Formation and Evolution of Binary Asteroids

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ABSTRACT

Satellites of asteroids have been discovered in nearly every known small body population, and a remarkable aspect of the known satellites is the diversity of their properties. They tell a story of vast differences in formation and evolution mechanisms that act as a function of size, distance from the Sun, and the properties of their nebular environment at the beginning of Solar System history and their dynamical environment over the next 4.5 Gyr. The mere existence of these systems provides a laboratory to study numerous types of physical processes acting on asteroids and their dynamics provide a valuable probe of their physical properties otherwise possible only with spacecraft.

Advances in understanding the formation and evolution of binary systems have been assisted by: 1) the growing catalog of known systems, increasing from 33 to \( \sim 250 \) between the Merline et al. (2002) Asteroids III chapter and now, 2) the detailed study and long-term monitoring of individual systems such as 1999 KW4 and 1996 FG3, 3) the discovery of new binary system morphologies and triple systems, 4) and the discovery of unbound systems that appear to be end-states of binary dynamical evolutionary paths.

Specifically for small bodies (diameter smaller than \( 10 \) km), these observations and discoveries have motivated theoretical work finding that thermal forces can efficiently drive the rotational disruption of small asteroids. Long-term monitoring has allowed studies to constrain the system’s dynamical evolution by the combination of tides, thermal forces and rigid body physics. The outliers and split pairs have pushed the theoretical work to explore a wide range of evolutionary end-states.

1. INTRODUCTION

There have been considerable advances in the understanding of the formation and evolution of binary systems since the Asteroids III review by Merline et al. (2002) and another comprehensive review
by Richardson and Walsh (2006). The current properties of this population are detailed in the chapter by Margot et al., and this review will rely on their analysis in many places as we review work on the formation and dynamics of these systems. While the inventory of known binary systems in all populations has increased, for some populations the understanding of dynamics and formation have advanced only minimally while in others places research has moved rapidly. Therefore this chapter will not be evenly weighted between different populations, rather there will be substantial discussion of small asteroids and the YORP effect.

The scope of this chapter will be different than the Asteroids III chapter by Merline et al. (2002). Thanks to an excellent review of binary systems in the Kuiper Belt in the Solar System Beyond Neptune book by Noll et al. (2008), and the apparent physical, dynamical and evolutionary differences between binary minor planets in the outer and inner regions of the Solar System, we will exclude the Kuiper Belt population from our discussion here.

1.1 The Known Population of Binary Minor Planets

The known population of asteroid satellites has increased from 33 to ∼244 between the Merline et al. 2002 Asteroids III chapter and now: 49 near-Earth, 19 Mars-crossing, and 93 Main Belt asteroids (Pravec and Harris 2007; Johnston 2014). As noted in 2002, the binary systems found among near-Earth asteroids (NEAs) have only a subset of the properties of those found among the Main Belt asteroids (MBAs). While the orbital and collisional dynamics differ substantially in these two populations, further study has found that the variation and similarities between binary properties is most strongly dependent on size.

The known binary systems among NEAs have primary component diameters exclusively less than 10 km. These small systems typically have moderately-sized secondaries between 4–58% the size of the primary —corresponding to a mass ratio range of $6.4 \times 10^{-5} – 2.0 \times 10^{-1}$ assuming equal densities, are on tight orbits with typically 2.5–7.2 primary radii separation, and have a fast-spinning primary with rotation period between 2.2–4.5 hours —all are below twice the critical disruption spin period of 2.3 hours for a sphere of density 2 g cm$^{-3}$. The data for these systems is presented in Figure 1. When lightcurve surveys probed similar sized asteroids in the Main Belt, they found systems with the same characteristics existing at roughly the same proportion of the population (Warner and Harris 2007).

The known binary systems among MBAs have properties that vary with their size. The small population ($D < 15$ km; (4492) Debussy is the largest) look similar to the various morphologies found among NEAs including a few that appear similar to (69320) Hermes, while asteroid satellites around large asteroids ($D > 25$ km; (243) Ida is the smallest of this group) fall into other categories. These larger asteroid systems have by comparison much smaller satellites on much more distant orbits. While a number of the large asteroids with satellites have rotation periods lower than the average asteroids of these sizes (geometric means and 1-$\sigma$ deviations are $7.6 \pm 0.4$ hours versus $12.2 \pm 0.5$ hours; Warner et al. 2009; Pravec et al. 2012), their rotation periods are all more than twice the critical disruption spin period of 2.3 hours for a sphere of density 2 g cm$^{-3}$ with the exception of (22) Kalliope (Pravec et al. 2012; Johnston 2014).
The techniques used to increase this database of known systems over time are important as they define any biases of our knowledge of each population. Lightcurve techniques, which are important for finding close companions around small asteroids, are strongly biased against finding distant companions. Meanwhile radar can discover satellites widely separated from their primaries, but is ineffective for observing distant Main Belt asteroids (Ostro et al. 2002). Direct high-resolution imaging is best for finding distant companions of large Main Belt asteroids (Merline et al. 2002). The size of the known population of small binary asteroid systems has increased substantially owing to the ready availability of small telescopes to survey asteroid lightcurves and the increased frequency of radar observations. Meanwhile many large Main Belt asteroids have been surveyed with ground-based telescopes with far fewer recent discoveries — though new Adaptive Optics (AO) technologies may uncover previously unseen satellites at previously studied asteroids (Marchis and Vega 2014).

1.2 The YORP effect

The largest shift in the understanding of binary formation and evolution has come from studies of thermal forces that can affect a single body or a binary system. The reflection and reemission of solar radiation can produce a torque that changes the rotation rate and obliquity of a small body. This effect is referred to as the YORP effect, coined by Rubincam (2000), and evolved out of the work of many researchers on similar topics (Radzievskii 1952; Paddack 1969; Paddack and Rhee 1975; O’Keefe 1976). We only provide a brief summary here (see Bottke et al. (2006) and the Vokrouhlický et al. chapter in this volume for a detailed discussion of the effect).

The YORP effect has been directly detected for several asteroids through observed rotation rate changes (Taylor et al. 2007; Lowry et al. 2007; Kaasalainen et al. 2007; Durech et al. 2008a,b; 2012). These rotation rate changes match the predicted magnitude of the effect from theoretical predictions (Rubincam 2000; Bottke et al. 2002; Vokrouhlický and Čapek 2002; Čapek and Vokrouhlický 2004; Rozitis and Green 2013b). The YORP effect has a straightforward dependence on asteroid size (timescales increase with $R^2$) and distance from the Sun (timescales increase with $a^2$), but a complicated relationship with shape (Nesvorný and Vokrouhlický 2007; Scheeres 2007b). This shape dependence is characterized by a YORP coefficient, which measures the asymmetry of the body averaged about a rotation state and a heliocentric orbit. While instantaneous estimates of the YORP coefficient are available from astronomical measurements of the radial accelerations of asteroids, theoretical models of long-term averaged values are stymied by a sensitive dependence on small scale topography (Statler 2009; McMahon and Scheeres 2013; Cotto-Figueroa et al. 2014) and regolith properties (Rozitis and Green 2012, 2013a). NEAs and MBAs with diameters below about 20 km are likely to be affected on Solar System timescales (Bottke et al. 2006; Jacobson et al. 2014b). Kilometer-size NEAs can have rotation rate doubling timescales shorter than their dynamical lifetime of $\sim 10$ Myr and MBAs shorter than their collision lifetime of $\sim 100$ Myr (Bottke et al. 2006; Jacobson 2014).

The distribution of spin rates observed for bodies smaller than 40 km in size show excesses of very fast and slow rotators (Pravec and Harris 2000; Warner and Harris 2007), which is matched very well by a spin distribution model including the YORP effect (Pravec et al. 2008; Rossi et al. 2009; Marzari et al. 2011) as
Fig. 1.— The known population of binary asteroids. Three panels show (Bottom) the component separation in terms of the primary radius, (Middle) the size ratio of the two components, and (Top) the rotation period of the primary all plotted as a function of the system’s heliocentric orbit’s pericenter (Johnston 2014). The size of the symbol indicates the size of the primary body, with the scale being on the left side of the bottom panel.
suspected in the *Asteroids III* chapter by Pravec et al. (2002). Note that the very large asteroid lightcurve survey of Masiero et al. (2009) found a more Maxwellian distribution of spin rates among small asteroids though it is not necessarily incompatible with YORP spin evolution. Among larger bodies, a subset of the Koronis asteroid family was found to have aligned obliquity and clustered spin rates (Shvian 2002), which is due to the YORP effect driving them into spin-orbit resonances (Vokrouhlický et al. 2003). Amongst asteroid families, whose spreading is controlled by the Yarkovsky drift of family members, there are clear signatures of the YORP effect changing the obliquity of smaller bodies and in turn changing their Yarkovsky drift rates (Vokrouhlický et al. 2006; Bottke et al. 2006, 2015).

