THE SIZES OF KUIPER BELT OBJECTS

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ABSTRACT

One of the most fundamental problems in the study of Kuiper belt objects (KBOs) is to know their true physical size. Without knowledge of their albedos we are not able to distinguish large and dark from small and bright KBOs. *Spitzer* produced rough estimates of the sizes and albedos of about 20 KBOs, and the *Herschel* space telescope will improve on those initial measurements by extending the sample to the ∼150 brightest KBOs. *SPICA*'s higher sensitivity instruments should allow us not only to broaden the sample to smaller KBOs but also to achieve a statistically significant sample of KBO thermal light curves (*Herschel* will measure only six objects). A large sample covering a broad range of sizes will be key to identify meaningful correlations between size and other physical and surface properties that constrain the processes of formation and evolution of the solar system.

Key words: Solar system: formation – Kuiper belt objects: physical properties – Missions: SPICA

1. INTRODUCTION

In this paper I discuss the importance of the upcoming *'Space Infrared Telescope for Cosmology & Astrophysics'* (hereafter, *SPICA*) for the study of the icy small bodies of the outer solar system. Here, I focus on the study of Kuiper belt objects (KBOs) but the same ideas can be applied to any atmosphereless bodies. I will mainly discuss how *SPICA* can help us to measure the sizes of KBOs, and how that leads to more accurate estimates of the size distribution and total mass of KBOs. I will also mention how this new infrared space telescope might probe the rotational properties, chemical composition and thermophysical parameters of those icy bodies. Other uses of a space-based infrared telescope for solar system studies are detailed elsewhere, in the context of *SPICA*'s precursor observatory, *Herschel* (Lellouch, 2009). In §2 to §4 I begin by summarising what we know about KBOs and why their study is interesting and important. Although many accounts exist elsewhere I believe these proceedings should include a broad overview of the subject. In §5 and §6 I discuss how *SPICA* may contribute to the study of KBOs.

2. OUR SOLAR SYSTEM: THE 1980'S VERSUS NOW

Just a couple of decades ago our understanding of the solar system was quite different from what it is today. Scientific interest lay mainly with the nine planets: six (Mercury to Saturn) already known to the Greeks, another two (Uranus and Neptune) discovered in the 18th and 19th centuries and a very peculiar ninth planet (Pluto) discovered in 1930. The small rocky planets, all within 1.5 astronomical units (AU) from the Sun, stood in sharp contrast with the outer gaseous giants extending out to 30 AU. More intriguing was Pluto, a moon-sized world on an eccentric and very inclined orbit beyond Neptune. Pluto did not seem to fit in with the rest and was oddly isolated given its small size. Comets, asteroids, and even some planetary moons had a mysterious character to them and were for the most part not well understood.

This view of the solar system has changed dramatically in the last 20 years or so, mainly following the discovery of the Kuiper belt and of discs and planetary systems around other stars. The focus of planetary science has moved to the smaller bodies of the solar system as most of the interesting results and paradigm-shifting discoveries have come from the study of their properties. We begin to understand how the planets formed and evolved, how different families of small bodies relate to one another, and how our solar system fits in the larger picture of what we are finding in extrasolar planetary systems.

3. THE KUIPER BELT

The Kuiper belt was identified in 1992 with the discovery of 1992 QB$_1$ (Jewitt & Luu, 1993). Since then more than 1000 KBOs have been discovered in the region roughly from 30 to 50 AU. The *known* KBOs range from about 25 to 2500 km in diameter (Bernstein et al., 2004; Brown, 2008) but numerous smaller objects are believed to exist down to the micrometer-sized dust grains that have been detected by Voyager 1 and 2 (Gurnett et al., 1997). Larger bodies could also exist and remain undetected. The Kuiper belt is the solar system analogue to the debris discs found around other stars (Wyatt, 2008).

