The Asteroid Redirect Mission (ARM): Exploration of a Former Binary NEA?

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The National Aeronautics and Space Administration (NASA) is developing the Asteroid Redirect Mission (ARM) as a capability demonstration for future human exploration, including use of high-power solar electric propulsion, which allows for the efficient movement of large masses through deep space. The ARM will also demonstrate the capability to conduct proximity operations with natural space objects and crewed operations beyond the security of quick Earth return. The Asteroid Redirect Robotic Mission (ARRM), currently in formulation, will visit a large near-Earth asteroid (NEA), collect a multi-ton boulder from its surface, conduct a demonstration of a slow push planetary defense technique, and redirect the multi-ton boulder into a stable orbit around the Moon. Once returned to cislunar space in the mid-2020s, astronauts aboard an Orion spacecraft will dock with the robotic vehicle to explore the boulder and return samples to Earth. The ARM is part of NASA's plan to advance technologies, capabilities, and spaceflight experience needed for a human mission to the Martian system in the 2030s. The ARM and subsequent availability of the asteroidal material in cis-lunar space, provide significant opportunities to advance our knowledge of small bodies in the synergistic areas of science, planetary defense, and in-situ resource utilization (ISRU). The current reference target for the ARM is NEA (341843) 2008 EV5, which may have been the primary body of a former binary system (Busch et al., 2011; Tardivel et al., 2016). The ARRM will perform several close proximity operations to investigate the NEA and map its surface. A detailed investigation of this object may allow a better understanding of binary NEA physical characteristics and the possible outcomes for their evolution. An overview of the ARM robotic and crewed segments, including mission operations, and a discussion of potential opportunities for participation with the ARM will be provided in this presentation.

Radar observations and population trends of binary near-Earth asteroids

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The Arecibo and Goldstone planetary radars are invaluable instruments for the discovery and characterization of binary and triple asteroids in the near-Earth asteroid (NEA) population. To date, 41 out of 56 known binaries and triples (73% of the objects) have been discovered by radar. Furthermore, 49 of these multiple systems have been detected by radar. Their absolute magnitudes range from 12.4 for (1866) Sisyphus to 22.6 for 2015 TD144 and have a mean and rms dispersion of 18.1+-2.0. There is a pronounced decrease in abundance of binaries for absolute magnitudes H>20. Among 366 NEAs with H<22 (corresponding to diameters larger than 200 m) detected by radar since 1999, 13% have at least one companion. NEA binary systems are known among the S, Q, V, B, C, and P spectral classes, but not among the NEAs that have been classified as E- or M-types. The first well-studied binary system was (66391) 1999 KW4 (Ostro et al., 2006). The primary showed evidence for a prominent equatorial bulge, sloped hemispheres, and flat polar regions, shape attributes that have since been found on the primaries of numerous other NEA binaries. Additional evidence that the KW4-like shapes are real and not artifacts of the shape modeling occurred with Goldstone observations of 2013 WT44. 2013 WT44 was imaged at nearly pole-on subradar latitudes and the delay-Doppler images clearly show the signature of an equatorial bulge, sloped hemispheres, and polar flattening. We estimate the abundance of KW4-like primaries to be at least 40% based on the 49 radar-detected multiple systems. At least 10% of the primaries do not have KW4-like shapes. For example, the primaries of (276049) 2002 CE26 (Shepard et al., 2006) and (285263) 1998 QE2 (Springmann et al., 2014) have rounded shapes, with no obvious equatorial ridges, and the primaries of (164121) 2003 YT1, (1862) Apollo, and (363599) 2006 VV2 have irregular, moderately elongated shapes that show the presence of a bulge at only selected longitudes.

The Study of Binaries with Occultations

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In recent years, direct imaging and lightcurve observations have come of age for the discovery of asteroid satellites. As powerful as these techniques have proven to be, they both suffer limitations and biases. Direct imaging is limited by the resolution of the telescope and camera system. Lightcurve searches are dependent on special geometries to see mutual events. Stellar occultations are a third technique that has been in use for decades for size and shape measurements with an occasional binary object. Occultations have a lot of promise for providing complementary measurements to direct imaging and lightcurves by being especially sensitive to close-separation binaries regardless of viewing geometry. The Research and Education Collaborative Occultation Network (RECON) has been in operation since April 2015 and is uniquely capable of searching for close companions for Centaurs and TNOs. We will present a summary of the RECON project and illustrate its capabilities by showing recent results of a stellar occultation by the Jupiter Trojan asteroid, Patroclus and its nearly equal size moon, Menoetius. Successful observations of an occultation by (229762) 2007 UK126 will also be shown as an example of working with faint TNO events. The synergy between the large RECON footprint and expected results from the ESA Gaia mission will also be discussed.

The environment around fast spinning asteroids: The case of (65803) Didymos, target of the AIDA mission

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This study is carried on in the frame of the working group on physical and dynamical characterization of the AIDA mission. We have collected available data on binary NEA systems with fast rotating primaries with good estimates of primary's spin rates and system mass. We mainly focus on the binary system (65803) Didymos. In order to study the dynamics of particles, we use a numerical code that integrates the equations of motion of individual particles that are ejected from the asteroid surface when centrifugal acceleration is strong enough to overcome local gravity. The equation of motion is written in a non-inertial asteroid-centered reference frame, taking into account the asteroid, the secondary, and solar gravity, solar radiation pressure and inertial terms. We then study the motion of particles in the 1 m to 1 cm range in the described non-inertial reference frame of the rotating primary. The eccentricity of the heliocentric orbit of the system and the obliquity of the system are taken into account. The dynamics of particles of a wide mass range is calculated during many orbital cycles as a function of their initial position on the asteroid surface for each system under study. A mass density of levitating particles is calculated as a function of distance to surface, latitude, and longitude. In the very case of Didymos, the study has been refined taking into account the shape model of the primary and has been discussed in the available range of size and mass. We present the results of our ongoing study in the case of Didymos. We find that fine particles (< 100 m) are quickly swept away from the system by solar radiation pressure, while larger particles may undergo landing and lift off cycles that form a dusty environment above the surface at near-equatorial latitudes. The mass density of floating particles drops quickly beyond 10-20 degrees of latitude. Consequences in the AIM navigation around the Didymos' primary can be derived from this study

