ASTEROID CAPTURE USING A BINARY EXCHANGE MECHANISM

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Abstract

A new method of capturing an asteroid in an orbit around the Earth is proposed, inspired by the theory that the irregular satellites of Jupiter and Neptune may have at one time been members of a binary asteroid. After a close approach with the planet, the binary asteroid was disrupted, and one member was captured into a permanent orbit. A parametric study was conducted by simulating binary-Earth encounters. The total mass of the binary system and the velocity of the binary asteroid relative to the Earth were found to be the two dominant parameters affecting capture. These results were used to select a candidate near-Earth binary asteroid, 1999 HF1, with which additional simulations were conducted. It was found that the candidate asteroid could only be captured with a high probability at low velocities, and the resulting orbits were larger than the Earths Hill sphere. However, larger non-near-Earth binary asteroids could be captured within the Hill sphere. The effect of treating the larger member of the binary system as an extended body and the effect of the moon were also considered. A close approach with the moon sometimes resulted in one or both binary members being captured within the Hill sphere.

1   Introduction

It has been proposed that many of the irregular satellites within the solar system were not formed by accretion within circumplanetary disks as is the case for regular satellites[1]. Instead, irregular satellites are believed to have once been asteroids that were captured into permanent orbits around their respective planets[2]. Various methods describing how these asteroids were captured have been formulated. While these capture mechanisms give us a description of irregular satellite formation in the early solar system, they also provide potential methods by which an asteroid could be captured in an orbit around the Earth. A captured asteroid would have many uses and could offer financial, technological, and political benefits for government agencies or private companies willing to explore this novel resource. The recent decommission of the NASA space shuttles and the accompanying push by the United States government for private space exploration makes these incentives for private companies particularly interesting.

Having an asteroid in such close proximity to Earth would allow for scientific studies of asteroid composition and origin of unprecedented accuracy. Colonizing an asteroid would provide a training ground for astronauts and allow for deeper missions into space. Such asteroids could be set up as interplanetary gas stations where spacecraft refuel after liftoff before beginning a long mission. Asteroids are also a rich source of minerals that will one day be scarce on Earth. If mineral excavation rises just two percent annually, the Earths supply of accessible lead will be gone in 17 years, tin in 19 years, copper in 25 years, and iron in 54 years[3]. The economics of mining asteroids has been analyzed and deemed feasible[4]. Finally, a captured asteroid could be used as a shield to protect the Earth form potentially hazardous objects[5]. Clearly, there are many reasons for exploring the feasibility of capturing an asteroid.

Within this report, we propose a new method for capturing a near Earth asteroid by using a binary exchange mechanism. This technique relies on a two asteroid system, known as a binary asteroid, making a close approach to the Earth. This method has been used to explain the formation of the irregular moons of Jupiter[6,7] and Neptune[8,9]. In Section 2, we will first explore binary exchange and other models of asteroid capture that have been proposed. Section 3 provides an overview of the solar systems binary asteroid population and which of these asteroid could be potential candidates for capture. Section 4 presents results of numerical simulations of binary-Earth encounters for a wide range of binary parameters and initial conditions. In Section 5, a candidate binary asteroid is chosen based on the results presented in the previous section. Section 6 presents additional simulations of encounters between the candidate asteroid and Earth. In Sections 7 and 8, the effects of treating the larger asteroid as a non-spherical extended body and the effects of the moon are examined, respectively. Concluding remarks are given in Section 9.

2   Previously Proposed Methods of Asteroid Capture

While regular satellites are characterized by nearly circular and uninclined orbits, irregular satellites move along highly eccentric and/or inclined orbits. These differences suggest that the formation mechanisms for each type are different, and that irregular satellites were once on hyperbolic orbits and later captured. Four models of capture have been proposed in previous literature:

(1) Collisions between an asteroid and a planet resulting in a captured satellite

(2) Capture through dissipation of orbital energy due to gas drag

(3) Pull-down capture, in which a planets mass suddenly increases

(4) Capture through multi-body gravitational interactions

A review of last three methods is given in Jewitt 2007[10]. In (1), the size of the asteroid required for capture would be large enough to produce a catastrophic collision, and the ejection speed of large fragments after collision would not be great enough to produce stabilized orbits[11]. Studies of gas drag capture have shown that permanent capture due to gas drag is possible, but unlikely to have occurred in the early solar system[12]. Pull-down capture was also shown to be able to produce capture in a Sun-Jupiter-Satellite environment[13].