Kuiper belt objects provide us with probably the best picture of what the planetesimals that formed the planets might have looked like. Dynamically, most KBO orbits are stable against gravitational perturbations from the giant

planets on Gyr timescales. Chemically, the low temperatures found at such large heliocentric distance ensure that KBOs preserve significant volatile content from the protosolar nebula. KBOs display the largest spread in surface colours of all objects in the solar system (Jewitt, 2002). The origin of the diversity is unknown but could reflect dynamical mixing resulting from planetary migration (Tsiganis et al., 2005). Physically, as the largest ($D > 1000$ km) remnants of the planetesimals that formed the planets, KBOs retain valuable information about the size, density and angular momentum distributions at the poorly understood epoch of accretion. The study of KBOs can thus provide unique clues about the formation of solar system bodies.

Figure 2. Orbital structure of Kuiper belt objects. Grey vertical lines indicate mean motion resonances with planet Neptune. Objects plotted beyond 30 AU and above the black solid curve cross the orbit of Neptune.
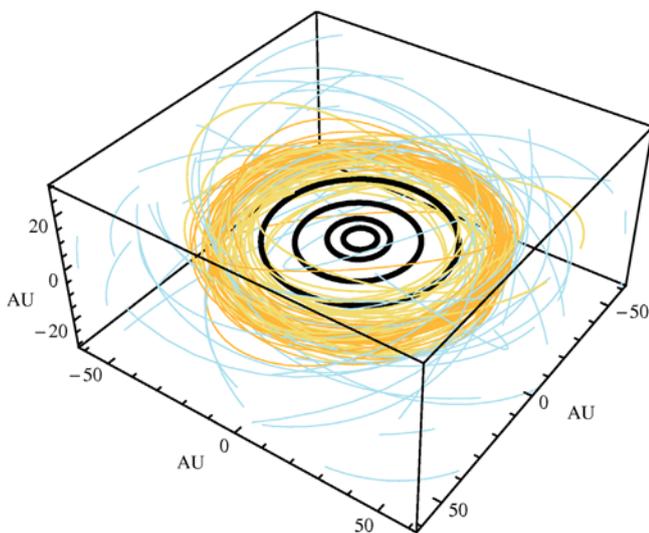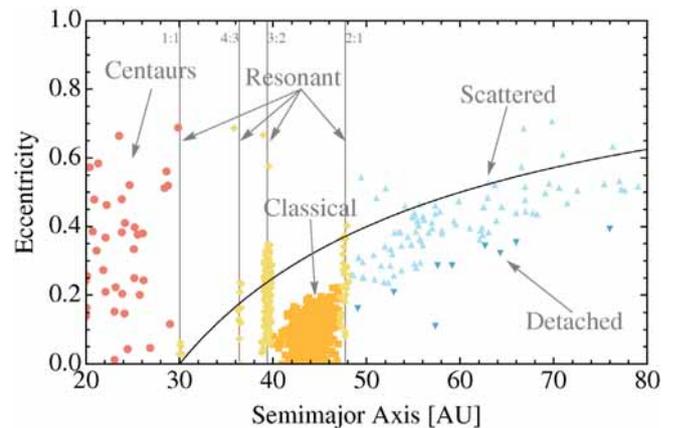

Figure 1. Three-dimensional representation of the Kuiper belt. Roughly 10% of known orbits are plotted. The colours match those in Fig. 2. The thick black lines indicate the orbits of Jupiter, Saturn, Uranus and Neptune. Centaurs are not shown for clarity.

Kuiper belt orbits form a thick disc (7% of known KBOs have inclinations $i > 30°$) beyond Neptune (Fig. 1) but the orbital distribution within that disc is not random. Most orbits fall in one of four dynamical classes (Fig. 2).

Resonant KBOs lie in mean motion resonances with Neptune. Because of their resonant character they avoid close encounters with the massive planet and are stable over the age of the solar system. Pluto lies in the 3:2 resonance at roughly 39 AU from the Sun and so other KBOs in the same resonance are often called Plutinos.

Classical KBOs are the dynamically quintessential objects. They have relatively low eccentricity and low inclination orbits between the 3:2 and the 2:1 resonances at ∼ 39 AU and ∼ 48 AU. They are called classical because their orbits most closely match what would be expected for a cold dynamically stable disc. The classical

belt turned out to have a broader inclination distribution than first expected. 1992 QB$_1$, the first object discovered in the Kuiper belt, is a classical KBO.

