The Hayabusa Re-entry and Recovery Operation

Paul A. Abell (Planetary Science Institute, NASA Johnson Space Center, USA)

The Hayabusa spacecraft returned to Earth on June 13, 2010 after a multi-billion km journey to and from asteroid (25143) Itokawa. The sample return capsule was recovered in the Outback of South Australia and hopefully contains the first material directly returned from the surface of an asteroid.

New NASA Initiatives for the Exploration of NEOs

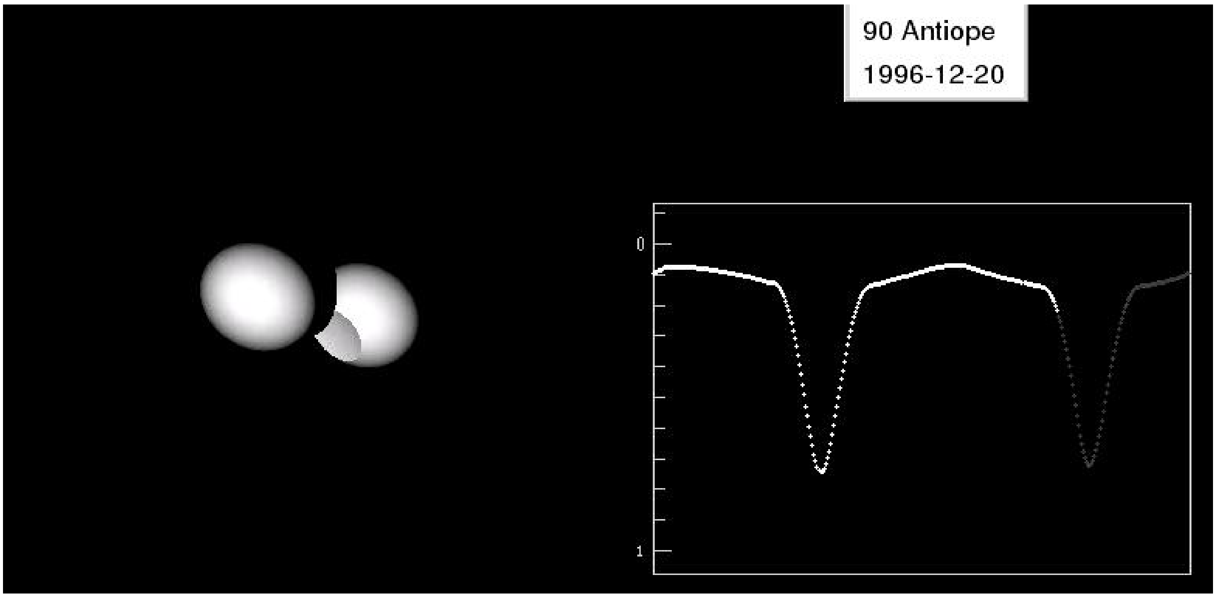
Paul A. Abell (Planetary Science Institute, NASA Johnson Space Center, USA)

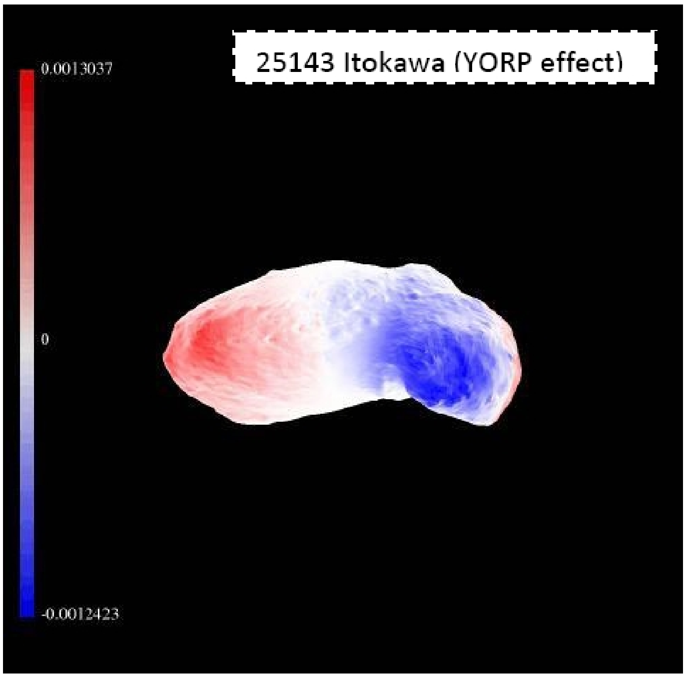
On April 15, President Obama stated that NASA's next human mission to deep space would involve sending astronauts to an asteroid by the year 2025. In response to this statement there are several new initiatives under consideration within NASA for future robotic and human exploration of NEOs.

Modeling of Double Asteroids with PIKAIA Algorithm

Przemysław Bartczak
(Astronomical Observatory, A. Mickiewicz University, Poznań, Poland)

The modeling parameters of binary systems base on brightness variation of asteroids. Minimal difference between real and simulated asteroid lightcurve is found by genetic algorithm PIKAIA. The simulated lightcurve is implemented using methods for computer graphics (Ray tracing, z-buffer). The application consists of dynamical and kinematic part and YORP module. The method is used to determine parameters of synchronous asteroids: 90 Antiope, 4492 Debussy, 809 Lundia and calculated YORP effect for 25143 Itokawa, 1998KY26, 6489 Golevka. All calculations are performed by the computer cluster.





Multi-opposition Spectroscopy of Binary Asteroid 809 Lundia

Mirel Birlan (IMCCE, Paris Observatory, France), Agnieszka Kryszczyńska (Astronomical Observatory, A. Mickiewicz University, Poznań, Poland), Francois Colas (IMCCE, Paris Observatory, France)

Florczak et al. (2002) basing on spectroscopic observations in the spectral region of the visible wavelenght classified 809 Lundia as V type asteroid. Carruba et al. (2005) argued the attachment of 809 Lundia to the Vesta family, as the Yarkovsky effect and the secular resonances could explain the drift of the orbital elements. Photometric observations of this asteroid allowed (Kryszczynska et al. 2009) to detect that 809 Lundia is a binary system.

Near VIR spectroscopic observations, performed with SpeX/IRTF (Hawaii), were obtained for this asteroid at three oppositions in 2005, 2007, and 2010. The observations were done in December 21 and 22, 2005 to investigate a possible variation of the surface among the components of this double asteroid. We obtained two spectra in the 0.8-2.5 μm spectral region in two specific geometries, during a mutual phenomenon. The results show spectra typical of V-type asteroids. Moreover, we observe a clear spectral variation, and the differences between the spectra are over the error-bars. This result is consistent with a small variation of the surface composition and/or grain distribution between the components of binary system. The observations done in 2007 and 2010 show spectra identical to the one from December 22, 2005. In these cases, the spectra were obtained outside mutual events. The lightcurves obtained during 2007 and 2010 oppositions exhibit small amplitudes. We will present the spectral data of Lundia and their interpretations in terms of mineralogy of the surfaces.

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Radar Images and Shape Model of a Triple Asteroid (136617) 1994CC

M. Brozovic [1], L.A.M. Benner [1], M.C. Nolan [2], E.S. Howell [2], C. Magri [3], J. D. Giorgini [4], P. A. Taylor [2], J. L. Margot [4], M. W. Busch [5], M. K. Shepard [6], D.J. Scheeres [7], L. M. Carter [8]

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[8]Smithsonian Institution

We report radar observations and shape modeling of asteroid (136617) 1994CC, which is only the second triple system known in the near-Earth population, after (153591) 2001 SN263. This object was observed at Goldstone (8560 MHz, 3.5 cm) and Arecibo (2380 MHz, 12.6 cm) from June 12 to June 21, 2009. The radar images and subsequent shape modeling reveal that the primary is ~600 m in diameter with a shape that closely resembles that of 1999 KW4 Alpha. The secondary is ~130 m in diameter and appears to be in a synchronous orbit with a period of ~30 hours. The tertiary satellite is ~90 m in diameter and has an orbital period of ~9 days. Its semimajor axis of ~20 primary radii is the largest discovered so far among near-Earth multiple systems. Among the 37 NEA binary or ternary systems currently known, ~80% have been observed by radar and 2/3 were discovered by radar. Since January 1999, 17% of radar-detected NEAs with diameters greater than 200 m have been found to be multiple systems.

