Repurposing the Kepler spacecraft to search for Near Earth Objects

We propose a plan to use a repurposed Kepler telescope to search for near Earth objects (NEOs). Kepler-NEO can effectively be used to discover tens to hundreds of thousands of NEOs as small as 10 meters. Kepler-NEO will also be sensitive to asteroids that are generally not observable from the Earth. Over a multi-year mission, Kepler-NEO can be used to retire almost all significant impact risk from NEOs, provide space mission target candidates, and constrain the history of the inner Solar System. This project will require significant software upgrades, but in return will address several of NASA's strategic goals at a fraction of the price of a new mission.

1 Context

The extremely successful exoplanet era of the Kepler mission has now ended, but the spacecraft can still be used as a space-based telescope asset. One very promising use of a repurposed Kepler would be to search for near Earth objects (NEOs) — asteroids whose orbits bring them close to the Earth's orbit. NASA is very interested in near Earth objects (NEOs) at this time, and is considering robotic and manned NEO missions. The NEOCam mission has received preliminary funding from NASA, and the privately-funded space-based Sentinel mission would also search for NEOs. These mission costs will be roughly $1B. Utilizing a repurposed Kepler telescope would allow NASA to achieve many NEO science goals for a tiny fraction of the cost.

We propose a plan to use a repurposed Kepler telescope to search for near Earth objects (NEOs). Kepler-NEO can effectively be used to discover tens to hundreds of thousands of asteroids as small as 10 meters. Kepler-NEO will also be sensitive to asteroids that generally are not observable from the Earth. Over a multi-year lifetime, Kepler-NEO can be used to retire almost all significant impact risk from NEOs, provide space mission target candidates, and constrain the history of the inner Solar System.

2 Observing strategy

NEOs are moving Solar System objects. Their rates of motion against the sidereal sky can be as large as several degrees per day (five arcseconds or more per minute) at opposition; away from opposition, where Kepler points, the rates of motion can be reduced by a factor of ten or more, such that in a single exposure NEOs will move less than one Kepler pixel.

The most promising observing mode for Kepler-NEO may be to carry out medium-length staring observations, on the order of 30 minutes. (Each of these of course is a stack of 6- or 8-second exposures, as in the nominal observing approach.) During this time the telescope will drift some 25 arcseconds. The telescope is then reset to the original pointing, and allowed to drift again over 30 minutes. This is repeated a number of times (see below). The telescope drift will produce trails for sidereal sources; these trails will be used to identify and remove stationary sources, and allow identification of moving objects, whose trails would look different. The nominal observations would be on or near the ecliptic plane, at solar elongations around 90 degrees. The exact configuration of pointings and repeats would be driven by the onboard storage capability, and optimized based on various systems-level engineering studies.

NEOs must be observed multiple times to determine their orbits: the longer the arc, the better known the orbit. We suggest visiting a series of adjacent fields six times over the span of a few days to week(s). These same fields are then revisited two times at the end of the visibility window (weeks later). Thus, each NEO has a many week arc, which generally will provide a good orbit. The second epoch also allows the detection of slower moving outer Solar System objects (see below).

The biggest problem for faint object searches with Kepler-NEO is that the pixels are very large, which means that the background is relatively high — but static, whereas NEOs move. The suggested data processing strategy is therefore as follows:

- Observe a given field for 30–60 minutes, in a series of 8 second exposures that are summed onboard (as is the current practice)
- Using new onboard processing software, identify all sidereal trails using a Fourier transform method (all sidereal trails will share the same location in Fourier space)
- Remove all sidereal trails
- Median-combine a stack of six independent images of a field to provide a sky-background image
- Subtract this sky-background image from each of the six independent images
- Identify and extract all remaining trails, which should be moving object trails
- Download the moving object postage stamps (trails)

An alternate complementary method to downloading and analyzing the data is to take a swath of pixels across the entire array (10K pixels long) that is 500 pixels high, for 5×10^6 pixels total. In a 30 minute long cadence observation, assuming a nominal drift rate of 1.4 degrees in 4 days, the stars would trail 26 arcsec and stay within the 500 pixel band (if chosen so the drift sweeps through the 500 pixel direction) for 9.5 hours. Formerly, Kepler was able to reliably downlink 5×10^6 pixels at a 30 minute cadence for 30 days in a given downlink activity. With increased geocentric distance, this throughput has likely decreased somewhat.

