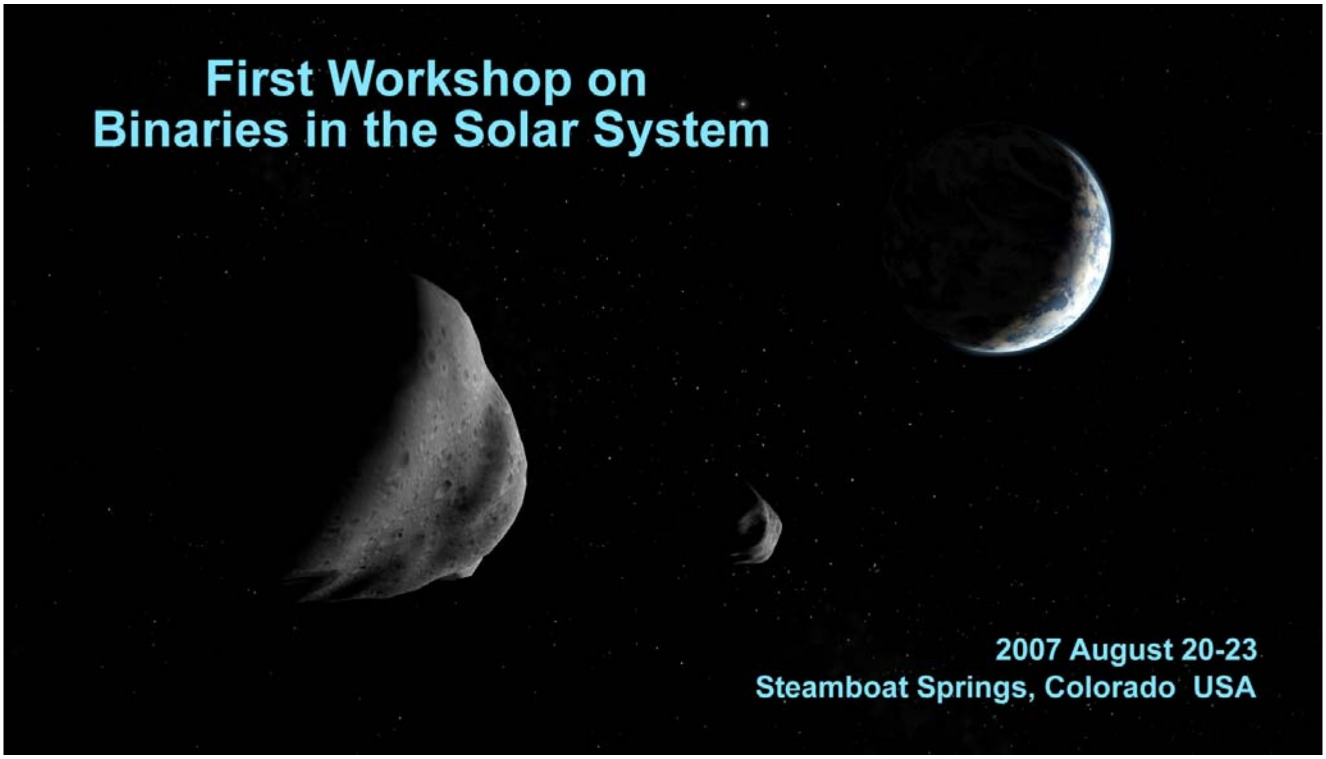
First Workshop on
Binaries in the Solar System
2007 August 20-23
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ABSTRACTS

Radar images of ten binary near-Earth asteroids

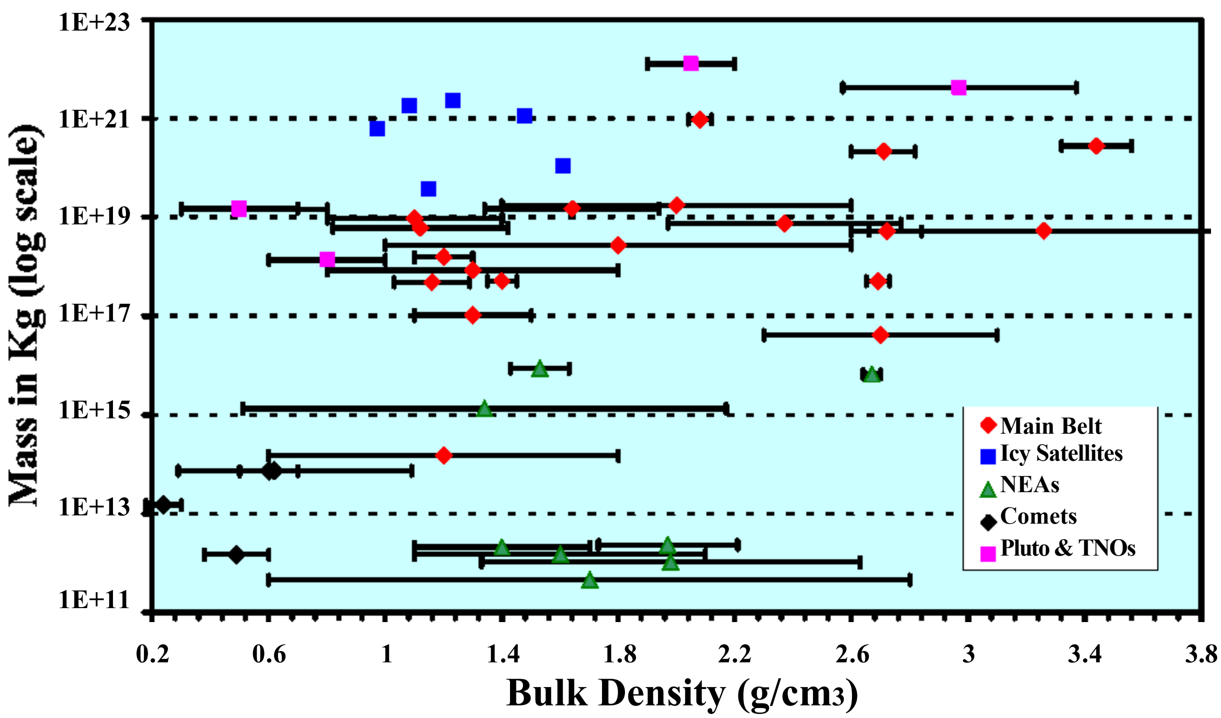
Lance A. M. Benner (JPL/Caltech), Steven J. Ostro (JPL/Caltech), Michael C. Nolan (Arecibo Observatory), Jon D. Giorgini (JPL/Caltech), Jean-Luc Margot (Cornell University), Michael W. Busch (Caltech), Randy Rose (JPL/Caltech), Joseph S. Jao (JPL/Caltech), Raymond F. Jurgens (JPL/Caltech)

We report Goldstone (8560 MHz, 3.5 cm) and Arecibo (2380 MHz, 13 cm) delay-Doppler radar observations of binary near-Earth asteroids (NEAs) (1862) Apollo, (65803) Didymos, (66063) 1998 RO1, (85938) 1999 DJ4, 1990 OS, 1994 XD, 1998 ST27, 2005 AB, 2006 VV2, and 2007 DT103. Of these, several are suitable for shape and orbit estimation, at least two have secondaries that are rotating more rapidly than their orbital periods, one is an M-type, some primaries have irregular shapes, and one system has the largest relative semimajor axis, eccentricity, and most dynamic orbit seen to date. Since completion of the Arecibo upgrade in 1999, 75% (18/24) of binary NEA discoveries have been by radar. 47% (14/30) have been discovered at Arecibo, 13% (4/30) at Goldstone, and four objects discovered photometrically have been detected, so that 92% (22/24) of binary NEAs found since 1999 have been observed by radar. Radar has become the "primary" technique for binary NEA discovery and characterization. This talk will discuss what we can learn from radar observations of each object with an emphasis on 2006 VV2 and 1998 ST27, the two systems with the most outstanding properties.

