

Binary Minor Planets

Derek C. Richardson and Kevin J. Walsh

Department of Astronomy, University of Maryland, College Park, Maryland 20740-2421;
email: dcr@astro.umd.edu, kwalsh@astro.umd.edu

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Key Words

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Abstract

A review of observations and theories regarding binary asteroids and binary trans-Neptunian objects [collectively, binary minor planets (BMPs)] 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, trans-Neptunian 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.

Binary: two objects orbiting a common barycenter

BMP: binary minor planet

MBA: main belt asteroid

NEA: near-Earth object

Perihelion: close-approach distance to the Sun

KBO: Kuiper Belt Object

TNO: trans-Neptunian object

INTRODUCTION

Binary asteroids and binary trans-Neptunian objects [collectively, binary minor planets (BMPs)] 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 familiarize the reader with the subject of 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 borrow from the detailed research conducted by those authors, augmenting it with new data, and taking a more theoretical approach to the subject.

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 billions of years 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 $\sim 60^\circ$ 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 trans-Neptunian objects (TNOs), are on more-or-less stable orbits beyond Neptune, but also include the Plutinos that, like Pluto, come inside Neptune's orbit but are protected from collision owing 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 BMP 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.¹

Although none have been definitively observed, minor planet systems of more than two components could exist, as suggested by numerical simulations.² We call these multiples following the same convention as for multiple stars. Hence a triple minor planet system is one consisting of three 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, Tanga et al. 2001, Hestroffer et al. 2002), 11066 Sigurd (an NEA; Benner et al. 2004a), one component of known binary 121 Hermione (an MBA; Marchis et al. 2004b, 2005c), 2001 QG₂₉₈ (a TNO Plutino; Sheppard & Jewitt 2004), and 2005 CR₃₇ (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

¹Note added in proof: Brown et al. (2005) recently announced the discovery of several large TNO binaries, including the 2003 UB₃₁₃ system (unofficially dubbed Xena-Gabrielle). The primary of this system is larger in radius than Pluto.

²Note added in proof: Marchis et al. (2005b) found a second companion interior to the known companion of 87 Sylvia, making this the first observed asteroid triple.

Barycenter: the center of mass of a system of two or more gravitationally bound objects

Hill sphere: a region around a massive celestial body outside of which a test particle will be gravitationally stripped from the body owing to solar tides

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

properties of these objects from rotation alone, such as the combined mass (usually only lower bounds can be obtained).

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 (Britt et al. 2002).

External perturbing forces, such as solar tides, major planet resonant interactions, thermal forces, etc., or internal forces arising between nonspherical, nonhomogeneous, 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 (for further discussion, see below).

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 $R_H = (M/3M_\odot)^{1/3} a_{CM}$ is the radius of the mutual Hill sphere, M_\odot is the mass of the Sun, and a_{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, $R_H \sim 150\text{--}200 R_p$, and scales linearly with a_{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 $\sim 2.5 R_p$. 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). 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, stable orbits are expected for $a \gtrsim 2-3 R_{p,\max}$, where $R_{p,\max}$ 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**).

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 January 1, 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 in the direct detection of extra-solar planets.

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 charge-coupled devices, coronagraphic 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). Owing 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 afterward, several more AO binary MBAs were announced. In the meantime, lightcurve techniques revealed possible binary asteroids in the NEA