Double Asteroids as Equilibrium Shapes of Rotating Gravitational Aggregates

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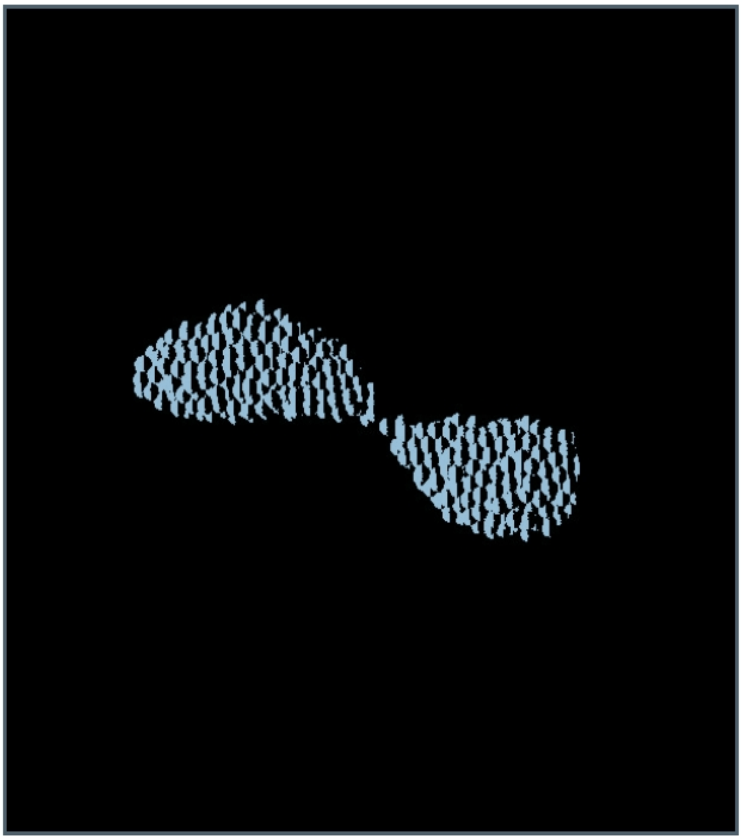
Derek C. Richardson (Department of Astronomy, University of Maryland, USA)

Many asteroids are believed to be "rubble piles", gravitational aggregates with no relevant internal cohesion.Yet, they apparently behave very differently to the classic self-gravitating bodies of the idrostatic equilibrium theory, since the clustering of the observed shapes near the MacLaurin or Yacobi sequences of ellipsoids is not observed. Notable exceptions are many double asteroids, which apparently are more prone to fall near the equilibrium for fluid, rotating bodies.

As we showed in a recent work, the shape distribution of asteroids can be reproduced by the equilibrium states into which a set of self-gravitating aggregates will eventually settle if left free to evolve from arbitrary initial shapes, provided that a small internal resistence to deformation is accounted for. We have tried to apply this principle in mass-shedding conditions, i.e. when aggregates are spun up beyond the mass losing threshold. We will discuss the results thus obtained on the generation of binary asteroids and on the shapes of the components. Such shapes have been compared both to those of single asteroids and of observed binaries.



a gravitational aggregate splitting by centrifugal force

Improved Asteroid Density Estimates: New methods for determining shape by combining AO, light-curve, and occultation data

A. R. Conrad, W. J. Merline, B. Carry, J. D. Drummond, M. Kaasalainen, R. Chapman, H. A. Weaver, P. M. Tamblyn, J. C. Christou

We will present background on the importance of having accurate density to support conjectures as to an asteroid's structure and composition; and a brief history of the circumstances and motivation that lead to our development of KOALA (Knitted Occultation, Adaptive-Optics, and Light-Curve Analysis) as a system for determining shape from ground-based observations. We use KOALA to better determine volume and, in cases where mass is well known, for example when a satellite is present, to better determine density. We then report on our specific application of KOALA to three observed asteroids: (41) Daphne, (2) Pallas, and (21) Lutetia; and on our future plans for KOALA.

Orbital Evolution of Small Binary Asteroids

Matija Ćuk (Harvard-Smithsonian Center for Astrophysics)

I will discuss our recent theoretical work on the orbital evolution of small (D<10km) binary asteroids under BYORP (Ćuk and Nesvorný, 2010). Our 2-D model assumes an oblate primary and a near-synchronous triaxial secondary. We find a number of new effects in our simulations, including large secular perturbations from secondary's librations and a possibility of chaotic rotation. We conclude that most small binaries should not dissociate, and are expected to eventually merge. I will compare our findings with the latest data on heliocentric pairs. Results of Pravec et al. on the properties of the two populations imply that the two populations are formed by YORP through two distinct mechanisms, and that the heliocentric pairs do not derive from binaries.

Comparing the Properties of Observed Main-belt Asteroid Binaries and Modeled Binaries from Numerical Simulations

Daniel D. Durda (SwRI), Brian L. Enke (SwRI),
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William J. Merline (SwRI),
Derek C. Richardson (University of Maryland),
Erik Asphaug (UC Santa Cruz),
William F. Bottke, Jr. (SwRI)

The recent discovery of a new main-belt binary asteroid system (317 Roxane; Merline et al. 2009, IAU Circular No. 9099) with widely separated and similar size, low-mass components adds to the number of known systems that match the characteristics of the so-called Escaping Ejecta Binaries (EEBs) produced in numerical models of asteroid satellite formation due to impacts (Durda et al. 2004, Icarus 170, 243-257). The range of parameters of the modeled systems can be compared with observed asteroid pairs to provide clues to better understand the details of origin and evolution of these systems.

We have modeled hundreds of impacts to examine the dependence of the rate of satellite formation and the properties of the resulting satellite systems on the parameters of the impacts (e.g., impactor-to-target mass ratios, impact speeds, impact angles). From any single impact event as many as thousands of EEB systems can be formed.

We will present and examine the range of EEB system properties resulting from several collision simulations and compare mutual orbital and system component properties with observed main-belt binary systems.

Behavior of Primary Ejecta Due to Impact or Blast within Small Binary Asteroid Systems

Eugene G. Fahnestock (Jet Propulsion Laboratory, California Institute of Technology)

I present a detailed study of the behavior of ejecta liberated by energetic events from near equatorial locations on the surface of the primary of a small binary near-Earth asteroid (NEA). While a particular system (65803 Didymos) is adopted for specificity, to provide inputs for the modelling, the general qualitative results of this study also apply to any other system in the class of binary NEAs similar to the well-studied 1999 KW4 system. A key feature of such systems is proximity of the primary spin rate to the surface disruption spin rate, implying nearly zero net acceleration felt by material at equatorial points on the primary surface. This not only makes possible surface material motion through interaction with the secondary and continued YORP spin up, as previously studied in (Fahnestock and Scheeres, 2009, Icarus, 201:135-152) and (Harris, Fahnestock, and Pravec, 2009, Icarus, 199:310-318). It also means the equatorial region is the most interesting location known, across all small solar system body surfaces, from which ejecta can be liberated and at which a crater can be formed: crater excavation there take places within an $\mathcal{O}(10^{-6})$ -g acceleration environment.

I focus on human-initiated energetic events constrained to these locations of greatest interest, of the explosive package detonation type rather than the kinetic impactor type. Such an experiment is being considered for a scientific investigation of μ-g cratering processes, primary internal structure, etc., as part of a general rendezvous characterization of such a binary. I seek to use the most rigorous (yet reasonable) models available for the system itself and for the physics involved, combining existing numerical tools and new modelling tools to characterize the expected ejecta behavior. I also quantify various implications of the ejecta behavior for design of such a mission's proximity operations and observations planning, defining appropriate constraints thereupon.