The density and porosity of binary asteroids

Daniel T. Britt (University of Central Florida), Guy J. Consolmagno (Vatican Observatory), Nate Lust (University of Central Florida)

A consequence of the explosion of observations of binary asteroids over the past 10 years is a much improved view of the bulk density and porosity of small bodies. Binary observations provide system mass and with radiometric estimates of object volume we can tackle bulk density. Shown below are bulk density measurements of 42 asteroids, comets, dwarf planets, and icy satellites. From these data macroporosity is estimated by comparing the small body's bulk density with the grain density of the object's spectroscopically determined meteoritic or mineralogical analogue. The difference between these two values provides the object's bulk porosity. Subtracting the average microporosity of the analogue material gives and estimate of the object's large-scale macroporosity. The objects of the main asteroid belt span the full range of both bulk densities and porosities with objects that are essentially intact over the age of the solar system to objects that are pervasively rubblized. NEA's tend to have low-bulk densities and relatively high porosities.



Dynamical and physical studies of the Pluto system

Marc W. Buie (Lowell Observatory), David J. Tholen (University of Hawaii), William M. Grundy (Lowell Observatory)

The study of binaries in our solar system started with the discovery of Charon. This discovery led to a fundamental increase in our knowledge of Pluto as well as Charon. As the oldest known case of a binary object, the most is known about it and yet it is amazing that the pace of discovery in this system continues. The discovery of two new satellites, Nix and Hydra, makes further discoveries possible about this distant system.

We have two active programs based on Hubble Space Telescope observations that strive to further refine our knowledge of the orbital motion of this perturbed 4-body system, determine the rotational states of Nix and Hydra, and obtain photometric and spectral data on their surface compositions. One program is to look back into past observations of the Pluto system with a particular emphasis on Cycle 2 observations taken with the pre-Co-Star aberrated WFPC/PC images. These observations will extend the observational astrometric arc by more than a decade and will vastly improve our knowledge of their orbital motions. New observations were taken in Cycle 15 – a total of 19 visits – to collect lightcurve and spectral data. These observations will also improve the orbits and help refine the masses of Nix and Hydra but will also constrain their rotational properties and determine broad spectral colors from 0.4-1.4 microns.

We will present results from our ongoing work on these data. Substantial work has been completed on the perturbed motion and we can provide fundamental refinements on their orbital elements that will permit further dynamical studies. The perturbed motion will be presented along with error analysis that constrains the interpretation of the work. We will also present an update on new astrometry from the Cycle 15 observations along with discussions of the measurements made possible in a multi-body system based on our experience with these data.

Implications for small-body binaries from doublet craters

Clark R. Chapman (SwRI)

Doublet craters have been recognized on the surfaces of many planets and satellites, including the Earth, Mars, and Venus. Various processes can produce crater pairs, including endogenic crater-forming processes, very oblique impacts, tidal splitting just before impact, and purely random pairing of unrelated individual impacts. Of relevance to this Workshop are binary craters produced by the near-simultaneous impact of a binary small body. In principle, attributes of paired craters can be studied to separate those formed by impacts of binary bodies from random doublets and those formed by other processes. By such studies of doublet craters, it should be possible to assess some features of the binary component of small body populations, especially in the outer solar system where small binaries are too faint to detect.

I am presenting no new research, but rather I will summarize the present state of knowledge as gleaned from the literature and will lead a discussion on this topic.

Shape, size, and pole of resolved asteroids

Albert R. Conrad (WMKO), William J. Merline (SwRI), Jack D. Drummond (AFRL), Christophe Dumas (ESO), Benoit Carry (ESO)

Using adaptive optics and the Keck II telescope, we have been able to determine the shape, size, and pole of resolved asteroids. For this workshop, we will discuss how this work relates to the study of asteroid satellites. This includes combining improved size estimates with the mass measurements obtained from satellite tracking to improve density estimates; and plans for relating the pole solution of resolved asteroids with the orbital plane of satellites.

Numerical models of the formation of asteroid satellites in large impacts

Daniel D. Durda (SwRI), William F. Bottke (SwRI), Erik Asphaug (UC Santa Cruz), Derek C. Richardson (University of Maryland), Brian L. Enke (SwRI), William J. Merline (SwRI),David Nesvorny (SwRI), Zoe M. Leinhardt (Harvard University)

We have been investigating the properties of satellites and the morphology of size-frequency distributions (SFDs) resulting from a suite of 160 SPH/*N*-body simulations of impacts into 100-km diameter solid basalt parent asteroids (Durda et al. 2004, *Icarus* **170,** 243–257; Durda et al. 2007, *Icarus* **186,** 498–516). Because many asteroids have undergone a series of battering impacts that likely have left their interiors substantially fractured we have also re-mapped the matrix of solid target simulations using rubble-pile target objects.

Our simulations utilize a 3-dimensional smooth-particle hydrodynamics (SPH) code to model the impact between the colliding asteroids. The outcomes of the SPH models are handed off as the initial conditions for *N*-body simulations, which follow the trajectories of the ejecta fragments to search for the formation of satellite systems. Our results show that catastrophic and large-scale cratering collisions create numerous fragments whose trajectories can be changed by particle-particle interactions and by the reaccretion of material onto the remaining target body. Some impact debris can enter into orbit around the remaining target body, which is a gravitationally reaccreted rubble pile, to form a SMAshed Target Satellite (SMATS). Numerous smaller fragments escaping the largest remnant may have similar trajectories such that many become bound to one another, forming Escaping Ejecta Binaries (EEBs).

Our simulations so far seem to be able to produce satellite systems qualitatively similar to observed systems in the main asteroid belt. We find that impacts of 34-km diameter projectiles striking at 3 km s^{-1} at impact angles of ~30° appear to be particularly efficient at producing relatively large satellites around the largest remnant as well as large numbers of modest-size binaries among their escaping ejecta.

For computational expediency, our simulations so far have treated the resulting collision fragments as spheres, such that our models miss the complex gravitational perturbations on impact debris near the largest remnant that are produced by realistic, irregular asteroid shapes. To address this we have now enhanced our existing simulations of satellite formation in large cratering impacts by conducting SPH simulations of impacts into realistic, irregularly-shaped targets and by computing the *N*-body phase of the simulations using a new version of pkdgrav that *preserves the irregular shapes of the reaccumulated largest remnants.* These simulation upgrades are ideally suited to investigating the details of formation scenarios for multiple, small satellites around irregular primaries.

Satellite-forming impact simulations: past, present, and funded future

Brian L. Enke (SwRI), Daniel D. Durda (SwRI), William J. Merline (SwRI), William F. Bottke (SwRI), Erik Asphaug (University of California, Santa Cruz), Derek C. Richardson (University of Maryland), Michael C. Burl, (JPL/California Institute of Technology), Robert Grimm (SwRI), David Nesvorny (SwRI)

In 2001, we began to simulate satellite-forming asteroid impacts as part of a three-year project funded by NASA's Intelligent Systems (IS) program. At first glance, "Intelligent Systems" seems an unusual home for such research. The primary goal of the IS project was to determine whether state-of-the-art Artificial Intelligence (AI) techniques could speed up the "understanding" of non-chaotic numerical simulations.

