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Capturing near-Earth asteroids around Earth

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ABSTRACT

The list of detected near-Earth asteroids (NEAs) is constantly growing. NEAs are likely targets for resources to support space industrialization, as they may be the least expensive source of certain needed raw materials. The limited supply of precious metals and semiconducting elements on Earth may be supplemented or even replaced by the reserves floating in the form of asteroids around the solar system.

Precious metals make up a significant fraction NEAs by mass, and even one metallic asteroid of ~ 1 km size and fair enrichment in platinum-group metals would contain twice the tonnage of such metals already harvested on Earth. There are ~ 1000 NEAs with a diameter of greater than 1 km. Capturing these asteroids around the Earth would expand the mining industry into an entirely new dimension. Having such resources within easy reach in Earth's orbit could provide an off-world environmentally friendly remedy for impending terrestrial shortages, especially given the need for raw materials in developing nations.

In this paper, we develop and implement a conceptually simple algorithm to determine trajectory characteristics necessary to move NEAs into capture orbits around the Earth. Altered trajectories of asteroids are calculated using an ephemeris model. Only asteroids of eccentricity less than 0.1 have been studied and the model is restricted to the ecliptic plane for simplicity. We constrain the time of retrieval to be 10 years or less, based on considerations of the time to return on investment. For the heliocentric phase, constant acceleration is assumed. The acceleration required for transporting these asteroids from their undisturbed orbits to the sphere of influence of the Earth is the primary output, along with the impulse or acceleration necessary to effect capture to a bound orbit once the Earth's sphere of influence is reached. The initial guess for the constant acceleration is provided by a new estimation method, similar in spirit to Edelbaum's. Based on the numerically calculated trajectories, 23 asteroids are recommended for future consideration for capture missions, provided necessary technological developments are made.

1. Introduction

1.1. Motivation

Asteroid mining is a concept that involves the extraction of useful materials from asteroids. Due to their accessibility, near-Earth asteroids (those asteroids that pass near the Earth, also known as NEAs) are a particularly accessible subset of the asteroids that provide potentially attractive targets for resources to support space industrialization. NASA's Jet Propulsion Laboratory maintains a database of NEAs, consisting of approximately 7900 asteroids [1] (at the time of this study).

Many materials could be extracted and processed from NEAs which are useful for propulsion, construction, life support, agriculture, metallurgy, semiconductors, and precious and strategic metals [2,3]. Volatiles such as hydrogen

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and methane could be used to produce rocket propellant to transport spacecraft between space habitats, Earth, the Moon, the asteroids, and beyond. Rare-Earth metals could be used to manufacture structural materials as well as solar photovoltaic arrays which could be used to power space or lunar habitats. These solar cells could also be used in a constellation of solar power satellites in orbit around the Earth in order to provide electrical power for its inhabitants [4]. Precious metals such as platinum, platinum-group metals (PGMs), and gold are also available. NEAs are understood to consist largely of nickel–iron ore and smaller proportions of precious metals among other constituents [5–7].

Furthermore, the environmental hazards associated with existing mining methods are posing ethical issues to all communities. Earth's deposits of raw materials may be supplemented by those mined from captured asteroids. The idea of capture itself is not entirely artificial as some planetary satellites are believed to be captured naturally, e.g., Neptune's moon Triton is believed to be a Kuiper belt object [8]. Jupiter may have also captured asteroids naturally [9].

The advantages of studying capture mechanics of NEAs are not limited to the mining industry. Space-based commerce may develop within the next few decades, including manufacturing, solar power stations, and space tourism. There is interest in space-based production of high value pharmaceuticals, semiconductors, ultra-pure crystals for many applications, and generally anything requiring large-scale material purity. The feasibility of space tourism is also being promoted. Market research in the United States, Japan, Canada and Germany has shown that as many as 80% of people younger than 40 would be interested in commercial space travel. A majority would be willing to pay up to three months' salary for the privilege. Ten percent would pay a year's salary [10]. Space development would be immensely facilitated by having a source of raw materials already in space. The cost of launching matter from Earth to space is a major limiting factor currently.

1.2. Current technology

Technological developments will be needed for successfully maneuvering asteroids. Even though work has been done to model capture using low cost methods [11,12], further advancements in low-thrust technology would greatly expand mission capabilities. Fig. 1 shows the increase in thrust capability over the last few decades

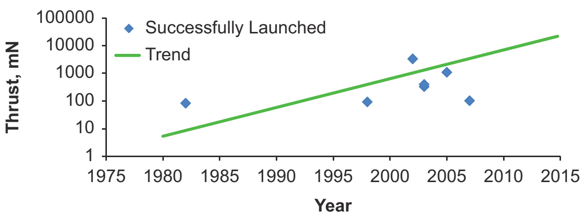

Fig. 1. Progress of thrust capability over the past few decades [17–26]. Note the scale is in milli-Newtons.

Table 1
Thrust technologies [17–26].