The best values derived so far from radar and photometric observations for properties of the Didymos binary NEA system are used. Two equally probable concurrent solutions for the primary's spin pole and its shape model are available, one more favorable for the considered mission. For each system model, I first propagate the full-two-body-problem (F2BP) dynamics of the binary itself, then propagate large numbers of ejecta particles on top of the F2BP output in a barycentric "inertial" frame, subject to all relevant accelerations. These include full-detail binary gravity and differential solar gravity and SRP, with shadowing. I use a realistic ejecta particle size distribution, and employ a realistic model of the crater excavation physics to determine the initial conditions of ejecta particles, in time. Results are obtained for several distinct simulation cases, half for each system orientation and primary shape model solution, spanning different sun to primary centroid to blast location angles at the blast instant. Several interesting visualizations of the results are made (e.g. animations in 3D and parameter space, time history of particles reaching their outcomes, surface spatial distributions of re-impacting ejecta, etc.).

Acknowledgements

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Highly Elongated Models of Asteroids Derived by Lightcurve Inversion Method: Possible Candidates for Close Binaries

Josef Hanuš (Astronomical Institute of Charles University, Prague),
Josef Ďurech (Astronomical Institute of Charles University, Prague)

The lightcurve inversion method (LI) is a powerful tool that allows us to derive basic physical properties of asteroids (the rotational state and convex shape) from their disk-integrated photometry. In the past decade, more than one hundred asteroid models were derived using the lightcurve inversion method. Measured by the number of derived models, LI has become the leading method for asteroids shape determination.

Kaasalainen & Torppa (2001) showed, that convex models of non-convex bodies are very similar to their convex hulls. It is also possible to derive a unique shape model of an asteroid which has signicant non-convex features. Even close binary system can be successfully modeled as a single body, however this approach leads in this case to a completely wrong and weird shape, although the t of lightcurves is good. The shape result is similar to an elongated convex ”brick” (Ďurech & Kaasalainen 2003).

We gathered dense photometry for ∼ 1000 asteroids, used it together with sparse data from several astrometric observatories for LI and derived ∼ 100 new asteroid models. We found in this sample several asteroids with highly elongated "brick-like" shapes. These object are possible candidates for close binaries. We present a short list of these asteroids and their convex shape models.

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Solar System binaries with the VLT and Gaia

Daniel Hestroffer (IMCCE, Observatoire de Paris, France)

I will present ongoing observations of transneptunian binaries and other systems with the ESO/VLT and discuss the astrometric possibilities given by the Gaia satellite.

Characterization of Binary Near-Earth Asteroid 2000 CO101

Ellen S. Howell (Arecibo Obs.), Nicholas Jimenez (Alfred College), Michael C. Nolan (Arecibo Obs.), Patrick Taylor (Arecibo Obs.), Lance A. M. Benner (JPL), Marina Brozovic (JPL), Jon Giorgini (JPL), Ronald Vervack Jr. (JHU/APL), Yan Fernandez (UCF), Michael Mueller (Obs. Nice)

We observed the near-Earth binary system 2000 CO101 with radar in September 2009 from Goldstone Observatory and Arecibo Observatory. We also obtained near-infrared spectra from the IRTF using SpeX. Asteroid 2000 CO101 was discovered to be a binary system from Arecibo images taken on September 26, 2009 (Taylor et al. 2008). However, the orbit is not well determined due to only lower resolution images on subsequent days. Shape modeling of the primary of this system will constrain the size of the asteroid, its spin rate and orientation.

The near-infrared spectrum of asteroid 2000 CO101 was measured on Sept 21, 2009 and March 13, 2010. The 0.8-2.5 micron spectrum was measured on both dates, and shows a featureless, red-sloped spectrum. On Sept 21 we also measured the thermal emission between 2-4.0 microns to determine the albedo and thermal properties. Both standard therma modals and thermophysical models have been applied to these data. The albedo we derive from the thermal modeling must also be consistent with the radar size. Preliminary results of the characterization of this unusual NEA binary system will be presented.

Dynamical Evolution of Binary Asteroid Systems

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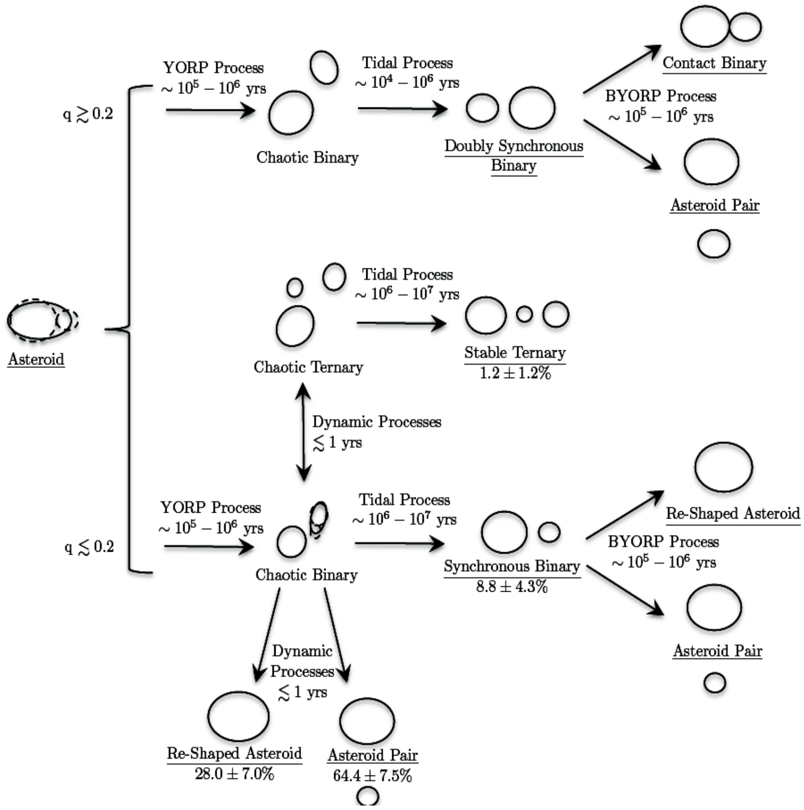
We present a model of near-Earth asteroid (NEA) rotational fission that results in the evolution of all NEA systems. The model draws from the YORP and binary YORP effects, "rubble pile" asteroid geophysics, and mutual gravitational interactions. These systems include synchronous binaries, asteroid pairs, doubly synchronous binaries, high-*e* binaries, ternary systems, and contact binaries. The YORP effect torques a "rubble pile" asteroid until the asteroid reaches its disruption spin limit. The system dynamically evolves under the effects of nonspherical gravitational potentials, solar gravitational perturbations, and mutual body tides. The coupling between the spin states and orbit state chaotically drives the system into the observed asteroid classes with mass ratio *q* distinguishing two evolutionary tracks as shown in the figure. Arrows in the figure indicate the direction of evolution along with the process propelling the evolution and a typical timescale. Simple schematics show evolutionary states, an underline indicates an observed NEA class, and the proportions are given for the various low mass evolutionary outcomes. We propose that a new binary process termed secondary fission results in the smaller body being rotationally accelerated via gravitational torques until it fissions, creating a chaotic ternary system. This process coupled with material impacting the primary stabilizes the initially chaotic binaries to create synchronous binaries. It is important to note that the eventual outcomes are single asteroids (re-shaped asteroids, contact binaries, each member of asteroid pairs), so this evolutionary process represents a lifecycle. These results emphasize the importance of the initial component size distribution and configuration within the parent body and imply that NEAs may go through multiple rotational fission life cycles before being ejected from the inner solar system. Rotational fission and the ensuing dynamics are responsible for all NEA systems including the most commonly observed synchronous binaries.