The runtime of each 100,000-particle impact simulation described by Durda et al (Icarus **170,** 243-257 and Icarus **186,** 498-516) varied from hours to months. We ran a coarse grid of 160 simulations as ground-truth, to understand the landscape, i.e. determine which combinations of 3-D impact parameters (relative size, velocity, and speed) produce the desired populations of binary asteroids - either SMATS or EEBs (see Durda abstract). Completing the suite of runs required over six months on a 16-node Beowulf cluster at JPL. Using AI techniques, we hoped to reduce the overall run-time in half - or better - while improving the resolution of the results.

Within the IS project, the main purpose of the 160-run grid of simulations was to benchmark the results of the AI techniques. Our algorithms require each run to be "graded", and for convenience, we eventually opted to use a grading formula based upon the size-frequency distribution of the impact remnants rather than the production of SMATS and EEBs. At that point, the goals of the IS project and the satellite formation research diverged.

Presently, we continue to simulate satellite formation under other projects. We are completing a 4-D grid of ~100 Kuiper Belt impact simulations to study whether low-velocity, icy impacts produce SMATS and EEBs as prolifically as Basalt asteroid impacts. Recent N-body code extensions by Derek Richardson, SPH support from Erik Asphaug, and a new, local 18-CPU Opteron cluster allow us to study target/remnant shapes, sizes, rotations, and thermal properties.

Over the next two years, we intend to revisit our AI heritage. We believe that improved AI algorithms can learn the best combinations of satellite-producing impact parameters 10x faster than dumb-grid techniques. Achieving this high level of efficiency requires us to tighten the focus of our grading tools, enhance our AI processes, and use better visualization tools. The challenges ahead are substantial, as are the potential benefits to runners of non-chaotic numerical simulations.

The dynamics of binary NEAs and their evolution: Perspectives from the KW4 investigation

Eugene G. Fahnestock (University of Michigan), Daniel J.Scheeres (University of Michigan)

As part of the KW4 investigation, full-detail numerical simulations of the coupled rotational and orbital dynamics of KW4's components indicated that the system exists in an excited state, following complex internal motions that match multiple dynamic modes with different periods. Such excited dynamic configurations should not be atypical for binary NEAs. We have investigated the likely excitation sources, specifically incorporating a third body's perturbing effects during a flyby or perihelion passage. Results of high fidelity simulations of such passages clearly show that for such systems with low perihelia, solar gravity perturbation excites the longest period dynamic mode as expected, while results are less clear for excitation of the shorter period modes.

The former is a variant of a Cassini state rarely observed elsewhere in the solar system but perhaps common in small binaries, which is well understood through conservation of angular momentum, and a consequence of oblateness of the larger component, Alpha. The latter modes follow from the triaxiality of the smaller component, Beta. Independent of the excitation level of such systems, which determines the amplitudes of these motions, their frequencies can be analytically related to the Alpha oblateness and Beta triaxiality body mass properties, allowing for remote estimation of inertia parameters. We have developed these analytic relationships and achieved partial verification of them against the observation-supported full-detail simulations of KW4, although results point toward the need for relaxing the assumptions behind the simple analytic formulae and employing a more rigorous method, capturing further shape detail, for best mass properties estimation independent of observed shape.

KW4 has also informed our understanding of the formation and evolution of such systems. KW4 Alpha's proximity to its rotational stability limit suggests a fairly recent formation from spin-up and disruption of a loosely bound precursor, due to some combination of tidal torque in flybys and/or YORP torque. Also, the system may have rapidly evolved from formation to its present state through a momentum transfer mechanism driven by YORP and involving regolith transport on Alpha, with accompanying resurfacing. This would be an interesting form of dynamic interaction between low speed `ejecta' particles and the binary components. The exotic trajectory dynamics of more conventional ejecta particles or a spacecraft in the KW4 system, as revealed through new numerical simulations, should also apply broadly to small body binaries, and foresee both unique challenges and unique in-situ observation opportunities for rendezvous missions to such a pair.

A new, large HST survey of trans-neptunian binary orbits: Strategy and early results

Will Grundy (Lowell Observatory), Keith Noll (STScI), Marc Buie (Lowell Observatory), Susan Kern (STScI), Denise Stephens (Brigham Young University), John Stansberry (University of Arizona), Hal Levison (SwRI)

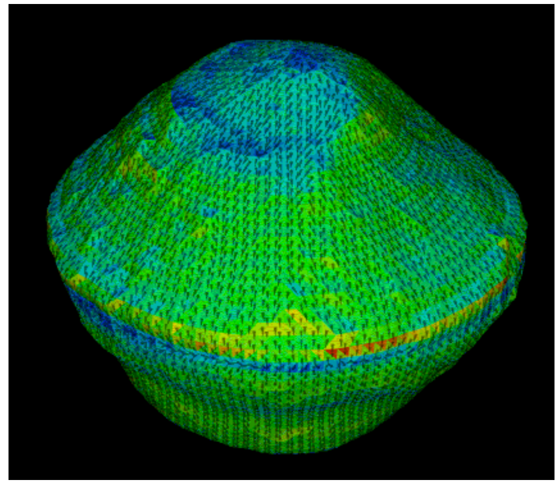
We have just begun a large Hubble Space Telescope (HST) Cycle 16 survey of trans-neptunian binaries (TNBs). Our primary goal is to determine the mutual orbits of a sample of more than 20 of them in order to use the statistical characteristics of their orbits to probe their dynamical history. We also want to find out which TNB pairs have mis-matched colors, and compare their colors with dynamical properties to help constrain their formation conditions. With its extremely stable PSF and dark background, HST is the premier facility for resolving the very faint and close TNB pairs.

One key aspect of our program is the use of Monte Carlo techniques based on the statistical ranging methods of Virtanen et al. (2001, 2003, 2007) to achieve efficient scheduling of the HST observations. This approach allows us to use earlier observations to quantitatively constrain the possible orbital element space. Follow-up observations are scheduled at times when the remaining possible orbital elements are best distinguished on the sky plane.

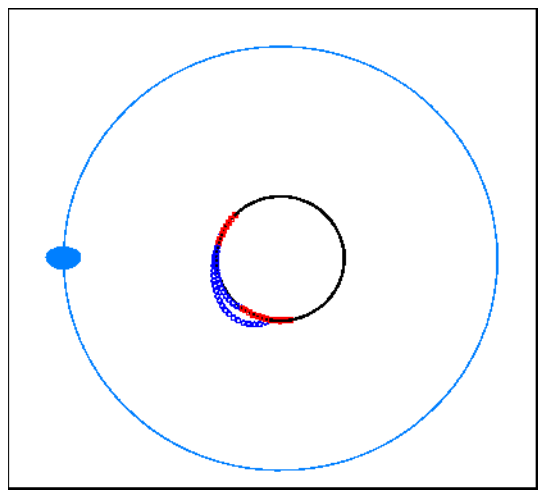
Although most of the planned observations will not yet have occurred at the time of the meeting, we will present a few early results and will discuss our target sample and our observing and analysis strategies.

