Asteroids and the Solar System: insights from the thermal infrared

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ABSTRACT

Many asteroids larger than ~100 km in diameter are thought to be primordial bodies that have avoided catastrophic disruption by collisions over their 4 Gy-long histories. Understanding their compositions can thus reveal clues about their formation and constrain planet formation and Solar System early dynamical evolution models. However, remote observations are limited to their surfaces and spectroscopic data are costly; furthermore, meteorite spectral association cannot unambiguously constrain the composition of primitive asteroids that do not show any distinct spectral features. Thermal infrared data taken by surveys like the *AKARI* IRC all-sky survey have provided the community with information about few thousands of asteroids, enabling the computation of sizes and albedos in large numbers. Sizes are an important prerequisite to infer density, and albedos are indicative of composition. When asteroid shapes and rotational states are known, thermal infrared data can help constrain more detailed thermal properties. Here I provide an overview of how *AKARI* data are being exploited in this context and illustrate their importance in the study of asteroids, including an outlook into the future.

Keywords: Solar System and planetary formation

1. INTRODUCTION

Planet formation has long been established as being the result of the build up of material from the protoplanetary disc of gas and dust surrounding the star (for a review, see e.g., Armitage 2011). A number of fundamental observables in our Solar System are robustly explained in that framework, e.g., the fact that most planets orbits lie in basically the same plane with low-eccentricity orbits, and that this plane is more or less perpendicular to the solar rotational axis. This is important because, even though the notion that our planetary system as an archetypical example has been abandoned thanks to the discovery and characterisation of thousands of exoplanetary systems, the Solar System still provides the strongest observational constraints for planet formation theories. There remain several open problems in this context, some of them related to the population of small bodies. According to Morbidelli & Raymond (2016), the growth of planetesimals and the peculiar *trimodal* structure of the Solar System (the existence of the rocky planet, asteroid belt, and giant planet regions) are two of the five major problems hindering progress in planet formation theories.

The small bodies, including asteroids, comets and trans-Neptunian objects, are remnants of the population of planetesimals out of which the planets formed, so studying their compositions and physical properties offer a window into the conditions prevailing during initial stages of the Solar System's history. The primitive asteroids contain volatile materials such as water and organics (Campins et al. 2010; Licandro et al. 2011) that may have contributed to the budget of volatiles of the rocky planets, which formed in more dry regions of the inner Solar System. As they are considered to contain the least processed materials among the asteroids, recent efforts in the field have materialized in space missions to primitive bodies such as NASA's *OSIRIS-REx* (Lauretta et al. 2015) and JAXA's *Hayabusa-2* (Yoshikawa et al. 2008).

Here I provide a review of a selection of topics in which *AKARI* (and other thermal infrared space missions) has played a major role in advancing our knowledge about the nature of asteroids. Although I do not provide a comprehensive presentation of the field of study (e.g., Michel et al. 2015), Section 2 offers a broad overview aimed at demonstrating the role of the *AKARI* IRC in its greater context. For the sake of brevity and due to my personal biases, I do not cover several other prominent Solar System fields of study to which *AKARI* has also contributed significantly. To highlight a few, these include characterisation and volatile content studies of comets by Ootsubo et al. (2010, 2012); Usui et al. (2009); Ishiguro et al. (2013), or Perna et al. (2015); studies of the sizes, albedos and orbital properties of dormant comets/comet-like objects by Kim et al. (2014) and Bach et al. (2017), the zodiacal light (Pyo et al. 2010; Kondo et al. 2016; Ishihara et al.

