Binary Minor Planets

Derek C. Richardson†
`dcr@astro.umd.edu`

Kevin J. Walsh†
`kwalsh@astro.umd.edu`

†Department of Astronomy
University of Maryland
College Park MD 20740-2421

Running title: Binary Minor Planets

Please address all editorial correspondence and proofs to:

Derek C. Richardson
Dept. of Astronomy, Univ. of Maryland
Comp. & Space Sci. Bldg., Stadium Dr.
College Park MD 20742-2421
Tel: 301-405-8786
Fax: 301-314-9067
E-mail: `dcr@astro.umd.edu`

Contents

1. INTRODUCTION

Binary asteroids and binary transneptunian objects (collectively, "binary minor planets") are a relatively recent discovery, with the first confirmed observation—apart from the Pluto-Charon system—coming just over ten years ago. They are exciting for a number of reasons: 1) they had been hypothesized to exist since shortly after the discovery of the first asteroid, 1 Ceres, more than 200 years ago; 2) they provide information on important physical quantities of small bodies such as mass and density that would generally otherwise require a spacecraft encounter to obtain; and 3) they provide clues to both past and present dynamical mechanisms, such as collisions, that have bearing on the origin and future evolution of our solar system.

In this review we aim to familiarize the reader with the subject of binary minor planets (BMPs), provide an inventory of the known BMPs, and summarize the ongoing observational and theoretical investigations of BMPs. The last major review of the subject was provided by Merline et al. (2002c)—we will borrow from the detailed research conducted by those authors, augmenting it with new data, and taking a more theoretical approach to the subject.

1.1. What is a Binary Minor Planet?

As is often the case when dealing with astronomical terms, there is considerable ambiguity in assigning a descriptive label to the objects that are the main focus of this review. We have elected to use the term "binary minor planet" (or BMP) to mean any mutually orbiting pair of minor planets in our solar system, where we loosely define a "minor planet" as any substantial body orbiting the Sun that is not a major planet (Mercury through Neptune, and sometimes including Pluto) nor is bound to a major planet. So, BMPs do not include planetary moons, planetary ring particles, or insubstantial material such as dust. This definition is somewhat arbitrary but is made to conform with the community expectation of what a BMP should be. We use "minor planet" in preference to "planetesimal" because the latter term is usually reserved for small bodies that existed long ago and were largely incorporated into the major planets. However, it is likely the case that many (large) asteroids and most comets we see today are remnants of the original planetesimal population.

Minor planets are found throughout the solar system. Main-belt asteroids (MBAs) are located between Mars and Jupiter in orbits that are generally stable for Gyr but that gradually diffuse to produce the population of less stable planet-crossing bodies, such as the near-Earth asteroids (NEAs) (see Bottke et al. 2000; 2002b). NEAs have perihelia (close-approach distances to the Sun) inside 1.3 AU. The Jupiter Trojans share Jupiter's orbit at 5.2 AU but lead or trail the giant by 60° in longitude. The Centaurs, large comet-like bodies, are giant-planet crossers (no binary Centaurs have been found to date). Kuiper-belt objects (KBOs), also known as transneptunian objects (TNOs), are on stable orbits beyond Neptune, but also include the "Plutinos" that, like Pluto, come inside Neptune's orbit but are protected from collision due to an orbital resonance with the giant. Short-period comets and Centaurs are believed to originate from the TNOs (Duncan et al. 1998). Long-period comets, barely bound to the Sun, originate from the Oort cloud believed to surround our solar system out to distances of 50,000 AU. Like Centaurs, no binary comets have been unambiguously identified, so we do not address these putative objects further in this review.

The term "binary minor planet" is meant to be fairly inclusive. It reflects the reality that binary objects have been found in various distinct solar system populations. Thus a BMP that consists of two asteroids is a binary asteroid; a BMP that consists of two TNOs is a binary TNO; etc. We distinguish components as the higher-mass "primary" (subscript p) and lower-mass "secondary" (subscript s) where appropriate. In the literature, small secondaries are often called satellites; systems with large secondaries are sometimes called doubles.

The Pluto-Charon system is a special case. Although the International Astronomical Union (IAU) has avoided assigning a minor planet number to Pluto, many consider this body to be the largest example of a TNO and not a major planet, given its comet-like composition and similar orbital properties to many smaller TNOs (notably the Plutinos). A'Hearn (2002) suggests a pragmatic compromise of considering Pluto both a planet and a TNO for classification purposes. We adopt this approach; Pluto-Charon is therefore the largest BMP found to date.

Although none have been definitively observed, numerical simulations suggest that minor planet systems of more than two components could exist. We will call these "multiples" following the same convention as for multiple stars. Hence a triple minor planet system is one consisting of 3 mutually orbiting minor planets.

Finally, we restrict this review to detached binaries, that is, binaries whose components are not in contact. Examples of possible contact binaries include 624 Hektor (a Jupiter Trojan; e.g., Hartmann & Cruikshank 1978), 4769 Castalia (an NEA; Ostro et al. 1990), 4179 Toutatis (a tumbling NEA; Ostro et al. 1995), 2063 Bacchus (an NEA; Benner et al. 1999), 216 Kleopatra (an MBA; Ostro et al. 2000a; Merline et al. 2000a), 11066 Sigurd (an NEA; Benner et al. 2004a), one component of known binary 121 Hermione (an MBA; Marchis et al. 2004b), 2001 QG$_{298}$ (a TNO Plutino; Sheppard & Jewitt 2004), and 2005 CR$_{37}$ (an NEA; Benner et al. 2005, with a review of radar-imaged contact binaries to date). The reason for excluding these objects at this time is that ambiguity often exists as to whether the object in question is truly a contact or near-contact binary—in the sense that the components are in near equilibrium between gravitational and centrifugal forces, or that it is a geometrically bifurcated body with components supported by surface normal forces, or even that it is merely an elongated body with a large concavity. In the case of a bifurcated body, for example, normal forces at the contact point balance some or all of the gravitational forces between the components, so that it becomes difficult to infer some of the basic dynamical properties of these objects from rotation alone, such as the combined mass (usually only lower bounds can be obtained).

1.2. Binary Physics

Newton's form of Kepler's Third Law relates the orbital period P, combined mass $M = M_p + M_s$, and mean separation (orbital semimajor axis) a of an isolated binary, where the components are taken to be point masses: $P^2 = 4\pi^2 a^3/GM$, where G is the gravitational constant. In principle, measuring any two of the quantities yields the third; generally P and a are obtained from observations, and M is deduced. To obtain masses of the individual components requires an assumption that either $M_p \gg M_s$ (so that $M \simeq M_p$), or, if reliable estimates of the sizes of either component are available, that they have the same bulk density ρ (that is, they are constructed of essentially the same material in equal proportions, which may not necessarily be true). Measured sizes and masses may be combined to estimate ρ, a fundamental property indicative of composition. Presently, BMP density uncertainties are dominated by size uncertainties (Merline et al. 2002c). The porosity may also be inferred if a likely analog material (such as a meteorite with similar spectral signatures to an asteroidal component) with known bulk density is available—this can provide a clue to the internal structure, such as whether large void spaces may be present.

External perturbing forces, such as solar tides, major planet resonant interactions, thermal forces, etc., or internal forces arising between non-spherical, non-homogeneous, spinning components, generally will alter the orbit of a binary over time. Observations can determine the current orbital state of the system; theory then predicts how the system might evolve in the future. We defer further detailed discussion of evolution until near the end of this review.

If only solar perturbations are considered, initially circular coplanar orbits (i.e., for which the mutual binary orbit is in the same plane as the center-of-mass—or barycenter—orbit around the Sun) are stable out to a separation of roughly $R_H/2$ for components that orbit each other in the same sense as their barycenter motion around the Sun, and to a distance of R_H if the motion is retrograde, where $R_H = (M/3M_\odot)^{1/3} a_{\rm CM}$ is the mutual Hill radius, $M_\odot$

is the mass of the Sun, and $a_{\rm CM}$ is the semimajor axis of the binary barycenter (Hamilton & Burns 1991; we have generalized their analysis for the case of a massive secondary). For binary orbits that are inclined with respect to the barycenter orbit, the critical distance lies between these extremes. Similarly, initially eccentric orbits have different critical distances. For a binary at 1 AU with a primary of radius R_p and a typical asteroid density ρ, and a secondary of negligible mass, $R_H \sim 150$–$200R_p$, and scales linearly with $a_{\rm CM}$.

The innermost stable orbit of a BMP depends on the spins, shapes, and internal structures of the components. If the components are rigid and spherical, they can be just touching and still be stable, regardless of spin. If the components are mildly deformable, tidal evolution requires the secondary to be at or beyond the synchronous point (where $P = P_p$) to prevent it from spiralling inward (Goldreich & Soter 1966). If the components are strongly deformable, e.g., if they are loose aggregates of material, the secondary may begin to shed mass inside the Roche limit $R_R \simeq 2.46(\rho_p/\rho_s)^{1/3}R_p$ (e.g., Chandrasekhar 1969), so for comparable-density aggregate components, a practical inner limit is $\sim 2.5R_p$. For irregularly shaped components, the secondary should be of order a few times the synchronous radius away from the primary, to reduce the chance of strong resonant interactions (Hu & Scheeres 2004). As we shall see, most binary NEAs have fast primary spins, so the synchronous point can be fairly close to the primary. These limits will also depend on the relative spin orientations compared to the orbital plane, the eccentricity of the orbit, etc. Generally speaking then, stable orbits are expected for $a \gtrsim 2$–$3R_{p,\rm max}$, where $R_{p,\rm max}$ is the longest semiaxis of the primary; whether orbits inside this limit are stable requires detailed knowledge of the physical nature of the components. Interestingly, all BMPs with known primary sizes have $a/R_p \geq 3$ (see Table 1).

1.3. Historical Overview

In 1610, Galileo Galilei was the first to discover moons orbiting a world other than our own, when he found what are now called the Galilean satellites of Jupiter. This was a crucial observation that helped dispel the popular geocentric view of the Universe at that time. The first minor planet, asteroid 1 Ceres, was discovered by Giuseppe Piazzi on 1 January 1801 in Sicily. The following year William Herschel, with several planet moons to his credit, began searching for moons of this new body, but he was unsuccessful. With hindsight, we now know that BMPs are very difficult to detect, a few having secondary-to-primary brightness ratios of ~ 0.001 or smaller (and minor planets themselves are generally quite faint), and separations of just a few tenths of an arcsecond on the sky or less (Merline et al. 2002c). This type of observational challenge comes up in a variety of contexts, perhaps most notably these days in the direct detection of extra-solar plaents.

By our definition, the first BMP was found in 1978, with the discovery of Pluto's moon, Charon (Christy & Harrington 1978). However, since at that time the existence of the Kuiper Belt had yet to be established, Pluto was considered exclusively a major planet; observers searching for BMPs were only targeting asteroids. Van Flandern et al. (1979) in *Asteroids* summarized the results of lightcurve and occultation searches for binary asteroids up to that time, with no confirmed detections. Weidenschilling et al. (1989) in *Asteroids II* proposed a variety of mechanisms for forming binary asteroids, even though none had been detected to that point either. As technology and observing facilities improved, such as the introduction of CCDs, coronographic techniques, and the use of speckle interferometry, stricter limits could be placed on possible binary asteroid populations, but none were found.

Finally, in 1993, the Galileo mission to Jupiter discovered the first confirmed binary asteroid: tiny Dactyl apparently orbiting 243 Ida (Chapman et al. 1995; Belton et al. 1995; 1996). Due to the encounter geometry, a good orbit was not obtained for this binary, but the odds that two such objects could appear together in the same field without being mutually bound were deemed vanishingly small.

It would not be until 1998 before the second binary asteroid was unambiguously discovered: 45 Eugenia and its companion Petit Prince in the main belt (Merline et al. 1999a,b). This discovery was made from the ground using the adaptive optics (AO) technique. Soon afterwards, several more AO binary MBAs were announced. In the meantime, lightcurve techniques revealed possible binary asteroids in the NEA population (see Pravec et al. 2005b for the latest compilation), many of which have now been confirmed by radar.

Also during this time, detailed analytical and numerical techniques began to be applied to the problem of the origin and evolution of binary asteroids: Hamilton & Burns (1991), Chauvineau et al. (1993), and Scheeres (1994) (for example) studied the dynamics and stability of binary orbits; Durda (1996) and Doressoundiram et al. (1997) used computer simulations to show that asteroid impacts could generate orbiting companions similar to Ida's Dactyl; and Bottke & Melosh (1996a,b) showed that doublet craters on Earth and Venus could be explained by a $\sim$15% binary NEA population.