Scattered KBOs are objects that interact strongly with Neptune near perihelion and are thus being scattered by the giant planet. It is generally believed that scattered KBOs originate in slightly unstable regions within the Resonants and Classicals. Once in the scattered population these KBOs can be thrown into planet crossing, *Centaur*-type orbits which eventually feed the Jupiter family comet population (Duncan & Levison, 1997). This scenario is not unique, though (Volk & Malhotra, 2008). Centaurs are a population closely related to KBOs. They have giant-planet-crossing orbits unstable on Myr timescales. Possible end-states for Centaurs are collision with a giant planet, or ejection from the solar system. Some return to the Scattered Kuiper belt and a few end up (or spend part of their lifetime) as Jupiter family comets (Bailey & Malhotra, 2009).

Detached KBOs have perihelia beyond 40 AU indicating that Neptune had little influence in their orbital evolution. They may have been emplaced at an earlier epoch by the pull of a star passing close to the Sun or by past gravitational perturbations by an unseen (or since ejected) planet beyond (Lykawka & Mukai, 2008).

The orbital architecture of the Kuiper belt has provided many clues about the past dynamical evolution of the solar system. For instance, we now know that the giant planets did not form in their current locations but instead started out in a much more compact configuration, from roughly 5 to 15 AU and then migrated to their current positions. The stable resonances in the Kuiper belt were populated as Neptune migrated outwards into a cold disc of planetesimals by sweeping bodies as they moved along with the planet. Indeed, the most encompassing model of the dynamical evolution of the solar system – the *Nice*

Table 1. *A selection of known KBOs and their properties. Listed are object name, followed by approximate values for diameter, axis ratio (shape), spin period, light curve range, bulk density, surface albedo, surface composition, and orbital parametres. Question marks indicate unknown or poorly constrained entries.*

Object	D [km]	a/b	P [hr]	Δm [mag]	ρ [kg m^{-3}]	Albedo	Surface Comp.	a [AU]	e	i [°]
Eris	2400	1.0	?	< 0.01	2300	0.85	CH$_4$	67.8	0.44	44.0
Pluto	2290	1.0	153.2	0.33	2000	0.60	CH$_4$, CO, N$_2$	39.6	0.24	17.1
Haumea	1500	1.2	3.9	0.29	2600	0.70	H$_2$O	43.2	0.19	28.2
Quaoar	1250	1.1	17.7	0.13	?	0.09	H$_2$O	43.1	0.04	8.0
Varuna	1000	1.3	6.3	0.42	1000	0.07	H$_2$O?	42.8	0.06	17.2
Huya	530	1.0	?	< 0.06	?	0.06	H$_2$O?	39.8	0.28	15.5
2000 GN$_{171}$	320	1.6	8.3	0.61	600	0.06	?	39.7	0.29	10.8
2001 QG$_{298}$	230	2.9	13.8	1.14	600	?	?	39.6	0.20	6.5

model (named after the French city; Tsiganis et al., 2005) – is largely designed to fit the observed properties of KBOs and small solar system bodies in general. It fits, among other things, the global architecture of solar system orbits, the migration of the planets by interaction with the planetesimals, the enhanced lunar cratering record ~3.8 Gyr ago known as late heavy bombardment, the formation of the Oort cloud, the origin of Trojan asteroids and the existence of hot (high-i) and cold (low-i) classical KBO populations. The strength and weakness of the *Nice* model lies in its adaptability to new observational discoveries. New and more stringent observational constraints should be sought to truly test the model.

The cumulative luminosity function of KBOs is well described by a power law, $\log \Sigma = \alpha(m_R - m_0)$, with $\alpha \sim 0.65$ and $m_0 \sim 23.5$ (Trujillo et al., 2001). To translate luminosity into size requires knowing the surface albedo. Assuming a uniform albedo for all KBOs and no relation between heliocentric distance and size, the slope of the size distribution can be inferred from that of the luminosity function as $q = 4\alpha + 1$ (Irwin et al., 1995). However, the few known albedos (see examples in Table 1) show that albedo is probably a strong function of size and surface properties. Measuring and understanding the albedo distribution is crucial if we are to constrain the size distribution and total mass of the Kuiper belt; *SPICA* is expected to play a major role in achieving this goal.