How binaries color themselves green, and other just-so stories

Alan W. Harris (Space Science Institute)



In the recent *Science* papers by Ostro et al. and Scheeres et al., the asteroid (66391) 1999 KW4 is remarkable in the cover illustration in being almost entirely a constant shade of green, where the color coding represents the surface slope, green being in the range of 30-35°. Furthermore, the slopes are almost uniformly in the direction of the equator, as can be seen in the figure to the right, copied from the cover of *Science.* The explanation appears to be that as KW4 is spun up by YORP, the local slope increases to the critical angle for land-sliding, which moves material toward the equator and reestablishes an equilibrium with the average slope of the surface being the angle of repose, which for most dry loose material is around 30-35°. The "top" shape is essentially the figure of quasi-equilibrium of a body that is spinning at a rate that is critical at the equator (gravity = centrifugal force), and has a constant slope at other latitudes, except for the poles, which would be pointed otherwise, and the equator, where slope must pass through zero. Indeed, the detailed shape of the figure allows us to infer the critical angle of slide of the regolith.



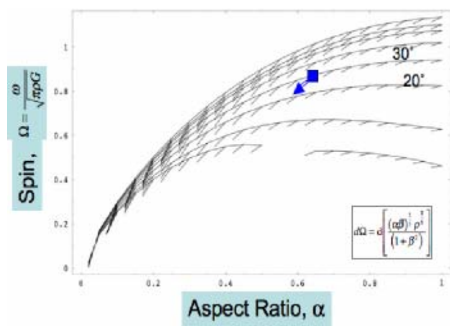
A second remarkable feature of 1999 KW4 is the extremely regular equatorial band, which is within about 1% of cancellation of gravity by centrifugal force. I suggest that this equilibrium is established by tidal forces from the satellite moving regolith around the equator. I have computed the motion of material drawn along and even levitated off the surface by the satellite for the case where the tidal force is nearly equal to the imbalance between gravity and centrifugal force on the primary. The figure to the right shows example trajectories of material levitated off the surface briefly as the primary spins below the satellite (the vertical scale is exaggerated several hundred times; rotation is counterclockwise; red is dragging along the surface, blue is levitated; two different ratios of tide to gravitational imbalance are shown). Clearly such mass motion will dissipate energy and transfer angular momentum from the primary to the secondary very quickly compared to elastic tidal friction, and presumably maintains the balance of spin rate between YORP and the critical rate at which such mass flow occurs.

Both of the processes described here will tend to regularize the figure of the primary and eventually shut down the process of YORP evolution. It is especially noteworthy that the very regular equatorial band is a nearly ubiquitous feature of small asynchronous binaries, as revealed by their radar delay-Doppler images and low lightcurve amplitude, as is the tendency to near-critical spin rate, revealed by the very short rotation periods. Thus, I offer this as a "just-so story" of the mode of origin and evolution of most, or maybe all, small asynchronous binaries.

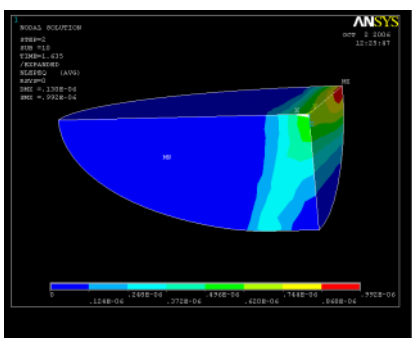
The spin fission of small asteroid into binaries

K. A. Holsapple (University of Washington)

Mechanisms suggested for the formation of binary asteroids include reaccumulation from a tidal encounter or an impact, and, more recently, the spin fission of a body due to spin-up by Yorp or other means (Richardson and Walsh 2006). Spin fission requires that a continuum body have its spin increased to a value where the internal stresses are larger than some failure criterion in a region across the body. An analysis of the internal stresses and failure criteria are required to determine those spin limits, and to determine the failure deformations. Then a final state with a separation of the two parts to give a configuration that is a distinct binary requires sufficient energy for the orbit mechanics of a bound pair. An analysis of spin fission into binaries then has three distinct parts: the spin limits, the deformation mechanics of the disruption, and the energy budget for the subsequent binary dynamics.



I shall first review the spin limits for continuum ellipsoidal bodies with solid strength (Holsapple 2007). Those fall into two regimes: a gravity regime for all bodies with a diameter greater than 10km, and a strength regime for bodies with cohesion and a diameter less than 10km. Then the nature of the failure when the limits are exceeded will be discussed. For the larger, gravity dominated bodies with D>10-20 km or so, the failure mode is a uniform lengthening of the body: that increases its rotational inertia and, via angular momentum conservation, slows the body to a new spin state that is within the new spin limits for its new shape. Curves of spin limits and the path in this spin-shape space are depicted in the figure to the left. Thus, these bodies are generally stable to global disruption due to spin-up, and unlikely candidates for binary formation. This result for continuum bodies is analogous to the loss of mass from the extremities in spin-up seen by the analyses using the strengthless n-body codes (Walsh and Richardson 2006).



So it is the bodies in the strength regime, with a diameter of 10-20 km and smaller, that are candidates for spin fission. With spin-up, these bodies do not fail uniformly and globally, but instead the failure region initiates at the equator and grows to encompass a conical region across its center. The beginnings of such a failure is shown in the cut body figure to the left as the red and light blue regions.

Then what would happen to the two pieces indicated by the failure analysis? They must have enough kinetic energy to overcome the mutual binding energy if they are to separate. However, it they have too much, they will simply fly apart to become two distinct unbound bodies. That limits the spins for disruption to form binaries to distinct limits. I have determined those energy states using a numerical method to get the mutual gravitational potentials of such separated bodies. I find that for a binary outcome the body must have some cohesive strength, but not too much. A spin fission of a very strong and small body will just produce two distinct bodies, at the other limit a spin fission of a very weak body will not be able to separate into two distinct pieces, but will remain in contact.

So, in summary, the analysis of spin limits for solid bodies and the consequences of exceeding those limits suggests that spin fission will not create binary bodies unless the original body is less than about 10 km in diameter. In those cases, and when the cohesive strength is important, the body will tend to split into two pieces of roughly equal size. And, if the spin is not too fast (not too strong) the bodies can remain relatively close, creating a binary outcome with a slightly smaller spin. But if the strength is too large then the spin limit is larger, and the two pieces will just fly apart and escape each other's mutual influences. This suggests binaries formed by spin fission should be spinning near the gravity limit, and with 0.1-10 km diameter.

References: Richardson, D. C., Walsh, K. J. 2006 Annu. Rev. Earth Planet. Sci. 34:47–81. Holsapple, K. A. 2007. Spin limits of Solar System bodies: From the small fast-rotators to 2003 EL61. Icarus 187, 500-509. Walsh, K. J., Richardson, D. C. 2006. Steady-state populationof the NEA binaries and Yorp spinup models. DPS Meeting 38, #38.08.

Radar detection of binary asteroids

Ellen S. Howell (Arecibo Observatory), Michael C. Nolan (Arecibo Observatory)

Radar observations of NEAs have revealed many binary systems, and confirmed others discovered by lightcurve observations. The inherent biases are different and in many ways complementary to photometric observing, making the combination powerful indeed. Radar observations will reveal a binary system nearly independent of viewing geometry. Except during total eclipse of the secondary, the objects will be separated by either range, Doppler frequency or both. Usually, the secondary is rotating synchronously with the orbital period, and usually the orbital velocity and primary rotation velocity are very different. This leads to a very different bandwidth for each object. However, processing at a variety of resolutions can separate the objects very clearly. Down to a size comparable to the resolution (7.5-15m) the secondary can be detected, except when it happens to fall at the same range as the primary, and the images may be superposed. Images from the next day will generally separate the two objects again. We look up to several tens of radii from the primary for secondary objects. The detection limit is not otherwise dependent upon separation distance, but may be biased against possible fast rotating secondaries. Radar observations would not detect a binary system if viewed with the orbit plane face-on, but with sky motion of tens of degrees, this situation would change enough in a day (2.5 hours at Arecibo) or by the following day to allow detection. In the case of Hermes, where two similar-sized objects are in synchronous mutual orbits, the radar observations clearly showed the separation of the objects. Most of the radar observations have been made at Arecibo, but when the object is beyond the declination limit, and high enough signal-to-noise ratio, the Goldstone radar system can follow objects for a longer time per day which helps determine the orbital period with fewer aliasing problems. Implications of the radar detection biases on the discovery rate of near-Earth binary systems will be discussed.