We end this section with more "firsts." 90 Antiope was the first confirmed fully synchronous binary (other than Pluto-Charon), and the first truly "double" MBA found at the time (see Merline et al. 2002c). 2000 DP_{107} was the first confirmed binary NEA and the first detected by radar (see Margot et al. 2002). 1998 WW_{31} was the first known binary TNO (Veillet et al. 2002). 107 Camilla was the first binary detected by the Hubble Space Telescope (HST; Storrs et al. 2001). 22 Kalliope was the first M-class binary MBA detected

(Merline et al. 2001b; Margot and Brown 2001; 2003; Merline et al. 2002c—previous binary MBAs were of primitive taxonomic type: C-, F-, and P-class). The first (and so far only) binary Jupiter Trojan was 617 Patroclus (Merline et al. 2001a; 2002c). 1998 TC_{36} was the first binary TNO found using HST (Trujillo & Brown 2002). 3749 Balam was the first known wide binary MBA, indicating a new class of object, and also the first S-class MBA binary found from Earth (Merline et al. 2002c). Finally, 3782 Celle was the first binary MBA found using the lightcurve technique (Ryan et al. 2003; 2004).

2. THE OBSERVATIONS

Table 1 lists the BMPs in the solar system that are either confirmed or considered likely, grouped by population. Figures 1 and 2 show some of this data graphically. Below we discuss the successful detection techniques and then consider population trends.

[Table 1]

[Figure 1]

[Figure 2]

2.1. Techniques

There are 3 broad categories of techniques that have been used to discover BMPs: direct imaging (including spacecraft, HST, and ground-based observations with and without AO); lightcurves; and radar. We discuss these in turn.

2.1.1. Direct imaging

Of the 4 asteroids (951 Gaspra, 243 Ida, 253 Mathilde, and 433 Eros) and 3 comets (1P/Halley, 19P/Borrelly, and 81P/Wild 2) visited by spacecraft, only one (Ida/Dactyl) has revealed itself to be a BMP from images taken during the encounter. The asteroid missions in particular had companion detection as an objective. No companions of Gaspra over 27 m radius were found out to $\sim 10R_p$ (Belton et al. 1992); there were none of Mathilde over 40 m diameter within 4% of the Hill sphere volume ($\sim 20R_p$) and none over 10 km diameter within 1 R_H (Merline et al. 1998; Veverka et al. 1999); and none of Eros over 20 m diameter (95% confidence) or 10 m diameter (70% confidence) within 1 R_H (Veverka et al. 2000; Merline et al. 2001c). The next minor planet to be visited by spacecraft is comet 9P/Tempel 1 on 4

July 2005 by the Deep Impact mission (A'Hearn et al. 2005).

Direct imaging from space of potential BMPs is also possible with HST. Although HST has a comparatively small-diameter primary mirror compared to modern world-class telescopes, its location eliminates the distorting effects of the atmosphere, allowing for diffraction-limited imaging over a large field of view. HST observations to date have revealed 3 binary MBAs and 7 binary TNOs, using a selection of instruments available on the telescope. From the ground, most BMP searches use AO (see below), but generally TNOs are too faint for this technique. Early direct ground-based searches for binary TNOs were successful because of the surprisingly wide separations and large component sizes of binary TNOs.

Directly observing a BMP requires overcoming difficulties in contrast and angular resolution. Adaptive optics (AO) improves astronomical imaging greatly by changing a deformable mirror in real time to minimize distortions in the image caused by atmospheric turbulence. Such systems can result in diffraction-limited imaging on the world's largest telescopes, allowing resolution of objects of widely disparate brightness (so far, 8.5 magnitudes) or very small angular separation (so far, 0.1 arcsec), but not both simultaneously.

2.1.2. Lightcurves

The lightcurve of Eros in 1901 prompted suspicion that the NEA may have a companion (André 1901). More serious attempts to discern a body's binarity began in the late 1970s with many reports of possible binaries derived from lightcurves. The first widely accepted binary from this technique came from NEA 1994 AW_1. It was observed to have a lightcurve featuring two periods and events interpreted as eclipses/occultations due to a binary configuration (see Pravec & Hahn 1997). This interpretation was validated when 2000 DP_{107} was shown to be a binary by radar observations and subsequent lightcurves of that object showed the same eclipse/occultation signature seen with 1994 AW_1. The lightcurve technique has been used extensively to discover slightly more than half of binary NEAs to date.

Essentially, a lightcurve is a measurement of reflected light from a body over time. An elongated rotating body may reflect varying amounts of light during its rotation and create a lightcurve with a single period. A BMP will have a complex lightcurve dependent on its orbital properties and geometry with respect to Earth. The most detectable scenario involves the secondary rotating/orbiting with a period different from that of the primary, producing a lightcurve consisting of two linearly added periods. However, this is not sufficient to prove that a minor planet is a binary, as a body in non-principal axis rotation may also produce a two-period lightcurve. Surface features and albedo variations may also complicate the interpretation. The most robust detection will include evidence of mutual events—eclipses or occultations—where the Sun-Earth-BMP geometry is favorably aligned. (An eclipse occurs when one component of the BMP casts a shadow on the other that can be seen by the observer; an occultation occurs when one component passes directly between the other and the observer.) Mutual events in the midst of a two-period lightcurve have largely convinced the community of the robustness of binary NEA detections using this technique (see Pravec et al. 2005b for a summary of observations to date). Recent detections have also been made of fully synchronised systems, for which $P_p = P = P_s$. This scenario produces only a single-period lightcurve, but binarity is revealed through resolved mutual events.

There are significant selection effects involved in lightcurve observations. To date observed secondary bodies all have $D_s \gtrsim 0.18 D_p$ (Pravec et al. 2005b). A smaller secondary may not have an observable signal above the noise of the primary period. The lightcurve technique also has a strong preference for close secondaries as this increases the chance and frequency of mutual events. Favorable geometry is also needed as eclipse/occultations require either the Sun or Earth to lie close to the binary orbital plane. The selection effects are well understood and when modeled have helped constrain distributions of properties for binary systems (Pravec et al. 2005b).

2.1.3. Radar

A variety of Earth-bound telescopes—most notably Arecibo in Puerto Rico and Goldstone in California—have been used to observe asteroids with radar. The simplest technique is continuous wave imaging, in which a steady monochromatic wave is transmitted at an object. Rotation of the object causes Doppler broadening of the returned signal. The presence of an orbiting, rotating companion in the beam alters the signal in an identifiable way. More information can be obtained using delay-Doppler imaging: a coded signal is transmitted that is both Doppler broadened and time delayed on return, indicating the rotation state of the target(s), possible presence of a nearby companion, and the target shape(s). To successfully extract all this information requires a strong return signal, so the target(s) must be either large or nearby (signal strength is inversely proportional to target distance raised to the 4th power and directly proportional to target diameter to the 3/2 power) . In addition, a stronger signal is obtained if the secondary is a slow, ideally synchronous rotator (strength proportional to square root of rotation period). Ostro et al. (2002) review the use of radar for asteroid imaging.

Optimally, for a nearby BMP, radar can reveal more/better information about a binary than any of the other techniques, including the component sizes/shapes, spin periods, orbital parameters/total mass (indirectly via orbit fitting to range and Doppler data), and mass ratio (from reflex motion with respect to the center of mass). The technique was first used successfully on 2000 DP_{107} (Margot et al. 2002), a binary NEA that has also been examined by lightcurve (see Pravec et al. 2005b and references therein); radar served as a validation of the lightcurve analysis. In fact, since it is not possible to unambiguously determine the orbit plane of a binary without multiple viewing angles and/or occultations/eclipses, combining radar data with lightcurve data is yielding the best orbits, particularly for binary NEAs. It should be noted though that radar is much more sensitive to small secondaries than the lightcurve technique. Within the next 10 years, 9 known binary NEAs will make radar-favorable approaches to Earth; 5 of these have not been detected by radar before (L.A.M. Benner 2005, personal communication). No doubt many more binaries will be discovered by radar, and other techniques, over the next decade.

2.2. Populations

To a large extent, observation techniques have dictated the nature of binaries detected among minor planets, with radar favoring NEAs, AO favoring MBAs, and HST observations favoring TNOs. Lightcurve techniques have been attempted for all populations. Below we discuss the observed trends in each of these groups.

2.2.1. Near-Earth asteroids

Binary NEAs have been discovered from a combination of lightcurve and radar observations. For the most part they share similar physical and orbital traits. All currently known or suspected binaries have $D_p < 5$ km (2003 SS_{84} has $D_p \sim 100$ m!) and P_p between 2.2 and 4.4 h (except for 69230 Hermes with $P_p = 13.89$ h). These spins are very fast, many near the breakup limit for unconsolidated material. The critical spin limit for a test particle on the surface of a rigid sphere is $P_{\mathrm{crit}} \simeq 3.3\rho^{-1/2}$ h, with ρ measured in g cm^{-3} (Harris 1996; Pravec & Harris 2000; also Richardson et al. 2005 gives spin limits for more generalized configurations). For a body with $\rho = 2.2$ g cm^{-3}, $P_{\mathrm{crit}} = 2.2$ h, which is the observed lower limit for P_p. The fast-spinning primaries are also very nearly spherical (or oblate), with lightcurve amplitudes all below 0.2 mag, where an amplitude of 0.2 mag corresponds to a body with $\sim$ 1.2:1.0 axis ratio (Pravec et al. 2002b).

The secondaries have D_s typically between 0.2 and 0.6 D_p. Again, the exception is

Hermes, which is a synchronously rotating binary ($P_p = P_s = P$) with near-equal-sized components. There is an observational bias against detecting secondaries smaller than 0.18 D_p, but between 0.6 and 1.0 D_p no such biases are known. The secondaries are also consistent in their separation from the primary, with most being within 6 R_p (lightcurves are biased against finding large-separation binary NEAs). The exception is 1998 ST_{27} (found by radar) with a separation $\sim 10\ R_p$; this system also has a relatively fast-spinning secondary ($P_s < 6$ h) and a high eccentricity ($e > 0.3$; Benner et al. 2003). Other than ST_{27}, the few eccentricities that are known are all below 0.1. Few secondary rotations are well known; those that are appear to be mostly synchronized with the orbital motion ($P_s \sim P$), consistent with short despinning timescales (Margot et al. 2002; also see discussion on binary evolution below), but are not mutually synchronous due to the fast primary spins. Again, 1998 ST_{27} is an exception.

Pravec et al. (2005b) find that $15 \pm 4\%$ of NEAs with $D_p > 300$ m are binaries with $D_s/D_p \geq 0.18$. This agrees with previous estimates from simulations and radar, the latter currently standing at 15 binaries with $D_p \gtrsim 200$ m from 92 targets, or 16%, and 1 binary (2003 SS_{84}) with $D_p \lesssim 200$ m from 44 targets, or 2% (L.A.M. Benner 2005, personal communication). Among those NEAs with known fast rotations (P_p between 2.2 and 2.8 h), the binary percentage is an astonishing $66^{+10}_{-12}\%$, so binaries appear to be more common than singles among fast-rotating objects approaching Earth's orbit. Note that ~30% of km-sized asteroids are fast rotators with $P_p < 4$ h (Pravec and Harris 2000).

2.2.2. *Main-belt asteroids and Jupiter Trojans*

Binary MBAs have properties that are quite distinct from their NEA counterparts. It is currently estimated that only $\sim 2\%$ of $D_p \gtrsim 20$ km MBAs are binary (Merline et al. 2002c; W.J. Merline 2005, personal communication), compared to the much larger incidence of binarity among NEAs. The one binary Jupiter Trojan implies an occurence rate also $\sim 2\%$ in that population for $D_p > 50$ km (W.J. Merline 2005, personal communication). Of those with measured sizes, binary MBAs all have $D_p \gtrsim 3$ km, with nearly half > 100 km (we caution that the lower limit is entirely a selection effect; in fact increasing evidence suggests that the fraction of binaries among the smallest MBAs may turn out to be not much different from that of NEAs of the same size: A.W. Harris 2005, personal communication). Thus most MBA primaries observed so far are larger than the largest NEA primary. MBAs have P_p between 2.6 and 27 h (only 3 of 16 measured have $P_p < 4$ h). By contrast, 19 of 21 measured binary NEAs have $P_p < 4$ h. Of binary MBAs with measured component size ratios, half have $D_s/D_p < 0.15$ (the smallest ratio being 0.02), whereas only 1 binary NEA has $D_s/D_p < 0.15$. Finally, the observed separations are larger for binary MBAs, ranging from $\sim$ 3–100 R_p (mean 27 R_p, median 12 R_p), most at least double those measured for NEAs.

Different discovery techniques and formation mechanisms are likely both responsible for the differences between observed binary MBAs and NEAs. Over half of binary MBAs have been discovered with AO, which preferentially finds distant companions outside of the point spread function of the brighter primary. These observations are also sensitive to large brightness differences, Petit Prince being $\sim$ 600 times fainter than 45 Eugenia at discovery (Merline et al. 2002c). Hence binary MBAs found by AO typically have large separations and a wide range of size ratios (a lower limit to secondary size in the main belt may be set by the collisional lifetime against disruption, although secondaries may reaccrete if they are not completely dispersed). All techniques (but particularly AO) are sensitive to primary size, as a 1 km asteroid in the main belt is much fainter than one in the near-Earth region; HST and lightcurves have found most of the small binary MBAs, but they are still larger than all binary NEAs. Generally, a typical binary NEA (with $D_p \sim 1$ km and a small, close secondary) is extremely difficult to observe in the main belt with present techniques.

