Trans-Neptunian objects with K2: targeting our own Solar System white paper

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Abstract

We propose to observe trans-Neptunian objects (TNOs) with the Kepler space telescope along the ecliptic fields (K2 Mission). The aim of the proposed program is to follow the brightest TNOs in K2 fields for a time interval of about 40 days each. This will provide us a completely new view of TNOs, uncovering the shape distributions, albedo variations, and moons - even small ones - around the targets, based on a data set which is unprecedented in all senses. These data would help us to learn more about the formation, structure and evolution of our own Solar System. K2 pointings offer an unprecedented opportunity, since the 60-130 deg planned elongation coincides with the lowest apparent speed (stationary point) of the TNOs orbiting at 30-50 AU. By capitalizing on this unique and fortunate fact we elaborate and suggest an observing mode that would require one pixel block to cover each slowly moving object's path. This approach fits nicely to the observing strategy of the K2 Mission and the project would compete for pixel sets like any other proposal. We recommend to adopt this observing mode that open up new vistas in studying our own Solar System.

Introduction

Trans-Neptunian objects are believed to represent one of the most primordial populations in the Solar System. More than 1500 TNOs have been detected so far revealing a rich orbital structure and intriguing physical properties. Concerning dynamical classes, most TNOs are found in the Classical belt or main Kuiper belt, at 32 to 50 AU distance from the Sun in resonant as well as non-resonant orbits with Neptune. In addition, there exists a halo of objects on high inclination and high eccentricity orbits beyond 50 AU: the scattered disk and detached objects (SDOs). The known TNOs represent only a few percent of the estimated 30,000 TNOs brighter than V=24 mag.

TNOs are the frozen leftovers from the formation period of the outer Solar System (Morbidelli et al. 2008). The current total mass in the Kuiper Belt is estimated to be around 0.03–0.3 Earth masses (Trujillo et al. 2001), but there is evidence that a much larger mass (10-40 M_{Earth}) was originally present at the time of formation (Kenyon and Luu 1998). The ensemble of these bodies is analogous to the debris disks observed around others stars. However, in those exo-solar debris disks we can only detect a cloud of tiny, short-lived dust particles, while most of their mass is likely in the form of undetectable, from meter to thousand kilometer sized planetesimals, similar to the trans-Neptunian objects in our Solar System. Our trans-Neptunian region is the only place where we can observe the individual objects of a debris disk.

Although there are several methods to observe and characterize these bodies, observation of brightness variation, i.e. a light curve due to rotation has proved to be a very important tool that can help to answer many questions about the formation and physical properties of TNOs (Sheppard et al., 2008), including the following ones:

1. How did small and large TNOs form in the Solar System? The currently observable size-density relationship of TNOs is unable to explain the formation of large TNOs by merger/coagulation of smaller ones.

2. What is the internal structure of TNOs? What is their internal (compressive) strength and what could it be at the time of their formation? What is their porosity, i.e. what is the fraction of 'voids' in their interiors?
3. How did binaries form in nearly equal sized and in hierarchical systems (dynamical capture vs. collisions)?
4. What is the origin of small, high (>20%) albedo objects? Are these the remnants of past disruptive events?

Scientific justification

In this white paper we propose to use a small fraction of the available pixels of Kepler to study the brightest slowly moving TNOs, hence extend the K2 Mission to our Solar System, where certain questions regarding formation and dynamical processes can be studied in much more detail than in any exo-solar planetary system. Specifically, the analysis of the the precise K2 optical light curves will allow us to target to investigate the rotation of TNOs, the shape of the bodies, surface inhomogeneities and their albedo. In addition, we have a high chance to discover companions and improve the statistics (or upper limits) of companions, which has not been possible by ground-based instruments.

Rotation and surface inhomogeneities

The light variation of a rotating body results in a periodic light curve, and of course the period will be the same as the sidereal rotation period of the asteroid itself. The shape of the light variation will describe the convex envelope of the body, which can be reconstructed by inverse methods from precise light curves. Large bright or dark spots can be recognized as features that cannot be modeled by a rotation light curve assuming any shapes. This concept is based on an internal symmetry of rotation light curves: all characteristics connected to the shape of the body are seen twice in a very similar position during a rotation (once from one side and a half period later from the other side). Spots, however, emerge only once per rotation, since a half rotation later the spot is on the invisible side of the body. This ensures that the separation of spot and shape effects is possible.