A combination of the two methods (onboard moving object detection and large area downloads) maybe the optimal approach. In any case, we suggest always downloading one entire chip in order to (1) check of the asteroid-trail detection method and (2) confirm the orbits of those objects that have been found by the onboard software.

3 Data management

The Kepler-NEO data management, reduction, and analysis team will be the same group of people who successfully designed and executed the Spitzer ExploreNEOs program. This team will apply their algorithms and modeling of the data, and will design new software tools specifically suited to the Kepler-NEO dataset.

The Smithsonian members of the team are located in one of the key Kepler-prime institutions, and have access as needed to a large group of experts in Kepler hardware and software, including John Geary, David Latham, and others. The Smithsonian also hosts the Minor Planet Center, with whom we have already made contact about Kepler-NEO, and who will carry out orbit calculations and minor planet (asteroid) archiving.

4 Expected yield

There are a large number of unknowns in the expected yield estimate. Here we construct "reasonable" cases to give us a best-guess at the expected NEO discovery numbers from Kepler-NEO.

The Kepler documentation reports SNR$\sim$1000 at V=16 in a single 8 second exposure. If the sensitivity behaves as with normal telescopic observations and $\sqrt{N}$ obtains, then this sensitivity implies SNR$\sim$10 at V=26 in a single 8 second exposure. An NEO survey could effectively operate at 10σ, which has a random occurrence probability of around 10^{-23}, given that the Kepler focal plane has 95 million pixels; the false probability rate at 10σ is negligible.

At present, ground-based NEO searches have their greatest yield around V=20.5 (a combination of the rising size distribution to smaller objects and decreasing sensitivity at fainter magnitudes). This ground-based peak yield very roughly corresponds to H=21–23, where H is the Solar System absolute magnitude: the hypothetical magnitude an object would have at 1 AU from the Sun and 1 AU from the Earth and at zero phase. H=21–23 corresponds to diameters 50–150 meters, roughly. We expect to reach V=26 with Kepler-NEO, or around five magnitudes fainter than current NEO searches. This implies reaching objects with diameters around 5–15 meters. (The proposal team is currently executing a Spitzer program to characterize the 10 meter NEO 2009 BD.)

Note that the above estimate is based on a single 8 second exposure depth of V=26, but we anticipate 30 minute summed exposures. We will not gain the full three extra magnitudes available (assuming $\sqrt{t}$) with the 30 minute exposures since our moving objects will be trailed. However, even in a "worst-case" scenario with V=24 in a single 8 second exposure, which would be far worse than $\sqrt{N}$, Kepler-NEO will still be sensitive to objects as small as $\sim$20 meters in a single exposure and less than 10 meters in the summed 30 minute exposures. At present, essentially nothing is known about the NEO size distribution at this size.

There are around 1000 NEOs larger than 1 km and 20,000 NEOs larger than 100 m (Mainzer et al. 2011, Trilling et al. 2013). For lack of a better assumption, we simply extrapolate these populations to smaller sizes and find that there are, very roughly, 100,000 NEOs larger than 10 meters. The number of NEOs larger than 10 meters is very poorly constrained, with evidence suggesting both more and fewer NEOs than 100,000 at this size range, so we take 100,000 as a best-guess.

