Binary and Multiple Systems

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Abstract

A sizable fraction of small bodies, including roughly 15% of NEOs, is found in binary or multiple systems. Understanding the formation processes of such systems is critical to understanding the collisional and dynamical evolution of small body systems, including even dwarf planets. Binary and multiple systems provide a means of determining critical physical properties (masses, densities, and rotations) with greater ease and higher precision than is available for single objects. Binaries and multiples provide a natural laboratory for dynamical and collisional investigations and may exhibit unique geologic processes such as mass transfer or even accretion disks. Missions to many classes of planetary bodies – asteroids, Trojans, TNOs, dwarf planets – can offer enhanced science return if they target binary or multiple systems.

Introduction

Asteroid lightcurves were often interpreted through the 1970s and 1980s as showing evidence for satellites, and occultations of stars by asteroids also provided tantalizing if inconclusive hints that asteroid satellites may exist. By the mid 1980s, however, the scientific consensus had more or less crystallized that binary asteroids were exceedingly rare at best due to difficulty conceiving of formation mechanisms and a still-evolving conception of their internal strength and surface properties (Merline et al. 2002).

It was a great surprise, therefore, when the Galileo spacecraft discovered Ida's satellite Dactyl in 1993. The discovery of comet [D/1993 F2] Shoemaker-Levy 9, or SL9, at roughly the same time led to a realization that at least some small bodies had exceedingly small tensile strengths and that tidal disruption during close approaches to planets could potentially occur for asteroids as well. A study by Bottke and Melosh (1996) suggested that a NEO binary fraction of roughly 15% was required to explain doublet craters on the terrestrial planets, an estimate that has held up well. At present, 35 NEO multiple systems are known (including one triple system) along with 7 Mars crossers, 58 main-belt asteroids, and more than 70 TNOs.

A current database of asteroids with satellites (Johnston et al. 2009) lists over 170 objects in binary or multiple systems, whose mutual orbits are known to varying levels of certainty. Objects with satellites are found in each of the near-Earth, Mars-crossing, main belt, Trojan, and TNO populations. Table 1 is a selection of objects in binary or multiple systems, which have particularly well-observed mutual orbits and which are also numbered objects.

Binary NEOs: Implications for Impact Hazard

One of the first indications that binary asteroids are a large fraction of the NEO population came from a study of doublet craters (Fig. 1). While many impact mitigation schemes (e.g, Morrison et al. 2002) consider the best way to prevent the would-be impactor from breaking into pieces, little work has been done on how the hazard changes when the impactor begins as multiple pieces or as a binary. While not a science driver per se, a mission to a binary NEO could serve as a "test run" for characterizing the particular hazard a typical binary may pose in terms of densities, gravitational binding energy and other physical properties, and allow data to be inserted for parameters that are currently only estimates at best.

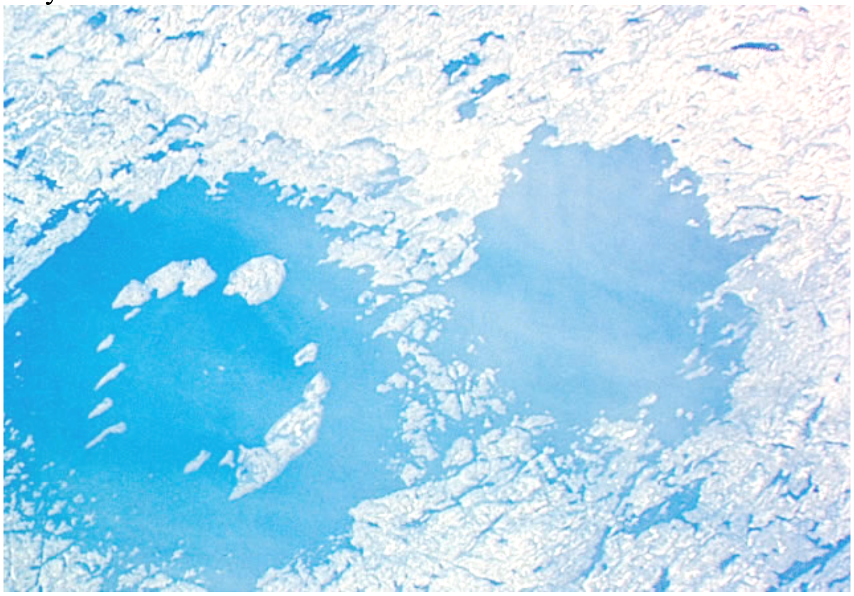

Fig. 1. The Clearwater Lakes in Canada (30 km and 20 km diameter), a famous doublet crater which resulted from a binary asteroid impact