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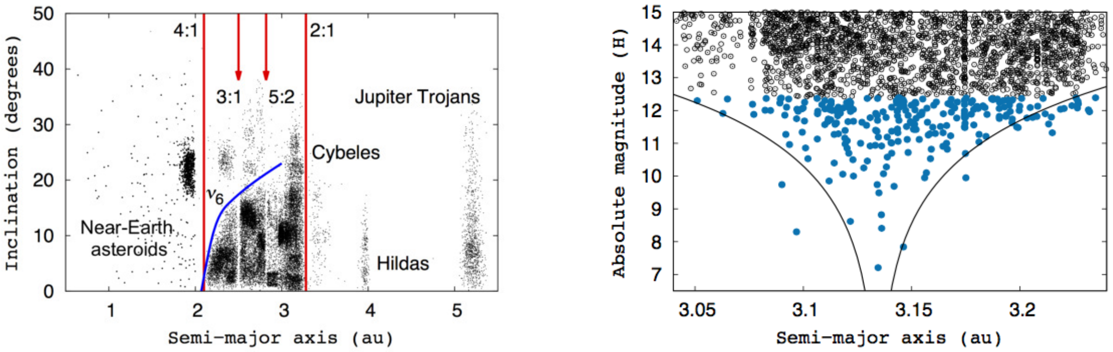

Figure 1. *Left panel*: Inclination versus semi-major axis of the few thousand largest asteroids. All main belt asteroids larger than $\sim$20 km were observed in the *AKARI* IRC all-sky survey. Prominent mean motion resonances with Jupiter are marked in red and the ν_6 secular resonance with Saturn is indicated in blue. *Right panel*: Asteroid absolute magnitude versus semi-major axis plot of the Themis collisional family. Objects with higher H value are smaller. Asteroid (24) Themis, the single lowest point, is the largets member. The extent to which a family member can spread depends on the time elapsed since the collision and its size and thermal properties, with smaller objects spreading faster due to the Yarkovsky effect (see Section 3.2). This explains the “triangular” shape. The solid line or “V-shape” indicates the maximum distance an object of a given size can travel for a given family age, so objects well below the line are most likely not members of the family even though they appear to belong to the orbital element cluster (see also Section 2.2). The blue circles roughly indicate the completeness limits of the *AKARI* catalogue.

2017), interplanetary dust bands (Ootsubo et al. 2016), or the near infrared spectral catalogue provided by Tsumura et al. (2013). Some of these topics are addressed in other contributions to the *AKARI* 2017 Conference.

Section 3 focuses on the thermo-physical characterisation of asteroids and the invaluable contributions made thanks to the *AKARI* IRC asteroid observations (Murakami et al. 2007; Onaka et al. 2007; Ishihara et al. 2010; Mainzer et al. 2011), and Section 4 concludes with an outlook enumerating further expected scientific applications of *AKARI* asteroid data.

2. ASTEROIDS

The study of asteroids is a multidisciplinary endeavor that involves experts in numerous fields including Dynamics, Geophysics, observational and (space) instrumentation techniques, and laboratory work. In my view, it is useful to explore the subject as an effort to tackle three major questions stated in each of the following sections. Because the answers to these questions are often necessary to the other fields, this approach conveniently illustrates the relevance of the *AKARI* asteroid data by placing the topic of this review –the physical and thermal properties of asteroids inferred from observations in the thermal IR– in its full context.

2.1. Where are the asteroids? Discovery and orbit determination

The drive to discover and monitor potentially hazardous asteroids and the efficiency with which asteroids are discovered in the various CCD surveys carried out during the last 20 years has lead to a steady increase in the discovery statistics of asteroids (see e.g., Jedicke et al. 2015, for a review). As of November 2017, the International Astronomical Union Minor Planet Center reports 506 410 numbered minor planets and 239 001 unnumbered ones, i.e. a total of 745 411 objects with well established orbits.

Most discoveries involve asteroids in the main belt between Mars and Jupiter (see the left panel of Figure 1), as it is the closest major reservoir of small bodies and where most near-Earth asteroids (NEAs) originate. About one out of every ten NEAs (17 000 discovered so far) are classified as Potentially Hazardous Asteroids or PHAs. At the other end of the inner Solar System, between the main belt and the orbit of Jupiter, we find two populations of primitive bodies, the Hildas and the Cybeles. Finally, co-orbiting the Sun with Jupiter in libration around its L_4 and L_5 Lagrangian points, we find the Jupiter Trojans.