If these 100,000 NEOs are distributed around the ecliptic sky (360 degrees longitude) and in a band 30 degrees tall (latitude) then the total area for these 100,000 NEOs is roughly 10,000 deg^2. This implies 10 NEOs/deg^2 at 10 meters, or around 1000 NEOs per Kepler field. The details of the orbital geometries may reduce this yield somewhat, but we can take

1000 NEOs per Kepler field as a zero-order approximation.

A patch of sky — adjacent fields that are repeated six times — may have 10 or more pointings. (That is, fields 1,...,10 are observed six times in sequence.) Thus, each patch may have a yield as large as 10,000 small NEOs, or more. Depending on pointing constraints, not all patches may be on the ecliptic, which could lead to a factor of 10 decrease in sky density. Nevertheless, one year of Kepler-NEO observing is likely to result in the detection of tens to hundreds of thousands of NEOs.

5 Additional science

There are relatively few known NEOs that have orbits that are mostly or entirely within the Earth's orbit because most NEO searches are opposition searches. Kepler-NEO, because of its pointing requirements and location in the Solar System, would be sensitive to objects whose orbits are interior to the Earth's orbit, either for their entire orbit or just when they pass the Earth. Measuring the number and properties of the interior object population would both allow us to constrain the history of the inner Solar System and to constrain the impact risk from objects from that population.

This moving object search would also be sensitive to moving objects throughout the whole Solar System, including the smallest known main belt asteroids and outer Solar System small bodies. The dynamics of the outer Solar System suggest a complex history, but the properties of some minor subpopulations — which would provide significant constraints on outer Solar System history — are not well known. A very large area and deep survey such as Kepler-NEO would provide would yield a comprehensive and novel understanding of the population of small outer Solar System objects. It would, for example, for the first time provide a well-characterized survey of Centaurs — objects that are in transition from the Kuiper Belt to the inner Solar System — and therefore the determination of their size distribution. This in turn would probe the size distribution of small Kuiper Belt objects (<20 km) beyond what is typically achieved with ground base surveys and will constrain the formation, the dynamical history, and the collisional evolution of the outer Solar System. A Kepler-NEO survey would also allow us to study the detailed properties of the small main belt asteroids, which replenish the NEO population.

Additional science that would also be enabled by this wide-area, deep moving object survey includes surveys for new Trojan asteroids from Mars out to Neptune; new irregular satellites of outer planets; inbound comets before they turn on; small (<10 m) impactors on ballistic trajectories; Earth mini-moons; space debris of various types; distant Sedna-like KBOs; and the spatial distribution of impactor population, among many other topics.

6 Significance

The significance of Kepler-NEO is as follows:

- Interest is high right now in characterizing the NEO population, and no other existing facility could provide as significant an advance as Kepler-NEO

- Essentially nothing is known about the NEO population at sizes of $\sim$10 meters

- Kepler-NEO would allow us to measure the size distribution of very small NEOs, with implications for both impact risk and scientific understanding

- Kepler-NEO would provide a measurement of the interior NEOs, where much of the impact risk is contained, but which is very difficult to constrain from the ground

- Kepler-NEO would allow us to constrain the history of the inner Solar System by measuring the size distribution of NEOs, and also provide additional information on the smallest main belt asteroids, as well as the outer Solar System small bodies

- Kepler-NEO would be revolutionary for the field of NEO studies at a fraction of the \$1B+ cost of future dedicated NEO missions

7 Work required

The primary new work required of the Kepler spacecraft team would be the development of new software. This includes flight software, to execute the observations; onboard software, to detect NEOs for downloading; and post-processing, to understand the properties of the detected asteroids.

Development of onboard detection and compression algorithms for Kepler-NEO could be considered as technology demonstration with implications for future NEO detection spacecraft missions. JPL's `AutoNav` flight software has much of this functionality, and could be used in part as the baseline for some software construction for Kepler-NEO.

It is clear that this proposed program would require extensive software development, and we understand that this is very expensive. We view the Kepler-NEO project as one that carries a relatively high cost (though low compared to a new NEO mission), but would have a very significant return.

We suggest that, if feasible, a pilot study be carried out to test several of these data acquisition and analysis steps before implementing the entire survey.

If requested by NASA, NAU and the Smithsonian are prepared to implement an educational program in conjunction with the Kepler-NEO mission based on their current, extensive E/PO activities.

8 Contributors

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