Kepler Alternative Science: Many Possibilities

Issued in response to the request for white papers.

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Summary

In response to the call for white papers for alternative science to be performed with the *Kepler* spacecraft, we convened approximately a dozen astronomers of STScI and JHU to "brain storm" on possibilities. The most compelling ideas to us were the following:

- Monitoring *Kepler* Exoplanetary Candidates
- Microlensing parallaxes
- Augmenting the data quality of the original *Kepler* mission
- All-sky variability survey

In a second tier were the following:

- Transit search of open clusters
- Search for transits of known RV planets
- Look back at Earth, other planets

Discussion

We briefly discuss the seven ideas below. For nearly all of them, the technical feasibility has considerable uncertainty, commensurate with the current uncertainty of the effective photometric stability of *Kepler* and the possibility of anticipating, or measuring in real time, the focal plane's drift across the sky.

Monitoring *Kepler* Exoplanetary Candidates

Ofir (2013) independently considered continuing to monitor the ~5000 *Kepler* planetary candidate stars at 1 minute cadence. We feel this has considerable merit, but it requires that one can anticipate, or measure in real time, the focal plane's drift across the sky, so that subarrays of the focal plane can be dynamically assigned to create a "postage-stamp" sized aperture around each star. Its scientific usefulness is largely contingent upon an assumption that de-trending can improve the photometric precision to better than the ~1 to ~10 mmag precision described in the call for white papers.

Microlensing parallaxes

Gould & Horne (2013) independently proposed to simultaneously observe microlensed stars from both the Earth and from *Kepler*'s location in an Earth-trailing orbit. We feel this has considerable merit, and may indeed be feasible with no more than the spacecraft capabilities outlined in the call for white papers. Two light curves of a given microlensing event obtained from two well-separated locations can significantly constrain models of the lens, in particular, its distance from our Solar System. This can be especially helpful in the case of planetary microlensing events within the longer-duration stellar microlensing events. It can provide planetary masses and associated projected distances from the host star for each specific case. The microlensing technique is well suited to planets far distant from the host stars, complementary to the original *Kepler* mission's observations of transiting planets that tend to be very near to their host stars.

Augmenting the data quality of the original *Kepler* mission

The original *Kepler* mission inevitably sought compromises in order to focus resources on the core mission goals of detecting small planets in distant orbits and learning enough about the host stars to be able to characterize the planets well. It is well recognized that one of those compromises was to forego a full photometric calibration of the detector systems and to settle for relative photometry.

A full calibration of *Kepler* may not be possible at this time, but the Extended *Kepler* Mission (XKM) offers an extraordinary opportunity to recapture some of what was lost in that compromise, and the operational limitations from the drift rate may actually improve this particular project. What we propose is to first assemble a small working group of individuals with deep knowledge of *Kepler*, of photometric calibration, and of CCD calibration in particular. This group can create the plan needed and the technical specifications.

The immediate goal would be to calibrate pixel-to-pixel variations in sensitivity so as to augment the quality of what is in the *Kepler* archive from the original mission. This group can study scenarios for obtaining the needed data, but one way we believe is feasible is to observe the zodiacal light at about 45 degrees away from the Sun. We estimate the zodiacal brightness at V=20.6 mag per sq arcsec at ecliptic (l,b) = (45,0) deg. For 4"x4" pixels, that's equivalent to a 17.6 mag star. The Poisson noise associated with a 17.6 mag star is 0.7 mmag in 30-min with *Kepler*. Hence, after a few days of observing bright zodiacal light, one should be able to derive flat fields on orbit with a precision of ~0.1 mmag in a pixel-to-pixel sense. The low-spatial-frequency component of the flat field would come from dithered photometry of stars. We also note that zodiacal light has very nearly the same spectral energy distribution as the G stars that dominate the *Kepler* sample, and that helps improve the calibration as well.

Multiple observations of the zodiacal region would be beneficial to be able to eliminate point source contributions and to improve signal-to-noise, but it is likely that this very mundane and yet very valuable task would take only a month or two of the XKM's time.