Photometry of Binary Astroid 8373 Stephengould

Yu.N. Krugly [1], P. Pravec [2], R. Behrend [3], K. Hornoch [2], P. Kušnirák [2], A. Galád [4], P. Vereš [4], R. Crippa [5], F. Manzini [6], M. Audejean [7], L. Bernasconi [8], N.M. Gaftonyuk [9], B. D. Warner [10], I.E. Molotov [11], L. Elenin [11], R.Y. Inasaridze [12]

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[8] Les Engarouines, France;
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[11] Keldysh Institute of Applied Mathematics, Moscow,
[12] Abastumani Observatory, Georgia

Binary asteroids appear ubiquitous, they were found in many zones of the solar system. We present the discovery of a binary asteroid in the small group in the Hecuba gap with high-inclination orbit laying in the Jupiter 2:1 mean-motion resonance and with dynamical lifetime about 10 Myr (Mon. Not. R. Astron. Soc. 335, 417 (2002)). The discovery was a result of collaboration of three groups of photometric observers.

The photometric observations of asteroid (8373) Stephengould obtained during 2010 Jan. 16 - Feb. 6 revealed that it is a binary system with an orbital period of 34.15 +/- 0.1 hr. The primary showed a period of 4.4345 hr with a lightcurve amplitude of 0.33 to 0.39 mag. Earlier observations in this apparition taken on 2009 Nov. 30 and Dec. 22 showed a lower primary amplitude of 0.18 and 0.28 mag, respectively; the amplitude changes were likely caused by changes of the illumination and viewing aspect of the minor planet. Mutual eclipse/occultation events observed during Jan. 17 - Feb. 1 indicate a lower limit on the secondary-to-primary mean-diameter ratio of 0.27. The events were more shallow on Feb. 4 and 6; a possible cause is that the system was moving away from the eclipse geometry. Later observations taken during 2010 March-June did not show obvious events while observed small changes of lightcurve shape could be caused by aspect changes. Measured color indices in the Johnson-Cousins system are: B-R = 1.20 +/- 0.043, V-R = 0.435 +/- 0.041, R-I = 0.43 +/- 0.045. The calibrated data of Jan. 17 gave the mean absolute magnitude H_R = 14.2 +0.3/-0.4, assuming G = 0.2 +/- 0.2. Re-examination of 2004 observations by Warner (Minor Planet Bull. 31, 67) showed what appears to be an event that was overlooked in the original analysis. Since only one event was captured (2004 Jan. 9), it was not possible to determine the orbital period from the 2004 data. Images of some nights were co-added for up to 15 kiloseconds equivalent exposures (with 0.6-m class telescopes); there was seen no sign of cometary activity for this object.

Rotational Period Determination Techniques for Sparse, Low S/N, and Unevenly Sampled Data

Nate B Lust, Daniel T Britt (University of Central Florida)

Accurately determining asteroid periods from lightcurves is critical in a range of investigations including shape determination, rotation rates, and the determination of mass in multiple systems. Period determination is commonly done with Fourier transforms of one form or another. While these do work quite well in some instances, they can be increasingly problematic problematic in cases of low signal-to-noise data or low sampling rates. To this end we have been exploring alternative methods of period determination using well-proven statistical methods that have been used for period determination in other fields. These methods of period determination are explored for both synthetic and real data sets comparing the results with the published values.These techinques can give us a wider range of tools to extract additional information from noisy or poorly sampled lightcurves.

Recent Observations of Binary and Multiple Systems

J. L. Margot (University of California, Los Angeles)

I will summarize results from recent observations of binary and multiple systems in near-Earth asteroids (NEAs), main belt asteroids (MBAs), and trans-Neptunian objects (TNOs).

NEAs: Our efforts currently focus on studies of 2000 DP107 [Margot et al., 2002], 1991 VH [Margot et al., 2008], and 1994 CC [Brozovic et al., 2009], all high-quality data sets with the potential for 1999 KW4-class characterizations. We characterized the orbit of 2000 DP107 in 2000, and we observed this system again in 2008, at much higher SNR, with the explicit goal of studying orbital evolution in a spin-locked system. This data set promises a decisive test of radiative (BYORP) influences on the orbital evolution of binary NEAs. 1991 VH has an eccentric mutual orbit, and exhibits 2, and sometimes 3, periods in lightcurves [Pravec et al., 2006]. Because even moderately asymmetrical secondaries in an eccentric orbit cannot sustain synchronous or regular rotation [Wisdom et al., 1984, Margot et al., 2008, Ćuk and Nesvorný , 2010], we are attempting to quantify irregular rotation of the secondary. Brozovic et al. [2009] have shown that 1994 CC is a triple system. We are extending our orbital fitting software to perform full N-body characterizations that offer the prospect of studying dynamical interactions in detail and extracting masses for all components.

MBAs: Rojo and Margot [2007] reported the discovery of a satellite to (702) Alauda from adaptive-optics imaging with the 8-m Very Large Telescope (VLT) on Cerro Paranal, Chile. This is the first satellite discovered to a large minor planet of type B in the SMASSII taxonomy. Because mass and density estimates of B-type (2) Pallas vary by 50%, our measurements offer the prospects of improved density constraints for this asteroid type.

TNOs: In 2005, we presented strong indications that 1999 TC36 is a hierarchical triple system [Margot et al., 2005], based on point-spread-function fits and orbital fits. This was followed by an independent argument, based on our mass measurement and a Spitzer size determination, that the system might be a triple [Stansberry et al., 2006]. We performed more work on the triple nature of this system [Jacobson and Margot, 2007] and additional observations confirm our suggestion [Benecchi et al., 2010]. However an N-body analysis remains to be done to fully characterize the system, ideally in conjunction with additional lightcurve and imaging observations.

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A Detailed Model for BYORP

Jay McMahon (University of Colorado)
Daniel Scheeres (University of Colorado)

We present an accurate secular theory of the effects of Binary YORP (BYORP) and discuss its implications. The theory represents the solar radiation pressure force, which is responsible for the BYORP effect, as a Fourier series based on the physical properties of the secondary body in a binary asteroid system. The theory averages over the binary orbit and over the heliocentric orbit separately. Averaging over the circulation of the node (due to J2 and perturbations from the Sun) can also be averaged separately.

The theory predicts that the orbit expansion rate is independent of the asteroid's thermal inertia for a near circular orbit, although the evolution of the angular momentum and eccentricity vectors do depend on the thermal inertia. This is similar to the results found for YORP where the spin rate evolution is independent of thermal inertia, but the spin axis orientation evolution is not.

The predicted secular rates from the theory can be used to make long term predictions of a binary asteroid system's complete orbital evolution. We have applied the theory to the binary asteroid 1999 KW4 for which we have accurate models of the secondary body. These results are scaled to apply to other binary systems, the results showing that, if expanding, the orbits will grow to the Hill radius in 104 - 106 years.

The effects of having a librating secondary have also been considered. Basically, a librating secondary body will slow the orbit expansion. It is shown that if the present libration amplitude is sufficiently small, BYORP induced expansion will grow the orbit to the Hill radius before the secondary libration becomes circulation. Implication of these results for the long-term evolution of the general binary population is to be discussed.

Lightcurves and Model of the Binary Asteroid 90 Antiope

T. Michałowski, P. Bartczak
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90 Antiope was observed during 8 oppositions. In some of them (1996, 2001/2002, 2002/2003, 2005, 2007/2008) brightness variations showed two-component lightcurves with the same period. It is characteristic for synchronous binary asteroids. The first component is associated with the rotation of two non-spherical bodies (rotational lightcurve), the second one, showing two sharp minima is due to mutual eclipse/occultation events in the binary system (eclipsing lightcurve). However, during the 2000, 2004, and 2006) Antiope showed only rotational lightcurves and no eclipses were visible. Observational data from all oppositions have allowed us to construct a model of this binary asteroid. This model will be presented and the calculated lightcurves will be compared with the observational ones.