With the expected precision of Kepler in the K2 era (Howell et al. 2014) we estimate that the reconstruction of the shape of the TNOs as well as the extent of local features will be possible with a few percent uncertainty. We expect that any light curve feature above the 2% amplitude that cannot be modeled by a rotating body will reflect the presence of surface spots. Assuming 20% variation of the albedo between the spot and its environment (e.g. a 4% albedo spot in a 5% albedo large area), spots reaching 10% of the cross section will be detectable. The body can be totally covered by 40 of this kind of spots, that means that the albedo variegation on the surface of the TNOs can be detected as an 1/40 resolution map - which is similar how the largest Main Belt asteroids looked like with the Hubble Space Telescope (Parker et al. 2002).

The high albedo (e.g. in the case of 2002 GV31) indicates that its surface may not be homogeneous - in the case of high albedo objects at least part of the body is usually covered by ices. High albedo also often an indication of collisional origin (resulting in irregular shape) that should be reflected in the light curve. Using the high precision photometry that Kepler is capable of, the shape of the target can be reconstructed and the surface albedo variegations determined. Even in the case of the lack of a companion, the shape and rotation period can be used to set limits on the mass and internal strength of our TNO sample.

It is likely that in some cases we will find more than one periodicity in the light curve. This can be related to either to the precession of the asteroids (and therefore a rotation around a second instantaneous axis) or a moon around the TNO, rotating with a period which is different from the orbital one. The distinction between the two possibilities again refers to light curve modeling, since once the light curve cannot be explained by a body rotating around two axes, the interpretation about the moon will be confirmed. The time scale of the second period will help, too: free precession of a TNO is related to its orbital period via the tensor of inertia (that can be estimated from the light curve itself), and whenever the length of the second period is not in this order of magnitude, the possibility of a moon is highly plausible.

Companions

In the case of the presence of a second period, the moon interpretation will be more likely, since many of the target TNOs - mostly cold classicals - are expected to host large moon. In a brightness limited sample of cold classicals (dynamically not excited, ie. low-eccentricity subgroup) a binary fraction of $22^{+10}/_{-5}$ % was found, which is much higher than the general value of $5^{+4}/_{-2}$ % found for the whole TNO population (Stephens and Noll, 2006). Among the dynamically more excited hot classicals almost no binary systems could be found. Note that in most of the cold classical binaries the companions have similar brightness values (and likely similar or comparable sizes) indicating that these systems were formed by dynamical capture during the formation period of the Solar System. High brightness (and size) differences are characteristic of the largest TNOs (this dominates the binary detection fraction of ~5% for the whole TNO sample). In the case of these large TNOs the moons were likely formed by collisional fragmentation. The high fraction of binaries among cold classicals show that this is the less "stirred" population that was able to keep its original conditions over the evolution of the Solar System.

A long (>1d) light curve period is a proxy for companion. Typical rotation periods of TNOs are 6h-24h. However, rotation periods in binary systems are typically an order of magnitude longer, e.g. the orbital period in the Sila-Nunam system is 12.5 days, and there are several binaries with orbital periods in the same order. On the timescale of the age of the Solar System, the rotation of binaries have likely been synchronized, and possible albedo variegations on the surface of the two bodies cause a light curve variation even in those cases when our line of sight is off the plane of the mutual orbit.

The described method of light curve analysis will open a completely new road to study the multiplicity of TNOs. By today, moons around TNOs were discovered by imaging, that limited the size range that could have been explored, and also favored the largely separated moons. With photometry, these biases will be eliminated, and we will have an unbiased estimate for the satellite occurrence rate of the largest TNOs.

In order to demonstrate the feasibility of finding companions to TNOs we performed a set of simulations. First we generated a 40-day long synthetic light curve of a TNO with a companion using the expected Kepler noise during the K2 Mission (Howell et al. 2014), which is about 0.23 magnitude at 20 mag. The simulations show the light variation of a TNO at 40 AU distance, with an albedo similar to Ceres, which is 240 km in diameter and has a rotation period of 13.54h. The shape asphericity (which is defined as 1-b/a, where b and a are semiminor and semimajor axes of the best-fitting ellipse) is 14%. The companion has a diameter of 67 km, 48% shape asphericity and 6.28h rotation period. The simulation and the signals from the individual components are plotted in Fig. 1. We took into account that the amplitude of the signal from the secondary is diluted by the light from the primary. The sampling was set to mimic the K2 long cadence observations (1 point every 30 minutes).