Engine	Propellant	Thrust (mN)	Year
SPT-100	Hall	83	1982
NSTAR	Xenon	92	1998
NASA-457M	Xenon	3300	2002
NEXT	Xenon	327	2003
NEXIS	Xenon	400	2003
HiPEP	Xenon	460–670	2003
BHT-1500	Hall	102	2005
VASIMR	Argon	~5000	2006
RIT 22	Xenon	50–200	2007
BHT-20k	Hall	1080	2007

as technological advancements (Table 1) have been made. Thus far, ion thrusters have been at the center of most thrust applications in space. Both ion thrusters and liquid rockets have been successfully used in space missions. These engines provide thrust on the order of 10 N. Stronger engines, e.g., magnetoplasmadynamic thrusters which take advantage of the Lorentz force, have been tested in laboratories for thrust up to 200 N [13–16].

The current work does not set a limit on the thrust required for asteroid capture. Instead, a minimum thrust is suggested, based solely on orbital mechanics and measured asteroid orbital parameters.

1.3. Capture of asteroid into stable Earth orbit

Significant work has been done to deter and deflect hazardous asteroids and other spatial bodies (e.g., [27]). On the other hand, our work is part of a growing body of literature (e.g., [11,12]) to consider the energetics and acceleration requirements to *capture* an asteroid into a stable orbit around the Earth. The present work focuses on using 2-body and 3-body dynamics, along with low-thrust acceleration or impulsive ΔV maneuvers, to capture an NEA into a stable orbit around the Earth. In order to do so, an acceleration term has been introduced to the 2-body and 3-body equations of motion. This capture acceleration works to maneuver the asteroid until it enters the Earth's sphere of influence. Upon entering the sphere of influence of the Earth, two different methods of capturing the asteroid have been studied. First, an impulsive force method is studied, which provides an instantaneous change in velocity required for capture. The second method approximates the continuous acceleration required over a period of time to capture the asteroid. The only fixed parameter in the study is selected to be the maximum time required from rendezvous to capture. Based on the general principle of a timely return on an investment, the maximum capture time is set to be 10 years.

The results of the asteroid transfer trajectory calculations (described in Sections 2 and 4) are summarized in Table 2. Twenty-three asteroids are suggested as candidates for capture using an impulsive force in the second stage of the capture sequence. Fourteen of the asteroids have an inclination separation with the Earth of less than 10°.

Table 2
Captured asteroid data.

Designation	Stage 1			Stage 2						
	LTA$_1$[a] (μm/s^2)	Size[b] (m)	Thrust$_1$[c] (kN)	Δi (deg)	TOF[d] (year)	ΔV[e] (m/s)	q/r_m[f]	LTA$_2$[g] (mm/s^2)	Thrust$_2$[h] (kN)	v_∞[i] (km/s)
MIN	4	10	0.025	4.5	2.3	700	0.086	0.18	0.54	1.2
MAX	20	887	9000	17	9.1	4900	3	6.7	547 000	6.3
1999 RA32	20	226	360	17	2.3	2300	0.53	1.8	32 300	3.3
2008 CX118	16	45	2	9.1	2.5	1500	0.11	0.51	73	1.7
2006 BZ147	18	28	1	8.1	2.5	4900	0.34	6.7	230	6.3
2010 KJ37	13	56	4	15	2.8	2500	0.87	1.9	520	3.3
1999 SO5	15	172[j]	130	9.5	3.5	810	1.8	0.33	14 000	1.4
2008 CD70	16	10[j]	0.025	7.6	3.5	2300	0.53	1.8	0.54	3.3
2007 CB27	15	62[j]	6	12	3.6	700	0.64	0.18	69	1.2
2001 QJ142	4	71	2	4.8	4.2	2600	1.3	1.9	1100	3.3
2008 BT2	16	47	3	4.5	4.3	2100	2.8	1.6	260	2.7
2009 OS5	13	60	4	6.4	4.5	3800	1.5	3.8	1300	4.6
1993 HD	14	30	1	7.6	4.7	1900	0.2	1.3	53	2.8
2008 PG2	11	80	9	16	4.8	780	1.9	0.28	220	1.3
2006 HC	5.3	20[j]	0.066	15	5.4	1900	1.2	1.1	14	2.6
2008 SV150	9.1	14[j]	0.043	15	5.5	1200	0.44	0.6	2.8	1.9
2004 EO20	12	106[j]	22	12	5.6	1600	1.8	0.89	1700	2.2
2011 BO40	15	61[j]	6	13	5.6	1600	0.4	0.96	340	2.4
2002 NW16	8.2	887	9000	9	6.3	910	3	0.5	547 000	1.5
1999 YB	15	558[j]	4100	12	6.3	1700	0.37	1.2	327 000	2.6
2001 AE2	19	415[j]	2100	8.6	6.4	3500	1.1	3.1	349 000	4.3
1999 LP28	11	277[j]	360	9.7	6.7	2900	1.7	2.5	84 000	3.6
2010 VB72	12	185[j]	120	9.9	7.2	1800	0.086	0.65	6500	2.0
2003 SM84	7.6	100	12	6.1	8.3	3700	0.65	3.7	5900	4.7
1996 XB27	10	150	54	7.7	9.1	3200	1.3	2.8	15 000	4.0

