Many binary minor planets (BMPs; both binary asteroids and binary trans-Neptunian objects) are known to exist in the solar system. The currently observed orbital and physical properties of BMPs hold essential information and clues about their origin, their evolution, and the conditions under which they evolved. Here, we study the orbital properties of BMPs with currently known mutual orbits. We find that BMPs are typically highly inclined relative to their orbit around the Sun, with a distribution consistent with an isotropic distribution. BMPs not affected by tidal forces are found to have high eccentricities with non-thermal eccentricity distribution peaking at intermediate eccentricities (typically 0.4–0.6). The high inclinations and eccentricities of the BMPs suggest that BMPs evolved in a dense collisional environment, in which gravitational encounters in addition to tidal and secular Kozai effects played an important role in their orbital evolution.

Key words: Kuiper belt: general – minor planets, asteroids: general – planets and satellites: dynamical evolution and stability – planets and satellites: fundamental parameters

Online-only material: color figures

1. INTRODUCTION

The binary asteroids and binary trans-Neptunian objects (TNOs) discovered in recent years show a large diversity of orbital properties, with a wide range of eccentricities, inclinations, separations, and mass ratios. Many models have been suggested for the origin of these binary minor planets (BMPs) and their orbital configurations (Richardson & Walsh 2006). An essential component in constraining theoretical models for the origin and evolution of BMPs is understanding the distribution of their orbital parameters. The number of BMPs with known orbital parameters is currently small. Nevertheless, 29 BMP systems already have full solutions for their mutual orbits, including 17 TNOs and 12 asteroids (we do not consider near-Earth objects which have much shorter lifetimes). We study the orbital properties of the 29 main belt and trans-Neptunian binaries (which we refer to corporately as BMPs) to provide clues to and constraints on their evolutionary history. Several reviews have presented the observed separations of BMPs (e.g., Richardson & Walsh 2006; Noll et al. 2008; Walsh 2009); here we focus on the distributions of eccentricities and inclinations, which have not been previously shown. In addition, we discuss the relations between the orbital parameters of BMPs, including their observed periods/separations.

In the following, we present and discuss the published orbital solutions of BMPs. We present the distributions of the orbital parameters of these BMPs, treating binary TNOs and binary asteroids separately. We also discuss the selection biases affecting both samples. We then briefly study the implications of our findings regarding the conditions in the early solar system and the formation and evolutionary scenarios of BMPs.

2. THE ORBITAL PARAMETERS OF BMPs

2.1. The Data

The mutual orbits of 30 BMPs have been published in the literature (see Tables 1 and 2), some of them with two degenerate solutions, and a few published with no indicated inclination. Table 1 shows the physical properties and orbital parameters of BMPs with known orbital parameters of BMPs in the solar system. In the literature, the orbital parameters of BMPs are typically given with respect to the ecliptic plane, while the inner orbital parameters are given with respect to the equatorial frame of reference. For our analysis, we are interested in the mutual inclinations between the BMP orbit around the Sun and the BMP inner orbit; therefore, we used the published data to calculate these inclinations for our analysis of the dynamical evolution (see the Appendix).

In some cases, two degenerate orbital solutions were found for the BMPs; these solutions differ significantly in their derived inclinations, but have very similar eccentricities. In these cases, we detail both solutions (see Table 1) and we use the published eccentricities to derive the eccentricity distribution (shown in Figure 1). All published binary asteroids’ orbits have a unique solution for the inclination (besides the binary asteroids Balam for which only the eccentricity is known) and we show their mutual inclination distribution (in cos i; Figure 2). Only five of the binary TNOs, however, have a unique non-degenerate solution for their inclinations. We therefore cannot show the true inclination distribution for binary TNOs with significant statistics (Figure 2 shows the distribution of binary TNO inclinations for an arbitrary choice of one solution for each binary TNO from the two possible degenerate solutions published). Nevertheless, we do consider all the possible distributions of the binary TNOs in a statistical manner (see Section 3). Note that both binary TNO and binary asteroid populations are presented. Given that these two populations differed in the conditions under which they evolved, their orbital properties are presented separately.

