Final report for the project ”Debris zones in solar systems”

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Kiss, Cs., Szabó, Gy.M., Sárneczky, K., Kiss, L.L., Pál, A., Moór, A., Farkas-Takács, A., Kereszturi, Á., Marton, G., Varga-Verebélyi, E.

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Executive summary

The debris disk of our Solar system have special importance: this is the only place where the bodies building up the disk can be studied individually. The aim of our project was to get the key to understand the evolution of the debris disk in our Solar system through the properties of minor body populations and link this to exosolar debris disks. To achieve this goal we studied near-Earth, main belt and Trojan asteroids, Centaurs, trans-Neptunian objects, comets and the zodiacal dust, explored the connection between these groups and the debris zones in our Solar systems and investigated the characteristics of gas and dust in exoplanetary systems.

We determined the characteristics of near-Earth, in some cases potentially hazardous asteroids, targets of sample-return missions, giving important constraints for mission planners. These minor planets will finally give us the clue to the origin and evolution of the main asteroid belt The K2 mission has been identified as a new and powerful tool to obtain spin properties for a large sample of targets. We used it for main belt and Jovian Trojan asteroids, as well as for Centaurs and trans-Neptunian objects, with interesting results for Solar system evolution theories. We have for the first time obtained a comprehensive sample of objects with accurate size, albedo and thermal properties in the outer Solar system. This lead to important conclusions on size distributions, surface characteristics and evolutionary scenarios in the early phases of debris disk evolution. In addition, major results were published on individual objects, too. Our results on the activity of comets are directly applicable to the dust replenishment theories in the inner solar system. The meteorite samples we analysed give direct information on the Solar system's debris disk at the time of its formation. We studied the incidence of debris disks in young moving groups and also the survival of gas, and identified candidate systems where planets may caused the stirring of the disk.

The results we achieved are in principle in line with the original aims of the project. In addition to these goals, new research topics have been added, not foreseen at the start. This includes the study of extreme Centaurs and irregular satellites that are both important probes of the Solar system debris disk evolution; and the application of the K2 mission of the Kepler Space Telescope for Solar system studies, a very promising new field.

In addition to the original team Ákos Kereszturi, Gábor Marton (employed as postdoc researcher on project budget from January 1, 2013 to December 31, 2014) and Erika Verebélyi have joined the project at later stages. Their work significantly contributed to the success of the project, adding important expertise in the field of meteorite sample analysis, extended dust emission and zodiacal emission studies.

Our results have led to the publication of 32 papers in high-impact astronomical journals, doubling the number of papers originally promised in our research plan. In addition to the numerous conference appearances, one ESA and one NASA press release have been published based on our results.

A more detailed summary of our science results is given below.

Science results

The inner debris zone

We observed 2005 YU_{55} during a very close earth approach from the ground in the mid-infrared, with the Submillimeter Array at 1.3 mm and with the PACS camera of the Herschel Space Observatory. We found that 2005 YU55 has an almost spherical shape with a diameter of 306 m and a geometric albedo of 0.065, with a retrograde sense of rotation. The analysis revealed a discrepancy with the radar-derived size. We found a thermal inertia very similar to that of the rubble-pile asteroid 25143 Itokawa, indicating a surface with a mixture of low conductivity fine regolith and larger rocks and boulders of high thermal inertia (**Müller et al., 2013, A&A, 558, A97**).

With the Herschel Space Observatory we obtained the first thermal measurements of (99942) Apophis, at similar phase angles before and after opposition. A thermophysical model analysis found that this potentially hazardous asteroid has an elongated shape with a mean diameter of 375^{+14}_{-10} m and a geometric albedo of $0.30^{0.05}_{-0.06}$. Our newly derived mass is 2-3 times larger than previous estimates that will influence impact scenario studies and the long-term orbit predictions (**Müller et al., 2014, A&A, 566, A22**).