Measurements of primary spin rate should not be biased between populations however. The differences in P_p between binary MBAs and NEAs are commonly cited as the main evidence for different formation scenarios: binary NEAs likely result from rotational disruption, so the primaries have fast spin; by contrast, binary MBAs likely result from impacts, yielding a larger range of spin rate. The collisional origin of binary MBAs suggests a possible correlation between binaries and family-forming events, although a recent survey of the young Karin cluster (identified by Nesvorný et al. 2002) failed to discover any binaries among them (Merline et al. 2004b).

Of particular note among binary MBAs are the 4 loosely bound ($a/R_H > 0.1$), small-component, large-separation systems, of which 3749 Balam is the archetype (Merline et al. 2002a,c). These may be examples of mutually bound ejecta from catastrophic impacts, systems that have been observed in numerical simulations (e.g., Durda et al.2004). We note also an increasing number of relatively small binary MBAs in the inner belt, suggesting there may be a continuum of sizes between the NEA and MBA populations (though we caution there is a strong selection effect here). Also of note is the surprisingly low density of $\sim$ 2300 kg m^{-3} inferred for 22 Kalliope by virtue of its companion (Merline et al. 2002c; Margot & Brown 2003); for an M-class asteroid this implies a very high porosity if it truly has metallic composition (M-class asteroids are hypothesized to be metallic core fragments of differentiated bodies). However, the inability of lightcurves and often also radar to map concavities means that some volumes may be overestimated, and hence the densities underestimated

(A.W. Harris 2005, personal communication). Finally, we note that most observed binary MBAs, including the Trojan, are of primitive taxonomic type (C, F, P), yet surveys have to date sampled primitive and altered bodies about equally, suggesting the binary fraction among larger primitive asteroids may be twice that of the population as a whole (Merline et al. 2002c).

2.2.3. Transneptunian objects and Pluto-Charon

The first binary TNO discovered (since Pluto-Charon) was 1998 WW_{31}, found via ground-based telescope in December 2000 (Veillet et al. 2002). The images revealed two objects separated by 1.2 arcsec on the sky. Archived images, and subsequent HST observations solidified the orbit for this system which has near-equal-size components (diameters of 150 and 120 km), a large orbit (a = 22,300 km), and high eccentricity ($e = 0.8$). These characteristics are similar to those of most binary TNOs discovered from ground-based telescopes: separations (a) greater than 10,000 km and components of comparable size greater than 100 km in diameter.

HST discoveries of binary TNOs began in late 2001 and early 2002 as a series of binaries were found (Trujillo & Brown 2001; Brown & Trujillo 2002; Noll et al. 2002a,b,c). With HST providing angular resolution superior to ground-based telescopes, the discovered binaries were on much smaller orbits, all between 5000–8000 km. Current estimates suggest the frequency of TNO binaries to be $4.5 \pm 2\%$ (Petit & Mousis 2004; Stephens et al.2004b suggest the fraction may be even higher). Future observations using the Spitzer space telescope, when combined with HST observations, will provide measurements of the bodies' albedos and sizes, which, when folded in with the combined masses derived from the bodies' orbital periods, will provide very accurate measures of TNO densities and reveal important information about the Kuiper Belt.

One seemingly ordinary binary TNO, 2003 QY_{90}, is unusual due its dynamical situation. This binary is a scattered disk object (SDO), belonging to a group of TNOs with large semi-major axes ($a_{\mathrm{CM}} > 50$ AU) and high eccentricities. This dynamically hot region is thought to have gained their high a_{CM} and large eccentricity through scattering off a large outer planet. However, with most theories of binary TNO formation pointing to primordial capture methods, this binary may not have been tightly bound enough to have survived a scattering event intact. Thus some binary TNO formation theories may have to be reconsidered to account for binary SDOs.

3. THE THEORIES

Prior to the confirmed discovery of BMPs (apart from Pluto-Charon), a number of theories were put forward regarding how such binaries might form and whether they should be common or rare (see Weidenschilling et al. 1989 for a review; updated in Merline et al. 2002c). For the most part these theories of the origins of binaries are still applicable, and can be placed into three broad classes: mutual capture via gravitational processes; formation from debris following an impact; formation via rotational disruption of the progenitor. Perhaps surprisingly, each of these in turn matches a broad category of BMP: capture seems most favorable for TNOs (Pluto-Charon being a notable exception; recent work suggests a giant impact event may have been responsible: Canup 2005); impacts for MBAs; and rotational disruption for NEAs.

3.1. Mutual Capture

In this scenario the two components of the binary become mutually bound by virtue of having relative speeds at encounter below their mutual escape speeds. For typical members of the three main minor planet populations we are considering (NEAs, MBAs, TNOs), escape speeds are of order m s^{-1} whereas encounter speeds are of order km s^{-1} (e.g., Bottke et al. 1994a,b; Petit & Mousis 2004). Hence the chances of direct capture are vanishingly small in the present-day populations of all these bodies.

However, the presence of a third large body, or perhaps a swarm of smaller bodies, within the mutual Hill sphere of the interacting pair, may be enough to reduce the encounter speed sufficiently to allow capture (Goldreich et al. 2002). In the present day, the chance of a 3-body encounter is exceedingly small in all populations, but in the past, when planetesimal densities were much higher, these mechanisms may have been viable. The Goldreich et al. (2002) model attempts to explain large-separation systems, but would also neccessarily create many more small-separation systems via evolution by the same dynamical friction mechanism used to explain capture. If a sea of small bodies were creating and hardening binaries, the chances of multiple systems would be significant as well. Alternatively, Weidenschilling (2002) proposes that a binary could form following the collision of two large bodies within the Hill sphere of a third. This method favors formation of large-separation binaries as their abundance would be expected to increase with distance from the primary due to increased likelihood of encounter at greater distance. Both processes require that the density of TNOs was $\sim 10^2$ to 10^3 times greater than now. Finally, Funato et al. (2004) suggest that rather than relying on a sea of small bodies, a typical observed binary TNO could come about through an exchange reaction between an existing primordial binary with a small secondary and a single TNO of mass comparable to the primary. In this scenario, the exchange causes the small secondary to be ejected and replaced by the third body in a wide but eccentric orbit. However, subsequent interactions with other TNOs are needed to reduce these initially very high eccentricities.

Given the short dynamical lifetime of NEAs and the relatively short collisional lifetime of (small) MBAs, the mutual capture mechanism is not favored for those groups (any binaries formed in this fashion have long since been destroyed). A substantial fraction of primordial binary TNOs on the other hand may have endured to the present day, although recent estimates suggest that the primordial population needs to be an order of magnitude more numerous than previously proposed to account for the present rate of binary destruction (Petit and Mousis 2004; they estimate the lifetimes of 1998 WW_{31} and 2001 QW_{322} to be ∼1–2 Gyr). Note that binary TNOs tend to have large separations and roughly equal-size components; this makes formation via the impact scenario energetically prohibitive. Also, there are no objects in the TNO population capable of efficiently causing rotational disruption of a TNO via tidal encounters. This leaves mutual capture as the most favored mechanism for forming the binary TNOs observed to date (selection effects have favored finding large, wide-separation components).

3.2. Impacts

If a close encounter between two minor planets results in a collision, binaries may be formed by virtue of interactions between the debris pieces and/or between the debris and the largest remnant (see Scheeres et al. 2002 for a review; also Paolicchi et al. 2002). By Newton's laws, material ejected from the surface of a spherical body generally either escapes or reimpacts. In order to put significant material in orbit, a "kick" is needed, which in this case could be provided by collisions and/or gravitational interactions between the ejecta pieces. For a rotating non-spherical primary, the necessary perturbations can arise from the complexities of the gravity field. Captured ejecta from a sub-catastrophic impact will likely preferentially orbit in the same sense as the primary spin, since the ejecta get a rotation kick as well (Weidenschilling 1989), but retrograde orbits are more stable against perturbations from a non-spherical primary (Chauvineau et al. 1993; Scheeres 1994). Subsequent damping collisions between captured ejecta pieces gradually build up the companion mass. Weidenschilling et al. (1989) points out that angular momentum conservation requires that the companion accrete within a few R_p to remain bound but be outside the synchronous radius to evolve outward. Hence it is expected that BMPs formed via sub-catastrophic impacts consist preferentially of gravitationally aggregated companions in direct orbits around rapidly rotating, non-spherical primaries.

Durda (1996) and Doressoundiram et al. (1997), soon after the Ida/Dactyl system was discovered, demonstrated some of these ideas numerically, showing that binaries could be formed from catastrophic and sub-catastrophic impacts. These initial studies relied on an assumed ejecta pattern and found more contact binaries than orbiting binaries, both accounting for less than 10% of the total mass of the system.

Michel et al. (2001; 2004) showed that the physical and dynamical properties of some asteroid families could be explained by gravitational reaccumulation of debris following a catastrophic impact. (The idea that family-forming events may produce orbiting fragments was proposed by Hartman 1979.) The Michel et al. (2001) model combined a Smoothed Particle Hydrodynamics (SPH) algorithm for the impact physics with a large-scale N-body integrator for the reaccumulation physics. The SPH model (see Benz and Asphaug 1995; Asphaug et al. 1998) provided a realistic post-impact velocity field for the ejecta while the N-body code (see Richardson et al. 2000; Leinhardt et al. 2000) treated both gravitational and collisional interactions between the pieces after the SPH phase was complete. As part of the Michel et al. (2001) study, numerous companions of the largest remnant were seen to form, but no in-depth analysis of their properties was carried out.

Durda et al. (2004) conducted a detailed investigation into the efficiency of binary formation in catastrophic and sub-catastrophic asteroid impacts. They modeled 161 impacts into 100 km diameter spherical basalt targets using a similar SPH/N-body combination to that of Michel et al. (2001). They found impact debris could enter into orbit around the remaining target body. They also found that ejecta on similar escape trajectories could become mutually bound. Their results produced binary systems qualitatively similar in many cases to observed binary MBAs, from large primaries with small secondaries (captured during reaccretion of the largest remnant) to equal-size primaries and secondaries (from mutual ejecta capture). The properties and statistics of the binaries were computed using a separate code designed for rapid identification of bound systems in N-body simulations (Leinhardt & Richardson 2005). Durda et al. (2004) found that impacts of 34 km diameter projectiles striking at 3 km s^{-1} at impact angles of $\sim 30^\circ$ had the highest effeciency for producing relatively large bound companions of the largest remnant as well as many modest-size binaries among their escaping ejecta. They propose that binary MBAs 3749 Balam and 1509 Esclangona are examples of mutually captured ejecta (because companions of the largest remnants form close in and cannot evolve to the needed separation). They also predict a formation rate of small companions to large primaries that matches the observed number of binary MBAs with $D_p > 140$ km that are not associated with known families. This assumes the main belt has changed relatively little over the last 4 Gyr. But recent work (Bottke et al. 2005) suggests there was a much higher collision frequency in the past, so many more such binaries would be expected, unless the collisional environment at the time destroyed binaries faster than they were created, or the dynamical excitation event that cleared 99% of the belt mass also eliminated most of these early binaries.

An important limitation of the Durda et al. (2004) model is that reaccreting particles are merged into single spheres, so shape and rotation information is lost (even though angular momentum is conserved in the spin of the spheres) and there is no possibility of tidal interactions between the remnant and debris. More sophisticated simulations planned for the future will address these issues.

Impacts are currently the favored formation mechanism for binary MBAs because most are likely not primordial, present-day encounter speeds are too high for capture, typical impact speeds are sufficient to create binaries in qualitative agreement with what is observed, and rotational disruption is less likely due to the typically large primary sizes, the reduced efficiency of thermal effects (see next section) at main belt distances, and the lack of fast rotators.

3.3. Rotational Disruption

For NEAs, the median dynamical lifetime against ejection from the solar system or collision with a planet or the Sun is ~ 10 Myr (Gladman et al. 1997; 2000). Unless binary NEAs can survive the injection process from the main belt (see Bottke et al. 2000 and 2002b for discussion of the dynamical pathways from the main belt to the NEA region; no detailed calculations have been performed to determine binary survivability during this process: W.F. Bottke Jr. 2005, personal communication), there must be some mechanism operating presently in the NEA region that can form binaries with reasonable efficiency. Note that the dynamical lifetime of NEAs is much shorter than the collisional disruption lifetime of ~ 100 Myr for typical NEA sizes, so NEAs are much more likely to encounter a terrestrial planet (or the Sun) before they encounter each other. Hence a rotational disruption mechanism such as tidal disruption may be viable for the formation of binary NEAs.