Eclipsing Binary Trojan Patroclus: Thermal Inertia from Spitzer Observations

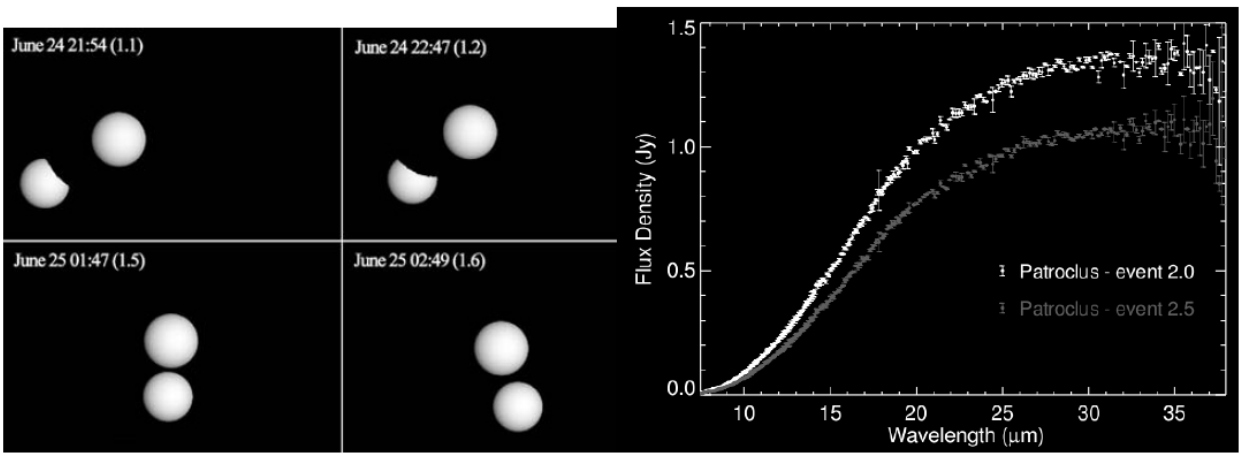
Michael "Migo" Mueller (OCA Nice), Franck Marchis (SETI), Joshua P. Emery (U Tennessee), Alan W. Harris (DLR Berlin), Stefano Mottola (DLR Berlin), Daniel Hestroffer (IMCCE), Jérome Berthier (IMCCE), Mario di Martino (INAF)

As is well established from observations of planetary satellites, thermal observations of eclipse events allow a uniquely direct determination of the thermal inertia from measurements of temperature change in real time. Thermal inertia is a sensitive indicator for the presence or absence of surface regolith.
We report the first thermal observations of an eclipsing asteroid, the binary L5-Trojan system (617) Patroclus–Menoetius. We obtained mid-infrared (8—33 μm) observations of Patroclus before, during, and after two shadowing events, using the Infrared Spectrograph (IRS) onboard the Spitzer Space Telescope. A new detailed thermophysical model for eclipsing binaries is presented.

We obtain two local thermal-inertia values, representative of the respective shadowed areas: 21 ± 14 J $s^{-1/2}$ K^{-1} m^{-2} and 6.4 ± 1.6 J $s^{-1/2}$ K^{-1} m^{-2}. The average thermal inertia is estimated to be 20 ± 15 J $s^{-1/2}$ K^{-1} m^{-2}, potentially with significant surface heterogeneity. This first thermal-inertia measurement for a Trojan asteroid indicates a surface covered in fine regolith. Independently, we establish the presence of fine-grained (<a few μm) silicates on the surface, based on emissivity features near 10 and 20 μm similar to those previously found on other Trojans.

The diameters of Patroclus and Menoetius are 106 ± 11 and 98 ± 10 km, respectively, in agreement with previous findings. Taken together with the system's known total mass, this implies a bulk mass density of 1.08 ± 0.33 g cm^{-3}, significantly below the mass density of L4-Trojan asteroid (624) Hektor and suggesting a bulk composition dominated by water ice.

All known physical properties of Patroclus, arguably the best studied Trojan asteroid, are consistent with those expected in icy objects with devolatilized surface (extinct comets), consistent with what might be implied by recent dynamical modeling in the framework of the Nice Model.



Final Spitzer Results for TNO Binaries

*Michael "Migo" Mueller (OCA Nice), John Stansberry (U Arizona),
Will Grundy (LowellObservatory), John Spencer (SWRI), Keith Noll (STScI)*

We have re-processed all Spitzer MIPS radiometric observations of TNOs. This has allowed us to use the final flux calibration factors, target ephemeris positions, and photometric procedures to produce a uniform catalog of fluxes in the MIPS 24 and 70 micron bands. We present final results for the albedos and diameters of the 25 known TNO binaries.

Where mass determinations are available, we also summarize our current knowledge about the mass density of these primitive binary systems.

Binary Asteroids Modeled Using Gaussian Random Ellipsoids

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Small solar-system bodies may exhibit irregular shapes with preferential elongation or flattening. Here the shapes of such irregular bodies are modeled using the stochastic geometry of what can be called a Gaussian random ellipsoid (GE; Muinonen & Pieniluoma 2010). GE is a natural extension for the Gaussian sphere (GS): in particular, GE transforms to GS in the limit of vanishing elongation and flattening. In GE, lognormal height statistics are imposed on a base ellipsoid with semiaxes a, b, and c (a > b > c) along the local normal direction. As compared to GS, GE introduces two additional shape parameters: the axial ratio b:a or, equivalently, the elongation (a-b):a; and c:b or the flattening (b-c):b.

The ellipsoidal base geometry raises fundamental issues concerning the homogeneity of the superimposed statistics. In GS, the great-circle distance utilized in the correlation of two radial distances can be interpreted in two ways: first, the distance can be taken literally as the great-circle angle between the two points; second, it can be unambiguously mapped to the Cartesian distance for the two points on the base sphere. In a corresponding way for GE, the distance between two points on the base ellipsoid can be measured along the geodetic line connecting the points or as the Cartesian distance between the points. In the present context, we utilize the Cartesian distance in correlating heights on the base ellipsoid.

Due to the requirement of height variation along the local normal vector, further constraints must be introduced for the mean height corresponding to the mean radial distance in GS. We define the mean height h to coincide with the minimum radius of curvature for the base ellipsoid. This implies that the single center point of GS evolves into a surface of center points for GE (note that this surface is not ellipsoidal in shape).

We simulate lightcurves of binary asteroids by describing the shapes of the primary and secondary components using GE with realistic statistical shape parameters. First, these direct simulations will allow us to characterize the morphology of binary-asteroid lightcurves; and, second, the simulations may pave the way to lightcurve inversion for binary asteroids (cf. Oszkiewicz et al. 2010).

References:

K. Muinonen and T. Pieniluoma (2010). Scattering of light by Gaussian-random-ellipsoid particles. In Electromagnetic and Light Scattering XII, Conference Proceedings, K. Muinonen, A. Penttila, H. Lindqvist, T. Nousiainen, and G. Videen, Eds., University of Helsinki, Finland, 190-193.

D. Oszkiewicz, K. Muinonen, and T. Pieniluoma (2010). Asteroid spin and shape inversion for simulated Gaia photometry. In Electromagnetic and Light Scattering XII, Conference Proceedings, K. Muinonen, A. Penttil, H. Lindqvist, T. Nousiainen, and G. Videen, Eds., University of Helsinki, Finland, 214-217.

Formation of Kuiper Belt Binaries by Gravitational Collapse

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A large fraction of ∼100-km-class low-inclination objects in the classical Kuiper Belt (KB) are binaries with comparable mass and wide separation of components. A favored model for their formation was capture during the coagulation growth of bodies in the early KB. Instead, recent studies suggested that large, $\gtrsim$100-km objects can rapidly form in the protoplanetary disks when swarms of locally concentrated solids collapse under their own gravity. Here we examine the possibility that KB binaries formed during gravitational collapse when the excess of angular momentum prevented the agglomeration of available mass into a solitary object. We find that this new mechanism provides a robust path toward the formation of KB binaries with observed properties, and can explain wide systems such as 2001 QW_{322} and multiples such as (47171) 1999 TC_{36} . Notably, the gravitational collapse is capable of producing ∼100% binary fraction for a wide range of the swarm's initial angular momentum values. The binary components have similar masses (∼80% have the secondary-over-primary radius ratio >0.7) and their separation ranges from ∼1,000 to ∼100,000 km. The binary orbits have eccentricities from e = 0 to ∼1, with the majority having e < 0.6. The binary orbit inclinations with respect to the initial angular momentum of the swarm range from i = 0 to $\sim 90^\circ$, with most cases having $i < 50^\circ$. The total binary mass represents a characteristic fraction of the collapsing swarm's total initial mass, Mtot , suggesting Mtot equivalent to that of a radius ∼100 to 250-km compact object. Our binary formation mechanism also implies that the primary and secondary components in each binary pair should have identical bulk composition, which is consistent with the current photometric data. We discuss the applicability of our results to the Pluto-Charon, Orcus-Vanth, (617) Patroclus-Menoetius and (90) Antiope binary systems.