Kuiper belt objects exhibit a tremendous diversity in surface colours, unparallelled in the solar system (Luu & Jewitt, 1996). This probably reflects significant chemical diversity, which is a puzzle given the small range of temperatures in the 30 to 50 AU region. Spectroscopy, only possible for the few brightest objects, shows that the largest KBOs are predominantly coated in either methane ice (e.g. Eris, Pluto) or water ice (e.g. Haumea, Quaoar). Smaller objects are generally too faint for spectroscopic studies but the few observed at sufficient S/N show mostly featureless spectra.

In summary, the Kuiper belt is now understood as a significant component of the Sun's debris disc, as the most likely source of Centaurs and Jupiter family comets, and possibly even of the Trojans, unusual planetary moons (e.g. Triton, Phoebe) and the irregular satellites of the giant planets. The belt has also provided a context for global models of the evolution of the solar system.

4. Interesting KBOs

1992 QB$_1$ was the first identified KBO. It is roughly 250 km in diameter assuming a cometary albedo of 4%. Its orbit is nearly circular and has low inclination.

Varuna was discovered on 28 Nov. 2000 by R. S. McMillan. Being one of the brightest known KBOs at the time, Varuna was intensely observed and studied. Combined sub-millimetre and optical observations were used to solve the degeneracy between size and albedo (Jewitt et al., 2001) and estimate Varuna's diameter (~ 1000 km) and albedo (~ 0.07). Light curve observations revealed a rotationally deformed, fast-spinning object ($P_{\rm rot} = 6.34$ hr; Jewitt & Sheppard, 2002). Varuna is too large to support significant topography and its overall shape is set by the balance between gravitational and rotational accelerations. This property allows its bulk density to be estimated ($\rho \sim 1000$ kg m^{-3}; Lacerda & Jewitt, 2007).

1998 WW$_{31}$ was the first binary KBO to be discovered after Pluto/Charon (Veillet et al., 2002). Like most KBO binaries, this system has nearly equal sized components. Binaries are important because their total mass can be estimated using Kepler's 3rd law and, if the size of the components is known, their densities can be estimated.

2001 QG$_{298}$ was found to display extremely large photometric variability, $\Delta m = 1.14 \pm 0.04$ mag (Sheppard & Jewitt, 2004). The large Δm combined with a relatively slow rotation, $P \sim 13.8$ hr, suggest this object is a contact binary. The shape of the components, as inferred from the light curve, and the spin period imply a low bulk density of about $\rho \sim 650$ kg m^{-3} (Lacerda & Jewitt, 2007). Statistically, about 20% of KBOs could display the extreme properties of QG$_{298}$, meaning that many more await dis-

covery. The prospect of measuring densities from contact-binary-type light curves is compelling.

Eris was the first truly Pluto-sized KBO found (Brown et al., 2006); those are the only KBOs than can currently be resolved by *HST*. The possibility that Eris is larger than Pluto intensified the planethood controversy. Eris is covered in methane ice and has a high albedo ($> 80\%$) surface. Its density is about 2300 kg m^{-3}, comparable to that of Pluto.

Haumea is one of the strangest known KBOs. It spins extremely rapidly, $P = 3.9$ hr and, like Varuna, it is rotationally distorted into a triaxial shape (Rabinowitz et al., 2006). Unlike Pluto and Eris, Haumea is covered in almost pure water ice but its high bulk density ($\rho \sim 2500$ kg m^{-3}, estimated in the same way as for Varuna; Lacerda & Jewitt, 2007) indicates that it must have a rocky core and thus be differentiated. A violent collision has been proposed to explain Haumea's fast rotation, the fact that it has two small, water-ice-rich moonlets, and the presence of half a dozen water-ice-rich KBOs in its orbital vicinity. The collision would have happened more than 1 Gyr ago, onto a proto-Haumea that was differentiated and had a thick water ice mantle (Brown et al., 2007).