Rotational disruption generally requires that the progenitor have low tensile strength, that is, that the object cannot resist being stretched (such as by centrifigual forces). Richardson et al. (2002) describe the evidence for the existence in the minor planet population of these so-called gravitational aggregates (of which “rubble piles” are an often-discussed special case of loosely consolidated bodies with very low tensile strength and moderate porosity). The low bulk densities of primitive asteroids, many of which were measured by virtue of an orbiting companion, are suggestive of possible jumbled interiors: bulk porosities of 40–60% are required if such bodies are the parent bodies of chondritic material that falls to Earth in the form of meteorites. We have already seen that simulations of catastrophic main-belt impacts followed by gravitational reaccumulation of fragments are a good match for present-day asteroid families, and moreover can lead naturally to binary formation. Indeed, after their long history of sub-catastrophic impacts, surviving present-day asteroids of diameter $\gtrsim$ 100 m likely have fractured or rubblized interiors, which paradoxically may explain how asteroids such as 253 Mathilde endured giant-crater-forming impacts (Asphaug et al. 1998). Pravec & Harris (2000; also see Pravec et al. 2002b; 2005b) noted from lightcurve data that most NEAs with $D \gtrsim$ 150 m are spinning below the breakup limit for strengthless objects (for an assumed typical bulk density), and moreover that there is a large concentration of bodies just inside that limit, suggesting that most objects can spin up to their breakup point, but not beyond, possibly because most are strengthless or nearly so. Comets also have demonstrably weak structures, as evidenced by the breakups of comets D/Shoemaker-Levy 9 (SL9; e.g., Asphaug & Benz 1994) and LINEAR C/1999 S4 (Farnham et al. 2001).

A minor planet at equilibrium can be spun up in one of three ways: 1) a tidal encounter that distorts the shape of the progenitor with the resulting torque from the planet changing the spin; 2) surface forces such as jetting from volatile outgassing or the "YORP" thermal effect (Rubincam 2000; Vokrouhlický & Capek 2002); 3) off-axis collisions. With sufficiently large torque, the resulting spin angular momentum may be enough for tensile stress in the body to exceed its material and/or gravitational strength, causing fracture and/or mass loss. Roughly speaking, for a small impactor delivering the critical angular momentum, the ratio of impact energy to gravitational binding energy required is proportional to the ratio of impact speed to escape speed from the target. In the present-day asteroid belt, for example, impact speeds are so high that the target would be destroyed, so this case becomes equivalent to the catastrophic impact scenario discussed previously.

To date, no comet binaries have been discovered (TNOs are thought to be the progenitors of Centaurs and short-period comets; Duncan et al. 1988), but the jetting mechanism has been invoked to explain the spontaneous breakup of comets (e.g., Weissman et al. 2003). Bottke et al. (2002c) has suggested YORP as a means of forming binary NEAs. However, both YORP and to a lesser extent jetting are relatively slow, quasi-adiabatic processes. If the object in question has little tensile strength, mass shedding from the equator will likely begin shortly after exceeding the critical spin rate; the subsequent mass loss and shape change will soon bring the object below the critical spin rate and mass shedding will cease. Hence the evolution with this mechanism likely consists of short, separated bursts of equatorial mass loss, so no large companion would be formed immediately. It may be possible to gradually build up a large object in orbit, but this scenario has yet to be simulated. Alternatively, it may be that the existence of some strength would allow a buildup of stress well in excess of the critical limit for the no-strength case, resulting in a large burst of mass loss. Subsequent interactions of the secondary with the presumably non-spherical primary (or some other kick) would be needed to lift the periapsis to a stable distance.

Tidal disruption is a relatively impulsive event, so there is insufficient time for the object to reach equilibrium as it is accelerated. In this scenario, a minor planet passes within the Roche zone of a major planet and experiences a tidal stress that distorts, torques, and possibly disrupts the object. The result, depending on how deep the object penetrates the planet's gravitational well, and how long it remains there, can range from mild distortion/mass loss/spin change to major disruption (Figure 3). In the case of mass loss, once the system has exited the planet's Roche zone, reaccumulation can occur, resulting in one or more reformed bodies. If the imparted angular momentum was large, these reaccumulated bodies will remain gravitationally isolated and will follow similar but distinct orbits that will gradually separate due to solar tides and other external perturbations. This is likely what happened to form the SL9 "string of pearls" that eventually reimpacted Jupiter (Asphaug & Benz 1994). This scenario is also consistent with the presence of crater chains (not associated with secondary ejecta) on the Galilean satellites and our own Moon (e.g., Richardson et al. 1998). For small imparted angular momentum, most material will likely slump back into a single body, with perhaps a few small fragments escaping or going into orbit around the remnant. In between these extremes we expect to find binaries created with moderate size ratio and separation: there is too much angular momentum in the system to reform into a single body, but not so much that the components fly apart.

[Figure 3]

Richardson et al. (1998) conducted a survey of tidal disruption outcomes by simulating NEAs as ellipsoidal collections of self-gravitating hard spheres of fixed density. They found that disruption by a planet such as Earth is enhanced for closer approach distances, slower encounter speeds, faster direct spins (i.e., spin and orbital angular momenta vectors aligned), and favorable orientation at periapse (body long axis nearly pointing at and rotating toward the planet). They found binaries formed readily, but that was not the primary focus of the paper so the resulting systems were not well characterized. Walsh & Richardson (2005) revisited this model with higher resolution, a range of progenitor shapes, and many more encounters (over 100,000 scenarios were constructed), with the specific aim of determining the range of possible resultant binary systems. They found that tidal disruption produces binaries that are a good match for the separations and size ratios of observed binary NEAs; they predict that binaries with elongated primaries and larger a remain to be found. Their simulations did not produce primaries spinning quite as fast as binary NEA primaries; this may be an artifact of the chosen bulk density and/or the idealized nature of the progenitors, issues to be addressed in future work.

Rotational disruption, whether through tides or YORP, is currently the favored mechanism for NEA binary formation, assuming most NEAs have low tensile strength. Binary NEAs have fast-rotating, spherical or oblate primaries, consistent with reaccumulation after catastrophic rotational disruption (Richardson et al. 2005). Moreover, NEA collision frequencies exceed their mean dynamical lifetime and three-body encounters leading to mutual capture are highly improbable. Rotational disruption is less likely in the asteroid belt, since there is no dense body with a large enough cross section that can exert tides efficiently, and spinup mechanisms such as YORP are reduced in effectiveness due to the larger distance from the Sun and the larger sizes of the bodies in question (though YORP may be a factor for the smallest of the discovered binary MBAs). In the TNO population, there is again no effective large body capable of disrupting small bodies (Pluto has too small a cross section), and YORP is not a factor.

3.4. Triple and Multiple Systems

In general, most triple or multiple systems will not survive long due to their inherent instability. However, as is the case with stellar systems, certain configurations may be stable for long periods, most notably hierarchical systems in which pairs of particles form tight binaries that do not interact strongly with the remaining particles (or other pairs); effectively each binary behaves as a single particle (and binaries of binaries may form, etc.). Goldreich et al. (2002) predict some stable multiple systems could be produced in their TNO binary formation mechanism.

Triples and multiples have been observed to form in numerical simulations. Durda (1996) and Michel et al. (2001) found primaries with multiple companions; Doressoundiram et al. (1997) and Durda et al. (2004) reported temporary multiple systems; Durda (1996) also found contact binaries with single companions. Leinhardt & Richardson (2005) characterized the multiples in the simulation of Durda et al. (2004) that produced the most binaries, finding 10% triples and 3% quadruples, with some of these systems surviving at least several days of simulated time (to the end of the simulations). Walsh & Richardson (2005) reported $\sim 1\%$ of their simulations of binary formation via tidal disruption produced hierarchical systems in which a body was bound to the second-largest remnant, which in turn was bound to the largest remnant (more complicated configurations were also seen, but less frequently). Such configurations have only been seen immediately post disruption; longer simulations are needed to determine if they persist.

3.5. Binary Evolution

Once a binary (or multiple) has formed, many factors may influence its evolution. We have already discussed initial stability. More generally, if the total energy of the system is known, the range of possible short-term outcomes due to mutual gravitational interactions between the spinning, irregular components can be narrowed down (Scheeres 2002). Escape of the secondary could leave the primary with slow/tumbling spin, possibly explaining the surprising prevalence of asteroids in this state (Harris 2002; Pravec et al. 2005a). Over the long term however, tidal dissipation, thermal effects, outgassing, collisions, planetary encounters, and solar tides may all play a role in the evolution of the binary. We review some of these factors here, but caution that much work remains to be done, particularly in the form of long-term numerical simulations to characterize the (quasi) steady-state outcome of these multiple evolutionary factors.

Assuming the secondary is beyond the primary's synchronous radius, mutual tidal forces may: 1) expand the orbital semimajor axis a; 2) lock the secondary's rotation period with the orbital period ($P_s = P$); 3) reduce the orbital eccentricity e (a large secondary could actually cause e to increase in some circumstances). Weidenschilling et al. (1989) give timescales for these effects, which depend critically on the assumed energy dissipation efficiency of the components. Margot et al. (2002) estimated this efficiency for 2000 DP$_{107}$ by assuming the secondary had evolved from nearly touching the primary to its present separation over the median NEA lifetime of 10 Myr, finding this binary is likely made up of material 10^5 times less rigid than solid rock. Using these values, Walsh & Richardson (2005) showed that for $D_s/D_p \sim 0.1$, a would evolve from 1 R_p to 4 R_p in $\sim$ 10 Myr. Larger D_s/D_p binaries evolve much faster, but are limited by the total amount of angular momentum available in the primary's rotation for expanding the orbit. For example, 69230 Hermes is in a doubly synchronous state at $\sim 3.3R_p$ with $P_p = P \sim 13.9$ h; since the components are roughly equal size, the system evolved rapidly to this state but cannot evolve significantly further through tidal dissipation (90 Antiope is another example, perhaps formed from a glancing collision long ago when MBA encounter speeds were low; Merline et al. 2002c). Similarly, e damps quickly for small D_s/D_p and a; Walsh & Richardson (2005) estimate that all but one well-observed NEA binary has a damping timescale less than 10 Myr, and only 7 have a damping timescale greater than 1 Myr. The outlier is 1998 ST$_{27}$, with a separation of $\sim 10R_p$ and $e \gtrsim 0.3$ (Benner et al. 2003). This is the only known binary NEA with $e > 0.1$, and is the only one for which the estimated damping timescale is greater than 10 Myr. This suggests that large-a binaries discovered in the future may also have high e.

Chauvineau et al. (1995) and Bottke & Melosh (1996a,b) showed that tidal encounters with Earth or Venus can lift the periapse of a binary or even split the binary apart completely.

Wider-separation binaries than presently observed (apart from 1998 ST_{27} perhaps) could explain the incidence of well-separated doublet craters on these planets (Melosh & Stansberry 1991); repeated tidal planetary encounters may provide the necessary separating mechanism once a binary is formed (Bottke & Melosh 1996a,b). Detection methods are currently biased against finding wide-separation binaries in the NEA population; future observations may show such BMPs are fairly common. Note also that for a wide-enough binary, capture of one component by a planet is also possible; Agnor & Hamilton (2005) invoked this scenario to suggest Triton was tidally stripped from a binary TNO by Neptune.

Particularly intriguing is the possible role thermal effects may play on binary evolution. Yarkovsky and YORP effects have been identified as responsible for both orbital evolution and spin axis re-orientation of small ($D < 50$ km) asteroids (Chesley et al. 2003; Vokrouhlický et al. 2003). Ćuk & Burns (2005) propose that YORP can alter the orbit of a synchronized secondary in a manner similar to how it affects a single body. Under favorable circumstances it may work on timescales as short as 10^5 yr, dominating tidal evolution (damping e and synchronizing P_s) in some situations. In fact, YORP may be overly efficient, and could destroy binaries too quickly (causing separation or contact), unless the binary can be driven to a YORP-stable state (Ćuk & Burns 2005). We would expect to see a signature of this effect in the orbital parameters of the binary if YORP plays a significant evolutionary role.

4. CONCLUSIONS

We have reviewed the status of binary minor planet observations and theories as they currently stand. Inevitably we have omitted many details; the interested reader is encouraged to consult the references provided. In summary, binaries have been found in various minor planet populations using a variety of techniques, including adaptive-optics direct imaging from the ground, analysis of photometric lightcurve data, and radar sensing and imaging. It appears a different binary formation scenario is needed for each population, with rotational disruption induced by planetary tidal encounters or thermal torquing effects favored for binary NEAs, impact followed by reaccumulation and capture for (present-day) formation of binary MBAs, and perhaps early mutual gravitational capture by multi-body dissipative processes for binary TNOs. The future likely holds many more discoveries as observing facilities and techniques improve. As the sample of BMPs grows, true trends will be distinguished from selection effects, and the presence or absence of correlations will be strengthened. New data will spawn new theories, and simulation methods will become more sophisticated. This is a rich field for observers and theorists alike and will continue to provide challenges and surprises in the years to come.

5. ACKNOWLEDGMENTS

This review would not have been possible without the assistance of the following individuals: M. A'Hearn, L. Benner, W. Bottke, D. Durda, D. Hamilton, A. Harris (SSI), J-L. Margot, W. Merline, P. Pravec, A. Raugh, D. Scheeres, and the BMP community in general. Any errors/omissions are our own. This material is based in part upon work supported by the National Science Foundation under Grant No. AST0307549.