Morning and evening thermal differences across regolith blocks torque the asteroid similarly in magnitude to the “normal” YORP effect. Unlike the effect described above, this “tangential” YORP effect does depend on the rotation rate, material properties of the regolith, and size distribution of the blocks (Golubov and Krugly 2012; Golubov et al. 2014). Furthermore, the tangential YORP effect has a prograde bias unlike the normal YORP effect, which is unbiased. This additional torque may explain the difference between the predicted rotational deceleration of Itokawa (Scheeres et al. 2007; Durech et al. 2008b; Breiter et al. 2009) and the observed acceleration by the Japanese space mission Hayabusa (Lowry et al. 2014; Golubov et al. 2014). Similarly, a preference for spinning up may be necessary to explain the large fraction of observed binary systems, ∼15% of small asteroids, which are presumed to be formed from rotational disruption caused by continued YORP spinup (discussed in detail below).

As mentioned as early as the Vokrouhlický and Čapek (2002) and Bottke et al. (2002) works on the YORP effect, this effect was a very good candidate to rotationally disrupt rubble pile asteroids. As the catalog of known systems has grown, and the sub-populations of binary systems became more defined, rotational disruption by the YORP effect emerged as the primary candidate to be the dominant formation mechanism. Much of the recent research, and the discussion below, is focused on the step(s) between when the YORP effect starts increasing the angular momentum of an asteroid and when we observe the diverse catalog of systems today. Some sub-populations may emerge directly from YORP-induced rotational disruption, while others seem to demand further evolutionary forces.

### 2. Binary Sub-Populations

With over 100 systems spread between NEAs and MBAs, clear sub-populations of binary systems have emerged. Pravec and Harris (2007) compiled the parameters for the catalog of known binary systems, including a calculation of the total angular momentum of each system. They used this data to create a classification system of the known inner Solar System binary systems that is well suited for the topics in this chapter, (most of these populations are clear in Figures 1 and 2), and we update it below:

- **Group L**: Large asteroids (diameter: \( D > 20 \) km) with relatively very small satellites (secondary to primary diameter ratio: \( D_2/D_1 \lesssim 0.2 \)). We identify 11 members.
- **Group A**: Small asteroids (\( D < 20 \) km) with relatively small satellites (\( 0.1 \gtrsim D_2/D_1 \lesssim 0.6 \)) in tight mutual orbits (semimajor axis, \( a \), less than 9 primary radii, \( R_p \)). We identify 88 members.
• **Group B**: Small asteroids ($D < 20$ km) with relatively large satellites ($0.7 \gtrsim D_2/D_1$) in tight mutual orbits ($a \lesssim 9 R_p$). We identify 9 members.

• **Group W**: Small asteroids ($D < 20$ km) with relatively small satellites ($0.2 \gtrsim D_2/D_1 \lesssim 0.7$) in wide mutual orbits ($a \gtrsim 9 R_p$). We identify 9 members.

• **Three outliers**: Two would-be Group L members (90 Antiope and 617 Patroclus) have the Group B characteristic of similar sized components but are much larger than the other Group B members ($D \sim 87$ and 101 km, respectively), and a would-be Group W member (4951 Iwamoto) has the Group B characteristic of similar sized components but a much wider mutual orbit ($a \sim 17R_p$).

• **Split Pairs**: These are inferred systems due to dynamical models that very closely link their heliocentric orbits. Therefore they are not actual binaries, but are rather inferred dynamical end-states. Some pair members are binaries themselves.

The principal change in this classification scheme from Pravec and Harris (2007) is the size—splitting “large” and “small” asteroids. Previously, “large” was defined to be asteroids with diameters larger than 90 km, but from more recent binary asteroid observations and YORP theory, a more natural boundary between “large” and “small” is 20 km (Pravec et al. 2012; Jacobson et al. 2014a). The boundaries between the various defining characteristics appear robust in Figure 1, where adjustments on the order of 10% lead to the creation of no or only a few new outliers. The data in the paragraphs above come from Petr Pravec’s binary catalogue (Pravec et al. 2012).

### 2.1 Large Systems—Group L

These are distinct in the bottom two panels of Figure 1, and are defined by having large primaries with $D > 20$ km (large symbols), and relatively smaller size ratios ($D_2/D_1 \lesssim 0.2$). These size ratios range from 0.03 to 0.2 with the lowest mean of any group: $0.08 \pm 0.06$ (1-$\sigma$) (Pravec et al. 2012). They are typically discovered with ground-based high-resolution imaging with (243) Ida a notable exception, whose satellite was discovered by the Galileo space mission (Belton and Carlson 1994). There are 11 known systems, with the largest being (87) Sylvia ($D \sim 256$ km) with its satellites Romulus and Remus (Brown et al. 2001; Marchis et al. 2005) and the smallest being (243) Ida ($D \sim 32$ km) with its satellite Dactyl (Belton and Carlson 1994). None of the 8 asteroids larger than (87) Sylvia have been reported to have satellites but there are likely many satellites amongst the asteroids with sizes near (243) Ida and up to (87) Sylvia since severe biases limit detection in that population.

The rotation periods of these large asteroids range from 4.1–7.0 hr with a geometric mean: $5.6 \pm 0.8$ (1-$\sigma$ hr) (Pravec et al. 2012). With the exception of (22) Kalliope, all of the Group L members rotate at less than half the critical disruption rate for a spherical body with a density of $2$ g cm$^{-3}$ (2.3 hr rotation period). As discussed in Descamps et al. (2011), the lower than typical rotation periods (asteroids of similar sizes have $12.2 \pm 0.5$ hr rotation periods; Warner et al. 2009) and the elongated shapes of the primaries (e.g. the bean-shape of (87) Sylvia; Marchis et al. 2005) are suggestive of a violent disruption process, with
the reaccumulation of the parent body into high angular momentum shape and spin configurations. However, previous numerical models of asteroid disruptions did not retain shape and spin information of the re-accumulated remnants (Durda et al. 2007), except in the case of Itokawa (Michel and Richardson 2013), so this has not been explicitly tested.

It is important to note that due to an increase of YORP timescales with surface area, YORP cannot play a role for these large systems.

2.2 Small Systems—Groups A, B and W

Systems with small primary bodies \((D < 20\) km) almost all fit in the sub-population of Group A, and are found among NEAs, small MBAs and Mars Crossers. Members of Group A have diameters between 0.15 and 11 km (Pravec et al. 2012). Their mutual orbits are within 2.7 and 9.0 primary radii (mean statistics: \(4.8 \pm 1.3\) \(R_p\)), and the satellites are between 0.09–0.58 the size of the primary (mean statistics: \(0.3 \pm 0.1\)).

Group A members have similar amounts of angular momentum relative to their critical values (where critical is enough to breakup the combined masses if in a single body). Typically this is due to the rapidly rotating primary with a period between 2.2 and 4.4 hr (Margot et al. 2002; Pravec et al. 2006, 2012) — always within a factor of two of the critical disruption rate for a spherical body with a density of 2 g cm\(^{-3}\) (2.3 hr rotation period). The geometric mean of their rotation periods is \(2.9 \pm 0.8\) (1-\(\sigma\)) hr compared to 7.4 \(\pm 0.3\) hr for asteroids in the same size range (Pravec et al. 2012; Warner et al. 2009).

While the orbit period is never synchronous with the very fast primary rotation (see Fig 1. and 2.), the synchronicity of the satellite period with the orbit period divides Group A into two distinct subgroups. Most belong to the synchronous satellite subgroup (~66%; Pravec et al. 2012), although it is possible that these satellites have chaotic rotation but appear nearly synchronous (Naidu and Margot 2015). The rest of the asteroids have satellites that are asynchronous, and have rotation periods between the primary rotation period and the orbit period (Pravec et al. 2012).

There are very few well characterized mutual orbits—only seven binary and two triple systems (Fang and Margot 2012b). Among these there is a trend between their measured orbital eccentricity and the synchronicity of the satellites rotation and orbit periods (see Fig. 1 of Fang and Margot (2012b)), where synchronous satellites are generally less eccentric. This trend is consistent with limits on the eccentricity determined by lightcurve studies (Pravec and Harris 2007). Some asynchronous satellites on eccentric orbits may be in chaotic rotation as a result of torques on their elongated shapes (e.g. 1991 VH; Naidu and Margot 2015). This could explain the high frequency (~33%) of asynchronous satellites in light of possibly rapid theoretical de-spinning timescales —around \(10^2–10^8\) years (the tidal parameters are very uncertain; Goldreich and Sari 2009; Jacobson and Scheeres 2011c; Fang and Margot 2012b) compared to a \(\sim 10^7\) year dynamical lifetime in the NEA population or a \(\sim 10^8\) year collisional lifetime in the MBA population.

The Group B members have nearly equal-sized components (mean \(D_2/D_1\) is \(0.88 \pm 0.09\); they stand out in the middle panel of Figure 1). There is a break amongst the small binary population between Group A and Group B, suggesting an alternate evolutionary route (Scheeres 2004; Jacobson and Scheeres 2011a).
These systems are in a doubly synchronous state with synchronized rotation and orbital periods \cite{PravecHarris2007}. Orbital periods extend from 13.9 hr to 49.1 hr similar to the Group A binaries (11.7 hr to 58.6 hr; \cite{Pravec2012}). Nearly all of this population is found in the Main Belt and discovered by lightcurve observations with the exception of the NEA (69230) Hermes. Hermes is decisely smaller ($D \sim 0.6$ km; Margot et al. p.c.) than the next smallest confirmed Group B member ((7369) Gavrilin, $D \sim 4.6$ km; \cite{PravecHarris2007}), but an unconfirmed member of Group B 1994 CJ$_1$ is even smaller ($D < 0.15$ km; \cite{Taylor2014}). The mean size $D$ is $7 \pm 3$ km, and the largest (4492) Debussy is 12.6 km \cite{Pravec2012}. Because these systems are doubly synchronous, there are strong biases against discovery; only mutual events reveal the presence of the satellite. Furthermore, they are not typically separated enough to be detected by high-resolution imaging (the widest is (854) Frostia with a component separation of only 36.9 km) and too distant and small for radar detection in the Main Belt. Thus they are possibly significantly under-represented amongst known asteroid binaries.

