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Deposition of steeply infalling debris — pebbles, boulders, snowballs, asteroids, comets — around stars

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Based on MNRAS (2017), 468, 1575-1593

Abstract

When Comet Lovejoy plunged into the Sun, and survived, questions arose about the physics of infall of small bodies. [1,2] has already described this infall in detail. However, a more general analysis for any type of star has been missing. [3] generalized previous studies, with specific applications to white dwarfs.

High-metallicity pollution is common in white dwarf stars hosting remnant planetary systems. However, they rarely have detectable debris accretion discs, possibly because much of the influx is fast steeply infalling debris in star-grazing orbits, producing a more tenuous signature than a slowly accreting disc. Processes governing such deposition between the Roche radius and photosphere have so far received little attention and we model them here analytically by extending recent work on sun-grazing comets to white dwarf systems. We find that the evolution of cm-to-km size infallers most strongly depends on two combinations of parameters, which effectively measure sublimation rate and binding strength. We then provide an algorithm to determine the fate of infallers for any white dwarf, and apply the algorithm to four limiting combinations of hot versus cool (young/old) white dwarfs with snowy (weak, volatile) versus rocky (strong, refractory) infallers.

We find: (i) Total sublimation above the photosphere befalls all small infallers across the entire white dwarf temperature range, the threshold size rising with it and 100× larger for rock than snow. (ii) All very large objects fragment tidally regardless of temperature: for rock, $a0 \gtrsim 10^5$ cm; for snow, $a0 \gtrsim 10^3 - 3 \times 10^4$ cm across all white dwarf cooling ages. (iii) A considerable range of infaller sizes avoids fragmentation and total sublimation, yielding impacts or grazes with cold white dwarfs. This range rapidly narrows with increasing temperature, especially for snowy bodies. Finally, we briefly discuss how the various forms of deposited debris may finally reach the photosphere surface itself.

1. Figures

Destruction of infalling bodies occurs by a combination of: (a) sublimative mass-loss by an energy flux of starlight that is sufficiently large to raise the bodies above the vaporization temperature of at least some, and eventually all, of their components; (b) fragmentation due to the stellar tidal or possibly internal pressure forces exceeding the internal strength and self-gravity of the body; and (c) frictional ablative mass-loss and ram-pressure pancaking and deceleration effects in the dense low atmosphere.

The importance of these various processes all decline with distance, but at differing rates. An example of all three processes at work can be found in Fig. 1, which details the fate of rocky infallers of sizes ranging from 10^0 to 10^6 metres. The white dwarf has an effective temperature of about 15,000 K. Fig. 2 then provides a more abstract representation of the different regimes, which may be applicable to any stars and any impactors. Finally, Fig. 3 provides an algorithm from [3] that one may apply to any system in order to determine the fate of infallers. This algorithm may be used to help determine the fate of planetary systems.

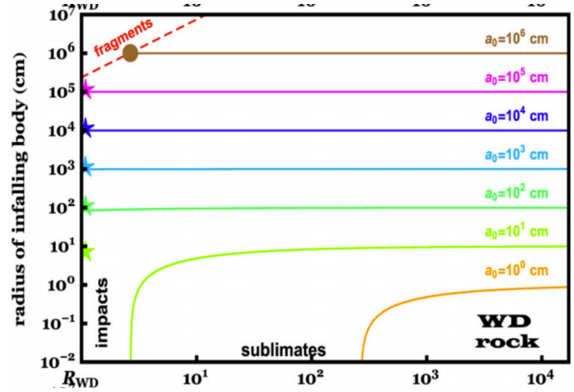

Figure 1: Size evolutions and fates for rocky bodies falling in towards a white dwarf with an effective temperature of about 15,000 K.

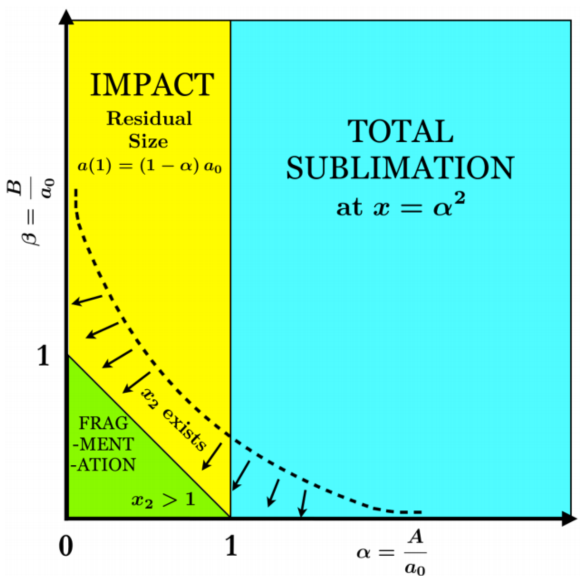

Figure 2: The three distinct domains of infaller destruction in the α, β plane (see [3] for definitions) – total sublimation, impact after partial sublimation, and fragmentation after partial sublimation. Fragmentation is restricted to the green triangular domain in the bottom left corner.

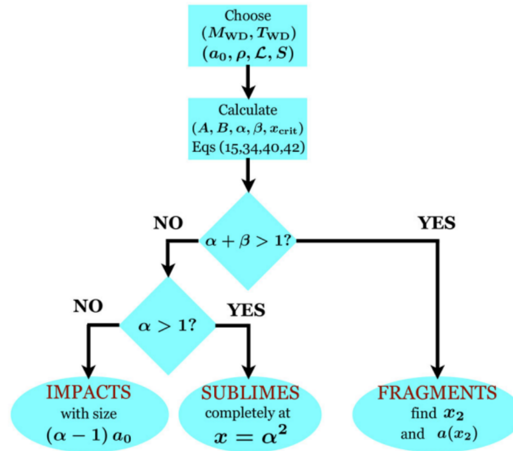

Figure 3: Schematic flow chart of how to determine the mode and position of destruction of any infaller for any star starting from adopted values of the physical parameters of each.

Acknowledgements

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The Ceres and Vesta effect on some young asteroid families

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Abstract

Large asteroids (Ceres, Vesta) can a very significant perturb of orbits of very young compact asteroid families, in some cases principally change the stability of motion. The effect of most massive asteroids on dynamics of young compact asteroids clusters is different for different clusters. Moreover, it may be different for the members of the same cluster. In particular, we note Ceres+Vesta+Asteroid resonance in Lucascavin family.

1. Introduction

An asteroid family is a group of asteroids with similar orbits and spectra that was produced by a collisional breakup of a large parent body. The ages of asteroid families are in wide range from hundred of thousands up to few Gyrs. The research of young minor planets clusters is easier, because many factors have no sufficient time to operate.