Asteroid (41) Daphne and its moon

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We provide a progress report on our analysis of past observations, and our plans for future observations, of asteroid (41) Daphne and its tiny moon, Leucippos (unofficial name). Leucippos was discovered on March 28, 2008 [Conrad, et al., IAUC 8930 (2008)] during an observation using the NIRC2 imager on Keck II. Both Daphne and Leucippos were then imaged in follow-up observations carried out with NIRC2 on April 23rd and with VLT/NACO on 5 different nights during May of that same year [Conrad et al., AAS/DPS, (2008); Merline et al., ACM/LPI (2008)]. Our analysis indicates a highly irregular shape for Daphne with an equivalent diameter of about 190 km, and an extreme mass ratio between Daphne and Leucippos of about one million. Density of an asteroid can be measured for systems like Daphne/Leucippos. Daphne is resolved, allowing a volume estimate; while the orbit of Leucippos around Daphne provides the mass estimate. Density leads to better knowledge of composition. Knowledge of asteroid composition has become increasingly important for understanding planet formation and for determining the potential use of asteroid resources. For the upcoming opposition during March 2017, we plan to better constrain the volume and mass, and hence density, of the Daphne system by conducting observations with new technology coming on line at the Large Binocular Telescope (LBT). We will use LBT in 8-meter mode with extreme AO and the recently commissioned LUCI-1 imager, in 12-meter mode (combined aperture, un-phased) using both LUCI-1 and LUCI-2 simultaneously, and in 23-meter mode using the soon to be commissioned imager LINC-NIRVANA (LN). LN will bring a new, experimental mode to LBT. This mode, a variant of Fizeau imaging that uses light from surrounding stars for fringe tracking, can be used with resolved sources like (41) Daphne. We will report the status of our planning, and the expected resolution and performance, for each of these 3 future modes coming on line at LBT.

Dynamics of the Trans-Neptunian Triple (47171) 1999 TC_{36}

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Plutino (47171) 1999 TC_{36} is the only known Trans-Neptunian Object (TNO) that is a hierarchical triple, as opposed to more planet-like multiple-moon systems of Pluto and Haumea. As described by Benecchi et al. (2010), the tight inner equal-sized binary (with diameters of 250-300 km) with a 1.9 day orbital period is orbited by a third component about 140 km in diameter on a 50-day orbit with an eccentricity of 0.3. It is possible, but still unconfirmed, that the inner binary is doubly-synchronous, and the densities of the three component are only about 500 kg/m^3. Apart from the question of formation, the most interesting feature of the system is that eccentricity of the inner binary is about 0.1, despite the expected tidal circularization timescale being on the order of 10^8 years. I will present analysis of the triple's orbital evolution over the age of the Solar System, and discuss the implication for its formation. Our preliminary work indicates that, unlike an oblate planet with a close satellite, a pair of tidally evolved triaxial bodies have a much less stable secular orbital behavior. Not only does the triaxiality slow down apsidal precession, but the precession rates are also sensitive to librational behavior of each component (Borderies and Yoder 1990). Forced librations depend on the eccentricity (Wisdom et al. 1984), which opens a possibility of a feedback loop between librations and secular resonances with the outer component. At the workshop, I will present numerical simulations of the dynamics of the system for a range of possible shapes and tidal parameters of the components.

Update on SAGE algorithm: uncertainty maps for asteroid shape and pole solutions.

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SAGE (Shaping Asteroids with Genetic Evolution) inversion method is based on genetic algorithm to obtain pole solutions, rotation periods and non-convex shapes of asteroids. During the process computer graphics methods are used to compare model's synthetic lightcurves to photometric observations. The method is suitable of modelling both single and binary objects. A modelling run starts with a sphere, with no assumptions about the shape, and subsequently it converges to a stable spin and shape solution. Asteroid modelling process consists of many such runs, each of them going a different path and arriving at slightly different solution for the shape, creating a family of models. By comparing multiple solutions we are able to construct a map of uncertainties for the shape, showing areas of good and poor agreement between various solutions, which then can be represented with a 3D visualisation. Also, we create a map of errors for pole solutions and periods. Model of (3169) Ostro will be used as an example of this upgrade of the SAGE method.

On the orbit deflection of potentially hazardous binary asteroids

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The binary asteroid (65803) Didymos, target of the Asteroid Impact & Deflection Assessment (AIDA) mission, belongs to the dynamical class of Potentially Hazardous Asteroids (PHA). In the framework of AIDA, a kinetic impact (DART) is intended to change the orbit of Didymos' moonlet around the binary's center of mass. The aim is to change the mutual orbit of the binary asteroid. However, net momentum is also imparted on the whole system. The consequent change in the asteroid's velocity will change the heliocentric orbit of the Didymos system as well. Even if those changes are expected to be small, they can affect long term predictions of the encounter distances between Didymos and the Earth. In order to make sure that no planetary safety issues arise as a consequence of such a kinetic impact, post-mitigation impact risk assessments (PMIRA, Eggl et al. 2015, 2016) similar to those already performed for the deflection demonstration scenarios elaborated in the framework of the European Commission funded NEOShield projects are necessary. An essential part of the PMIRA is the evaluation of uncertainties in the deflection process, the dynamical model, as well as their influence on the final change and the consequences for long term impact risk assessment. We discuss the role of several subtle differences in the dynamical behavior of binary asteroids as compared to single asteroids with respect to the post mitigation impact risk assessment of the AIDA mission.