2.2. How and when did asteroids get to their current orbits? Dynamics and collisions

If all the material of the proto-planetary disc started off with co-planar and quasi-circular orbits, how did the small body population in the Solar System develop the rich orbital architecture that we observe today? The relatively high eccentricities and prominent resonances shown in the left panel of Figure 1 are understood to be related to the dynamical influence of Jupiter (and, to a lesser extent, Saturn) during the last 3 to 4 billion years. But the fact that not all regions of stable orbital element space are filled homogeneously with small bodies suggests that Jupiter must have had a different orbit before this long “quiescent” evolutionary period (Morbidelli et al. 2015).

In the last two decades, great progress in the study of small bodies has lead to insights into early dynamical stages such as giant planet migration (Walsh et al. 2011), episodes of dynamical instability whose consequences could explain the so-called “late heavy bombardment” (LHB) of the Moon (Gomes et al. 2005), or the fact that many Hildas and virtually all Jupiter Trojans (see Figure 1, left panel) have spectral properties more akin to those of comets than asteroids. The so-called "Nice model" suggests that these bodies were originally trans-Neptunian objects that were scattered and captured during the LHB (Morbidelli et al. 2005; Levison et al. 2009).

In addition to dynamical evolution, asteroid catastrophic collisions have played a fundamental role in the shaping of the asteroid population that we observe today. Collisions must be accounted for in long-term dynamical evolution models since large planetesimals can be destroyed by such processes, which in turn affects the gravity felt by the other planetesimals (for more details, see Bottke et al. 2015). Moreover, the evolution of the resulting family of fragments, referred to as a collisional family, depends on the physical and geological properties of the parent body, and these are the result of the process of planetesimal formation itself.

Asteroid collisional families were first identified as groupings in proper orbital element space that could be easily explained as sharing their origin in a common parent body (Hirayama 1918). Some of the most numerous are in fact apparent as noticeably denser regions in the left panel of Figure 1. The right panel shows the collisional family of (24) Themis in a plot of asteroid absolute magnitude (H) versus semi-major axis. Objects spread in semi-major axis around the centre of the family, and due to the Yarkovsky effect smaller objects, i.e. those with higher H, spread more rapidly than larger ones, producing this "V-shape" in this type of plot. Because the Yarkovsky effect is related to the thermal properties of the parent body and the collisional fragments, this topic is revisited in Section 3.

2.3. What are their compositions and physical properties?

The composition of asteroids are inferred by comparing their reflectance spectra in visible and near-infrared (VNIR) wavelengths to those of meteorites observed under varying conditions in the laboratory. Several spectral associations have been proven correct, e.g., (25143) Itokawa was confirmed to be an LL chondrite by the *Hayabusa* mission (Binzel et al. 2001; Nakamura et al. 2011). However, the approach suffers from several inherent limitations. For example, the collection of meteorites might not be complete and subject to biases that are impossible to account for; also, primitive meteorites with different compositions and physical properties produce indistinguishable VIR reflectance spectra, rendering compositional analyses ambiguous. This has partly contributed to devote resources to explore primitive asteroids in situ by missions like *Hayabusa-2* and *OSIRIS-REx*.

Still, some primitive bodies do show important diagnostic absorption bands at near IR wavelengths related to the presence of water, either in the form of ice or bound in hydrated minerals. Also, thermal IR emission spectra have proven to be crucial to infer composition and physical structure of the material. With thousands of spectroscopic observations by the IRC camera, *AKARI* will surely play a major role in this field (see invited review by Usui et al., and Usui et al. 2017).

During their ~4.0 Gy-long lifetimes, asteroids have experienced different levels of physical and geological processing, like surface space weathering, differentiation, aqueous alteration, or collisions (see also the previous section). Their current physical properties are the result of these processes, which is why we require to carry out a through physical characterisation of the heterogeneous asteroid population. Given the relevance of the *AKARI* data in this field, we examine this topic in more depth in the following section.