Table 1 Orbital and physical properties for well-observed or suspected BMPs*

Binary	a_{CM} (AU)	e	D_p (km)	P_p (h)	a (km)	D_s (km)	P_{orb} (d)	Disc.	References
(66391) 1999 KW ₄	0.64	0.68	1.2	2.77	2.5	0.4	0.73	R	(Benner et al. 2001b, Pravec et al. 2005b and references therein)
1998 ST ₂₇	0.81	0.53	0.8	3.0	4.0	0.12		R	(Benner et al. 2001a, 2003)
1999 HF ₁	0.81	0.46	3.5	2.32	7.0	0.8	0.58	L	(Pravec et al. 2002c, 2005b and references therein)
(5381) Sekhmet	0.94	0.29	1.0	2.7	1.5	0.3	0.52	R	(Neish et al. 2003, Nolan et al. 2003)
(66063) 1998 RO ₁	0.99	0.72	0.8	2.49	1.4	0.38	0.60	L	(Pravec et al. 2003, 2005b and references therein)
1996 FG ₃	1.05	0.35	1.5	3.59	2.6	0.47	0.67	L	(Pravec et al. 2000b, 2005b and references therein; Mottola & Lahulla 2000)
(88710) 2001 SL ₉	1.06	0.27	0.8	2.40	1.4	0.22	0.68	L	(Pravec et al. 2001, 2005b and references therein)
1994 AW ₁	1.10	0.07	1.0	2.52	2.3	0.5	0.93	L	(Pravec & Hahn 1997, Pravec et al. 2005b and references therein)
2003 YT ₁	1.10	0.29	1.0	2.34	2.7	0.18	1.25	L/R	(Nolan et al. 2004, Pravec et al. 2005b and references therein)
(35107) 1991 VH	1.13	0.14	1.2	2.62	3.2	0.44	1.36	L	(Pravec et al. 1998, 2005b and references therein)
2000 DP ₁₀₇	1.36	0.37	0.8	2.77	2.6	0.3	1.76	R	(Ostro et al. 2000b; Pravec et al. 2000a, 2005b and references therein; Margot et al. 2002)
(65803) Didymos	1.64	0.38	0.8	2.26	1.1	0.17	0.49	L/R	(Pravec et al. 2002a, 2005b and references therein)
(69230) Hermes	1.65	0.62	0.6	13.89			0.58	R	(Margot et al. 2003, Pravec et al. 2005b and references therein)

(Continued)

Table 1 (Continued)

Binary	a_{CM} (AU)	e	D_p (km)	P_p (h)	a (km)	D_s (km)	P_{orb} (d)	Disc.	References
1990 OS	1.67	0.46	0.3		0.6	0.05	0.88	R	(Ostro et al. 2003)
(5407) 1992 AX	1.83	0.27	3.9	2.55	6.8	0.78	0.56	L	(Pravec et al. 2000b, 2005b and references therein)
2002 BM ₂₆	1.83	0.44	0.6	2.7		0.1		R	(Nolan et al. 2002a)
(85938) 1999 DJ ₄	1.85	0.48	0.4	2.51	0.8	0.17	0.74	L	(Benner et al. 2004b; Pravec et al. 2004, 2005b and references therein)
2000 UG ₁₁	1.92	0.57	0.2	4.44	0.4	0.08	0.77	R	(Nolan et al. 2000, Pravec et al. 2005b and references therein)
2003 SS ₈₄	1.93	0.57	0.1			0.06		R	(Nolan et al. 2003)
2002 KK ₈	1.95	0.46	0.5			0.1		R	(Nolan et al. 2002b)
(31345) 1998 PG	2.01	0.39	0.9	2.52	1.5	0.3		L	(Pravec et al. 2000b, 2005b and references therein)
(3671) Dionysus	2.19	0.54	1.5	2.71	3.8	0.3	1.16	L	(Mottola et al. 1997, Pravec et al. 2005b and references therein)
2002 CE ₂₆	2.23	0.55	3.0	3.29	5.1	0.21	0.67	R	(Shepard et al. 2004, Pravec et al. 2005b and references therein)
2005 AB	3.21	0.65		3.33			0.75	L	(Reddy et al. 2005)
(4674) Pauling	1.86	0.07	8		250	2.5		AO	(Merline et al. 2004a)
(1509) Esclangona	1.87	0.03	12	2.64	140	4		AO	(Merline et al. 2003b, Warner 2004)
(5905) Johnson	1.91	0.07	5.0	3.783		2.0	0.91	L	(Warner et al. 2005a,b)
(9069) Hovland	1.91	0.11	3	4.22		0.9		L	(Warner et al. 2005a)
(1089) Tama	2.21	0.13	13	16.44	20	(9)	0.68	L	(Behrend et al. 2004b)
(3749) Balam	2.24	0.11	7		350	1.5	100	AO	(Merline et al. 2002a,c)
(854) Frostia	2.36	0.17					1.57	L	(Behrend et al. 2004a)
(3782) Cella	2.41	0.09	6.1	3.84	20	2.6	1.52	L	(Ryan et al. 2003, 2004)

(Continued)

Table 1 (Continued)