Binaries in the Trans-Neptunian population

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Our main scientific goal is to characterize physical properties of Trans-Neptunian Objects (TNOs). In the past, we used different analyses of time series photometry through which we studied the rotational light curves of these objects. As a result, we obtained rotational periods of a large sample of TNOs. Our own results and other results from the literature lead to a mean period of TNOs of around 8 hours; nevertheless, the reality is that shorter and longer periods exist. One of the explanations of the extremely slow rotators is that these objects could be part of a binary system or even they could have large satellites. The secondary body could slow down the main body. On the other hand, the extremely fast rotators could have broken-up to form satellites systems or even unbound pairs like in the asteroid belt. However, from light curve analysis alone it is often not possible to find out whether these objects are binaries or not. We need other techniques to obtain additional information in order to contrast all data. In this work we present objects with anomalies in their light curves due to slow rotation periods or even due to other characteristics that guide us to think about the possibility of a binary system. We discuss prospect of detectability with different techniques. The research leading to these results was partially supported from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement no 687378.

Evolution of binary asteroids due to BYORP

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Binary YORP effect, or BYORP, causes binary systems to alter their semimajor axis, inclination, and obliquity, and can cause the binary to finally settle into a stable BYORP-Tide equilibrium, merge or expand. We study BYORP in the framework of the Steinberg and Sari (2011) model, but generalize their results for non-zero heat conductivity, using the approach developed by Golubov et al. (2016) for the normal YORP effect. We describe the state of a binary asteroid as a point in three-dimensional phase space, composed of the semimajor axis, the inclination, and the obliquity, and simulate dynamical evolution of a binary in this phase space. The general formalism is exemplified by simulation of orbital evolution of asteroid (66391) 1999 KW4.

Gaia and the asteroids

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The ESA Gaia satellite is scanning regularly the sky and sending daily to ground 100Gb of data. While the Gaia space mission is aimed at providing a 3D census of our Galaxy, it is nevertheless observing a large number of solar system objects, mainly 350,000 asteroids down to V20.7. Gaia is hence unique in providing photometric and astrometric measurements for a huge number of objects with unprecedented accuracy. Indeed, the Gaia stellar catalogue provides positions and parallaxes of stars almost free of zonal errors; and transit astrometry for SSO at sub-milli-arcsec level and photometry at milli-mag level. The first data to be released for (selected) asteroids will be published starting on the GDR2, mid-2017. All the data acquired so far is presently reduced and validated. Among the many scientific results we expect from Gaia for SSO [Hestroffer & Tanga 2014] there is the derivation of masses and bulk densities of asteroids. These two parameters are fundamental to better understand the interior of such bodies, the Solar System, and also to derive more accurate ephemerides of the planets. Gaia will make it possible to "Unveil a population of asteroid satellites" and produce an entirely new statistics of these systems. Given the resolution and astrometry capabilities of Gaia, we expect to detect a large number of binaries either by resolving the system, or from its astrometric signature, as well as deflections during close encounters between big and smaller asteroids. The size and shape are derived through the 'light-curve' inversion, possibly combined with other data as WISE or stellar occultations. Indeed Gaia will also enable a giant step forward in the technique of stellar occultations. Besides, combination of space and ground-based data will bring new insight in research on binary and multiple asteroids. We will present general aspects of the Gaia mission and observations of SSOs, with particular emphasis on the mass and density determination with binaries.

Thermal Observations and Modeling of NEA Binary Systems

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Over the past several years we have been using near-infrared spectroscopy (0.8-4 μm) of near-Earth asteroids (NEAs) to characterize their composition and thermal properties. The combination of visible and thermal observations of asteroids have long been used to derive diameters, but for small, irregular asteroids, models that assume a spherical shape can result in large uncertainties. In addition, effects of varying thermal inertia, and surface roughness cannot in general be disentangled from effects due to irregular shape. Our thermal targets are imaged using radar, so that the detailed shapes and spin states are known. We apply our shape-based thermal model, SHERMAN, to determine the extent to which the shape affects the thermal emission, through uneven surface temperature distribution, as well as inhomogeneous regolith properties. Although the primaries of NEA binary systems are often close to spheroidal in shape, we find that the thermal emission from these bodies does not always match that of a model sphere when the observations span several different viewing geometries. We will explore the extent to which albedo, thermal inertia and surface roughness affect the observed thermal emission. In particular, we have studied (285263) 1998 QE2 and (175706) 1996 FG3, and will discuss the observations and thermal modeling of these and other NEA binary systems.

PHOTOMETRY OF SYNCHRONOUS BINARY ASTEROID (8474) RETTIG IN 2015

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We present photometric observations of the small main belt asteroid (8474) Rettig which were carried out in May - July 2015 in the frame of the Binary Asteroid Photometric Survey [1]. We suggested that this object could be a binary system from the observations at Kharkiv Observatory on May 19 what was confirmed in the next observations by joint project. The obtained lightcurve is a typical one for a synchronous binary asteroid (similar to asteroid (809) Lundia [2]). In results we estimated an orbital period of the binary system equal of 30.54 hours and a lower limit on the secondary-to-primary mean-diameter ratio of 0.86 [3]. Calibrated photometry of Rettig on June 8 and 10 allowed us to obtain absolute magnitude and color V-R of the asteroid. Diameters of the components of binary system (8474) Rettig were estimated. The results of photometry of Rettig and other known small synchronous main-belt binary asteroids will be discussed. References

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Asteroid geophysics from applying tidal theory to binary asteroids