3. *AKARI* OBSERVATIONS AND THERMAL AND PHYSICAL PROPERTIES OF ASTEROIDS

Asteroids smaller than about 50 km have been thought to be collisional fragments (see Section 2.2) as opposed to most asteroids larger than ~100 km, considered primordial bodies that were never catastrophically disrupted. It is then important to infer the shapes, rotational properties and bulk densities of the primordial asteroids, as they provide information about their interior structure and their collisional histories. Thus, these clues can serve as constraints to the problem of planetesimal formation and early Solar System dynamical and collisional models that describe the conditions prevailing at phases such as planet formation and migration (Sections 1 and 2.2). In this section I describe how asteroid physical and thermal properties can be studied based on thermal infrared observations and focus on achievements enabled by *AKARI* data.

3.1. Thermal models and asteroid diameter and albedo catalogues

Determining the size and volume of asteroids, the most basic properties conducive to the calculation of their density, is not trivial because the vast majority of them cannot be resolved by direct imaging from the ground. Nonetheless, the use of models of asteroid thermal emission, typically based on idealised non-rotating spheres, have enabled the estimation of asteroid sizes (i.e. the diameters of the sphere with the same volume) with reasonable accuracy, sometimes as good as 10%.

The thermal emission of asteroids typically peaks at thermal IR wavelengths owing to their composition and the physical nature of their surfaces. This makes them powerful sources in space-based infrared surveys with measurements between ~10 and 30 μm. Thus, starting with *IRAS* in the 1980s and culminating with the *AKARI* IRC and *WISE*/NEOWISE all-sky surveys (Murakami et al. 2007; Onaka et al. 2007; Ishihara et al. 2010), it has been possible to derive asteroid diameters in large numbers (see Mainzer et al. 2015, for a review on the impact of space-based observatories on asteroid science).

Usui et al. (2011) derived diameters and visible geometric albedos of more than five thousand asteroids (doubling the number obtained from *IRAS* data) by fitting a version of the so-called "standard thermal model" of Lebofsky et al. (1986) to *AKARI* IRC 9- and 18-μm fluxes. Shortly afterwards, serendipitous asteroid detections among the IRC slow-scan

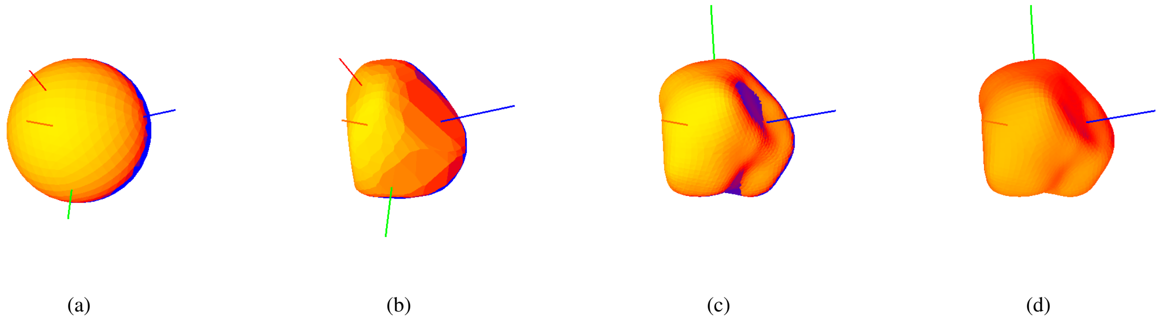

Figure 2. Three-dimensional shape models of asteroid (9) Metis coloured as a function of temperature (the epoch was chosen arbitrarily). The red, green, and blue lines correspond to the x, y, and z axes relative to an Earth-based observer (North is upwards). The orange axis indicates the direction toward the sun. Panel a: spherical shape with zero thermal inertia ($\Gamma = 0$). Panel b: convex hull approximation with $\Gamma = 0$. Panel c: SAGE model (see Section 4) with $\Gamma = 0$ and no roughness. Panel d: SAGE model with $\Gamma = 75\,\mathrm{J\,m^{-2}s^{-1/2}K^{-1}}$. The hottest areas (bright yellow) in panel d are lower than in panel c because some energy is being transported into the subsurface as a consequence of the non-zero thermal inertia. Conversely, the shadowed concave areas and the night-side are warmer in panel d because the heat absorbed at an earlier time is being conducted back to the surface.

observations (Takita et al. 2012) were added to the *AKARI* asteroid data catalogue and used by Hasegawa et al. (2013) to add 88 completely new or updated diameters and visible geometric albedos. This collection of diameters was complete for main belt asteroids down to ~20 km (Usui et al. 2013, 2014).