Clearly, (1) and (3) are not reasonable methods for capturing an asteroid around the Earth. Also, method (2) would be very difficult to implement, as a spherical dust cloud would need to be created around the Earth. Thus, (4) is the most feasible method for Earth capture. One type of gravitational capture occurs when a satellite interacts with two planets and becomes bound to one of the planets. It has been shown that in the early solar system, encounters between the outer planets within the planetesimal disk could have resulted in capture[11]. It has also been shown that planetary resonance could lead to irregular satellite capture[14].

The most feasible mechanism to implement in an Earth environment is binary exchange. This method has been used to explain the capture of Triton by Neptune[8,9] and the irregular moons of Jupiter[6,7]. This method relies on a close encounter between a two member system, known as a binary asteroid, and the planet. If at the closest approach the binary asteroid is oriented correctly, one of the two asteroids could be moving slowly enough relative to the planet to be captured. This method of capture was examined in an Earth environment for a wide range of binary asteroid parameters and initial conditions. An illustration of binary exchange is shown in Figure 1.
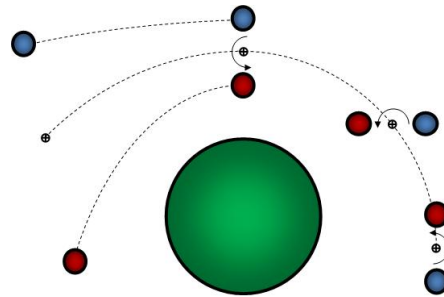

Figure 1: Schematic of Binary Exchange

3   Binary Asteroid Population

A binary asteroid is comprised of two asteroids that orbit their center of mass as the system follows some larger orbit. In Pravec 2007[15], an overview of the characteristics of 73 binary asteroids is given, including the 36 known near-Earth binary asteroids. For the entire population surveyed, the total mass of binary systems ranges from 3.1×10^9 kg to 2.6×10^{19} kg, the mass ratio, defined as ratio of the mass of the larger member to the mass of the both members, ranges from 0.5 to 0.999, and the binary semi-major axes range from 500 m to 3400 km. The orbital eccentricity of the majority of binary asteroids is very small.

Simulations were conducted using these parameter ranges, however, the 36 near-Earth asteroids were only considered as potential candidates for capture. The process of steering a binary asteroid from its current orbit to an orbit with a close encounter with the Earth was left for future work. Near-Earth binary asteroids would be the easiest to steer to the Earth. The near-Earth binary asteroids have total masses ranging from 3.1×10^9 kg to 6.7×10^{13} kg, mass ratios ranging from 0.578 to 0.999, and semi-major axes ranging from 500 m to 6 km.

4   Results of Parametric Study

This section presents the results of numerical simulations of binary-Earth encounters conducted in three dimensions with all three bodies treated as spherical masses. Simulations were conducted using a six stage adaptive step size Gragg-Bulirsch-Stoer integration scheme constructed using Matlab[16]. To check the accuracy of the simulations, the relative change in total energy was tracked, and was found to never vary by more than 10^{-6}. The simulations were run for 6×10^6 seconds. Binary parameters and initial conditions were selected using a Latin hypercube sampling technique in order to efficiently span the parameter space[17].