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While the application of tidal theory to binary asteroids has been used in the past to deduce their geophysical properties, three important developments in the field have occurred: the discovery of the tidal-BYORP equilibrium end-state (Jacobson Scheeres 2011, Scheirich et al. 2015), the discovery of paired binary asteroids (Vokrouhlicky Nesvorny 2009, Pravec et al. 2013), and the development of a tidal theory based on a more sophisticated rheological model (Efroimsky 2012 and 2015). Using the most recent release of the Binary Asteroid Parameters database (Pravec et al. 2015) and selecting the known and suspected singly synchronous binary asteroids, we show that tidal parameter ratio (k/Q) estimates from the tidal-BYORP equilibrium are much higher than the limits calculated by estimating tidal timescales (e.g. Taylor Margot 2013). These much higher dissipation rates are validated by an analysis of two paired binary asteroids (3749 Balam and 8306 Shoko), which have known tidal timescales if pair formation is associated with binary formation. This may be indicative of much shorter lifetimes or different tidal dissipation mechanisms in the primary and secondary. Furthermore, the tidal parmaeter estimates drawn from the tidal-BYORP equilibrium do not follow the size scaling predicted from tidal theory, neither classical or Goldreich Sari (2009). Applying a newly proposed tidal model (Efroimsky, 2012, 2015), the size scaling can be matched, however the asteroid must possess a very low effective viscosity at the relevant tidal frequencies. Some hypotheses for how this all fits together will be presented at the end.

DEEP-South: Round-the-Clock Physical Characterization and Survey of Small Solar System Bodies in the Southern Sky

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Korea Microlensing Telescope Network (KMTNet), which consists of three identical 1.6 m wide-field telescopes with 18k by 18k CCDs, is the first optical survey system of its kind. The three stations (CTIO in Chile, SAAO in South Africa and SSO in Australia) are longitudinally well-separated, and thus have the benefit of 24-hour continuous monitoring of the southern sky. The wide-field and round-the-clock operation capabilities of this network facility are ideal for survey work and the physical characterization of small Solar System bodies. Continuous monitoring of the sky with the KMTNet is considered to be optimized for spin characterization of various kinds of asteroids, including binaries, slow/fast-rotating bodies, non-principal axis rotators, and hence expected to facilitate the debiasing of previously reported lightcurve observations. The DEEP-South (DEep Ecliptic Patrol of Southern sky) team were awarded 45 full nights every year at each site for five years (2015 - 2019) excluding the “bulge season” when the telescope time is exclusively used for exoplanet search. The primary scientific objective of DEEP-South is physical characterization of 70 percent of km-class PHAs until 2019. In order to achieve this goal, we implemented an observation mode called “OC (Opposition Census)” targeting objects around opposition. We present here DEEP-South strategy, observation modes, software subsystem, test runs, early results, and the near terms plans.

NEA PHOTOMETRY IN FRAME OF ISON PROJECT: DETECTION OF BINARIES

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Photometric survey of near-Earth asteroids (NEAs) are carried out in the frame of Asteroid Search and Photometry Initiative (ASPIN) of the International Scientific Optical Network (ISON). The observational program is aimed (1) to acomplete available data on the rotation and shape of NEAs, (2) to investigate an influence of the YORP effect on rotation of these bodies, (3) to detect and characterize binaries among NEAs. The studied objects include both newly discovered and well-known NEAs, targets of radar observations (Goldstone and Arecibo support), and very small asteroids with diameters D < 200 m. We use the network of 19 telescopes with different apertures from 25 cm up to 2.6 m situated at 14 observatories and worked in coordination on photometric survey of asteroids. More than 80 NEAs were observed in 2015. We present photometric observations of several binary NEAs as well as asteroids suspected to be binaries which were carried out last years. The results of recent observations of (8373) Stephengould and (337866) 2001 WL15 are discussed in details.

Contact Binaries Among the Jupiter-Family Comet Population

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Observations by spacecraft and earth-based radar have shown the existence of asteroids that strongly indicate a contact-binary nature. Some of these objects have very distinctive shapes with a near-ellipsoidal large lobe with a near-spherical smaller lobe at one end (eg. 1996 HW1 [1] and now 1999 JV6 [2]). Recent results for the contact-binary asteroid Itokawa, that utilised the thermal response of its surface, imply significant density differences between its two components [3]. While not as common as their asteroid counterparts, some cometary nuclei also have pronounced bi-lobed appearances. Examples include comet 8P/Tuttle [4] 103P/Hartley 2 [5], 19P/Borrelly [6], and possibly comet 1P/Halley [7]. The strongest case for a contact-binary or merged system is based on imaging from the ESA Rosetta spacecraft, currently in the vicinity of the bi-lobed comet 67P/Churyumov-Gerasimenko. Layering is visible across its entire surface, which strongly implies that this comet formed from the merging of two independently-formed comets [8]. This in turn implies that low velocity collisions (cm-m's per second) were occurring presumably in the early stages of formation of these bodies, which is further supported by recent hydrocode simulations of such events [9]. Here I will review this topic in more detail and provide a discussion of the implications these observations have on the formation processes of cometary nuclei and the collisional environment that cometessimals were subjected to early in their formation histories. References: [1] Magri et al. 2011. Icar. 214, p210. [2] Rozek et al. 2016 (this meeting). [3] Lowry et al. 2014. AA 562, A48. [4] Harmon et al. 2010. Icar. 207, p499. [5] A'Hearn et al. 2011. Sci. 332, p1396. [6] Soderblom et al. 2002. Sci. 296, p1087. [7] Keller et al. 1986. Nat. 321, p320. [8] Massironi et al. 2015, Nat. 526, p402. [9] Jutzi and Asphaug. 2015. Sci. 348, p1355.