2.2. Selection Effects

There are significant observational selection effects present in the current distribution of binary TNOs and asteroids. These effects are very difficult to correct since they depend on several
| Name          | Satellite Name | Period (days) | Separation (km) | $e$   | $i$ (J2000) (deg) | $\omega$ (deg) | $D$ ratio | $D_p$ (km) | $\Omega$ (deg) | Ref. |
|---------------|----------------|---------------|-----------------|-------|------------------|----------------|-----------|------------|-----------------|------|
| 3749 Balam*   | ...            | 61 ± 10       | 289 ± 13        | 0.90  | ...              | ...            | 0.43      | ...        | ...              | 15.25|
| 45 Eugenia*   | Petit-Prince   | 4.77 ± 0.001  | 1180 ± 8        | 0     | 109 ± 2          | 126.78         | 112       | 0.81       | 202             | 16.17|
| 22 Kalliope   | Linus          | 3.6 ± 0.001   | 1095 ± 11       | 0     | 99.6 ± 0.5       | 103.42         | −92.5 ± 0.6| 0.15       | 181 ± 4.6       | 16.17|
| 283 Emma      | ...            | 3.35 ± 0.00093| 581 ± 3.6       | 0.12 ± 0.01 | 94.2 ± 0.4       | 65.46         | 40 ± 4    | 0.06       | 160             | 16.25|
| 130 Elektra   | ...            | 5.26 ± 0.0053 | 1318 ± 24       | 0.13 ± 0.03 | 25 ± 2          | 23.75         | 311 ± 5   | 0.04       | 215             | 15.25|
| 379 Huenna    | ...            | 87.6 ± 0.026  | 3335.8 ± 54.9   | 0.22 ± 0.01 | 152.7 ± 0.3     | 168.84        | 284 ± 5   | 0.06       | 92              | 15.25|
| 762 Pulcova   | ...            | 4.44 ± 0.001  | 703 ± 13        | 0.05 ± 0.01 | 132 ± 2         | 131.9         | −189 ± 20 | 0.14       | 137 ± 3.2       | 16.25|
| 90 Antiope    | ...            | 0.69 ± 4.1 × 10^{-6} | 171 ± 13       | 0.03  | 63.70 ± 2       | 54.74         | 60 ± 30   | 0.95       | 87.8 ± 1        | 6.17 |
| 121 Hermione  | ...            | 2.56 ± 0.0021 | 747 ± 13        | 0     | 79.1 ± 4         | 70.19         | 84.3      | 0.17       | 187 ± 68        | 7.13 |
| 107 Camilla   | ...            | 3.72 ± 0.003  | 1250 ± 10       | 0     | 17 ± 5           | 28.32         | −32       | 0.06       | 249             | 15.25|
| 87 Sylvia*    | Romulus        | 3.65 ± 0.0007 | 1356 ± 5        | 0     | 7               | 27.89         | −87 ± 11  | 0.46       | 282 ± 4         | 10.21|
| 617 Patroclus | Menoetius      | 4.28 ± 0.004  | 680 ± 5         | 0.02 ± 0.02 | ...            | ...           | ...       | 0.92       | 60.9            | 17   |
| 42355 Typhon  | Echidna        | 18.97 ± 0.0064| 1628 ± 5        | 0.53 ± 0.02 | 37.9 ± 2        | 50.56         | 99        | 0.55       | 76.14 ± 1       | 10.21|
| 1999 OJ4      | ...            | 84.09 ± 0.016 | 3303 ± 5        | 0.37 ± 0.01 | 53.80 ± 1.2    | 119.56        | 53.96     | ...        | 37.5 ± 8.5      | 11   |
| 90482 Orcus   | Vantu          | 84.14 ± 0.016 | 3225 ± 18       | 0.36 ± 0.01 | 99.8 ± 1.5      | 56.7          | 71.7      | ...        | 37.5 ± 8.5      | 11   |
| 47171 TC36*   | ...            | 9.5392 ± 0.0001| 8985 ± 24       | 0     | 305.8 ± 0.6      | 70.02         | 0         | 0.31       | 900             | 4    |
| 134340 Pluto* | Charon         | 6.39 ± 10^{-6} | 19571.4 ± 24    | 0     | 96.16           | 119.61        | 0.49      | 2302       | 223.05 ± 10^{-4} | 3.19, 21.25 |
| 134860 20000 OJ67 | ...        | 22.04 ± 0.004 | 2361 ± 36       | 0.09 ± 0.02 | 84.6 ± 3        | 85.21         | −233.9    | ...        | 69 ± 16         | 11   |
| 2001 XR254    | ...            | 22.04 ± 0.0036| 2352 ± 35       | 0.09 ± 0.02 | 73.80 ± 2.9    | 94.45         | 136.8     | ...        | 69 ± 16         | 11   |
| 66652 Borassii | ...            | 126.5 ± 0.12  | 9326 ± 75       | 0.56  | 41.07 ± 0.22    | 20.27         | −94.76    | ...        | 84.5 ± 19.5     | 11   |
| 136108 Haumea*| Hi'taka        | 126.5 ± 0.13  | 9211 ± 69       | 0.55  | 154.50 ± 0.22   | 155.36        | −21.88    | ...        | 84.5 ± 19.5     | 11   |