JAXA's Hayabusa-2 spacecraft will arrive to the near-Earth asteroid 162173 Ryugu in 2018, perform a survey, land, obtain surface material, then depart in Dec 2019 and return in Dec 2020. We observed Ryugu with the Herschel Space Observatory in Apr 2012 at far-IR thermal wavelengths, supported by ground-based observations. With these data we refined the 'design reference model' which is currently used for planning, operational and modelling purposes by the Hayabusa-2 team. (**Müller et al., 2016, A&A, accepted, arXiv:1611.05625**)

The near-Earth asteroid 2015 TB 145 had a very close encounter with the Earth on October 31, 2015. We obtained 3-band mid-IR observations with the ESO VLT-VISIR instrument and visual lightcurves during the close-encounter phase, provinding a rotation period of 2.939±0.005 h. We found that the NEA has a size of 625-700 m, notably larger than early estimates based on radar measurements. (**Müller et al., 2016, A&A, accepted, arXiv:1610.08267**)

We used data from four programs completed with the MIPS camera of the Spitzer Space Telescope at 24 μm to probe the large scale brightness distribution as well as the small-scale (subarcmin) structure of the Zodiacal Could. As the Spitzer Space Telescope looked at different parts of the Zodiacal Cloud as it was orbiting the Sun, we could also investigate the 3D distribution of zodiacal dust (**Verebélyi et al., 2014, Asteroids, Comets, Meteors 2014, #555**).

The K2 mission of the Kepler Space Telescope provided the opportunity to obtain long, uninterrupted light curves of solar system targets. In a close cooperation with the Kepler group in Konkoly Observatory we investigated the effect of main belt asteroids on the photometry of Kepler targets in the K2 engineering field-of-view (**Szabó, R., et al., 2015, AJ, 149, 112**) and derived light curves of asteroids passing the Kepler field in Campaigns 0 and 3 (**Szabó, R., et al., 2016, A&A, 596, A40**).

We analysed lightcurves of 56 Jovian Trojans observed in the K2 mission. We found an overabundance of rotation periods above 60 h and from amplitude analysis we derived a binary rate of 20±5%. Our spin rate distribution confirms the previously obtained spin barrier of ∼5 h and the ∼0.5 g cm^{-3} cometary-like density limit, suggesting a high internal porosity for Jovian Trojans. (**Szabó, Gy.M., et al., 2016, A&A, accepted, arXiv:1609.02760**).

Planets and satellites

A summary paper of all Herschel/PACS far-infrared photometer observations of Mars, Saturn, Uranus, Neptune, Callisto, Ganymede, and Titan was published. Our results show the potential of using the observed solar system targets for cross-calibration with other ground-based, airborne, and space-based instruments and our results will lead to improved model solutions for future calibration applications (**Müller et al., 2016, A&A, 558, A109**).

We performed an analysis of K2 observations of the irregular Neptune satellite, Nereid. Our results excludes the previously suggested very elongated shape and shows that Nereid's spin axis cannot be in forced precession due to tidal forces. Thermal emission data indicate that Nereid's shape is actually close to the axis ratio limit of 1.3:1 we obtained, and it has a very rough, highly cratered surface (**Kiss et al., 2016, MNRAS, 457, 2908**)

The Kuiper belt and beyond

In the "TNOs are Cool!" Open Time Key Program of the Herschel Space Observatory we observed about 140 trans-Neptunian object and Centaurs, roughly 10% of all known objects in the outer Solar system. Our goal was to determine basic physical properties, including size, albedo, and the thermal characteristics of the surface. This is an exceptional dataset, the results obtained from this program will remain unique in the next decades and it is one of the greatest legacies of the Herschel mission.

In our research program we have developed special data reduction techniques for the far-infrared observations of moving targets, and our team at Konkoly Observatory performed the whole data reduction of the "TNOs are Cool!" research program. These methods will also be applicable in the observation strategy and data reduction of future infrared space measurements (**Kiss et al., 2014, Experimental Astronomy, 37, 161**). Several population-specific papers were published presenting the main physical properties of these targets, also analysing the size, albedo and surface thermal relations within these groups. We presented our results for Centaurs (**Duffard et al., 2014, A&A, 564, A92**) and for Classical Kuiper belt objects (**Vilenius et al., 2014, A&A, 564, A35**). A separate paper was devoted to the brightest trans-Neptunian objects (**Fornasier et al., 2013, A&A, 555, A15**) involving Herschel/SPIRE measurements. We gave new size estimates for some of the largest TNOs and for a handful of binary systems. We also identified a trend of decreasing emissivity for longer wavelength, a sign of porous subsurface structures and layers notably colder than the dayside surface temperatures.