The variables within each simulation were the total mass of the two asteroid system, M_{tot}, the mass ratio,

c, as defined earlier, the velocity of the binary system at an infinite distance away from the earth, v_∞, the closest approach of the binary center of mass to the Earth, r_p, the initial semi-major axis of the binary orbit, a, the initial eccentricity of the binary orbit, e, one angle prescribing the true anomaly, θ, three angle prescribing the orientation of the binary orbit, α, β, γ, and a variable determining the direction in which the binary rotates, g. The asteroids were assumed to have a density of 3 g/cm^3 and were initially located at the edge of the Earths Hill sphere. The variables were varied across the following ranges: $M_{tot} \in [10^8\text{kg}, 10^{20}\text{kg}], c \in [0.5, 0.99], v_\infty \in [0\text{m/s}, 100\text{m/s}], r_p \in [2R_e, 60R_e], a \in [4R_1, 16R_1], e \in [0, 0.8], \theta, \alpha, \beta, \gamma \in [0, 2\pi]$, and $g = -1$ or 1, where R_e is the radius of the Earth and R_1 is the radius of the larger asteroid. After each time step, the distance between the two asteroids was compared with the sum of the asteroids radii. If the distance was less than this sum, the simulation was marked as resulting in a collision. Figure 2 shows one simulation in which capture occurred and the resulting orbit was contained within the Earths Hill sphere. For this simulation, $M_{tot} = 5.94 \times 10^{17}$ kg, $c = 0.95, v_\infty = 100$ m/s, $r_p = 2R_e, a = 1.5R_1, e = 0, \theta = 1.8, \alpha = 0, \beta = 0, \gamma = 0$, and $g = 1$.
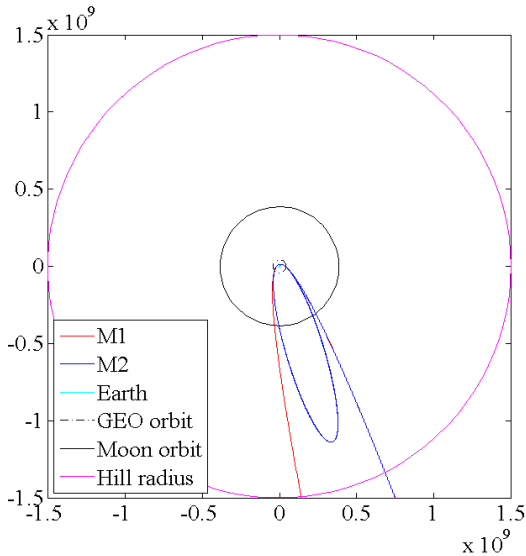

Figure 2: Example of Asteroid Capture through binary exchange

The following plots represent results from 100,000 simulations. First, the effect of each variable on the probability of capture was examined. Figure 3 shows plots of the probability of capture as a function of the variables $\log M_{tot}, c, v_\infty, r_p, a$, and e for the larger of the two asteroids, while Figure 4 shows the same plots for the smaller of the two.

The probability of capturing the smaller of the two asteroids is higher than that of capturing the larger asteroid in all cases. It can be seen that v_∞ and M_{tot} have the most profound effect on the probability of capture, with the probability decreasing as v_∞ is increased and increasing as M_{tot} is increased. The probability is also seen to decrease with increasing r_p and e for both asteroids. Increasing a and c causes an increase in the probability of capture.
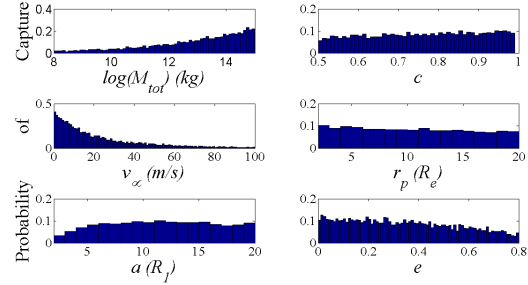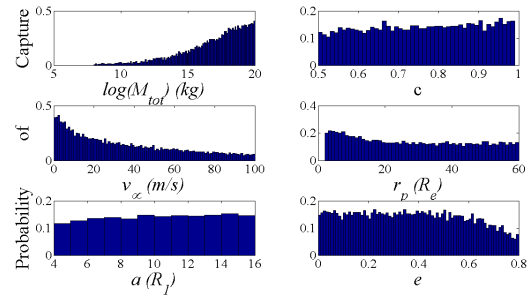

