Final report, "Small body transport and the initial conditions for planetesimal formation", NKFIH K-125015

Executive summary

The main goal of the "Small body transport and the initial conditions for planetesimal formation" project was to determine physical characteristics for a large number of small bodies in various populations (main belt asteroids, Jovian Trojans, Centaurs, trans-Neptunian objects), as well as to perform more detailed studies on some selected targets, in order to get a more comprehensive picture on their formation and evolution. The determination of rotational characteristics of various small body populations using space telescope data (K2 and TESS) has been a major research topic during our project, and our team has gained a world-leading position in this field. Our result that in most small body populations the number of slowly rotating bodies has previously been underestimated has since been confirmed by data from other large surveys, and triggered a reconsideration of the possible formation mechanisms of these bodies. Detailed studies of individual targets indicated that a reassessment of the dwarf planet definition may be necessary in the inner solar system; it is also suggested that there is a common density of trans-Neptunian dwarf planets, based on Haumea and Gonggong data, as predicted by formation theories. Stellar occultations have been used to obtain accurate shape and size for Centaurs and trans-Neptunian objects (TNOs), and led to the discovery of the ring of the dwarf planet Haumea, the first time around a Kuiper belt object. Thermal emission measurements of Kuiper belt objects confirmed the status of members of the Haumea collisional family, and showed that the same albedo-colour bimodality exists among scattered disc and resonant trans-Neptunian objects as in other trans-Neptunian populations, further strengthening the evidence for a compositional discontinuity in the early Solar system at ~20 au. We also investigated the origin of dust in debris disks of young planetary systems. We published altogether 27 peer-reviewed papers of which 25 are in Q1/D1, and 7 in D1 journals, and 14 papers have been first authored by our team members; we organized one conference (Thermops 2019), and an EPSC 2020 special session "Small Body Surveys" related to the topics of our project.

A more detailed description of the results is given below.

Stellar occultations of Centaurs and trans-Neptunian objects

Observation of the stellar occultation is a very effective tool to derive the basic physical characteristics (size, shape, albedo, presence of atmosphere) of distant solar system bodies, Centaurs and trans-Neptunian objects. Our group participated in several international campaigns and observed stellar occultations using the 1-m RCC, 0.6/0.9-m Schmidt, and the 0.8-m automated telescopes at the Piszkéstető Mountain Station of Konkoly Observatory (A. Pál, R. Szakáts, Cs. Kiss), as well as the 0.8-m telescope at the ELTE Gothard Observatory, Szombathely (Gy. Szabó), in the framework of our NKIFH project. The occultation results were combined with radiometric (infrared) data and light curve (rotational) information to obtain a thorough characterisation of the target. We have published four papers on stellar occultations, including a paper in Nature on the discovery of the first ring system of a trans-Neptunian object around the dwarf planet Haumea.

During a stellar occultation in 2017 secondary events were observed around the main body of Haumea, consistent with the presence of a ring with an opacity of 0.5, width of 70 kilometres and radius of about 2,287 kilometres. The ring is coplanar with both Haumea's equator and the orbit of its satellite Hi'iaka. The radius of the ring places it close to the 3:1 mean-motion resonance with Haumea's spin period—that is, Haumea rotates three times on its axis in the time that a ring particle completes one revolution. The occultation by the main body provides an instantaneous elliptical projected shape with axes of about 1,704 kilometres and 1,138 kilometres. Combined with rotational light curves, the occultation constrains the three-dimensional orientation of Haumea and its triaxial shape, which is inconsistent with a homogeneous body in hydrostatic equilibrium. Haumea's largest axis is at least 2,322 kilometres, larger than previously thought, implying an upper limit for its density of 1.885 $g\,cm^{-3}$ and a geometric albedo of 0.51, both smaller than previous estimates. In addition, this estimate of the density of Haumea is closer to that of Pluto than are previous estimates, in line with expectations. No global nitrogen- or methane-dominated atmosphere was detected [Ortiz et al., 2017].

We observed the occultation of the large trans-Neptunian object 2002 TC_{302} on 28 January 2018, the best observed occultation by a TNO other than Pluto. From the chords an elliptical fit to the projection of the body was obtained with major and minor axes of 543±18 km and 460±11 km, and a position angle of 3±1 deg. Combined with rotational light curves, this allowed us to derive possible three-dimensional shapes and density estimates. The effective diameter is by ∼84 km smaller than the radiometric diameter, indicating the existence of an unresolved satellite of up to ∼300km size [Ortiz et al., 2020].

