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BINARY ASTEROID ENCOUNTERS WITH TERRESTRIAL PLANETS: TIMESCALES AND EFFECTS

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ABSTRACT

Many asteroids that make close encounters with terrestrial planets are in a binary configuration. Here we calculate the relevant encounter timescales and investigate the effects of encounters on a binary's mutual orbit. We use a combination of analytical and numerical approaches with a wide range of initial conditions. Our test cases include generic binaries with close, moderate, and wide separations, as well as seven well-characterized near-Earth binaries. We find that close approaches (<10 Earth radii) occur for almost all binaries on 1-10 million year timescales. At such distances, our results suggest substantial modifications to a binary's semi-major axis, eccentricity, and inclination, which we quantify. Encounters within 30 Earth radii typically occur on sub-million year timescales and significantly affect the wider binaries. Important processes in the lives of near-Earth binaries, such as tidal and radiative evolution, can be altered or stopped by planetary encounters.

Subject headings: minor planets, asteroids: general – minor planets, asteroids: individual (2000 DP107, 1999 KW4, 2002 CE26, 2004 DC, 2003 YT1, Didymos, 1991 VH)

1. INTRODUCTION

Near-Earth asteroids (NEAs) live in a dynamic environment that includes gravitational encounters with planets and the Sun as well as other non-gravitational perturbations, with average dynamical lifetimes on the order of a few million years (Bottke et al. 2002). They are replenished from source regions in the main belt of asteroids, which include strong resonances with Jupiter and Saturn. Radar and light curve studies by Margot et al. (2002) and Pravec et al. (2006) have determined that approximately 15% of these short-lived objects larger than 200 m in diameter are in a binary configuration, with a primary and secondary orbiting their common center of mass. The mutual orbits of these binary asteroids are affected by tides, by external perturbations such as the radiative binary YORP effect (Ćuk & Burns 2005; Ćuk 2007), and by close encounters with terrestrial planets. In this work, we investigate the effect of close planetary encounters on the mutual binary orbits of NEA systems by studying changes in semi-major axis, eccentricity, and inclination. We also calculate the frequency of such terrestrial planet flybys.

Early work on the subject of planetary encounters with NEA binaries was accomplished by Farinella (1992) and Farinella & Chauvineau (1993). They employed analytical estimates and Monte Carlo techniques to estimate the change in orbital energy and angular momentum due to an encounter. Recent work by Fang et al. (2011) examined the effect of close planetary encounters on the mutual orbits of NEA triples 2001 SN263 and 1994 CC. They found that scattering events by terrestrial planets can excite the eccentricities as well as mutual inclinations of the satellites' orbits to currently observed values on million-year timescales. During close approaches with Earth, the outer satellites in both triple systems

can have their orbital eccentricities excited to values of at least 0.2 as far away as encounter distances of ~ 40 Earth radii for 2001 SN263 and ~ 50 Earth radii for 1994 CC. Since the orbital effects of encounters on triples have been previously examined, this present study focuses only on binary systems. Other recent studies have invoked planetary encounters to explain the rotational dynamics of asteroids (Scheeres et al. 2004; Sharma et al. 2006), the tidal disruption of rubble pile asteroids to form binaries (Walsh & Richardson 2006), and the resurfacing of NEAs (Nesvorný et al. 2010; Binzel et al. 2010). Prior studies include Bottke & Melosh (1996a,b), Asphaug & Benz (1996), and Richardson et al. (1998).

In this work, we perform N-body simulations and employ analytical expressions to evaluate a binary's orbital changes due to a close planetary encounter with Earth. Initial conditions include 3 generic cases (a "close binary" with a separation of 4 primary radii, a "moderately-separated binary" with a separation of 8 primary radii, and a "wide binary" with a separation of 16 primary radii) as well as parameters drawn from known, well-characterized NEA binaries. By "well-characterized" we mean a binary for which the system mass, semi-major axis, eccentricity, and approximate component sizes are known - in practice this corresponds to a subset of the radar-observed binaries. Table 1 shows a compilation of these binaries and their parameters such as primary size, primary mass, and primary-secondary separation. In Section 2, we perform single flyby simulations and use analytical equations to determine the orbital effects of a close planetary encounter, by thoroughly examining a variety of encounter geometries, distances, and velocities. We study the changes in the semi-major axis, eccentricity, and inclination of the binary orbit. In Section 3, we present long-term simulations with test particles and planets to calculate encounter timescales for observed NEA binaries, whose encounter frequencies are strongly dependent on their individual evolutionary histories. We discuss and summarize this study in Section 4.

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Table 1
Well-Characterized Near-Earth Binaries

System	R_p (km)	M_p (kg)	a (km)	a/R_p	a_\odot (AU)	e_\odot	i_\odot (deg)
(185851) 2000 DP107 ^a	0.40	4.38×10^{11}	2.62	6.6	1.37	0.38	8.67
(66391) 1999 KW4 ^b	0.66	2.35×10^{12}	2.55	3.9	0.64	0.69	38.89
(276049) 2002 CE26 ^c	1.75	2.17×10^{13}	4.87	2.8	2.23	0.56	47.31
2004 DC ^d	0.17	3.57×10^{10}	0.75	4.4	1.63	0.40	19.45
(164121) 2003 YT1 ^e	0.55	1.89×10^{12}	3.93	7.1	1.11	0.29	44.06
(65803) Didymos ^f	0.40	5.24×10^{11}	1.18	3.0	1.64	0.38	3.41
(35107) 1991 VH ^g	0.60	1.40×10^{12}	3.26	5.4	1.14	0.14	13.91

Well-characterized near-Earth binaries and their parameters are compiled in this table, including the radius of the primary R_p , mass of the primary M_p , semi-major axis a (in units of km), and semi-major axis divided by the primary radius a/R_p . Rough uncertainties in binary parameters are $\sim 20\%$ in sizes, $\sim 10\%$ in masses, and $\lesssim 5\text{--}10\%$ in semi-major axes. Heliocentric orbital data are given for the semi-major axis a_\odot , eccentricity e_\odot , and inclination i_\odot with respect to the ecliptic.