In this paper we consider the effect of Ceres and Vesta on young families dynamics. The role of large asteroids on dynamics of main belt is significant and multivariate. A secular resonance between the dwarf planet Ceres and other asteroids first studied by Novakovic et al **[4, 5, 6]**. Galad studied the effect of main belt perturbers on asteroid pair age estimation **[2]**. Christou put forward the idea about Ceres and Vesta Trojans existence and had given some examples **[1]**.

The main goal of present paper is to study effect of Ceres and Vesta perturbation on some very young and compact asteroid families (age<1Myr). We have shown that the influence of Ceres and Vesta is complex and not bounded only secular resonances and close encounters.

2. Method

To study the dynamical evolution of these compact asteroid clusters, the equations of the motion of the systems were numerically integrated 800 kyrs into the past, using the N-body integrator Mercury and the Everhart integration method. On base of previous age estimation, we expect that this time interval is sufficient. We made four series of integration. In the first we use only large planets perturbations. In the second we add Ceres only and only Vesta in the third. Finally, we add perturbations of both Ceres and Vesta. We have not taken into account any non-gravitational forces, because they poorly known and have no time to sufficient change of orbital elements in considered pairs.

3. Results

The Lucascavin family was discovered by Nesvorny & Vokrouhlicky **[3].** They estimate the age of this family 50-250 kyrs old. The problem of Lucascavin family age estimation is still difficult, more difficult than in case, for example, Emilkowalski family. The possible reason of this is resonance related chaos in semimajor axis of 180255 2003 VM9 due to joint Ceres and Vesta perturbations.

There are few high order mean motion resonances in vicinity of orbit of family: Jupiter 31:9 resonance at 2.2811701 au, Mars 6:11 resonance at 2.2824255 au, Ceres 4:3 resonance at 2.2841907 au, Vesta 19:20 resonance at 2.282122 au. In addition, secular perturbations by Ceres and Vesta may be important [6].

But semimajor axis of Ceres and Vesta are dependent on time. By this reason, resonance conditions are changed. Around to epoch -300 kyrs, orbits of Ceres and Vesta become close to the mutual 4:5 resonance and to the 3-body resonance with asteroids of Lucascavin cluster type: 5V:4C :6A. It explain the behavior of 180255 2003 VM9 semimajor axis in figure 2. Other members of cluster have smaller perturbations maybe due to phase protection.

Ceres and Vesta perturbations contribute significant effect on Kap'bos young asteroid cluster. But in this case is it not so easy to explain it. We can only state significant chaotic variation of semimajor axis of all members of Kap'bos family. As in case Lucascavin family, it is strongly complicate the estimation of age of cluster. In contrary, in cases Emilkowalski and Brugmansia (1992YC2) family, perturbations of Ceres and Vesta have not significant effect on angular elements convergence and age estimation.

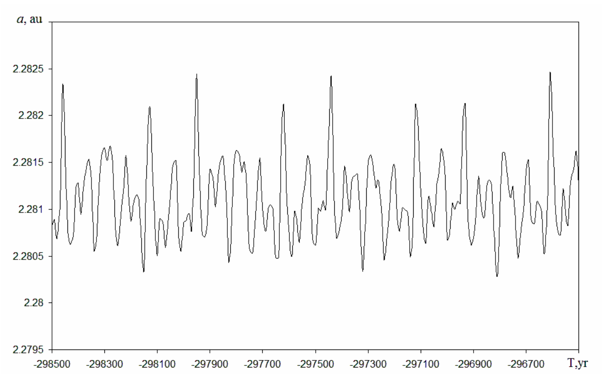

Figure 1: Perturbations in semimajor axis 180255 2003 VM9. Only Ceres effect have taken into account.

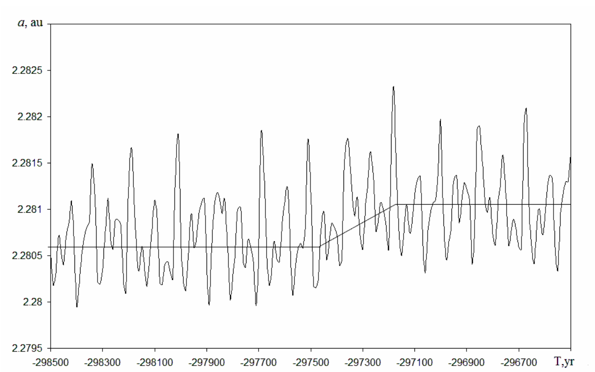

Figure 2: Perturbations in semimajor axis 180255 2003 VM9. Both Ceres and Vesta effect have taken into account

4. Conclusions

Finally, we can say following. Large asteroids (Ceres, Vesta) can produce a very significant perturbations of orbits of very young compact asteroid families, in some cases principally change the stability of motion. The effect of most massive asteroids on dynamics of young compact asteroids clusters is different for different clusters. Moreover, it may be different for the members of the same cluster!
Influenced by Ceres and Vesta, resonant changes in semimajor axis in Lucascavin cluster are comparable with differences between members of cluster, the problem of age determination becomes very complex, much more complex, than for Emilkowalski and Brugmansia cases. Similar situation of strong chaos, induced by Ceres and Vesta, we have in Kap'bos family.

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Dust analysis on board the Destiny$^+$ mission to 3200 Phaethon

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Abstract

The Japanese Destiny$^+$ spacecraft will be launched to the active asteroid 3200 Phaethon in 2022. Among the proposed core payload is an in-situ dust instrument based on the Cassini Cosmic Dust Analyzer. We use the ESA Interplanetary Meteoroid Engineering Model (IMEM), developed by Dikarev et al. (2005a,b), to study detection conditions and fluences of interplanetary and interstellar dust with a dust analyzer on board Destiny$^+$.

1. The Destiny$^+$ Mission

The Japanese Space Exploration Agency (JAXA) recently approved a new space mission, Destiny$^+$. The mission target is the active asteroid 3200 Phaethon which is an Apollo asteroid with an orbital period of about 1.4 years. The launch is presently planned for 2022, and the spacecraft will be orbiting the Sun between 0.8 and 1.2 AU (Fig. 1), with a Phaethon flyby planned for 2025 (Sarli et al., 2016).

Among the proposed core payload is an in-situ dust instrument based on the Cosmic Dust Analyzer on board the Saturn orbiting Cassini spacecraft (Srama et al., 2004). The Destiny$^+$ dust analyzer will be an impact ionization time-of-flight mass spectrometer capable of analyzing sub-micron and micron sized dust grains with a mass resolution of $m/\Delta m \approx 150$. In addition to the investigation of Phaethon and its dust environment, the mission goals comprise the analysis of interplanetary and interstellar dust grains with the Destiny$^+$ dust analyzer.