6. Chapter Components

6.1. Key Words

1. asteroids
2. comets
3. evolution
4. origin
5. satellites

6.2. Abstract

A review of observations and theories regarding binary asteroids and binary transneptunian objects (collectively, binary minor planets) is presented. To date, these objects have been discovered using a combination of direct imaging, lightcurve analysis, and radar. They are found throughout the solar system, and present a challenge for theorists modeling their formation in the context of solar system evolution. The most promising models invoke rotational disruption for the smallest, shortest-lived objects (the asteroids nearest to Earth)—consistent with the observed fast rotation of these bodies; impacts for the larger, longer-lived asteroids in the main belt—consistent with the range of size ratios of their components and slower rotation rates; and mutual capture for the distant, icy, transneptunian objects—consistent with their large component separations and near-equal sizes. Numerical simulations have successfully reproduced key features of the binaries in the first two categories; the third remains to be investigated in detail.

6.3. Glossary

1. Barycenter: the center of mass of a system of two or more gravitationally bound objects.
2. Binary: two objects orbiting a common barycenter.
3. Gravitational aggregate: a self-gravitating object with low tensile strength (unable to resist stretching forces); may have a shattered or rubblized structure.
4. Hill sphere: a region around a massive celestial body outside of which a test particle will be gravitationally stripped from the body due to solar tides.
5. Perihelion: close-approach distance to the Sun.
6. Roche radius: distance inside of which a perfect self-gravitating fluid body in a circular orbit around a massive body can no longer maintain an equipotential surface.
7. Rubble pile: a gravitational aggregate with moderate porosity.
8. Yarkovsky effect: anisotropic re-radiation of thermal energy following solar heating of a body, resulting in a net torque on the body's orbit.
9. YORP effect: like the Yarkovsky effect, except the torque also affects the (non-spherical) body's spin.

6.4. Acronyms

1. AO—Adaptive Optics
2. BMP—Binary Minor Planet
3. HST—Hubble Space Telescope
4. KBO—Kuiper-Belt Object
5. MBA—Main-Belt Asteroid
6. NEA—Near-Earth Asteroid
7. SL9—Comet D/Shoemaker-Levy 9
8. SPH—Smoothed Particle Hydrodynamics

9. TNO—TransNeptunian Object
10. YORP—Yarkovsky-O'Keefe-Radzievskii-Paddack (coined by Rubincam 2000)

6.5. Summary

1. Since the first confirmed discovery of a binary asteroid in 1993, 60 binary minor planets (BMPs) have been found. Of these, 24 are near-Earth asteroids (NEAs), 22 are main-belt asteroids (MBAs, plus 1 Jupiter Trojan), and 13 are transneptunian objects (TNOs, not counting Pluto-Charon). Current estimates suggest that $\sim 15\%$ of NEAs, $\sim 2\%$ of MBAs, and $\sim 5\%$ of TNOs are binaries.
2. The principal techniques for finding BMPs include: direct imaging by spacecraft, ground-based telescopes, or the Hubble Space Telescope; photometric detection via lightcurvesl; and radar.
3. It is likely that different mechanisms are responsible for forming binaries in the different minor planet populations: rotational disruption for NEAs; impact for MBAs; and dynamical capture for TNOs.
4. Measured ranges in binary component size, spin, and separation help constrain the origin and likely future evolution of the binaries seen so far, and provide insight into the composition and internal structure of small bodies as a whole, important clues for understanding the origin of the solar system.

6.6. Future Directions

1. More observations and simulations are needed to determine whether biases seen between BMP populations are real or a result of selection effects. Many tentative detections need to be followed up.
2. Theories need to be refined in light of the increasing wealth of observational data. Formation theories for TNOs in particular are still fairly speculative. More sophisticated numerical simulations are needed to account for realistic body and fragment shapes.
3. The promise of future detection of wide-separation eccentric binaries, triple or multiple systems, and binaries in certain stable resonant states ensures BMPs will remain an exciting topic of study throughout the next decade.

6.7. Annotated References

1. Durda et al. (2004): most comprehensive numerical study to date of the collisional origin of binary MBAs.
2. Margot et al. (2002): summary article on the first binary asteroids discovered by radar.
3. Merline et al. (2002c): first review of binary asteroids after discovery of Ida/Dactyl.
4. Pravec et al. (2005b): complete summary of all photometric (lightcurve) observations of binary NEAs to date.
5. Walsh & Richardson (2005): most comprehensive numerical study to date of the rotational disruption origin of binary NEAs.

6.8. Side Bars

[no suggestions]

6.9. Related Annual Reviews Chapters

1. Bottke WF Jr. 2006. The Meteorite-Asteroid Connection (Yarkovsky Effect). *Ann. Rev. Earth Planet. Sci.* In press (vol. 34)
2. Luu JX, Jewitt DC. 2002. KUIPER BELT OBJECTS: relics from the accretion disk of the Sun. *Ann. Rev. Astron. Astrophys.* 40:63–101
3. Ryan EV. 2000. Asteroid fragmentation and evolution of asteroids. *Ann. Rev. Earth Planet. Sci.* 28:367–389
4. Chapman CR, Williams JG, Hartmann WK. 1978. The asteroids. *Ann. Rev. Astron. Astrophys.* 16:33–75
5. Marsden BG. 1974. Comets. *Ann. Rev. Astron. Astrophys.* 12:1–22

7. Figure Legends

Figure 1: (Top) Binary system separation in units of primary radii as a function of binary perihelion. Circle sizes are proportional to $\log(D_p)$. Color coding is as follows: black: binary NEAs (perihelia $\lesssim 1.3$ AU); red: binary MBAs ($1.8 \lesssim a_{\rm CM} \lesssim 4.2$ AU); magenta: the single binary Jupiter Trojan ($a_{\rm CM} \sim 5.2$ AU); blue: binary TNOs ($a_{\rm CM} \gtrsim 30$ AU); green: Pluto-Charon ($a_{\rm CM} \sim 39.5$ AU). (Bottom) Binary perihelion vs system separation in units of the mutual Hill sphere.

Figure 2: (Top) Binary perihelion vs primary spin period, where known (see Figure 1 caption for scaling and color coding). (Bottom) Binary perihelion vs size ratio (D_s/D_p), where known.

Figure 3: Snapshots of the tidal disruption of a rubble-pile asteroid as it passes close to Earth. The arrows in the final frame point to substantial reaccumulated bodies orbiting the largest remnant.

8. LITERATURE CITED

A'Hearn MF. 2002. Pluto: a planet or a trans-Neptunian object? In *Highlights of Astronomy*, ed. H Rickman, 12:201–4. San Francisco: Astron. Soc. Pacific

A'Hearn MF, Belton MJS, Delamere A, Blume WH. 2005. Deep Impact: a large-scale active experiment on a cometary nucleus. *Space Sci. Rev.* In press

Agnor CB, Hamilton DP. 2005. Satellite capture via binary exchange reactions: application to Triton. *Bull. Am. Astron. Soc.* DDA Meeting #37:11.05 (Abstr.)

André C. 1901. Sur le système formé par la planète double (433) Eros. *Astron. Nachr.* 155:27–30

Asphaug E, Benz W. 1994. Density of comet Shoemaker-Levy 9 deduced by modelling breakup of the parent "rubble pile." *Nature* 370:120–24

Asphaug E, Ostro SJ, Hudson RS, Scheeres DJ, Benz W. 1998. Disruption of kilometre-sized asteroids by energetic collisions. *Nature* 393:437–40

Behrend R. 2004. (4492) Debussy. IAU Circular No. 8354

Behrend R, Bernasconi L, Klotz A, Durkee R. 2004a. (854) Frostia. IAU Circular No. 8389

Behrend R, Roy R, Rinner C, Antonini P, Pravec P. 2004b. (1089) Tama. IAU Circular No. 8265

Behrend R, Roy R, Sposetti S, Waelchli N, Pray D, Berger N et al. 2004c. (1313) Berna. IAU Circular No. 8292

Belton M, Carlson R. 1994. 1993 (243) 1. IAU Circular No. 5948

Belton MJS, Chapman CR, Thomas PC, Davies ME, Greenberg R, et al. 1995. Bulk density of asteroid 243 Ida from the orbit of its satellite Dactyl. *Nature* 374:785–88

Belton MJS, Mueller BEA, D'Amario L, Byrnes DV, Klaasen KP, et al. 1996. The discovery and orbit of 1993 (243) 1 Dactyl. *Icarus* 120:185–99

Belton MJS, Veverka J, Thomas P, Helfenstein P, Simonelli D, et al. 1992. Galileo encounter with 951 Gaspra—first pictures of an asteroid. *Science* 257:1647–52

Benner LAM, Hudson RS, Ostro SJ, Rosema KD, Giorgini JD, et al. 1999. Radar observations of asteroid 2063 Bacchus. *Icarus* 139:309–27

Benner LAM, Nolan MC, Carter LM, Ostro SJ, Giorgini JD, et al. 2004a. Radar imaging of near-Earth asteroid 11066 Sigurd. *Bull. Am. Astron. Soc.* DPS Meeting #36:32.29 (Abstr.)

Benner LAM, Nolan MC, Margot JL, Ostro SJ, Giorgini JD. 2003. Radar imaging of binary near-Earth asteroid 1998 ST27. *Bull. Am. Astron. Soc.* DPS Meeting #35:24.01 (Abstr.)

Benner LAM, Nolan MC, Ostro SJ, Giorgini JD, Magri C, Margot J-L. 2005. Near-Earth asteroid 2005 CR_{37}: radar images of a candidate contact binary. *Icarus* In press

Benner LAM, Nolan MC, Ostro SJ, Giorgini JD, Margot J-L. 2001a. 1998 ST_{27}. IAU Circular No. 7730

Benner LAM, Nolan MC, Ostro SJ, Giorgini JD, Margot J-L, Magri C. 2004b. 1999 DJ_4. IAU Circular No. 8329

Benner LAM, Ostro SJ, Giorgini JD, Jurgens RF, Margot J-L, Nolan MC. 2001b. 1999 KW_4. IAU Circular No. 7632

Benz W, Asphaug E. 1995. Simulations of brittle solids using smooth particle hydrodynamics. *Comput. Phys. Commun.* 87:253–65.

Bottke WF Jr, Cellino A, Paolicchi P, Binzel RP, ed. 2002a. *Asteroids III.* Tucson: Univ. of Arizona Press. 785 pp.

Bottke WF Jr, Durda DD, Nesvorný D, Jedicke R, Morbidelli A, et al. 2005. The fossilized size distribution of the main asteroid belt. *Icarus* 175:111–40

Bottke WF Jr, Jedicke R, Morbidelli A, Petit J-M, Gladman B. 2000. Understanding the distribution of near-Earth asteroids. *Science* 288:2190–94

Bottke WF Jr, Melosh HJ. 1996a. The formation of asteroid satellites and doublet craters by planetary tidal forces. *Nature* 381:51–53

Bottke WF Jr, Melosh HJ. 1996b. The formation of binary asteroids and doublet craters. *Icarus* 124:372–91

Bottke WF Jr, Morbidelli A, Jedicke R, Petit J-M, Levison HF, et al. 2002b. Debiased orbital and absolute magnitude distribution of the near-Earth objects. *Icarus* 156:399–433

Bottke WF Jr, Nolan M, Greenberg R. 1994a. Velocity distributions among colliding asteroids. *Icarus* 107:255–68

Bottke WF Jr, Nolan MC, Greenberg R, Kolvoord RA. 1994b. Collisional lifetimes and impact statistics of near-Earth asteroids. In *Hazards Due to Comets and Asteroids*, ed. T Gehrels, MS Matthews, A Schumann, pp. 337–57. Tucson: Univ. of Arizona Press

Bottke WF Jr, Vokrouhlický D, Rubincam DP, Brož M. 2002c. The effect of Yarkovsky thermal forces on the dynamical evolution of asteroids and meteoroids. See Bottke et al. 2002a, pp. 395–408

Brown ME, Margot J-L. 2001. S/2001 (87) 1. IAU Circular No. 7588

Brown ME, Trujillo CA. 2002. (26308) 1998 SM_{165}. IAU Circular No. 7807

Canup RM. 2005. A giant impact origin of Pluto-Charon. *Science* 307:546–50

Chandrasekhar S. 1969. *Ellipsoidal Figures of Equilibrium.* New Haven, CT: Yale University. 252 pp.