^aMargot et al. (2002)

^bOstro et al. (2006)

^cShepard et al. (2006)

^dTaylor et al. (2008)

^eNolan et al. (2004)

^fBenner et al. (2010)

^gMargot et al. (2008); Pravec et al. (2006)

2. EFFECT OF A SINGLE PLANETARY ENCOUNTER

2.1. Methods

We perform N-body numerical integrations to investigate the effects of a close approach to an Earth-mass planet on a binary’s mutual orbit. We use a Bulirsch-Stoer algorithm from an N-body numerical integration package, *Mercury* (Chambers 1999). Our simulations incorporate 3 massive bodies (all assumed to be spherical), which include an asteroid binary and an Earth-mass perturber on a hyperbolic trajectory at various close encounter distances. We explore a wide range of initial conditions in encounter distance and velocity, which we describe in detail below. For each pair of encounter distance and velocity, systematic simulations are performed with nearly 7,000 permutations of the following mutual orbital parameters: inclination, longitude of the ascending node, and mean anomaly. Our test cases include all of the NEA binaries shown in Table 1 as well as a few generic cases with a typical rubble pile density of 2 g cm^{-3} and a primary radius of 0.5 km: a “close binary” with a separation of 4 primary radii, a “moderately-separated binary” with a separation of 8 primary radii, and a “wide binary” with a separation of 16 primary radii.

The hyperbolic encounter velocity v_∞ , defined as the relative speed between the binary and Earth at infinity, can be described by a probability distribution of relative velocities as shown in Figure 1. As a result, our simulations appropriately cover a range of v_∞ from 8–24 km s^{-1} with increments of 4 km s^{-1} . We also systematically repeat the ensemble of simulations for various close encounter distances whose range is dependent on the binary’s semi-major axis, and with typical increments of $1\text{--}2 R_\oplus$.

In this paper, the “encounter distance” q is defined as the distance of closest approach and the “impact parameter” b is the hypothetical encounter distance that would result in the absence of gravitational focusing. The impact parameter can be described as the perpendicular distance between the non-focused path of the

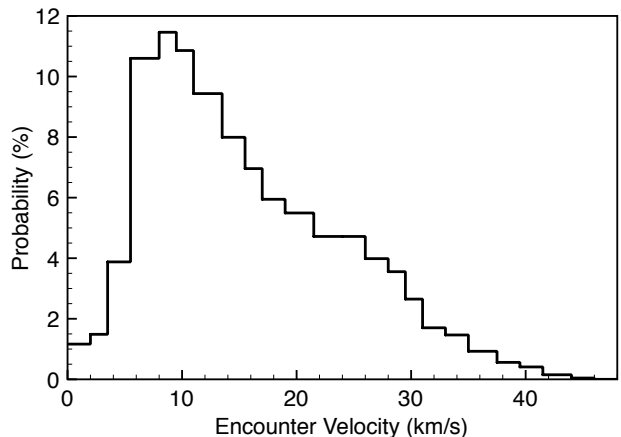


Figure 1. This probability distribution of expected encounter velocities v_∞ of NEAs with Earth is obtained from numerical simulations of asteroid migration from source regions (Mars-crossing region, ν_6 resonance, and 3:1 mean-motion resonance with Jupiter) in or adjacent to the main belt (Bill Bottke and Kevin Walsh, personal communication, 2011).

perturber and the binary. The usual definition relating impact parameter b and encounter distance q is $b^2 = q^2(1 + (2GM_\oplus)/(qv_\infty^2))$, where G is the gravitational constant, M_\oplus is the mass of Earth, and v_∞ is the encounter velocity at infinity. For most cases we consider here, the difference between b and q is less than 1 Earth radius.

All of the simulations begin with asteroid binaries in circular orbits. After a scattering encounter, possible outcomes include (a) an intact, stable binary system, or instability marked by (b) collision between any two bodies or (c) ejection of the secondary from the binary system. Encounter results are recorded for changes in semi-major axis, eccentricity, and inclination in stable encounters only. Stable systems are defined as binaries

with no collisions nor ejections of the secondary.

The output from numerical simulations is compared with approximate analytical results. We consider close planetary encounters with NEA binaries to be impulsive events, defined as swift encounters where the planet’s interaction with the binary is much shorter than the orbital period of the binary. The encounter delivers an impulse representing a shift in velocity of the binary’s orbit, and this impulse approximation is valid in the domain where $q/v_\infty \ll P$, where P is the binary’s mutual orbital period. For such impulsive encounters, the change in a binary’s orbital elements has been analytically approximated by previous studies. Heggie & Rasio (1996) derived the change in a binary’s eccentricity, Collins & Sari (2008) derived the change in both eccentricity and inclination, and Farinella & Chauvineau (1993) and Chauvineau & Farinella (1995) derived the change in energy (which we can relate to a change in semi-major axis). The typical change in a binary’s orbital elements after averaging over all encounter geometries (which include stable and unstable encounters) can be estimated as

$$\Delta a \approx 1.48 \sqrt{\frac{G}{M}} \frac{M_\oplus a^{5/2}}{v_\infty q^2} \quad (1)$$

$$\Delta e \approx 1.89 \sqrt{\frac{G}{M}} \frac{M_\oplus a^{3/2}}{v_\infty q^2} \quad (2)$$

$$\Delta i \approx 0.75 \sqrt{\frac{G}{M}} \frac{M_\oplus a^{3/2}}{v_\infty q^2} \quad (3)$$

where G is the gravitational constant, M_\oplus is the mass of Earth, v_∞ is the encounter velocity, and q is the encounter distance. The binary’s semi-major axis is represented by a , its eccentricity is e , its inclination is i , and its system mass is M . The constants in front of Equations 2 and 3 represent the averaging of encounter geometries, and have been calculated by Collins & Sari (2008). In their paper, we note there is a factor of 2 missing in the denominator of Equation A3. By analogy, we obtain the constant in front of Equation 1 by scaling the analytical curve to our numerical simulation results.