**Table 1**

The Orbital Parameters of BMPs

*Note: Some values are rounded for readability.*

**Ref.** refers to the reference number in the original document.
Table 1
(Continued)

| Name         | Satellite Name | Period (days) | Separation (km) | $e$         | $i$(J2000) (deg) | $i_m$ (deg) | $\omega$ (deg) | $D$ ratio | $D_p$ (km) | $\Omega$ (deg) | Ref. |
|--------------|----------------|---------------|-----------------|------------|-----------------|-------------|---------------|-----------|------------|-----------------|------|
| 2003TJ58     | ...            | 137.32 ± 0.19 | 3799 ± 54       | 0.53 ± 0.01 | 38.1 ± 2.1      | 62.25       | −110.04       | ...       | 32.5 ± 7.5 | 194.60 ± 4.2    | 11   |
| ...          | ...            | 3728 ± 44     | 96.1 ± 2        | 116.77     | −88.90          | ...         | 32.5 ± 7.5    | 150.80 ± 2.8 | 11         |
| 1998WW31     | ...            | 574 ± 10      | 22300 ± 44      | 0.82 ± 0.05 | 41.7 ± 0.7      | 51.96       | 159.50        | 0.83      | 118        | 94.30 ± 0.8     | 25,26|
| 2004PB108    | ...            | 97.02 ± 0.07  | 10400 ± 130     | 0.44 ± 0.01 | 89.1 ± 1.1      | 84.13       | 229.93        | ...       | 120.5 ± 27.5 | 121.99 ± 0.75   | 11   |
| ...          | ...            | 10550 ± 130   | 106.55 ± 0.99   | 95.23      | 211.91          | ...         | 120.5 ± 27.5  | 30.19 ± 0.86 | 11         |
| 58534 Logos  | Zoe            | 312 ± 3       | 8010 ± 80       | 0.45 ± 0.03 | 121.5 ± 2       | ...         | 310.13 ± 2.87 | 0.825     | 80         | ...             | 19,25|
| ...          | ...            | 7970 ± 80     | 69.2 ± 2        | ...        | 298.09 ± 5.73   | 0.825       | 80            | ...       | 19,25      |                 |      |
| 2000QL251    | ...            | 56.46 ± 0.018 | 4991 ± 17       | 0.49 ± 0.01 | 127.78 ± 0.62   | 135.7       | 42.2          | ...       | 74 ± 17     | 109.5 ± 1.1     | 11   |
| 136199 Eris  | Dysnomia       | 56.44 ± 0.017 | 5014 ± 16       | 0.49 ± 0.01 | 45.62 ± 0.66    | 46.58       | 45.70         | ...       | 74 ± 17     | 71.20 ± 1.1     | 11   |
| 65489 Ceto   | Phorcys        | 15.77 ± 0.002 | 37430 ± 140     | 0.01       | 61.3 ± 0.7      | 94.98       | ...           | 2400 ± 100 | 139 ± 1    | 3.82 ± 0.8      | 87   |
| ...          | ...            | 37370 ± 150   | 142.3 ± 3       | 85.74      | ...             | 2400 ± 101  | 68 ± 3        | 3.82 ± 0.8 | 87         | 105.5 ± 3.7     | 9.23 |

Notes. Error estimates are also shown where available. Unnamed satellites are omitted. Multiple systems are marked with (*) and the orbital parameters are for the (listed) outer satellite. All measured orbital parameters are given with respect to J2000 equatorial plane. Calculation method of the mutual inclinations is given in the Appendix.

References. (1) Benecchi et al. 2010; (2) Brown et al. 2005; (3) Brown & Schaller 2007; (4) Brown et al. 2010; (5) Buie et al. 2006; (6) Descamps et al. 2007; (7) Descamps et al. 2009; (8) Greenberg & Barnes 2008; (9) Grundy et al. 2007; (10) Grundy et al. 2008; (11) Grundy et al. 2009; (12) Hestroffer et al. 2005; (13) Marchis et al. 2005; (14) Marchis et al. 2006; (15) Marchis et al. 2008b; (16) Marchis et al. 2008a; (17) Margot & Brown 2001; (18) Noll et al. 2003; (19) Noll et al. 2004a; (20) Noll et al. 2004b; (21) Noll et al. 2008; (22) Osip et al. 2003; (23) Petit et al. 2008; (24) Rabinowitz et al. 2006; (25) Richardson & Walsh 2006; (26) Veillet et al. 2002.
Figure 1. Eccentricity distribution of observed binary asteroids and TNOs (panels (a) and (b), respectively). Panel (c) shows the cumulative distribution of both samples (asteroids and TNO binaries, solid lines, respectively) as well as comparison to a thermal distribution (lower solid line). The dashed line shows the cumulative eccentricity distribution of binary TNOs excluding binaries that are likely affected by tides ($e < 0.05$).

(A color version of this figure is available in the online journal.)