Chapman CR, Veverka J, Thomas PC, Klaasen K, Belton MJS, et al. 1995. Discovery and physical properties of Dactyl, a satellite of asteroid 243 Ida. *Nature* 374:783–85

Chauvineau B, Farinella P, Harris AW. 1995. The evolution of Earth-approaching binary asteroids: a Monte Carlo dynamical model. *Icarus* 115:36–46

Chauvineau B, Farinella P, Mignard F. 1993. Planar orbits about a triaxial body: applications to asteroidal satellites. *Icarus* 105:370–84

Chesley SR, Ostro SJ, Vokrouhlický D, Capek D, Giorgini JD. 2003. Direct detection of the Yarkovsky effect by radar ranging to asteroid 6489 Golevka. *Science* 302:1739–42

Christy JW, Harrington RS. 1978. The satellite of Pluto. *Astron. J.* 83:1005–8

Doressoundiram A, Paolicchi P, Verlicchi A, Cellino A. 1997. The formation of binary asteroids as outcomes of catastrophic collisions. *Planet. Space Sci.* 45:757–70

Duncan M, Quinn T, Tremaine S. 1988. The origin of short-period comets. *Astrophys. J. Lett.* 328:L69–73

Durda DD. 1996. The formation of asteroidal satellites in catastrophic collisions. *Icarus* 120:212–19

Durda DD, Bottke WF Jr, Enke BL, Merline WJ, Asphaug E, et al. 2004. The formation of asteroid satellites in large impacts: results from numerical simulations. *Icarus* 167:382–96. Erratum. 2004. *Icarus* 170:242. Reprinted article. 2004. *Icarus* 170:243–57

Elliot JL, Kern SD, Clancy KB. 2003. 2003 QY_{90}. IAU Circular No. 8235

Elliot JL, Kern SD, Osip DJ, Burles SM. 2001. 2001 QT_{297}. IAU Circular No. 7733

Farnham TL, Schleicher DG, Woodney LM, Birch PV, Eberhardy CA, Levy L. 2001. Imaging and photometry of comet C/1999 S4 (LINEAR) before perihelion and after breakup. *Science* 292:1348–54

Funato Y, Makino J, Hut P, Kokubo E, Kinoshita D. 2004. The formation of Kuiper-belt binaries through exchange reactions. *Nature* 427:518–20

Gehrels T, ed. 1979. *Asteroids.* Tucson: Univ. of Arizona Press. 1181 pp.

Gladman B, Michel P, Froeschlé C. 2000. The near-Earth object population. *Icarus* 146:176–89

Gladman B, Migliorini F, Morbidelli A, Zappalà V, Michel P, et al. 1997. Dynamical lifetimes of objects injected into asteroid belt resonances. *Science* 277:197–201

Goldreich P, Lithwick Y, Sari R. 2002. Formation of Kuiper-belt binaries by dynamical friction and three-body encounters. *Nature* 420:643–46

Goldreich P, Soter S. 1966. Q in the solar system. *Icarus* 5:375–89

Hamilton DP, Burns JA. 1991. Orbital stability zones about asteroids. *Icarus* 92:118–31

Harris AW. 1996. The rotation rates of very small asteroids: evidence for “rubble pile” structure. *Bull. Am. Astron. Soc.* DDA Meeting #27:5.01 (Abstr.)

Harris AW. 2002. On the slow rotation of asteroids. *Icarus* 156:184–90

Harris AW, Young JW, Dockweiler Thor, Gibson J, Poutanen M, Bowell E. 1992. Asteroid lightcurve observations from 1981. *Icarus* 95:115–47

Hartmann WK. 1979. Diverse puzzling asteroids and a possible unified explanation. See Gehrels 1979, pp. 466–79

Hartmann WK, Cruikshank DP. 1978. The nature of Trojan asteroid 624 Hektor. *Icarus* 36:353–66

Hu W, Scheeres DJ. 2004. Numerical determination of stability regions for orbital motion in uniformly rotating second degree and order gravity fields. *Planet. Space Sci.* 52:685–92

Kavelaars JJ, Petit J-M, Gladman B, Holman M. 2001. 2001 QW_{322}. IAU Circular No. 7749

Kern SD, Elliot JL. 2005. 2005 EO_{304}. IAU Circular No. 8526

Leinhardt ZM, Richardson DC. 2005. A fast method for finding bound systems in numerical simulations: results from the formation of asteroid binaries. *Icarus.* In press

Leinhardt ZM, Richardson DC, Quinn T. 2000. Direct N-body simulations of rubble pile collisions. *Icarus* 146:133–51

Marchis F, Berthier J, Clergeon C, Descamps P, Hestroffer D, et al. 2005. On the diversity of binary asteroid orbits. *Asteroids, Comets, and Meteors: ACM 2005.* In press

Marchis F, Descamps P, Hestroffer D, Berthier J, de Pater I. 2004a. Fine analysis of 121 Hermione, 45 Eugenia, and 90 Antiope binary asteroid systems with AO observations. *Bull. Am. Astron. Soc.* DPS Meeting #36:46.02 (Abstr.)

Marchis F, Descamps P, Hestroffer D, Berthier J, Vachier F. 2003. A three-dimensional solution for the orbit of the asteroidal satellite of 22 Kalliope. *Icarus* 165:112–20

Marchis F, Laver C, Berthier J, Descamps P, Hestroffer D, et al. 2004b. (121) Hermione. IAU Circular No. 8264

Margot J-L. 2003. S/2003 (379) 1. IAU Circular No. 8182

Margot J-L, Brown ME. 2001. S/2001 (22) 1. IAU Circular No. 7703

Margot J-L, Brown ME. 2003. A low-density M-type asteroid in the main belt. *Science* 300:1939–42

Margot JL, Brown ME, Trujillo CA, Sari R. 2004. HST observations of Kuiper Belt binaries. *Bull. Am. Astron. Soc.* DPS Meeting #36:08.03 (Abstr.)

Margot J-L, Nolan MC, Benner LAM, Ostro SJ, Jurgens RF, et al. 2002. Binary asteroids in the near-Earth object population. *Science* 296:1445–48

Margot J-L, Nolan MC, Negron V, Hine AA, Campbell DB, et al. 2003. 1937 UB (HERMES). IAU Circular No. 8227

Melosh HJ, Stansberry JA. 1991. Doublet craters and the tidal disruption of binary asteroids. *Icarus* 94:171–79

Merline WJ, Chapman CR, Robinson M, Veverka J, Harch A, et al. 1998. NEAR's encounter with 253 Mathilde: search for satellites. *Proc. Lunar Planet. Sci. Conf.* 29th:#1954 (Abstr.)

Merline WJ, Close LM, Dumas C, Chapman CR, Ménard F, et al. 2003a. Discovery of new asteroid binaries (121) Hermione and (1509) Esclangona. *Bull. Am. Astron. Soc.* DPS Meeting #35:31.06 (Abstr.)

Merline WJ, Close LM, Dumas C, Chapman CR, Roddier F, et al. 1999a. S/1998 (45) 1. IAU Circular No. 7129

Merline WJ, Close LM, Dumas C, Chapman CR, Roddier F, et al. 1999b. Discovery of a moon orbiting the asteroid 45 Eugenia. *Nature* 401:565–68

Merline WJ, Close LM, Dumas C, Shelton JC, Ménard F, et al. 2000a. Discovery of companions to asteroids 762 Pulcova and 90 Antiope by direct imaging. *Bull. Am. Astron. Soc.* DPS Meeting #32:13.06 (Abstr.)

Merline WJ, Close LM, Shelton JC, Dumas C, Ménard F, et al. 2000b. SATELLITES OF MINOR PLANETS. IAU Circular No. 7503

Merline WJ, Close LM, Siegler N, Dumas C, Chapman C, et al. 2002a. S/2002 (3749) 1. IAU Circular No. 7827

Merline WJ, Close LM, Siegler N, Potter D, Chapman CR, et al. 2001a. S/2001 (617) 1. IAU Circular No. 7741

Merline WJ, Close LM, Tamblyn PM, Ménard F, Chapman CR, et al. 2003b. S/2003 (1509) 1. IAU Circular No. 8075

Merline WJ, Dumas C, Siegler N, Close LM, Chapman CR, et al. 2003c. S/2003 (283) 1. IAU Circular No. 8165

Merline WJ, Ménard F, Close L, Dumas C, Chapman CR, Slater DC. 2001b. S/2001 (22) 1. IAU Circular No. 7703

Merline WJ, Tamblyn PM, Chapman CR, Colwell WB, Gor V, et al. 2001c. An automated search for moons during approach of the NEAR spacecraft to asteroid Eros. *Proc. 6th Internation Symposium on Artificial Intelligence, Robotics, and Automation in Space, 2001 (Montreal)* CD-ROM:#AM128

Merline WJ, Tamblyn PM, Chapman CR, Nesvorný D, Durda DD, et al. 2003d. S/2003 (22899) 1. IAU Circular No. 8232

Merline WJ, Tamblyn PM, Dumas C, Close LM, Chapman CR, et al. 2002b. S/2002 (121) 1. IAU Circular No. 7980

Merline WJ, Tamblyn PM, Dumas C, Close LM, Chapman CR, Ménard F. 2003e. S/2003 (130) 1. IAU Circular No. 8183

Merline WJ, Tamblyn PM, Dumas C, Ménard F, Close LM, et al. 2004a. S/2004 (4674) 1. IAU Circular No. 8297

Merline WJ, Tamblyn PM, Nesvorný D, Durda DD, Chapman CR, et al. 2004b. Discovery of binaries among small asteroids in the Koronis dynamical family using the HST Advanced Camera for Surveys. *Bull. Am. Astron. Soc.* DPS Meeting #36:46.01 (Abstr.)

Merline WJ, Weidenschilling SJ, Durda DD, Margot J-L, Pravec P, Storrs AD. 2002c. Asteroids *do* have satellites. See Bottke et al. 2002a, pp. 289–312

Michel P, Benz W, Richardson DC. 2001. Collisions and gravitational reaccumulation: forming asteroid families and satellites. *Science* 294:1696–700

Michel P, Benz W, Richardson DC. 2004. Catastrophic disruption of asteroids and family formation: a review of numerical simulations including both fragmentation and gravitational reaccumulations. *Planet. Space Sci.* 52:1109–17

Millis RL, Clancy KB. 2003. 2003 UN_{284}. IAU Circular No. 8251

Mottola S, Hahn G, Pravec P, Šarounová L. 1997. S/1997 (3671) 1. IAU Circular No. 6680

Mottola S, Lahulla F. 2000. Mutual eclipse events in asteroidal binary system 1996 FG_3: observations and a numerical model. *Icarus* 146:556–67

Neish CD, Nolan MC, Howell ES, Rivkin AS. 2003. Radar observations of binary asteroid 5381 Sekhmet. *Bull. Am. Astron. Soc.* AAS Meeting #203:134.02 (Abstr.)

Nesvorný D, Bottke WF Jr, Dones L, Levison HF. 2002. The recent breakup of an asteroid in the main-belt region. *Nature* 417:720–22

Nolan MC, Hine AA, Howell ES, Benner LAM, Giorgini JD. 2003. 2003 SS_{84}. IAU Circular No. 8220

Nolan MC, Howell ES, Hine AA, Galad A, Gajdos S, et al. 2004. 2003 YT_1. IAU Circular No. 8336

Nolan MC, Howell ES, Magri C, Beeney B, Campbell DB, et al. 2002a. 2002 BM_{26}. IAU Circular No. 7824

Nolan MC, Howell ES, Ostro SJ, Benner LAM, Giorgini JD, et al. 2002b. 2002 KK_8. IAU Circular No. 7921

Nolan MC, Howell ES, Rivkin AS, Neish CD. 2003. (5381) Sekhmet. IAU Circular No. 8163

Nolan MC, Margot J-L, Howell ES, Benner LAM, Ostro SJ, et al. 2000. 2000 UG_{11} . IAU Circular No. 7518

Noll KS, Stephens DC, Cruikshank W, Grundy W, Romanishin W, Tegler S. 2003. 1999 RZ_{253}. IAU Circular No. 8143

Noll KS, Stephens DS, Grundy WM, Cruikshank D, Tegler S, et al. 2002a. 2001 QC_{298}. IAU Circular No. 8034

Noll KS, Stephens DS, Grundy WM, Griffin I. 2004a. The orbit, mass, and albedo of transneptunian binary (66652) 1999 RZ_{253}. *Icarus* 172:402–07

Noll KS, Stephens DS, Grundy WM, Osip DJ, Griffin I. 2004b. The Orbit and Albedo of Trans-Neptunian Binary (58534) 1997 CQ_{29}. *Astron. J.* 128:2547–52

Noll KS, Stephens DC, Grundy W, Spencer J, Millis R, et al. 2002b. 1997 CQ_{29}. IAU Circular No. 7824

Noll KS, Stephens DC, Grundy W, Spencer J, Millis R, et al. 2002c. 2000 CF_{105} . IAU Circular No. 7857

Osip DJ, Kern SD, Elliot JL. 2003. Physical characterization of the binary Edgeworth-Kuiper belt object 2001 QT_{297}. *Earth Moon Planets* 92:409–21

Ostro SJ, Chandler JF, Hine AA, Shapiro II, Rosema KD, Yeomans DK. 1990. Radar images of asteroid 1989 PB. *Science* 248:1523–28

Ostro SJ, Hudson RS, Benner LAM, Giorgini JD, Magri C, et al. 2002. Asteroid radar astronomy. See Bottke et al. 2002a, pp. 151–68.