Measurements were obtained with 29 telescopes throughout Europe during the stellar occultation of the Centaur 2002 GZ_{32} on 2017 May 20, with six successful detections. We obtained the limb that corresponds to an ellipse with axes of 305 ± 17 km × 146 ± 8 km. Considering the rotational light curve obtained shortly after the occultation, we derived the geometric albedo of 2002 GZ_{32} ($p_V = 0.043 \pm 0.007$) and a 3D ellipsoidal shape with axes 366 km × 306 km × 120 km. This shape is not fully consistent with a homogeneous body in hydrostatic equilibrium for the known rotation period of 2002 GZ_{32}. The size (albedo) obtained from the occultation is respectively smaller (greater) than that derived from the radiometric technique but compatible within error bars. No rings or debris around 2002 GZ_{32} were detected from the occultation [Santos-Sanz et al., 2021].

A paper is in preparation on the the physical properties of the cubewano (19521) Chaos obtained from a multi-chord stellar occultation [Vara-Lubiano et al., 2021], and another paper has been submitted on the occultation measurements of (38628) Huya [Santos-Sanz et al., 2022, A&A, submitted].

We have also shown that even single-chord detections of TNOs allow us to measure their milliarcsecond astrometric positions in the reference frame of the Gaia second data release (DR2). We analyzed data from various stellar occultation detections to obtain astrometric positions of the involved bodies. The events published before the Gaia era were updated with Gaia DR2, providing accurate positions. Events with detection from one or two different sites (single or double chord) were analyzed to determine the event duration. Previously determined sizes were used to calculate the position of the object center and its corresponding error with respectto the detected chord and the ICRS propagated Gaia DR2 star position. We derive 37 precise astrometric positions for 19 TNOs and four Centaurs. Although about 68% of our results are based on single-chord detection, most have intrinsic precision at the submilliarcsecond level. Using the Gaia DR2 catalog, we show that even a single detection of a stellar occultation allows improving the object ephemeris significantly, which in turn enables predicting a future stellar occultation with high accuracy [Rommel et al., 2020].

Rotational properties of small Solar system bodies from Kepler/K2 and TESS mission data

One of the main topics of our research project was to obtain rotational properties of various populations of small Solar system bodies, from the main belt to the trans-Neptunian region, covered by several, population-specific papers. The general conclusion is that previous statistics significantly underestimated the number of slowly rotating objects in all populations that may suggest a collisional evolution and/or binary frequency different from the previous models. We summarized the K2 solar system results in a chapter of 'The NASA Kepler Misson' book [Kiss et al., 2020].

We investigated the K2 light curves of a large sample of untargeted main-belt asteroids (MBAs) detected with the Kepler Space Telescope. The asteroids were observed within the Uranus superstamp, a relatively large, continuous field with a low stellar background designed to cover the planet Uranus and its moons during Campaign 8 of the K2 mission. The superstamp offered the possibility of obtaining precise, uninterrupted light curves of a large number of MBAs and thus determining unambiguous rotation rates for them. We obtained photometry for 608 MBAs, and were able to determine or estimate rotation rates for 90 targets, of which 86 had no known values before. In an additional 16 targets we detected incomplete cycles and/or eclipse-like events. We found the median rotation rate to be significantly longer than that of the ground-based observations, indicating that the latter are biased toward shorter rotation rates. Our study highlights the need and benefits of further continuous photometry of asteroids [Molnár et al., 2018].

We presented the first data release of TESS asteroid observations, focusing on the bright end of main-belt and Jovian Trojan asteroids. This data release contains 9912 light curves, and triples the number of bodies with unambiguous fundamental rotation characteristics. Our catalog shows that the number of bodies with long rotation periods are underestimated by all previous ground-based surveys, at least an order of magnitude [Pál et al., 2020].