[a] LTA$_1$ is the low thrust acceleration for stage 1.
[b] Estimated diameter of asteroids [28–31].
[c] Estimated thrust for stage 1.
[d] Total time-of-flight for capture for both stages.
[e] Instantaneous change in velocity.
[f] Radius of perigee divided by radius of Moon's orbit.
[g] LTA$_2$ is the low thrust acceleration for stage 2.
[h] Estimated thrust for stage 2.
[i] Velocity upon entering Earth's sphere of influence.
[j] Estimated using absolute magnitude data and approximate albedo of 0.25. See Eq. (7).

2. Mathematical model

Transfer trajectories from asteroids' current orbits to Earth rendezvous are calculated in an ephemeris model (including the location of the Sun, Earth and Moon), given the initial conditions at the time of perihelion of the asteroid of interest. Due to the purely conceptual nature of the work, certain approximations are made. Firstly, a two-dimensional system where only the components of the orbit that are in the reference plane are considered, thereby neglecting the third dimension, but since $\Delta i < 10^\circ$, the planar approximation was considered reasonable as a first-order approximation. The other major approximation is the number of bodies that are considered in the model. When the asteroids are far from the Earth, the model is set up as a two-body problem consisting of the Sun and the asteroid. When the asteroid approaches the Earth's sphere of influence, the model is changed to a three-body problem to include the Earth's influence. This is related to the standard 'patched-conics' assumption [32]. With the masses and relative speeds involved in the problem, this approximation is close enough to introduce minimal error, and we need not consider the more accurate, but more complex, patched three-body approximation [33].

Newton's second law is used to determine the equation of motion of the asteroid effected by the bodies of interest, given at their ephemeris-based locations. Considering both the x and y components in a Sun-centered inertial frame, the differential equations of motion in first-order form are

$$\dot{x} = v_x$$

$$\dot{y} = v_y$$

$$\dot{v}_x = -\mu_s (x^2+y^2)^{-3/2} x + a_x$$

$$\dot{v}_y = -\mu_s (x^2+y^2)^{-3/2} y + a_y \tag{1}$$

where x and y indicate the position of the asteroid in a heliocentric reference frame and $\mu_s = GM_s$, where G is the gravitational constant and M_s is the mass of the Sun. The variables a_x and a_y are functions of position that represent the acceleration profile that is applied to the asteroid. These equations can be solved with initial conditions for both the x and y components of position and velocity of the asteroid. To obtain Cartesian position and velocity components from orbital elements, we use the usual transformations (see, e.g., [32]).

When the three-body problem is necessary the equations of motion for the Earth are the same as the equations for the asteroid in (2). The equations of motion for the asteroid including the effects of the Earth's gravitation are

$$\dot{x} = v_x$$

$$\dot{y} = v_y$$

$$\dot{v}_x = -\mu_s(x^2+x^2)^{-3/2}x + a_x - \mu_e\{(x-x_E)^2+(y-y_E)^2\}^{-3/2}(x-x_E)$$

$$\dot{v}_y = -\mu_s(x^2+x^2)^{-3/2}y + a_y - \mu_e\{(x-x_E)^2+(y-y_E)^2\}^{-3/2}(y-y_E) \quad (2)$$

where (x_E,y_E) indicates the position of the Earth. Our concern will be to estimate the magnitude of the acceleration profile $a(t) = \|\mathbf{a}(t)\|$ required to capture asteroids within 10 years.

3. Order of magnitude approximation

A method for approximating the thrust acceleration is developed, which assumes near-circular, co-planar orbits, a constant rate of radial velocity, and only considers the gravitational force of the Sun (see Appendix A). This method of approximation is based on energy balance. The resulting acceleration is

$$a_{circ} = \frac{\sqrt{\mu_s}}{t_f}\left(\frac{1}{r_i} - \frac{1}{r_f}\right)\frac{(r_f - r_i)}{4(\sqrt{r_f} - \sqrt{r_i})} \quad (3)$$

where r_i and r_f are the initial and final semimajor axes, respectively (and we considered the case $r_f > r_i$).