The Fate of Expanding Binary NEAs

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Singly synchronous binary asteroid systems have several evolutionary end-states, which depend heavily on the BYORP effect. If BYORP is contractive, the primary and secondary could re-impact to form a contact binary, or they could end in a tidal-BYORP equilibrium. Alternatively, if BYORP is expansive, the binary system could evolve to become a wide asynchronous binary system, or the system could expand far enough to become disrupted to form a heliocentric pair. The distinction between the two expansive outcomes depends on whether the secondary asteroid stays synchronized, which keeps the BYORP effect active and the orbit expanding. As the orbit expands, the secondary will librate around the tidally locked orientation to some degree, and the amplitude of this libration will grow with the orbit. This libration also causes variations in the osculating binary orbit eccentricity due to the elongation of the secondary body. This coupling is key to determining the fate of the expanding system. If the eccentricity grows large enough, the secondary will begin circulating; conversely, if the eccentricity and libration are bound to small enough values the system can expand significantly. In this work, we discuss the stability of the libration and orbital motion as a binary expands. In particular we investigate how various levels of tidal and BYORP strengths change the stability of the librational motion - an important aspect is the speed of BYORP expansion - slower expansion is more stable. Thus an understanding of the BYORP coefficients are of fundamental importance for determining the fate of a binary system. The variation in BYORP coefficients has been investigated for a variety of asteroid shapes. This has a further implication in that this knowledge can be used to constrain Q/k based on the work of Jacobson and Scheeres. This analysis helps to inform the expected production rates of heliocentric pairs and wide asynchronous binary systems from singly synchronous systems.

The Asteroid Impact and Deflection Assessment (AIDA) mission to the binary near-Earth asteroid Didymos

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AIDA is a joint ESA-NASA mission, which includes the ESA Asteroid Impact Mission (AIM) rendezvous spacecraft and the NASA Double Asteroid Redirection Test (DART) mission. The target is the binary near-Earth asteroid (65803) Didymos. The primary goals of AIDA are (i) to characterize the moon of a binary asteroid, including for the first time the internal and subsurface properties, (ii) to perform various technology demonstrations, including the deployment of a small lander and CubeSats, inter-satellite communication systems and optical communication with the Earth (iii) to test our ability to impact a small asteroid by an hypervelocity projectile, (iv) to measure the deflection caused by the impact. The separate launches of the two spacecraft is planed in 2020. AIM will arrive in May 2022 for the early characterization of Didymos' moon and the deflection experiment is planed to occur in October, 2022. The DART impact on the secondary member of the binary at 7 km/s will alter the binary orbit period, which can be measured by Earth-based observatories. The AIM spacecraft will monitor results of the impact in situ at Didymos, including possible changes in the moon's properties and dynamics. The decision to launch the european AIM component will take place at ESA Council and Ministerial level in December 2016. Meanwhile, four working groups are supporting the mission study, which includes impact modeling issues, ground based observation planing, studies of the dynamics and physical properties of the binary asteroid, and close-proximity operations. The current status of the mission as well as working group activities, in particular concerning the dynamics and physical properties of the binary system, will be presented. References: Michel, P. et al. 2016. Science case for the Asteroid Impact Mission (AIM): a component of AIDA. Adv. Space Res., in press; Cheng et al. 2016. AIDA Mission: Kinetic Impactor. Plan. Space Sci. 121, 27-35. AIDA web site: http://www.oca.eu/AIDA/

Shape and spin state modeling of binary near-Earth asteroid 65803 Didymos

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Binary near-Earth asteroid 65803 Didymos is the target of the proposed Asteroid Impact and Deflection Assessment (AIDA) space mission. The mission consists of two spacecraft, the Demonstration for Autonomous Rendezvous Technology (DART) spacecraft that will impact the asteroid's satellite and the Asteroid Impact Mission (AIM) spacecraft that will observe the impact. We used radar observations obtained at Arecibo and Goldstone in 2003, and lightcurve data from Pravec et al. (2006) to model the shapes, sizes, and spin states of the components. The primary is top shaped and has an equatorial ridge similar to the one seen on 2000 DP107 (Naidu et al. 2015). A 300 m long flat region is also seen along the equator. The primary has an equivalent diameter of 780 m (+/- 10 %) and its extents along the principal axes are 826 m, 813 m, and 786 m (10% uncertainties). It has a spin period of 2.2600 +/- 0.0001 h. A grid search for the spin pole resulted in the best fit at ecliptic (longitude, latitude) = (296, +71) degrees (+/- 15 degrees). This estimate is consistent with the spin pole being aligned to the binary orbit normal at (310, -84) degrees. Dividing the primary mass of 5.24e11 kg (Fang Margot 2012) by the model volume we estimate a bulk density of 2100 kg m-3 (+/- 30 %). We summed multiple radar runs to estimate the range and Doppler extents of the satellite. We estimated the motion in successive images and used a shift-and-sum technique to mitigate smearing due to translational motion. This boosted the SNRs and allowed us to obtain size and bandwidth estimates of the satellite. The visible range extent of the satellite is roughly 60-75 m at the 15 m resolution of the Arecibo images. Assuming that the true extent is twice the visible extent, we obtain a diameter estimate of 120-150 m. The bandwidth of the satellite suggests a spin period between 9-12 h that is consistent with the orbit period of 11.9 hours and with synchronous rotation.

Detection of YORP spin-up for (101955) Bennu

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Spheroidal asteroids like the OSIRIS-REx target (101955) Bennu may form (or be formed from) binary systems through YORP spinup. On 17–18 September and 10–11 December 2012 we obtained HST photometry of Bennu in order to refine the rotation state and search for YORP effects. Nolan et al. (2013) determined the rotation rate based on lightcurve and radar observations in 1999 and 2005. The lightcurve data from four days in 2005 constrained absolute rotation rate to be 4.29764 ± 0.002 h. The radar and lightcurve data from 1999 additionally constrain the period to a comb of values spaced by 0.000352 h, which is one full rotation over the ~ 6 year interval. In sessions of 5 HST orbits each, we obtained nearly-complete lightcurves in September and December 2012. We then tested the relative lightcurve phases between the two session using each possible value of the comb, ± 26 rotations ($\pm 5\sigma$) The solutions with $+5$ and -20 rotations ($+1\sigma$ and -4σ) fit well. We reject the -4σ period as it visibly does not fit the 2005 data. The period of 4.296052 h has 5 additional full rotations between 1999 and 2005 compared to the original period reported by Nolan et al. (2013). Next we attempted to fit all three epochs, 1999, 2005, and 2012, with the same rotation period. Using a period that fits 1999 and 2005, the asteroid has rotated 15 degrees farther in 2012 than predicted. If we allow an angular acceleration, we can fit all of the data with a period of 4.296045 ± 0.000002 h on 2005 September 14 and an angular acceleration of $+2.5 \times 10^{-6}$deg/day^2, which we attribute to the YORP effect. We will be able to refine and confirm this detection of the YORP effect during the OSIRIS-REx encounter. Work is ongoing to re-fit the model using this period, and to refine the pole position, which is linked to the rotation rate when fitting the radar images, to confirm that there are no YORP-free solutions.