Hildas orbit at 2:3 mean motion resonance with Jupiter and show a mixed taxonomy suggesting mixed origin, with members migrated to the current orbit either from the outer Main Belt or from the Trojans swarms. We identified 125 individual light curves observed in the K2 mission. We found that despite the mixed taxonomies the Hilda group highly resembles the Trojans in the distribution of rotation periods and amplitudes, and even the LR group (mostly C- and X-type) Hildas follow this rule. Contrary to the Main Belt, the Hilda group lacks the very fast rotators. The ratio of extremely slow rotators (P>100 hr) is a surprising 18%, which is unique in the solar system. The occurrence rate of asteroids with multiple periods (4%) and with three maxima in the light curves (5%) can be signs of a high rate of binarity, estimated as 25% within the Hilda group [Szabó et al., 2020].

Light curves of ten Centaurs from K2 measurements: We analysed the visible range light curves of ten Centaurs using Kepler/K2 data. Well defined periodic light curves are obtained in six cases allowing us to derive rotational periods, a notable increase in the number of Centaurs with known rotational properties. (463368) 2012 VU_{85} has the longest rotation period, P=56.2 h observed among Centaurs. Two targets with P>20 h are identified as binary candidates [Marton et al., 2020].

We studied the photometric properties of 45 Jovian Trojans from the K2 mission and phase-folded light curves for 44 targets, including (11351) Leucus, a Lucy mission target. There is a dichotomy in the periods of Trojans with a separation at ∼100 hr – 25% of the sample are slow rotators ($P \geq 30$ hr), an excess that can be attributed to binaries. 32 systems can be classified as potential detached binaries. Both the spin barrier and strengthless ellipsoid models indicate low densities and thus compositions similar to that of comets and trans-Neptunian objects, supporting the scenario of outer solar system origin for Jovian Trojans [Kalup et al., 2021].

We analysed the distribution of rotation periods and light curve amplitudes in 17 Main Belt asteroid families based on 10,000 light curves in the TSSYS-DR1 asteroid light curve database. The distribution of the light curve properties follow a family-specific character in the Hungaria, Maria, Juno and Eos families, and distributions in the other large families are in general very similar to each other. Older families tend to contain a larger fraction of rounded, low-amplitude asteroids. Rotation period distributions are different in the cores and outskirts of the Flora and Maria families, while the Vesta, Eos and Eunomia families lack this feature. We also confirm that very fast spinning asteroids are close to spherical (or spinning top shapes), and minor planets rotating slower than 11 hour are also more spherical than asteroids in the 4–8 hour period range [Szabó et al., 2022].

Characterisation of solar system small bodies with thermal emission data

A group of trans-Neptunian objects (TNOs) are dynamically related to the dwarf planet (136108) Haumea. Ten of them show strong indications of water ice on their surfaces, are assumed to have resulted from a collision, and are accepted as the only known TNO collisional family. Nineteen other dynamically similar objects lack water ice absorptions and are hypothesized to be dynamical interlopers. In this work we reported on the results of thermal infrared observations with the Herschel Space Observatory to determine sizes and geometric albedos of six of the accepted Haumea family members and one dynamical interloper. We compared the individual and statistical properties of the family members and interlopers, examining the size and albedo distributions of both groups. We also examined implications for the total mass of the family and their ejection velocities. The detected Haumea family members have a diversity of geometric albedos 0.3-0.8, which are higher than geometric albedos of dynamically similar objects without water ice. The median geometric albedo for accepted family members is $p_V = 0.48$, compared to 0.08 for the dynamical interlopers. In the size range $D = 175$–300 km, the slope of the cumulative size distribution is $q = 3.2$ for accepted family members, steeper than the $q = 2.0$ slope for the dynamical interlopers with $D < 500$ km. The total mass of Haumea's moons and family members is 2.4% of Haumea's mass. The ejection velocities required to insert them on their current orbits show a dependence on diameter, with a power-law slope of 0.21-0.50 [Vilenius et al., 2018].