Group W binary members have very large separations (between 9 and 116 $R_p$), and are typically detected by the Hubble Space Telescope or adaptive optics observations ground-based telescope observatories. The existence of some of this group in the Main Belt defies formation only from planetary encounters \cite{FangMargot2012}. Like Group A and B members, they are small (mean size $D$ is 4.8 $\pm$ 2.3 km) \cite{Pravec2012}, so radiative torques like the YORP effect are important. Like Group A members, they are rapidly rotating (geometric mean primary rotation period $3.3 \pm 0.8$ hr; \cite{Polishook2011}) and have moderate size ratios (mean size ratio $D_2/D_1$ is $0.4 \pm 0.2$; \cite{Pravec2012}). They follow the pattern of the asynchronous subgroup of Group A and all of their satellites have rotation periods that are between that of the primary’s rotation and the satellites orbital period. The links between Group A and Group W are strong and \cite{Jacobson2014} developed an evolutionary pathway from the former to the latter. Previously, Group W members have been suspected to be debris from catastrophic collisions (dubbed EEBs in \cite{Durda2004}), but further study consistently finds rapidly rotating primaries \cite{Polishook2011}.

Many of these systems were discovered and characterized by lightcurve observations, which produce rotation periods as well as some information on shape from the amplitude of the lightcurve \cite{PravecHarris2007}. The lightcurve amplitude principally constrains two of the axes of the body, the long $a$ and intermediate $b$ axis (for principal axis rotation about its shortest $c$ principal axis). It can constrain the other axis ratio if there are multiple observing geometries. The lightcurve amplitude can be converted to determine the $a/b$ relationship, which roughly describes the shape of the body’s equatorial cross-section. Group A, B and W members have $a/b$ from 1.01 to 1.35 with an average value of 1.13 $\pm$ 0.07 \cite{Pravec2012}—nearly-circular equatorial cross-sections. Meanwhile the satellites of Group A, B and W members have $a/b$ from 1.06 to 2.5 with an average value of 1.44 $\pm$ 0.24 \cite{Pravec2012}. Thus satellites represent a much larger variety of equatorial cross-sections.

Lastly, some primary members of Group A and W have a characteristic spheroidal “top” shape due to a pronounced deviation from a sphere along an equatorial ridge. This radar-derived shape was made famous by 1999 KW$_4$ \cite{Ostro2006}, but has been found for many other binary and single asteroids ((29075) 1950 DA \cite{Busch2007}; 2004 DC \cite{Taylor2008}; 2008 EV$_5$ \cite{Busch2011}; (101955) Bennu \cite{Nolan2013}; (136617) 1994 CC \cite{Brozovic2011}; (153591) 2001 SN$_{263}$ \cite{Becker2015}).
Fig. 2.— The population of small binary systems, showing their (Bottom) size ratio, (Middle) primary rotation period and (Top) component separation, all plotted as a function of their Primary Diameter (Pravec and Harris 2007; Johnston 2014). The NEAs are blue symbols and MBAs are red symbols.
This ridge preserves a low $a/b$ ratio, i.e., a circular equatorial cross-section, but due to the confluence of rotation and shape this reduces the gravitational binding energy of material on the ridge (Ostro et al. 2006; Busch et al. 2011; Scheeres 2015). At high rotation rates, the entire mid-latitudes obtain high slopes and so disturbed loose material would naturally move towards the potential low at the equator; this material upon reaching the equator may move off the surface entirely and enter into orbit (Ostro et al. 2006; Walsh et al. 2008; Harris et al. 2009). This discovery has driven studies of asteroid re-shaping focusing on the granular and cohesive properties of the surface material and possible secondary fragmentation and in-fall of orbital material (Ostro et al. 2006; Walsh et al. 2008; Harris et al. 2009; Holsapple 2010; Jacobson and Scheeres 2011a; Scheeres 2015).

2.4 Triples

The first discovered triple in the Main Belt was (87) Sylvia, with two small satellites orbiting its bean-shaped primary body (Marchis et al. 2005). More triples have since been found, with (45) Eugenia (Marchis et al. 2007), (93) Minerva (Marchis et al. 2009) and (216) Kleopatra joining the list (Marchis et al. 2008). As discussed below, this is believed to be a natural outcome of formation via asteroid collisions.

There are also a few confirmed and suspected small asteroid triple systems (136617) 1994 CC, (153591) 2001 SN$_{263}$, (3749) Balam and (8306) Shoko (Brozovic et al. 2009; Nolan et al. 2008; Shepard et al. 2006; Marchis et al. 2008; Pravec et al. 2013). All have rapidly rotating primaries (2001 SN$_{263}$ is the lowest at 3.425 hours) and low size ratios between the smaller two members and the primary (Balam has the largest measured satellite at 46.6% its size). For the two triple systems with known primary shapes ((136617) 1994 CC, (153591) 2001 SN$_{263}$), both have the typical “top” shape described above (Brozovic et al. 2011; Becker et al. 2009).

Both Balam and Shoko are also members of split pairs and the other members are 2009 BR$_{60}$ and 2011 SR$_{158}$, respectively (Vokrouhlický 2009; Pravec et al. 2013). As explained in the next subsection, split pairs have a dynamical age that is interpreted as the rotational fission formation age. Since it is unlikely that the split pair member could have formed without significantly affecting the triple system, it is possible that all components were created at the same time from a single rotational fission event (Jacobson and Scheeres 2011b).

2.5 Outliers

Large double asteroids such as the MBA (90) Antiope and Trojan (617) Patroclus appear unique in the inner Solar System. These are too large, with diameters greater than 100 km, to have gained angular momentum from thermal effects and collision simulations do not typically create such systems (Durda et al. 2004). They have very large angular momentum content, owing to the similar-sized components (Pravec and Harris 2007; Descamps et al. 2007; Michałowski et al. 2004). Antiope is notable as it is among the largest fragments in an asteroid family owing to the exceptional size of Themis and its family. Meanwhile, Patroclus is a Trojan, and Solar System formation models suggest that many or all of them may have been
implanted from the primordial Kuiper Belt region (Morbidelli et al. 2005; Nesvorný et al. 2013). Thus this system may share a common origin with the systems found in the Kuiper Belt (see Noll et al. 2008; Nesvorný et al. 2010).

The other outlier, (4951) Iwamoto, has a much wider mutual orbit than other Group B members, but this may be explained by orbit expansion due to the BYORP effect as discussed below (Čuk 2007; Jacobson and Scheeres 2011b).

2.6 Split Pairs

An important discovery related to the dynamics of binary systems is the existence of individual asteroids that are not bound to each other but instead show convincing signs of being split pairs (Vokrouhlický and Nesvorný 2008, 2009; Pravec and Vokrouhlický 2009; Pravec et al. 2010). These were found using dynamical studies similar to those that search for families of asteroids, but here pairs were found to be closely linked dynamically.

Follow-up observations have found convincing links in both size and rotation of the pairs (Pravec et al. 2010) and also the photometric appearances (Moskovitz 2012; Duddy et al. 2012). Their sizes and rotation make a very strong case that the smaller member of the pair was ejected during a rotational fission event, with the signature of this in the slow rotation of the larger object as a function of the size of the smaller object. The latter work finds similar photometric colors for the pairs, supporting the dynamical links between them. The dynamical models suggest that some of these pairs separated less than just $\sim 17$ kyr ago, and hence the photometric colors have not had time to evolve significantly due to space-weathering or other effects (Vokrouhlický and Nesvorný 2009; Vokrouhlický et al. 2011).

3. Formation

While the community and literature largely agree on the collisional origin of large asteroid’s satellites (Group L), there is continued work on the details of how the small systems (Groups A, B, W) form and evolve. An important part of understanding the formation of the small systems concerns both the properties and variety of outliers and the possible complicated evolutionary paths for satellites or building blocks of satellites once in orbit around a rubble pile asteroid.

3.1 Large Systems—Collision

Collisions were proposed as a potentially important formation mechanism even before the discovery of Ida’s moon Dactyl in 1993. Most works focused on ejecta from a collision becoming mutually bound, becoming bound around the largest remnant, or rotational fission due to a highly oblique or glancing impact (Weidenschilling et al. 1989; Merline et al. 2002; Richardson and Walsh 2006). Both Weidenschilling et al. (1989) and Merline et al. (2002) found that complete disruption is a far more likely outcome than
collisionally-induced rotational fission, and there are no observed systems that can be clearly attributed to this later process.

The study of the other collisional mechanisms first focused on cratering events on the asteroid Ida, numerically tracking the evolution of ejected debris in order to form its small satellite Dactyl ([Durda] 1996, [Doressoundiram et al.] 1997). Studies of asteroid impacts gained a numerical boost by combining Smoothed Particle Hydrodynamics models of asteroid fragmentation with $N$-body models of their gravitational re-accumulation ([Michel et al.] 2001, 2002, 2003, 2004, [Durda et al.] 2004, 2007). These models were more capable of modeling the physics of catastrophic collisions and maintaining high-resolution models of the fragments long-term gravitational interactions and re-accumulation. They found that the formation of satellites is a natural outcome in an asteroid disruption.