Next, *WISE*/NEOWISE provided observations of hundreds of NEAs, more than a hundred thousand main belt asteroids, and thousands of Hildas, Cybeles and Jupiter Trojans (Mainzer et al. 2011; Masiero et al. 2011; Grav et al. 2012). As discussed by Usui et al. (2014), *AKARI* and *WISE*/NEOWISE are complementary since the former compensates for the absence of a number of large asteroids in the latter. Furthermore, the largest targets saturated in the *WISE* detectors and their higher uncertainties are not optimal for more demanding thermo-physical models (see below). Nonetheless, partial saturation corrections have been applied successfully to estimate diameters using a thermal model.

Despite the limiting assumptions of the thermal models, the invaluable scientific return afforded by the diameter and albedo catalogues based on *AKARI* is too vast to be enumerated here comprehensively. Works directly exploiting this database range from case studies of individual targets to statistical studies of dynamical groups, spectral taxonomic classes, and asteroid collisional families. Perhaps it is worthwhile highlighting the recent identification of a primordial, 4-Gy-old collisional family by Delbo' et al. (2017) in the inner asteroid belt as an achievement that would have not been possible without the diameters and albedos afforded by the infrared space surveys. This finding allowed Delbo' et al. to unambiguously identify asteroids that do not originate in a collisional family. In other words, it is possible to distinguish which planetesimals accreted directly from the proto-planetary nebula. Given their large diameters (> 35 km), this finding favours models of planetesimal formation that lead to the early formation of big bodies.

3.2. Thermo-physical models

It is possible to model asteroid thermal emission more accurately from their instantaneous surface temperature distribution when their shape, spin axis orientation, and surface physical and thermal properties are reliably known. These models, called thermo-physical models or TPMs (see e.g., Delbo' et al. 2015, for a review), lead to estimates of more sophisticated thermal properties than do thermal models, e.g., thermal inertia, surface roughness, or estimates of the average grain size if combined with thermal conductivity models (Gundlach & Blum 2013). Thermal inertia is a measure of how slowly the surface temperature of the material responds to changes in illumination. It is a very useful property to derive because it informs us about the thermal conductivity of the material and its porosity (Figure 2), allowing us to distinguish between low-conductivity fine-grained regolith and rockier surfaces.

Thermal inertia has strong consequences on several aspects of asteroid dynamical and physical evolution. For example, the strength of the Yarkovsky effect, the non-gravitational force responsible for the faster spreading of the semi-major axes of the smaller objects of a collisional family (Figure 1, right panel), is driven by thermal inertia. This effect helped identify fast dynamical routes delivering small asteroids from collisional families to the near-Earth space (e.g., Morbidelli et al. 2002; de León et al. 2010). Also, a good knowledge of thermal inertia is needed to make accurate medium- and long-term predictions of orbital evolution and impact probability of potentially hazardous asteroids. From a more practical point of view, it is also relevant for sample-return space mission operations, since it is requisite to select adequate landing sites in terms of their maximum surface temperatures and how coarse or fine-grained the material is (see e.g., Alí-Lagoa et al. 2014).

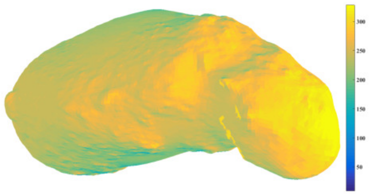

Figure 3. Sky view of *Hayabusa* target (25143) Itokawa as of 28 November 2017 coloured with the temperatures given by the thermo-physical model of Müller et al. (2014a). The temperatures in the colour palette are given in K.