Figure 3: Probability of Capture of Larger Asteroid

Figure 4: Probability of Capture of Smaller Asteroid

These trends should be expected, as binary systems with lower v_∞ have less total energy, and therefore less energy loss is required for capture to occur. Binaries with higher total masses rotate at faster rates than those with lower masses. Thus, at the closest approach, the asteroid closest to the Earth will be moving slower relative to the Earth (see Figure 1). Smaller close approaches result in higher probability of capture since the tidal forces responsible for disrupting the binary and pulling one member into a permanent orbit are stronger. The trends observed in a and e can be attributed to greater probability of collision at low a and high e, as the two asteroids had closer encounters in these regions.

The next group of plots displays the resulting semi-major axes of the captured asteroids as functions of the system variables. Figure 5 represents data for the larger binary members, while Figure 6 represents data for the smaller member.
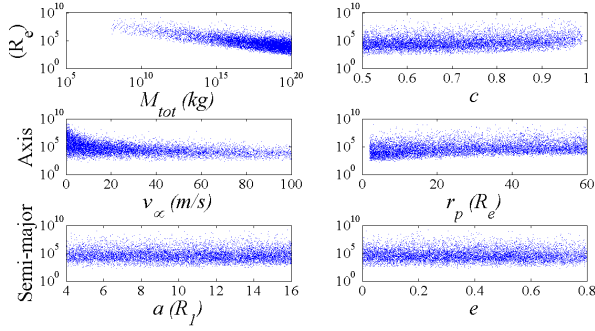
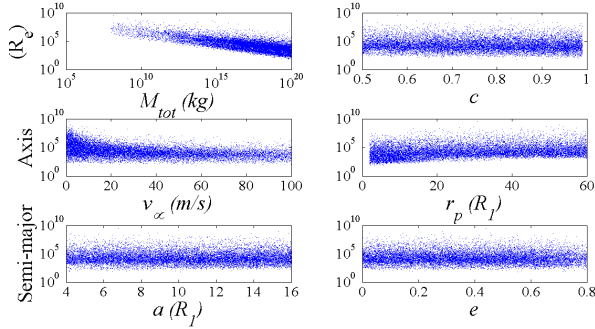Figure 5: Resulting Semi-major Axis of Larger Asteroid

Figure 6: Resulting Semi-major Axis of Smaller Asteroid

The resulting semi-major axes of the smaller member tend to be smaller than those of the larger member, and the plots are denser for the smaller member, again showing a higher probability of capture. Some small trends can be seen in each variable; however, the total mass is the dominant variable in determining the size of the orbits. Figure 7 contains plots showing v_∞ vs. M_{tot} for the smaller and larger binary members. These are the most important variables affecting the probability of capture and the size of the resulting orbit. In the plots, a blue mark represents a captured asteroid, a red mark represents an uncaptured asteroid, and a black mark represents a collision between the two asteroids.
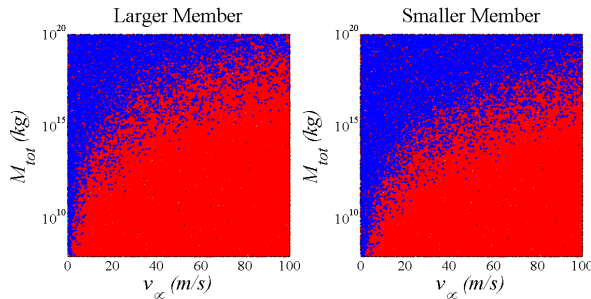

Figure 7: Capture Distribution Over M_{tot} vs. v_∞

There are distinct regions for both members in which capture is more likely to occur. For a given binary system of know total mass, the plots above can be used to determine the maximum v_∞ at which capture can occur. Simulations conducted in two dimensions exhibited the same trends as those observed in three dimensions.