Table 2

| Name                  | SMA (AU) | $e_{out}$ | $i_{out}$ (deg) | $\Omega_{out}$ (deg) | Mass ($10^{18}$ kg) | Error ($10^{18}$ kg) | Class | Ref. |
|-----------------------|---------|-----------|-----------------|----------------------|---------------------|----------------------|-------|------|
| 3749 Balam*           | 2.24    | 0.11      | 5.39            | 295.84               | 0                   | $\pm0.00002$         | FF    | 1    |
| 45 Eugenia*           | 2.72    | 0.08      | 6.61            | 147.92               | 5.69                | $\pm0.12$            | MB    | 1    |
| 22 Kalliope           | 2.91    | 0.1       | 13.71           | 66.23                | 8.10                | $\pm0.2$             | MB    |      |
| 283 Emma              | 3.04    | 0.15      | 8               | 304.42               | 1.38                | $\pm0.03$            | EF    |      |
| 130 Elektra           | 3.12    | 0.21      | 22.87           | 145.46               | 6.6                 | $\pm0.4$             | MB    |      |
| 379 Huerna            | 3.13    | 0.19      | 1.67            | 172.07               | 0.38                | $\pm0.019$           | TF    |      |
| 762 Pulcova           | 3.15    | 0.1       | 13.09           | 305.8                | 1.4                 | $\pm0.1$             | MB    | 1    |
| 90 Antiope            | 3.16    | 0.16      | 2.22            | 70.22                | 0.83                | $\pm0.02$            | TF    |      |
| 121 Hermione          | 3.44    | 0.14      | 7.6             | 73.18                | 4.7                 | $\pm0.2$             | OMB   |      |
| 107 Camilla           | 3.48    | 0.08      | 10.05           | 173.12               | 11.2                | $\pm0.3$             | OMB   |      |
| 87 Sylvia*            | 3.49    | 0.08      | 10.86           | 73.31                | 14.87               | $\pm0.06$            | OMB   |      |
| 617 Patroclus         | 5.22    | 0.14      | 22.05           | 44.35                | 1.36                | $\pm0.11$            | JT    |      |
| 42555 Typhon          | 37.65   | 0.53      | 2.43            | 351.96               | 0.95                | $\pm0.052$           | Cent  |      |
| 1999Q04               | 38.10   | 0.02      | 2.61            | 127.46               | 0.40                | $\pm0.0087$          | ICC   | 11   |
| 90482 Orcus           | 39.17   | 0.23      | 20.38           | 268.65               | 652                 | $\pm5$               | 3:2N  | 4    |
| 47171 TC36*           | 39.7    | 0.23      | 8.41            | 97.08                | 14.2                | $\pm0.05$            | 3:2N  |      |
| 134340 Pluto*         | 39.45   | 0.25      | 17.09           | 110.38               | 14570               | $\pm9$              | 3:2N  |      |
| 13460 2000OJ67        | 42.9    | 0.01      | 1.33            | 96.76                | 2.15                | $\pm0.099$           | CC    | 11   |
| 2001 XR254            | 43      | 0.02      | 2.66            | 52.73                | 3.92                | $\pm0.089$           | CC    | 11   |
| 136108 Haumea*        | 43.08   | 0.2       | 28.22           | 122.1                | 4200                | $\pm100$            | HF    |      |
| 66652 Borasisi        | 44.07   | 0.09      | 0.56            | 84.74                | 3.8                 | $\pm0.4$             | CC    |      |
| 2001QW322             | 44.28   | 0.02      | 4.8             | 124.67               | 1.5                 | ...                 | CC    |      |
| 88611 Teharonhiawako  | 44.29   | 0.02      | 2.57            | 304.63               | 3.2                 | $\pm0.3$            | CC    |      |
| 2003TJ58              | 44.5    | 0.09      | 1.31            | 37.12                | 0.22                | $\pm0.0078$         | CC    | 11   |
| 1998WW31              | 44.64   | 0.09      | 6.81            | 237.1                | 2.7                 | ...                 | CC    |      |
| 2004PB108             | 45.1    | 0.11      | 19.19           | 147.38               | 9.88                | $\pm0.37$           | HC    | 10   |
| 58534 Logos           | 45.5    | 0.12      | 2.9             | 132.64               | 0.42                | $\pm0.02$           | CC    |      |
| 2000QL251             | 47.8    | 0.21      | 5.83            | 223.29               | 3.14                | $\pm0.03$           | 2:1N  | 10   |
| 136199 Eris           | 67.96   | 0.44      | 43.97           | 35.99                | 16600               | $\pm200$            | SD    |      |
| 65489 Ceto            | 100.17  | 0.82      | 22.32           | 172.04               | 5.42                | $\pm0.42$           | Cent  |      |

Notes. Unless noted otherwise all outer parameters are taken from the JPL small bodies database (see http://ssd.jpl.nasa.gov/sbdb.cgi). Errors are shown where available. Multiple systems are marked with *. References are detailed in Table 1. The heliocentric orbital classification is noted as “class”, where we used the following notations: MB, OMB, JT, CC, ICC, HC, SD, Cen, HF, TF, EF, FF, and $n : mN$ for main belt, outer main belt, Jupiter Trojan, cold classical, inner cold classical, hot classical, scattered disk, Centaur, Haumea family, Themis family, Eos family, Flora family for $n : m$ Neptune resonances, respectively. Asteroid family membership is based on listings in Zappala et al. (1995). The prevalence of binaries among the cold classical population of the trans-Neptunian belt is discussed further in Noll et al. (2008).
factors, and the currently observed population of binaries comes from very heterogeneous observing conditions. Although we do not correct for these effects in the current analysis, we discuss them below to recognize the possible biases they may produce.

2.2.1. Binary TNOs

Binary TNOs are primarily discovered in two ways. Ground-based observations can detect two comoving objects if the projected separation of the objects is roughly larger than the typical seeing, >0.5 arcsec (e.g., Kern & Elliot 2006), or if adaptive optics are used on bright targets (e.g., Brown et al. 2006). The widest binaries, such as 2001 QW322 (Petit & Mousis 2004), can be found with this mechanism, assuming that discovery and follow-up images have been searched for binaries (generally true, but not always). Pan-STARRS and other future surveys will probably detect dozens of binaries this way (Holman et al. 2007). The second discovery mechanism is using Hubble Space Telescope (HST) observations combined with point-spread function (PSF)-fitting techniques, which has discovered the great majority (~80%) of known binary TNOs. HST can resolve binaries as close as tens of milliarcseconds and generally probes much fainter objects than ground-based telescopes (Noll et al. 2008).

Each of these two methods suffers from important observational biases. The main bias is a detection bias: the secondary must be bright enough and far enough away from the primary to be detected. In both the ground- and space-based cases, there is no simple prescription that describes this detection bias, especially since these are coupled close to the primary: a bright secondary can be discovered at smaller separations than a faint secondary. Furthermore, since HST observations are always nearly the same duration (one HST orbit), observations are essentially magnitude limited, implying that low-brightness ratios (and mass ratios) can only be seen around brighter targets.

A discussion of these biases and their effects on the observed population is also given by Noll et al. (2008). Despite the observational biases, these authors believe that there is a good evidence that binaries composed of moderate-sized TNOs (diameters less than ~1000 km) are actually clustered at nearly equal brightness, with Ångström < 1 corresponding to a mass ratio of greater than ~0.25 assuming equal albedos and densities.

This latter assumption seems reasonable given that the colors of components of binary TNOs are known to be similar (Benecchi et al. 2009).