Variability of Kuiper Belt binaries

Susan Kern (STScI), Keith Noll (STScI)

The variability of small bodies provides information about their shape, interesting surface features, and rotation of that object. For bright or close objects these are relatively straightforward measurements to obtain with meter-class telescopes, however for moderately sized (d~100-200km) objects in the Kuiper Belt (KBOs) these observations are telescope-time intensive. Sparse sampling can adequately quantify variability, including the amplitude and period, with a small number of observations. Therefore, we are attempting to pre-sample the variability characteristics of KBOs before attempting to collect full lightcurves. We have chosen to focus on the ~50 identified Kuiper Belt binaries (KBBs) because variability studies of these systems has the added benefits of constraining physical properties and orbital evolution.

We have obtained variability measurements (resolved and unresolved) using new observations from the Magellan telescopes and archival data from HST. To date ~40% of the KBB population has been probed. Objects with the largest variations include 26308 (1998SM165), 2003QY90, (88611) Teharonhiqwako/Sawiskera and 200 1QG298. Some of the larger KBBs, 2003UB313, 2004DW and (50000) Quaoar, do not show large amplitude variation, although the sample size is still small. With our current HST program for binary orbits we will add sparse variability sampling for ~23 additional binaries.

Among the near earth asteroid population it has been found that fast rotating objects with low amplitude lightcurves are indicative of binaries and among the main belt asteroids there are numerous synchronous systems. Both of these observations provide important clues to the formation and evolution of binaries in these small body populations. It remains to be seen whether any similar trends will be observed in the Kuiper Belt.

Decelerating spin state of 25143 Itokawa due to YORP effect

Kohei Kitazato (University of Tokyo), Abe Masanao (Japan Aerospace Exploration Agency), Masateru Ishiguro (Seoul National University)

Abstract: The Hayabusa mission revealed fundamental physical properties of the small near-Earth asteroid 25143 Itokawa, such as shape and mass, during its rendezvous with the asteroid in 2005. Resulting from this, the YORP-induced change in asteroid's spin state has been predicted theoretically. We present the results of ground-based photometric observations of the asteroid Itokawa from March 2001 to December 2006 and of numerical modeling of its lightcurves using the detailed shape model and global surface photometric properties derived from the Hayabusa mission. As a non-linear time evolution of rotational phase lag is shown, we found that Itokawa has been decreasing its spin rate. The detected deceleration rate is almost consistent with, but slightly smaller than, the theoretically predicted value due to YORP effect.

809 Lundia - a new synchronous V-type binary in the Flora family

Agnieszka Kryszczynska (Astronomical Observatory, A. Mickiewicz University, Poznan, Poland), Francois Colas (IMCCE, Paris Observatory, France), Magdalena Polinska (Astronomical Observatory, A. Mickiewicz University, Poznan, Poland), Tomasz Kwiatkowski (Astronomical Observatory, A. Mickiewicz University, Poznan, Poland), Mirel Birlan (IMCCE, Paris Observatory, France), Przemyslaw Bartczak (Astronomical Observatory, A. Mickiewicz University, Poznan, Poland), Pascal Descamps (IMCCE, Paris Observatory, France)

Binary nature of 809 Lundia was discovered during observing campaign of the Flora family objects carried out at Borowiec Observatory (Poland) in Sept. 2005 (IAUC 8614). Photometric observations of Lundia were continued in Borowiec and Pic du Midi Observatory in till Jan. 2006 and in Jan. 2007 when no eclipses were visible. Photometric data allowed us to determine a preliminary model of the Lundia system.

809 Lundia was known as V-type (Florczak et al. 2002) and was supposed to be an interlooper in the Flora family. Our spectroscopic observations from Dec. 2005 and Mar. 2007 done with SpeX/IRTF show that both components are V-type.

Carruba et al. (2005) analysed possible migration of Lundia type bodies from Vesta family to its current orbits (in the Flora family) taking into account nonlinear secular resonanses and the Yarkovsky effect. However they assumed migration of a single body. It would be good to know how Yarkovsky effect influence binary asteroids.

References:

Carruba et al. 2005, A&A 441, 819
Florczak et al. 2002, Icarus 171, 120

The abundance of contact binaries in the Kuiper belt

Pedro Lacerda (University of Hawaii), David Jewitt (University of Hawaii)

We use Roche binary models to improve previous estimates of the contact binary fraction within the Kuiper Belt object (KBO) population (Sheppard & Jewitt 2004). Our simulations can be used to determine the lightcurve range of Roche binaries at arbitrary observing geometries, and for different surface types. This allows us to better correct the apparent fraction for observing geometry effects. We find that at least 9% of KBOs are contact binaries. Such high incidence of KB contact binaries has important implications to binary formation and collisional evolution scenarios.

Evidence for asteroidal satellites from 30 years of occultation observations

Paul D. Maley (United Space Alliance & International Occultation Timing Association), David W. Dunham (International Occultation Timing Association), David Herald (International Occultation Timing Association)

Ground based observations of occultations of stars by asteroids using portable and fixed conventional telescopes have been conducted by the International Occultation Timing Association since the 1970's. This has resulted in 42 observations which have suggested the detection of possible satellites of minor planets between 1977 and 2006. Except for last November's occultation by the known satellite Linus of (22) Kalliope in Japan, none of these have been unambiguously confirmed either by adjacent ground observers or by larger ground based instruments or space-borne telescopes. But such observations can be used to help characterize the environment around minor planets and to improve shape and size data on asteroids themselves. This can be important for future space missions such as one proposed for an inspection by the spacecraft "Orion" to a near earth asteroid. Efforts continue to intercept occultation paths involving stars by minor planets using video, image intensification devices, and visual methods principally by teams in the US, Europe, Japan, and Australia. Approaches are described to tactically specify the problem of ground intercepts and interpretation of observations.

Recent observations of binaries

Jean-Luc Margot (Cornell University)

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

Arecibo radar observations by Taylor et al. [1] showed that Apollo-type NEA 2004 DC is a binary asteroid. Range-Doppler data from Arecibo and Goldstone reveal a non-circular orbit ($e \sim 0.2$) despite a small orbital separation ($a \sim 0.75$ km, $P \sim 1$ day). This is the only known binary with an eccentric orbit and a semi-major axis only ~ 5 times the primary radius. We will discuss the origin of the eccentricity.

Immediately after the discovery of a satellite to MBA 22 Kalliope [2] it was realized that the primary-to-secondary radius ratio of ~ 5 would allow the detection of mutual events with the potential to improve measurements of component sizes and density of this M-type system. Our orbit solution showed that the best observational circumstances would arise in Feb-Mar 2007 and a campaign of observations was organized [3]. We will report on the event detection [4].