We investigated the thermal properties of the surface materials of 85 Centaurs and TNOs using Spitzer and Herschel data. We found a large variety of surface roughness (cratering) that also shows up in the infrared properties. The calculated thermal inertiae show a strong decrease for larger heliocentric distances and are 2-3 orders of magnitude smaller than that seen e.g. in the satellite system of Saturn or in the Pluto-Charon system (**Lellouch et al., 2013, A&A, 557, A60**).

With new albedo data obtained using the Herschel Space Observatory we revealed two distinct type of surfaces among mid-sized TNOs. The existence of these two, color-albedo separated groups is an evidence for a compositional discontinuity and supports evolutionary scenarios involving the outward migration of Neptune in the young Solar system (**Lacerda et al., 2014, ApJ, 793, L2**).

We investigated two members from a new group of objects, the extreme Centaurs. We observed both targets, 2012 DR 30 and 2013 AZ 60, using Herschel director's discretionary time, supplemented by ground-based measurements. Dynamical analysis of their orbits shows that they have recently been originated from the Oort cloud. Objects in this class were likely the parents of the highest absolute brightness comets in human history (**Kiss et al., 2013, A&A, 555, A3; Pál et al., 2015, A&A, 583, A93**)

We explored the environment of Pluto and Charon in the far-infrared with Herschel to identify signs of a possible dust ring, in preparation for the New Horizons flyby. We did not find any clear evidence for an extended emission but placed upper limits on the total disk mass and on the column density in a reasonable disk configuration, and analysed the hazard during the flyby. (**Marton et al., A&A, 579, L9**)

We observed the thermal light curve of the Pluto-Charon system using Herschel data from 70 to 500 μm. Combining these with earlier measurements indicates that the brightness temperature of the system drastically decreases with increasing wavelength. This kind of behaviour is usually not observed in asteroids, but is found in several icy surfaces of the solar system. We tentatively identify that a combination of a strong dielectric constant and a considerable surface material transparency is responsible for the effect. (**Lellouch et al., 2016, A&A, 558, A2**)

Observation of an occultation by the trans-Neptunian object 2007 UK126 on 15 November 2014 were performed, the first multi-chord dataset obtained for a detached object. By combining our analyses with far-infrared data, we could constrain the shape and obtained an effective diameter of 599–629 km (**Schindler et al., 2016, A&A, accepted, arXiv:1611.02798**)

We performed the first photometric observations of trans-Neptunian objects with the Kepler space telescope in the K2 mission. We obtained rotation periods and light curve amplitudes for 2007 JJ43 and 2002 GV31. These observations clearly showed the excellent capabilities of the K2 mission to obtain unbiased rotational light curves of distant Solar system objects, and their potential to derive shape and albedo characteristics. (**Pál et al., 2015, ApJL, 804, L45**).

We conducted a comprehensive thermal and rotational analysis of the distant trans-Neptunian object 2007 OR10. We found that it is likely larger and darker than derived by earlier studies, the new diameter of 1535 km places 2007 OR10 as the third largets TNO after Pluto and Eris. We suspected that the slow rotation rate of 44.81 h is caused by tidal forces from a massive satellite. (**Pál et al., 2016, AJ, 151, 117, NASA press release: http://www.jpl.nasa.gov/news/news.php?feature=6509**). In a subsequent study we identified a candidate satellite of 2007 OR10 on archival Hubble Space Telescope images. The moon orbits the central body at a distance of at least 15000 km, and its low brightness indicates that it cannot contribute notably to the total thermal emission of the system, i.e.

the previously obtained size of ∼1535 km for 2007 OR10 remains likely unchanged (**Marton et al., 2016, AAS/DPS meeting #48, id.120.22**)

Comets

Comet C/2013 A1 (Siding Spring) recevied a considerable attention since it passed Mars at a distance of ∼ 40000 km in November 2014, and its coma swept the surface of the red planet. The thermal emission of the comet was observed at a heliocentric distance of 6.48 AU using Herschel/PACS. The comet was clearly active, showing a coma that could be traced to a distance of ∼50000 km. The derived grain size distribution indicate an overabundance of large grains. (**Kiss et al., 2015, A&A Letters, 574, L3; ESA press release: http://sci.esa.int/herschel/54802-herschel-view-of-comet-siding-spring/**).