5   Choice of Candidate Asteroid

From the results presented in the previous section, it is clear that the total mass of the binary system has the largest impact on the probability of capture and the size of the resulting orbits. For this reason, we propose that the best candidate near-Earth binary asteroid for capture is 1999 HF1. This is the most massive of the known near-Earth binary asteroids, with a total mass of 6.7×10^{13} kg. The mass ratio of this binary is 0.988, and the orbital semi-major axis is 6 km[16]. In the following sections, results of simulations considering this particular binary asteroid are presented. In these simulations, the eccentricity of the binary system was assumed to be 0. Therefore, θ was not varied, since varying θ and α are the same for circular orbits.

6   Candidate Asteroid Simulations

In the Section 5, many different total binary masses, mass ratios, and initial semi-major axes were considered. Therefore, no critical value of close approach was observed in the data. However, now that only one binary system is being considered, we expect to observe some tidal radius, below which capture is more likely to occur. In previous literature[6,7,8], an approximation of this tidal radius has been given by Eq (1).

$$r_{td} = a \left(\frac{3M_e}{m_1 + m_2} \right)^{1/3} \tag{1}$$

Where m_1 and m_2 are the masses of the two members of the binary and M_e is the mass of the Earth. For the binary asteroid 1999HF1, this tidal radius is 6.02 Earth radii.

Figures 8 and 9 show the probability of capture as functions of v_∞ and r_p for the larger and smaller members of the binary, respectively.
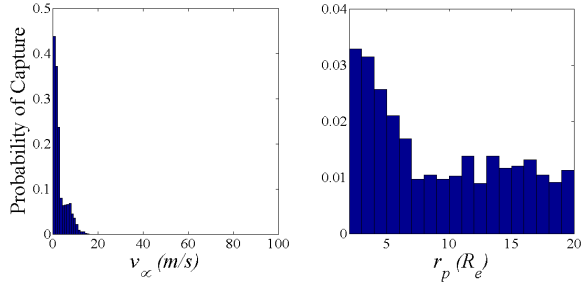
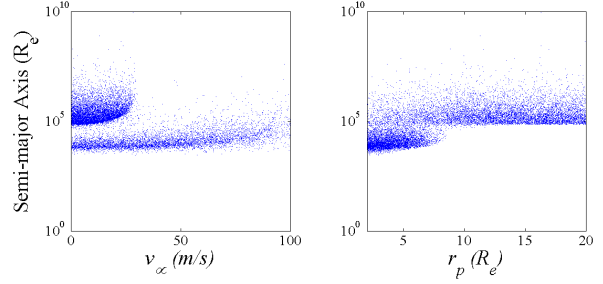Figure 8: Probability of Capture of Larger Asteroid Candidate
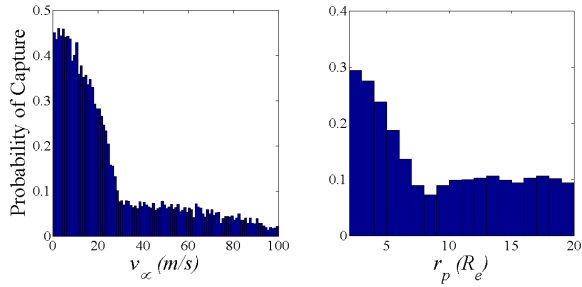

Figure 9: Probability of Capture of Smaller Asteroid Candidate

For the larger mass, the probability of capture drops quickly as v_∞ is increased and is slightly higher for smaller close approaches. For the smaller mass, the probability of capture drops below 10% above $v_\infty = 30$ m/s, and is highest when r_p is less than 6 Earth radii.

Figures 10 and 11 present the resulting semi-major axes from simulations that resulted in capture as functions of v_∞ and r_p for the larger and smaller members of the binary, respectively.