Binary	a_{CM} (AU)	e	D_p (km)	P_p (h)	a (km)	D_s (km)	P_{orb} (d)	Disc.	References
(1313) Berna	2.65	0.20		25.464			1.061	L	(Behrend et al. 2004c)
(45) Eugenia	2.72	0.08	215	5.70	1190	13	4.69	AO	(Merline et al. 1999a, 2002c)
(4492) Debussy	2.76	0.17		26.59			1.11	L	(Behrend 2004)
(17246) 2000 GL ₇₄	2.84	0.02	4.5		230	2		HST	(Tamblyn et al. 2004)
(22899) 1999 TO ₁₄	2.84	0.08	4.5		170	1.5		HST	(Merline et al. 2003d)
(243) Ida	2.86	0.05	31	4.63	108	1.4	1.54	SC	(Belton & Carlson 1994, Merline et al. 2002c)
(22) Kalliope	2.91	0.10	181	4.14	1020	38	3.58	AO	(Margot & Brown 2001, Merline et al. 2001b, Marchis et al. 2003b)
(283) Emma	3.04	0.15	148	6.88	600	12	3.36	AO	(Stanzel 1978, Merline et al. 2003c, Marchis et al. 2005a)
(130) Elektra	3.12	0.21	182	5.22	1250	4	3.9	AO	(Magnusson & Lagerkvist 1990, Merline et al. 2003e, Marchis et al. 2005a)
(379) Huenna	3.13	0.19	92	7.02	3400	(7)	81	AO	(Stanzel 1978, Harris et al. 1992, Margot 2003)
(90) Antiope	3.16	0.16	110	16.50	170	110	0.69	AO	(Merline et al. 2000b, 2002c; Marchis et al. 2004a)
(762) Pulcova	3.16	0.09	137	5.84	810	20	4.0	AO	(Merline et al. 2000a, 2002c)
(121) Hermione	3.43	0.14	209	5.55	775	13	2.57	AO	(Merline et al. 2002b, 2003a; Marchis et al. 2004a,b)
(107) Camilla	3.47	0.08	223	4.84	1240	9	3.71	HST	(Storrs et al. 2001, Merline et al. 2002c)

(Continued)

Table 1 (Continued)

Binary	a_{CM} (AU)	e	D_p (km)	P_p (h)	a (km)	D_s (km)	P_{orb} (d)	Disc.	References
(87) Sylvia	3.49	0.07	261	5.18	1370	15	3.66	AO	(Brown & Margot 2001, Merline et al. 2002c)
(617) Patroclus	5.22	0.13	105		610	95	3.41	AO	(Merline et al. 2001a, 2002c)
Pluto/Charon	39.48	0.24	2302	153.29	19640	1186		T	(Christy & Harrington 1978, Tholen & Buie 1990)
(47171) 1999 TC ₃₆	39.53	0.22	147		7640	54	50.38	HST	(Trujillo & Brown 2002, Margot et al. 2004)
2003 QY ₉₀	42.64	0.59	(240)		10,800	(230)		T	(Elliot et al. 2003)
2003 UN ₂₈₄	42.99	0.08	(252)		61,000	(192)		T	(Millis & Clancy 2003)
(66652) 1999 RZ ₂₅₃	43.58	0.08	316		4660	316	46.26	HST	(Noll et al. 2003, 2004a)
2005 EO ₃₀₄	43.84	0.00	(270)		83,000	(156)		T	(Kern & Elliot 2005)
2000 CF ₁₀₅	44.20	0.04	170		23,000	106		HST	(Merline et al. 2002c, Noll et al. 2002c)
2001 QW ₃₂₂	44.22	0.03	200		130,000	200		T	(Kavelaars et al. 2001, Merline et al. 2002c)
(88611) 2001 QT ₂₉₇	44.80	0.03	196	9.50	31,409	136	876	T	(Elliot et al. 2001, Osip et al. 2003)
1998 WW ₃₁	44.95	0.08	150		22,300	120	574	T	(Veillet et al. 2001, Merline et al. 2002c)
(58534) 1997 CQ ₂₉	45.34	0.12	80		8010	66	312	HST	(Noll et al. 2002b, 2004b)
2001 QC ₂₉₈	46.09	0.11	117		3690	98	19.23	HST	(Noll et al. 2002a, Margot et al. 2004)
2000 CQ ₁₁₄	46.37	0.11	(240)		5880	(180)		HST	(Stephens et al. 2004a)
(26308) 1998 SM ₁₆₅	47.82	0.36	116	7.98	11,310	39	130.1	HST	(Brown & Trujillo 2002, Margot et al. 2004)

*The discovery techniques are AO, adaptive optics; HST, Hubble Space Telescope; L, lightcurve; R, radar; SC, spacecraft; and T, ground-based telescope.