Dwarf Planet Binaries: The Discovery of a Satellite of Makemake

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The discovery of faint satellites of the Pluto/Charon binary (Weaver et al. 2006, Showalter et al. 2012) demonstrated that deep searches with HST are capable of finding faint satellites otherwise lost in the scattered light of the primary. We applied this technique to the two largest and most Pluto-like transneptunians, Eris and Makemake. Observations searched for faint satellites around both objects and can break the orbit-plane degeneracy of the orbit of Eris' known companion, Dysnomia. A new satellite orbiting the dwarf planet (136472) Makemake was found in HST images obtained on April 27, 2015 (Parker et al 2016). A co-moving companion, 7.80+/-0.04 magnitudes fainter than Makemake, was clearly detected 0.57 arcsec from the primary. The satellite was not detected in a second observation on April 29, 2015, nor in less-deep observations obtained in 2006, most likely because it was lost within the glare of Makemake. Makemake requires two different albedo components to fit the observed thermal emission spectrum (Stansberry et al. 2008, Lim et al. 2010). This observation, combined with the low-amplitude lightcurve, led to suggestions of a pole-on orientation. The discovery of the satellite suggests instead, that the dark material in the system is associated with the smaller companion with Makemake being primarily covered by higher albedo ice. The non-detections rule out a high-inclination configuration for the mutual orbit plane and favor nearly equator-on orientations. This orientation is consistent with the occultation-derived shape of Makemake (Ortiz et al. 2012). Makemake's non-spherical shape yields tidal circularization timescales at the observed separation that are short enough that the orbit could be circularized. If so, we can constrain the orbit to have P $>$12.4 days and a $>$21,000 km. With this discovery, all of the IAU-defined dwarf planets have known satellites, an observation that constrains the collisional evolution of the protoplanetary disk.

Determination and prediction of binary asteroid orbits

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Binaries are crucial to determine asteroid masses, hence densities. If reflectance spectra is available, we can investigate its bulk composition. This provides constraints on the processes that took part in the formation and evolution of these objects. Over the last few years, we have set up a suite of tools at IMCCE to mine large ground-based telescope archives for high-angular resolution images of binary asteroids. We identify the images, and reduce them with an in-house pipeline. Satellites astrometry and photometry are measured on images where flux from the primary has been self-substracted. If the primary is angularly resolved, we deconvolve the images and extract its 2-D profile on the plane of the sky. We determine orbits from the relative positions of the satellite with respect to the primary using our algorithm GENOID (GENetic Orbit IDentification, Vachier et al., 2012, A&A 543). We construct 3-D shape models from the profiles and optical lightcurves using KOALA algorithm (Carry et al. 2010, Icarus 205). Further, we use these orbits to predict stellar occultations by the satellites. We aim at preparing occultation campaigns for the satellites, which is the most fruitful technique to measure physical properties of very small bodies. We have now very precise orbital solution for a handful of systems, and growing. We will illustrate our work with (107) Camilla, whose satellite was discovered in March 2001 using the HST (Storrs et al., 2001). Previous orbit was obtained by Marchis et al. (2008, Icarus). We use a comprehensive data set of direct imaging from large telescopes: HST and telescopes with AO camera (VLT, Keck-II and Gemini). The orbit we determine fits 48 satellite positions taken over 14 years, with an RMS residual of only 8.6 mas, which corresponds to sub-pixel accuracy. Similarly, the 3-D shape we build fits all LC, and AO profiles to very good levels (0.03 mag and 0.30 pixel, resp.). Combining both provides a very precise density determination.

Constraining local slopes and failure stress from shape models of asteroid pairs

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Pairs of Asteroids had a single progenitor that split in the last $\sim 10^6$ years due to rotational-fission of a weak, 'rubble-pile' structured body. By constructing shape models of Asteroid Pairs from multiple-apparition observations conducted at the Wise Observatory in Israel (Polishook 2014) and by using the lightcurve inversion technique (Durech et al. 2010), we mapped the gravitational and rotational accelerations on the surfaces of these unique asteroids. This allows us to construct a map of topographic slopes on the asteroids' surfaces.
The local slope is defined to be the angle between the inwards surface normal and the local gravity vector including the centrifugal term. In order to test for frictional failure, for each asteroid in the set, we determine the maximum rotation rate at which an area larger than half the surface area of the secondary member (assumed to be the ejected component) has a slope value larger than 40 degrees, the angle of friction of lunar regolith (Mitchell et al. 1974), where a loose body will start sliding. We use this critical state to indicate the location of the failure on the surface of the primary member and to constrain the failure stress operating on the body just before disruption, using the Drucker–Prager failure criterion (Holsapple 2007).
Our current preliminary sample includes 7 primary members of asteroid pairs with diameter range of 3 to 10 km, and diameter ratio range (secondary/primary) of 0.1 to 0.6. Our spun-up models have wide enough areas with high slopes when they reach ~ 2.8 hours, suggesting they disintegrate at this spin, even though it is slower than the 'rubble pile spin barrier'. Assuming this rotation period in the failure criterion, we can place a lower limit on the cohesion for 3 asteroids in our sample, while the other 4 are consistent with a cohesionless body. We will further present the parameter space of our model and discuss its implications.