In addition to securing orbital parameters, our characterization of five TNO binaries with the Hubble Space Telescope has revealed two striking results. First, color differences based on the flux measured in HST's F606W and F814W filters show that the primaries and secondaries have very similar color indices (~ 0.1 mag) despite substantial variations in color indices between objects (~ 1 mag). This suggests that components have weathered identically or have similar compositions. Second, all of our 1999 TC36 data are much better fit by three components in a hierarchical configuration than by a binary configuration.

[1] Taylor et al., CBET 535, 2006. [2] Margot and Brown, Science 300, 2003. [3] Margot, Kramer, Warner, Pravec, Hicks, Young, Bauer, in preparation. [4] Warner and Margot, IAUC 861, 2007.

Lightcurves of the synchronous eclipsing binary asteroids

Tadeusz Michalowski (Poznan Astronomical Observatory, Poland)

Brightness variation of the synchronous eclipsing binary asteroid shows two-component lightcurve with each showing the same period. 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).* It means that the rotational periods of both bodies are equal to the orbital period, which is characteristic for synchronous rotation. Models and *eclipsing lightcurves* of such asteroids will be presented and compared with the observational data known for some objects.

Radar observations of binary asteroids

Michael C. Nolan (Arecibo Observatory), Cast of Several

Since the discovery of the binary nature of 2001 DP 107 (Margot et al) we have observed about 20 near-Earth binary asteroids with the Arecibo and Goldstone radars. The radar observations give independent estimates of the sizes of both primary and secondary components. Usually, the primary rotation is near the breakup limit and the secondary's rotation is tidally locked to the orbital period. The exceptions to this rule are Hermes, which is a symmetric system, 1998 ST27, which has a small distant, more rapidly rotating secondary, and 2003 YT1, which may have a more rapidly rotating secondary. The statistics of this outcome may shed light on the lifetimes of these objects if we can estimate the tidal evolution timescale.

The secondaries are typically 20-40% the diameter of the primaries. The orbits are largely consistent with close alignment of the orbit and spin axes, but only a few have been examined in detail.

The uncertainty in density determined is dominated by the uncertainty in the volume of the primary. In the best determined case (1999 KW4) with a detailed shape model, this uncertainty is of order 10%. The uncertainties in densities reported from low-resolution imaging (both NEA and MB) need to be carefully considered.

Obtaining vis/IR spectra of NEAs is often serendipitous, as the radar opportunities are independent of lunar phase, weather, and time of day. Thus most radar-observed binaries have unknown spectral types. We have seen at least S and C group objects, including a range of S group mineralogies from pyroxene-rich to olivine-rich.

Statistics of transneptunian binaries

Keith S. Noll (Space Telescope Science Institute)

More than 50 transneptunian binaries (TNB) are known, with all but Charon having been discovered since 2001. The sample size is now large enough that interesting statistical information can begin to be derived from discovery data alone. In general, three pieces of information are returned from the successful identification of a TNB: separation, relative magnitude, and the fraction of searched objects that are binary.

The separation of TNB components at discovery is a randomly timed sample of the possible separations over the course of a TNB orbit. The apparent angular separation is a function of the TNB's orbital elements and is subject to strong observational biases. It is possible to show, nonetheless, that the ensemble distribution of separations closely reproduces the distribution of semimajor axes. We find that the fraction of binaries increases rapidly at smaller separations down to the limit of HST resolution.

The relative magnitude of TNB components is a measure of the relative sizes of these bodies (assuming equal albedo). We find a marked preference for similar-sized binaries, particularly among Classical TNBs.

Finally, we have found a remarkable concentration of TNBs among low-inclination Classicals with an equally notable absence at higher inclinations. This difference can be best explained if the low and high inclination Classicals originated in different parts of the early protoplanetary nebula.

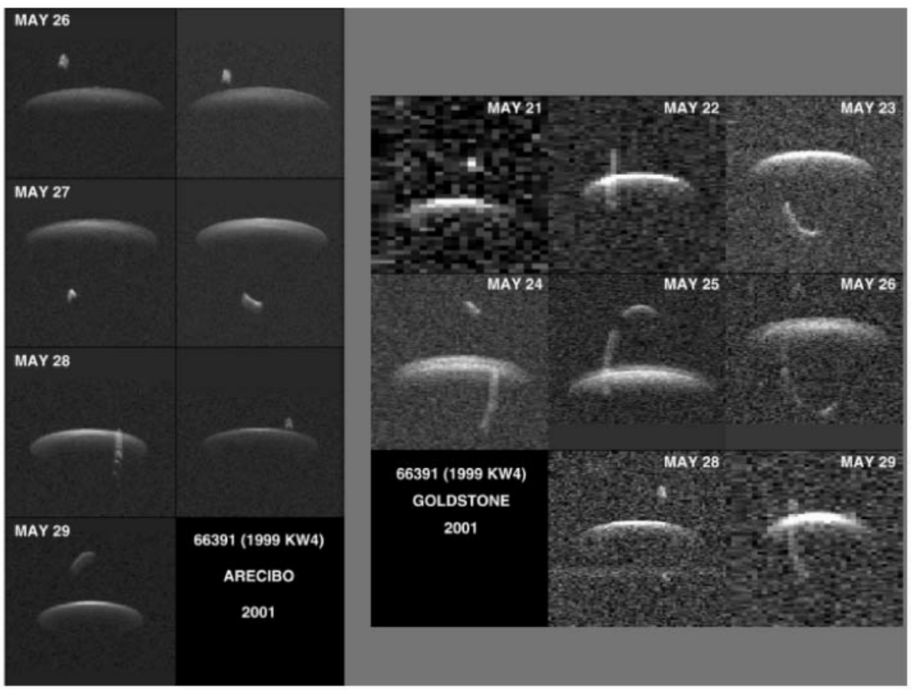
Actual and potential radar information about binary NEAs: Perspectives from the KW4 investigation

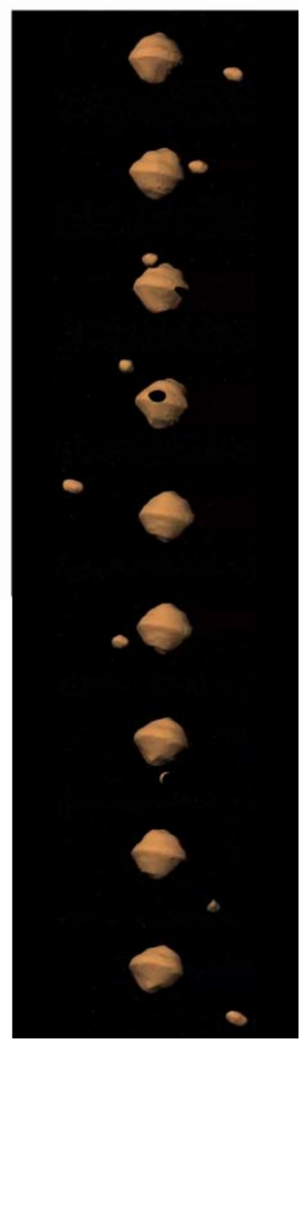
Steven J. Ostro (JPL/Caltech)

The KW4 investigation produced our most detailed physical information about a small-body binary, revealing novel physical phenomena and a new realm of complex dynamics.

It used a radar dataset superior to any of the 21 other binary NEA radar datasets obtained to date plus optical lightcurve and astrometric results, and its five years of analysis proceeded in a manner radically unlike that in previous radar experiments.

The community deserves to be aware of the factors that led to the success of the KW4 investigation, the potential information extractable from other existing binary NEA radar datasets and what is necessary for optimization of future binary NEA radar experiments, as well as implications of the KW4 results for spacecraft exploration of binaries.