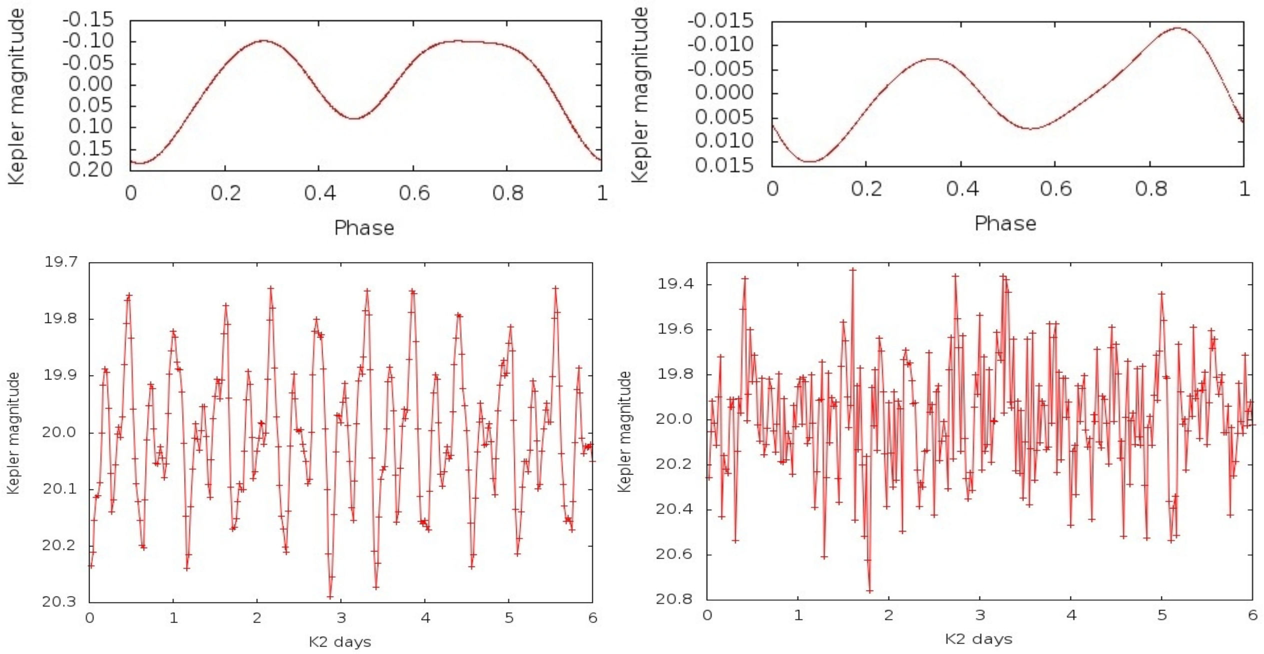

Figure 1. *Simulations of the light variation of a TNO with a companion.* ***Upper left panel:*** *the signal from the primary alone.* ***Upper right panel:*** *the signal from the secondary component.* ***Lower left panel:*** *The combined signal without added noise.* ***Lower right panel:*** *The combined signal with an added normally distributed noise of 0.23 mag.*

Fig. 2. shows the Fourier-transform of the optical light variation of this hypothetical system. Light variation components of the primary can be identified up to the 3rd order (having Fp frequency and its multiples). The second harmonic has the highest amplitude because the light variation originates from a dominantly elongated (rather than spotted) body. The first two harmonics of the secondary (moon) component (Fs and 2Fs) can be detected. Here also the second harmonic has a higher amplitude, because of the shape properties.

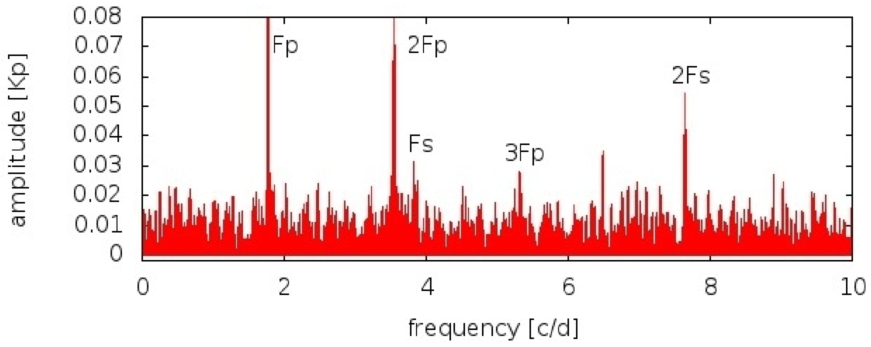

Figure 2. *Fourier spectrum of the synthetic light curve of a binary TNO. Fp and harmonics come from the primary, while Fs and harmonics signal the presence of the secondary component.*