[Durda et al.] (2004) further explored the different types of systems formed during a collision. This large suite of 161 impact simulations studied 100 km basalt targets being impacted by impactors of various sizes hitting at a range of velocities and angles. In their suite of collision and re-accumulation simulations they observed, and named, the two previously proposed types of systems: Escaping Ejecta Binary systems (EEBs) and SMAshed Target Satellites (SMATS). The SMATs, generally featured small satellite(s) orbiting the re-accumulated target body. The known satellites around large ($D > 10$ km) Main Belt asteroids share similar properties—extreme size ratio between primary and secondary and large orbital separation (where the orbital separations are too large to be explained by tides: see Section 4.2). They predicted a formation rate that should roughly produce the observed number of satellites detected around very large asteroids ($D > 140$ km) accounting for their production due to collisions, satellites destroyed by collisions and the very early clearing of the asteroid belt.

Meanwhile they proposed that some small Main Belt systems featuring two small components of roughly similar size on distant orbits are possibly EEBs. Their examples were (3749) Balam and (1509) Esclangona, and while at the time both were interesting candidates, (3749) Balam has been discovered to have a third component and a split pair and (1509) Esclangona has been found to have a very rapid rotation period similar to that found among many of the binary systems formed by the YORP effect ([Warner et al.] 2010). The best remaining candidates are (317) Roxane because of its slow primary rotation (8.2 hr; [Harris et al.] 1992, [Polishook et al.] 2011, [Jacobson et al.] 2014b) and (1717) Arlon because of its slow primary rotation (5.1 hr; [Cooney et al.] 2006) and high size ratio ($> 0.22$; [Cooney et al.] 2006, [Jacobson et al.] 2014b). The lack of EEBs in the known catalog is curious, as the simulations of [Durda et al.] (2004) formed hundreds of systems immediately after a collision, although the stability of these binaries was not thoroughly examined. This is an important avenue for future work especially given the importance of spin-orbit coupling for binaries after rotational fission ([Jacobson and Scheeres] 2011a). Tens of asteroid families are known (see Chapter by Nesvorný et al.) and there is evidence for even very recent impacts throughout the Solar System ([Nesvorný et al.] 2002, [Vokrouhlický and Nesvorný] 2009). However, small and wide binary systems are difficult to find and small components are more susceptible to collisional grinding (see Chapter by Bottke et al.), which may explain the lack of discoveries of this type of system. Meanwhile the known systems need substantial characterization (rotation periods etc.) to try to distinguish between possible EEBs and end-states of YORP/BYORP evolution processes (see below).
All of the numerical work to understand formation of satellites during collisions have found triple and multiple systems in their simulations. Durda et al. (2004) reported temporary multiple systems, and Leinhardt & Richardson (2005) re-analysis of a single simulation found 10% triples and 3% quadruple systems that lasted the length of the simulations (days). While triples have now been found among some large systems, longer-term dynamical simulations of their formation and evolution following large impacts would be needed to quantify the match between observations and models.

Catastrophic impact modeling has generally relied on very similar collision scenarios (impact speeds and angles etc.) to model both the formation of satellites and asteroid families (Michel et al. 2001, 2003; Durda et al. 2004, 2007). While asteroid families are strictly correlated with collisions, it does not mean that the presence of a family demands satellites, as not every collision forms satellites, and small satellites themselves are susceptible to collisional evolution/destruction on timescales shorter than the age of many observed asteroid families (Durda et al. 2004).

3.1 Small Systems—Rotational Disruption

Even before the discovery of small binary systems, the doublet craters found on the terrestrial planets (Melosh and Stansberry 1991; Bottke and Melosh 1996) and crater chains on the Moon (see Richardson et al. 1998) suggested that there were mechanisms to disrupt small asteroids. The demonstration provided by Comet Shoemaker-Levy 9 and its tidal disruption at Jupiter further instigated models of “rubble pile” interiors and their tidal disruptions while encountering planetary bodies (Asphaug and Benz 1996; Richardson et al. 1998).

Bottke and Melosh (1996) suggested that searches for asteroid satellites “place emphasis on kilometer-sized Earth-crossing asteroids with short-rotation periods”, and lightcurve surveys found many interesting targets in this sample. Observations of multi-frequency lightcurves and possible eclipse/occultation events became common, and gave very strong indications of possible satellites (Pravec and Hahn 1997; Pravec et al. 1999; Mottola and Lahulla 2000; Pravec et al. 2000). The radar imaging of near-Earth asteroid 2000 DP107 confirmed that the lightcurve observations were detecting actual satellites (Margot et al. 2002). Combining all possible detections (Margot et al. 2002) suggested that up to 16% of the population were binaries and that rotational disruption was a primary culprit (Pravec et al. 1999; Margot et al. 2002; Pravec and Harris 2007).

Rubble pile asteroids encountering the Earth were studied with a granular dynamics code by Richardson et al. (1998) and again by Walsh and Richardson (2006). While both groups found that binaries are at least initially formed following some disruptive tidal event, Walsh and Richardson (2006) found that the primary bodies were typically elongated, the secondaries were on very eccentric orbits and the primary rotated with period around 3.5–6 hours, rather than the near-critical 2-4 hr periods. Walsh and Richardson (2008) took the resulting simulation outcomes and built a Monte Carlo model including the expected time between planetary encounters, expected encounter outcomes, nominal tidal evolution of orbits and primary spin, and observed asteroid shape and spin characteristics. They found that the produced systems are not expected to survive very long, owing to the large semimajor axes and high eccentricities. These works, and the discovery of
small binary systems in the Main Belt (Warner and Harris 2007) where there is no planetary body to tidally disrupt an asteroid, strongly suggested that tidal disruption is not a primary mechanism. Tidal disruption of NEAs could still account for a small subset of the population, though it is not clear if the elongated primaries and eccentric secondaries could survive long enough to be observed (Walsh and Richardson 2008).

A more ubiquitous method for rotational disruption of small asteroids is the YORP effect. Rubincam (2000) proposed that the YORP effect could spin cm-sized objects so fast that they would eventually burst. Vokrouhlický and Čapek (2002) pointed out that this effect will likely drive asteroids to $0^\circ/180^\circ$ obliquity end-states and then in many cases of continued spin-up could drive them to “rotational fission”. YORP was connected directly with binary formation in Asteroids III (Bottke et al. 2002), where it was proposed as a possible means for forming small binary asteroids and inducing re-shaping.

Ostro et al. (2006) observed NEA 1999 KW$_4$ with radar and produced an incredibly detailed shape model of the primary while Scheeres et al. (2006) analysed the dynamics of the system (see Fahnestock and Scheeres 2008). This system was similar to previously discovered NEA systems—it featured a rapidly rotating primary (essentially at critical rotation rate) and a small secondary on a close orbit just beyond its Roche Limit. However, owing to the exceptional resolution of these radar observations, the derived shape model was found to have a bulging equatorial ridge (see Fig 3).

As part of the dynamical analysis of the system Scheeres et al. (2006) hypothesized that the system disrupted and shed mass due to tidal torques from a planetary flyby or the YORP effect. The primary would have evolved to build the ridge and reach the very rapid rotation rate due to the in-fall of material that was not accreted/incorporated in the satellite.

Starting with the Scheeres et al. (2006) work on the state of the 1999 KW$_4$ system, and their suggestion that the equatorial ridge could have been formed by the in-fall of material—this started one of two tracks of thought about the ridge and its formation which were followed up in a number of works (Scheeres 2007b; Jacobson and Scheeres 2011a). These works posited that the mass-loss was a more singular catastrophic event—a fission event—and that later processing of this lost mass accounts for the equatorial ridge and other widely observed system properties. At the other end of the discussion, Walsh et al. (2008) modeled YORP-spinup of rubble piles made of thousands of constituent particles and posited that the equatorial ridge was caused by re-shaping of the primary rubble-pile asteroid as a result of spin-up and consequent mass-loss. In this model the satellite was slowly built in orbit by repeated mass-shedding events.

These models in some ways were working from opposite ends of a spectrum of model resolution and techniques. The Scheeres (2007b) work focused on the rigid body dynamics of separated contact binaries, and Jacobson and Scheeres (2011a) extended this to consider what might happen if the ejected fragment itself was allowed to fragment once in orbit, which is critical to prevent rapid ejection of the fragment, and also through the fall-in of some of the material could explain the ubiquitous top-shape primaries. Meanwhile, Walsh et al. (2008, 2012) started with model asteroids constructed of thousands of individual solid spherical particles interacting through their gravity and through mutual collisions. While the gravity and collisions of the particles are efficiently modeled throughout the simulations, the timescales for spin-up were necessarily shortened for computational reasons and the structure of the body consisted of different, but very simple, size
Fig. 3.— The radar-derived shape model of 1999 KW₄. The coloring indicates local gravitational slopes with green’s being near 30-40 and the blue colors at the equator and poles near zero (Ostro et al. 2006; Scheeres et al. 2006).
distributions of spherical particles. A valuable test of these different ideas may occur when NASA’s OSIRIS-REx space mission reaches asteroid Bennu, which shows signs of having an equatorial ridge (Nolan et al. 2013; Lauretta et al. 2014).