2. Dust Simulations

We study the detection conditions for interplanetary and interstellar dust particles during the spacecraft's interplanetary cruise. Our particular goal is to predict dust impact speeds, impact directions and fluences.

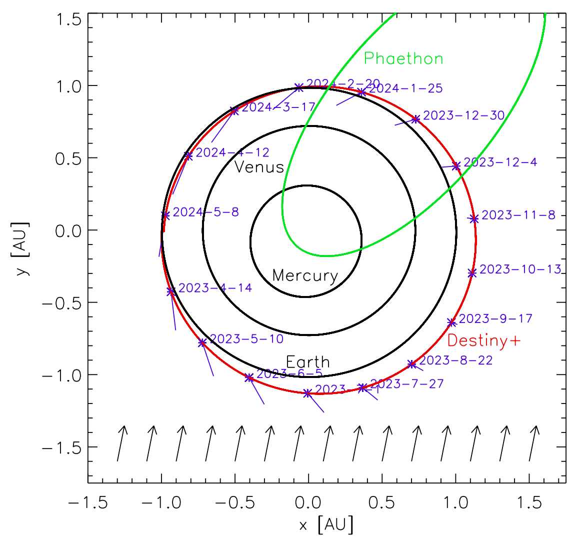

Figure 1: Trajectories of Destiny$^+$ (*red*, only the initial 1.3 years of the heliocentric trajectory are shown for clarity) and 3200 Phaethon (*green*). The interstellar dust flow in the heliocentric system is indicated by black arrows, and the ram direction of interstellar grains is shown by blue bars, bar lengths being proportional to the grain impact speed. Times are indicated at the Destiny$^+$ trajectory.

We perform our analysis with the ESA Interplanetary Meteoroid Engineering Model (IMEM) developed by Dikarev et al. (2005a,b). The model is based on infrared observations of the zodiacal cloud by the Cosmic Background Explorer (COBE) DIRBE instrument, in-situ flux measurements by the dust detectors on board the Galileo and Ulysses spacecraft, and the crater size distributions on lunar rock samples retrieved by the Apollo missions. It simulates the dynamics of cometary and asteroidal dust in the planetary system. Interstellar dust is described in a simplified form: A mono-directional stream of grains with an assumed ratio of gravitational to radiation pressure force $\beta = 1$ is parameterised by its apex direction and heliocentric flow speed of $26\,\mathrm{km\,s^{-1}}$ (Landgraf, 2000), as well as the mass distribution of the constituent particles.

3. Results and Conclusions

The initial 1.3 years of the Destiny$^+$ interplanetary trajectory are shown in Figure 1. In spring 2023, and during all later times when the spacecraft traverses the same region of the inner solar system, Destiny$^+$ moves approximately antiparallel to the interstellar dust flow. At this time impact speeds of interstellar grains are high, reaching a maximum of $55\,\mathrm{km\,s^{-1}}$. The spacecraft motion around the Sun leads to strong variations of the impact angle and impact speed with time.

In the simulations, the approach direction of the interstellar grains forms a narrow peak (at azimuth 165° and declination 90° in Figure 2), while the interplanetary dust has a much wider distribution of impact angles (*top panel*). In the time interval shown, the impact speed of the interstellar grains exceeds the speed of the interplanetary impactors by far (*bottom panel*). Thus, the impact speed is a crucial parameter to identify interstellar impactors.

Our simulations show that for Destiny$^+$ the best time period to detect interstellar grains and to separate them from the interplanetary particle background is the spatial region traversed by the Earth in winter and spring when impact speeds of interstellar grains are high. In the region traversed by the Earth in summer and autumn, impact speeds of interstellar grains are much lower and these grains can hardly be identified. We also present dust fluxes and fluences for the Destiny$^+$ dust analyzer for a total mission duration of 1200 days. Future work will focus on a more realistic model for the dynamics of the interstellar grains to predict more reliable impact speeds and directions than provided by the IMEM interstellar dust module.

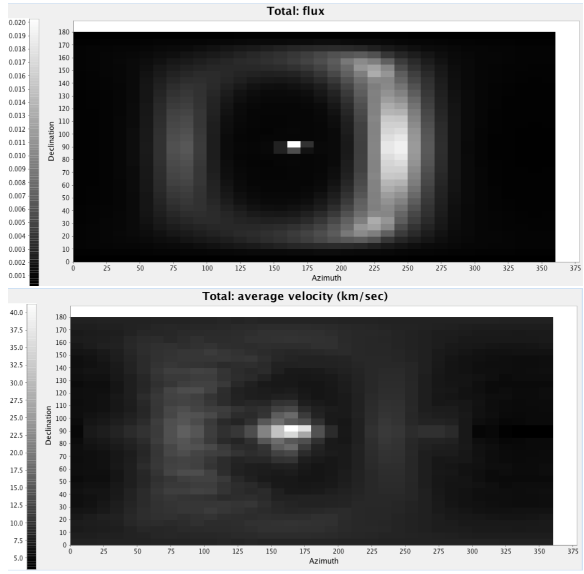

Figure 2: IMEM sky maps showing the distribution of particle fluxes (*top panel*) and impact speeds (*bottom panel*) of interplanetary and interstellar grains in a spacecraft-fixed coordinate system for the time period 1 to 15 April 2023. Azimuth 180° points toward the direction of the spacecraft speed vector and declination 90° is close to the ecliptic plane.

Acknowledgements

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Serendipitous observations of asteroids in Herschel PACS and SPIRE maps

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1. Introduction

The Herschel Space Observatory was an ESA mission in the Horizons 2000 program. The telescope could observe in far infrared and sub-millimetre wavelengths. For imaging, two of its instruments were used: the PACS camera at 70, 100 and 160 μm and the SPIRE photometers at 250, 350 and 500 μm. Amongst its targets there were galaxies, young stars, interstellar clouds and solar system objects. Due to their strong thermal emission solar system bodies, especially main belt asteroids, may contaminate the photometric measurements. Our goal is to find these objects, flag sources contaminated by passing solar system objects, and integrate these results into the PACS and SPIRE point source catalogs.

2. Search for SSOs

2.1 Main steps

We collected all Level 2.5 or Level 3 PACS and SPIRE scan maps from the Herschel Science Archive, and selected one image for every OBSID, because the same area could have two or three map in different wavelengths. In some cases the maps consist of images from very different epochs. To filter this, we selected those maps, where the difference between the start and end date is bigger than one day. In these cases we used the individual sub-maps (OBSIDs) for the search.