2.2. Results

The change in semi-major axis due to a planetary flyby is shown for three generic cases presented in Figure 2. Output from numerical simulations are shown as points and represent the mean values of the change (after taking the absolute value) in semi-major axis resulting from stable encounters. The curves represent analytical estimates, which provide a reasonable match to our numerical results. We show the average changes in semi-major axis for $v_\infty = 12, 16, 20,$ and 24 km s^{-1} . The results using a v_∞ of 8 km s^{-1} are not shown because the resulting spread in the post-encounter semi-major axis is very broad (e.g. at an encounter distance of 10 Earth radii, the standard deviation is $\sim 2.1 \text{ km}$) and not accurately portrayed by a single value. We wish to show orbital effects of only stable encounters; the range of close encounter distances for each binary type shown in this figure is determined by the distances at which all encounters resulted in stable binaries. Since the 3 types of binaries have different separations, they will have different

ranges of encounter distances at which stable encounters occur. These plots show that larger binary separations produce greater changes in semi-major axis at any given encounter distance because wider binaries are less tightly bound and thus more susceptible to passing perturbers.

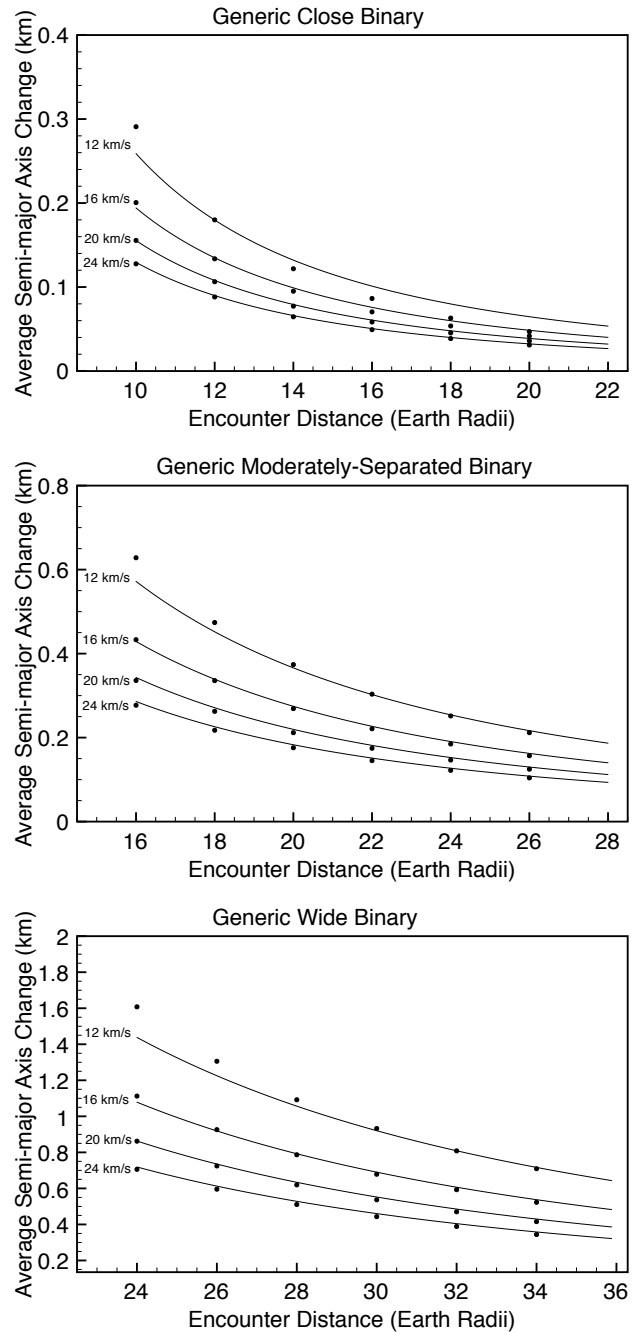


Figure 2. The change in a binary’s semi-major axis is shown as a function of encounter distance and velocity for 3 types of binaries: close binaries, moderately-separated binaries, and wide binaries. Results from numerical simulations are shown as dots and analytical calculations are depicted by solid lines.