Ostro SJ, Hudson RS, Jurgens RF, Rosema KD, Campbell DB, et al. 1995. Radar images of asteroid 4179 Toutatis. *Science* 270:80–83

Ostro SJ, Hudson RS, Nolan MC, Margot J-L, Scheeres DJ, et al. 2000a. Radar observations of asteroid 216 Kleopatra. *Science* 288:836–39

Ostro SJ, Margot J-L, Nolan MC, Benner LAM, Jurgens RF, Giorgini JD. 2000b. 2000 DP_{107}. IAU Circular No. 7496

Ostro SJ, Nolan MC, Benner LAM, Giorgini JD, Margot JL, et al. 2003. 1990 OS. IAU Circular No. 8237

Paolicchi P, Burns JA, Weidenschilling SJ. 2002. Side effects of collisions: spin rate changes, tumbling rotation states, and binary asteroids. See Bottke et al. 2002a, pp. 517–526.

Petit J-M, Mousis O. 2004. KBO binaries: how numerous were they? *Icarus* 168:409–19

Pravec P, Benner LAM, Nolan MC, Kušnirák P, Pray D, et al. 2002a. (65803) 1996 GT. IAU Circular No. 8244

Pravec P, Hahn G. 1997. Two-period lightcurve of 1994 AW_1: indication of a binary asteroid? *Icarus* 127:431–40

Pravec P, Harris AW. 2000. Fast and slow rotation of asteroids. *Icarus* 148:12–20

Pravec P, Harris AW, Michalowski T. 2002b. Asteroid rotations. See Bottke et al. 2002a, pp. 113–22

Pravec P, Harris AW, Scheirich P, Kušnirák P, Šarounová L, et al. 2005a. Tumbling asteroids. *Icarus* 173:108–31

Pravec P, Kušnirák P, Hicks M, Holliday B, Warner B. 2000a. 2000 DP_{107}. IAU Circular No. 7503

Pravec P, Kušnirák P, Šarounová L, Brown P, Esquerdo G, et al. 2003. (66063) 1998 RO_1. IAU Circular No. 8216

Pravec P, Kušnirák P, Šarounová L, Brown P, Kaiser N, et al. 2004. 1999 DJ_4. IAU Circular No. 8316

Pravec P, Kušnirák P, Warner B. 2001. 2001 SL_9. IAU Circular No. 7742

Pravec P, Šarounová L, Hicks MD, Rabinowitz DL, Wolf M, et al. 2002c. Two periods of 1999 HF_1—another binary NEA candidate. *Icarus* 158:276–80

Pravec P, Šarounová L, Rabinowitz DL, Hicks MD, Wolf MD, et al. 2000b. Two-period lightcurves of 1996 FG_3, 1998 PG, and (5407) 1992 AX: one probable and two possible binary asteroids. *Icarus* 146:190–203

Pravec P, Scheirich P, Kušnirák P, Šarounová L, Mottola S, et al. 2005b. Photometric survey of binary near-Earth asteroids. *Icarus.* In press

Pravec P, Wolf M, Šarounová L. 1998. Occultation/Eclipse Events in Binary Asteroid 1991 VH. *Icarus* 133:79–88

Reddy V, Dyvig R, Pravec P, Kušnirák P. 2005. 2005 AB. IAU Circular No. 8483

Richardson DC, Bottke WF Jr, Love SG. 1998. Tidal distortion and disruption of Earth-crossing asteroids. *Icarus* 134:47–76

Richardson DC, Elankumaran P, Sanderson RE. 2005. Numerical experiments with rubble piles: equilibrium shapes and spins. *Icarus* 173:349–61

Richardson DC, Leinhardt ZM, Melosh HJ, Bottke WF Jr, Asphaug E. 2002. Gravitational aggregates: evidence and evolution. See Bottke et al. 2002a, pp. 501–15.

Richardson DC, Quinn T, Stadel J, Lake G. 2000. Direct large-scale N-body simulations of planetesimal dynamics. *Icarus* 143:45–59

Rubincam DP. 2000. Radiative spin-up and spin-down of small asteroids. *Icarus* 148:2–11

Ryan WH, Ryan EV, Martinez CT. 2004. 3782 Celle: Discovery of a binary system within the Vesta family of asteroids. *Planet. Space Sci.* 52:1093–101

Ryan WH, Ryan EV, Martinez CT, Stewart L. 2003. (3782) Celle. IAU Circular No. 8128

Scheeres DJ. 1994. Dynamics about uniformly rotating tri-axial ellipsoids. *Icarus* 110:225–38

Scheeres DJ. 2002. Stability of binary asteroids. *Icarus* 159:271–83

Scheeres DJ, Durda DD, Geissler PE. 2002. The fate of asteroid ejecta. See Bottke et al. 2002a, pp. 527–44.

Shepard MK, Schlieder J Nolan MC, Hine AA, Benner LAM, et al. 2004. 2002 CE_{26}. IAU Circular No. 8397

Sheppard SS, Jewitt D. 2004. Extreme Kuiper belt object 2001 QG298 and the fraction of contact binaries. *Astron. J.* 127:3023–33

Stanzel R. 1978. Lightcurves and rotation period of minor planet 283 Emma. *Astron. Astrophys. Suppl.* 34:373–76

Stephens DC, Noll KS, Grundy W. 2004a. 2000 CQ_{114}. IAU Circular No. 8289

Stephens DC, Noll KS, Grundy W. 2004b. Second generation binary TNO search with HST. *Bull. Am. Astron. Soc.* DPS Meeting #36:17.06 (Abstr.)

Storrs A, Vilas F, Landis R, Wells E, Woods C, et al. 2001. S/2001 (107) 1. IAU Circular No. 7599

Tamblyn PM, Merline WJ, Chapman CR, Nesvorný D, Durda DD, et al. 2004. S/2004 (17246) 1. IAU Circular No. 8293

Tholen DJ, Buie MW. 1990. Further analysis of Pluto-Charon mutual event observations—1990. *Bull. Am. Astron. Soc.* DPS Meeting #22:25.14 (Abstr.)

Trujillo CA, Brown ME. 2002. 1999 TC_{36}. IAU Circular No. 7787

van Flandern TC, Tedesco EF, Binzel RP. 1979. Satellites of asteroids. See Gehrels 1979, pp. 443–65

Veillet C, Doressoundiram A, Shapiro J. 2001. S/2000 (1998 WW_{31}) 1. IAU Circular No. 7610

Veillet C, Parker JW, Griffin I, Marsden B, Doressoundiram A, et al. 2002. The binary Kuiper-belt object 1998 WW_{31}. *Nature* 416:711–13

Veverka J, Robinson M, Thomas P, Murchie S, Bell JF III, et al. 2000. NEAR at Eros: imaging and spectral results. *Science* 289:2088–97

Veverka J, Thomas P, Harch A, Clark B, Bell JF III, et al. 1999. NEAR encounter with asteroid 253 Mathlide: overview. *Icarus* 140:3–16

Vokrouhlický D, Capek D. 2002. YORP-induced long-term evolution of the spin state of small asteroids and meteoroids: Rubincam's approximation. *Icarus* 159:449–67

Vokrouhlický D, Nesvorný D, Bottke WF Jr. 2003. The vector alignments of asteroid spins by thermal torques. *Nature* 425:147–51

Walsh KJ, Ricardson DC. 2005. Binary near-Earth asteroid formation: rubble pile model of tidal disruptions. *Icarus.* In press

Warner B. 2004. *The Minor Planet Observer.* `http://www.minorplanetobserver.com/htms/pdo_lightcurves.htm`

Warner B, Pravec P, Kušnirák P, Pray D, Galad A, et al. 2005a. (5905) Johnson. IAU Circular No. 8511

Warner B, Pravec P, Harris AW, Galad A, Kušnirák P. 2005b. Binary Hungarias (5905) Johnson and (9069) Hovland: their relations to small binary Vestoids and NEAs. *Asteroids, Comets, and Meteors: ACM 2005.* In press

Weidenschilling SJ. 2002. On the origin of binary transneptunian objects. *Icarus* 160:212–15

Weidenschilling SJ, Paolicchi P, Zappalà V. 1989. Do asteroids have satellites? In *Asteroids II*, ed. RP Binzel, T Gehrels, MS Matthews, pp. 643–58. Tucson: Univ. of Arizona Press

Weissman PR, Richardson DC, Bottke WF Jr. 2003. Random disruption of cometary nuclei by rotational spin-up. *Bull. Am. Astron. Soc.* DPS Meeting #35:47.05 (Abstr.)

Table 1:: Orbital and physical properties for well-observed or suspected binary NEAs. The discovery techniques are (AO) adaptive optics, (HST) Hubble Space Telescope, (L) lightcurve, (R) radar, (SC) for spacecraft, and (T) ground-based telescope.

Binary	a_{CM} (AU)	e	D_{p} (km)	P_{p} (h)	a (km)	D_{s} (km)	P_{orb} (d)	Disc.	ref
(66391) 1999 KW_4	0.64	0.68	1.2	2.77	2.5	0.4	0.73	R	[1,2]
1998 ST_{27}	0.81	0.53	0.8	3.0	4.0	0.12		R	[3,4]
1999 HF_1	0.81	0.46	3.5	2.32	7.0	0.8	0.58	L	[2,5]
(5381) Sekhmet	0.94	0.29	1.0	2.7	1.5	0.3	0.52	R	[6,7]
(66063) 1998 RO_1	0.99	0.72	0.8	2.49	1.4	0.38	0.60	L	[2,8]
1996 FG_3	1.05	0.35	1.5	3.59	2.6	0.47	0.67	L	[2,9,10]
(88710) 2001 SL_9	1.06	0.27	0.8	2.40	1.4	0.22	0.68	L	[2,11]
1994 AW_1	1.10	0.07	1.0	2.52	2.1	0.5	0.93	L	[2,12]
2003 YT_1	1.10	0.29	1.0	2.34	2.7	0.18	1.25	L/R	[2,13]
(35107) 1991 VH	1.13	0.14	1.2	2.62	3.2	0.44	1.36	L	[2,14]
2000 DP_{107}	1.36	0.37	0.8	2.77	2.6	0.3	1.76	R	[2,15,16,17]
(65803) Didymos	1.64	0.38	0.8	2.26	1.1	0.17	0.49	L/R	[2,18]
(69230) Hermes	1.65	0.62	0.6	13.89			0.54	R	[2,19]
1990 OS	1.67	0.46	0.3		0.6	0.05	0.88	R	[20]
(5407) 1992 AX	1.83	0.27	3.9	2.55	6.8	0.78	0.56	L	[2,21]
2002 BM_{26}	1.83	0.44	0.6	2.7		0.1		R	[22]
(85938) 1999 DJ_4	1.85	0.48	0.4	2.51	1.5	0.17	0.74	L	[2,23,24]
2000 UG_{11}	1.92	0.57	0.2	4.44	0.4	0.08	0.77	R	[2,25]
2003 SS_{84}	1.93	0.57	0.1			0.06		R	[26]
2002 KK_8	1.95	0.46	0.5			0.1		R	[27]
(31345) 1998 PG	2.01	0.39	0.9	2.52	1.5	0.3		L	[2,28]
(3671) Dionysus	2.19	0.54	1.5	2.71	3.8	0.3	1.16	L	[2,29]
2002 CE_{26}	2.23	0.55	3.0	3.29	5.1	0.21	0.67	R	[2,30]
2005 AB	3.21	0.65		3.33			0.75	L	[31]
(4674) Pauling	1.86	0.07	8		250	2.5		AO	[32]
(1509) Esclangona	1.87	0.03	12	2.64	140	4		AO	[33,34]
(9069) Hovland	1.91	0.11	3	4.22		0.9		L	[35]
(5905) Johnson	1.91	0.07	3.6	3.783		1.44	1.16	L	[35,36]