Asteroid clusters similar to asteroid pairs

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We study five small, tight and young clusters of asteroids. They are placed around following largest (primary) bodies: (11842) Kap'bos, (14627) Emilkowalski, (16598) 1992 YC2, (21509) Lucascavin and (39991) 1998 HR37. Each cluster has 2-4 secondaries that are tightly clustered around the primary body, with distance in the 5-dimensional space of mean orbital elements mostly within 10 m/s, and always < 23 m/s. Backward orbital integrations indicate that they formed between $\sim 10^5$ and $\sim 10^6$ yr ago. In the P_1-ΔH space, where P_1 is the primary's spin period and $\Delta H \equiv H_{\mathrm{seceq}} - H_1$ is difference between the equivalent total secondary absolute magnitude and the primary's absolute magnitude, the clusters lie in the same range as asteroids pairs formed by rotational fission. We find these tight clusters to be similar to asteroid pairs and we suggest they are "extended pairs", having 2-4 escaped secondaries rather than just one secondary as in the case of an asteroid pair. We compare them to six young mini-families (1270) Datura, (2384) Schulhof, (3152) Jones, (6825) Irvine, (10321) Rampo and (20674) 1999 VT1. These mini-families have similar ages, but they have a higher number of members and they show a significantly larger spread in the mean orbital elements (d_{mean} on an order of tens m/s) than the five tight clusters. In the P_1-ΔH space, all but one of the mini-families lie in the same range as asteroid pairs and the tight clusters; the exception is the mini-family of (3152) Jones which appears to be a collisional family. A possibility that the other five mini-families were also formed by rotational fission as we suggest for the tight clusters ("extended asteroid pairs") will be explored.

Evolution of Asteroid Binaries under the BYORP effect

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In recent years there has been an effort to understand the process of creating binary asteroids & contact binaries. Our research specifically focuses on understanding the evolutionary mechanisms for synchronous binaries, including conditions under which they may evolve into a contact binary state. The model of this system includes 3rd body perturbations, J2, & BYORP. If the secondary is asymmetrical in shape & the body's rotation is synchronous with its orbit, the secondary will experience the BYORP effect. BYORP can cause secular motion such as the semi-major axis of the secondary expanding or contracting. For this work, we will assume that BYORP causes the binary to expand & the secondary will begin near the primary at the equator. As the system expands the influence of the sun can either cause an evection resonance or the system can follow the Laplace plane. Depending on the obliquity of the primary, the secondary will have different outcomes. If the primary has an obliquity of 75° or below, the secondary will go through the evection resonance. The evection resonance occurs when the longitude of periapsis on the secondary's orbit is equal to the mean motion of the Sun. This resonance causes a secular increase in eccentricity. If the primary has an obliquity above 105°, the secondary will not experience the evection resonance. However between 75° & 105° the secondary may be captured in the evection resonance, the Laplace plane instability or pass through both regions. The Laplace plane is a plane normal to the axis about which the pole of a satellite's orbit precesses, causing a near constant inclination for such an orbit. The Laplace plane has an instability region where the eccentricity of the orbit can increase greatly. Our research will help understand & characterize when the evection resonance or Laplace plane will dominate evolution depending on the obliquity of the primary & the eccentricity of the binary's orbit.

Shape and spin-state modelling of the NEA (85990) 1999 JV_6 from radar and optical observations

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The asteroid (85990) 1999 JV_6 is an object of the Apollo group, classified as spectral type Xk [1] with an estimated diameter of 498^{+134}_{-88} m [2]. Here we present results from an observational campaign conducted at optical and radar wavelengths in order to constrain the shape and spin state of this asteroid.

We obtained optical photometric measurements in 2007, 2008, and 2016 with the 2.5 m Isaac Newton Telescope in La Palma (Spain), in January 2015 with JPL's Table Mountain Observatory 0.6 m telescope (USA), and in February 2013 with the ESO 3.6 m New Technology Telescope at La Silla (Chile). We also include published lightcurves from 2014 and 2015 [3, 4], available via the MPC.

We obtained radar echo power spectra and delay-Doppler images with a ranging resolution of 30 m/pixel at the Arecibo 305 m radio telescope in January 2015 and at resolutions as fine as 7.5 m/pixel at Arecibo, Goldstone 70 m, and Green Bank 100 m telescopes in January 2016. The echoes revealed a pronounced bi-lobed shape.

We used the convex lightcurve inversion method to constrain the rotation pole orientation. This approach indicates an ecliptic latitude of the pole below -40°. By combining the radar and lightcurve data we were able to produce several possible solutions for the spin state and corresponding shape. The dimensions of all models are similar, with a contact-binary configuration. The object has a sidereal rotation period of 6.53679±0.00006 h, and maximum extents along principal axes of the best-fit model are 700 m, 360 m and 330 m.

References:
[1] Binzel et al, 2001, Icarus 151, 139
[2] Mueller et al., 2011, Astron. J. 141, 109
[3] Warner 2014, MPBu 41, 157
[4] Warner 2015, MPBu 42, 172

Rigorous Constraints on the Formation of Disrupted Asteroid Systems

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A past success of the asteroid fission model was the identification of asteroid pairs that followed the same mass cutoff limit and increased spin periods predicted from a simple binary model of asteroid fission. However, more recent observations have shown that there are some asteroid pairs that violate the limits from this model, in addition detailed observations of some asteroid pair systems show that their larger members are in fact multiple component systems. These observations indicate that the simple physics of the binary fission model may need to be generalized to more complex systems which have several components and bodies at play, as is appropriate for models of asteroids as rubble piles. In this talk I will describe research progress on the generalization of the previously developed asteroid pair fission model to accommodate multiple body systems. For multi-component systems it is possible to develop strong constraints on these systems for when fission can lead to the escape of one or several components. The goal of this work is to develop updated diagnostic tests for asteroid pair systems that could help sort through the possible formation circumstances for these systems, ultimately exposing the underlying physics of asteroid fission.