In the second step we queried which SSOs could be in the field of view from the Herschel's location at a specific date. We did this for three epochs: the start-, the mid- and the end date of the observation. Then we checked whether these positions were on the image area. If every three points were on the image, the first and the last point was kept as starting and ending coordinates.

In the case, when only one or two pints were on the image area, we calculated an intersection with the edge of the image. The internal point and the intersection was kept for the coordinate pairs.

If none of the three points were on the image area, we checked if the SSO had any intersection with the image, because the maps could have weird edges. If there were any intersections, the first and the last intersection points were used as starting and end points.

In the case of two points from the query we checked if that the SSO trajectory were on the image area or had any intersection with the map.

If we had only one point for an object from the query, we did additional query for two more coordinate pairs with +/- 1 day from the epoch of this one detection. Then we investigated if it could have any intersection with the image and where could it be.

2.2 Problems, exceptions

In some cases the observing time was too short, and the trajectory of the SSOs could not be determined properly. In these cases no intersection with the map was calculated and we used the original coordinates of the SSO from the query.

3. Tools

We used the *ephemd* package to obtain the targets in the actual field of view and *wcstools* for various supplementary tasks and python scripts for spherical geometry calculations. The thermal infrared emission of the targets are estimated via the Near Earth Asteroid Thermal Model.

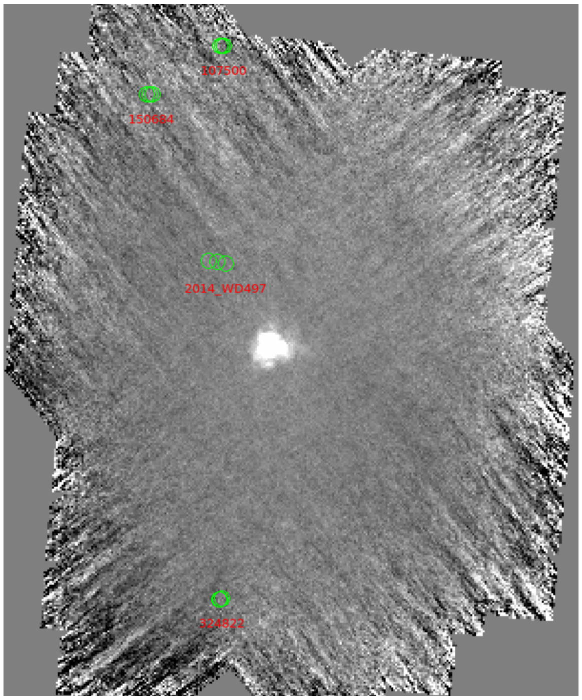

Figure 1: PACS 70 μm map of α Tau (1342183532) with the positions of the contaminating SSOs overlaid

4. Summary and Conclusions

The database developed here will be used as supplementary information in the Herschel PACS and SPIRE point source catalogs. We will also use these results to obtain thermal infrared fluxes from serendipitously observed asteroids supplementing the dedicated Herschel observations of solar system bodies.

https://www.cosmos.esa.int/web/herschel/spire-point-source-catalogue
https://www.cosmos.esa.int/web/herschel/pacs-point-source-catalogue

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NASA's Discovery Mission to (16) Psyche: Visiting a Metal World

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Abstract

The Psyche mission has been selected as the fourteenth in the NASA Discovery program. This mission will investigate what is likely an exposed planetary metallic core, the asteroid (16) Psyche. Estimates of density range widely but cluster between 6,500 and 7,500 kg/m^3 [1, 2, 3, 4]. Any density higher than 3,500 kg/m^3 likely indicates metal: rocky main belt asteroids have average densities roughly one-third to one-half their parent rock density [5]. Orbiting in the outer main belt at ~3 AU, the asteroid (16) Psyche has an effective diameter of ~235 km [7], and is thought to be made almost entirely of Fe-Ni metal [8, 9].

Models show that among the accretionary collisions early in the solar system, some destructive “hit and run” impacts strip the silicate mantle from differentiated bodies [6]. This is the leading hypothesis for Psyche’s formation: it is a bare planetesimal core. If our observations indicate that it is not a core, Psyche may instead be highly reduced, primordial metal-rich materials that accreted closer to the Sun.

The mission has five objectives:
• Determine whether Psyche is a core, or if it is unmelted material.
• Determine the relative ages of regions of its surface.
• Determine whether small metal bodies incorporate the same light elements as are expected in the Earth’s high-pressure core.
• Determine whether Psyche was formed under conditions more oxidizing or more reducing than Earth’s core.
• Characterize Psyche’s topography and impact crater morphology.

We will meet these objectives by examining Psyche with three high heritage instruments and radio science:
• Two block-redundant multispectral imagers (MSL Mastcam heritage) with clear and seven color filters that provide surface geology, composition, and topographic information. Lead: J.F. Bell, ASU, collaborating with Malin Space Science Systems.
• A gamma-ray and neutron spectrometer (MESSENGER heritage) determines the elemental composition for key elements (e.g., Fe, Ni, Si, and K) as well as compositional heterogeneity across Psyche’s surface. Lead: D.J. Lawrence, APL.
• Dual fluxgate magnetometers in a gradiometer configuration characterize the magnetic field. Investigation Lead: B.P. Weiss, MIT. Development Lead: C.T. Russell, UCLA.
• Radio science will map Psyche’s gravity field using the X-band telecomm system. Lead: M.T. Zuber, MIT.

The solar-electric propulsion chassis will be built by Space Systems Loral in Palo Alto, California [10], the mission will be led by Arizona State University and the Jet Propulsion Laboratory will be responsible for mission management, operations, and navigation.

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Small Bodies Near and Far (SBNAF): Characterization of asteroids and TNOs

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Abstract

We present results from an EU Horizon2020-funded benchmark study (2016-2019) that addresses critical points in reconstructing physical and thermal properties of near-Earth, main-belt, and trans-Neptunian objects. The combination of the visual and thermal data from the ground and from astrophysics space missions is key to improving the scientific understanding of these objects. The development of new tools will be crucial for the interpretation of much larger data sets, but also for the operations and scientific exploitation of interplanetary missions. We combine different methods and techniques to get full information on selected bodies: lightcurve inversion, stellar occultations, thermophysical modeling, radiometric methods, radar ranging and adaptive optics imaging. The applications to objects with ground-truth information from interplanetary missions Hayabusa, NEAR-Shoemaker, Rosetta, and DAWN allow us to advance the techniques beyond the current state-of-the-art and to assess the limitations of each method.