We note that the Edelbaum approximation for low-thrust orbits [34] can also be used to formulate an order of magnitude approximation of the thrust acceleration required to capture the asteroids. We discuss this approximation in Appendix B. This approximation is also valid only for near-circular orbits, but assumes constant acceleration, constant thrust yaw angle, and takes account of orbital inclination,

$$a_{edel} = \frac{\sqrt{\mu_s}}{t_f}\sqrt{\frac{1}{r_i} + \frac{1}{r_f} - \frac{2\cos\left(\frac{\pi}{2}\Delta i\right)}{\sqrt{r_f r_i}}} \quad (4)$$

which is correct, ignoring factors of order 2 or higher in the eccentricities of the initial and final orbit. For co-planar orbits, $\Delta i = 0$, and this reduces to

$$a_{edel} = \frac{\sqrt{\mu_s}}{t_f}\left(\frac{1}{\sqrt{r_i}} - \frac{1}{\sqrt{r_f}}\right) \quad (5)$$

Note that both (3) and (5) converge to the same value,

$$a \to \frac{\sqrt{\mu_s}}{2t_f r_i^{3/2}}\Delta r \quad (6)$$

in the limit of small changes $\Delta r = r_f - r_i$.

Due to the assumptions of these approximations, only asteroids of heliocentric eccentricity less than 0.1 are considered. Fig. 2 shows the thrust accelerations for the 130 asteroids with such an eccentricity. For a fixed t_f of 10 years, the approximation methods in (3) and (4) yield typical accelerations on the order of $0.1-100\ \mu m/s^2$. This range provides us with a baseline for initial guesses for appropriate thrust accelerations. In higher fidelity numerical integrations, described in a later section, we found accelerations in the range $4-20\ \mu m/s^2$.

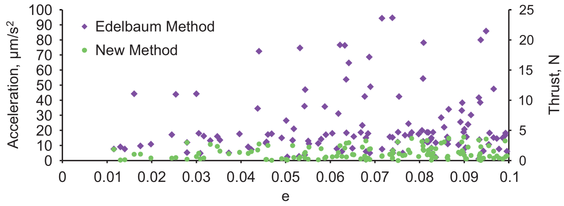

Fig. 2. One hundred and thirty asteroids whose eccentricity is less than 0.1 are shown here with their approximate thrust acceleration required to enter the Earth's heliocentric orbit calculated from (3) and (4). Assuming an average radius of 2.67 m, and density $\rho = 3000\ kg/m^3$, the estimated thrust force is shown on the right hand side.

In the comprehensive list of NEAs, there are only 108 asteroids whose size has been calculated. The asteroid radius ranges from 0.03 to 31.7 m, with an average of 2.67 m. It must be noted that these are only the asteroids whose radius is known with great confidence; there may exist larger asteroids. Using the average radius and assuming a density of $3000\ kg/m^3$ and a spherical shape, average asteroid mass is approximated to be 239,000 kg. Using this average mass and the approximated capture acceleration from (4), the average force requirements are calculated and shown on the right hand side of Fig. 2. The thrust forces and accelerations in Fig. 2 are those required to transport an asteroid from its existing heliocentric orbit into the Earth's heliocentric orbit, without considering phasing. The thrust force ranges from 0.1 to 25 N.

For the list of final candidate asteroids in Table 1, only some have known estimated sizes. Consequently, the other asteroids' diameters are calculated [35] using absolute magnitude h and albedo p as

$$D = \frac{1329}{10^{0.2H}\sqrt{p}}\ \text{km} \quad (7)$$

Although absolute magnitude values are known, the albedo values are approximated as 0.25.

4. Computational results

The capture strategy is broken up into two separate stages. Stage 1 is a continuous low thrust approach to transport the asteroid to a rendezvous with the Earth's sphere of influence. Stage 2 is to create a stable orbit around the Earth after the rendezvous. We choose a constant acceleration thrust that is opposite to the velocity due to its simplicity and its efficiency in changing heliocentric orbital radius. An example profile of this kind operating for 10 years on asteroid 2001 QJ142 is shown in Fig. 3, with a large exaggerated magnitude to illustrate the effect.

Increasing the magnitude of the acceleration makes it more difficult to physically implement the profile but also decreases the time from the start of the profile to rendezvous with the Earth.

It is important to make sure that the asteroid not only intersects the Earth's orbit, but also has the same heliocentric true anomaly as the Earth when it gets within the sphere of influence of the Earth. We measure the difference in the true anomaly using the angle ϕ, shown in Fig. 4. The phase angle ϕ is the absolute value of the difference in the anomaly of the Earth and the anomaly of the asteroid. The Earth's sphere of influence extends to a radius of approximately 0.01 AU, which means the angular width of the sphere of influence of the Earth can be approximated by a ϕ value of 1°.

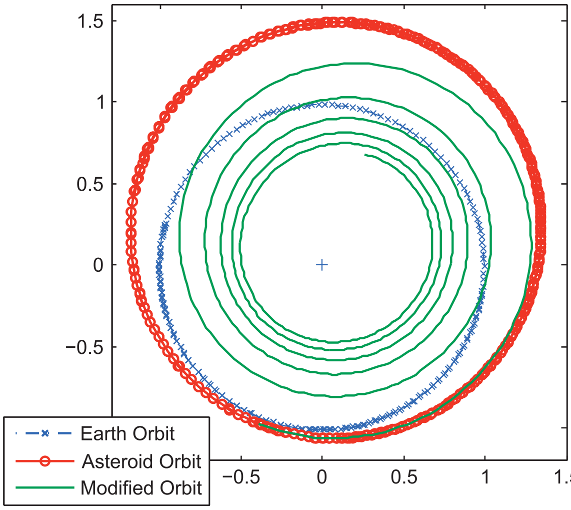

Fig. 3. Result of an exaggerated acceleration profile on asteroid 2001 QJ142. The original asteroid orbit is shown, as well as the hypothetical transfer trajectory, and the Earth's orbit.