The change in eccentricity is shown in Figure 3, with similar encounter distance and velocity ranges as shown

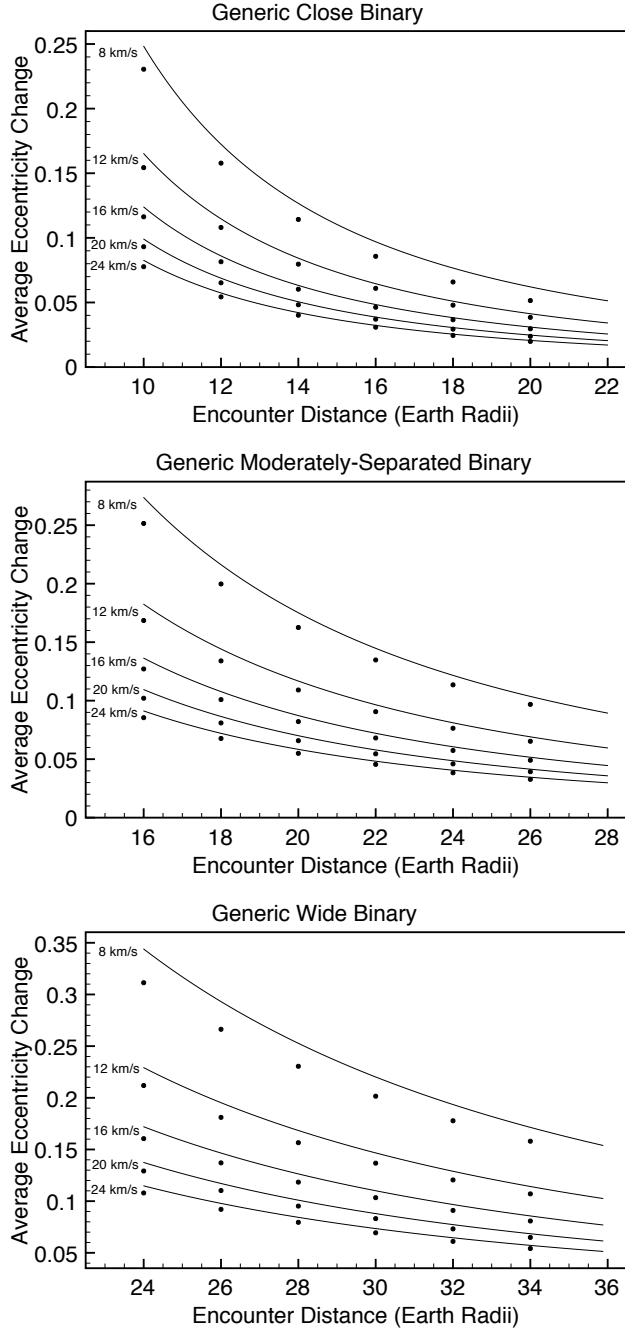


Figure 3. The change in a binary’s eccentricity is shown as a function of encounter distance and velocity for 3 types of binaries: close binaries, moderately-separated binaries, and wide binaries. Results from numerical simulations are shown as dots and analytical calculations are depicted by solid lines.

in Figure 2. Results from numerical simulations are given as the mean value of the eccentricity increase of all stable encounters. Analytical and numerical results are in agreement, especially for greater encounter velocities. For our test NEA binaries (Table 1) and using a typical v_∞ of 12 km s^{-1} , we also show the close encounter distances at which their eccentricities can be excited to a value of at least 0.2 (Figure 4) and how the distance

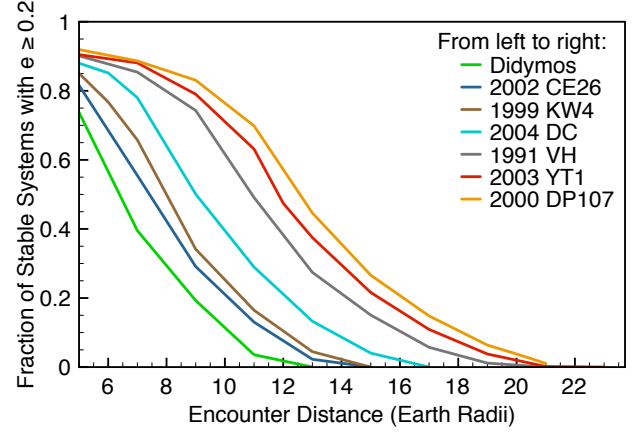


Figure 4. Using orbital and physical parameters from the sample of NEA binaries given in Table 1, we show the fraction of stable systems (no ejections nor collisions) with excited eccentricities ($e \geq 0.2$) as a function of encounter distance for $v_\infty = 12 \text{ km s}^{-1}$.

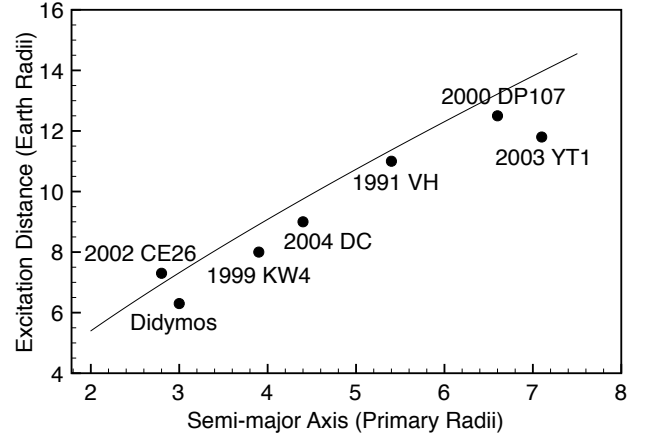


Figure 5. The eccentricity excitation distance (defined as the close encounter distance where 50% of stable NEA binary systems showed $e \geq 0.2$) is given as a function of the secondary’s semi-major axis in units of primary radii. The curve shows the result obtained from the analytical expression. This case is for v_∞ of 12 km s^{-1} .

at which eccentricity excitation occurs is a function of binary separation (Figure 5). The eccentricity excitation distance is defined in Figure 5 as the encounter distance where 50% of stable encounters resulted in binaries with $e \geq 0.2$. Since it is evident from this figure that there is a relationship between the critical encounter distance q and the binary’s semi-major axis a (when expressed in units of primary radii), we solve for its analytical relationship by rearranging Equation 2, and find

$$\frac{q}{R_\oplus} \approx \frac{1}{R_\oplus} \left(\frac{1.89 M_\oplus}{\Delta e v_\infty} \right)^{1/2} \left(\frac{3G}{4\pi\rho} \right)^{1/4} \left(\frac{a}{R_p} \right)^{3/4} \quad (4)$$

where R_p is the primary’s mass, R_\oplus and M_\oplus are the radius and mass of Earth, G is the gravitational constant, Δe is the change in eccentricity due to the encounter, v_∞ is the encounter velocity, and ρ is the binary’s density.