Binary and Multiple Systems: Miniature Dynamical Laboratories

While it is well-accepted that studies of small bodies guide our understanding of the composition of the solar nebula, study of binary systems also can potentially provide insight into the dynamics of early solar system times, when small bodies were accreting. Known binary asteroids have relative sizes ranging from two similar-sized objects to secondaries with diameters only a few percent of the primary (and correspondingly larger mass ratios). Competing effects such as solar radiation pressure, Poynting-Robertson drag, Lagrangian stability points, and surfaces moving near their critical angular speeds might result in a variety of dust structures in the system. The effects of radiation reaction forces (Bottke et al. 2006) on the heliocentric orbital motions (the so-called Yarkovsky effect) and on asteroid rotations (the YORP effect) are of particular dynamical interest. Yarkovsky is believed to drive radial transport of asteroids within the main belt as well as out of the main belt (together with gravitational resonances) and into the near-Earth population. YORP may explain both strangely rapid and strangely slow spin rates of asteroids. The physics of these effects and the hypothesized “Binary YORP” (where a tidally-locked satellite is effectively a surface feature on a primary for the purposes of YORP) are still poorly understood.

A Spacecraft Visit Provides Ground Truth

The bulk of our knowledge about binary and multiple systems has been gained via lightcurve observations and direct imaging from the Hubble Space Telescope and with adaptive optics (for systems from the near-Earth population out to the TNOs) and radar observations (for NEOs). Lightcurves can provide long-baseline information and can be inverted to produce highly-detailed models. Those models, however, are often nonunique and require assumptions to be made about albedos and absolute sizes, in addition to ambiguities about pole positions. Imaging can produce mostly complete orbital information on time scales comparable to an orbit, but lacks such detail as velocity information, which is provided by radar and which can in some cases provide masses of individual components. Radar observations are highly detailed, but rarely are available for a span of more than a few days. In addition, radar shape models are usually constrained to provide a convex hull, with the modeling of concavities difficult for radar data. A visit to a binary NEO will allow binary formation and evolution models to be better tested and grounded. It will provide context for the dozens of other binary systems for which only radar or lightcurve data are available, and allow a better sense of where those models succeed or fall short. This is particularly important since only a tiny fraction of NEOs or binary systems (or, indeed, small bodies) will ever be visited by spacecraft.

Binary Formation Theories

There are several theories that have been considered for the creation of small-body binaries from NEOs through TNOs (Richardson and Walsh 2006; Noll et al. 2008). It is currently thought that different formation processes dominate in different parts of the solar system and for different size regimes, resulting in the characteristics seen in the different populations we see today. There is also a bias inherent in the searches, in that objects the size of typical NEOs are unobservable in the TNO population (and happily, there are no Pluto- or Eris-sized objects in the NEO population). We are only now able to observe binaries in the main-belt population with the same sizes as NEOs, and the best current data suggest that the NEO binary and small main-belt binary populations are similar in their character. The observed distributions of binary separations, relative sizes (primary/secondary diameters) and rotations appear to be different among larger main belt binaries and in NEO binaries, and such differences may reflect differences in formation processes. The still larger TNO binaries also appear to be different from main belt binaries.

Binaries among the larger main-belt asteroids most likely form via collisions, either of a catastrophic nature, followed by mutual capture of individual fragments, or in a large cratering event (sub-catastrophic), with reaccumulation of some ejecta orbiting a large primary remnant (Michel et al. 2001 and 2003; Durda et al. 2004). A large central remnant may retain a piece (or pieces) of ejecta as a satellite in a stable orbit through N-body gravitational interactions of many pieces of ejecta (most of which either escape or reaccrete to the primary), or two pieces of ejecta may escape together along close enough paths to one another to allow mutual capture. Collisional processes tend to make relatively wide binaries with slowly spinning primaries, apparently well-matched to the population observed in the main belt, although observational selection must be considered.