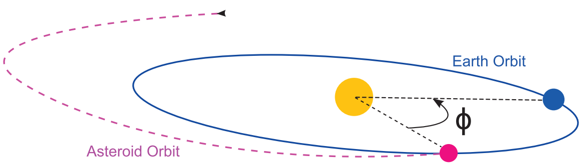

Fig. 4. The phase angle upon the asteroids intersection of the Earth's orbit.

The 130 asteroids with eccentricity less than 0.1 are used in the simulation. Of these, due to the two-dimensional assumption of the model, the separation between the orbital planes of the asteroid and Earth, Δi, needs to be small, where Δi is defined in (B.4). For each of these asteroids the optimal acceleration is determined by minimizing the value of ϕ (the value for ϕ is only calculated when the asteroid comes within the radius of the Earth). To determine the optimal acceleration, the asteroid's equation of motion is solved over the set of accelerations ranging from 2 to 20 $\mu m/s^2$. The acceleration resulting in the minimum ϕ (as long as $\phi < 1^\circ$) is recorded as LTA_1 in Table 2 and corresponding flight time, or 'time of interception' is also recorded; once the stage 2 flight time is determined (see below), the sum is given as the total time-of-flight, TOF. For instance, in Fig. 5, we show the ϕ and time of interception for asteroid 2003 SM84.

Of note is the discontinuity where ϕ drops from approximately 70° to 35° in Fig. 5 (right panel). The jump in ϕ can be explained by studying the acceleration versus time of interception plot which also contains a discontinuity at the same acceleration magnitude. The discontinuity exists due to the eccentricity in the orbit of the asteroid and is the point where the asteroid has to make an entire additional revolution around the Earth before intercepting the Earth's orbit again.

The phase angle is calculated as a function of acceleration for each of the asteroids and the minimum phase angle is determined. Once the asteroid has rendezvoused with the Earth, stage 2 of the capture is initiated. After entering the Earth's sphere of influence, the asteroid's velocity needs to be adjusted in order to create a stable orbit around the Earth. If the asteroid is to continue traveling at its rendezvous velocity, it would most likely not be captured by the Earth. Instead, the asteroid would simply be slingshot back into a different heliocentric orbit.

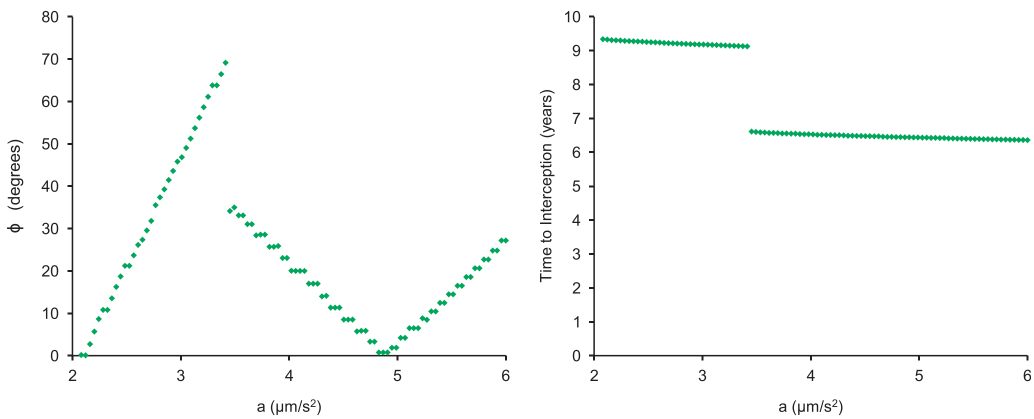

Fig. 5. (left) ϕ vs. acceleration a; (right) time of interception vs. acceleration a.

Two approaches for transforming the asteroid's heliocentric orbit into a captured geocentric orbit (i.e., stage 2) are considered. Firstly, an impulsive force could be applied at a critical moment causing the transformation in the orbit. A second approach is to use low thrust applied by a continuous acceleration, as in stage 1.

4.1. Capture—impulsive method

The first method is a simple approach that determines an instantaneous change in velocity that would effect a capture to a bound geocentric circular orbit. The necessary ΔV is executed at q, the close approach distance of the asteroid with the Earth. An example of the capture of asteroid 2008 PG2 using a two-stage method (low-thrust heliocentric stage and impulsive geocentric stage) is shown in Fig. 6.