1. Targets

For our benchmark study on minor bodies we selected important targets which were already visited by spacecraft (or will be visited soon), which have a wealth of data from different observing techniques available (or are candidates for being observed with new techniques), which are or will be useful in the calibration context, or which will allow us to address and solve specific scientific questions [1].

2. Techniques

The characterization of small bodies is based on lightcurve inversion, radiometry, occultation, radar, and direct imaging techniques. We extract the crucial information from all available observations for a given target. The combination of different data sets leads to the development of new tools and methods which are validated against ground-truth information and to test capabilities and limitations. Figure 1 shows the different available techniques for our sample targets.

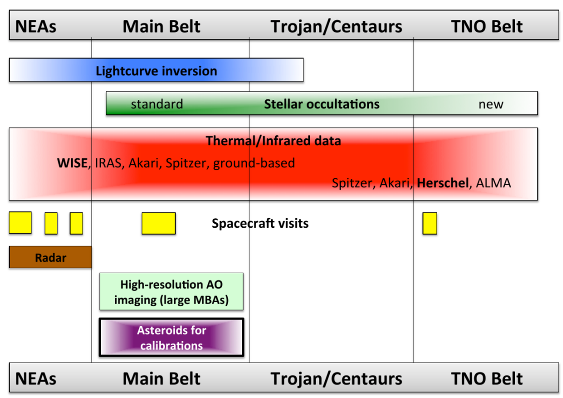

Figure 1: Overview of the SBNAF sample and the available observations.

3. Tools, Services, and Products

ISAM (`http://isam.astro.amu.edu.pl/`) contains a collection of own and literature shape models for more than 900 asteroids. It allows to (i) display an asteroid orientation as seen from Earth at any date; (ii) to generate lightcurves; (iii) to animate the rotation; (iv) to produce 3D views; and (v) to investigate viewing and illumination geometries. The **Gaia-GOSA page** (`http://www.gaiagosa.eu`) is an interactive tool which supports observers in planning photometric observations of asteroids. The asteroid prediction tool is based on the Gaia orbit and scanning law (ESA) and SSO ephemerides (MPC). The planned **Asteroid IR database** will contain thermal IR/submm/mm observations of small bodies (NEAs, MBAs, Trojans, Centaurs, TNOs), including measurements from ground (MIR, submm, mm instruments), airborne (SOFIA), and space projects (IRAS, MSX, AKARI, ISO, Spitzer, WISE, Herschel, Planck).

The SBNAF project makes **occultation predictions** for MBA events in 2017/18/19, as well as long- and short-term planning/calculations for TNO events. We also produce **high-quality images and fluxes** for NEAs, MBAs, and Centaurs/TNOs derived from Herschel photometric measurements. The new products are publically available from the Herschel Science Archive. We also support **asteroid-related calibration activities** for Herschel, ALMA, APEX, SOFIA, ISO, AKARI, IRAM, etc. calibration work.

4. Scientific results

Our first-year SBNAF scientific results are documented in a number of publications: [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18]. We will present selected results and highlights from our first 18 months of the SBNAF project.

Acknowledgements

Figure 2: Left: The SBNAF project logo: `http://www.mpe.mpg.de/~tmueller/sbnaf/`. Right: The research leading to these results has received funding from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement no 687378.

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Herschel-PACS high-precision FIR fluxes of NEAs and MBAs

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Abstract

We present Herschel-PACS photometer observations of near-Earth and main-belt asteroids. All measurements were carefully inspected for quality problems, were reduced and calibrated in a (semi-)standard way. The derived flux densities are tied to the standard PACS photometer response calibration, which is based on repeated measurements of five fiducial stars. Most of the measurements have signal-to-noise ratios well above 100, but the overall absolute flux uncertainty is dominated by the estimated 5% model uncertainty of the stellar models in the PACS wavelength range between 60 and 210 μm. The relative PACS photometric accuracy is related to the stability of about 1% of the bolometer detector over the entire *Herschel* lifetime. The high scientific potential of these measurements is shown via radiometric studies of selected objects: the determination of the objects' sizes, albedos, and thermal properties. At the same time, the PACS results will lead to improved asteroid model solutions for future calibration applications for far-IR, submm, and mm-projects.

1. Targets

The Herschel Space Observatory [1] was operational from 2009 to 2013. One of the three instruments on board was the Photodetecting Array Camera and Spectrometer (PACS) [2] which covered the wavelength range between 55 and 210 μm. The reference wavelengths of the three photometer filters are 70.0, 100.0, and 160.0 μm. Most of the on-sky calibration work for Herschel's photometric observations was done on bright point-like sources like Uranus, Neptune [3], a selection of fiducial stars [4, 5], and a sample of well-known large main-belt asteroid [6]. In addition to the asteroid calibration observations there were several smaller scientific project on near-Earth (NEAs) and prominent main-belt asteroids (MBAs). The full list of dedicated small-body observations comprises: NEAs: 101955 Bennu, 433 Eros, 308635 (2005 YU_{55}), 175706 (1999 FG_3), 162173 Ryugu, 99942 Apophis. MBAs: 1 Ceres, 2 Pallas, 3 Juno, 4 Vesta, 6 Hebe, 8 Flora, 10 Hygiea, 18 Melpomene, 19 Fortuna, 20 Massalia, 21 Lutetia, 29 Amphitrite, 47 Aglaja, 52 Europa, 54 Alexandra, 65 Cybele, 88 Thisbe, 93 Minerva, 253 Mathilde, 360 Carlova, 423 Diotima, 511 Davida, 704 Interamnia, 2000 Herschel, and 2867 Šteins.

2. Data reduction, calibration & flux extraction

For the bright main-belt asteroids the standard data reduction and calibration schemes worked fine, for the fainter objects we followed the optimized Herschel/PACS photometer observing and data reduction strategies for moving solar system targets [7]. The absolute flux calibration of 5% (relevant for radiometric size determinations) is based on repeated measurements of five fiducial stars [4, 5], the relative photometric error is typically below 1% and allows to characterize thermal surface properties with unprecedented accuracy. Flux densities were derived from aperture photometry and are currently prepared for a catalogue publication [15] with about 40 far-Infrared (FIR) fluxes for the six NEAs, and more than 1060 FIR fluxes for MBAs.

3. Scientific results

The NEA observations were all part of small dedicated science projects and the corresponding results were presented in a list of publications [8, 9, 10, 11, 12, 13]. A small fraction of the MBA fluxes has also been used in the scientific context [6, 14]. Our new asteroid flux catalogue allows to study the all objects in great detail: We will be able to determine the thermal inertia for all objects with high precision. For objects with significant orbit eccentricities we can also study if the object's thermal inertia changes with heliocentric distance, similar to our findings for Hebe [14]. Specific cases where the observations were taken very close to a pole-on situation will help us to test the reliability of thermophysical models concepts. With our high-quality fluxes we will also make a first study on surface roughness variations for the different MBAs.