In our simulation this configuration allows us to detect 2Fs with 7.3σ, whereas Fs is found with 3.8σ confidence in the Fourier-spectrum. Some ambiguity enters if only one frequency component from the secondary can be detected (in fainter systems for instance). However, dynamical arguments usually come to the rescue and help to select the correct rotation period of the companion. We stress that – as our simulation shows - the presence of coherent periodic signals in the light curve makes it possible to reach significantly below the noise limit of the individual observations when one works in the frequency domain.

With this method we expect to discover the moons around TNOs down to 10% of the size of the host body at V=20 mag, the limit being somewhat larger at fainter magnitudes. If the moons do not exhibit eclipses during the observation, but show a light variation of 0.3 magnitude (a typical value of Main Belt asteroids in the similar size range), then we will be able to detect fairly small moons by their rotation signal. The detection limit of non-eclipsing moons will be 10-30% of the primary - depending on the asphericity of the companions assumed to be between 30-80%.

Why K2?

K2 is the only possible instrument for such a survey now and in the foreseeable future. The arguments are the followings:

- The continuous monitoring is the heart of the project, which can not be obtained from the ground.
- The aimed accuracy in the Fourier-spectrum of the combined signal requires very stable photometric conditions, therefore a space telescope.
- The pointing of 40 days to one direction is incompatible with any other space telescope, but is absolutely concordant with the K2 observation schedule.
- The instrument must observe along the Ecliptic - which will exactly be the task of K2.

Synergies with ground-based and space-borne observatories

Several of our potential targets were observed with the PACS camera of the Herschel Space Observatory in the framework of the 'TNOs are Cool!' Open Time Key Program. Light curve observations provide a precise rotation period which is an important characteristic of thermophysical models (Lagerros 1998) and its knowledge helps to better constrain the thermal properties of the target, in particular its thermal inertia and surface roughness.

Technical justification

Observing mode

This project would require blocks of pixels to cover part of the path of individual objects, as opposed to stellar apertures. This observing mode would not compromise other selected K2 projects. Thus, the TNO project would compete for pixels during the selection process, just like other proposals do.

We found that instead of requiring the total path of our objects, covering only the slowest parts of the orbits of our TNOs (~40 days) would minimize the necessary pixels while maximize the science return. We remark that the target TNOs will be in their stationary points, exhibiting a quadratically increasing proper motion. Therefore the targets will reside in the K2 mosaic during the entire pointing to a specific K2 field. However, 80 days long observations would require 4 times longer apertures, but would provide only 1.4-times higher precision. Thus 40 day long observations will lead to 4 times more objects assuming the same pixel number.

The technical aspect of this observation does not mean any relevant changes to the standard Kepler/K2 operation. The only difference is that the observation of moving objects will require a special pixel mask, which is elongated to the direction of the movement, and follows its curvature; and which is narrow to the perpendicular direction, since TNOs are faint and fit in few pixels. With 5-5 pixel halo on both sides of the TNOs trajectories for a typical object we need 1500±200 pixels to cover a 40-day arc. If later on during the K2 Mission, stability of the spacecraft allows this would be good to be reduced to 2-2 pixel extra padding, which would translate into 600 pixels for a typical trans-Neptunian object. Here we took into account that we aim at observing close to the stationary point, hence the curvature of the trajectory effectively reduces the required pixels. Of course these pixel masks must be defined individually for each TNOs, after the exact pointing of the field is fixed.

Data reduction and analysis

Once the pixel mask is downloaded for every long cadence observations, our group will perform all steps in evaluating the data with means of pixel photometry tools. The basic concept is that a synthetic background image will be subtracted from each observation, hence only the signal from the TNO remains. In the second step the TNO can be measured with aperture photometry, where the aperture follows the proper motion, and has an extension/structure that leads to optimal S/N ratio. In the final step, the light curve will be fed into a period analysis; folded and averaged light curves will be calculated.

Crowding will not be a problem in certain fields (e.g. in Fields 1, 3, 5 and 6). The problem of possible blending will be taken into account when prioritizing our targets during the subsequent K2 fields/runs.