2001 SN263

Mike Nolan (Arecibo Observatory, Puerto Rico)

Triple asteroid system 2001 SN263 consists of a rapidly-rotating primary, a larger, outer satellite, and a smaller, inner satellite. The satellite orbits appear to be nearly circular, with eccentricities of order .02. The rotation of the inner satellite appears to be locked to its orbit, but the outer satellite is rotating much faster than its orbital period. Initial estimates by JLM suggest that the orbit planes are not exactly aligned, but three-body effects are very important in this system and complicate the analysis. Initial shape modelling efforts allow rotation poles aligned with either of the apparent orbit planes.

Asteroid Spin and Shape Inversion for Simulated Gaia Photometry

Dagmara Oszkiewicz (University of Helsinki, Finland)

We present Markov-chain Monte-Carlo methods (MCMC) for the inversion of asteroid spins and shapes [1]. We focus on convex optimization of asteroid spin and shape (for conventional convex inverse methods, see [2] and [3]), obtaining realistic shape solutions, and exploring the regime of possible spin solutions. We apply the methods to simulated photometric data for the Gaia mission. We compare the inversion results obtained to the spin and shape originally used to generate the simulated photometric data.

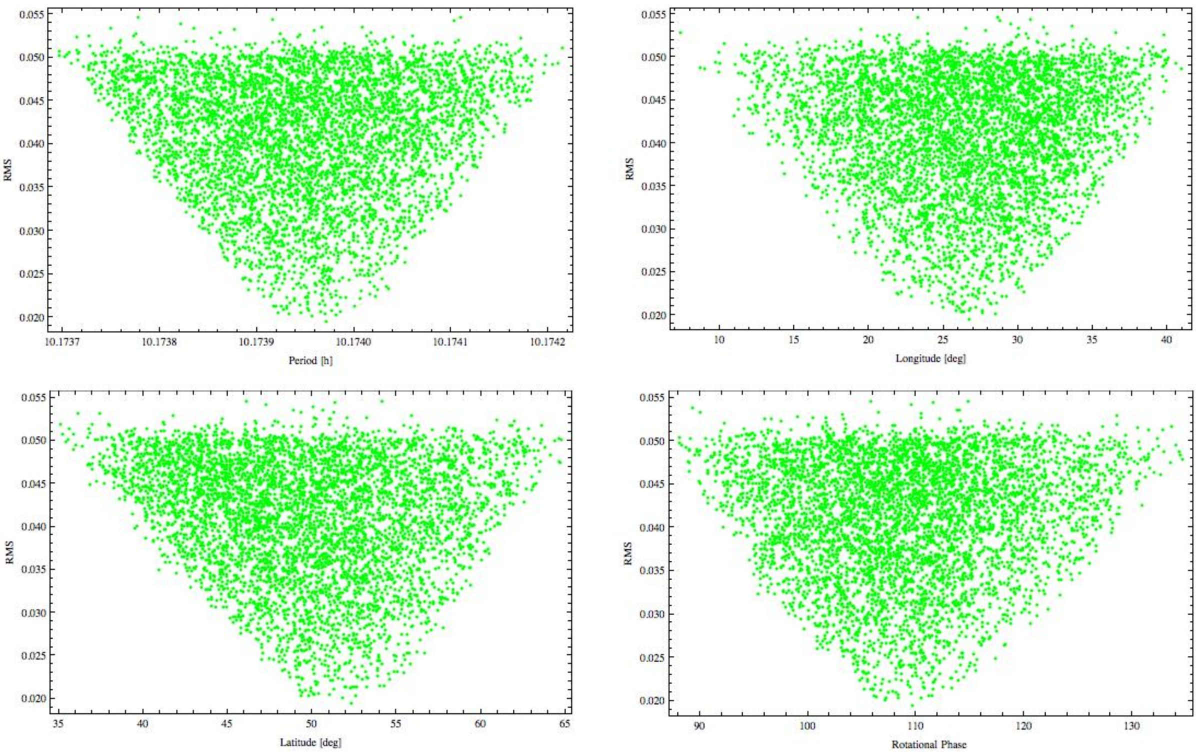

Figure 1: Rotational period and pole distributions as obtained from MCMC convex inversion. Original shape parameters: rotation period 10.17395622 (h), ecliptic longitude of rotational pole 25.02 (deg), ecliptic latitude of rotational pole 62.89 (deg), rotational phase 110.1 (deg).

References:

[1] K. Muinonen, D. Oszkiewicz. Markov-Chain Monte-Carlo inversion of asteroid photometric lightcurves. In 11th Electromagnetic and Light Scattering Conference, Extended Abstracts 181-184 (2008).
[2] J. Torppa, M. Kaasalainen, T. Michalowski, T. Kwiatkowski, A. Kryszczynska, P. Denchev, and R. Kowalski. Shapes and rotational properties of thirty asteroids from photometric data. In Icarus 164, 346-383 (2003).
[3] M. Kaasalainen, J. Torppa, and K. Muinonen. Optimization methods for asteroid lightcurve inversion. II. The complete inverse problem. Icarus 153, 37-51 (2001).

CCD Observations and Modeling of 4492 Debussy Eclipsing Binary Asteroid

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4429 Debussy belongs to the group of asteroids which are known as synchronous binary systems. It was observed in October-December 2002, March-May 2004 and April 2005 (Behrend et al., 2004). The lightcurve shows features typical for the eclipsing binaries – the amplitude of light changes associated with the rotation of two nonspherical bodies, and two minima due to their mutual eclipses. The period of brightness change was estimated as 26.606 ± 0.001 h, which is slightly longer than value from our model.

In 2006 Debussy was observed in: SAAO (South Africa) and Pic du Midi (France). The data are presented in the Fig.1. The lightcurve obtained from these observations contains more than half of the rotational period with eclipsing minimum of about 0.6 mag. The rotational period deduced from this data was 26.576 ± 0.005 h. This asteroid was also observed at four observatories (Prompt, Chile; Pic du Midi, France; Lick, USA; LNA, Brazil) in November and December 2007 (during its fifth apparition). Debussy was also observed in May 2010 in SAAO, the lightcurve is incomplete and only one eclipse can be visible (Fig.1).

4492 Debussy was observed during its six oppositions, with ecliptic longitudes evenly distributed along the orbit. All data present lightcurves with minima which are caused by mutual eclipses. This suggests that the edge of the orbit of the binary system is turned to the observer.

From presented data we are able to obtain model of this binary system and predict its future lightcurves.

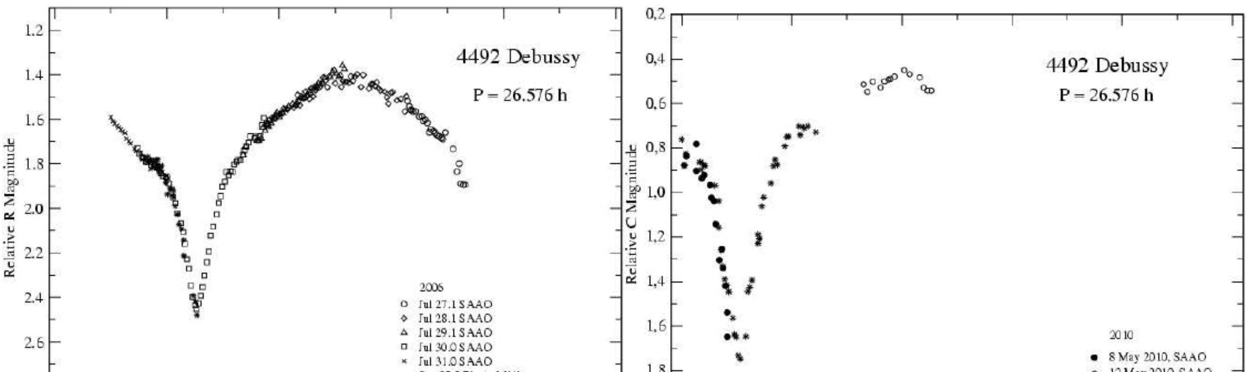

Figure 1: Composite lightcurves of 4429 Debussy obtained for the data from July/September 2006 and May 2010.