The known NEO binaries are characterized by typically closer separations and more rapidly spinning primaries than are seen in the main belt or outer solar system. These characteristics suggest that collisional formation may be less important for the NEO binaries. Instead, two theories have come to the fore: formation via tidal disruption and reaccretion and formation via YORP spin up and fission.

These formation mechanisms both suggest rubble-pile asteroids. Tidal disruption envisions a SL9-like process where an asteroid makes a close pass to a terrestrial planet (usually Earth) and disrupts, reaccumulating into a multiple system afterward (with some amount of mass loss possible). While this was the leading contender among competing theories for some time, more detailed studies find that close passes destroy as many binaries as they create, resulting in no real net gain of binaries. Furthermore, the similar characteristics of the small main-belt and NEO binary populations suggests that they share similar formation processes, and obviously main-belt asteroids do not have the opportunity for tidal disruption. And finally, the shape of the primary of rapidly rotating NEO binary systems like 1999 KW4 (Ostro et al. 2006; Scheeres et al. 2006), or the dynamically similar 1996 FG3 binary system (Morbidelli et al. 2006; Mottola and Lahulla 2000; Pravec et al. 2000; Walsh et al. 2008), is observed to be oblate or close to a sphere. However, systems formed by tidal disruption are expected to be elongated. While tidal disruption is no longer the leading contender for forming the majority of binary systems, it may still play a role in particular objects.

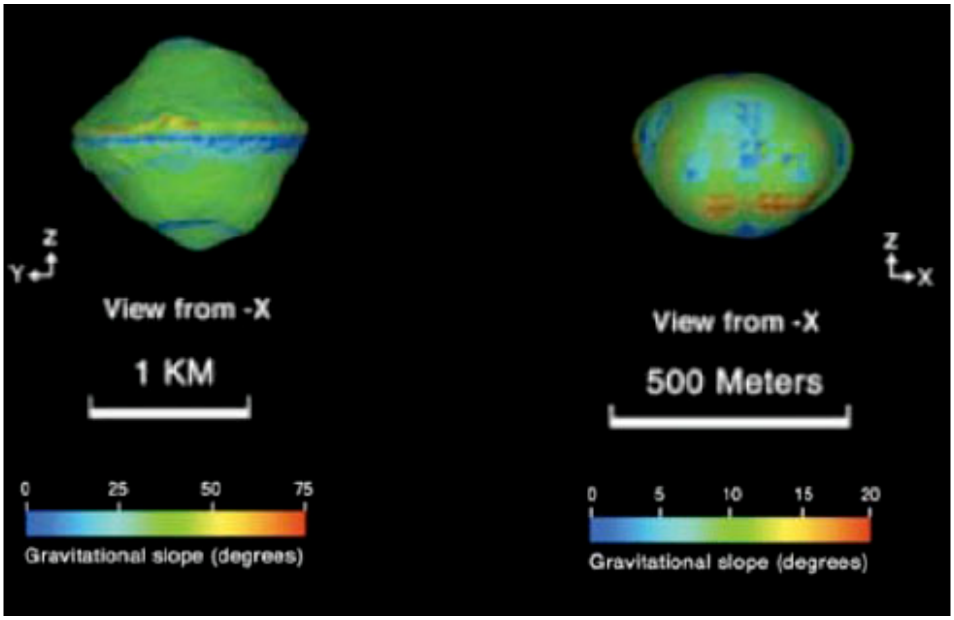

Fig. 2. Shape models of the binary asteroid 1999 KW4 from radar observations as it passed close to Earth (Ostro et al. 2006).

Science Advantages of Binary and Multiple Systems

A mission targeted to a binary or multiple object system will allow several investigations to occur more easily than they would at a single object, and also enables some investigations that would be impossible at a single object. In no particular order:

1. The sizes, mass and orbit pole direction of the system can be determined from distant observations (and, indeed, can already be estimated from Earth-based observations). This knowledge of basic physical parameters will enhance navigation accuracy and lower mission risk during the rendezvous, and it will reduce the time required for initial characterization before entering into close-in, bound orbits.
2. Precise measures of the mutual orbit and rotation state of the binary components can be used to probe higher-level harmonics of the gravitational potential, and thus internal structure.
3. Rendezvous with a binary gives a unique opportunity to study not only the dynamical evolution driven by YORP/Yarkovsky, but also that driven by the possibility of mass transfer. It will be important to measure the rate of mass transfer and to determine dynamical effects on binary evolution.
4. On rapidly rotating primaries, possible migration of regolith from poles to equator may allow the increasing maturity of asteroidal regolith with time to be expressed as a latitude-dependent trend, with the most-weathered material at the equator matching what is seen in the secondary.
5. The presence of a secondary may allow areas on the primary to be observed in "moonlight" (and vice versa), which could possibly help reduce pointing uncertainties when observing at local night time.
6. Up close observations can indicate the importance and effect of mutual tidal interactions, which are poorly understood.

