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Asteroids with Satellites: Inventory, Properties, and Prospects for Future Discoveries

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Abstract The population of binary asteroids numbers over 160 systems, and they can be found amongst near-Earth asteroids (NEAs), Main-Belt asteroids (MBAs), Jupiter Trojans, Centaurs and trans-Neptunian objects (TNOs). The discoveries have been made with space missions, radar observations, photometric lightcurves, and high resolution imaging from the ground and space. The properties of each population are widely different due to varying formation mechanisms and discovery techniques for each group. Future large-aperture telescopes will be capable of imaging both components for nearly all known systems and will drastically improve prospects for discovery of smaller and more tightly bound systems throughout the Solar System. The study of binary asteroids has provided valuable estimates on asteroid density and structure, a better understanding of the radiative YORP-effect, insights on catastrophic collisions, and may prove to be a key diagnostic for understanding the formation and evolution of the Kuiper Belt population.

Keywords Asteroids · Minor planets · Binary asteroids

1 Introduction

The first satellite orbiting an asteroid was discovered in 1993 when the *Galileo* spacecraft flew past the Main Belt asteroid Ida, imaging its satellite Dactyl. Ground- and space-based telescopes soon began making discoveries, starting with photometric lightcurves (Pravec and Hahn 1997; Pravec et al. 1998; Pravec and Harris 2007; Mottola et al. 2000), then by direct imaging (Merline et al. 1999) and also with radar (Margot et al. 2002). The population of known systems now exceeds 160, with over 170 known satellites, some of which reside in triple and even one quadruple system (Johnston 2008). The mere existence of these systems places constraints on models of Solar System formation and evolution, and

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also provide physical data on asteroids, mass and density in particular, previously accessible only from in situ measurements.

Asteroids with satellites have now been found in every major dynamical group: near-Earth asteroids (NEAs), Main Belt asteroids (MBAs), Jupiter Trojans, Centaurs and trans-Neptunian objects (TNOs). Each population is different in the properties of the systems, discovery techniques, and likely formation mechanisms. Investigations in all populations will benefit dramatically from the combination of higher angular resolution and deeper imaging capabilities offered by the next generation of large aperture telescopes. In Sect. 2 we summarize the properties of known binaries, how they have been discovered to date and their suspected formation mechanisms, in Sect. 3 we discuss the prospects for discovery and characterization with future technologies.

2 The Known Binary Population

2.1 Binary NEAs

The binaries among near-Earth asteroids have been discovered via photometric lightcurves and radar observations. Their properties are suggestive of formation via rotational disruption, with rapidly rotating primaries and close secondaries. The rotation rate of the primaries are nearly all between 2.2 and 3.6 h, which are among the most rapid known for any asteroids. The secondaries are almost always found between 2 and 6 R_{pri}, often with low eccentricity. When measured, the secondaries typically have rotation periods equal or very close to their orbital periods. The outliers (out of $\sim$ 35 total) are a doubly synchronized system with nearly equal-mass components, a triple system and one system with a widely separated secondary. Overall, it is estimated that $\sim$15% of all NEAs are binary.

Numerical simulations by Walsh et al. (2008) showed that spinup by the radiative YORP-effect (Rubincam 2000), an alteration to a bodies spin state from asymmetric reflection/re-emission of solar radiation, is capable of forming satellites around rubble-pile asteroids. The systems created by this model match the observed system properties closely, including the "top-shape" seen in great detail in the radar shape model of 1999 KW_4 (Ostro et al. 2006). The defining characteristic of the "top-shape" is the equatorial ridge, which has since been seen in a number of other binaries and also single asteroids. A predictive aspect of the numerical work was that surface material, regolith, could easily be scattered and removed from the primary during the process. Current thermal IR observations suggest that this may in fact be true, and pending confirmation with a larger sample size could provide a new way to target asteroids as candidate binaries (Delbo et al. 2008).

