A SALSO Concept: Kepler and Kuiper (K&K) Addressing Key Questions in Astrophysics & Planetary Science

Overview:

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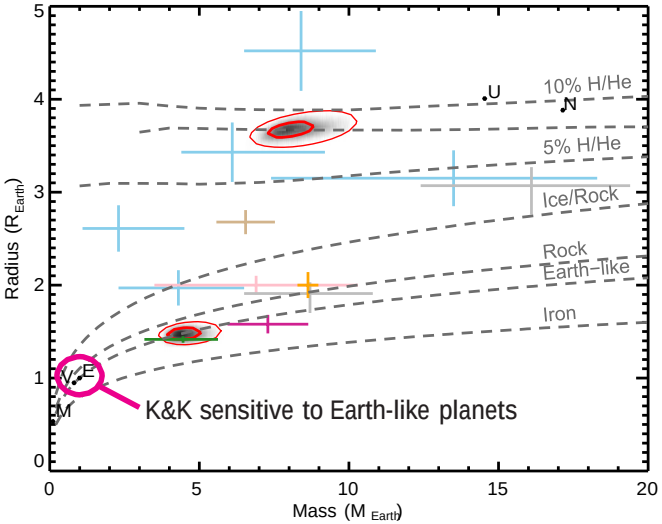
Short list of goals of the proposed concept:

- Determine masses for potentially habitable Earth-like planets from Kepler by measuring transit timing variations (TTV). This is the most promising method to determine these masses.
- Discover new, unseen terrestrial planets from TTVs in Kepler planets
- Directly image faint Kuiper Belt Objects as small as 10km in diameter (as faint as r~30)
- Detect KBOs as small as 1km by observing these objects as they pass in front of distant stars (the occultation technique)
- Carry out deep surveys in selected areas in support of WFIRST, Euclid, and similar missions

Graphic:

Estimates of masses and radii for a number of exo-planets, mostly from Kepler. The error ellipses refer to the well-studied Kepler 36 system. K&K will provide mass estimates for upward of 100 Kepler exoplanets with known radii, determining their densities, placing them on the theoretical curves, and revealing the frequency of planets of different type and composition (Carter et al., 2012).



Description:

Briefly describe the concept, implementation and operations approach:

- Very large CMOS focal plane working at visible wavelengths
  - 0.25 sq degree field of view
  - Dichroic beamsplitters allow simultaneous imaging in 4 bands
  - 300 million pixels in each band
- L2 Orbit – mission constrained by downlink capabilities
- Observing profile – three types of studies/surveys + parallel mode;
  - Timing studies of known objects in Kepler field
  - Optimized surveys for imaging of faint KBOs
  - Deep surveys complementing other data bases
  - Parallel high speed sampling of bright stars for transiting KBOs

Identify and describe the readiness level of key technologies:

- Assumes continued rapid improvement of CMOS technology

Identify external collaboration opportunities and dependencies:

- None identified to date

Identify proposed utilization of human exploration capabilities:

- None

Value to NASA:

What are the benefits of the proposed concept?

- Efficient use of existing hardware to address specific forefront problems in both astrophysics and planetary science
  - Within performance envelope of NRO telescopes
- Major scientific return with little risk using existing technologies

How does this concept advance Agency objectives across science, technology and human exploration?

- Addresses decadal priorities in both astrophysics and planetary science
  - Establishes frequency of terrestrial planets
  - Inventories the Kuiper Belt down to sub-km sizes
  - Enhances planned survey missions with targeted deep surveys
- Accelerates availability of CMOS detector technology as versatile, flexible alternative to CCDs with comparable performance

KEPLER AND KUIPER (K&K)

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Abbreviated Concept Summary: *The NRO 2.4m telescope will be equipped with CMOS focal planes for multi-band optical imaging and placed into orbit at the Earth Sun L2 point. It will be devoted to studies of exoplanets, the outer Solar System, and deep extragalactic surveys.*

Primary Concept Goal Category: *Astrophysics and Planetary Science.*

Goal of the Proposed Application:

1.Masses of Kepler habitable zone planets: We propose to use the NRO telescope to determine the masses and densities of habitable zone planets in the Kepler field. "**Seeking Nearby, Habitable Planets"** is one of three major science objectives of the Astro2010 survey.