Considering now biases in the binary mutual orbital elements, we again point out that the majority of binaries are discovered in single HST snapshots. Hence, biases are introduced by the fact that the orbital separation must be detectably large at a single epoch. While Noll et al. (2008) point out that the statistical distribution of observed separations is similar to the distribution of semi-major axes, it is clear that systems with larger eccentricities are more likely to be seen since the observability is increased at apoapse, both due to wider separations and to the longer residence time. This eccentricity bias is most important near the angular resolution limit where most of the binaries are discovered, but it is not important when semi-major axes exceed ~0.2 arcsec. Of course, separation-limited observations imply that the smallest semi-major axes are undetectable; these systems are best discovered through photometry, either through doubly periodic light curves or where eclipses and occultations may reveal contact binaries like 2001 QG298 (Sheppard & Jewitt 2004).

Finally, we also note a bias against observations of binary TNOs with large size/mass ratios, due to detection limits. For example, a typical TNO with a radius of 100 km located at 40 AU would have collisional satellites with V < 24.5 at separations of ~0.04 arcsec, perhaps barely detectable by HST if the satellite is at elongation. The most likely way to discover these systems is through photocenter–barycenter shifts (in this case, the size would be ~2 mas) detected through long-baseline highly accurate astrometry, potentially available from future Pan-STARRS or LSST surveys. Detecting a double-periodic

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Figure 2. Inclination distribution of observed binary asteroids and binary TNOs (panels (a) and (b), respectively). Panel (c) shows the cumulative distribution of both samples as well as comparison to a flat distribution (i.e., random in cos i). Note that many of the binary TNO inclinations have two degenerate solutions; here only one solution is chosen arbitrarily for each binary to illustrate their likely distribution (see the text). (A color version of this figure is available in the online journal.)
light curve (or serendipitous mutual events) may be possible for some systems, though the faintness of the components makes this very difficult and the result may be impossible to distinguish from a single object with arbitrary shape and spin orientation. The size ratio of the binary components can be important for the origin and evolution of the binary orbital parameters, and therefore may affect the statistics of the orbital parameters in our sample.

Another important bias is that systems with low inclinations \(^4\) present nearly edge-on orbits with respect to Earth-based observations, while systems with high relative inclinations are usually seen face-on. Since binaries are discovered when the components are significantly separated on-the-sky, there is a greater likelihood for low-inclination secondaries to be unresolvable when observed at a single random epoch. This bias is reduced as the projected semi-major axis grows, but remains significant even at a few times the resolution limit.

2.2.2. Binary Asteroids

While some binary asteroids have been imaged by HST, ground-based adaptive optics has been employed more often for these brighter systems than their trans-Neptunian counterparts. The much smaller sizes of typical asteroids are partly offset by their increased brightness and proximity. Discovery of binaries photometrically through double-periodic light curves and/or mutual events is common for near-Earth asteroids (Pravec et al. 2006; note, however that these are not included in our analysis, and are mentioned here for completeness). Other methods are radar observations that often reveal near-Earth binary asteroids (not discussed here), and stellar occultations that can reveal the presence of main belt binary asteroids (e.g., Descamps et al. 2007). Theoretically, the radar and occultation techniques have fewer observational biases than the other more common techniques, but their application is severely limited.

Binary asteroids are also clearly subject to detection bias: objects with smaller satellites are more difficult to observe. However, since asteroids are searched for binaries using ground-based facilities, there is a greater possibility of searching for companions in more than a single snapshot. Furthermore, the geocentric orientations of these systems change much more rapidly than for essentially fixed Kuiper Belt Object (KBO) orbits (\(\sim 60^\circ \text{yr}^{-1}\) for asteroids versus \(\sim 2^\circ \text{yr}^{-1}\) for KBOs). Therefore, the eccentricity and inclination biases are not as strong as in the Kuiper Belt. In binaries discovered through mutual events, there is an obvious bias toward edge-on systems, though “edge-on” can probe a wide range of inclinations.

3. DISCUSSION

Several different processes affect the mutual orbits of BMPs. Some are related to their initial formation and others to their later evolution either as isolated systems, or due to the effects of external perturbations and encounters with other objects. The studies of these processes have been focused on a specific type of BMPs such as binary asteroids or binary TNOs. However, all of these suggested processes could in principle be relevant for the formation/evolution of BMPs both close (binary asteroids) and far (binary TNOs) from the Sun.

The various suggested mechanisms for the formation of BMPs (see Astakhov et al. 2005; Richardson & Walsh 2006; Noll et al. 2008, for some overviews) predict different initial orbital configurations. These include the following.

1. Smashed target satellites (SMATS; Weidenschilling 2002; Durda et al. 2004, 2010): low-eccentricity distribution expected from collisionally formed satellites orbiting the main collision remnant body (which typically form as close binaries and are likely to be affected by tides).
2. Escape ejecta binaries (EEBs; Durda et al. 2004, 2010): intermediate eccentricities from bound ejecta pairs ejected following a collision of two larger bodies.
3. Exchanged binaries (Funato et al. 2004): typically high eccentricities (>0.8) for high-mass ratio binaries formed through exchanges.
4. Dynamical friction and chaos assisted capture (CAC) binaries (Goldreich et al. 2002; Lee et al. 2007): intermediate eccentricities (0.2 < e < 0.8) for binaries formed through CAC of satellites.

Unfortunately, only a few studies explored aspects of the inclination distribution of BMPs (Astakhov et al. 2005; Nazzario et al. 2007; Schlichting & Sari 2008; Perets & Naoz 2009).