2.2 Binary MBAs

The binaries among large MBAs are substantially more diverse than the NEAs: they have a wide range of component size ratio and orbital properties (see Fig. 1). Only 2–3% of MBAs have companions currently detectable with high-resolution imaging. Discovery of these systems has so far been dominated by direct imaging on ground-based telescopes with Adaptive Optics (AO). As AO technology has improved, systems have been re-imaged, sometimes finding second companions around some systems (Marchis et al. 2005, 2007).

The systems in the Main Belt are expected to be formed by collisions as numerical simulations of impacts into asteroids has successfully created satellites (Durda et al. 2004; Michel et al. 2002). These simulations characterized two distinct types of binaries,

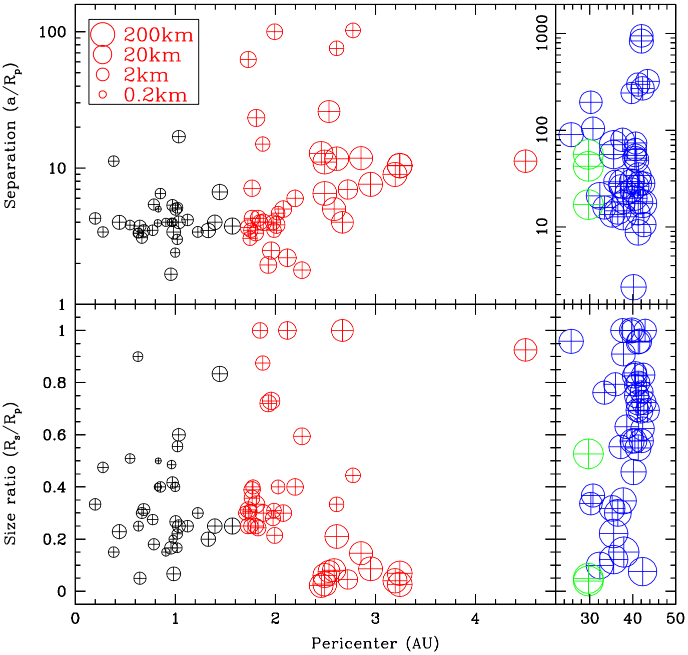

Fig. 1 Overview of known binary asteroid properties, separated into dynamical classes: NEAs (*black*), MBAs (*red*), Jupiter Trojans (*red*; at 4.5 AU), TNOs (*blue*), and Pluto's satellites (*green*). The *top panel* shows the separation of the components in terms of the primary's radius plotted against the system's heliocentric perihelion. The *bottom panel* is the size ratio of the two components plotted against the system's perihelion. The size of the symbols relate to the size of the primary body. The data are from Richardson et al. 2006, and Johnston 2008 (Color figure online)

SMAshed Target Satellites (SMATS) and Escaping Ejecta Binaries (EEBs). The largest remnant of the collision naturally collects substantial debris in orbit, some of which, by way of collisions and accumulation, form satellites in stable orbits. These systems are SMATS, and make up the bulk of the known MBA binaries. The EEBs are created by ejected debris that become bound to each other, and can have a wider range of possible size ratios and separations. The few observed systems considered to be EEBS are similar sized and among the most widely separated known. The limits for discovery of this type are more a matter of depth of search, since the ejected debris can be quite small, rather than spatial resolution.

2.3 Binary TNOs

The population of TNO binaries has a dramatic range of constituents, from widely separated systems with similar sized components to the three satellites around Pluto. They have been discovered in all of the different dynamical groups of the TNOs; among the resonant populations, cold and hot classical disks, the scattered disk and the Centaurs. The binaries in the different dynamical groups are fundamentally dissimilar, with nearly ~30% of the cold classical belt objects (low eccentricities and inclination, not in resonance) having satellites, while dynamically excited classes are closer to ~10% (Noll et al. 2008b).

Discoveries are currently limited by the size and separation for these distant systems (Noll et al. 2008a). Space-based observations have dominated discoveries due to their capability for very deep observations, and extremely stable PSFs allowing very close companions to be separated. The wide separations and similar-sized components have led to a number of proposed formation mechanisms, typically based on dynamical capture. The various scenarios involve 3-body encounters, collisions near a 3rd body, dynamical friction acting to bind two closely passing bodies, and binary exchange mechanisms operating after collisions form small satellites. One difficulty in characterizing KBO binaries, which will remain challenging, is characterizing their orbits since periods can be as long as 25–30 years in extreme cases (Petit et al. 2008).