Many more scientific applications will be possible when combining these measurements with auxiliary thermal data from IRAS, MSX, AKARI, WISE, or ALMA. New shape and spin solutions for our prominent objects (from AO imaging, non-convex lightcurve inversion techniques, occultations, or interplanetary missions) will help us to disentangle shape, thermal, surface roughness, albedo or emissivity effects. Dedicated studies of some NEAs and MBAs with ground-truth information will be used for benchmarking radiometric and lightcurve inversion techniques as part of our EU-funded "Small Bodies Near and Far (SB-NAF)" project.

Acknowledgements

Figure 1: Left: The SBNAF project logo: `http://www.mpe.mpg.de/~tmueller/sbnaf/`. Right: The research leading to these results has received funding from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement no 687378.

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"Jumping" Trojans

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Abstract

The term "jumping" Trojans is used to specify those asteroids that pass at time to time from the motion around one triangular libration point to another one. We explore the motion of "jumping" Trojans under the scope of the restricted planar elliptical three-body problem. Via double numerical averaging we construct evolutionary equations which allow to analyze the details of the transition between different regimes of the orbital motion.

Retrospective

In the case of 1:1 mean motion resonance with some of the main planets the asteroid most often moves in "tadpole" orbit (T-orbit in abbreviated form) or in "horseshoe" orbit (HS-orbit). T-orbit cycles around one of the triangular libration points. HS-orbit encompasses both triangular libration points as well as the collinear libration point L_3. Other types of the resonance coorbital motion are also possible (in particular, quasi-satellite (QS) regimes or compound QS+HS-orbits), but they are less common. The formal difference between these orbits is the behavior of the resonance phase $\varphi = \lambda - \lambda'$, where λ and λ' are the mean longitudes of the asteroid and the planet, respectively [6].

If several modes of motion are possible for Hamiltonian system at resonance, then under certain conditions the transitions between them can be observed. In [10] Tsiganis et al. demonstrated that Trojan asteroid (1868) Thersites in the future will make a transition $T_L \rightarrow T_T$ (T_L and T_T denote T-orbits encompassing "leading" libration point L_4 and "trailing" libration point L_5, respectively). Numerical integration indicates also, that the asteroid 2010TK$_7$ (the first Trojan asteroid of the Earth) makes transitions between the motions in the neighborhood of L_4 and L_5 [2].

The secular evolution of Trojan asteroids has been studied by many specialists (a detailed bibliography can be found in [4, 8]). Nevertheless, it is likely that only K.Oshima and T.Yahao [7] attempted to investigate theoretically the transitions

$$T_L \rightarrow T_T\,,\ T_T \rightarrow T_L\,,\ T_{L,T} \rightarrow HS,\ HS \rightarrow T_{L,T}\,. \quad (1)$$

Their analysis was based mainly on the consideration of the planar restricted circular three-body problem. Motions with transitions (1) were searched by K.Oshima and T.Yahao in the region of chaotic dynamics generated by the intersection of stable and unstable manifolds of periodic solutions encircling the libration point L_3. Unfortunately, the interpretation of transitions (1) as a certain homoclinic phenomenon has a serious disadvantage: the measure of the initial conditions giving rise to motions with transitions turns out to be very small ($\sim e^{-1}/\mu^{C}$, where μ characterizes the relative part of the planet's mass in the total mass of the system "Sun+planet", C is some positive constant).

Interpretation of transitions between resonance motions on the base of Wisdom's approach

Our investigation was undertaken with the aim to demonstrate that in the context of the planar restricted elliptic three-body problem "Sun+planet+asteroid" there exists another mechanism providing the transitions (1). To reveal this mechanism, we apply the basic ideas of the approach proposed by J.Wisdom to study the transformations of the resonance motions [11]. It allows to establish also the dynamical robustness of these transitions in the elliptic problem: they occur for the set of initial conditions which measure does not depend on μ. Previously we studied in a similar way the formation and the destruction of the QS regimes of the orbital motion [9].

Technically, the Wisdom's approach is reduced to two averaging of the motion equations. The first averaging is carried out over the orbital motion, whereafter the phase variables are rescaled, and the problem is shaped into a form called a "slow-fast" system (SF-system). This is a two degrees of freedom Hamiltonian system with the variables evolving at different rates: some variables are "slow", while the other are "fast". The second averaging is then performed over the "fast" motions of the SF-system. This provides us the evolutionary equations describing the secular effects in the asteroid's motion.

Summary

We hope that our analysis will be a useful addition to previous studies of the secular effects in the dynamics of Trojan asteroids on the basis of the modern theory of resonance phenomena in Hamiltonian systems [1,5]. Considering the three-body problem, we can't explain the transition $T_L \rightarrow T_T$ demonstrated by the asteroid (1868) Thersites: the numerical results presented in [10], indicate a significant influence of secular resonances on the dynamics of this asteroid. The mechanism of transitions that we are discussing is probably realized in the dynamics of the so called "temporary" Trojans [3]. Since their stay in certain regime of motion is relatively short, the effects due to secular resonances might be neglected.

Acknowledgements

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Groups of meteorite-producing meteoroids containing carbonaceous chondrite meteorites

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Abstract

The possibility of existence of groups of meteorite-producing meteoroids which contain meteorites Maribo, Murchison, Shutters Mill, classified as carbonaceous chondrites and ungrouped carbonaceous chondrite Tagish Lake was analyzed. The main argument for existence of groups of meteorite-producing bodies is the existence of bolides and meteorites with similar orbits and time-correlated meteorite falls. The IAU Meteor Database of Photographic orbits and the other published sources were used to bright sporadic fireballs with currently similar orbits to orbits of analyzed meteorites. The analysis used known and widely used similarity functions – the orbital D_{SH} criterion of Southworth and Hawkins and D_D criterion of Drummond. As a result, some meteorite-dropping sporadic fireballs as possible members of the studied meteorite groups were found and possible regions of origin were considered. Especially the small bodies (50 – 100 m in size) with Earth-crossing orbits on the timescale of human civilization represent natural hazards because of the greatest probability of risk of collision with the Earth. Purposeful monitoring of these bodies in the identified periods of increased fireball and meteorite activity by the means of both land fireball network and space equipment installed in orbital satellites is important to prevent the danger of such impacts.