Binary	$a_{\rm CM}$ (AU)	e	$D_{\rm p}$ (km)	$P_{\rm p}$ (h)	a (km)	$D_{\rm s}$ (km)	$P_{\rm orb}$ (d)	Disc.	ref
(1089) Tama	2.21	0.13	13	16.44	20	(9)	0.68	L	[37]
(3749) Balam	2.24	0.11	7		350	1.5	100	AO	[38,39]
(854) Frostia	2.36	0.17					1.57	L	[40]
(3782) Celle	2.41	0.09	6.1	3.84	36.57	2.6	1.52	L	[41,42]
(1313) Berna	2.65	0.20		25.464			1.061	L	[43]
(45) Eugenia	2.72	0.08	215	5.70	1190	13	4.69	AO	[39,44]
(4492) Debussy	2.76	0.17		26.59			1.11	L	[45]
(22899) 1999 $\rm TO_{14}$	2.84	0.08	4.5		170	1.5		HST	[46]
(17246) 2000 $\rm GL_{74}$	2.84	0.02	4.5		230	2		HST	[47]
(243) Ida	2.86	0.05	31	4.63	108	1.4	1.54	SC	[39,48]
(22) Kalliope	2.91	0.10	181	4.14	1020	38	3.58	AO	[49,50,51]
(283) Emma	3.04	0.15	148	6.88	600	12	3.36	AO	[52,53,54]
(130) Elektra	3.12	0.21	182	5.22	1250	4	3.9	AO	[52,55,56]
(379) Huenna	3.13	0.19	92	7.02	3400	(7)	81	AO	[54,57,58]
(90) Antiope	3.16	0.16	85	16.50	170	85	0.69	AO	[39,59]
(762) Pulcova	3.16	0.09	137	5.84	810	20	4.0	AO	[39,60]
(121) Hermione	3.43	0.14	209	5.55	775	13	2.57	AO	[61,62,63,64]
(107) Camilla	3.47	0.08	223	4.84	1240	9	3.71	HST	[39,65]
(87) Sylvia	3.49	0.07	261	5.18	1370	15	3.66	AO	[39,66]
(617)Patroclus	5.22	0.13	105		610	95	3.41	AO	[39,67]
Pluto/Charon	39.48	0.24	2302	153.29	19640	1186		T	[68,69]
(47171) 1999 $\rm TC_{36}$	39.53	0.22	147		7640	54	50.38	HST	[70,71]
2003 $\rm UN_{284}$	42.99	0.08	(252)		61,000	(192)		T	[72]
(66652) 1999 $\rm RZ_{253}$	43.58	0.08	316		4660	316	46.26	HST	[73,74]
2005 $\rm EO_{304}$	43.84	0.00	(270)		83,000	(156)		T	[75]
2000 $\rm CF_{105}$	44.20	0.04	170		23,000	106		HST	[39,76]
2001 $\rm QW_{322}$	44.22	0.03	200		130,000	200		T	[39,77]
(88611) 2001 $\rm QT_{297}$	44.80	0.03	196	9.50	31,409	136	876	T	[78,79]
1998 $\rm WW_{31}$	44.95	0.08	150		22,300	120	574	T	[39,80]
(58534) 1997 $\rm CQ_{29}$	45.34	0.12	80		8010	66	312	HST	[81,82]
2001 $\rm QC_{298}$	46.09	0.11	117		3690	98	19.23	HST	[71,83]
2000 $\rm CQ_{114}$	46.37	0.11	(240)		5880	(180)		HST	[84]
(26308) 1998 $\rm SM_{165}$	47.82	0.36	116	7.98	11,310	39	130.1	HST	[71,85]
2003 $\rm QY_{90}$	63.36	0.59	(240)		10,800	(230)		T	[86]

References: [1] Benner et al. (2001b); [2] Pravec et al. (2005b) and references therein; [3] Benner et al. (2001a); [4] Benner et al. (2003); [5] Pravec et al.(2002c); [6] Nolan et al. (2003); [7] Neish et al. (2003); [8] Pravec et al. (2003); [9] Pravec et al. (2000b); [10] Mottola & Lahulla (2000); [11] Pravec et al. (2001); [12] Pravec & Hahn (1997); [13] Nolan et al. (2004); [14] Pravec et al. (1998); [15] Ostro et al. (2000b); [16] Pravec et al. (2000a); [17] Margot et al. (2002); [18] Pravec et al. (2002a); [19] Margot et al. (2003); [20] Ostro et al. (2003); [21] Pravec et al. (2000b); [22] Nolan et al. (2002a); [23] Pravec et al. (2004); [24] Benner et al. (2004b); [25] Nolan et al. (2000); [26] Nolan et al. (2003); [27] Nolan et al. (2002b); [28] Pravec et al. (2000b); [29] Mottola et al. (1997); [30] Shepard et al. (2004); [31] Reddy et al. (2005); [32] Merline et al. (2004a); [33] Merline et al. (2003b); [34] Warner (2004); [35] Warner et al. (2005b); [36] Warner et al. (2005a); [37] Behrend et al. (2004b); [38] Merline et al. (2002a); [39] Merline et al. (2002c); [40] Behrend et al. (2004a); [41] Ryan et al. (2003); [42] Ryan et al. (2004); [43] Behrend et al. (2004c); [44] Merline et al. (1999a); [45] Behrend (2004); [46] Merline et al. (2003d); [47] Tamblyn et al. (2004); [48] Belton & Carlson (1994); [49] Merline et al. (2001b); [50] Margot & Brown (2001); [51] Marchis et al. (2003); [52] Marchis et al. (2005); [53] Merline et al. (2003c); [54] Stanzel (1978); [55] Merline et al. (2003e); [56] Magnusson & Lagerkvist (1990); [57] Margot (2003); [58] Harris et al. (1992); [59] Merline et al. (2000b); [60] Merline et al. (2000a); [61] Merline et al. (2002b); [62] Merline et al. (2003a); [63] Marchis et al. (2004a); [64] Marchis et al. (2004b); [65] Storrs et al. (2001); [66] Brown & Margot (2001); [67] Merline et al. (2001a); [68] Christy & Harrington (1978); [69] Tholen & Buie (1990); [70] Trujillo & Brown (2002); [71] Margot et al. (2004); [72] Millis et al. (2003); [73] Noll et al. (2003); [74] Noll et al. (2004a); [75] Kern & Elliot (2005); [76] Noll et al. (2002c); [77] Kavelaars et al. (2001); [78] Elliot et al. (2001);[79] Osip et al. (2003); [80] Veillet et al. (2001); [81] Noll et al. (2002b); [82] Noll et al. (2004b); [83] Noll et al. (2002a); [84] Stephens et al. (2004a); [85] Brown & Trujjilo (2002); [86] Elliot et al. (2003).

Figure 1

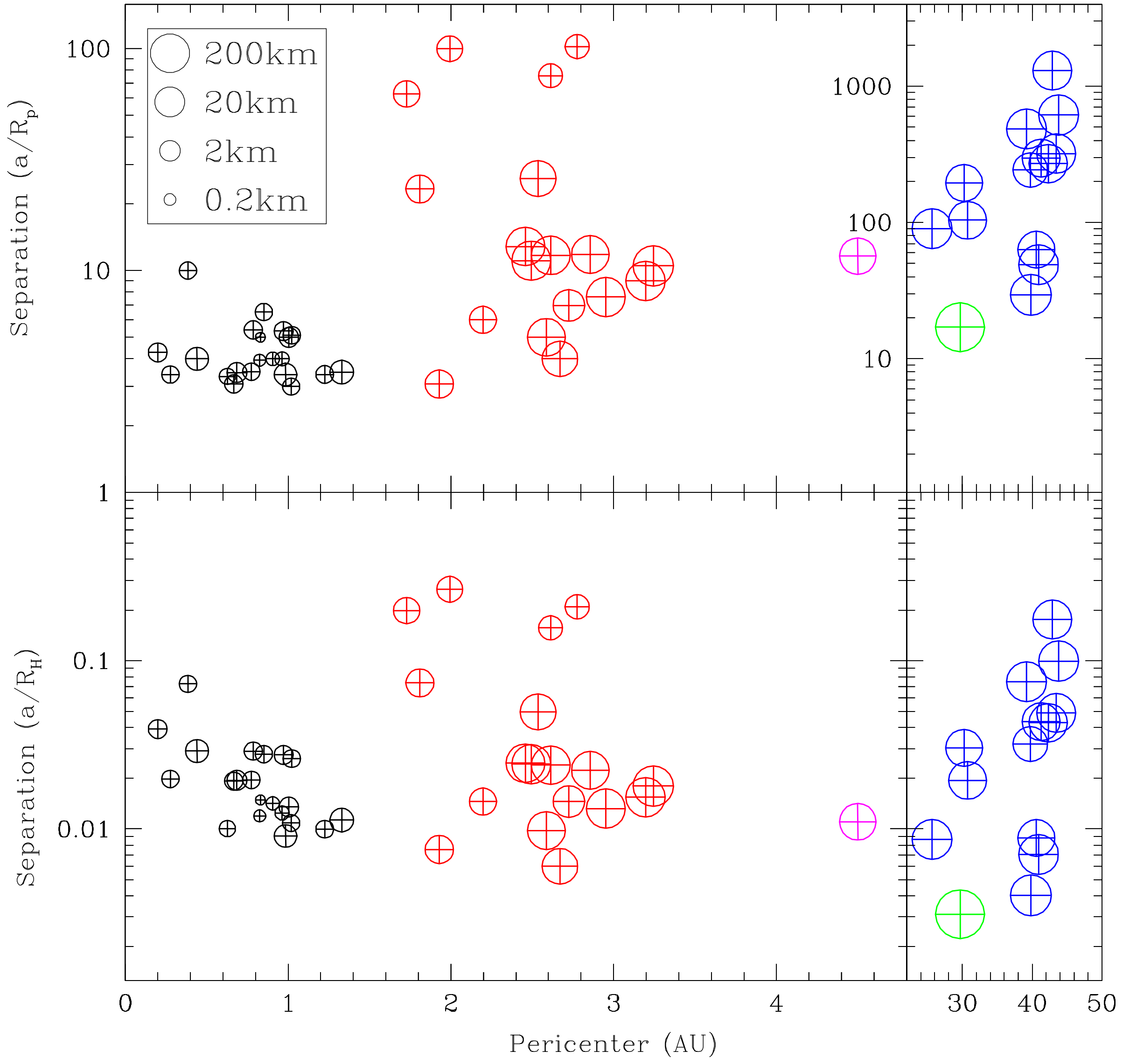
200km
20km
2km
0.2km
Separation (a/R$_p$)
100
10
1
1000
100
10
Separation (a/R$_H$)
0.1
0.01
0
1
2
3
4
30
40
50
Pericenter (AU)

Figure 2

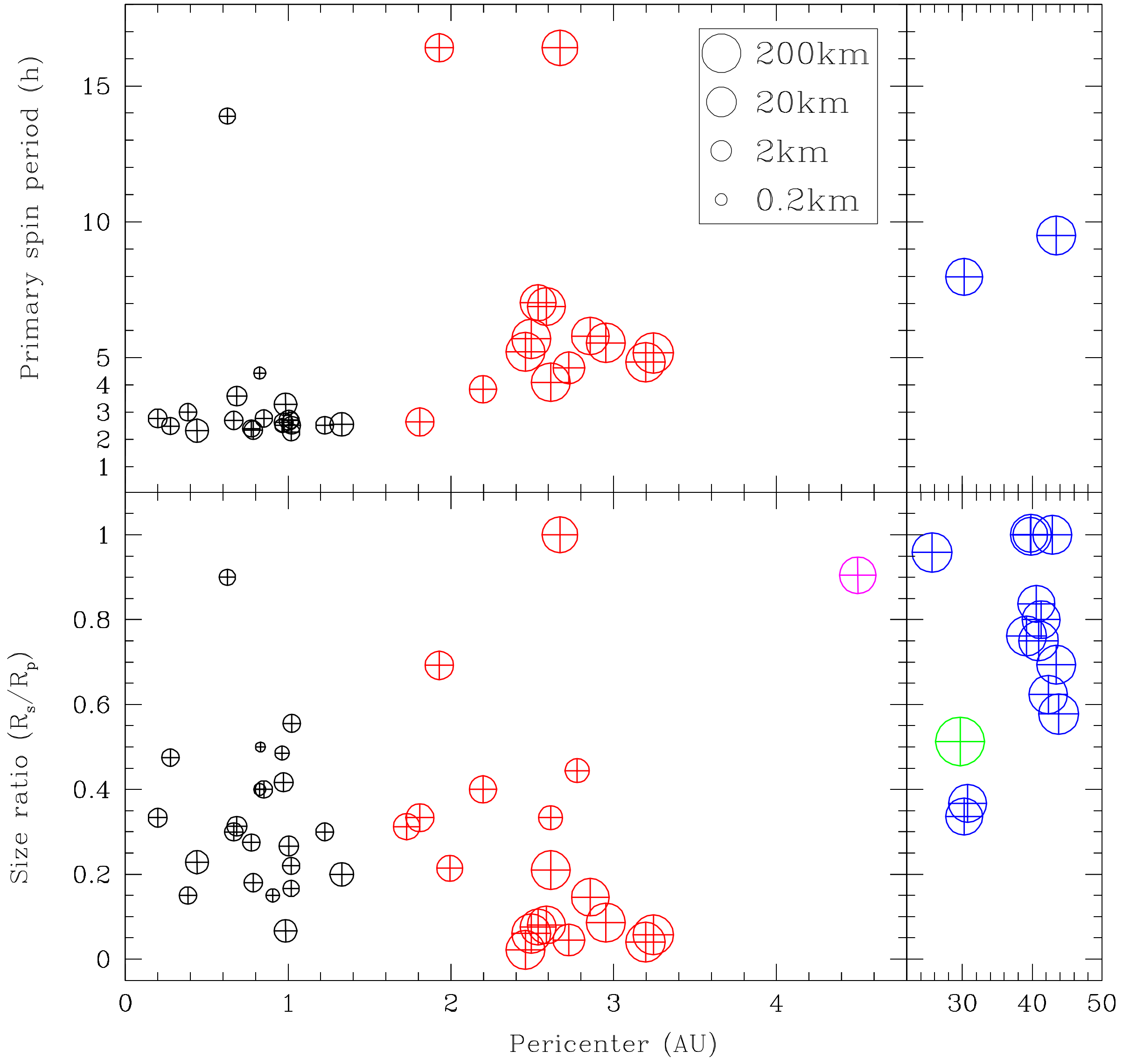
Primary spin period (h)
15
10
5
4
3
2
1
200km
20km
2km
0.2km
Size ratio (R_s/R_p)
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
30
40
50
Pericenter (AU)

Figure 3