The recent occultation measurement of the dwarf planet Haumea (Ortiz et al. 2017) revealed an elongated shape with the longest axis comparable to Pluto's mean diameter. The chords also indicate a ring around Haumea's equatorial plane, where its largest moon, Hi'iaka, is also located. The Haumea occultation size estimate (equivalent diameter 1595 km) is larger than previous radiometric solutions (in the range between 1150 and 1350 km), which lowers the object's density to about $1.8\,g\,cm^{-3}$, a value closer to the densities of other large TNOs. In this work we presented unpublished and also reprocessed Herschel and Spitzer MIR and FIR measurements. We compared 100 and 160 μm thermal lightcurve amplitudes - originating from

Haumea itself - with models of the total measured system fluxes (ring, satellite, Haumea) from 24-350 μm. The combination with results derived from the occultation measurements show that Haumea's crystalline water ice surface must have a thermal inertia of 5 SIu. We also have indications that the satellites (at least Hi'iaka) must have high geometric albedos ≥ 0.5, otherwise the derived thermal amplitude would be inconsistent with the total measured system fluxes at 24, 70, 100, 160, 250, and 350 μm. The high albedos imply sizes of about 300 and 150 km for Hi'iaka and Namaka, respectively, indicating unexpectedly high densities >1.0 g cm^{-3} for TNOs this small, and the assumed collisional formation from Haumea's icy crust. We also estimated the thermal emission of the ring for the time period 1980-2030, showing that the contribution during the Spitzer and Herschel epochs was small, but not negligible. Due to the progressive opening of the ring plane, the ring emission will be increasing in the next decade when JWST is operational. In the MIRI 25.5 μm band it will also be possible to obtain a very high-quality thermal lightcurve to test the derived Haumea properties [Müller et al., 2019].

Based on thermal emission measurements with Herschel/PACS and Spitzer/MIPS we determined size, albedo, and surface thermal properties for 23 objects using radiometric modeling, first time for a notable sample of TNOs in the outer resonances. The objects show a large variety of beaming factors, indicating a diversity of thermal properties, and they follow the albedo-color clustering identified earlier for Kuiper belt objects and Centaurs [Farkas-Takács et al., 2020].

We have created the "Small Bodies: Near and Far Infrared Database", a tool intended to facilitate the modelling of thermal emission of small bodies. It contains data of large surveys and a collection of small body observations of infrared space telescopes, and provides a web interface to access these data. As an immediate application we showed how different scaling of thermal inertia with heliocentric distance may affect our interpretation of the data and discussed why the widely-used radiative conductivity exponent (α=-3/4) might not be adequate in general [Szakáts et al., 2020].

We used Herschel PACS data (70, 100, 160 μm) and state-of-the-art shape models derived from adaptive-optics observations and/or optical light curves to constrain for the first time the thermal inertia of twelve large main-belt asteroids. Using the scale as a free parameter, most targets required a re-scaling 5% consistent with what would be expected given the absolute calibration error bars. We obtained low thermal inertia values, typical of large main belt asteroids studied before, supporting the notion that these surfaces are covered by fine-grained insulating regolith. We also proposed a new approach to examine how different values of the exponent used for scaling the thermal inertia as a function of heliocentric distance affect the interpretation of the results [Alí-Lagoa et al., 2020].

Results from the TESS mission showed that previous studies strongly underestimated the number of slow rotators. For most slowly rotating asteroids ($P > 12$ h), no spin and shape model is available because of observation selection effects. This hampers determination of their thermal parameters and accurate sizes. Our goal in this study was to provide their scaled spin and shape models together with thermal inertia, albedo, and surface roughness to complete the statistics. Rich multi-apparition datasets of dense light curves are supplemented with data from Kepler and TESS. In addition to data in the visible range, we also use thermal data from infrared space observatories in a combined optimisation process using the Convex Inversion Thermophysical Model. We present the models of 16 slow rotators. All provide good fits to both thermal and visible data. The obtained sizes are on average accurate at the 5% precision, with diameters in the range from 25 to 145 km. The rotation periods of our targets range from 11 to 59 hours, and the thermal inertia covers a wide range, not showing any correlation with the period. With this work we increase the sample of slow rotators with reliable spin and shape models and known thermal inertia by 40%. The thermal inertia values of our sample do not display a previously suggested increasing trend with rotation period, likely due to their small skin depth [Marciniak et al., 2021].