Figure 3. Predicted flux density of KBOs of different radii at 30 and 50 AU from the Sun versus the wavelength coverage of SPICA. *The expected sensitivity of* SPICA, *$50\mu m$, is indicated by a horizontal dotted line.*

be studied in their pristine state before they reach the inner solar system.

5. The sizes of Kuiper belt objects

Without knowing the surface albedo of a KBO it is not possible to tell large and dark from small and bright objects. Ideally, the albedo can be measured by combining visible and thermal infrared observations. The reflected, visible light is proportional to the KBO cross-section, S, and albedo, A, while the thermal emission is proportional to $S \times (1 - A)$, i.e. to the fraction of light absorbed by the object which contributes to heating its surface. Visible and thermal observations can thus be used to solve for S and A. In practice, other unknown parameters describing the spin state and orientation of the KBO, and its surface roughness, emissivity, and thermal diffusivity (or inertia) complicate the process and generally require more detailed observations at different wavelengths.

Due to their great heliocentric distances, KBOs have very cold surfaces with equilibrium temperatures around 40 to 50 K. Consequently, their thermal emission peaks at 50 to 80 μm, well within *SPICA*'s wavelength coverage (Fig. 3). But by far the most important feature of *SPICA* will be its enhanced sensitivity. Active cooling of the mirror should bring the sensitivity down to $\sim$50 μJy, nearly two orders of magnitude better than *Herschel*. *SPICA* will be able to detect objects almost as small as 10 km across, one order of magnitude smaller than *Herschel*, meaning that thousands more bodies will be accessible to the new telescope. *Herschel* will carry out a key project to observe $\sim$140 large KBOs and Centaurs. *SPICA* should vastly increase this number and extend the sample to smaller bodies, approaching the sizes of comet nuclei which could then
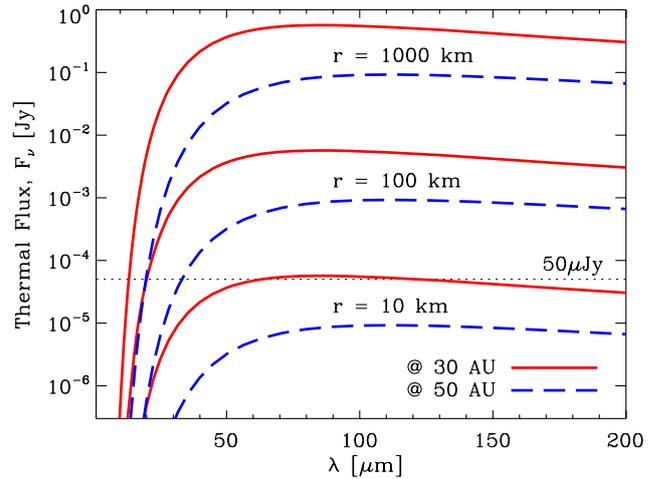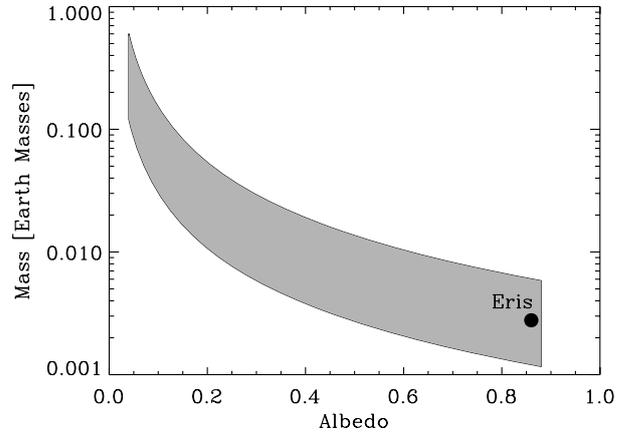

Figure 4. Mass of large KBO Eris as a function of the assumed albedo. The current best estimate is plotted as a black dot. The vertical extent of the gray area reflects a range of plausible bulk densities, from 1 to 5 g cm^{-3}.