Observing cadence

Long cadence (30-min) sampling is satisfactory for this project. The typical rotation period of TNOs is in the range of 8-24 hour, such as in the case of asteroids (or even the planets); therefore the shortest expected rotational period will still exceed the cadence by at least one order of magnitude. 30 minute sampling will of course result in some smearing, acting as a low-passing filter on the light curves; but this is not a problem because 1) it does not modify the frequencies, and therefore the detectability of possible moons; 2) while modeling the shape features, exactly the same smearing can be incorporated in producing the model light curve, too, so the best fitting solution will really show our best estimate of the shape and surface properties, regardless to the smearing.

Periodic signals above the Nyquist-frequency can cause problems in the data analysis, but we surely do not expect and signal with a period less than an hour - simply because such rapid rotators suffer a rotation friction very soon, and they cannot survive in the Solar System.

It is also worth noting that K2 long cadence sampling fits nicely our aims. As a rule of thumb, the moving objects should not move more than a half pixel during one exposure, because their profile will be extended in comparison to the stars in other case, and it will reduce the S/N ratio. Since the TNOs will move away by less or about one half pixel during a LC observation, we can conclude that the 30 minute sampling is the optimal one (in terms of S/N) that fits a 4 arcsec resolution imaging and the proper motion of TNOs.

Object coordinates

Since Kepler attained a considerable distance from Earth since its launch, coordinates of the TNOs will have to be converted to a coordinate system centered on the spacecraft's actual position in the Solar System. This can be easily done using NASA' Horizons portal.[1]

Targets

We realized that the chosen K2 fields and observing times are perfect to monitor the stationary points of the TNOs orbiting at 30-50 AU. It means that these objects can be observed when they move with the lowest speed on their trajectories. We carefully checked the K2 pointings and anticipate 4-5 targets bright enough for Kepler in each K2 fields. Their brightness (in Johnson V) varies from 20-23 magnitude (the latter is set to obtain meaningful photometry with Kepler), with a median of 22.0 magnitude. The broader wavelength coverage may help to reach a slightly better SNR.

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[1] http://ssd.jpl.nasa.gov/horizons.cgi

We expect to request only the brightest ones while ensuring that different dynamical groups would be represented (plutinos, classical, SDO, etc). Table 1. list the potential targets with their rotational periods – if known – and whether Herschel observed it. Fig. 4. demonstrates Field4, where 4 TNOs will fall on silicon with the presently available pointing. The trajectories demonstrate the slow motion near the stationary point.

Additional objects falling on the required pixels (galaxies, supernovae, other transients) will be of great interest for other groups as well. A coordination among the interested parties will greatly enhance the scientific yield. The extended stripes will be downloaded during the entire K2 pointing, which will support all other non-stellar science, as possible SN and transient searching projects and extragalactic studies.

K2 field	Object	V [mag]	family/group	rot. per. [h]	Herschel obs.
2	(119951) 2002 KX14	20.5	classical		yes
2	(278361) 2007 JJ43	20.3	1:2	6.04	yes
2	(307251) 2002 KW14	21.4	classical	8.58	yes
2	2007 JH43	21.0	plutino		yes
3	(225088) 2007 OR10	21.5	SDO	11.69	yes
3	(275809) 2001 QY297	22.2	classical		yes
3	2000 PE30	22.3	SDO		yes
3	2003 QA91	22.2	classical		yes
3	2004 PT107	22.0	classical	20.0	yes
4	(19299) 1996 SZ4	22.8	plutino		no
4	1998 UU43	22.7	3:4		no
4	2004 VC131	22.3	classical		no
4	2004 VD131	23.0	classical		no
5	(79360) Sila-Nunam	21.9	classical		yes
5	(82075) 2000 YW134	21.5	SDO		yes
5	2002 CY248	22.5	1:2		yes
5	2012 BX85	22.1	classical		no
6	(82155) 2001 FZ173	21.5	SDO		yes
6	(184314) 2005 EO302	22.6	classical		no
6	2003 HC57	22.6	classical		no
6	2010 FE49	22.1	SDO		no
8	(35671) 1998 SN165	21.5	classical	8.84	yes
8	(135182) 2001 QT322	22.1	classical		yes
8	(139775) 2001 QG298	22.5	plutino	13.77	yes
8	(307616) 2003 QW90	22.0	classical, 4:7		yes
8	(308379) 2005 RS43	21.8	1:2		No