After their formation, BMPs can be affected by several processes which can change their orbits. Tidal effects are most important when the BMP components approach each other at a close distance. These effects couple the orbital evolution of the BMP to the spin of the BMP components, and the tides raised on the objects serve to dissipate the total angular momentum of the system. Tidal effects can also excite and enlarge the eccentricity and inclination of a given BMP (e.g., Goldreich & Soter 1966). At long enough timescales (depending on specific configurations), however, tidally evolved systems are expected to relax into more circularized configurations, possibly locked configurations, and even mergers. Such effects are thought to produce the period–eccentricity distributions of (close) binary systems such as stellar binaries and planetary systems, and are likely to play a similar role in BMP systems (Mazeh 2008).

Another evolutionary process is the Kozai–Lidov (Kozai 1962; Lidov 1962) mechanism, which is the effect of a secular perturbation from a third object (in a triple system, i.e., the Sun serves as the third companion for BMPs) on the (bound) binary system. It could lead to large (order unity) periodic oscillations (Kozai cycles) in the eccentricity and inclination, i.e., it could both raise and lower the inclinations and eccentricities of a system. Note, however, that such a process is effective only for systems with initially high inclinations (40° > \(i_m\) < 140°; with a somewhat wider inclination range for initially eccentric systems).

The combined effects of the Kozai mechanism in addition to tidal friction (Kozai cycles and tidal friction (KCTF); Mazeh & Shaham 1979; Kiseleva et al. 1998) can change the orbital parameters of the BMPs, and reduce both the eccentricity and separation of the BMPs (Perets & Naoz 2009). In essence, this effect rapidly lowers the eccentricity of BMPs and shortens their period.

These mechanisms are effective in isolated systems (although including the Sun). In collisional systems, encounters between BMPs and other minor planets or BMPs can change the orbital parameters of the BMPs. The distribution of inclinations in such systems is likely to be randomized, whereas the eccentricity distribution is expected to approach high eccentricities, on average (Funato et al. 2004), possibly producing a thermal-like distribution (Heggie 1975).

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4 Here, inclination means the mutual inclination between the heliocentric orbit and the mutual binary orbit; for objects at these great distances, the difference between heliocentric and geocentric viewing angles is not significant for this bias.
In the following, we discuss the implications of the observed distributions in the light of the dynamical processes discussed above.

3.1. Eccentricities

The observed eccentricity distribution of BMPs (Figure 1) shows both low (and zero) eccentricity BMPs as well as high eccentricity ones (up to 0.82 and 0.22 for binary TNOs and asteroids, respectively). The clear correlation between the eccentricity and the semi-major axis of the BMPs (eccentricity-period distribution of BMPs is shown in Figure 3), reminiscent of other binary populations (e.g., binary stars, exoplanets; Mazeh 2008), indicates that low-eccentricity BMPs are likely to be produced by tidal circularization, which become important for BMPs of small separations. In principle, the period eccentricity distribution can be used to constrain tidal evolution theories and/or the physical parameters of BMPs which affect the tidal evolution (e.g., the $Q$ parameter, and its evolution; Efroimsky & Lainey 2007). Although current statistics are still too small to produce strong constraints on such theories/parameters, one can already check specific tidal evolution cases (see, e.g., the theoretical lines shown in Figure 3).

The apparent lack of zero and low ($<0.2$) eccentricity binary TNOs at large separations (where tidal forces are not effective) suggests that either the formation processes of binary TNOs are not inclined to form them at such eccentricities, e.g., in the EEB and CAC scenarios for BMP formation, and/or that later dynamical evolution changed their eccentricities. The current sample of binary TNOs, showing the lack of many high-eccentricity BMPs ($e > 0.8$), is already large enough to rule out the exchange formation scenario for binary TNOs as formulated by Funato et al. (2004) as the main single process producing their current distribution. We note that the lack of high eccentricity for the largest binary TNOs together with the frequent intermediate eccentricity population of the lower mass binary TNOs could be consistent with a collisional scenario. In this process, EEBs are made from smaller remnant bodies following a collision whereas the bigger remnants may form SATMs with lower eccentricities in non-disruptive collisions (Durda et al. 2004).

The eccentricity distribution of binary asteroids appears to differ from that of binary TNOs, with a larger fraction of binaries at shorter, more circular orbits. However, the general trend is similar to that of binary TNOs, showing close binaries to typically have more circular orbits and wider ones to have higher eccentricities. Such distribution could be consistent with that of binary TNOs, given the selection effects (e.g., the difficulty in finding close small-sized binary TNOs) and the small statistics. Moreover, the lack of wider period binaries with higher eccentricities is likely related to the much smaller phase space available to binary asteroids, due to their smaller Hill radii (see Figure 3). The binary asteroid distribution may therefore also be suggestive of a collisional origin. The known collisional families in the asteroid belt give further support for this scenario.