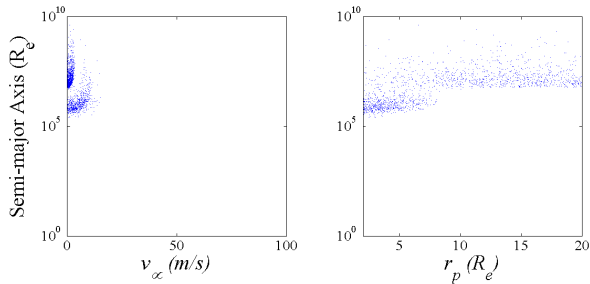Figure 10: Resulting Semi-major Axis of Larger Asteroid Candidate

Figure 11: Resulting Semi-major Axis of Smaller Asteroid Candidate

These plots show that the smallest resulting semi-major axes occur when the close approaches is less than the tidal radius. We also observe two bands on the v_∞ plot for each asteroid. The lower bands in the v_∞ plots correspond to the data points in the lower left portion of the r_p plots. Figure 11 displays captured and uncaptured data points for r_p and v_∞. The colors have the same meaning as in Figure 7.
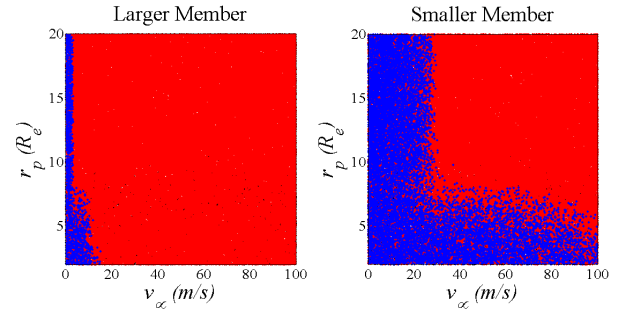

Figure 12: Candidate Capture Distribution Over M_{tot} vs. v_∞

If the binary asteroid's approach to the Earth is less than the tidal radius, the range of v_∞ in which capture can occur is greatly increased. Also, the probability of collision is much greater just above the tidal radius, as can be seen by the concentration of black data points. Again, two dimensional simulations exhibited the same trends.

While these results show that capture is possible, the orbits of the captured asteroids all extend well outside of the Earth's Hill sphere, which is 1.5×10^9 m, or roughly 235 Earth radii. Once outside of this region, the asteroid could interact with other bodies in the solar system, rendering it uncaptured by the Earth. Looking back at the data presented in Section 4, we see that capture is possible within the Hill sphere with asteroids larger than the chosen candidate asteroid. However, these larger non-near-Earth binary asteroids would be much more difficult to reach, and steering them onto an orbit with a close ap-

proach to the Earth would be much more difficult compared to a near-Earth binary asteroid.

7 Extended Body Effects

While some binary asteroid members can be nearly spherical, it is also possible for them to have elongated shapes. To convey a more accurate dynamic relation between non-spherical binary members, a higher order gravitational potential field was implemented into the model. Prior to implementing this gravitational field model, only point mass gravitational field models had been used to represent the gravitational interaction of the binary. The extended body approach offers a detailed description of the gravitational interaction between the two bodies of the binary by taking into account the rotation and physical shape of the larger asteroid. MacCullagh's gravity potential approximation[18] (shown in Eq (2)) was chosen because it added the desired degree of precision, without incorporating unnecessary complexity into the model. In addition an axial symmetric geometry was chosen so that the physical shape of the body could be varied and to simplify the mathematical description of the potential without compromising the insight gained from the higher order approximation.

$$V(r) = -\frac{Gm}{r} - \frac{G}{2r^3}\left[I_{xx}\left(1 - 3\frac{x^2}{r^2}\right) + I_{yy}\left(1 - 3\frac{y^2}{r^2}\right)\right] \quad (2)$$

Here, I_{xx} and I_{yy} are the principal moments of inertia and x and y are the distances between the two asteroid in the body fixed frame of the larger member.