Table 1 lists a selection of 27 objects that are binary and multiple systems and which are recommended as potential mission targets. These are numbered objects with well-determined heliocentric orbits, and they have satellites with permanent designations or well-observed mutual orbits (Johnston et al. 2009). There are 12 main belt asteroids and one Trojan in Table 1, as well as 9 TNOs, all of which are observed by optical and infrared telescopes. There are 5 near-Earth asteroids in Table 1, three of which are Potentially Hazardous Objects (whose orbits pass within 0.05 AU of Earth's orbit). The NEOs in Table 1 have been, or are planned to be, observed by planetary radar.

Needless to say, missions to the different small body populations are in different cost categories, owing to the greater accessibility of NEOs, for instance, or the distance of TNOs from the Sun and the Earth. However, ***all else being equal, missions to binary or multiple systems offer enhanced science return.***

Rapidly Rotating Binary Near-Earth Asteroids

The rapidly rotating binary NEAs 1999 KW4 and 1996 FG3 (see Table1) are particularly interesting mission targets. As NEOS they are in accessible heliocentric orbits. They are also PHAs, objects whose heliocentric orbits venture within 0.05 AU of Earth's orbit.

It is currently believed that such NEO binaries can form via YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) effect spin up, which results from a torque on non-spherical bodies created by asymmetry in the reflection of solar light and thermal emission. It can have the effect of changing the obliquity and rotation period of an object. In the present case, it is hypothesized that rotation rates increased without bound until the breakup limit was reached and material left the surface, removing angular momentum and reducing the rotation rate below the critical level. The material in orbit reaccumulated into a satellite, provided that collisions between the ejected material were dissipative enough. Interactions between the primary and secondary can modulate the continuing YORP spin-up of the primary. Because the material from the pole of the progenitor moves toward the equator during the spin-up and then escapes from this region, the final shape of the primary tends to be spherical or oblate, in agreement with radar observations of 1999 KW4. An oblate primary also makes the orbit of the secondary stable.

Radar observations of binaries and considerations of YORP also suggest considerable regolith mobility on primaries. Observations of the primary in the 1999 KW4 system show evidence of an equatorial ridge, which has the lowest gravitational potential on the object (taking the rotation period and the satellite orbit into account). Indeed, the angular velocity at the equator is only just low enough to allow material to remain on the primary rather than become lofted into orbit. The ridge has been interpreted as due to regolith on the primary which moves "downhill" toward the equator and piles up there. A similar process might occur at 1996 FG3 and may be a signature of close binary systems formed via YORP spin up. These systems may exhibit signatures of mass motion in their surface geology. In addition, these processes may produce spectral differences across the surfaces, corresponding to recent surface exposures of material. Perhaps the secondary will be painted by material from the primary.

If binary NEOs are created via YORP spin up, and regolith migration occurs in general, we might expect more recently exposed material at the pole of a primary than at the equator. Thus, sampling the pole of such object would be a way to get material formerly within the interior and only recently exposed without having to drill into the surface. On the other hand, this process also suggests that the poles of a primary are the most likely places in the system to be free of regolith, unless the polar regolith layer is deep enough that not all of it migrates away.

Binary satellites formed by YORP spin up are likely to be loose accumulations of regolith. These models also suggest that both members of the binary have a rubble pile structure. To date, the only well-observed example of surface geology on a rubble pile object is Itokawa. Will we see similar geological features in the members of a binary system which should also be rubble piles?

As mentioned above, the leading theories for NEO binary creation require the secondary to be formed from the primary. It is conceivable that a collisionally-created binary originating via mutual capture of escaping ejecta from a differentiated parent body could have different compositions, but those compositions would still be related geochemically. A significantly different composition for the satellite vs. primary would require a serious revision of binary formation scenarios. Up-close observations of a binary asteroid system from rendezvous will answer important questions about binary formation mechanisms and test our ideas about accretion and collisional evolution.