3.2. Inclinations

The distribution of BMP inclinations shows a large fraction of them to have high inclinations. The inclinations of binary asteroids are consistent with a random distribution of inclinations (flat in $\cos i$). The underlying true inclination distribution of the larger sample of binary TNOs cannot be derived directly (given the degenerate inclination solutions for most of the samples). Nevertheless, we can statistically verify whether it too could be consistent with a flat distribution. To do so, we consider all the possible inclination distributions of the binary TNOs (i.e., $2^{N_{\text{deg}}}$, where $N_{\text{deg}} = 9$ is the number of orbits with two degenerate solutions used). We then use the two-sample Kolmogorov–Smirnov test to check whether each possible distribution is consistent with it being drawn from a flat distribution (in $\cos i$). We find that all of these distributions are consistent with an isotropic distribution. We conclude that the inclinations of both binary TNOs and asteroids are consistent with a random distribution of inclinations (flat in $\cos i$); clearly BMPs are not restricted to planar configurations as suggested by Goldreich et al. (2002) and Schlichting & Sari (2008). In some scenarios (Goldreich et al. 2002), BMPs are formed in a thin planetesimal disk with low-velocity dispersion. It was suggested that BMPs with high inclinations are therefore not likely to be produced under these conditions. However, three body encounters can easily change the inclinations of BMPs, as these could be highly chaotic, and produce highly inclined orbits even under such conditions (H.B. Perets & G. Kupi 2010, in preparation). Collisionally formed BMPs are also likely to produce a range of inclinations, as material could be ejected in a wide fan, and specifically EEBs could have random inclinations (however further studies in this direction are required). The high inclinations of BMPs could therefore be suggestive of the collisional environment at which BMPs were formed. Note that since encounters between BMPs and other single planetesimal can easily erase the initial distribution of BMP inclinations, predictions of the inclination distribution such as suggested by Schlichting & Sari (2008), which do not seem to be consistent with the currently observed distribution of inclinations (i.e., non-planar configurations), are not likely to constrain formation scenarios of BMPs.

We note that the combined processes of secular Kozai evolution (due to perturbations by the Sun$^5$) and tidal friction

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$^5$ Note that alternatively/in addition planets or even a third companion in triple minor planet systems could also produce such perturbations.
(KCTF) can lead to specific correlations between inclinations and separations of BMPs (as well as eccentricities). These processes and the currently observed relations they may have produced have been discussed in detail elsewhere (Perets & Naoz 2009, see also D. Ragozzine & M. E. Brown 2010, in preparation). We find that the probability of the eccentricity and inclination (|cos i|) distributions to be uncorrelated is \( \sim 0.04 \) (with the correlation coefficient found to be 0.7).

We conclude that although understanding the shape of the inclination distribution requires more data, it is clear that high inclinations serve as the rule and not the exception, and point to an excitation mechanism, possibly a highly collisional environment at the epoch of BMP formation and/or evolution, with further KCTF evolution playing a role and producing correlations between the BMP’s orbital properties (separations/ eccentricities/inclinations).

### 3.3. Dependence on Mass/Size

The masses and sizes of BMP components, mostly the smaller secondaries, are not accurately known. Nevertheless, some interesting trends with masses/sizes may already be observed in our binary TNO sample. Binary TNOs with the largest primaries (>500 km; see Table 1 and Figure 3) are observed to have satellites at small separations and low eccentricities, possibly indicating a collisional formation mechanism (Canup 2005; Brown 2008; Ragozzine & Brown 2009). We also note that these binaries seem to cluster at relatively high inclinations (not shown, but see Table 1); although this may not be statistically significant given our currently small sample, it may suggest that KCTF (highly efficient at high inclinations) was involved in catalyzing mergers/collisions or tidal evolution of pre-formed binaries (see Perets & Naoz 2009). We do not see any trends in the current sample of binary asteroids, but note that no massive (>500 km) binary asteroids are known. Nevertheless, it is worth pointing out that most of the binary asteroids share similarities with the massive binary TNOs, i.e., small separations and low eccentricities, as discussed above, suggesting a similar, possibly collisional, origin.

### 3.4. Binary Trans-Neptunian Objects versus Binary Asteroids

We find that both the observed populations of binary asteroids and binary TNOs present similar orbital properties (e.g., high inclinations). This suggests that some basic features in their formation and evolution were similar (e.g., dense collisional environment). Although binary TNOs typically show much higher eccentricities, most of these binaries have much wider orbits than those of binary asteroids (due to both observational selection effects as well as the much smaller Hill radii in which binary asteroids can exist; see Figure 3). The differences in eccentricities may therefore only reflect the tendency of closer binaries to be more circularized (since tidal friction effects become stronger).

### 3.5. Multiple Systems

The last few years have seen the discovery and characterization of the first asteroids and TNOs with multiple satellites, which deserve special mention. Such systems with well-known published orbits include Pluto (Tholen et al. 2008), Haumea (Ragozzine & Brown 2009), 1999 TC36 (Benecchi et al. 2010), and Sylvia (Marchis et al. 2006), while the asteroids Eugenia, Balam, Kleopatra, Minerva, 2001 SN263, and 1994 CC have only recently been announced as triple systems. Though the detection biases described in Section 2 are present for these systems, the majority of these systems were first known as binaries with additional companions found during subsequent study. It is therefore difficult to estimate the frequency of multiple systems in the various populations. Nevertheless, the existence of several such objects indicates that these are not rare. Detailed observations of these systems can yield mass determinations for each of the bodies independently, which is not possible for binaries (Tholen et al. 2008; Ragozzine & Brown 2009).

Multiple systems provide unique additional leverage in determining the formation and evolution of binaries. For example, the coplanar nature of the satellite system of Pluto likely requires a dense collisional formation (Stephens & Noll 2006), although the detailed formation and evolution of this system is still not understood (Ward & Canup 2006; Lithwick & Wu 2008). Even for systems with unknown orbits, the small sizes and compact configurations suggest that all of these systems are collisionally formed, except for 1999 TC36; though multiple episodes of YORP-induced fission may be relevant for the smaller bodies (Walsh et al. 2008). The hierarchical and nearly equal mass nature of the 1999 TC36 triple system cannot be explained by a single collision and is likely to be the result of sequential formation by capture (e.g., Goldreich et al. 2002; Lee et al. 2007). Balam has a very unusual satellite system, including an outer satellite with a putative eccentricity of \( \sim 0.9 \) (Marchis et al. 2008b), and possibly an unbound satellite that was separated from Balam less than a million years ago (Vokrouhlicky 2009).