3 Prospects for Future Discoveries and Characterization

Estimating the prospects of future discoveries depends both on the capabilities of future technologies and extrapolating the known population of binaries into currently unobservable regimes. Currently, discoveries are largely limited by faintness and/or spatial resolution, both of which will be addressed with large aperture ground-based telescopes. Additionally, upcoming all-sky surveys will rapidly increase the rate of asteroid discoveries, producing more complete inventories of asteroid populations, down to much fainter magnitudes than what is currently available.

The proposed 42 m ELT telescope would provide resolutions superior to current ground- or space-based telescopes. Diffraction limited resolution would be 0.006 acrsec at 1 micron. The enormous collecting area would allow for S/N of 25 for 180 sec exposures of 25th magnitude targets. Estimating capabilities to uncover a dim secondary at close separations (delta magnitude vs. separation) is more difficult, but likely superior to all current observatories. In this section we address prospects for future discoveries and potential improved characterization of known binary asteroids.

3.1 NEAs

Binaries among the NEAs are efficiently discovered using small-aperture telescopes used to collect a huge amount of lightcurve data. The likelihood of discovery by lightcurves falls off rapidly with secondary separation, and is essentially zero at 10 R_{pri} (Pravec et al. 2006). Lightcurve discoveries are also limited to finding companions greater than $\sim$20% the size of the primary. Similarly, a lightcurve discovery can only be made where the primary body is bright enough to be observed at a given telescope: typically small aperture telescopes with abundant available time (where abundant available telescope time is not expected at future large aperture telescopes). Radar observations are capable of detecting distant and smaller companions, but are limited to asteroids which pass close to the Earth. Combined, the two techniques offer imperfect sampling of population, with the potential for a small fraction of NEAs with more distant or much smaller companions. Only recently have the two components of an NEA system been separately imaged with ground-based observations (Merline et al. 2008), but this has not yet been employed for discoveries.

Discovery by lightcurve is efficient at discovering tightly bound systems, and the radar survey so far suggest that only a very small percentage of NEAs have secondaries in wide orbits (greater than 10 R_{pri}). The largest gains by an ELT will be through increased spatial resolution and the ability to easily separate, and separately study, the two components of an NEA binary. Even the tightest bound systems ($\sim$1 km separation) will be accessible for individual study during favorable observing geometries, and similar systems could be discovered with a few images rather than 100's of hours of lightcurve data. Similarly, targets down to 100’s of meters can be included in surveys. Beyond characterization of the two components, it will likely be possible to even characterize different regions of some primary’s surface.

3.2 MBAs

Ground-based telescopes using AO have discovered nearly all of the binary MBAs, and thus future large-aperture telescopes will provide direct improvements on the technologies currently used. Figure 2. shows the magnitude differences between primary and secondary components as a function of an estimate of maximum spatial separation of the components (where MBAs are in red). This data is based on the current known population, showing the limits around 0.01 arcsec, below which detections have not been made. The most extreme discovery to date is of a satellite orbiting Daphne, approximately 10 magnitudes dimmer with a separation of only $\sim 6\ R_{pri}$ (Merline et al. 2008b).

Discovery and characterization of SMAT systems is extremely dependent on spatial resolution, and thus surveys with large aperture telescopes will be capable of making many discoveries. The enormous collecting power of a 42 m ELT will allow very quick and comprehensive surveys down to very small sizes in the Main Belt, characterizing the population of EEBs very well. With better statistics on the population of satellites, better characterization of individual systems, and more detections of multiple satellite systems,