Long-term evolution and orbital poles of binary NEAs and small MBAs

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I present two recent results based on photometric observations of near-Earth and small main-belt binary asteroids.
An evolution of binary system depends heavily on the BYORP effect. If BYORP is contractive, the primary and secondary could end up in a tidal-BYORP equilibrium. Observations of mutual events between binary components in at least four apparitions are needed for BYORP to be revealed by detecting a quadratic drift in the mean anomaly of the satellite.
I will show the observational evidence of two single-synchronous binary asteroids with tidally locked satellite (175706 1996 FG3 and 385186 1994 AW1), i.e, with the quadratic drift equal to zero, and one with contracting orbit (88710 2001 SL9), with a positive value of the quadratic drift (the solution for the quadratic drift is ambiguous, with possible values of +2.9 and +5.1 deg/yr^2).
The observed characteristics of asteroid systems suggest their formation by rotational fission of parent rubble-pile asteroids after being spun up by the YORP effect. The orientations of satellite orbits of observed binary systems are non-random; the orbital poles concentrate near the obliquities of 0 and 180 degrees, i.e., near the YORP asymptotic states.
Recently, a significant excess of retrograde satellite orbits was detected among both near-Earth and small main-belt binaries, which is not yet explained characteristic. Of 25 small MB binaries with unambiguously determined satellite orbits, 7 are prograde and 18 are retrograde. Similar fraction is observed among NEA and Mars-crossing binaries: of 10 systems with unambiguous orbits, 3 are prograde and 7 are retrograde.

The modulated Kozai-Lidov cycles in the binary's dynamics

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We consider the binary consisting of a massive primary and less massive secondary. The influence of the Sun as outer perturber can result in coupled changes in eccentricity and inclination of the secondary's orbit with respect to the primary (Perets and Naoz, 2009; Fang and Margot, 2012). While wide and ultra-wide binaries demonstrate classical Kozai-Lidov oscillations (Grundy et al., 2011), for more compact binaries the income of the quadruple and higher order terms in the gravitational field of the primary becomes essential. We investigate the possible modulation of Kozai-Lidov oscillations due to the primary's oblateness. A special attention is given to the resonance effects. References: Fang, J., Margot, J.-L. 2012, AJ, 143:59; Grundy, W.M., Noll, K.S., Nimmo, F., et al. 2011, Icarus, 213, 678; Perets, H.B., Naoz, S. 2009, ApJ, 699, L17

Binary Candidates in the Jovian Trojan and Hilda Populations

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Determining the binary fraction for a population of asteroids, particularly as a function of separation between the two components, helps describe the dynamical environment at the time the binaries formed. For asteroids with near-fluid rubble pile structures, very large light curve amplitudes can be explained by close or contact binary systems. Because the structure of most asteroids is not known to a high confidence level, objects with very high light curve amplitudes can only be considered candidate binaries. In Sonnett et al. (2015), we identified several binary candidates in the Jovian Trojan and Hilda populations using archival data from the NEOWISE space mission. We have since been conducting an extensive follow-up campaign to obtain densely sampled light curves of the binary candidates to allow detailed shape and binary modeling, helping discern whether or not these candidates are true binaries.

1994 CJ_1: The Smallest Binary Asteroid?

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Arecibo radar observations of asteroid 1994 CJ1 in late June/early July 2014 revealed two roughly equal-size bodies in mutual orbit. This is only the second such system identified in the near-Earth region following (69230) Hermes. The components of the 1994 CJ1 binary are, however, several times smaller than the components of the Hermes binary. At less than 150 meters in diameter, the components of 1994 CJ1 are comparable to the smallest primaries known. The maximum range separation of the components is at least 525 meters, implying a mutual orbit at least 7 primary radii wide, twice as wide as the (scaled) Hermes system, as well as a supercritical amount of angular momentum. Optical observations include a partial mutual event. Constraints on the physical parameters of the system will be presented along with comparisons to other known binary asteroid systems.

Some (Apparently) Very Wide Binary Asteroids

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We present lightcurves for 10 asteroids that appear to be the result of very widely-separated binaries. Jacobsen et al. (2014, ApJ 780) attribute the formation of such systems to a somewhat complex series of events that involves BYORP. The lightcurves consist of two components: Period 1 (P1) is very long, P1 = 50-624 h, with moderate to large amplitudes, A1 = 0.23-1.0 mag. The second periods and amplitudes (P2 and A1) are mostly similar to the primaries of close binary systems, i.e., P2 = 2.2-3.6 h, $A < 0.1$ mag. Two of the objects have secondary periods in the range of 5-7 hours. The most exceptional example is (19204) Joshuatree, which has values of P1 = 480 h, A1 = 0.25 mag and P2 = 21.25 h and 0.08 mag. Given the lack of mutual events, these can be considered to be only possible binaries. Since the orbital period is probably very long, it seems extremely unlikely that mutual events will ever be seen. Based on works by Jacobson et al. (2014, ApJ 780) and Pravec et al. (2016, Icarus 267), we suggest that P1 represents the primary (larger) body of the system and P2 represents the spin rate of the satellite. Another reason to accept this supposition is that the large amplitude (A1) has to be from the larger body, otherwise the dilution of amplitude would require the smaller body to be unreasonably elongate. The limiting size ratio for binaries is around 0.6 (see Pravec et al. 2010, Nature 466, Fig. 1), or a magnitude difference of about 1.0. For a secondary 1.0 mag fainter than the primary to produce a combined lightcurve amplitude of 0.4 mag would require that the secondary undiluted amplitude to be several magnitudes (near-infinite elongation) and also a near equatorial aspect. This is not likely.