These systems also present examples of unique orbital evolution. As pointed out by Ragozzine & Brown (2009), the combination of rapid orbital expansion (compared to the weak expansion around giant planets, which are ineffective at dissipating tidal energy) and gravitationally interacting satellites creates a unique brand of tidal evolution. Multiple resonance crossings can excite eccentricities and inclinations, perhaps leading to instability (e.g., Canup et al. 1999). In hierarchical systems with significant mutual inclination, the Kozai–Lidov effect may destabilize the system (Perets & Naoz 2009). For all multiple systems, survival to the present epoch can be difficult, and multiples must have been more common in the primordial population.

Additional study of these multiple minor planet systems will provide unique insights into the formation and evolution of these systems. See Benecchi et al. (2010) for an additional review of multiple minor planet systems, including a table of properties.

### 4. SUMMARY

In this paper, we compiled a catalog of BMPs, both binary TNOs and binary asteroids, with full orbital solutions. We presented a first analysis of the eccentricity and inclination distributions of BMPs as well as their semi-major axis–eccentricity distribution. These data and their analysis can be used to study and constrain formation and evolutionary scenario of BMPs. Specifically, we find high relative inclinations for the BMPs as well as typically large (but not extremely high) eccentricities for BMPs not affected by tidal evolution. By themselves these results already suggest BMPs evolved in dense environments in which collisions and close gravitational encounters formed/ perturbed the binaries and strongly affected their orbital evolution. We suggest that these encounters, together with secular Kozai evolution and tidal effects, could have erased much of the direct signatures of the initial formation of BMPs, as possibly reflected by their observed orbits (see also Perets & Naoz 2009). More theoretical work, however, is required to understand the different parts played by the initial formation and configurations.
of BMPs versus their later dynamical evolution. Especially important are better theoretical predictions for the observational signatures of different BMP formation scenarios, which could be compared with the data presented in this paper and additional future data.

We would like to thank Will Grundy for pointing out an incorrect transformation from the ecliptic plane to the equatorial frame of reference. We thank Eran Ofek for useful discussion regarding this issue. We also thank the anonymous referee for helpful comments. S.N. acknowledges the partial support by Israel Science Foundation grant 629/05 and U.S.-Israel Binational Science Foundation grant 2004386. S.N. and H.B.P. acknowledge the generous support of the Dan David Fellowship. H.B.P. is a CfA, Rothschild, FIRST, and Fullbright fellow. H.B.P. also acknowledges the Israeli commercial and industrial club for their support through the Ilan-Ramon-Fullbright fellowship. D.R. is grateful for the support by NASA Headquarters under the Earth and Space Sciences Fellowship.

APPENDIX

CALCULATION OF THE MUTUAL INCLINATION

The mutual inclination $i_m$ represents the angle between the inner and outer orbits. All of the heliocentric parameters are given with respect to the ecliptic plane, while the inner orbital parameters are given with respect to the equatorial frame of reference. Thus, we first transform the heliocentric inclination and the longitude of ascending node from the ecliptic plane ($i_c, \Omega_c$) to the equatorial frame of reference ($i_q, \Omega_q$). Let us define the pole vector with respect to the ecliptic (equatorial) frame, $P_c (P_q)$:

$$P_{c,q}(\chi, y, z) = \begin{pmatrix} \sin \Omega_{q,c} \sin i_{c,q} - \cos \Omega_{q,c} \sin i_{c,q} \\ \cos \Omega_{c} \end{pmatrix}.$$  

(A1)

The rotation matrix from the ecliptic to the equatorial is the rotation with respect to the $x$-axis of the invariable plane, i.e.,

$$R(x)_{\chi \rightarrow q} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \epsilon & -\sin \epsilon \\ 0 & \sin \epsilon & \cos \epsilon \end{pmatrix},$$  

(A2)

where $\epsilon$ is the ecliptic angle. Thus, the resulting equations of the transformation from the ecliptic to the equatorial are

$$\cos(i_q) = \cos(i_c) \cos(\epsilon) - \sin(i_c) \sin(\epsilon) \cos(\Omega_c),$$

$$\cos(\Omega_q) \sin(i_q) = \cos(i_c) \sin(\epsilon) + \sin(i_c) \cos(\epsilon) \cos(\Omega_c),$$

$$\sin(\Omega_q) \sin(i_q) = \sin(\Omega_c) \sin(i_c),$$  

(A3)

where from the last two equations, we can find $\Omega_q$ using the atan2($x, y$) function.

Now we turn to calculate the mutual inclination. We take the longitude of ascending node and inclinations with respect to equatorial frame (resulting from the above transformation) of the inner and outer orbits, i.e., $\Omega_{in, out}$ and $i_{in, out}$, and calculate the mutual inclinations. Again let us define the binary outer orbit and inner pole vectors as

$$P_{out,in}(\chi, y, z) = \begin{pmatrix} \sin \Omega_{out,in} \sin i_{out,in} \\ \cos \Omega_{out,in} \sin i_{out,in} \\ \cos i_{out,in} \end{pmatrix},$$  

(A4)

and thus, the mutual inclination is simply given by

$$i_m = \cos^{-1}(P_{out} \cdot P_{in}).$$  

(A5)