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Orbit determination for asteroid satellites

William M. Owen, Jr. (Jet Propulsion Laboratory)

The process of determining an orbit for an asteroid satellite proceeds in several stages. The discovery and confirmation observations usually span only a few days, during which the asteroid system moves not much in the sky. The initial problem is therefore quite similar to the problem of determining orbits for binary stars. Once an initial orbit—actually, a pair of candidate orbits, owing to the ambiguity in the location of the ascending node on the plane of the sky—has been established, further work proceeds by an iterative linearized least-squares fit. The rapid growth of the partial derivatives with time, combined with a small region of linearity, means that additional data must be added with care. A gradual expansion of the data arc is particularly important when orbits must be numerically integrated. Results are presented for seven binary asteroids, and the particular difficulties of fitting the four-body system of (134340) Pluto are discussed.

Trends in characteristics of small NEA and MB binaries

Petr Pravec (Astronomical Institute AS CR, Ondrejov, Czech Republic)

An abundant population of binary systems has been found among asteroids in the size range 0.3 to 10 km in heliocentric orbits from near-Earth to the main belt. Their size range is exactly the same as that where there is observed the cohesionless spin barrier. It does not appear to be a mere coincidence, but the two things actually appear related. Primaries of binary systems concentrate at fast spin rates (periods 2-3 h) and low amplitudes, i.e., in a pile up just below the cohesionless spin barrier. They have a total angular momentum very close to, but not generally exceeding, the critical limit for a single body in a gravity regime. This suggests that they formed from parent bodies spinning at the critical rate (at the gravity spin limit for asteroids in the size range) by some sort of fission or mass shedding. The YORP effect is a candidate to be the dominant source of spin-up to instability. Gravitational interaction during close approaches to the terrestrial planets cannot be a primary mechanism of formation of the binaries, but it may affect properties of the NEA part of the binary population. For example, the estimated short lifetime and its strong dependence on semi-major axis of the NEA binaries, together with the strength of the YORP effect being inversely proportional to the square of diameter, may be a reason that binaries in near-Earth orbits concentrate among NEAs smaller than 2 km in diameter and that the fraction of binaries decreases significantly among larger NEAs, as well as for their tendency to smaller relative separations (shorter periods) in comparison with main belt members of the binary population.

The interacting satellites of 2003 EL61

Darin Ragozzine (California Institute of Technology), Michael E. Brown (California Institute of Technology)

The Kuiper belt object (KBO) 2003 EL61 and its two satellites are unique in many ways. Brown et al. 2007 [Nature, 446, 294] have recently suggested that EL61 is the largest member of a collisional family, the first discovered in the Kuiper belt. Further studies substantiate this claim and imply that the family is ancient and probably primordial (Ragozzine & Brown 2007, submitted). Presumably, the two moons also formed in this impact event, making it the only well-known case where a family-forming impact also created satellites.

EL61 is also the only minor planet known to have two strongly interacting moons. Previous attempts to fit a Keplerian orbit for the inner satellite have yielded unreasonable results. Perturbations on the known orbit of the outer satellite are smaller but appear to be present. Accounting for these three-body effects, we present the results of new observations of the moons of 2003 EL61. We discuss the implications of the results on the formation of this system in the family-forming collision. We also consider the concurrent tidal evolution of the orbits of the moons of this interesting object.

Compositional diversity of binary near-Earth and main belt asteroids

Vishnu Reddy (University of North Dakota), Michael Gaffey (University of North Dakota), Paul Abell (NASA Johnson Space Center), Paul Hardersen,(University of North Dakota)

Composition of binary asteroids has important implications for their formation mechanism and impact hazard assessment. Constraining the composition can shed light on other physical parameters like albedo, bulk density, porosity and physical strength. Currently, it is possible to identify the surface mineralogy and estimate the mineral chemistry, mineral abundance, and petrologic history of binary asteroids using near-IR (0.75-2.5 pm) spectroscopic observations.

While no mineralogical characterization projects have been completed on the entire binary asteroid population to date, a vast database of visible and near-IR spectra of varying quality and wavelength coverage is currently available in the public domain. These databases can serve as a starting point to understand the compositional diversity among the binary asteroid population. Analysis of spectra from these databases could also help answer the following questions. Do asteroids with a certain composition dominate the binary asteroid population? Is there a relationship between composition and formation mechanism? Are there compositional differences between main belt and near-Earth binaries?

We intend to accomplish the above discussed tasks and present preliminary results at the workshop. This research was supported by NASA NEOO Program Grant NNGO4GII 7G.

Properties of binaries from photometric data

Peter Scheirich (Astronomical Institute, Czech Academy of Sciences, Ondrejov)

I briefly describe an inversion method for obtaining some properties of binary asteroids from long-period component of their lightcurves. There is assumed an ellipsoidal shape for both component and an elliptical or circular orbit of the secondary.

The emphasis is placed on determining pole of the mutual orbit and properties from which a bulk density of the system can be determined. Particular care was taken to assess the uncertainties of these parameters and their dependence on the sky arc spanned by an asteroid during the observation. I showed that for short arcs the uncertainty of the bulk density could grow to very high levels, and it seems to be anticorrelated with the length of the arc. Therefore, the sky arcs of observed binaries would have to be extended as much as possible.

Densities of distant binaries: Constraints from Spitzer

John A. Stansberry (University of Arizona), William M. Grundy (Lowell Observatory), John R. Spencer (SwRI), Michael E. Brown (Cal Tech), Michael Mueller (University of Arizona), Keith S. Noll (Space Telescope Science Institute)

We have observed 19 binaries classified as trans-Neptunian or Centaur objects using the Spitzer Space Telescope (SST). These observations, at wavelengths of 24 and 70 μm, are sensitive to the system-integrated thermal emission from the targets (SST is not capable of resolving these systems). Seven of the systems were detected at a signal-to-noise ratio > 5 in one or both bands, allowing their diameters to be determined to an accuracy of ≈15%. The detections of the other 12 objects are lower quality, but in some cases provide meaningful constraints on their size. Separate observations of these systems with the Hubble Space Telescope (HST), and in a few cases with Keck, constrain the binary orbital parameters, and therefore the system mass.

By combining the mass and diameter, we derive system-average densities. These densities provide some of our first observation-based insights into the bulk composition and internal structure of these primitive, icy bodies. Spitzer-derived densities have been reported previously by Grundy et al. 2007a (65489 Ceto, 1.4±0.45 g/cc), Grundy et al. 2007b (42355 Typhon, 0.44±0.2 g/cc), Stansberry et al. 2006 (47171 (1999 TC_{36}), 0.5±0.3 g/cc), and Spencer et al. 2006 (26308 (1998 SM165), 0.5±0.2 g/cc). Spitzer-based diameters for 136108 (2003 EL_{61}, 1150±200 km) and 136199 Eris (2600±300 km) are in accord with the diameters reported for those objects by Rabinowitz et al. (2006: 1350±150 km) and Brown et al (2006, 2007: 2400±100 km). The resulting densities for 2003 EL_{61} and Eris are 2.6 g/cc and 2.3 g/cc. The low density of 47171 (1999 TC_{36}) has recently been revised slightly upward (≈0.7 g/cc) by re-observation with Spitzer. These results reveal significant diversity in the densities of TNOs and Centaurs, as well as remarkably low densities for some of them, a result consistent with the conclusions of Lacerda and Jewitt (2007) based on their analysis of rotational lightcurves.