As stated earlier, the 1.89 factor is due to averaging

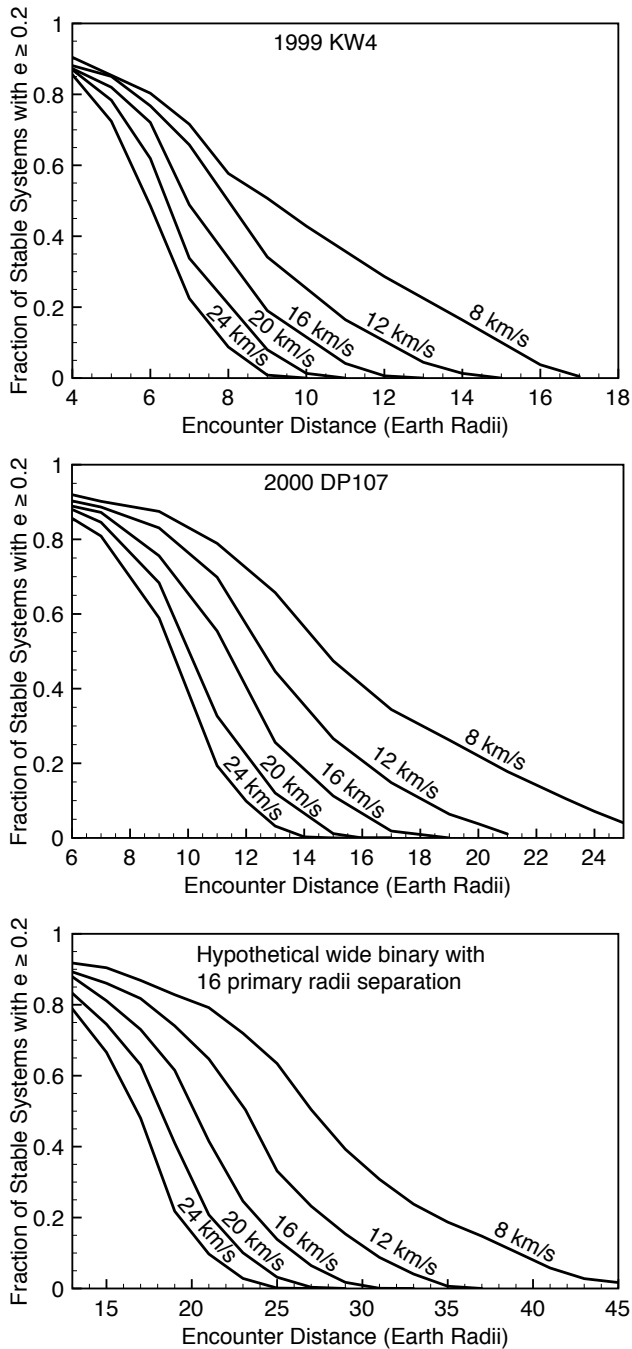


Figure 6. These plots show the characteristic behavior of close NEA binaries (i.e. 1999 KW4), moderately-separated NEA binaries (i.e. 2000 DP107), and wide NEA binaries (represented by a hypothetical binary with a separation of 16 primary radii) due to varying encounter velocities ($v_\infty = 8\text{--}24 \text{ km s}^{-1}$ with increments of 4 km s^{-1}). The fraction of stable systems (no ejections nor collisions) with excited eccentricities ($e \geq 0.2$) is shown as a function of encounter distance.

over all angles of encounter geometries (Collins & Sari 2008). This equation is valid for initially circular binaries. The same $q \propto a^{3/4}$ relationship holds for all binaries in our sample because for a uniform set of encounter parameters (encounter velocity and perturber’s

radius and mass), encounter strength (strong enough to excite $\Delta e = 0.2$), and binary density (assuming NEA binaries have similar rubble pile densities), the prefactor in front of the $a^{3/4}$ term is constant. In convenient units,

$$\frac{q}{R_\oplus} \approx 3.21 \left(\frac{0.2}{\Delta e} \times \frac{12 \text{ km s}^{-1}}{v_\infty} \right)^{1/2} \left(\frac{2 \text{ g cm}^{-3}}{\rho} \right)^{1/4} \left(\frac{a}{R_p} \right)^{3/4} \quad (5)$$

We overplot this analytical relationship in Figure 5 and find a good match to the numerical results. The agreement between numerical and analytical estimates for 2003 YF1 is not as good due to its higher density estimate (its nominal density is $\rho \sim 2.7 \text{ g cm}^{-3}$), since we assumed $\rho = 2 \text{ g cm}^{-3}$ in the calculation of Equation 5.

In Figure 6, we show the eccentricity excitation behavior due to $v_\infty = 8, 12, 16, 20,$ and 24 km s^{-1} for specific observed NEA binaries: a close binary (depicted by 1999 KW4), a moderately-separated binary (2000 DP107), and a wide binary (represented by a hypothetical binary with a 16 primary radii separation). As the value of v_∞ decreases, a greater fraction of stable systems have excited eccentricities due to a planetary flyby at a given encounter distance. In addition, as the value of v_∞ decreases, the final eccentricities of binaries in our simulations increased. These effects occur because a slower-passing perturber will have a longer encounter duration with the binary and therefore cause a stronger perturbation on the binary’s mutual orbit.