Another advantage of looking at the smaller bodies is to understand how albedo varies with size. Understanding the albedo distribution of KBOs is important in many ways. For instance, estimating the size distribution and total mass of the Kuiper belt from the observable luminosity function relies strongly on assumptions about the albedo. When derived from its brightness, the diameter of a KBO varies as $A^{-1/2}$, where A is the albedo, and its mass varies as $A^{-3/2}$. The mass estimate has the further complication that the densities are also unknown. Plau-

sible solar system densities range from $\rho \sim 500$ kg m^{-3} for comet nuclei, to $\rho \sim 5000$ kg m^{-3} for terrestrial planets. Figure 4 illustrates how uncertainties in albedo and density can lead to differences of a few orders of magnitude in the derived masses. The current estimated total mass of KBOs is 0.01 to 0.1 $M_\oplus$. Accretion models in the outer solar system require 10 $M_\oplus$ of material in the proto-Kuiper belt to explain the formation of Pluto-sized objects (Kenyon & Luu, 1999) in reasonable 10 to 100 Myr timescales, and the *Nice* model assumes 35 $M_\oplus$ to explain the current orbital architecture of the giant planets (Tsiganis et al., 2005). The *Nice* model can also explain how ~99% of the initial mass has been lost but the uncertainty in the current mass prevents it from offering a solid constraint to the model.

For binary KBOs it becomes even more interesting to be able to measure their physical size (cross-section). Binaries offer the opportunity of measuring mass which can be translated into bulk density if we know the size. Density is hard to measure remotely but is very useful as first indicator of inner structure and composition. Exactly how density depends on size may reveal whether the former is more strongly influenced by composition or porosity. By the time *SPICA* begins operations, the next-generation space telescope *JWST* will presumably have identified many more binary KBOs suitable for mass determination.

6. Chemical and physical properties of KBOs

Accurate albedos are also important for spectral modelling. Models by Hapke and Shkuratov to investigate the composition and relative abundances of surface materials can only be applied if the absolute reflectance is known. *SPICA*'s increased sensitivity will, for the first time, open the far-infrared domain to spectroscopic studies of KBO surfaces. The far-infrared is rich in diagnostic features diagnostic of silicates and ices expected to incorporate KBOs. Amorphous and crystalline water ice can also be identified through far-infrared spectral features at 44, 45 and 62 μm (Moore & Hudson, 1992). At low temperatures ice will form in the amorphous state and at 40 to 50 K it should remain so for the age of the solar system. However, whenever identified on the surfaces of the largest KBOs water ice appears consistently crystalline (Jewitt & Luu, 2004; Trujillo et al., 2007). Amorphous ice could exist in subsurface layers though, or in smaller KBOs, as it is thought to drive cometary activity of Centaurs beyond 5 AU by converting into the crystalline phase as these objects move in from the cold Kuiper belt (Jewitt, 2009).

The thermal emission of KBOs depends not only on their size and albedo, but also on thermophysical properties of the surface such as emissivity and thermal conductivity (or inertia), and on surface roughness. Multiwavelength measurements can be used to constrain these unknown parameters and provide extra information about the surface of the distant KBOs. However, to accurately model the temperature distribution across the surface of the KBO we need to know its spin state (rotation period and spin orientation; see below).
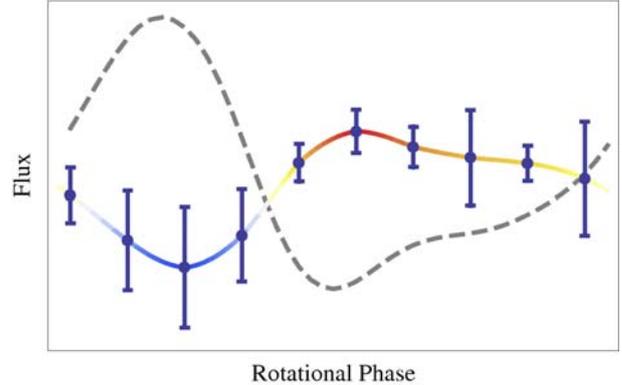