1. Introduction

Meteorites are very valuable samples coming from different objects in the Solar system that contain records of processes occurring at an early stage of formation of Solar system. Research focused on establishing links between meteorite-producing meteoroids, rare and primitive meteorites and their parent asteroids is very important to understand the origin and evolution of primitive Solar System materials. The Chelyabinsk meteorite incident [1] has shown that potentially dangerous Near Earth objects (NEOs) of 50-100 m in size and within the timeline of a human civilization can present the greatest threat to Earth because of their higher occurrence among the NEOs than that of bodies in with more than half kilometer in size. Here, we consider the possibility of existence of groups of meteorite-producing meteoroids that can generate carbonaceous chondrite meteorites falling on Earth at present time.

2. Groups of meteorite-producing meteoroids and carbonaceous chondrite meteorites

In this study, we investigate the feasibility of a connection between carbonaceous chondrite meteorites and meteorite-producing meteoroids which form groups of bodies with similar orbits. Groups of meteorite-producing meteoroids crossing the Earth's orbit are defined as the subset of linked orbits of meteoroids and meteorites on the basis of observed photographic data. At present, 4 orbits of carbonaceous chondrites have been published: Tagish Lake [2], Maribo [3], Murchison [4] and Shutter's Mill [5] meteorites. The incidents of these meteorites were observed during the periods of increased meteorite-dropping fireballs activity: January, April-May and September-October [6]. Within the time intervals adjoining the periods of increased activity of meteorite-dropping fireballs, a search for orbits similar to those deduced for the carbonaceous chondrites Tagish Lake, Maribo, Murchison, and Shutter's Mill was carried out. In this connection, the international meteor database IAU MDC_2003, as well as published scientific journals and international conference proceedings obtained from the SAO/NASA ADS database were used to compile a set of photographic orbits of bright and slow moving sporadic fireballs. This data set was used to detect groups of meteorite-producing meteoroids of linked orbits among photographic orbits. To detect a group, functions of distance D_{SH} [7] and D_D [8] were applied. Thresholds values of orbital similarity $Dc \leq 0.2$ [7] and $Dc \leq 0.105$ [8] were adopted to indicate the orbital similarity. Orbital similarity criteria also provided possible identification of parent body of group of meteorite-producing meteoroids. For each group of meteorite-producing meteoroids, the average orbit of the group was calculated. This average orbit was used to detect the link between meteorites and groups of meteorite-producing meteoroids. A group of meteorite-producing meteoroids and meteorites is a group of meteoroids which contributed to the final mean orbit. As a result, several members of each of the four groups were detected and accepted as members of meteorite-producing groups.

3. Summary and Conclusions

Proposed probable links between meteorites and meteorite-producing fireballs were been considered. Group associations between meteorite-producing meteoroids and meteorites were been determined for four carbonaceous chondrites: Murchison, Maribo, Shutters Mill, and Tagish Lake and potentially meteorite-producing bolides on the basis of relationships between their orbits. As a result, several meteorite-producing sporadic slow fireballs were identified as possible members of four studied groups of carbonaceous chondrite meteorites. One can presume that at present time, the identified groups may still contain large meteorite-dropping bodies. In practical terms, this can serve as an incentive for purposeful monitoring of the indicated groups of meteorite-producing fireballs during the identified periods of increased fireball and meteorite activity by the means of both land fireball networks and orbital satellite tools. Future discovery of additional meteorite-dropping carbonaceous chondrites could provide a deeper insight in the possible connection between their groups and meteorites.

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Near Earth Objects: observations with VIRAC radiotelescopes in VLBI mode

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1. Introduction

Large amount of Near Earth Objects (NEO, including asteroids and space debris, especially near the geostationary orbit, has to be monitored for space mission planning. Almost all sizes of NEO are dangerous to satellites. The small objects with a 1 mm diameter could damage commercial satellite sub-systems, object with a 1 cm diameter could disable satellite systems, while NEO with 10 cm diameters could cause catastrophic break-ups [1].

1.1 VLBI methods

The method of Very Long Baseline Interferometry (VLBI), one of the most powerful instruments used in radio astronomy, allows to get high accuracy determination of coordinates of radios sources. Since 1980-th VLBI method is successfully applied for angular coordinates determination of artificial Earth satellites and interplanetary space stations with the precision 0.01-0.03 arc.sec in single measurements. A promising field in coordinate research proves to be combination of VLBI with range measurements method, such as r-VLBI, laser ranging, telemtric mode and so on.

The rVLBI has been successfully used during the last decades for NEO tracking. By the exploitation of several distant receiver stations of reflected radar signal, the rVLBI has a potential for very high accuracy. Theoretically, rVLBI may even yield all the motion parameters required for a formulation of a Newtonian orbital solution in a single measurement. However, this is not a case yet. One of main limiting factors is the lack of reliable data processing methods and corresponding software.

1.2 Instruments

Since 2011 Ventspils International Radio Astronomy Centre has been involved in the large scale infrastructure project which allowed significant speeding-up of the upgrading activities related to radio telescopes RT-32 and RT-16 as to its fitting with appropriate VLBI receiving and recording equipment. Radio telescopes were instrumented with new state-of-art broadband cryogenic receivers for frequency range of 4.5 – 8.8 GHz developed and installed by company “Tecnologias de

The receiver is formed by a cooled RF subsystem and a room temperature IF subsystem. The RF and IF subsystems are designed to process two C/X band signals (LCP & RCP) in parallel. Normally, during observations, the measured vacuum level in the receivers dewar is from 10^{-6} to 10^{-8} mbar and the temperature inside dewar is at level of 14 K at second stage, 20 K at polarizer and 46 K at the first stage.

Since October 2015 radio telescope RT-32 with new receiver system took part in several successful international VLBI sessions. During preparation for VLBI observations preliminary aperture efficiency, system temperature and beam pattern measurements were carried out to evaluate RT-32 performance after the station’s renovation that besides the receiver also included repairing of the main reflector. Performance parameters were derived with the help of switching noise diode and “on-off” observations of calibration sources with known flux density at various elevations [2].

1.3 Data processing methods

The typical rVLBI (and VLBI) data processing is performed in a few major steps. The first, so called “correlation” step with high computational complexity acts on the raw sampled signals from the pairs of VLBI stations, yielding signal interference functions, so called “fringe function” (FF) and basic parameters (delays) needed for fringe function construction. The spectral characteristics of FF with the corresponding delays are used in the second step of data processing, which ultimately leads to the measured physical parameters of observed object, such as angular positions, velocities, etc. Due to NEO closeness to the Earth and its fast motion on the sky the standard routines for wave front path corrections in the data processor (correlator) has to be reworked. To achieve that, the existing methods for time and frequency delay compensations are reviewed and additional time-frequency analysis, such as extended short time Fourier transforms, specific data windows and Wavelet analysis are applied to the data for fractional step compensations in the correlation integral constructions.