The change in a binary’s orbital inclination is shown in Figure 7, with similar encounter distances and velocities as shown in Figures 2 and 3. Results from numerical simulations are given as the mean value of the inclination change of all stable encounters. Comparison between output from numerical simulations and analytical estimates provide a decent match. Possible reasons for the less-than-exact agreement between numerical and analytical results include our choice of using the mean value to represent the average change in inclination of stable encounters from simulations as well as the practical limit on the number of encounter geometries we were able to perform in our simulations. The analytical expressions are also only valid in the limit of impulsive encounters, suggesting that analytical results should provide better matches to simulations with faster encounter velocities, which is consistent with our results.

These results have implications for binaries observed with excited dynamical states. For instance, previous studies of 1999 KW4 (heliocentric a is 0.64 AU, e is 0.69, i is 38.89 degrees; current solar close approach distance is 0.2 AU) suggest that the binary’s close approaches to the Sun can excite its rotational and orbital states (Ostro et al. 2006; Scheeres et al. 2006). Their numerical simulations show that the binary’s mutual orbit pole can be modified by more than 0.5 degrees per pericenter passage for a pericenter distance of 0.2 AU and by more than 1 degree for a pericenter distance of 0.12 AU. From our simulations, we find that planetary encounters with an Earth-mass body can perturb the binary orbit pole by a similar amount. Therefore, even NEAs that do not come as close to the Sun as 1999 KW4 may exhibit excited rotational and orbital dynamics. For a generic binary with a semi-major axis of 4 primary radii (same as

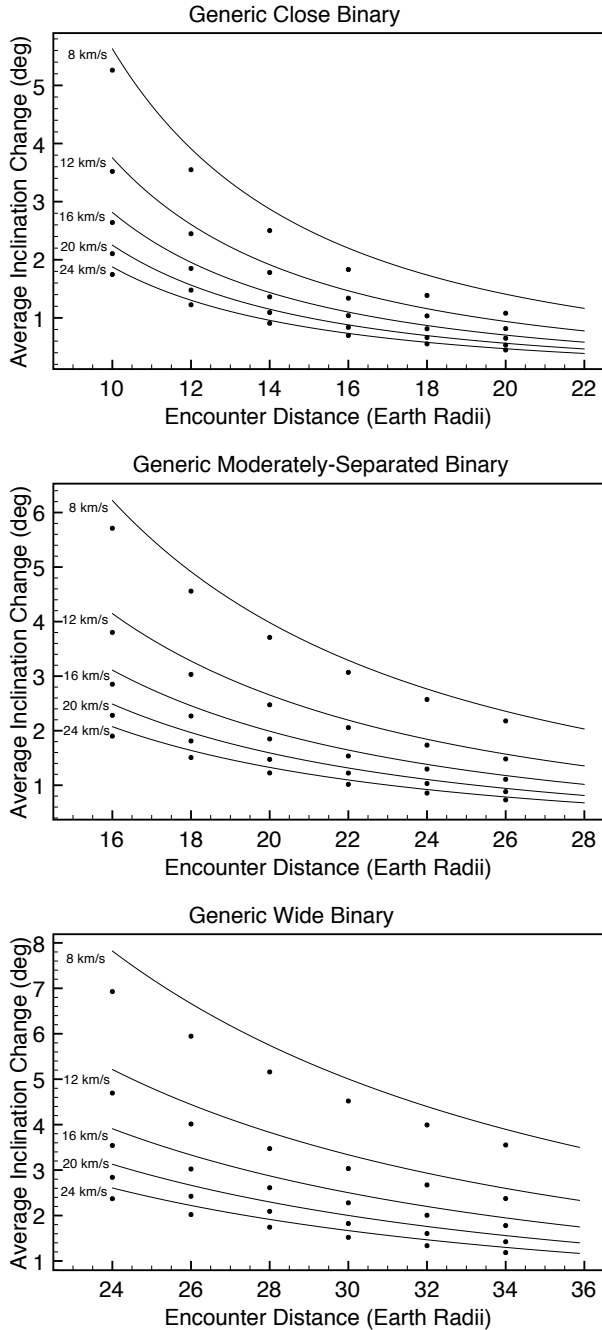


Figure 7. The change in a binary’s inclination is shown as a function of encounter distance and velocity for 3 types of binaries: close binaries, moderately-separated binaries, and wide binaries. Results from numerical simulations are shown as dots and analytical calculations are depicted by solid lines.

1999 KW4’s separation), our simulations using v_∞ from $8\text{--}24\text{ km s}^{-1}$ show that a 0.5 degree shift in inclination can occur due to a planetary encounter at distances of $18\text{--}28 R_\oplus$ and a 1 degree shift can occur at $13\text{--}20 R_\oplus$.

We briefly discuss instability trends seen in simulations with a typical v_∞ of 12 km s^{-1} for observed NEA binaries (Table 1). For nearly all encounter distances sampled in simulations, ejections dominated over collisions in un-

stable encounters. If planetary encounters close enough to disrupt a binary have occurred, an ejected secondary is more likely to occur than a collision between the primary and secondary. Therefore one would expect that planetary encounters can lead to the formation of asteroid pairs in the near-Earth population, in addition to the formation mechanisms responsible for pair production in the main belt. The different routes towards the creation of asteroid pairs are discussed in a companion paper by Fang & Margot (2011). Close binaries such as Didymos, 2002 CE26, 1999 KW4, and 2004 DC have similarly small component separations ($2\text{--}5 R_p$) relative to their primary’s radius R_p , and exhibit comparable disruption statistics. Instabilities, including both ejections and collisions, occurred at encounter distances of $\sim 5\text{--}7 R_\oplus$ and less. More moderately-spaced binaries such as 2000 DP107, 2003 YT1, and 1991 VH have comparable component separations ($5\text{--}9 R_p$). For these binaries, simulation results showed disruption occurring at encounter distances of $\sim 7\text{--}9 R_\oplus$ and less. Binaries with wide separations will have mutual orbits that are more easily perturbed than tighter systems.