All scenarios suffer confusion from new studies of the sensitivity of the YORP effect to very small changes of an asteroid’s shape. Model asteroids were generated, inclusive of small features such as boulders and small craters, and when YORP evolutions were calculated it was found that very small changes on the surface of a small body can dramatically change its YORP behavior (Statler 2009; Cotto-Figueroa et al. 2015). The changes could be so dramatic that nearly any re-shaping of a body during its YORP spin-up could essentially result in a completely different YORP-state. Essentially each shape-change, no matter the scale, results in a coin-flip outcome to determine if the body continues spinning-up or reverses and spins-down.

The population of asteroids with secondaries is $\sim 15\%$ (Pravec and Harris 2007), and so the rotational disruption mechanism appears to be quite efficient. If each movement on the surface of an asteroid results in a coin-flip to determine spin-up or spin-down, then seemingly bodies would never spin up enough to rotationally disrupt. This perplexing issue may demand some underlying tendency for small bodies to “spin-up” by the YORP effect. It is possible that the YORP effect could actually induce preferential spin-up for even a symmetrically shaped asteroid, following the “Tangential YORP effect”, which may play a big role in understanding these issues (Golubov and Krugly 2012; Golubov et al. 2014).

### 3.3 Split Pairs

The rotational fission hypothesis states that at a critical spin rate an asteroid’s components enter into orbit about each other from a state of resting on each other (Jacobson and Scheeres 2011a). The spin energy of the asteroid at this critical spin and any released binding energy is the free energy available to disrupt the asteroid system. Therefore, there is a direct energy and angular momentum relationship between the spin states of the newly formed components and the mutual orbit. From these considerations and some simple assumptions, this theory predicts a relationship between the sizes of the two components and the rotation rate of the larger component. Observations of split pairs directly confirm this theoretical prediction (Pravec et al. 2010). This is powerful evidence that the rotational fission hypothesis is correct for split pairs.

Further observations of split pairs confirm that each member is a good spectroscopic match to the other (Moskovitz 2012; Duddy et al. 2012; Polishook et al. 2014a). Interesting observations that there is no significant longitudinal spectroscopic variations and that the spin axes between members are identical are interesting twists that future theory must account for (Polishook et al. 2014ab).

### 4. Evolution of Binary Systems

There are a number of of different binary evolution mechanisms. Classical solid body tides are long studied and binary asteroids provide useful test cases. Meanwhile, thermal effects can affect a single body in the system or the pair of bodies. A single body having its spin state changed by a thermal effect can possibly
re-shape due to its angular momentum increase. Binaries on near-Earth orbits can encounter the terrestrial planets, which can destabilize or otherwise alter a system’s mutual orbit, while also distorting or disrupting either component. Finally, an impact can destroy a satellite, remove it from a system or simply perturb its orbit.

The small number of known large systems are unaffected by many of these evolutionary mechanisms: their satellites are typically too distant for tides and their sizes too large for thermal effects, and there are no planets in the Main Belt to perturb them. Meanwhile, the known small system’s may be affected by multiple effects simultaneously in ways that are difficult to disentangle. Therefore, the primary set of data used to understand evolutionary effects are the large number of small systems—Groups A, B and W. The majority of all systems (A) look quite similar—they have rapidly rotating primaries, secondaries just beyond the nominal Roche limit at \( \sim 2.5 \frac{a}{R_p} \), where \( a \) is the semimajor axis and \( R_p \) is the primary radius, and are between 9-58% the size of the primary (typically less than 2-3% of the primary mass). The outliers are a minority, but they and the split pairs point to important evolutionary end-states of the small systems.

### 4.1 Binary-YORP

The theory of binary YORP (BYORP) is a direct extension of the Yarkovsky and YORP; instead of modifying the spin state of an asteroid, the BYORP effect modifies the mutual orbit of a double asteroid system in a spin-orbit resonance, typically the synchronous 1:1 spin-orbit resonance (Cuk and Burns 2005). Similar to YORP, the back reaction force from the photon causes a torque, but here the lever arm connects the center of mass of the binary system to the emitting surface element. The back reaction torques the satellite about this mass center changing the mutual orbit. Unlike the YORP effect, the relative position and orientation of the emitting surface element can change the mutual orbit’s semimajor axis \( a \) with respect to the center of mass of the binary system (unlike a rigidly rotating asteroid in the case of the YORP effect), so only binary members that occupy a spin-orbit resonance have non-zero cumulative BYORP effects; the torques on all binary members outside of spin-orbit resonances cancel out over time.

Cuk and Burns (2005) recognized that this effect could be significant for small asteroids found throughout the binary asteroid population. Most discovered binaries in the near-Earth and Main Belt populations have small (Radius < 10 km) secondaries, which are tidally locked in a synchronous spin-orbit resonance (Richardson and Walsh 2006; Pravec et al. 2006). From these characteristics and shape estimates, simple estimates scaled from the YORP effect concluded that the BYORP effect is able to significantly modify an orbit in as little as \( \sim 10^5 \) years (Cuk and Burns 2005; Cuk 2007; Goldreich and Sari 2009). Secular averaging theory has agreed with these short timescales estimates (McMahon and Scheeres 2010a, b; Steinberg and Sari 2011).

Assuming the smaller secondary is synchronously rotating and expanding the solution to only first order in eccentricity, the secular evolution of the mutual orbit’s semi-major axis \( a \), measured in primary radii \( R_p \), and eccentricity \( e \) are (equations 93 and 94 from McMahon and Scheeres 2010a with re-defined
variables):\[
\frac{da}{dt} = 3H_\odot B_a a^{3/2} \sqrt{1 + q} \\
\frac{de}{dt} = -\frac{3H_\odot B_a a^{1/2} e \sqrt{1 + q}}{8\pi \rho \omega_d \rho^2 q^{1/3}} = -\frac{e}{4a} \frac{da}{dt}
\]

where \(q\) is the mass ratio between the secondary and the primary, \(\rho\) is the density of both asteroids assumed to be the same since they are likely to be of common origin, \(\omega_d = \sqrt{4\pi \rho G/3}\) is the critical rotational disruption rate for a sphere of density \(\rho\), \(G\) is the gravitational constant, \(H_\odot = F_\odot / \left( a_\odot^2 \sqrt{1 - e_\odot^2} \right)\) is a heliocentric orbit factor, \(F_\odot\) is the solar radiation constant, and \(a_\odot\) and \(e_\odot\) are the heliocentric semi-major axis and eccentricity of the binary asteroid system. Lastly, \(B_a\) is the BYORP coefficient of the secondary.

As defined here, \(B_a\) does not depend on the size of the secondary, only its shape relative to its orientation (see McMahon and Scheeres 2010a). The BYORP coefficient can be positive corresponding to outward expansion of the mutual orbit or negative corresponding to inward shrinking. \((66391)\, 1999\, KW_4\) has the only existing detailed secondary shape model (Ostro et al. 2006), and it has an estimated magnitude of \(|B_a| \sim 0.04\) (McMahon and Scheeres 2010a, 2012c). Estimates of \(B_a\), from other asteroid shape models and gaussian ellipsoids suggest that the BYORP coefficients are typically \(|B_a| < 0.05\) (McMahon and Scheeres 2012a). Scaling the \((66391)\, 1999\, KW_4\) estimate to other binary asteroid systems, Pravec and Scheirich (2010) calculated mutual orbit evolution predictions for seven observable binaries: \((7088)\, Ishtar\), \((65803)\, Didymos\), \((66063)\, 1998\, RO_1\), \((88710)\, 2001\, SL_9\), \((137170)\, 1999\, HF_1\), \((175710)\, 1999\, HF_2\), \((185851)\, 2000\, DP_{107}\). First results regarding \((175706)\, 1996\, FG_3\) have been reported in Scheirich et al. (2015) and are discussed below. Close observations of these candidates over the next few years will test the nascent BYORP theories.

As noticed initially by Cuk and Burns (2005), outward BYORP expansion of the mutual orbit damps the eccentricity. This potentially provides a disruption pathway for binary asteroids. Their orbit can expand until the semi-major axis reaches their Hill radii since outward expansion is a runaway process. If so, then these binaries would become unbound by three body interactions with the Sun and create asteroid pairs. Unlike most observed asteroid pairs, these would not follow the rotation-size ratio relationship set by immediate disruption after rotational fission (Scheeres 2004, Pravec et al. 2010). No such pairs have yet been identified, however the expected ratio between pairs formed from fission to those formed from BYORP expansion is high (Jacobson and Scheeres 2011a).

BYORP expansion of the orbit of the secondary will only continue if the rotation of the secondary remains synchronous with its orbital period. However, a numerical experiment by Cuk and Nesvorny (2010) found that the eccentricity may actually increase. Eccentricity growth induces chaotic rotation which is then halted by the BYORP effect, and if the orientation of the secondary is reversed, then the mutual orbit will contract. Cuk and Nesvorny (2010) rule out the role of the ejection resonance for responsibility of this eccentricity increase and attributes it to spin-orbit coupling. This disagrees with evolution resulting from the force decomposition and averaged equations (Cuk and Burns 2005, Goldreich and Sari 2009, McMahon and Scheeres 2010b, Steinberg and Sari 2011). Future work directly comparing long-term evolution of a Cuk
and Nesvorný (2010) type model and the secular evolution equations is needed to determine resolutely the consequences of outward BYORP evolution on eccentricity.

