluster stars), and the new study will not be as good as the original *Kepler* study (since the photometry is worse, and the duration much shorter). We gain in numbers, and we gain on individual interesting objects, but we do not gain much in a Bayesian sense – because of *Kepler* we have a strong prior on what to expect. It is where the prior is only weakly constrained, as in the longer temporal domain, that the information gain is maximized. In addition, a *very* significant disadvantage of leaving the original *Kepler* FOV is the loss of the huge amount of information gathered on this field. It would take many years of effort to reproduce the *Kepler Input Catalog* and all the Follow-Up Observations – far in excess of the effort needed to enable daily aperture rotations and the development of photometric measurement tools. Unless abundant time and funding is available to reproduce the KIC and FOP, the loss of information is near catastrophic. We conclude that while great science can be done along the ecliptic, even better science can be done in the original *Kepler* field.

8. References

- *The Kepler Eclipsing Binary Catalog* – third revision (beta): http://keplerebs.villanova.edu/
- Appendix: http://keplerebs.villanova.edu/includes/appendix.pdf

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