(b)

(a)

Figure 4. Sky view of *Hayabusa-2* target (162173) Ryugu as of 28 November 2017 (see the caption of Figure 2 for more information). The shapes and rotational properties correspond to the model of Müller et al. (2017a). Panel a: zero thermal inertia and zero roughness idealised case. Panel b: best fit by Müller et al. with thermal inertia 200 J $m^{-2}s^{-1/2}K^{-1}$ and zero surface roughness. The maximum temperatures in each case are 343 K and 324 K.

3.2.1. ***Hayabusa* and *Hayabusa-2* targets**

AKARI data have been exploited to thermally and physically characterise JAXA's mission targets (25143) Itokawa and (162173) Ryugu (Figures 3 and 4). Müller et al. (2014a) found a thermal inertia of 700 ± 200 J $m^{-2}s^{-1/2}K^{-1}$ for Itokawa. The corresponding average grain size of 21^{+3}_{-13} mm was in agreement with in-situ observations made by *Hayabusa* (Yano et al. 2006; Kitazato et al. 2008). In combination with visible light curves and other thermal IR data, *AKARI* allowed Müller et al. (2017a) to estimate the spin axis orientation and shape model, diameter, albedo, surface roughness, and thermal inertia of Ryugu. Namely, they found its size to be within 810 and 905 m, visible geometric albedo in the range 4.4–5.0 per cent, a thermal inertia of 150-300 J $m^{-2}s^{-1/2}K^{-1}$, a very low surface roughness, and grain sizes between 0.1 and 1 cm. This constitutes a fundamental baseline model to develop operational scenarios for the mission and to analyse the disc-resolved data that will be acquired throughout the mission. Moreover, if confirmed in situ, said model will become a pivotal benchmark case for further thermo-physical investigation.

3.2.2. **The challenge of determining asteroid shapes**

TPMs offer better constraints on asteroid diameters and, hence, densities than do thermal models. The accuracy of thermal model diameters are not usually better than 10% (see Section 3.1), and this propagates three-fold into the volume estimation, which must be propagated with the relative error of the mass. Still, achieving a high degree of accuracy ($< 2\%$ in diameter) is not guaranteed without good knowledge of the shape and rotational properties. Unfortunately, space craft missions are too costly and inevitably limited to very few visited targets, and for some of them we only have a partial coverage of the shape. Good-quality sets of stellar occultation chords also provide "ground truth" silhouettes, but this offers 2-D information. Successfully recording two or more events with high-quality coverage is complicated for the moment because predicting events to re-observe an object is not usually possible within a reasonable time scale (months to years). Thus, even considering radar and adaptive optics, which involve inescapable model assumptions, detailed high-quality knowledge of asteroid shapes has so far been restricted to a few tens of objects.

In spite of the availability of thermal IR fluxes collected from space observatories such as *AKARI* and *WISE* for thousands of targets, our limited direct knowledge of asteroid shapes constitutes a bottleneck hindering progress based on TPM analyses. This is why there are relatively few recent works (e.g., Rozitis et al. 2014; Alí-Lagoa et al. 2014; Hanuš et al. 2015, 2018; Bach et al. 2017) modestly contributing to the expansion of the list of ~50 asteroids with estimated thermal inertias available in the literature (see compilation by Delbo' et al. 2015).

Most shapes and rotational properties have been derived indirectly from optical light-curve inversion models applying the convex-hull approximation (Kaasalainen & Torppa 2001), an idealisation required to guarantee a unique optimum solution (for a review, see e.g., Ďurech et al. 2015). Panel b in Figure 2 shows the convex shape model derived for asteroid (9) Metis (Ďurech et al. 2010, 2011). Although this approach has been shown to produce adequate shapes and spin axis orientations for several particular bodies and to be extremely useful for statistical studies, more realistic shapes are needed to maximize the scientific return from e.g., TPM analyses. In the following section we mention various efforts to mitigate this situation and comment on several promising approaches to improve our knowledge of asteroid fundamental physical properties with the help of the *AKARI* asteroid data set.