Using the secular evolution equations and including mutual tides, Jacobson et al. (2014b) found that outward expansion can be interrupted by an adiabatic invariance between the mutual semi-major axis and libration state of the secondary. As the mutual orbit expands, a small libration can grow until the rotation of the secondary de-synchronizes and begins to circulate. This has been proposed as the mechanism to explain the small known population of wide binary asteroid systems that are found among NEAs and in the Main Belt, as this process can leave secondaries stranded so far from the primary to make tidal synchronization timescales very long (Jacobson et al. 2014b). As observations continue to be made of wide and possibly expanding binaries such as (185851) 2000 DP\textsubscript{107}, the theories regarding expansion due to the BYORP effect will continue to be tested.

The BYORP effect can also shrink orbits and simultaneously increase eccentricity (Čuk and Burns 2005; Goldreich and Sari 2009; McMahon and Scheeres 2010b; Steinberg and Sari 2011). This will be discussed after describing tides, which are important when considering very tight binary asteroid systems.

4.2 Tides

The evolutionary consequences of mutual body tides have been considered for the evolution of asteroids since the discovery of the first asteroid satellite, Dactyl about (243) Ida (Petit et al. 1997; Hurford and Greenberg 2000). These body tides are the result of the asteroid’s mass distribution chasing an ever-changing equilibrium figure determined by the asteroid’s spin state and the gravitational potentials of both binary members. Since the relaxation towards this figure is dissipative, energy is lost in the form of heat and removed from the rotation state of the asteroid. The difference in potential between the delayed figure and the theoretical equilibrium figure is referred to as the tidal bulge. This tidal bulge torques the mutual orbit ensuring conservation of angular momentum within the asteroid system. Unlike lunar tides on Earth, where most of the energy is dissipated at the ocean-seabed interface and in the deep ocean itself (Taylor 1920; Jeffreys 1921; Egbert and Ray 2000), the mutual tides between asteroids do not dissipate energy along an interface or in a fluid layer but throughout the solid body. However, new results indicate that tidal dissipation in rubble piles may be much higher (Scheirich et al. 2015) than previously expected (Goldreich and Sari 2009), so where and how tidal energy is dissipated must be examined much more thoroughly in the future.

Under most proposed formation circumstances and observed in nearly all small systems —except those with synchronous rotations, asteroids rotate at rates greater than their mutual orbit mean motion (Pravec et al. 2006). In this case, the tidal bulge lags behind the line connecting the mass centers of the binary members, and the binary’s primary is rotationally decelerated. In this case, the mutual orbit expands, similar to the Earth-Moon system. Alternatively, the tidal bulge precedes the line connecting the two asteroids, and the binary’s primary is rotationally accelerated. In this case, the mutual orbit shrinks, similar to the Mars-Phobos system. No observed binary asteroids currently occupy this state. A third tidal state also exists, librational tides can oscillate through tidally locked binary members. This tide is responsible for removing
libration from synchronous satellites. The tidal bulge oscillates from the trailing to leading hemisphere as the secondary librates, so the torque on the orbit cancels out and the orbit does not evolve.

Formally deriving an explicit set of equations to describe these torques has been a focus of research for over a century (Darwin 1879). Historically, most theoretical descriptions of tides have fallen into two camps split by their assumptions regarding the relationship between the tidal bulge and the line connecting the mass centers of the two asteroids: (1) some assume a constant lag angle (Goldreich 1963; Kaula 1964; MacDonald 1964; Goldreich and Soter 1966; Taylor and Margot 2010) and (2) some assume a constant lag time (Singer 1968; Mignard 1979, 1980; Hut 1980, 1981). Neither relationship is expected to accurately reflect potential asteroid rheology (Efroimsky and Williams 2009; Greenberg 2009; Goldreich and Sari 2009; Jacobson and Scheeres 2011c; Ferraz-Mello 2013). Although the constant lag angle is believed to better represent circulating tides through solid bodies, Greenberg (2009) describes its shortcomings in vivid starkness. For the sake of this review, we will consider using the theory only for nearly circular orbits and will be careful to state when we feel that this theory may not be adequate. If systems have a non-negligible eccentricity, the tidal de-spinning calculated by the first order theory will be a lower bound, but the effects on the orbital evolution, particularly the eccentricity, are more difficult to determine. For instance, the theories in Goldreich (1963) and Hut (1981) give different predictions regarding the orbital evolution of asynchronous asteroids depending on orbital parameters.

Constant lag angle tidal theory assumes that the tidal bulge raised by an orbiting companion lags the line connecting the bodies’ centers by a constant angle \( \epsilon \), which is related to a tidal dissipation number \( Q \) via: \( Q = \frac{1}{2\epsilon} \). The tidal dissipation number quantifies the amount of energy dissipated each tidal frequency cycle over the maximum energy stored in the tidal distortion (see the following for further discussion: Goldreich and Soter 1966; Greenberg 2009; Efroimsky and Williams 2009). This theory is appropriate for determining the tidal torque on a circulating body, but as the body approaches synchronization and when the body is librating, this theory likely overestimates the actual tidal torque. The circulating tidal torque on a spherical asteroid with radius \( R \) from a perturbing binary member with a mass ratio of \( q \) is:

\[
\Gamma_C = \frac{2\pi k_2\omega^2 R^5 q^2}{Qa^5} \left( \frac{\omega - n}{|\omega - n|} \right)
\]

where the semi-major axis \( a \) is measured in asteroid radii \( R \), \( (\omega - n/|\omega - n|) \) indicates the direction of the torque given the spin rate of the asteroid \( \omega \) and the mean motion of the mutual orbit \( n \), and \( k_2 \) is the second order Love number of the asteroid. The potential Love number \( k \) quantifies the additional gravitational potential produced by the tidal bulge over the perturbing potential. In other words, it captures how much the tidal bulge responds to the deforming potential. We are currently considering only the lowest order relevant surface harmonic, namely the second (see the following for a further discussion of the perturbing potential and its expansion, Ferraz-Mello et al. 2008). A perfectly rigid asteroid would have a tidal Love number of zero, whereas a inviscid fluid would have a Love number of 3/2 according to its definition (Goldreich and Sari 2009).

This tidal torque is most applicable to the primary, which is often rapidly rotating compared to the mean motion of the mutual orbit (Pravec et al. 2006; Richardson and Walsh 2006). In the most common
case, the secondary is tidally locked and so does not contribute to the evolution of the semi-major axis of the mutual orbit. Given the torque above, the semi-major axis $a$, measured in primary radii $R_p$, and the primary spin rate $\omega_p$, evolution are (Goldreich and Sari 2009):

$$\frac{da}{dt} = \frac{3k_{2,p}\omega_q \sqrt{1+q}}{Q_p a^{11/2}}$$ (3a)
$$\frac{d\omega_p}{dt} = -\frac{15k_{2,p}\omega_q^2 q^2}{4Q_p a^6}$$ (3b)

where $k_{2,p}$ and $Q_p$ are the tidal Love and dissipation numbers for the primary (for higher order expansions, see Taylor and Margot 2010).

The ratio of tidal de-spinning timescales for the primary and secondary are:

$$\frac{\tau_s}{\tau_p} = \frac{k_{2,p}Q_s}{k_{2,s}Q_p} q^2$$ (4)

where $k_{2,s}$ and $Q_s$ are the tidal Love and dissipation numbers for the secondary. Since the mass ratio is often of order $q \sim 0.01-0.1$, immediately it is clear that the secondary tidally locks first. It is possible that the ratio of tidal parameters could counteract this, however both the tidal parameters derived from a modified continuum tidal theory (Goldreich and Sari 2009) and the observed parameters from a hypothetical tidal-BYORP equilibrium (Jacobson and Scheeres 2011c) are consistent with faster tidal synchronization of the secondary, $\tau_s/\tau_p \propto q^{3/2}$ and $\tau_s/\tau_p \propto q^{5/2}$, respectively.

When the mass ratio is nearly equal, tides drive both bodies to synchronization in nearly the same timescale (Jacobson and Scheeres 2011a). From this configuration, where both members are tidally locked, the BYORP effect can expand or shrink the mutual orbit to great effect. Acting independently on each body, in addition to the YORP effect acting on each component, BYORP can effectively transfer angular momentum to the orbit (Taylor and Margot 2014). This could lead to rapid separation (Jacobson and Scheeres 2011a), or inward drift leading to unstable configurations (Bellerose and Scheeres 2008; Scheeres 2009; Taylor and Margot 2014), to gentle collisions and contact binaries (Scheeres 2007a; Jacobson and Scheeres 2011a).

Although circulating tides drive the secondary to synchronous rotation, the secondary still has significant tidal dissipation occurring within it due to librational tides. The circulating theory is inappropriate for libration since according to this theory the tidal bulge instantaneously moves across the body. Mignard (1979) developed an alternative approach that assumes that the phase lag is proportional to the frequency of the tidal forcing. Here $\lambda_0$ is the characteristic spin rate at which the body transitions from a circulation torque to the libration torque or vice versa (where $\lambda_0$ is related to tidal lag time $\Delta t$ by $2Q|\lambda_0|\Delta t = 1$; Mignard 1979). In the tidal torque, $\lambda_0$ takes the place of $|\omega - n|$ in the denominator Eq. 2. The libration torque is not only appropriate when the system is librating, but also when the system is circulating slowly compared to $\lambda_0$. However, this torque becomes inappropriate as the body begins to circulate quickly since the tidal bulge could wrap about the body.