Dust and surface materials

We investigated the dynamics of dust particles in the ring around dwarf planet Haumea. The point mass gravitational force, a second degree and order gravity field, and the solar radiation pressure as the main perturbations have been considered. The quasi-stationary state of the ring varies for different micron-sized grains and depends also on the spin-orbit resonances between the rotation rate of the main body and the orbital period of the dust particles. The simulations confirm the variable radial width of the ring observed during the transit ingress and egress. Results show that the micron-sized grains, initially on circular orbits, become eccentric and form an apse-aligned ring at the observed radial distance near to the 3:1 spin-orbit resonance. It is also demonstrated that this coincidence is only apparent and independent of 3:1 resonance [Kovács and Regály, 2018].

2012 DR_{30} is one of the known solar system objects with the largest aphelion distance, exceeding 2200 au, on a high inclination orbit ($i = 78°$). It has been recognized to be either a borderline representative of high inclination, high perihelion distance (HiHq) objects, or even a new class of bodies, similar to HiHq objects for orbit but with an aphelion in the inner Oort Cloud. Here, we present photometry using long-term data from 2000 to 2013 taken by the SDSS sky survey, ESO MPG 2.2 m and McDonald 2.1 m telescopes, and a visual+near-infrared spectrum taken with the Southern Astrophysical Research Telescope and Magellan telescopes, providing insights into the surface composition of this body. Our best fit suggests that the surface contains 60% of complex organics (30% of Titan and 30% of Triton tholins) with a significant fraction of ice (30%, including pure water and water with inclusions of complex organics) and 10% silicates. The models also suggest a low limit of amorphous carbons, and hence the fragmentation of long-chained complex organics is slower than their rate of generation. 2012 DR_{30} just recently passed the perihelion, and the long-term photometry of the object suggested ambiguous signs of activity, since the long-term photometric scatter well exceeded the supposed measurement errors and the expected brightness variation related to rotation. Photometric colors put 2012 DR_{30} exactly between dark neutral and red objects, thus it either can be in a transition phase between the two classes or have differing surface properties from these populated classes [Szabó et al., 2018].

While the dust material of debris disks is rather well studied, their possible gas content has been remained less explored so far. Nevertheless, investigations over the recent years revealed gas in emission in seventeen debris disks. The observed cold gas is located at radial distances larger than ∼20au and is generally attributed to collisions of icy bodies in exosolar analogues of our Kuiper-belt. To investigate the presence of gas in the inner regions of 15 known gas-bearing systems we obtained high-resolution optical spectra for them and searched for non-photospheric absorptions of circumstellar origin. Narrow, stable Ca II and/or Na I absorption features have been detected superimposed to the photospheric lines in 10 systems. Some stars also present transient variable events or absorptions extended towards red wavelengths. The observed features is thought to arise from relatively hot gas situated close to the star. This gas is likely released from evaporation of exocomets and dust grains, or grain-grain collisions [Rebollido et al., 2018].

Extreme debris disks (EDDs) are rare systems with peculiarly large amounts of warm dust that may stem from recent giant impacts between planetary embryos during the final phases of terrestrial planet growth. In this study we identified and characterised six new EDDs. These disks surround F5-G9 type main-sequence stars with ages >100 Myr, have dust temperatures higher than 300 K, and fractional luminosities between 0.01 and 0.07. Using time-domain photometric data at 3.4 and 4.6 μm from the WISE all-sky surveys, we conclude that four of these disks exhibited variable mid-infrared (IR) emission between 2010 and 2019. Analyzing the sample of all known EDDs, now expanded to 17 objects, we find that 14 of them showed changes at 3-5 μm over the past decade, suggesting that mid-IR variability is an inherent characteristic of EDDs. We also report that wide-orbit pairs are significantly more common in EDD systems than in the normal stellar population. While current models of rocky planet formation predict that the majority of giant collisions occur in the first 100 Myr, we find that the sample of EDDs is dominated by systems older than this age. This raises the possibility that the era of giant impacts may be longer than we think, or that some other mechanism(s) can also produce EDDs. We examined a scenario where the observed warm dust stems from the disruption and/or collisions of comets delivered from an outer reservoir into the inner regions, and explored what role the wide companions could play in this process [Moór et al., 2021].