Given the significant orbital perturbations in binary systems that can be caused by planetary flybys, the next section examines the frequency of such encounters.

3. FREQUENCY OF PLANETARY ENCOUNTERS

3.1. Methods

After investigating the orbital effects of a single planetary flyby on a binary in Section 2, we next determine the frequency of such close planetary encounters with Earth for well-characterized NEA binaries (Table 1). The timescale of close encounters is very dependent on the specific NEA’s past evolutionary path to its current heliocentric orbit (see Table 1 for current heliocentric parameters), and different NEAs can have very different close encounter histories. We do not backward-integrate the current heliocentric orbits because the orbits become chaotic over time and it is difficult to reconstruct their past history, even statistically. Consequently, we follow the methods of Bottke et al. (2002) by integrating test particles from the three strongest source regions (ν_6 secular resonance with Saturn, 3:1 mean-motion resonance with Jupiter, and Mars-crossing regions) in or adjacent to the main belt and by tracking the test particles as they migrate into near-Earth space. These source regions are the main dynamical pathways to NEA orbits. Integrations are performed using a hybrid symplectic/Bulirsch-Stoer algorithm from *Mercury* (Chambers 1999), and include the Sun and all 8 planets in addition to 3000 test particles per source (9000 test particles total). In the simulations, we ignore the effect of Yarkovsky. The Yarkovsky effect is an important perturbation that moves asteroids into main source regions; however, once asteroids have reached the source regions, the effect of Yarkovsky is negligible compared to the effect of strong resonances and planetary encounters.

After test particles have migrated into near-Earth space, we search for particles whose orbital elements (semi-major axis a , eccentricity e , and inclination i) closely match the current orbital elements of the actual NEA binaries in our sample (Table 1). For each binary, we search for ten test particles closest in orbital

Table 2
Encounter Timescales (Myr) with Earth

Name	Impact Parameter:														
	$2R_{\oplus}$	$4R_{\oplus}$	$6R_{\oplus}$	$8R_{\oplus}$	$10R_{\oplus}$	$12R_{\oplus}$	$14R_{\oplus}$	$16R_{\oplus}$	$18R_{\oplus}$	$20R_{\oplus}$	$22R_{\oplus}$	$24R_{\oplus}$	$26R_{\oplus}$	$28R_{\oplus}$	$30R_{\oplus}$
2000 DP107	60.73	15.18	6.75	3.80	2.43	1.69	1.24	0.95	0.75	0.61	0.50	0.42	0.36	0.31	0.27
1999 KW4	50.72	12.68	5.64	3.17	2.03	1.41	1.04	0.79	0.63	0.51	0.42	0.35	0.30	0.26	0.23
2002 CE26	391.40	97.85	43.49	24.46	15.66	10.87	7.99	6.12	4.83	3.91	3.23	2.72	2.32	2.00	1.74
2004 DC	109.90	27.47	12.21	6.87	4.40	3.05	2.24	1.72	1.36	1.10	0.91	0.76	0.65	0.56	0.49
2003 YT1	131.34	32.84	14.59	8.21	5.25	3.65	2.68	2.05	1.62	1.31	1.09	0.91	0.78	0.67	0.58
Didymos	46.30	11.58	5.14	2.89	1.85	1.29	0.94	0.72	0.57	0.46	0.38	0.32	0.27	0.24	0.21
1991 VH	72.86	18.21	8.10	4.55	2.91	2.02	1.49	1.14	0.90	0.73	0.60	0.51	0.43	0.37	0.32

For each NEA binary, we show the encounter timescale (in millions of years) with Earth for various impact parameters.

element space to the binary’s current heliocentric orbital elements using this scaling: $\delta a/a \sim \delta e \sim \delta \sin i$ (Vokrouhlický & Nesvorný 2008). Binaries 2003 YT1 and 1999 KW4 have either high inclinations and/or low semi-major axes, and these binaries proved to be difficult when searching for matches with test particles originating from the 3 main source regions given by Bottke et al. (2002). In our sample of binaries, the median δa is ~ 0.014 AU. The matching test particles are further integrated until they become dynamically unstable through ejection from the Solar System or collision with a planet or the Sun. For each NEA binary’s matching test particles, we record the orbital history with an Opik-type code similar to the procedure developed by Wetherill (1967) and implemented by Farinella & Davis (1992), which allows us to calculate the encounter velocity and intrinsic collisional probability with Earth at each timestep. We calculate the intrinsic collisional probability with Earth every 10,000 years from the time of injection in the source region up to the most recent epoch at which the test particle’s orbital elements matched those of the actual NEA binary. As a result, we obtain an intrinsic collisional probability value for each 10,000-year timestep in the history of each matching test particle. Based on this ensemble of values we associate an average intrinsic collisional probability to each test particle by averaging all non-zero values over time. Finally, we associate an intrinsic collisional probability to each NEA binary by averaging over all of its matching test particles.

The intrinsic collisional probability (in units of $\text{km}^{-2} \text{yr}^{-1}$) can be multiplied by the square of an impact parameter to obtain an encounter probability (in units of yr^{-1}), whose inverse yields an approximate encounter timescale. These timescales represent the average time between encounters with Earth since injection into main belt source regions and their subsequent migration into near-Earth space.