If a stage 1 acceleration of 11 $\mu m/s^2$ had been applied on 2008 PG2 starting in January 2010, it would rendezvous with the Earth in October 2014, 4.8 years later. The asteroid would be brought within $\sim 0.1^\circ$ of the Earth, well within the sphere of influence of the Earth. Subsequently, a $\Delta V = 780$ m/s impulse at perigee would circularize the asteroid's hyperbolic trajectory with respect to the Earth, thereby rendering it captured.

As a second example, in Fig. 7 we show the capture of 1999 RA32, the 'best' candidate in terms of rapid return—a stage 1 acceleration of 20 $\mu m/s^2$ would lead to Earth rendezvous in 2.3 years. A subsequent perigee ΔV of 2300 m/s would circularize the orbit to roughly half the Moon's semimajor axis. Note that since the incoming trajectory crosses the orbit of the Moon, with proper timing a flyby with the Moon can be used to provide the ΔV and thus effect a ballistic capture (without propulsion) [36,37]. In fact, for any asteroid considered, the Stage 1 trajectory can be adjusted to target a desired perigee distance $q < r_m$ such that a Moon flyby can be used to effect a ballistic capture.

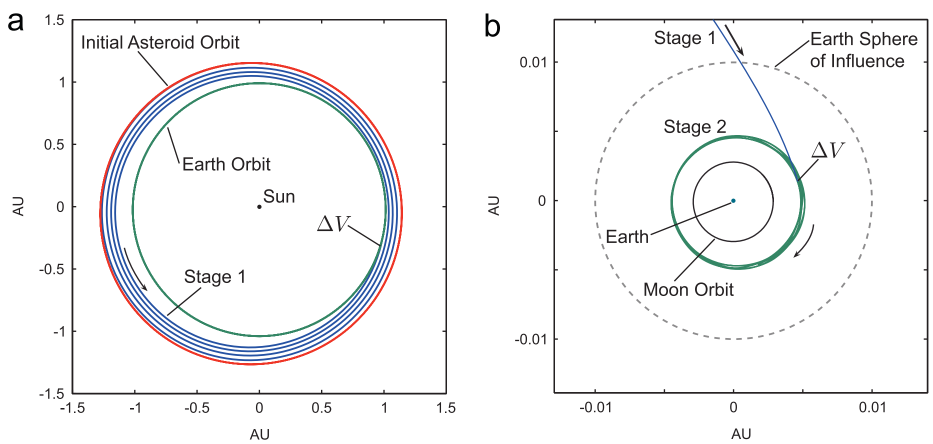

Fig. 6. Simulation of two stage capture of 2008 PG2. (a) The heliocentric stage, stage 1, requires an acceleration of 11 $\mu m/s^2$ over 4.8 years to bring the asteroid into rendezvous with the Earth. Sun-centered inertial frame is shown. (b) For the geocentric stage, stage 2, a $\Delta V = 780$ m/s impulse captures the asteroid around the Earth. Earth-centered inertial frame is shown.

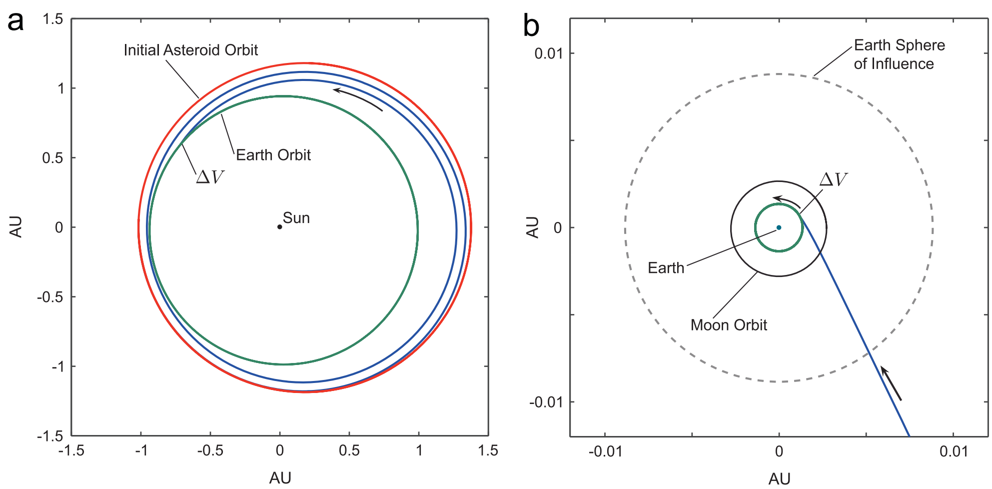

Fig. 7. Simulation of two stage capture of 1999 RA32. (a) The heliocentric stage, stage 1, requires an acceleration of 20 $\mu m/s^2$ over 2.3 years to bring the asteroid into rendezvous with the Earth. Sun-centered inertial frame is shown. (b) For the geocentric stage, stage 2, a $\Delta V = 2300$ m/s impulse captures the asteroid around the Earth. Earth-centered inertial frame is shown.