Complex shape, internal structure, tidal and chemical evolution models of asteroids and dwarf planets

The satellite of (225088) 2007 OR_{10} Gonggong was discovered on archival Hubble Space Telescope images and along with new observations with the WFC3 camera in late 2017 we have been able to determine the orbit. The orbit's notable eccentricity, $e \approx 0.3$, may be a consequence of an intrinsically eccentric orbit and slow tidal evolution, but may also be caused by the Kozai mechanism. Dynamical considerations also suggest that the moon is small, $D_{eff} < 100$ km. Based on the newly determined system mass of 1.75×10^{21} kg, 2007 OR10 is the fifth most massive dwarf planet after Eris, Pluto, Haumea and Makemake. The newly determined orbit has also been considered as an additional option in our radiometric analysis, provided that the moon orbits in the equatorial plane of the primary. Assuming a spherical shape for the primary this approach provides a size of 1230±50 km, with a slight dependence on the satellite orbit orientation and primary rotation rate chosen, and a bulk density of $1.75\pm0.07\,\mathrm{g\,cm^{-3}}$ for the primary. A previous size estimate that assumed an equator-on configuration (1535^{+75}_{-225} km) would provide a density of $0.92^{+0.46}_{-0.14}\,\mathrm{g\,cm^{-3}}$, unexpectedly low for a 1000 km-sized dwarf planet [Kiss et al., 2019].

(10) Hygiea is the fourth largest main belt asteroid. It suffered a giant impact ∼2 Gyr ago, the origin of one of the largest asteroid families. We performed high-angular-resolution imaging observations of Hygiea with the VLT/SPHERE instrument (∼20 mas at 600 nm) that reveal a basin-free nearly spherical shape with a volume-equivalent radius of 217±7 km, implying a density of $1944\pm250\,\mathrm{kg\,m^{-3}}$. We determined a new rotation period for Hygiea of ∼13.8 h. Numerical simulations of the family-forming event show that Hygiea's spherical shape and family can be explained by a collision with a large projectile (∼75-150 km). Hygiea appears to be nearly as spherical as Ceres, opening up the possibility for this object to be reclassified as a dwarf planet [Vernazza et al., 2020].

(704) Interamnia is the fifth largest main belt asteroid (∼330km), filling the gap between the largest bodies (Ceres, Vesta, Pallas, Hygiea) and the smaller asteroids. We tested at what size and mass the shape of a small body departs from a nearly ellipsoidal equilibrium shape to an irregular shape as observed for smaller (D≤200km) bodies. We observed Interamnia with ESO VLT/SPHERE, and several new optical lightcurves were recorded. We used the All-Data Asteroid Modeling algorithm to construct a 3D-shape model and determine its spin state. Interamnia's volume-equivalent diameter of 332±6 km implies a bulk density of $\rho = 1.98\pm0.68$ g/cm3, suggesting a high fraction of water ice. Our observations reveal an ellipsoidal shape compatible with a fluid hydrostatic equilibrium at the 2σ level. The regular shape of Interamnia implies that the size and mass limit under which the shapes of minor bodies become irregular, has to be searched among smaller ($D \leq 300$ km) and less massive ($m \leq 3\times10^{19}$ kg) bodies [Hanuš et al., 2020].

Gaia will determine the mass of hundreds of large main belt asteroids. Diameter estimates are based in most cases on simple thermal models, leading to volume uncertainties of 20-30%. We determined the 3D shape models and computed the volumes for 13 main belt Gaia asteroids, using the Shaping Asteroids with Genetic Evolution (SAGE) algorithm. These models were scaled by fitting them to available stellar occultation and/or thermal infrared observations. From our volumes it is possible to compute the bulk density, a fundamental physical property needed to understand the formation and evolution of small bodies [Podlewska-Gaca et al., 2020].

We developed an improved algorithm to model the serpentinization process in planetesimals in the early Solar system. Our model is based on the model by Gobi & Kereszturi (2017), but contains improvements in the consideration of heat capacities and lithospheric pressure, and in the calculation of the amount of interfacial water. Comparison of our results with previous calculations show that there are significant differences in e.g. the serpentinization time – the time necessary to consume most of the reactants at specific initial conditions – or the amount of heat produced by this process. We show that in icy bodies below the melting point of water ice, serpentinization reaction using interfacial water may be able to proceed and eventually push the local temperature above the melting point to start a 'runaway' serpentinization. In objects with radii $R \geq 200$ km serpentinization might have reformed nearly the whole interior of these bodies in the early Solar system. [Farkas-Takács et al., 2022].