These two theories are actually one and the same if $\lambda = \omega - n$ when $\omega - n > \lambda_0$ and if $\lambda = \lambda_0$ when
\( \omega - n \leq \lambda_0 \), in which case \( \lambda \) replaces \( \lambda_0 \) in equation 2. This approximate tidal torque can handle both libration and circulation for nearly circular and non-inclined systems (Jacobson and Scheeres 2011a).

### 4.3 BYORP effect and Tides

The leading hypothesized formation mechanism for Group A binary asteroids is by rotational disruption, which is observed to produce a rapidly rotating primary and a secondary that is quickly tidally locked—the secondary is even predicted to begin rotating more slowly (Scheeres 2007a; Walsh et al. 2008; Jacobson and Scheeres 2011a). When considering this configuration for nearly circular orbits, circulating tides on the primary and librational tides on the secondary contribute to the change in eccentricity of the mutual orbit. Since the libration of the secondary and the mutual eccentricity are coupled (McMahon and Scheeres 2012b), the librational tides on the secondary are often broken into direct librational and radial components (Murray and Dermott 2000). The sum effect of all these tides on the mutual eccentricity is that the eccentricity is always being damped due to the dominance of the librational tides on the secondary, for a wide range of tidal parameters considered (Goldreich and Sari 2009; Jacobson and Scheeres 2011c).

In the singly synchronous configuration—rapidly rotating primary and tidally locked secondary, the mutual orbit of a small binary asteroid can evolve according to both the BYORP effect and tides. While tides in synchronous binary asteroids systems act only to expand the semi-major axis and only to decrease eccentricity, the BYORP effect can expand or shrink the semi-major axis depending on the shape and orientation of the secondary. In the case of BYORP effect driven expansion, both processes are growing the semi-major axis and both are reducing the eccentricity. As discussed above, this process can lead to disruption at the Hill radius or de-synchronization of the secondary, which can strand the mutual orbit at a wide semi-major axis due. Alternatively, the BYORP effect and tides can act in opposite directions. These effects drive the semi-major axis to an equilibrium location:

\[
\alpha^* = \left( \frac{2\pi k_2 \rho \omega^2 R_p^2 q^{4/3}}{B_s H \odot q_p} \right)^{1/7}
\]

This semi-major axis location depends directly on the tidal parameters and the BYORP coefficient. If this location is distant, then secondaries could be rapidly lost (Čuk and Burns 2005; Čuk 2007; Goldreich and Sari 2009; McMahon and Scheeres 2010a), and the binary formation rate would have to be significant to account for the observed \( \sim 15\% \) fraction (Čuk 2007). Alternatively, the proposed equilibrium of tides and BYORP prevents this rapid destruction of systems and no longer requires binary formation rates to match potentially very fast BYORP disruption rates (Jacobson et al. 2014c).

A prediction for occupying this equilibrium is that the semi-major axis should not be changing significantly. While measured changes in the semi-major axis or orbital period require currently unobtainable precision, a change in the semi-major axis does lead to a quadratic drift in the mean anomaly (McMahon and Scheeres 2010a), which can be measured very precisely through the timing of mutual events in photometric light curves. A large survey has been undertaken to examine if these drifts occur (Scheirich and
Fig. 4.— $BQ/k_p$ were calculated directly from observed quantities according to equation 6 for each known synchronous binary, and plotted as a function of primary radius $R_p$ along with 1-sigma uncertainties. A red circle highlights the binary (175706) 1996 FG$_3$. All the data is from [http://www.asu.cas.cz/~asteroid/binastdata.htm](http://www.asu.cas.cz/~asteroid/binastdata.htm) maintained by Petr Pravec according to Pravec et al. (2006). The solid line is a fitted model to the data: $B_sQ_p/k_{2,p} = 6 \times 10^3 R_p$. The dashed lines indicate the range of predicted scatter in the model due to the BYORP coefficient (possibly 10 times stronger or 100 times weaker). Reproduced with some updated binary parameters from Jacobson and Scheeres (2011c).
The first results from this survey find no drift in mean anomaly for NEA binary (175706) 1996 FG₃ (Scheirich et al. 2015), which may point to this equilibrium. If the singly synchronous binary population occupies this equilibrium, then we are able to learn about the internal properties of asteroids from only remote sensing measurements (Jacobson and Scheeres 2011c), however the tidal and BYORP coefficients are degenerate:

$$\frac{B_s Q_p}{k_{2,p}} = \frac{2\pi \omega^2_0 \rho R_p^2 q^{4/3}}{H_\odot a^7}$$

(6)

This parameter relationship is shown in Figure 4 along with a fit to the data: $B_s Q_p/k_{2,p} = 6 \times 10^3 (R_p/1 \text{ km})$. As discussed above, estimates for the BYORP coefficient are around $B_s \sim 0.01$ (Cuk and Burns 2005; Goldreich and Sari 2009; McMahon and Scheeres 2010a, 2012a). From the data, the tidal parameters then follow: $Q/k_2 = 6 \times 10^5 (R_p/1 \text{ km})$, very different than the $Q/k_2 \gtrsim 10^7 (1 \text{ km}/R_p)$ predicted from a modification of the continuum theory for rubble pile asteroids (Goldreich and Sari 2009).

Taylor and Margot (2011) predict tidal properties by assuming a tidal evolutionary path from twice the primary radius to the current orbital separation in under a certain timescale. For (175706) 1996 FG₃, they estimate that $Q/k_2 \approx 2.7 \times 10^7$ in order to migrate from 2 to 3.6 primary radii in 10 Myr. Using the new estimate of the tidal parameters from Scheirich et al. (2015), $Q/k \approx 2.4 \times 10^5$ and this same tidal migration (assuming no influence from the BYORP effect) could take place in $5.6 \times 10^4$ years. This much higher rate of tidal dissipation or much larger tidal Love number can only be consistent with a tidal rheology very different than terrestrial planets and moons. Furthermore, the equations which convert the tidal Love number to a rigidity or elastic modulus, often denoted $\mu$, assume a continuum model that may not apply for this rubble pile tidal rheology.

So far, the discussed tidal theory assumes that all of the rotation axes are aligned and that the mutual orbit is nearly circular. If this is not the case, then the tidal bulge can have a significant effect on the mutual orbit and rotation state of the asteroid. The differences between the different tidal theories become more extreme, and they differ by more than a matter of magnitudes but also of direction. This is an ongoing area of active research with new tidal theories being developed to eventually describe asteroid lithologies accurately (Goldreich and Sari 2009; Efroimsky and Williams 2009).

A separate tidal effect relies on ’tidal saltation’, or the physical lofting of material off the surface of the primary. The very rapid, near critical, rotation of the primary permits the very small perturbations of the secondary to loft debris off the primary’s equator (Fahnestock and Scheeres 2009; Harris et al. 2009), and during flight angular momentum is transferred from the debris to the orbit of the secondary. This expands the orbit of the secondary at rates that could potentially compete with tidal forces. Given the direct physical alteration of the primary by the repeated lofting and landing of particles on the equator, this theory provides an interesting observational test for future observations of equatorial ridges on NEAs.

### 4.4 Asteroid re-shaping

If the asteroids were simply fluids then they would follow permissible shape and spin configurations.
that have been studied by many including Newton, Maclaurin, Jacobi, Poincaré, Roche and Chandrasekhar. Observations of asteroids clearly show that they are not fluids and their distribution of shape and spin configurations agree (Pravec et al. 2002). Observations also suggest that they are not simply monolithic rocks.

Rather, the population of small asteroids ($D < 10$ km) are thought to be primarily gravitational aggregates consisting of small bodies held together almost strictly by their self gravity. Numerous observations and models contribute to this line of thought, including their spin and shape distributions but also observations of crater chains on the Moon, the breakup of Comet Shoemaker-Levy 9, the very large observed impact crater on the large primitive asteroid Mathilde and of course the striking images of the small asteroid Itokawa. These arguments were last summarized in Asteroids III by Richardson et al. (2002), and the chapter by Scheeres et al. in this volume reviews our general knowledge of asteroid interiors.

Efforts to understand asteroid shape and spin configurations borrow cohesionless elastic-plastic yield criteria from soil mechanics (Holsapple 2001, 2004; Sharma 2009). These formulations calculate envelopes of allowable spin and shape configurations as a function of the material properties—typically relying on an angle of friction as the critical parameter. Neither cohesion nor tensile strength is required to explain the shapes and spins of nearly all large ($D > 200$ m) observed asteroids (Holsapple 2001, 2004), though the spins and shapes do not rule out any material strength either.

What about cohesion? Multiple recalculations of allowable spin rates as a function of cohesive forces find that even very small amounts of cohesion can dramatically change the allowable spin rates for a body. Even amounts as low as 100 Pa allow for km-sized asteroids to rotate much faster than the observed 2.3–4 hr limit (Holsapple 2007; Sánchez and Scheeres 2014). Only a single body is observed to be larger than 200 m and rotate faster than 2.3–4 hr (Warner et al. 2009).