4. OUTLOOK

The legacy of *AKARI* and other prominent space-based infrared surveys will continue to play a paramount role in the advancement of our knowledge of asteroid physical and thermal properties as our ability to determine better asteroid shapes increases (Section 3.2.2). More asteroidal masses are expected to be computed in the near future thanks to Gaia, which is triggering increasing efforts to determine more and better asteroid shapes, e.g., from occultations and/or adaptic optics. An additional approach that has proven to successfully reproduce complex asteroid shapes such as that of (433) Eros and high-quality occultation chords for (9) Metis is SAGE (Bartczak & Dudziński, accepted for publication in MNRAS). SAGE is a genetic algorithm that produces cumulative random mutations (deformations) on a sphere until it converges into a shape that can explain a rich database of optical light curves (Bartczak et al. 2014, 2017). The model of (9) Metis derived from SAGE is shown in panels c and d of Figure 2.

Funded by the Horizons 2020 programme, the "Small Bodies: Near and Far" (SBNAF) project aims to develop benchmark studies focused on assessing, validating, and advancing the different techniques involved in the studies of physical and thermal properties of small bodies (Müller et al. 2017b). Thus, SBNAF makes extensive use of *AKARI* data. In recent work (Alí-Lagoa et al., submitted to A&A), we enumerate a number of foreseen applications for the *AKARI* IRC catalogue within the framework of SBNAF. As an example, we have updated the asteroid diameters and albedos with an upgraded version of the near-Earth asteroid thermal model (or NEATM; Harris 1998) as implemented by Alí-Lagoa & Delbo' (2017). This improved the diameter and albedo estimates of the NEAs in the IRC catalogue and essentially cross-validated the radiometric diameters of main belt asteroids derived from two different source catalogues, *AKARI* and *WISE*/NEOWISE, and applying three independent thermal models.

Another recent example is the work by Marciniak et al. (2017), who performed the first TPM analysis featuring combined *IRAS*, *AKARI*, and NEOWISE data and shape models derived from SAGE. They constrained thermal inertias and produced more accurate diameters and albedos of four asteroids with long rotational periods, which are underrepresented in our light-curve catalogues. Given their irregular shapes, such combinations of infrared data from several space-based observatories like *AKARI*, *WISE*/NEOWISE, *Spitzer*, or *Herschel*, are required to cover different rotational phases and parts of the surfaces and gain sufficient three-dimensional information about the asteroids. In this sense, *AKARI* remains the longest-lasting fully-cryogenic all-sky survey, which resulted in about 200 objects being observed three times during the all-sky survey, in some cases at widely different observation geometries.

Yet another field where increasing knowledge of thermal inertias will guarantee interesting breakthroughs is the study of comminution of surface material from rocks and coarse-grained terrains to fine dust or regolith due to thermal cracking. This effect was shown to be faster in NEAs and main belt asteroids than micrometeorite bombardment, the traditional mechanism envisioned to develop fine regolith on asteroidal surfaces (see Delbo' et al. 2014, and references therein). Also, thermally-driven stress may be responsible for eroding surface materials of Rosetta's target comet 67P/Churyumov-Gerasimenko, triggering outbursts of cometary activity and reshaping the body's surface (Alí-Lagoa et al. 2015; Vincent et al. 2016; Pajola et al. 2017).

To conclude, the community devoted to the study of asteroids has virtually only started to exploit the data collected by *AKARI*. While it is hard to enumerate all conceivable future applications, *AKARI* will surely remain one of the major resources of information to tackle the thermal and physical characterisation of asteroids. Studying asteroids at the individual level to the extent made possible by space missions will be inevitable slow given how numerous and heterogeneous these bodies are. But a crucial benefit of the large infrared surveys is that they help us bridge the gap between the extremely detailed information learned from space mission targets to understand the bigger picture of planetary science.

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