References:
Behrend R. et al. (2004), Four new binary minor planets: (854) Frostia, (1089) Tama, (1313) Berna, (4492) Debussy, A&A 446, 1177–1184.

Studying Rotational Axes of Binary Asteroids and Asteroids Pairs

David Polishook, Noah Brosch, Dina Prialnik (Tel-Aviv University)

Small-sized (D<10 km) binaries are thought to be created by the rotational fission of rubble-pile asteroids as their spins were accelerated. In this case, the spin axis of the primary and the orbital plane of the secondary should be orthogonal. Similarly, spin axes of primaries of asteroids pairs, which are disrupted asteroids due to rotational fission (see Pravec et al. contribution for this workshop), should be perpendicular to the orbits of the drifting secondaries. As primaries and secondaries of pairs have the same orbital parameters (since is the way they are found and defined) primaries of asteroids pairs should have spin axis with zero obliquities. To derive the spin axes of asteroids, we observe binaries and pairs at different apparitions and aspects using the two reflectors (1m and 0.46m) of the Wise Observatory, and used the inversion algorithm and code of Durech et al. 2010. A few asteroids (1089 Tama, 1509 Esclangona, 3749 Balam, 3782 Celle, 5407 1992AX) were observed during multiple apparitions but more data is needed from other epochs to derive significant results. Any result for the spin axis (or a nullresult, in a case of a nonzero obliquity), can constrain the timescale of the binary creation and/or disruption or suggest the involvement of other physical mechanisms with competitive timescales. Some results of the photometric observations of binary asteroids done at the Wise Observatory will also be presented.

Reference:

Durech et al., 2010, A&A 513, A46.

Asteroid Pairs Formed by Rotational Fission

P. Pravec [1] , D. Vokrouhlický [2] , D. Polishook [3] , D.J. Scheeres [4] , A.W. Harris [5] , A. Galád [6,1] ,O. Vaduvescu [7,8] , F. Pozo [7] , A. Barr [7] , P. Longa [7] , F. Vachier [9] , F. Colas [9] , D.P. Pray [10] , J. Pollock [11] , D. Reichart [12] , K. Ivarsen [12] , J. Haislipp [12] , A. LaCluyze [12] , P. Kušnirák [1] , T. Henych [1] , F. Marchis [13,14] , S.A. Jacobson [15] , Yu.N. Krugly [16] , A.V. Sergeev [16] , A. Leroy [17]

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A population of small main-belt asteroid pairs residing on very similar heliocentric orbits have been found and studied recently (Astron. J. 136, 280 (2008), Icarus 204, 580 (2009), Astron. J. 137, 111 (2009)). These asteroid pairs show some common properties: they are ubiquitous with pairs found throughout the asteroid population, pair members are separated with low relative velocities (as low as 0.17 m/s), they are young with most pairs separated less than 1 Myr ago, and their sizes and mass ratios overlap with the population of orbiting, bound binary systems. Previous investigations of binary asteroids suggest that they were formed from parent bodies spinning at a critical rate by some sort of fission or mass shedding process (Icarus 190, 250 (2007), Icarus 189, 370 (2007), Nature 454, 188 (2008)), however the possibility that these two populations of asteroid pairs and binaries were related was intriguing but lacked of observational data.

We report on a systematic observation campaign of spin rates, relative sizes and shapes of paired asteroids which enables this population to be analyzed. Two key characteristics of the asteroid pairs population appear: the primary spin rate is correlated with the mass ratio between a pair's components, and there is a cut-off in mass ratios of asteroid pairs above a value of 0.2. Both of these results are predicted by the rotational fission process hypothesized in (Icarus 189, 370 (2007)), and suggests this or a similar process as the genesis of the asteroid pairs and by implication as a fundamental process in the formation of asteroid binary systems. This formation mechanism is distinct from previous hypotheses to explain the population of orbiting, bound binary asteroid systems (Nature 454, 188 (2008)).

Orbital Similarity of Hypothetic Disrupted Binary Asteroids

Agata Rożek , Sławomir Breiter, Tadeusz Jopek
(Astronomical Observatory, A. Mickiewicz University, Poznań, Poland)

Orbital distance (similarity) functions are commonly used for identification of asteroid families, meteoroid streams and their parent bodies. Recently, using a variant of orbital distance function DZ (introduced by Zappala) Vokrouhlicky and Nesvorny have found ~60 MB asteroid pairs having nearly identical orbits, which may suggest that the objects are fragments of e.g. distrupted binaries. We have followed their work applying DZ and a few different distance functions. So called D-criteria measure distances between orbits treated as points in 5-dimensional space of keplerian orbital elements: a, e, i, Ω and ω. Along with DZ we applied a few different distance functions: DSH by Southworth and Hawkins, DD by Drummond, DH by Jopek, DV by Jopek et al., DB by Jenniskens and orbital intersection parameter DI. We applied those functions to osculating and mean elements.

Using the orbital similarity functions we have searched for closest pairs among the MB asteroid orbits in astorb catalogue calculated by Ted Bowell and AstDys catalogue by Milani et al. For a reference, we have made a similar search among the orbits generated numerically using the histograms of the real data. After comparison of the results obtained in both searches, we have found that ~100 pairs of MBA are significantly more similar than any pair from the artificial data. However among 100 closest pairs obtained by each of D-functions only 50-90% were in common. On a list of the tightest pairs, position of a given pair has changed from one D-function to another, sometimes significantly.

In the next step, we have shown, that for each D-function the list of the closest pairs considerably depends on time - using the orbits at different epochs, the D-values calculated for the closest pair may differ by a factor 50-500, and that the D-values oscillate with a period close to the relative synodic period of two orbits.

We made a short study related to the interpretation of the results given by various D-functions applied to artificial pairs of orbits with specified orbital velocity differences δ v. The correlation between D and δ v was calculated for few epochs: at the time of pair creation and after 10 kyrs, 100 kyrs and a 1Myr of orbital propagation. The correlation strongly diffused in time, making even very close orbital pairs nearly impossible to identify as close pairs by means of orbital similarity criteria.

The Celestial Mechanics of Asteroid Rubble Piles

D.J. Scheeres (University of Colorado at Boulder)

The detailed mechanics of a rubble pile asteroid are expected to be complex and driven by random arrangements of the constituent components. Despite this, there are a number of systematic principles and mathematical analyses, arising from the field of Celestial Mechanics, which can be applied to such selfgravitating conglomerates. I review and present the physical implications of these mathematical results and discuss how they may control and underlie the fundamental process of asteroid fission and binary creation among the small NEA and Main Belt asteroids.

Material Properties of Binary Asteroids:
Evidence for Rubble Piles and BYORP?

Patrick A. Taylor (Arecibo Observatory), Jean-Luc Margot (UCLA)

Calculations of material strength based on limiting the tidal evolution time to the age of the solar system indicate that binary asteroids in the main belt with 100-km scale primary components are consistent with being made of monolithic or fractured rock as expected for binaries likely formed from sub-catastrophic impacts in the early solar system. To tidally evolve in their dynamical lifetime, near-Earth binaries with km-scale primaries or smaller created via a spin-up mechanism must be much weaker mechanically than their main-belt counterparts or else be formed in the main belt prior to injection into the near-Earth region. Small main-belt binaries, those having primary components less than 10 km in diameter, could bridge the gap between the large main-belt binaries and the near-Earth binaries, as, depending on the age of the systems, small main-belt binaries could either be as strong as the large main-belt binaries or as weak as the near-Earth binaries. The inherent uncertainty in the age of a binary system is the leading source of error in calculation of material properties, capable of affecting the product of rigidity μ and tidal dissipation function Q by orders of magnitude. Several other issues affecting the calculation of μQ are considered, though these typically affect the calculation by no more than a factor of two. We also find indirect evidence within all three groups of binary asteroids that the semimajor axis of the mutual orbit in a binary system may evolve via another mechanism (or mechanisms) in addition to tides with the binary YORP effect being a likely candidate.