We will summarize the current status of our Spitzer and Hubble programs to observe binaries in the outer solar system, present new results for a few objects with newly acquired observations, and discuss the need to improve the sample for which we have reliable diameters and densities.

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Rabinowitz et al. (2006) ApJ 639, 1238
Stansberry et al. (2006) ApJ 643, 556
Spencer et al. (2006) BAAS 38, 3401

Identifying binary transneptunian objects using model PSFs

Denise C. Stephens (Brigham Young University), Keith S.Noll (Space Telescope Science Institute)

Observations taken of TNOs using the Hubble Space Telescope (HST) have revealed several new binary systems. These discoveries show some apparently real differences in the frequency and types of binaries within each dynamical class. However, the significance of these results is limited by the small number of known binaries in each class, and the uncertainty in the binary frequency. This uncertainty is due to our inability to visually resolve binaries with small angular separations and/or faint companions. As a result the true binary frequency in any sample could be significantly larger. To identify additional unresolved binaries and improve the determination of the binary frequency requires that we either obtain higher resolution observations of each object or do a more careful analysis of the existing data to find partially resolved binaries using PSF-fitting.

In this poster we will describe how to use PSF-fitting to find partially resolved binary systems in existing HST data. Although this poster deals specifically with HST, the ideas and principles could be applied to other datasets. The advantage of working with HST data is that the point-spread function is stable throughout the duration of the observations. This stability means that with PSF-fitting we can identify binaries by the changes they induce in the combined PSF at separations considerably smaller than those defined by the Rayleigh limit. In this poster we will show how this technique has already been used to identify six new binary systems, and how we can apply it to other HST observations to better determine the binary fraction for each of these datasets.

Sizes of small main-belt binaries 17246 and 22899 from Spitzer IRAC thermal emission measurements

Peter Tamblyn (SwRI), William J. Merline (SwRI)

We observed the thermal infrared emission from Main Belt asteroid binaries 17246 and 22899 with Spitzer IRAC. We attempted to support these thermal observations with near-simultaneous ground-based photometry of the reflected sunlight to estimate the sizes of the primaries. The ground-based support observations for 17246 have an 8 day lag and a distinct viewing geometry, but include absolute photometry and sufficient repitition to constrain the lightcurve amplitude; the near-simultaneous support opportunity for 22899 was weathered out. The Spitzer measurements of 17246 have S/N 50 at 8 μm, and 10–20 in the other IRAC bands; the thermal measurements of 22899 are of lower quality due to less-favorable geometry during the scheduled visibility window. The size estimates from this project will be integrated with Hubble observations of the binary systems' periods to constrain the primaries' densities.

Binary asteroid observations with the Sonoita Research Observatory robotic 0.35m telescope

Dirk Terrell (SwRI and SRO), Walter R. Cooney (SRO), John Gross (SRO)

The Sonoita Research Observatory (SRO) is located in Sonoita, AZ about 40 miles from the Mexican border. The telescope is a 14" Schmidt-Cassegrain equipped with an SBIG STL-1000E CCD camera with Johnson-Cousins BVRI filters as well as a clear filter used primarily for observations of faint asteroids. The telescope is fully robotic, greatly increasing the productivity of the observatory.

A wide variety of stellar and extragalactic projects are carried out at SRO and we also collaborate with P. Pravec and other observers on observations of binary asteroid candidates. So far, SRO has contributed to the discovery of about a dozen binary asteroids.

The success of SRO has lead us to increase our capabilities. We will soon have a 0.5m telescope at the Sonoita site. SwRI has invested significant funding in the refurbishment of the 0.6m Optical Craftsman telescope at Mt. John Observatory in New Zealand. It is hoped that the New Zealand telescope (operated in an identical manner as the SRO 0.35m) will go online by the end of the year, giving us southern hemisphere coverage for our many projects including the binary asteroid survey.

Masses of Nix and Hydra

David J. Tholen (University of Hawaii), Marc W. Buie (Lowell Observatory), Will Grundy (Lowell Observatory)

We have used the two discovery observations of Nix and Hydra from 2005, the two confirmation observations from 2006, and the twelve prediscovery observations from 2002 and 2003, as well as available observations of Charon, to perform a four-body orbit solution for the Pluto system. Mutual perturbations have placed constraints on the masses of each member of the system. Previous work had already placed useful limits on the masses of Pluto and Charon, as well as their densities, given the known sizes of the bodies based on stellar occultation and mutual event observations, therefore our new work is aimed at placing constraints on the masses of Nix and Hydra. The best-fit GM values for Nix and Hydra are 0.036 ± 0.037 and 0.021 ± 0.042 km^3 $sec^{\ 2}$, respectively. At the one-sigma level, it appears that we can rule out masses near the upper limit of what is physically reasonable (corresponding to a combination of low albedos and high densities) for both satellites. Unfortunately, we do not yet have a useful lower limit on the mass of either satellite, though new HST data may be sufficient to do so. We have determined empirically that the rate of precession of the line of apsides of Charon's slightly eccentric orbit is proportional to the combined mass of Nix and Hydra, but in no case is the rate high enough to explain the difference in the longitude of periapsis derived from the 1992-1993 and the 2002-2003 observations. Instead, we believe that offsets between the center of mass and the center of light have adversely affected the earlier orbit solution for Charon. The orbits of the three satellites are coplanar to within a fraction of a degree, which argues for a common formation mechanism. Although the mean orbital periods of Hydra, Nix, and Charon are in the ratios of 6.06 : 3.99 : 1, we have not identified any state of resonance between them.

Spinup of strengthless bodies as a binary formation mechanism

Kevin J. Walsh (University of Maryland), Derek C. Richardson (University of Maryland), Patrick Michel (Observatoire de la Cote d'Azur)

We present preliminary results from a series of simulations of the slow spinup of strengthless aggregates with the goal of understanding the origin of Near-Earth and small Main-Belt binary asteroids. Our model consists of a strengthless body made up of identical self-gravitating spheres. The spin of the body is slowly increased in a way meant to mimic thermal spin-up effects, up to the point of shape change and mass loss. We simulate a variety of initial body shapes with varying simulation resolution and spin-up parameters. Each simulation is analyzed by monitoring the change in spin rate and body shape. Ejected particles are tracked to see if they are lost from the system or go into orbit around the primary. The potential for binary formation within this scenario is analyzed, and the prospects for future research in this field are discussed.

Asteroid photometry at the Palmer Divide Observatory

Brian D. Warner (Palmer Divide Observatory)

The Palmer Divide Observatory is owned and operated by Brian D. Warner and is located about 20 miles north of Colorado Springs, CO. Using three 0.35m SCT and one 0.5m Ritchey-Chretien telescopes with CCD cameras, its work is almost exclusively dedicated to asteroid lightcurves and photometry. Since 1999, it has generated data for almost 400 distinct asteroids and published almost 350 light-curves. Of these, approximately 10-15 have been binary asteroids with PDO being the primary discoverer on six. Furthermore, five of these were located in the Hungaria family and/or group.

Since the Hungarias are not planet-crossers, the discovery of binaries within that group helped establish that binary formation must come about by means other than tidal encounters alone and that the YORP effect may be the leading contender as an alternate mechanism (Warner and Harris, 2006). The concentration of work on the Hungarias has also shown an excess of fast and slow rotators, somewhat similar to what's seen among the NEA population.

The presentation will highlight past work, including that done in association with the Binary Asteroid Survey Group headed by Petr Pravec of Ondrejov Observatory, Czech Republic (Pravec 2007), and future plans for follow up for spin axis modeling and H-G determinations.

Acknowledgements

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