Concept papers for future instrumentation

The Transiting Exoplanet Survey Satellite (TESS) observes nearly the full sky, and provides timeseries imaging data in ∼27-day-long campaigns. TESS is equipped with four cameras, each of which has a field of view of 24 deg by 24 deg. During the first two years of the primary mission, one of these cameras, Camera #1, is going to observe fields centered at an ecliptic latitude of 18 deg. While the ecliptic plane itself is not covered during the primary mission, the characteristic scale height of the main asteroid belt and Kuiper Belt implies that a significant amount of small solar system bodies will cross this camera's field of view. Based on the comparison of the expected amount of information of TESS and Kepler/K2, we computed the cumulative étendues of the two optical setups. This comparison results in roughly comparable optical étendues, however, the net étendue is significantly larger in the case of TESS because all of the imaging data provided by the 30-minute cadence frames are downlinked. In addition, many principles of the data acquisition and optical setup are clearly different. TESS will yield timeseries photometry, and hence rotational properties for only brighter objects, but in terms of spatial and phase space coverage, this sample will be more homogeneous and more complete. In this study we reviewed the main analogs and differences between the Kepler/K2 mission and the TESS mission, focusing on scientific implications and possible yields related to our solar system [Pál et al., 2018].

The trans-Neptunian worlds are key to understanding the past history and the present geology of our solar system. In this Decadal Survey white paper we presented compelling scientific arguments for expanding our knowledge of this extremely diverse population of minor bodies through flybys of a wide range of sizes of TNOs, including dwarf planets and binary TNOs. We provided summaries of the state of knowledge of fifteen major TNOs, together with overviews of key smaller populations. Planning for future missions by international agencies has begun to shift towards combined missions to Centaurs, the ice giant planets, and TNOs, which benefits both scientific opportunities and logistics. Gravity assists from ice giants can be used for travel to distant TNOs, while at the same time returning valuable science on the ice giants and their ring and satellite systems. Trajectories to high-priority distant targets also include close approach opportunities to multiple other TNOs, in addition to remote observations of nearby TNOs [Holler et al., 2021].

We studied the feasibility and scientific potential of young stellar object measurements, the actual hosts of the planet formation process, as ancillary observations with the ESA's ARIEL space mission. We compiled a list of potentially interesting young stars: FUors, systems harbouring extreme debris discs and a larger sample of young stellar objects showing strong near/mid-infrared excess, and representing the early stages of planet formation. These objects can be observed as additional targets in the waiting times between the scheduled exoplanet transit and occultation observations. It was concluded that approximately 99.2% of the available gaps could be used effectively. This corresponds to an additional 2881 $\pm$ 56 hours of active data gathering. A typical signal-to-noise ratio of $\sim 10^4$ can be achieved along the whole spectral window covered by ARIEL [Gyürüs et al., 2021].

Conference organisation

We organised the workshop "Thermal Models in Planetary Science 3" supported partly by the Horizons 2020 project "Small Bodies: Near and Far", and by the Hungarian Academy of Sciences, between February 20-22, 2019. The main topic was the modelling and interpretation of thermal emission measurements of small, airless bodies in our Solar System, near-Earth, main-belt and trans-Neptunian objects, satellites, and our Moon. This focus workshop had more than 70 participants from 20 countries. More information can be found on the workshop's webpage: http://thermops2019.hu/

We also organized a successful special 'Small Body Surveys' session in the Europlanet Science Congress 2020 (conveners: Cs. Kiss and A. Pál).

Observing time proposals

We have been awarded with observing time in three consecutive years to measure the thermal emission of the ring of Haumea, in band-7 of the Atacama Large Millimetre Array (ALMA), to resolve and image it for the first time. However, due to bad weather conditions and later due to the COVID situation these measurements could not have been performed.

The James Webb Space Telescope measurements mentioned in the original work plan could not have been done due to the delayed launch of the JWST.

Project team

The project team broadly consisted of the persons predefined at the start of the project. Vera Dobos was employed as a post-doc for a short period of time, but the remaining post-doc funding could not have been used to employ a dedicated post-doc due to the COVID-19 situation. Instead, we used this funding to keep the project members A. Farkas-Takács and R. Szakáts on the project, partly financing their salaries. Cs. Kalup, V. Kecskeméthy and P. Sági also participated in the team's work as students.

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