We also calculate the close encounter timescale using an analytical, order-of-magnitude approach. Chauvineau & Farinella (1995) give the approximate timescale t

$$t \sim \frac{2\tau_{\text{coll}} R_{\oplus}^2}{b^2} \quad (6)$$

between close encounters up to an impact parameter b given an asteroid’s lifetime τ_{coll} against collision with Earth of radius R_{\oplus} . For a given asteroid size, Stuart & Binzel (2004) provide the total number

of NEAs with at least that size as well as the average interval between Earth impacts due to all asteroids of that size taken collectively. Thus, with these numbers we can calculate τ_{coll} and the encounter timescale for an individual asteroid.

3.2. Results

For each binary in our sample, Table 2 gives encounter timescales with Earth from numerical simulations for impact parameters ranging from $2R_{\oplus}$ to $30R_{\oplus}$. In this impact parameter range, encounter timescales can range from $\sim 10^5$ up to $\sim 10^9$ years for the NEA binaries considered here. Encounter probabilities can be obtained by taking the inverse of these timescales, and then suitably scaled (the probability varies as the square of the impact parameter) to a desired impact parameter. Recall that due to gravitational focusing, the impact parameter b is not the same as the closest encounter distance q , and are related in this manner: $b^2 = q^2(1 + (2GM_{\oplus})/(qv_{\infty}^2))$, where G is the gravitational constant, M_{\oplus} is the mass of Earth, and v_{∞} is the encounter velocity at infinity.

Timescale estimates from the analytical approach agree with results obtained from numerical integrations within an order of magnitude for all NEA binaries in our sample. Differences in timescales can be attributed to the fact that the analytical timescales do not take into account a specific NEA’s orbital trajectory as it migrates to near-Earth space, which affects its history of planetary encounters.

We repeat this analysis to determine encounter frequency with other terrestrial planets, namely Mercury, Venus, and Mars. For a given orbital effect such as increasing a binary’s eccentricity to a given value, we find that encounters with Venus are just as important as encounters with Earth. For all binaries in our sample, the encounter probabilities with Venus and Earth are comparable; these encounter probabilities for achieving a given change in the mutual orbit are a function of encounter velocity, planet mass, and binary separation.

4. DISCUSSION AND CONCLUSION

Encounter timescales presented in Table 2 show that some NEA binaries in our sample (Table 1) can typically encounter Earth frequently enough at close-enough distances to excite the binary’s orbital elements, as shown by single-flyby simulations in Section 2. We have presented the encounter timescales in this study, but the actual effects of encounters are also dependent on typical encounter velocities, which we plotted in Figure 1 for

a generic NEA. Consideration of these factors as well as comparison to observed eccentricities are discussed in a companion paper by Fang & Margot (2011).

We briefly address the possibility of repeat encounter passes. Repeat passes, which are most relevant for binaries with short encounter timescales and large binary separations, can increase or decrease the binary’s semi-major axis and eccentricity depending on its values prior to the encounter. The strength of repeat passes depends on flyby parameters such as encounter velocity. The net effect of repeat passes is still an eccentric orbit, since it is rare for an eccentric binary to undergo a planetary encounter and end up with near-zero eccentricity.

Close planetary encounters have important implications for an NEA binary’s evolution, since flybys can disrupt main evolutionary processes in a binary by expanding or contracting the mutual orbit. For a typical NEA binary with a separation of ~ 4 primary radii, we find that the semi-major axis increases on average 60% of the time for encounter distances from 2–10 R_{\oplus} and encounter velocities from 8–24 km s^{-1} . Since flybys can increase or decrease the semi-major axis of the binary’s orbit, tidal evolution can strengthen (if the semi-major axis decreases) or weaken (if the semi-major axis increases) since the tidal torque scales as the binary separation to the sixth power. When the semi-major axis is modified, the mean motion of the secondary changes and an initially spin-locked secondary may become asynchronous¹. Asynchronization can also occur by a change in the secondary’s rotation rate due to the flyby. The loss of spin-lock would imply that radiative perturbations dependent on synchronization such as binary YORP (BYORP) would be shut down. Lastly, planetary encounters are another mechanism that may form near-Earth asteroid pairs. The evolution of binaries under various influences, including the planetary model presented here, is further discussed in a companion paper by Fang & Margot (2011).

To summarize, in this study we have used numerical integrations and analytical expressions to investigate the effects of planetary encounters on NEA binaries. We found the encounter distances at which flybys can increase the orbital semi-major axis, eccentricity, and inclination for a variety of encounter velocities. There is reasonable agreement between results obtained from simulations and analytical methods. The possible outcomes, including collisions, ejections, and stable encounters, are discussed for close binaries, moderately-separated binaries, and wide binaries. We have also used N-body integrations to examine the past evolutionary histories of NEAs as they migrated from main belt source regions into near-Earth space. From these simulations, we calculated encounter probabilities and timescales for all

¹ In this paper, binaries with an absence of spin-orbit synchronism are called *asynchronous binaries*. Binaries with a secondary spin period synchronized to the mutual orbit period are called *synchronous binaries*. Binaries with both primary and secondary spin periods synchronized to the mutual orbit period are called *doubly synchronous binaries*. Most NEA binaries are *synchronous*. Note that our terminology is different from that of Pravec & Harris (2007), who used the term “asynchronous binaries” for binaries with spin-orbit synchronization. If generalization to systems with more than one satellite is needed, we affix the terms *synchronous* and *asynchronous* to the satellites being considered.

NEA binaries in our sample for different impact parameters. These encounter timescales provide rough agreement with analytical estimates, which do not take into account individual NEAs’ past orbital histories. Lastly, planetary encounters have important implications for evolutionary processes such as tidal and BYORP mechanisms.

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