25,000 simulations using this new gravity potential were conducted in two dimensions (so $\beta = \gamma = 0$) using the candidate asteroid. To vary the shape of the larger asteroid, the radius of the asteroid was calculated as if it were spherical. Then this radius was multiplied by stretching factors s_x and s_y in the x and y directions of the body fixed frame to create an ellipsoidal shape. An angle, ψ, giving the initial orientation of the larger member was also chosen. The new variables were chosen using the Latin hypercube method in the ranges $s_x \in [-0.9, 0.9], s_y \in [-0.9, 0.9]$, and $\psi \in [0, 2\pi]$. Figures 13 and 14 show the probability of capture and resulting semi-major axes as functions of v_∞ and r_p for the larger and smaller binary members. The trends seen in these plots agree with those seen in the previous section. Thus, treating the larger binary member as an extended body has little effect on capture.
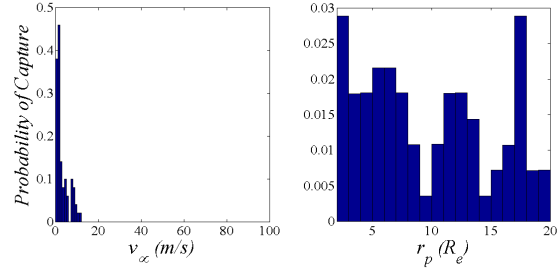

Figure 13: Probability of Capture of Larger Asteroid Candidate with Extended Body
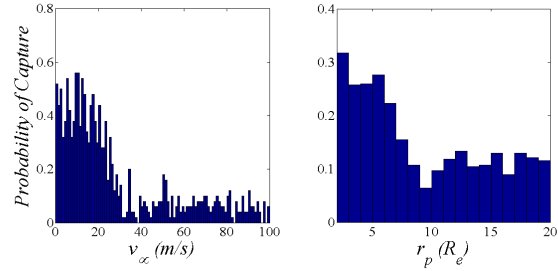

Figure 14: Probability of Capture of Smaller Asteroid Candidate with Extended Body
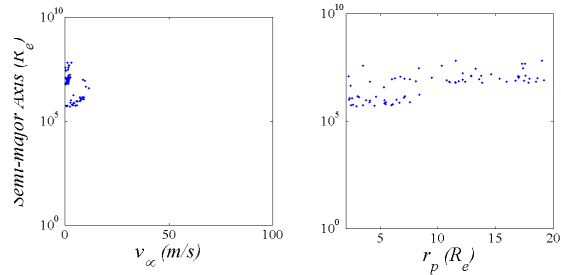

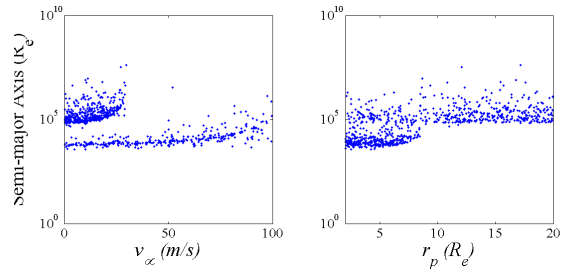Figure 15: Resulting Semi-major axis of Larger Asteroid Candidate with Extended Body

Figure 16: Resulting Semi-major axis Smaller Asteroid Candidate with Extended Body

8   Effects of the Moon

50,000 two dimensional simulations were also conducted with the effect of the moon included. When the binary asteroid did not have a close approach with the moon, the moon caused a small change in the phase of the binary asteroid as it passed by the Earth. Capture is very sensitive to this phase, however the effect of the moon did not change the overall statistical data presented earlier when the binary asteroid did not have a close approach with the moon. Figures 17 and 18 show the probability of capture as functions of v_∞ and r_p for the larger and smaller asteroids with the effects of the moon included.
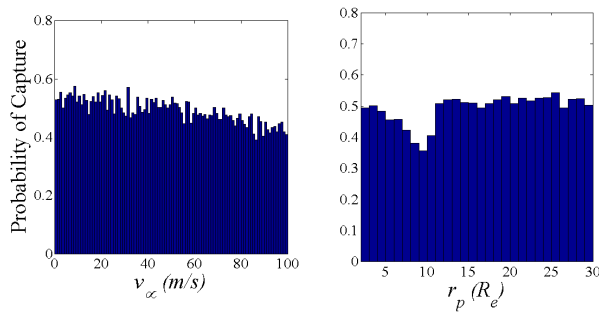