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 DP₁₀₇ was the first confirmed binary NEA and the first detected by radar (see Margot et al. 2002). 1998 WW₃₁ was the first known binary TNO after Pluto-Charon (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, 2002c; Margot & Brown 2001, 2003—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 TC₃₆ 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 binary MBA 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).

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.

Techniques

There are three 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.

Direct imaging. Of the five asteroids (951 Gaspra, 243 Ida, 253 Mathilde, 433 Eros, and 9969 Braille) and four comets (1P/Halley, 19P/Borrelly, 81P/Wild 2, and 9P/Tempel 1) visited by spacecraft, only one (Ida/Dactyl) has revealed itself to be a BMP from images taken during the encounter.³ The asteroid missions in particular

³Note added in proof: On September 12, 2005, the Hayabusa spacecraft operated by the Japan Aerospace Exploration Agency arrived at NEA 25143 Itokawa. A rover landing and sample return are planned. So far there has been no announcement of any orbiting companions, although early indications from imaging are that Itokawa itself may be a contact binary.

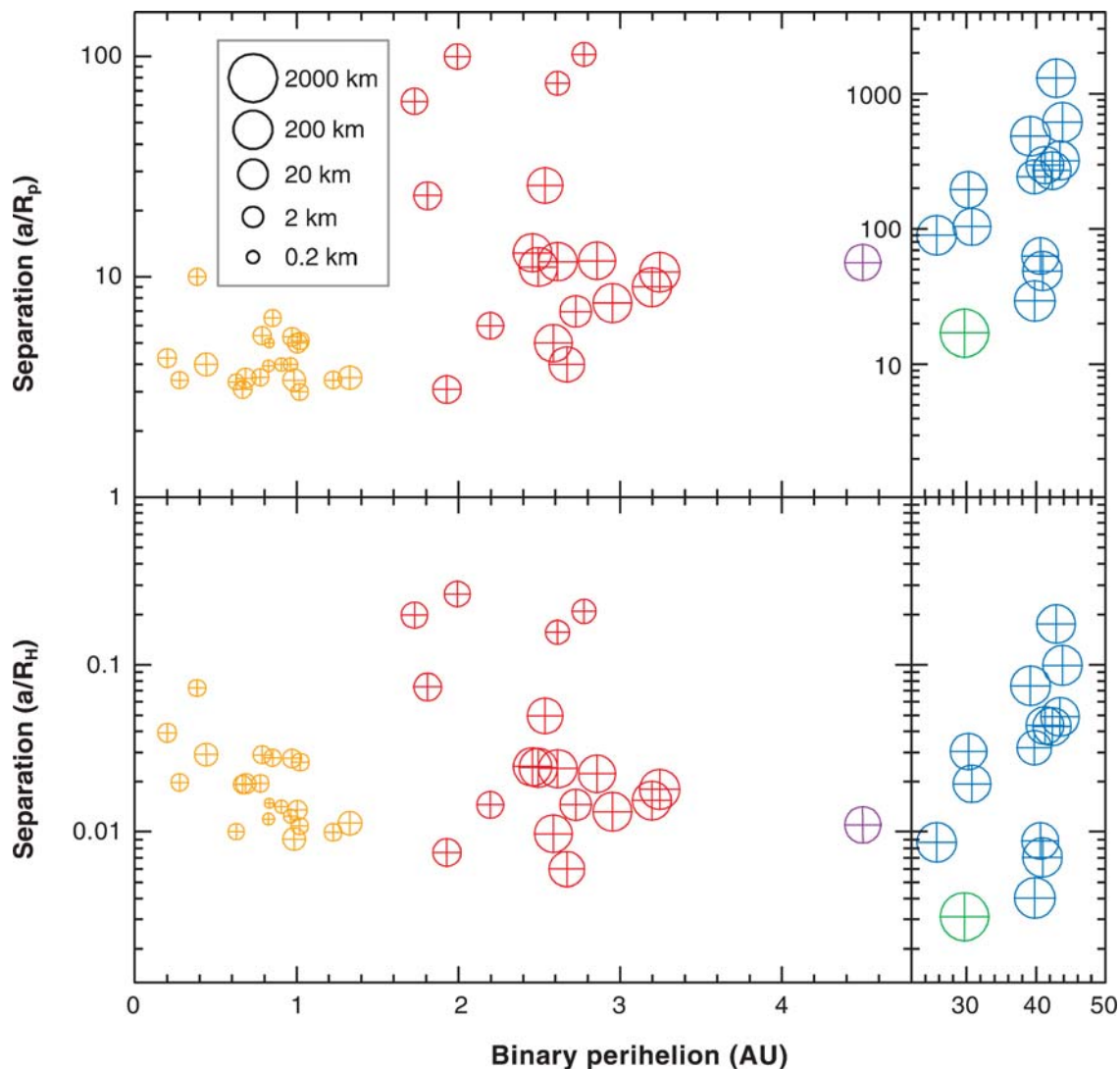


Figure 1

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

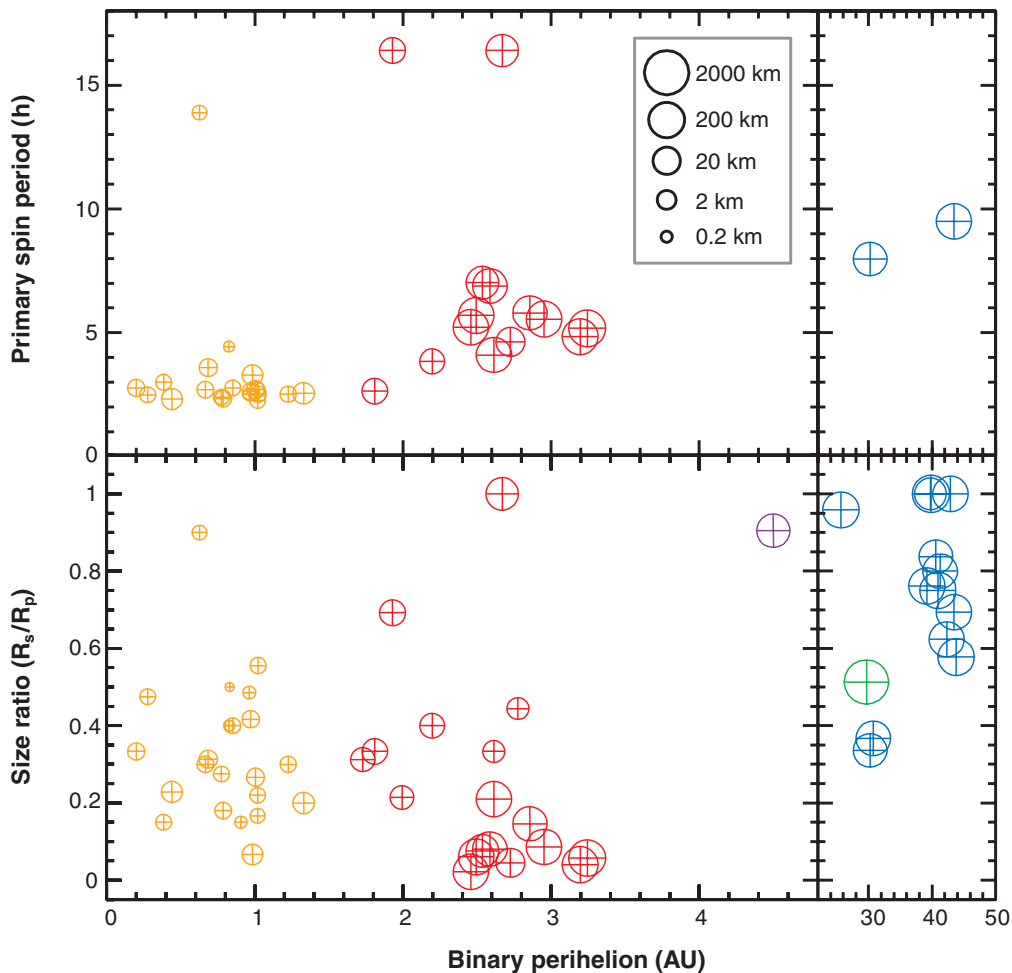


Figure 2

(*Top*) Binary perihelion versus primary spin period, where known (see **Figure 1** caption for scaling and color coding). (*Bottom*) Binary perihelion versus size ratio (R_s/R_p), where known.

had companion detection as an objective. No companions of Gaspra over 27 m radius were found out to $\sim 10 R_p$ (Belton et al. 1992); there were none of Mathilde over 40 m diameter within 4% of the Hill sphere volume ($\sim 20 R_p$) 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).