***Table 1.** Possible TNO targets in the K2 fields up to Campaign 8. Fields 7 and 9 are discarded, because of their low galactic latitude causing severe crowding.*

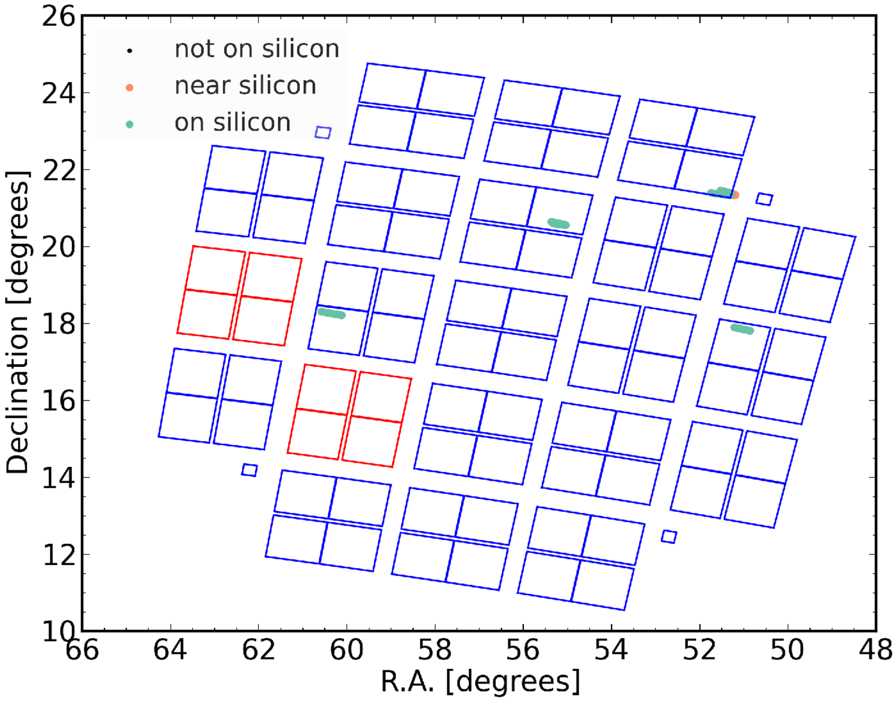

Figure 3. *TNOs are plotted in Field4 to show their path during the planned campaign, as an illustration. We will select those parts of their orbits that are closest to the stationary point to minimize the number of necessary pixels.*

Our group accumulated significant experience in photometry of Kepler data (e.g. Szabó et al. 2011a, Szabó et al. 2011b); background subtraction and photometry of moving objects in space telescope images (e.g. with Herschel, Kiss et al. 2013, Mueller et al. 2013, Kiss et al. 2014, Pál et al. 2012, Vilenius et al. 2012); interpretation of asteroid light curves, precession and binarity (e.g. Szabó 1998, Sárneczky at al. 1999, Kiss et al. 1999, Szabó et al. 2001, Szabó et al. 2004, Szabó and Simon 2009, Kiss et al. 2013).

Conclusions

With this white paper we request considering the above described *'moving target' mode* to allow the investigation of the slowest trans-Neptunian objects with K2. With a modest pixel requirement this observing mode would open up new avenues, greatly enhancing our knowledge of the smaller bodies in our Solar System, which in turn has significant ramifications for understanding planetary system formation and dynamics.

By placing a judiciously selected pixel mask (where the coordinates should be corrected for parallax effect due to the location of the spacecraft) TNOs can be followed for ~40 days at a reasonable pixel cost around their stationary point, where they turn back on their apparent trajectories, hence the required pixel number decreases effectively. We emphasize that although the precision of the K2 photometry will be limited at the TNO magnitude range, the persistence of periodicities due to rotation, surface inhomogeneities and companions will greatly facilitate the recovery of at least an order of magnitude smaller signals in the frequency domain.

The structure and formation mechanism of small and large TNOs is one of the key questions of current solar system formation and planetesimal disk evolution theories. With the help of Kepler's optical observations we may potentially identify companions, building a crucial sample to test these models.

Studying TNOs with the K2 Mission will nicely complement the original and revised strategy of Kepler, namely finding planetary systems, reveal their dynamical evolution and put our own Solar System and its origin into perspective. Solar System studies such as this proposed TNO program will perfectly complement the discoveries and analysis of other extrasolar planetary systems adding to the small mass/radius part of the distribution of the building blocks of our own Solar System.

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