4.2. Capture—low-thrust, constant acceleration method

The acceleration requirements for the orbit transformation are derived using the energy balance method. The total Keplerian energy per unit mass (with respect to the Earth) for an asteroid at the point that it enters the Earth's sphere of influence is

$$\frac{\Delta E}{m} = \frac{1}{2}v_\infty^2 - \frac{\mu_E}{r_{SOI}} > 0 \tag{8}$$

where r_{SOI} is the radius of the Earth's sphere of influence, ~ 0.01 AU, μ_E is the gravitational constant times the mass of the Earth; and v_∞ is the excess hyperbolic velocity of the asteroid in the geocentric frame upon entering the sphere of influence (which is far enough from Earth to count as 'infinity'). A positive energy indicates a hyperbolic geocentric trajectory. The energy must be decreased below zero in order to ensure an elliptical orbit around the Earth. The capture acceleration required to remove the excess energy above zero, ΔE, is derived as follows.

Based on its orbital elements at the moment of entering the Earth's sphere of influence, we can calculate the time ΔT that the hyperbolic trajectory would spend inside the Earth's sphere of influence. Let us consider that v_∞ is representative of the velocity of the asteroid during that time. With the thrust acceleration a_{cap} opposite to the velocity, the power performed by the thrust, $\mathbf{F}_T \cdot \mathbf{v}$, is approximately $-ma_{cap}v_\infty$. To decrease the Keplerian energy by ΔE during ΔT, we need $\Delta E/\Delta T = ma_{cap}v_\infty$. Thus, an (over)estimate of the acceleration needed to effect capture is

$$a_{cap} = \left(\frac{1}{2}v_\infty^2 - \frac{\mu_E}{2r_{SOI}}\right)\frac{1}{\Delta T v_\infty}. \tag{9}$$

Fig. 8 shows the ΔT and corresponding calculated a_{cap} for the NEAs considered. For the asteroids considered, ΔT was on the order of 10 days while a_{cap} was on the order of 1 mm/s^2.

Because the amount of time spent by these asteroids in the Earth's sphere of influence is on the order of weeks, a low thrust acceleration method may be warranted. However, for an asteroid of density 3000 kg/m^3, a 1 mm/s^2

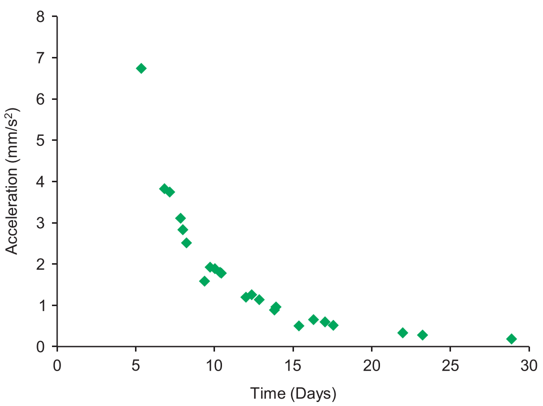

Fig. 8. The minimum acceleration required to transform the asteroid's orbit from heliocentric to geocentric orbits.

acceleration requires a thrust of

$$F_T \approx \left(\frac{R}{1\ \text{m}}\right)^3 12\ \text{N} \tag{10}$$

Thus, an asteroid of the average known radius 2.67 m would require a thrust of ~ 200 N, right at the edge of low-thrust capability currently in development (Fig. 1). Any significantly larger asteroid would require significant advancement in low-thrust propulsion technology.

5. Conclusions

The purpose of this paper was two-fold. First, we estimate the accelerations and impulsive changes which would be needed to direct a near-Earth heliocentric asteroid to an Earth close encounter—with a perigee well within the Earth's Hill sphere—through planar, ephemeris-based trajectory computations. Second, we developed an order-of-magnitude thrust acceleration estimate for both the heliocentric phase and geocentric capture phase. The algorithm developed was restricted to asteroids (i) with near-circular (eccentricities < 0.1), (ii) which come close to the Earth's orbit, (iii) have an orbital plane separation angle of 1°. Twenty-three asteroids which could be returned in 10 years are suggested as candidates for transfer from a heliocentric orbit to Earth encounter. Fourteen of the asteroids have an inclination separation with the Earth of less than 10°. The data for their capture is summarized in Table 2. The stage 1 acceleration ranged from 2 to 20 μm/s^2 and led to stage 2 impulses ranging from 700 to 4900 m/s. Stage 1 thrusts are more achievable from a technological standpoint. The stage 2 low thrust approximation simulations resulted in asteroids spending $\sim 1-3$ weeks within the sphere of influence of the Earth. During this time period, the asteroids could potentially be captured by continuous accelerations of magnitudes up to 6.7 mm/s^2, which may be problematic if the same propulsion system as stage 1 is used as this is three orders of magnitude higher than the stage 1 acceleration.