Direct imaging from space of potential BMPs is also possible with HST. Although HST has a comparatively small-diameter primary mirror compared with

modern world-class ground-based 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 three binary MBAs and seven 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. 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.

Lightcurves. The lightcurve of Eros in 1901 prompted suspicion that this NEA may have a companion (André 1901), but none was ever found. Concerted efforts to discover binarity among minor planets began in the late 1970s, leading to more reports of possible binary asteroids based on lightcurve measurements. The first widely accepted binary candidate found using this technique was NEA 1994 AW₁. It was observed to have a two-period lightcurve and showed events interpreted as eclipses/occultations owing to a binary configuration (see Pravec & Hahn 1997). This interpretation was validated when 2000 DP₁₀₇ was shown to be a binary from radar observations, and subsequent lightcurves of that object showed the same eclipse/occultation signature seen with 1994 AW₁. Subsequently, the lightcurve technique has been used extensively to discover slightly more than half of all binary NEAs to date.

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 behind the other as seen by 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 synchronized 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 detecting close secondaries as this increases the chance and frequency of mutual events. Favorable geometry is also needed as eclipses/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).

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 fourth 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 DP₁₀₇ (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, because 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. However, radar is much more sensitive to small secondaries than the lightcurve technique. Within the next 10 years, nine known binary NEAs will make radar-favorable approaches to Earth; five 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.

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.

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 SS₈₄ 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 $P_{\text{crit}} \simeq 3.3\rho^{-1/2}$ h, with ρ measured in g cm^{-3} (Harris 1996, Pravec & Harris 2000; also Holsapple 2004 and Richardson et al. 2005 give spin limits for more generalized configurations). For a body with $\rho = 2.2$ g cm^{-3} , $P_{\text{crit}} = 2.2$ 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 ($P_p = P = P_s$) 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 ST₂₇ (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 ST₂₇, the few eccentricities that are known are all below 0.1. Few secondary rotations are well known; those that 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 owing to the fast primary spins. Again, 1998 ST₂₇ 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 SS₈₄) 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 $66^{+19}\%$, so binaries appear to be more common than singles among fast-rotating objects approaching Earth's orbit. Note that $\sim 30\%$ of kilometer-sized asteroids are fast rotators with $P_p < 4$ h (Pravec & Harris 2000).

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 with the much larger incidence of binarity among NEAs. The one binary Jupiter Trojan implies an occurrence rate of $\sim 2\text{--}4\%$ in that population for $D_p > 40$ km (Marchis et al. 2003a, 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 $\sim 3\text{--}100 R_p$ (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. More than 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 ~ 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 binary whose characteristics are similar to those of a binary NEA (i.e., 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 four 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 (although we caution there is a strong selection effect here). Also of note is the surprisingly low density of $\sim 2300 \text{ kg m}^{-3}$ inferred for 22 Kalliope by virtue of its companion (Marchis et al. 2003b, 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).

SDO: scattered disk object

Trans-Neptunian objects and Pluto-Charon. The first binary TNO discovered (since Pluto-Charon) was 1998 WW₃₁, 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 ($a = 22,300 \text{ km}$), 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 and Stephens & Noll 2005 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 QY₉₀, is unusual owing to its dynamical situation. This binary is a scattered disk object (SDO), belonging to a group of TNOs with large semimajor axes ($a_{CM} > 50 \text{ AU}$) and high eccentricities. This dynamically hot region is thought to have gained its 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 (see below), 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.

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, and 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.

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 $m\text{ s}^{-1}$, 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 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 three-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 necessarily 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 owing to increased likelihood of encounter at greater distance. Both processes require that the space 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 & Mousis (2004); they estimate the lifetimes of 1998 WW₃₁ and 2001 QW₃₂₂ to be $\sim 1\text{--}2$ 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).