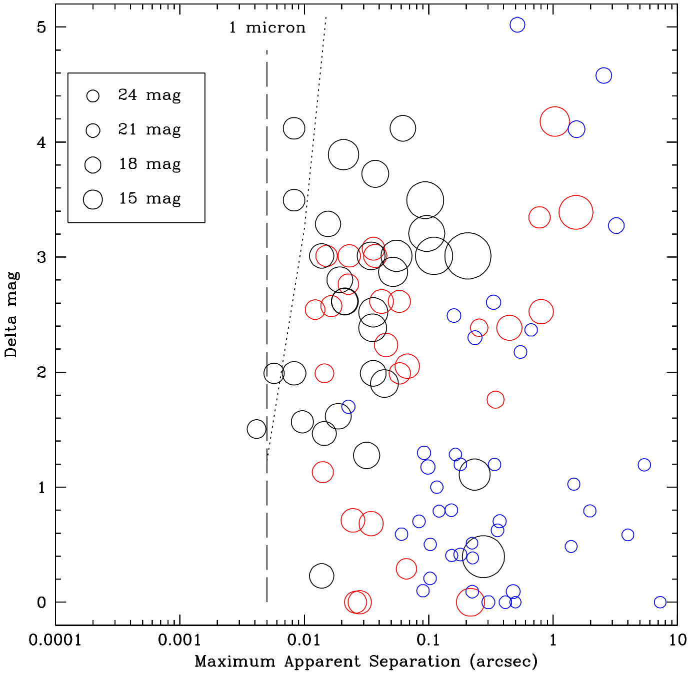

Fig. 2 Estimates for the difference in binary component magnitude as a function of maximum apparent separation for known NEA (*black*), MBA (*red*) and TNO (*blue*) binaries. The symbol size relates to an estimated visual magnitude of the primary body. Fiducials for diffraction limits of a 42 m ELT at 1 micron (*dashed line*) and a rough estimate on delta-magnitude limits (*dotted line*) are included. At optical and near-IR wavelengths nearly every known Solar System binary system could be resolved (Color figure online)

different parameters in collisional simulations can be explored. An important improvement, just recently implemented in favorable cases, is the resolution and shape determination of the primary body (Marchis et al. 2005). This previously unaccessible parameter will be diagnostic for collision and reaccumulation models, and help to better understand the dynamics of each system.

3.3 TNOs

Noll et al. (2008a) detailed current populations of TNO binaries, showing that discoveries are currently limited by angular resolution. Clearly, large aperture telescopes will greatly aid in improving resolving capabilities, while still being able to probe at the necessarily deep magnitudes to detect moderate sized TNOs. Survey limits with HST are 0.07 arcsec resolution and a maximum depth of 27.5 magnitudes, taking advantage of the stable PSF of HST and advanced PSF fitting algorithms. Currently, about half of the known TNO binaries were discovered with a separation below 0.1 arcsec (Noll et al. 2008a). With a 42 m ELT searches down to $\sim$0.006 arcsec will be possible, searching for much closer systems than currently detectable. With the current population showing increasing numbers at smaller separations, it is possible a huge population of closer TNO systems could be uncovered. Increasing the depth of search will provide another valuable asset of the next generation large-aperture telescopes, as searching for small satellites around anything other than the brightest TNOs is currently very difficult.

Constraints on TNO binary formation mechanisms will improve dramatically with better statistics, smaller satellites, and searches around a larger number of TNOs. With improved data, formation models will shed light on both the formation mechanism, but also the evolution of the entire Kuiper Belt.

4 Conclusions

Binary asteroids provide a powerful tool to explore properties of asteroids throughout the Solar System. Their study has produced constraints on internal structure of asteroids previously accesible only by space missions. Further discovery and characterization will continue to produce valuable science. Future large-aperture telescopes offer a number of tools to explore these systems. The current known population of solar system binary asteroids will nearly all be separated due to the substantial increase in spatial resolution, and undiscovered systems beyond the reach of every current observatory will become viable targets for discovery.