BVRI Photometry of Binary Asteroid 90 Antiope

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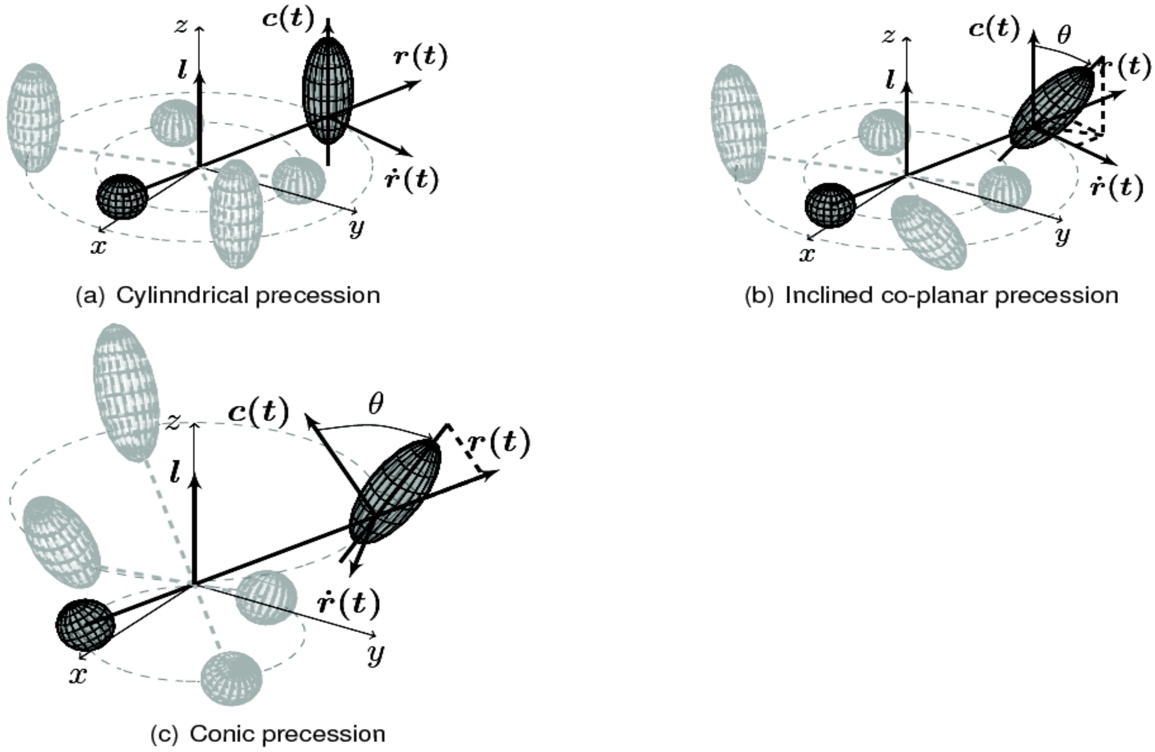
We present BVRI photometric observations of binary asteroid 90 Antiope which were carried out in 2002 and 2006 with the 0.7-m telescope of Institute of Astronomy of Kharkiv Karazin National University. According to data of observations in 2002 the asteroid shows events of mutual occultations and it's V-lightcurve amplitude equals to 0.20 mag. During a phase of occultation we detect variation of colour V-R with amplitude about of 0.05 mag. The obtained lightcurve of the asteroid in 2006 opposition does not show any eclipsing events. Amplitude of brightness variations is 0.07 mag in R spectral band. The lightcurve has regular form with two maxima and two minima and is due to rotation of asteroid’s components. It shows that at least one of the components is nonsperical or/and has albedo features on surface. The observations covered the phase angle range from 14.1 to 18.6 deg. Obtained linear part of phase angle dependences of brightness are characterized by values of phase coefficient from β_B=0.050±0.012 mag/deg in B-band to β_I=0.034±0.003 mag/deg in I-band. The values of phase coefficients correspond to average ones of the C-type asteroids.

Relative Equilibria in the Unrestricted Problem of a Sphere and Symmetric Rigid Body

Mikhail Vereshchagin (Nicolaus Copernicus University),
Andrzej J. Maciejewski (University of Zielona Góra)
and Krzysztof Goździewski (Nicolaus Copernicus University)

We consider the unrestricted problem of two mutually attracting rigid bodies, an uniform sphere (or a point mass) and an axially symmetric body. We present a global, geometric approach for finding all relative equilibria (stationary solutions) in this model, which was already studied by Kinoshita (1970). We extend and generalize his results, showing that the equilibria solutions may be found by solving at most two non-linear, algebraic equations, assuming that the potential function of the symmetric rigid body is known explicitly. We demonstrate that there are three classes of the relative equilibria, which we call cylindrical (Fig. 1(a)), inclined co-planar (Fig. 1(b)), and conic (Fig. 1(c)) precessions, respectively. Moreover, we also show that in the case of conic precession, although the relative orbit is circular, the point-mass and the mass center of the body move in different parallel planes. This solution has been yet not known in the literature.
The stability analysis of the found equilibria solutions is also presented. For all classes of relative equilibria a necessary and a sufficient conditions are derived. For some particular cases these conditions can be much more simplified.



(a) Cylinndrical precession

(b) Inclined co-planar precession

(c) Conic precession

Figure 1: Classes of relative equilibria motions

The Cool Surfaces of Binary Asteroids

Kevin J. Walsh [1], Marco Delbo [1], Migo Mueller [1], Alan Harris [2], Ellen Howell [3]
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[2] MoreData!, USA
[3] Arecibo Observatory, Puerto Rico

We present results from thermal-infrared observations of km-sized binary Near-Earth Asteroids (NEAs). These objects have, in general, surface temperatures cooler than the average values for non-binary NEAs. We discuss how this may be evidence of higher-than-average surface thermal inertia. This latter physical parameter is a sensitive indicator of the presence or absence of regolith: bodies covered with fine regolith have low thermal inertia, whereas a surface with little or no regolith displays high thermal inertia. Our results are suggestive of a binary formation mechanism capable of altering surface properties, possibly removing regolith: an obvious candidate is the YORP effect.

An Update of Binaries Among the Hungaria Asteroids and the Mars-crosser (218144) 2002 RL66

Brian D. Warner (Palmer Divide Observatory / MoreData!)
Alan W. Harris (MoreData!)

The Hungaria asteroids are small, inner main-belt objects with high albedos. This makes it possible to study the moderately-sized members, 2-10 km, with backyard telescopes. For the past five years, we have conducted an extensive campaign of the Hungaria population in order to compare rotation and binary statistics with the Near-Earth asteroid population. Our finding of binaries among the Hungarias, a population that has not experienced close planetary encounters, showed that tidal encounters were not the likely cause of binary formation among smaller asteroids but, instead, the YORP effect is the far more likely cause.

Most significantly, it has been found that the rotational statistics and binary populations are similar between the Hungarias and NEAs. For example, of the 176 Hungarias with useful periods, 12 (or about 7%) have been found to be binary. Another 4 Hungarias are possible binaries and need confirmation follow-up. This compares favorably to the binary population among the NEAs as found by Pravec et al. (2006, 2008).

We will present an update of statistics of the Hungaria binaries and compare them to those of the NEA population. We'll present recent observations of four Hungaria binaries, one being a prime example of "try, try again." Finally, we'll discuss the interesting case of the Mars-crosser, (218144) 2002 RL66, which may be a binary with unusual parameters.

References:

P. Pravec, P. Scheirich, P. Kušnirák, L. Šarounová, S. Mottola, G. Hahn, et al. (2006) Photometric Survey of Binary Near-Earth Asteroids. Icarus 181, 63-93.

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Acknowledgements

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