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. 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 nonspherical primary, the necessary perturbations can arise from the complexities of the gravity field. Captured ejecta from a subcatastrophic impact will likely preferentially orbit in the same sense as the primary spin because the ejecta get a rotation kick as well (Weidenschilling et al. 1989), but retrograde orbits are more stable against perturbations from a nonspherical primary (Chauvineau et al. 1993, Scheeres 1994). Subsequent damping collisions between captured ejecta pieces gradually build up the companion mass. Weidenschilling et al. (1989) point 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 subcatastrophic impacts consist preferentially of gravitationally aggregated companions in direct orbits around rapidly rotating, nonspherical 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 subcatastrophic 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 Hartmann (1979); also see Farinella et al. (1982).] 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 & Asphaug 1995, Asphaug et al. 1998) provided a realistic postimpact velocity field for the ejecta, whereas the N -body code

(see Leinhardt et al. 2000, Richardson 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 subcatastrophic 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 efficiency 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 $D_p > 140 \text{ km}$ that are not associated with known families. This assumes the main belt has changed relatively little over the past 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 owing 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.

Rotational Disruption

For NEAs, the median dynamical lifetime against ejection from the Solar System or collision with a planet or the Sun is $\sim 10 \text{ Myr}$ (Gladman et al. 1997, 2000). Unless

binary NEAs can survive the injection process from the main belt [see Bottke et al. 2000, 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 centrifugal 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 subcatastrophic 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).⁴

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

Gravitational aggregate: a self-gravitating object with low tensile strength (unable to resist stretching forces); may have a shattered or rubblized structure

Rubble pile: a gravitational aggregate with moderate porosity

SL9: Comet D/Shoemaker-Levy 9

YORP: Yarkovsky-O’Keefe-Radzievskii-Paddack (coined by Rubincam 2000)

⁴Note added in proof: On July 4, 2005, the Deep Impact spacecraft (A’Hearn et al. 2005) successfully deployed an impactor into Comet 9P/Tempel 1. Early indications are that this comet also has a weak internal structure.

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 some comets (e.g., Weissman et al. 2003). Bottke et al. (2002c) have 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 quickly 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 is large, these reaccumulated bodies will remain gravitationally isolated and will follow similar but distinct orbits that will gradually separate owing to solar tides and other external perturbations. This is likely what happened to form

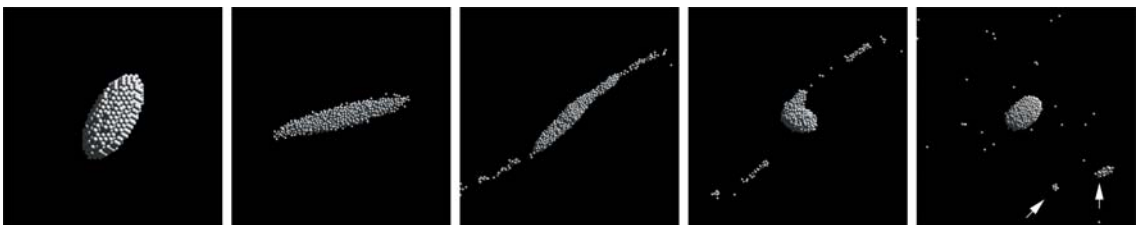


Figure 3

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.

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.

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 periape (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 observed 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 because 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 owing to the larger distance from the Sun and the larger sizes of the bodies in question (although 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.

Triple and Multiple Systems

In general, most triple or multiple systems will not survive long owing 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.

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 owing 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 ($P_s = P$), or 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 DP₁₀₇ 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 ~ 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 $\sim 3.3 R_p$ with $P_p = P \sim 13.9$ h; because 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 seven have a damping timescale greater than 1 Myr. The outlier is 1998 ST₂₇, with a separation of $\sim 10 R_p$ 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 ST₂₇ 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) invoke 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 reorientation of small ($D < 50$ km) asteroids (Chesley et al. 2003, Vokrouhlický et al. 2003). Čuk & 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 years, 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 (Čuk & 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.

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 that 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

Yarkovsky effect:

anisotropic reradiation of thermal energy following solar heating of a body, resulting in a net torque on the body's orbit

YORP effect:

like the Yarkovsky effect, except the torque also affects the (nonspherical) body's spin

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.

SUMMARY POINTS

1. As of this writing, since the first confirmed discovery of a binary asteroid in 1993, 60 BMPs have been found. Of these, 24 are NEAs, 22 are MBAs (plus 1 Jupiter Trojan), and 13 are 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 the following: direct imaging by spacecraft, ground-based telescopes, or HST; photometric detection via lightcurves; 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.
5. 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.
6. 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.
7. 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.

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