Figure 5. Simulated visible (dashed grey) and thermal (points with error bars and solid line) light curves of a spherical object with less and more reflective patches across its surface. The more reflective areas are brighter in visible light but cooler and thus fainter at thermal wavelengths. Conversely, the optically darker patches absorb more solar radiation and appear warmer, hence brighter in the far-infrared. In summary, an optical light curve caused by albedo appears anti-correlated with its thermal counterpart. Deviations from perfect anti-correlation are due to thermal inertia of the surface.
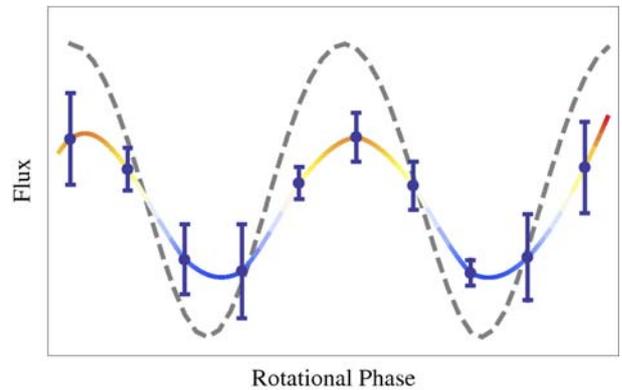
Figure 6. Same as Fig. 5 but for an elongated object with a uniform surface. Here, the brightness modulation in the reflected light (dashed grey) is due to the varying apparent cross-section as the object rotates. The thermal light curve (points with error bars and solid line) follows the same pattern because the emitting cross-section is larger when the reflecting cross-section is larger.

Six of the brightest KBOs to be observed by *Herschel* will be observed repeatedly as they spin to obtain thermal emission curves. Given *SPICA*'s high sensitivity we will be able to extend this type of observation to many more objects. By comparing the optical and thermal light curves

we will be able to establish with certainty whether the photometric variability is due to shape or albedo spottiness. If the variability is due to albedo markings then optically bright, high albedo regions will be fainter at thermal wavelengths because they reflect more sunlight and remain cooler – the optical and thermal light curves appear uncorrelated (see Fig. 5). If due to shape, the body will be brighter at optical and thermal wavelengths at roughly the same time (Fig. 6). Breaking this degeneracy between albedo and shape is important for studies of the shape distribution and angular momentum content of KBOs (Lacerda & Luu, 2003, 2006).

Time-resolved thermal observations may also constrain the orientation of KBO spin axes w.r.t. the line of sight. The closer the spin vector lies to the line of sight the warmer the object will be, on average, as a large fraction of its surface close to the pole is continuously exposed to sunlight. Modulations due to shape will also be smaller than if the object is seen equator-on. *SPICA* will extend these techniques to a much larger sample and for those six objects previously studies by *Herschel* the observations about a decade apart may help constrain the longitude of the spin pole as well. The alignment of KBO spin poles can test models of planetesimal formation and collisional evolution (Lacerda, 2005; Johansen & Lacerda, 2009).

7. Conclusions

The enhanced sensitivity of the upcoming *'Space Infrared Telescope for Cosmology & Astrophysics'* (*SPICA*) will play a key role in the study of Kuiper belt objects. Multiwavelength thermal observations will enable us to measure the albedos and sizes of several hundreds of bodies and to investigate their surface composition and thermophysical properties. The high sensitivity – two orders of magnitude better than *Herschel* – will allow the detection of KBOs as small as a few tens of kilometres across, very close to the sizes of cometary nuclei. Sizes measurements of binary Kuiper belt objects will lead to estimates of their bulk density, a first step into the interior structure of these bodies. Time resolved thermal observations of a statistical ensemble of KBOs will help break the degeneracy between albedo variability and shape as the cause for observed light curves, which is important for assessing the shape and angular momentum distributions of Kuiper belt objects. By extending the far-infrared domain to potentially hundreds of Kuiper belt objects and associated families, *SPICA* should allow us to identify meaningful correlations and patterns between orbital, physical and chemical properties and thus help us probe the formation and evolutionary processes that operated at the early stages of our solar system.

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