The present study demonstrates that the prospect of capturing NEAs is promising as both the timescale and forces required for capture are reasonable considering advancements in technology. The motivation was to come up with a 'short list' of asteroids that merit such further computations and consideration. The results obtained using a simplified model provide a set of asteroids on which future studies can focus using a higher fidelity models, incorporating, e.g., three-dimensional motion, all bodies of known gravitational influence, as well as other effects.

Appendix A. Estimate of acceleration based on energy balance

The energy required for getting an asteroid from one known orbit to another known orbit can be calculated using conservation of energy. The assumptions for this approximation are as follows:

1. The orbit is approximately a circular orbit about a central body throughout the motion.
2. The radius of the orbit changes at a uniform rate.

3. The force due to thrust is directed opposite to the asteroid's velocity.

The first assumption simplifies the equation of the velocity of the orbit to

$$v^2 = \frac{\mu}{r} \tag{A.1}$$

where v is the average velocity of the orbit, $\mu = GM$, G is the gravitational constant, M is the mass of the central body, and r is the radius of the circular orbit.

The second assumption allows the time differential to be expressed in terms of the radius differential:

$$dt = \frac{t_f}{r_f - r_i}\, dr \tag{A.2}$$

The work done to a system can be evaluated as the integral of the power of the system. Conservation of energy requires this value be equal to the sum of the change in the total energy (kinetic plus potential).

$$\int_0^{t_f} \mathbf{F}_T \cdot \mathbf{v}\, dt = \frac{1}{2} m (v_f^2 - v_i^2) - m\mu \left(\frac{1}{r_f} - \frac{1}{r_i} \right) \tag{A.3}$$

where $\mathbf{F}_T$ is the thrust force required to move the asteroid, m is the mass of the asteroid, and according to the third assumption, $\mathbf{F}_T = -F_T \hat{v}$. When Eqs. (A.1) and (A.2) are plugged into Eq. (A.3), and the integral is taken, the result is, as

$$F_T = m \frac{\sqrt{\mu}}{t_f} \left(\frac{1}{r_i} - \frac{1}{r_f} \right) \frac{(r_f - r_i)}{4(\sqrt{r_f} - \sqrt{r_i})} \tag{A.4}$$

The required acceleration may be determined by dividing Eq. (A.4) by the mass of the asteroid, m, yielding (3).

Appendix B. Estimate of acceleration based on Edelbaum's approximation

For an object in an eccentric orbit, the average orbital speed can be approximated as [38]

$$v_{ave} = \frac{2\pi a}{T} \left[1 - \frac{e^2}{4} - \frac{3e^4}{64} + \mathcal{O}(e^6) \right] \tag{B.1}$$

where the period of the orbit is

$$T = 2\pi \frac{a^{3/2}}{\mu^{1/2}} \tag{B.2}$$

and $\mu = GM$ is the gravitational parameter of the central mass M. So v_{ave} becomes

$$v_{ave} = \sqrt{\frac{\mu}{a}} \left[1 - \frac{e^2}{4} - \frac{3e^4}{64} + \mathcal{O}(e^6) \right] \tag{B.3}$$

The difference in inclination angle between an initial and final orbit is given by

$$\Delta i = \cos^{-1} \left[\frac{\mathbf{L}_i \cdot \mathbf{L}_f}{\|\mathbf{L}_i\| \|\mathbf{L}_f\|} \right] \tag{B.4}$$

where $\mathbf{L} = \mathbf{r} \times \dot{\mathbf{r}}$ is the angular momentum per unit mass.

For two eccentric orbits, we can use the average velocity values for the initial and final orbits, v_i and v_f, respectively, into Edelbaum's equation (see, e.g, [34]),

$$\Delta V_{edel} = \sqrt{v_i^2 + v_f^2 - 2 v_i v_f \cos\left(\frac{\pi}{2} \Delta i \right)}. \tag{B.5}$$

If this ΔV is delivered via a constant acceleration a_{edel} during a time of flight t_f, the approximate acceleration is

$$a_{edel} = \frac{\Delta V_{edel}}{t_f} \tag{B.6}$$

We can rewrite this using r_i and r_f as the initial and final semimajor axes, respectively, and e_i and e_f as the initial and final eccentricities, respectively,

$$a_{edel} = \frac{\sqrt{\mu_s}}{t_f} \sqrt{ \frac{1}{r_i} \left[1 - \frac{e_i^2}{4} + \mathcal{O}(e_i^4) \right] + \frac{1}{r_f} \left[1 - \frac{e_f^2}{4} + \mathcal{O}(e_f^4) \right] - \frac{2\cos\left(\frac{\pi}{2}\Delta i\right)}{\sqrt{r_f r_i}} \left[1 - \frac{1}{8}(e_i^2 + e_f^2) + \mathcal{O}(e_i^4) + \mathcal{O}(e_f^4) + \mathcal{O}(e_i^2 e_f^2) \right] } \tag{B.7}$$

where all the small terms are of order 4 or larger in the eccentricities. If one ignores terms of order 2 or larger in the eccentricities, one obtains (4).

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