Kepler reports evidence for Earth-like planets in orbits close to the habitable zones of their host stars. The new challenge is to characterize these planets, notably, determining their masses. The radial velocity technique is not presently able to determine the masses of Kepler's potentially habitable, Earth-like planets.

Transit timing variations (TTVs) offer the greatest promise in this regard, especially in those systems with more than one transiting planet. TTVs are disturbances, typically of order minutes, in otherwise regular transits caused by gravitational interactions between the planets in a system. K&K will provide sensitive determinations of TTVs for all of the promising Kepler systems, exploiting its larger collecting area to provide precise determination of transit times.

Sixty Kepler planets show TTVs. Transit times measured by K&K, ~2.4 times more precise than those measured by Kepler (the ratio of aperture diameters), would support the determination their masses, as well for transiting planets yet to be discovered.

Kepler is sensitive to Earth-size planets orbiting Sun-like stars, but K&K's 2.4m aperture could detect Mars or even Ganymede in transit. By monitoring a number of Kepler systems with 1 or more transiting planets, we could establish the frequency of even smaller planets. This would resolve present uncertainties in the histogram of small planet sizes

K&K it would be able to detect habitable, rocky moons orbiting transiting, giant planets. We would also have improved sensitivity to the signatures of planetary rings, oblateness, and obliquity. The multi-band data from K&K would allow more precise impact parameter determinations, better mitigation against systematic errors, and improved detection of star spots that contribute to errors in measurements of transit times.

2. Detection of small Kuiper Belt Objects: We will use the NRO telescope to obtain a census of Kuiper Belt Objects (KBOs) as small as 1km. Recent theoretical and computational work has shown that the processes of planet formation and subsequent migration during the early history of the Solar System determined the present day structure of the Kuiper Belt – a swarm of small planetesimals lying largely beyond the orbit of Neptune. The 2011 Planetary Science Decadal report lists KBOs among the targets to be studied in pursuit of four of the top ten science questions, most notably: *"What were the initial stages, conditions and*

processes of solar system formation and the nature of the interstellar matter that was incorporated?"

The primary need in the exploration of the Kuiper Belt is a comprehensive survey of small (<30 km in diameter), faint (r>27.5) KBOs. K&K will combine a sensitive direct imaging survey (down to ~10 km objects) with a powerful survey for occultations of bright background stars to probe smaller KBOs (down to ~1 km or smaller).

2a. Direct Imaging of KBOs as small as 10km in size. K&K will go both deeper than previous efforts with HST and cover a much larger area of the sky.

The survey will be divided into two phases, each of which will occupy about 1 year of telescope time. The first phase will cover a strip 0.5 degrees wide along the invariable plane of the solar system, covering 180 sq. degrees, sensitive to KBOs brighter than r~28.5, and will detect >10,000 (possibly ~40,000) objects, each with good orbital information.

The second imaging phase will probe much longer, and fainter, in ~12 "K&K deep fields": 2×2 mosaics each covering ~1 sq. degree. We anticipate detecting >20,000 objects as faint as r~30.

2b. Occultation survey of the outer solar system for smaller but more common KBOs down to ~1km in size. These KBOs are too small (and perhaps too distant) for direct imaging, but recent results from the FGS on HST show that they can be detected, and their sizes and distances determined, by the characteristic diffraction signal produced when they occult (pass between the telescope and) a distant star.

Next-generation CMOS imagers will enable rapid readout of small selected regions near bright stars, *while the imaging survey data are taken*! This powerful multiplex use of the telescope system is possible because CMOS imagers allow us to read out small regions ("windows") surrounding bright (r<15.5) stars. High speed (>30 Hz) photometry of these target stars will reveal the occultations of these stars by small KBOs (as demonstrated in the FGS data from HST).