All-sky variability survey

There are ~400 *Kepler* fields of view across the entire sky. In 4 years, one could observe ~3 days on each field of view, so one could make a short-term variability survey of the entire sky with whatever precision is enabled by the point-and-drift operation nominally proposed in the call for white papers. Kinemuchi (2011) found 260,000 variables (> 5 sigma) with eight full-frame-images (FFIs) from two days of *Kepler*'s commissioning period. Scaling from that, a full-sky survey would find ~100 million variable stars. Also evident in Figures 6 and 7 of Kinemuchi (2011) is the qualitative difference in the long-cadence *Kepler* photometry continuously monitored for very long periods of time compared to the photometry extracted from eight FFIs taken over two days. Although the TESS mission will provide excellent photometry for bright stars (V < 12 mag) over the entire sky, for the foreseeable future, a re-purposed *Kepler* mission may be the only practical manner to obtain ~3-days of uninterrupted, relatively high-precision (< 1 mmag), relative photometry for *fainter* stars all over the sky.

A variant of this theme would be to aim *Kepler*'s solar panels at the Sun and its high-gain antenna at the Earth, and then observe and download to Earth FFIs of whichever field of view results from that telescope attitude. The ecliptic poles are likely to satisfy these constraints, and we note that the Large Magellanic Cloud is near the south ecliptic pole. Hence, this idea may be combined with the microlensing science if FFIs are preferred for operational reasons, e.g. if subarrays cannot be adequately defined to anticipate or track the telescope drift. By downloading in parallel with observing, greater duty cycle would result. Also, if desired, the telescope could be repointed whenever the accumulated drift was too large, based upon imagery analyzed on Earth. However, this idea would require a dedicated receiver on Earth.

Alternatively, there may be telescope attitudes for which the drift rates may be very small and/or azimuthal about the telescope bore sight.

Transit search of open clusters

Meibom et al. (2013) discovered two transiting planets in the open cluster NGC 6811, using *Kepler* photometry of ~400 stars. The transit depths (~1 mmag) and durations (~4 hours) appear sufficient that *Kepler* could still discover similar planets in other open stellar clusters. In principle, discovering planets in open clusters of various ages could enable a study of the frequency of Neptune-sized and gas-giant-sized planets in short-period orbits as a function of stellar age. In particular this may reveal how quickly such planets are delivered to their interior orbits. However, with only a small number (of order two) planets expected per open cluster, with each cluster observed for ~90 days, and with ~20 clusters observed during an additional four years of operation, our immediate assessment is that small number statistics may limit the scientific results of such a study. Nevertheless, such a study adds critical information about hot Jupiters that is now missing, namely how their frequency of occurrence depends on the variables that star clusters control: composition and age, especially age.

Search for transits of known RV planets

Kepler could observe any of the hundreds of planets known to exist from radial velocities (RVs) at times for which a transit is expected if the unknown inclination were to be sufficiently close to 90 degrees. The predicted yield for transiting gas-giant planets could be estimated using the methods from similar work using ground-based telescopes (Kane et al. 2009). With less than 1000 RV planets to search for transits, each of which with an *a priori* probability of transiting of less than ~0.01, we expect a more rigorous calculation would predict *Kepler* could discover transits of not more than a few such planets if it was entirely devoted to doing so for 4 years. (We do not count planets smaller than gas giants because we assume *Kepler*'s photometric precision will not enable their detection; if that assumption is relaxed, smaller transiting planets could be discovered, especially in very short-period orbits.) Any such planets discovered to transit would be valuable for characterization of their atmospheres, because the stars tend to be very bright (V < 9 mag).

Look back at Earth, other planets

Just as the Deep Impact spacecraft was re-used to look back at Earth and the Moon, under the EPOXI program, *Kepler* similarly could be used to observe Earth and the Moon, and the other planets of our solar system, to create templates of their temporal photometric variability. Mitigation of saturation by the very bright planets and systematic errors of photometry may compromise this idea. Perhaps there may be some benefit to observing the interaction of coronal mass ejections with the Earth's magnetosphere, or in some other manner using *Kepler* in coordination with the STEREO mission.

Conclusions

We summarize seven ideas for potential re-uses of *Kepler*. We also place them in our own approximate rank-ordered list of scientific value. Of the four top-tier ideas, three of them could potentially occupy the telescope until it ceases to operate. Two of our four top-tier ideas were independently conceived and more thoroughly documented by other astronomers. One of the top-tier ideas (calibration of the Kepler data) could be performed with a few weeks of observing, and we advocate that due consideration be given to acquiring those observations in 2013.

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