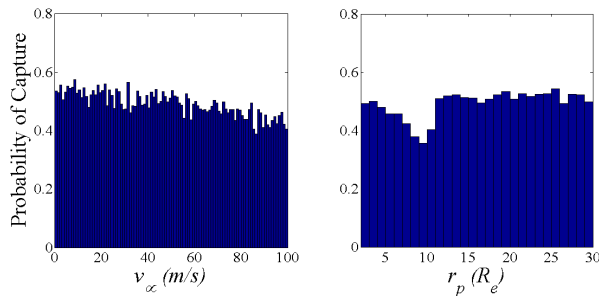Figure 17: Probability of Capture of Larger Asteroid Candidate with Moon

Figure 18: Probability of Capture of Smaller Asteroid Candidate with Moon

When the asteroid did have a close approach with the moon, the moon had an outstanding effect on the binary asteroid pair. The asteroids that had close approaches to the moon were sometimes captured on orbits contained within the Earth's Hill sphere. In some instances, the binary was not disrupted, and both members were captured on permanent orbits within the Hill sphere. Other

simulations in which the binary asteroid had a close approach with the moon did not result in capture. This phenomenon resulted in much higher probabilities of capture over the ranges of v_∞ and r_p. Further investigation must be undertaken to fully understand this moon assist phenomenon. The captured, but undisturbed binary asteroid result suggests that this mechanism could also work for a single asteroid. Figures 19 and 20 show the resulting semi-major axis of captured members as functions of v_∞ and r_p for the larger and smaller asteroids.
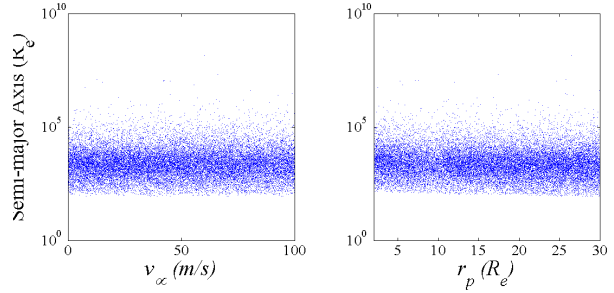

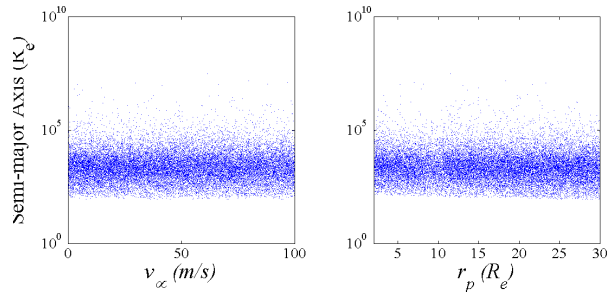Figure 19: Resulting Semi-major axis of Larger Asteroid Candidate with Moon

Figure 20: Resulting Semi-major axis Smaller Asteroid Candidate with Moon

9   Conclusions

A parametric study of binary-Earth encounters was conducted, and the results showed that the total binary mass and the approach velocity were the two dominant parameters affecting capture. This led to the choice of 1999 HF1 as a candidate near-Earth binary asteroid for capture, due to its large mass. Simulations with the candidate asteroid showed that while capture is possible, it only occurred at low v_∞, and the resulting orbits extend beyond the Earth's Hill sphere. Non-near-Earth binary asteroids with larger masses than the candidate asteroid

could be captured within the Hill sphere. Treating the larger member of the candidate binary as an extended body had little effect on capture. Including the moon in the simulations allowed for capture within the Hill sphere when the binary asteroid had a close approach with the moon. Future work could be directed toward understanding this moon assist phenomenon and applying it to a single near-Earth asteroid. Work could also be done on the feasibility of steering a non-near-Earth binary asteroid onto an orbit with a close approach with the Earth.

10   <u>Acknowlededgments</u>

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