Rozitis et al. (2014) combined measurements of Yarkovsky drift and thermal properties to estimate the density of a km-size NEA, 1950 DA. Measurements of this asteroid’s spin rate find that it is rotating faster than what simply gravity and friction would allow, and thus it must have non-zero cohesive strength to prevent disruption. As pointed out by Holsapple (2007) very small amounts of cohesive strength are needed to allow bodies to rotate faster than the classical spin limits. Hirabayashi et al. (2014) estimated between 40 and 210 Pa for the cohesive strength of main belt comet P/2013 R3 and Rozitis et al. (2014) estimated only $64^{+12}_{-20}$ Pa of cohesive strength of (29075) 1950 DA. This amount of cohesion is in line with the predictions for cohesion produced by fine grain “bonding” larger constituent pieces of an asteroid (Scheeres et al. 2010; Sánchez and Scheeres 2014), and would be similar to what is found in weak lunar regolith (see chapter by Scheeres et al. in this volume).

The exciting radar-produced shape model of 1999 KW4 showed that the asteroid shape held more information than could be contained in a simple tri-axial ellipsoid model (Ostro et al. 2006). The equatorial bulge seen in those radar shape models became ubiquitous among primaries of other rapidly rotating asteroids (see chapter by Margot et al.). A simple rigid ellipsoid that increases its angular momentum will drive surface material towards its equator and this happens before the material would simply become unbound (Guibout and Scheeres 2003). This suggests that shape change would precede mass-loss if there is loose material available.
Basic granular flow models can estimate what shapes the body might actually take. As the spin rate increases, the effective slope angle on the surface changes owing to the increased centrifugal force, and as slopes become higher on certain regions of the surface they can surpass critical values (angle of repose or angle of friction) and fail. After failing, material will flow “down” to the potential lows near the equator settling in at lower slopes. This model found a surprisingly good match for the equatorial ridge shape of 1999 KW₄, using an angle of failure of 37° (Harris et al. 2009). The failure causes very regular slopes through mid-latitudes on nearly-circular bodies, a trait clearly observed in the shape of 1999 KW₄ (Harris et al. 2009; S´ánchez and Scheeres 2014; Scheeres 2015).

Discrete particle approaches to modeling rubble pile interior structure and evolution rely on $N$-body billiard ball style granular mechanics. Many of the first models of rubble pile dynamics, tidal disruption and spin/shape configurations relied on hard spherical particles that never overlap or interpenetrate (Richardson et al. 1998, 2005). While these “hard-sphere” incarnations of the models did not directly account for friction forces, Richardson et al. (2005) showed that standard hexagonal closest packing configurations of the spheres produce enough shear strength so that modeled bodies can maintain spin and shape configurations within $\sim 40^\circ$ angle of friction allowable envelopes produced by Holsapple (2001). While different and more simplistic than the “soft-sphere” representations used to model rubble pile asteroids (S´anchez and Scheeres 2011, 2012; Schwartz et al. 2012), the modeled aggregates can hold shape and spin configurations similar to those observed on actual asteroids (see Walsh et al. 2012, Fig.10). Further detail can be found in Murdoch et al., in this book.

When a rubble pile asteroid is slowly spun-up by the YORP effect it can eventually be pushed to mass-loss (Rubincam 2000; Vokrouhlický and Čapek 2002; Bottke et al. 2002). If the asteroid is made of only a very few constituent pieces than they will reconfigure and eventually separate (Scheeres 2007b). What happens to those two components is a complicated dynamical dance that involves angular momentum transfer due to non-spherical shapes (Scheeres 2007b; Jacobson and Scheeres 2011a).

When the asteroid is made of thousands of particles different evolutions are found for different particle surface interactions. The “hard-sphere” models include dissipation of energy during collisions, but have to rely on structural packing (crystalline) to provide shear strength rather than surface friction (Walsh et al. 2008, 2012). These models found model asteroids can maintain oblate shapes at critical rotation rates, which leads to equatorial mass-shedding. While it was hypothesized that this could lead to in-orbit growth of the satellite (Cuk 2007; Walsh et al. 2008), it is clear from the dynamics of such close orbits (Scheeres 2009; Jacobson and Scheeres 2011a) that to avoid almost immediate ejection from the system that there would have to be many particles shed at the same time in order to collide, circularize and stabilize their orbits beyond the Roche Limit.

S´ánchez and Scheeres (2011, 2012) utilized “soft-sphere” granular models, which allow for more complex surface interactions, including various friction forces and inter-particle cohesion. These works explore a wider range of parameters and find a large variety of outcomes, including “fission” events of bodies splitting into nearly equal parts. There is still a strong dependence on the angle of friction for the outcome, with some of the observed oblate shaped and critically rotating outcomes observed.
Observed mass-loss events have been associated with YORP-induced rotational fission (Jewitt et al. 2013, 2014; Sheppard and Trujillo 2015; Jewitt et al. 2015). The rotation period of (62412) 2000 SY$_{178}$ is only 3.33 hrs (Sheppard and Trujillo 2015). Minor components outside of the dust are difficult to observe and the shape of the primary is impossible to deduce. Future observations are necessary to determine whether the dust is associated only with surface failure or satellite formation in these cases.

### 4.5 Kozai and planetary encounters

Most secondaries in NEA systems are too close to their primary to experience excursions in eccentricity or inclination due to the Kozai effect (Fang and Margot 2012c). For more distant NEA systems, such as 1998 ST$_{27}$ at $a \sim 16$ R$_{pri}$, the Kozai effect could play a role of disrupting systems or driving them to collision and possibly making contact-binaries (Fang and Margot 2012c).

Binary systems in the Main Belt do not encounter planets, but those on near-Earth orbits can have encounters with terrestrial planets close enough to alter or disrupt their systems (Farinella 1992; Farinella and Chauvineau 1993; Walsh and Richardson 2008; Fang and Margot 2012a). The timescales for encounters close enough to disrupt or disturb a system depend on its heliocentric orbit (how frequently it approaches a planet), and also depend strongly on the system’s properties—primarily the separation of the primary and secondary. Disruption of a typical system with $a = 4$ R$_{pri}$, where $a$ is semimajor axis and R$_{pri}$ is the primary’s radius, becomes significant (50% of encounters randomized over phasings) at encounters of 3 R$_{Earth}$, which occur on average every 2 Myr for NEAs (Walsh and Richardson 2008). Planetary flybys may also stymie other evolutionary effects, such as BYORP, by either torquing the secondary and breaking its synchronous rotation, or by exciting its orbital eccentricity (Fang and Margot 2012a). Eccentricity of 0.2 can be excited for a similar $a = 4$ R$_{pri}$ system at only 8 R$_{Earth}$, which happen every $\sim 1$ Myr on average for NEAs (Walsh and Richardson 2008; Fang and Margot 2012a).

### 5. The Future

The advances made in the last decades have been driven by the increased database of known binary systems and the mounting evidence and measurements of thermal effects acting widely in the Solar System. Naturally many questions remain, and we are optimistic that trajectory of current studies is well-aligned to answer many of the outstanding questions. We roughly outline the expected progress, discoveries and events that we think will be the focus of Asteroids V chapter on this topic in a decade.

1. More observations from a variety of sources will help to expand the catalog of rare and outlier populations. Large-scale surveys should provide a flood of data and continue to grow our catalog (GAIA, LSST). While small telescopes, including significant contributions from amateurs, have been the basis of many lightcurve discoveries of small systems, some of the high-cadence all-sky survey telescopes may begin to eclipse the production of the network of small telescopes.

2. The non-detection of BYORP at 1996 FG$_3$ is curious and possibly revealing (Scheirich et al. 2015). While there is a proposed theory to explain why and how the effect may be balanced by tides (Jacobson...
and Scheeres 2011a), and other non-tidal effects may be similarly important (Fahnestock and Scheeres 2009; Harris et al. 2009), a non-detection is not a detection, and the community awaits a measurement of this interesting thermal effect. A system with a more distant companion, or perhaps one of the triple systems, may allow for a detection in an environment where tides are small and BYORP is strong (Pravec and Scheirich 2010). The BYORP effect may be a fundamental and dominating mechanism that is widely shaping the observed population of small binary asteroids—so observing it in action will be a great step forward.

3. There are spacecraft visits planned to asteroids with “top-shapes”. The KW₄ shape, or top-shape that is becoming ubiquitous in shape models of the primaries of binary systems was a revealing discovery in this field. Hopefully careful mapping and geologic studies of these systems will reveal how small asteroids take that particular shape. In turn, knowing how the ridge formed might help researchers answer the many remaining questions about the formation and evolution of the satellites so often found around these top-shaped bodies. The currently planned space missions from NASA and JAXA, OSIRIS-REx and Hayabusa II respectively, are each currently seeking to visit primitive NEAs, and each target appears to show some signs of an equatorial ridge (Nolan et al. 2013; Lauretta et al. 2014). It is hoped that the mission surveys of the asteroid surface will elucidate the re-shaping histories of these bodies by showing signs of material flow patterns, variations in ages of different surface features and material differences in different geologic units.

Acknowledgments. KJW was partially supported by the NASA Planetary Geology and Geophysics Program under grant NNX13AM82G. SAJ was supported by the by the European Research Council Advanced Grant ACCRETE (contract number 290568).

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