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References

M. Delbo, K.J. Walsh, M. Mueller, The cool surfaces of binaries near-Earth asteroids. Bull. Am. Astron. Soc. **40**, 433 (2008)

D.D. Durda, W. Bottke, B.L. Bottke, W.J. Merline, E. Asphaug, D. Richardson, Z.M. Leinhardt, The formation of asteroid satellites in large impacts: results from numerical simulations. Icarus, **167**, 382 (2004)

W.R. Johnston, Asteroids with Satellites. http://www.johnstonsarchive.net/astro/asteroidmoons.html. Accessed 25 Jan 2009

F. Marchis, P. Descamps, D. Hestroffer, J. Berthier, Discovery of the triple asteroidal system 87 Sylvia. Nature. **436**, 822 (2005)

F. Marchis, M. Baek, P. Descamps, J. Berthier, D. Hestroffer, F. Vachier, S/2004 (45) 1. IAU Circular. **8817**, 1 (2007)

J. Margot, M. Nolan, L. Benner, S. Ostro, R. Jurgens, J. Giorgini, M.A. Slade, D.B. Campbell, Binary asteroids in the near-Earth object population. Science. **296**, 1445 (2002)

W.J. Merline, L.M. Close, C. Dumas, C.R. Chapman, F. Roddier, F. Menard, D.C. Slater, G. Duvert, C. Shelton, T. Morgan, Discovery of a moon orbiting the asteroid 45 Eugenia. Nature. **401**, 565 (1999)

W.J. Merline, A.R. Conrad, J.D. Drummond, P.M. Tamblyn, C. Dumas, B. Carry, S/2008 (35107) 1. IAU Circular. **8977**, 1 (2008)

W.J. Merline, A.R. Conrad, J.D. Drummond, B. Carry, C. Dumas, P.M. Tamblyn, C.R. Chapman, W.M. Owen, D.D. Durda, R.D. Campbell, R.W. Goodrich, Discovery of an Extreme Mass-Ratio Satellite of (41) Daphne in a Close Orbit. Asteroid Comets Meteors. **1405**, 8370 (2008)

P. Michel, P. Tanga, W. Benz, D. Richardson, Formation of asteroid families by catastrophic disruption: simulations with fragmentation and gravitational reaccumulation. Icarus. **160**, 10 (2002)

S. Mottola, F. Lahulla, Mutual eclipse events in asteroidal binary system 1996 FG3: observations and a numerical model. Icarus. **146**, 556 (2000)

K.S. Noll, W.M. Grundy, E.I. Chiang, S.D. Kern, in *Binaries in the Kuiper Belt*, ed. by M.A. Barucci, H. Boehnhardt, D.P. Cruikshank, A. Morbidelli. The solar system beyond Neptune (The University of Arizona Press, Tucson, 2008), p. 1

K.S. Noll, W.M. Grundy, D.C. Stephens, H.F. Levison, S.D. Kern, Evidence for two populations of classical transneptunian objects: the strong inclination dependence of classical binaries. Icarus. **194**, 758 (2008)

S.J. Ostro, and 15 others, Radar imaging of binary near-Earth asteroid (66391) 1999 KW4. Science. **314**, 1276 (2006)

J. Petit, and 14 others, The extreme Kuiper Belt binary 2001 QW322. Science. **322**, 432 (2008)

P. Pravec, G. Hahn, Two-period lightcurve of 1994 AW1: indication of a binary asteroid?. Icarus. **127**, 431 (1997)

P. Pravec, A.W. Harris, Binary asteroid population. 1. Angular momentum content. Icarus. **190**, 250 (2007)

P. Pravec, M. Wolf, L. Sarounova, Occultation/eclipse events in binary asteroid 1991 VH. Icarus. **133**, 79 (1998)

P. Pravec, and 57 others, Photometric survey of binary near-Earth asteroids. Icarus. **181**, 63 (2006)

D.C. Richardson, K.J. Walsh, Binary minor planets. Ann. Rev. Earth. Planet. Sci. **34**, 47 (2006)

D.P. Rubincam, Radiative spin-up and spin-down of small asteroids. Icarus. **148**, 2 (2000)

K.J. Walsh, D.C. Richardson, P. Michel, Rotational breakup as the origin of small binary asteroids. Nature. **454**, 188 (2008)