Main Belt and Trojan Asteroids; TNO and Dwarf Planet Populations

Binary and multiple systems are prevalent in many, and perhaps all, small body populations (see Table 1). Populations in the main belt and beyond are not only much less accessible to missions, when compared to NEOs, but they are also more difficult to observe, requiring large telescopes with advanced instrumentation. Binary and multiple systems will continue to be discovered with ever greater rapidity, partly thanks to all-sky surveys like Pan-STARRS, LSST, and GAIA, but our observational sample is still sparse. ***Significant research funds and observations capable of refining binary orbital parameters (e.g. adaptive optics on large [at least 8-meter class] telescopes; the Hubble Space Telescope) are needed to measure a large enough sample of well-known binary orbits to infer important statistical trends***. Fundamental questions remain to be answered: does the prevalence of binary and multiple systems differ between populations (e.g., NEOs versus main belt, Trojans versus TNOs)? Are the fundamental physical characteristics of binaries, which reflect their formation mechanisms and later evolution, different in these populations (their spin periods versus mutual orbit periods, their orbital separations versus sizes)? Are binary and multiple systems more likely to be found in asteroid families (suggesting collisional formation mechanisms; Ida and Antiope, for example, are major family members)?

Least accessible, and hardest to observe of the populations discussed here, are the TNOs and the dwarf planets in the trans-Neptunian region. Only one mission, New Horizons, has ever been sent to that region and will not reach its target, the Pluto system, until 2015. If a post-Pluto KBO target is identified, it will by necessity have a low ecliptic inclination. Such objects are known to have a high frequency (>30%) of binaries. Worthy of special mention among the TNOs as a mission target is the Haumea system (see Dwarf Planets white paper), which is a water ice-rich triple system and the parent (or center) of a collisional family as well (Ragozzine and Brown 2009).

Table 1. **Well-observed, numbered binary or multiple systems in the asteroid, Trojan, and TNO populations**

Designation	Name	a (AU)	e	i (deg)	H (mag)	Population
22	Kalliope	2.908	0.103	13.71	6.4	Main Belt
45	Eugenia	2.721	0.082	6.61	7.4	Main Belt
87	Sylvia	3.487	0.081	10.86	6.9	Main Belt
90	Antiope	3.157	0.157	2.22	8.2	Main Belt
107	Camilla	3.475	0.078	10.05	7	Main Belt
121	Hermione	3.446	0.136	7.6	7.3	Main Belt
130	Elektra	3.123	0.209	22.87	7.1	Main Belt
243	Ida	2.86	0.046	1.14	9.9	Main Belt
283	Emma	3.048	0.151	8	8.7	Main Belt
379	Huenna	3.137	0.189	1.67	8.8	Main Belt
617	Patroclus	5.225	0.139	22.04	8.1	Trojan
762	Pulcova	3.158	0.1	13.09	8.2	Main Belt
3749	Balam	2.237	0.11	5.39	13.4	Main Belt
42355	Typhon	37.644	0.535	2.43	7.2	TNO
58534	Logos	45.14	0.117	2.9	6.6	TNO
65489	Ceto	100.174	0.822	22.32	6.3	TNO
65803	Didymos	1.645	0.384	3.41	18.4	PHA
66063	1998 RO1	0.991	0.72	22.67	18.1	NEO
66391	1999 KW4	0.642	0.688	38.89	16.5	PHA
66652	Borasisi	43.978	0.092	0.56	5.9	TNO
88611	Teharonhiawako	44.212	0.024	2.57	5.5	TNO
134340	Pluto	39.798	0.254	17.11	-0.7	TNO
134860	2000 OJ67	43.106	0.023	1.11	6.1	TNO
136108	Haumea	43.192	0.193	28.22	0.2	TNO
136199	Eris	67.96	0.435	43.97	-1.2	TNO
175706	1996 FG3	1.054	0.35	1.99	18.2	PHA
185851	2000 DP107	1.365	0.377	8.67	18.2	PHA

Notes: PHA = Potentially Hazardous Asteroid, one whose orbit comes within 0.05 AU of Earth's orbit; NEO = Near-Earth Object. A more complete database of binary and multiple objects is found at http://www.johnstonsarchive.net/astro/asteroidmoons.html

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