1.4 Previous knowledge

An international VLBI experiment on radio location of the asteroid 2012 DA14 was organized on 2013 February 15-16, during its flyby close to Earth. The purpose of observations was to investigate and specify orbital parameters of the asteroid, as well as to evaluate its rotation period and other characteristics. The asteroid was irradiated by the 5010.024 MHz frequency signal (radar RT-70, Evpatoria, Ukraine), whereas the echo signals were received by the radio telescopes RT-32 in Irbene (Ventspils, Latvia) and Medicina (Italy) in VLBI regime. A series of observations was implemented for different distances between the Earth and the asteroid (from 30000 km to 250000 km). The reflected signals were successfully received by the both VLBI-stations. Processing of the recorded signals allowed of measuring the Doppler frequency and interference frequency in order to improve the calculation of the radial and angular velocity of the asteroid. Processing and interpretation of the data were performed both in the Radiophysical Research Institute and in the Ventspils International Radio Astronomy Center [1].

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Solar System Science with the Twinkle Space Mission

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Abstract

Twinkle is a space-based telescope mission designed for the spectroscopic observation (0.4 to 4.5 µm) of exoplanet atmospheres and Solar System objects. The system design and mission implementation are based on existing, well studied concepts pioneered by Surrey Satellite Technology Ltd for low-Earth orbit Earth Observation satellites, supported by a novel international access model to allow facility access to researchers worldwide.

Whilst Twinkle's primary science goal is the observation of exoplanet atmospheres its wide spectroscopic range and photometric stability also make it a unique platform for the observation of Solar system objects.

1. Introduction

Twinkle is a medium (450 mm diameter) aperture space-based telescope that is designed for operation in low Earth orbit [1]. The main instrument is a spectrometer that covers the spectral range 0.4 to 4.5 µm with a variable spectral resolving power of R=70 -300, depending on spectral band. Twinkle's primary mission is the observation of exoplanet atmospheres via techniques such as transit and eclipse photometry and spectroscopy. However, as a point source observatory above the Earth's atmosphere it can also provide significant new data on Solar System objects, especially in regions of the spectrum dominated by telluric absorption.

2. Examples of Twinkle's contribution to the spectroscopy of asteroids.

The spectroscopic and photometric performance requirements for Twinkle are set by its primary, exoplanet science, mission [1]. These ensure that a highly stable platform is also available for observations of our Solar System. For measurements of small bodies such as main belt asteroids, Twinkle will provide information on regions of the near-IR spectrum that are inaccessible from Earth for all but the brightest targets (e.g. Figure 1).

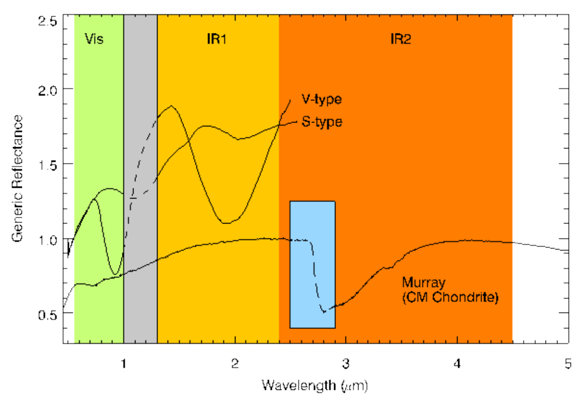

Figure 1. *Example spectra of a CM chondrite meteorite and two spectroscopic classes of asteroid in the visible/near-infrared.. The blue inset window represents the 3 µm region of the spectrum obscured by the Earth's atmosphere (spectrum from the RELAB database [2], composite figure courtesy S. Lindsay, Univ. Tennessee/Univ. Oxford).*

Spectral regions that are related to hydroxyl (OH) and water (ice and gas) should be fully resolved by Twinkle. Also of particular interest are absorption features at 0.7 and 3.0 µm that are often associated with primitive asteroids (e.g. [3], [4]). The 0.7 µm feature is readily observable by ground-based telescopes and *may* be diagnostic of aqueously altered mineral phases (e.g. phyllosicicates [3]), however without access to the other diagnostic bands its usefulness, as a compositional indicator is limited.

The 3 µm feature (e.g. Figure 1) can be made of a complex blend of several different features, including both bound water, hydroxyl (e.g. in phyllosilicate minerals [4]) or water ice). The shape of this band can be highly diagnostic of the different of the type of water/hydroxyl present [5].

Twinkle will provide an opportunity to understand the relationship between the 0.7 and 3.0 µm feature and their importance in mapping aqueous alteration in primitive asteroids. This in turn has implications for mapping the distribution and transport of volatiles in the inner Solar System.

Twinkle's spectral range also captures spectral features in the 3.2 to 3.6 µm range that may be associated with organic material on the asteroid's surface (e.g. [4]). The shortwave edge of this region can be blended with the 3 µm feature, however techniques developed by [4] can be used to infer the presence of e.g. organic compounds of varying complexity. Currently the strongest detections for organics in this spectral range are for the asteroids 24 Themis and 65 Cybele [6], making the Themis family (~1600 asteroids around 3.2 AU) a survey priority.

3. Composition of Comet Comae

Comets are reservoirs for some of the most primitive material in the Solar system. Twinkle's spectral range and sensitivity can provide access to key volatile bands (e.g. water ice, CO_2, NH_3). The ability to resolve the CO_2 emission feature at ~4.3 µm, again obscured by the Earth's atmosphere for ground-based telescopes, will allow Twinkle to map the abundance of this volatile species for a large number of targets for the first time.

4. Summary and Conclusions

Twinkle is a cost-effective space mission taking advantage of lowered costs of access to space. The Twinkle satellite is being built in the UK and will be launched into a low-Earth sun-synchronous polar orbit in 2020, using flight proven spacecraft systems designed by Surrey Satellite Technology Ltd and high Technology Readiness Level science payload components.

Although primarily designed to be an exoplanet survey mission Twinkle's wide spectral range (0.4 to 4.5 µm), sensitivity and resolving power (R=70-300) also make it well suited for observing a wide range of Solar system objects. Access to key spectral features at e.g. 2.7 -3 µm make Twinkle especially well suited to surveying the larger objects in the asteroid belt. This is a particularly timely investigation with recently selected small bodies missions due for launch as part of NASA's "Discovery" program in the early to mid 2020s.

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