The wavelength dependence of the occultation light curves would be captured by the multi-band capability of K&K, allowing reliable estimates of distances to and sizes of these objects.

The largest few objects detected by occultations could also be studied by direct imaging [2a above], providing valuable information about the albedos of the smallest KBOs.

A quick estimate suggests that >3,000 KBOs would be discovered by this occultation survey during the two-year KBO survey described in 2.a above.

In a few weeks of observation we would totally revolutionize our understanding of the size distribution of the smallest KBOs; this has implications for their collisional history and, therefore, physical properties.

3. Deep Surveys. The sensitivity and field of view of K&K will make it an attractive platform for deep surveys in support of data obtained by other missions, most notably Euclid and WFIRST. For example, K&K could augment Euclid's planned 40 square degree deep survey by observing the same area to mag=26 in 4 optical bands versus Euclid's single very wide optical band. The K&K photometric data would be provide higher precision and higher resolution, enabling the 'gold standard' in photometric redshift calculation. The photometric redshifts from the combined Euclid/K&K 40 square degree deep survey could then be used to calibrate the full photometric redshift sample for Euclid, LSST, and WFIRST, enhancing the dark energy constraints from those missions and enabling more accurate studies of galaxy evolution. Even deeper surveys would allow probing the dark matter

substructure of galaxies and clusters to unprecedented levels.

Benefits of the Application:

K&K is a straightforward mission that lies well within the envelope of the NRO telescopes and requires no new technology.

K&K addresses high priority objectives from two major NASA science theme areas, astrophysics and solar system exploration. It carries out studies that are possible only from a space telescope.

K&K builds on NASA's extremely successful Kepler mission, effectively doubling its time base from the 7.5 years of Kepler's observations to perhaps 15 years.

Top-level Description of the Design, Operation, and Results:

1. Instrument Design K&K is built around four very large CMOS focal planes each with a field of view of 0.25 sq. degrees. This optical configuration was discussed in greater detail at the recent NRO Meeting in Princeton, and is technically realizable using the NRO telescope in its TMA configuration.

The CMOS focal planes allow us to define small groups of pixels that can be read out at high frequency while the rest of the array is used in a deeper, imaging survey mode. The search for occultations by KBOs proceeds in parallel with imaging programs.

A major constraint on our focal plane and mission design is the need to fit within the downlink capability available from L2. Based on conversations with JPL engineers we assume 100 MBits/s for 8 hrs/day using the DSN. This translates into a 33 MBit/s rate of data collection and leads naturally into a trade-off between number of pixels and integration time. We explored several options, and concluded that the aggressive design with a total of 4×320 million pixels best serves the survey needs. This can be operated to be consistent with the overall data rate constraint. The configuration will be optimized in the next phase of this study.

The high data rate occultation data can be reduced on board using protocols developed at CfA with NASA support for the proposed *Whipple* Discovery mission.

2. Spacecraft and Mission Design: K&K will be operated at the Earth-Sun L2 point. The orbit and spacecraft/baffle/solar panel configuration allow continuous viewing of the Kepler field and the invariable plane.

The spacecraft will require pointing stability of order 0.1", only a modest improvement over what has been achieved by Chandra and much less demanding than the Hubble pointing requirements. As with Kepler, portions of the science focal plane can be used as star trackers. The direct addressability and rapid readout features of the CMOS detectors will facilitate this.

The spacecraft will observe continually from L2, with the highest priority given to transit events that occur in the Kepler field in known time windows. Observing at quadrature and repeating the observation within a day to identify candidate KBOs by their motion from frame to frame will optimize the imaging search for KBOs. The deep survey observations will be planned and carried out in collaboration with members of the Euclid and WFIRST teams.

3. Operations and Ground System: The observatory will exploit stored sequences, as is the case for other deep space missions. Downlinked data will be processed by existing science operations facilities at Cambridge and/or Pasadena.

The photometric reduction will employ techniques developed for the Kepler mission [for the exoplanet studies], for WISE and NEOWISE [for the KBO imaging], and for Whipple [for the occultation studies]. All K&K data will be archived and distributed following existing protocols.