We performed a decade-long survey of the distant activity of long-period comets and found that the most important separation in the data set is based on the dynamical nature of the objects. Dynamically new comets are characterized by a higher level of activity on average. New comets develop more symmetric comae, while the comae of recurrent comets can be less symmetrical (**Sárneczky et al., 2016, AJ, 152, 220**)

Laboratory astrophysics

The NWA 3118 CV3 chondrite was studied with optical microscopy and electron microprobe methods. We found that mostly intact chondrules were present, and fragmentation happened before the chondrules settled down. Our observations suggest that some features earlier termed as chondrule rims in CV meteorites might also form without chondrules or not directly around them. This may represent a knowledge gap in the understanding of processes inside CV parent bodies. (**Kereszturi et al., 2014, Planetary & Space Science, 104, 200**)

Signatures of partial chondrule destruction were observed in the NWA 6604 CK4 meteorite. During alterations opaque minerals crystallized along fractures firstly, large volume opaque and Ca-rich materials secondly, only Ca-rich plagioclase thirdly, and only fracture formation without crystallization happened fourthly. The observations are compatible with the CV-CK joint parent body model for these meteorties, where beside impact effects other heat sources contributed to the melting process. (**Kereszturi et al., 2015, Meteoritics & Planetary Science, 50, 1295–1309**)

Exosolar systems

Debris disks are previously believed to be gas-poor descendants of protoplanetary disks. Recent observations, however, revealed molecular or atomic gas in several 10-40 Myr old systems. To study this phenomenon further, we used the APEX and IRAM radio telescopes to search for CO gas in 20 bright debris disks resulting in a discovery of a new gas-bearing debris disk around the 16 Myr old A-type star HD 131835. Combining this with previous results, we suggested that the presence of gas in the most massive debris disks around young A-type stars was a common phenomenon (**Moór et al., 2015, ApJ, 814, 42**).

The origin of gas in these systems is not clear yet. It could be second generation, derived from the erosion of planetesimals or may also be leftover primordial gas. Using the ALMA interferometer we detected a large amount of CO around the 30 Myr-old star HD 21997. We argued that neither the large quantity of molecular gas, nor the only partially overlapping gas and dust distributions can be accommodated within the secondary gas production scenario, and what we see is the leftover gas from the primordial disk (**Moór et al. 2013, ApJ, 777, L25**).

A significant fraction of nearby young moving group members harbor circumstellar debris disks. With their proximity and well-dated young ages (<100 Myr), these groups offer an excellent laboratory for studying the early evolution of debris dust and planetesimal belts. We initiated a further exploration of the β Pic moving group and the Tucana-Horologium, Columba, Carina and Argus associations. We obtained and analyzed high resolution spectra of 54 candidate stars and identified 35 new likely members (**Moór et al., 2013, MNRAS 435, 1376**). Using the Herschel Space Observatory we also searched for far-infrared excess in 31 systems from these groups. We identified six stars with debris disks, four of them were new discoveries. We examined the incidence and general characteristics of debris disks around Sun-like members of the selected groups as well (**Moór et al., 2016, ApJ, 826, 123**).

For effective dust production via collisions, planetesimal motion must be dynamically stirred. This dynamical excitation is caused either by Pluto-sized planetesimals just formed in the disk (self-stirring) or by a giant planet (planetary stirring). Our Kuiper-belt is a highly excited system, where both embedded dwarf planets and icy giants contributed to the stirring. To evaluate the feasibility of stirring scenarios in 11 debris disks we analyzed their spatially resolved Herschel images and concluded that four of them are incompatible with the self-stirring model, making them promising candidates for excitation by a planet (**Moór et al., 2015, MNRAS, 447, 577**). In one of these systems, HD 95086, a wide separation giant planet has already been discovered. By exploring the structure of this debris disk, we investigated its possible interaction with the revealed planet (**Moór et al., 2013, ApJ, 775, L51**)