Preliminary Asteroid Deflection Mission Design for 2017 PDC Using Neutral Beam Propulsion

Anthony J. DeCicco*
Clark School of Aerospace Engineering
University of Maryland- College Park
College Park, MD 20742
adecicco@terpmail.umd.edu

Christine M. Hartzell†
Clark School of Aerospace Engineering
University of Maryland- College Park
College Park, MD 20742
hartzell@umd.edu

Robert B. Adams‡
NASA Marshall Spaceflight Center
Huntsville, AL 35812

Kurt A. Polzin‡
Senior Member; IEEE
NASA Marshall Spaceflight Center
Huntsville, AL 35812

Abstract—**The surprise Chelyabinsk air burst event in 2013 that caused significant building damage and injuries demonstrated to the public that there is a near-term pressing need to develop a robust portfolio of asteroid deflection techniques that can be applied to asteroids with varying size, spectral type, and time until impact. The neutral beam for asteroid control (NBAC) technology is a globally neutral plasma thruster that seeks to fill the operational gap between high impulse and slow push asteroid deflection methods. It is unlike other propulsive methods in that it does not tether to the asteroid or expel charged ion beams. Additionally, NBAC can be used to modify both the spin state and trajectory of an asteroid. In this work, NBAC's performance is discussed for a range of asteroid sizes and spectral types for de-spin and deflection using the orbit of the hypothetical asteroid 2017 PDC. The analysis assumes that several NBAC-equipped spacecraft are deployed, each with 10 keV neutral beam emitter. The achieved deflection and the applicability of NBAC to a deflection campaign is presented. Calculations for achieved deflection are done using the General Mission Analysis Tool with gravitational perturbations from major bodies included. Loss of a spacecraft during deflection and its effect on mission success is also investigated. One major requirement in this work is adaptability of the NBAC-based concept to deflection campaigns where the asteroid has not been fully characterized. This work demonstrates how uncertainty in asteroid composition is factored into propellant and deflection time requirements for NBAC. Assuming one perihelion passage, NBAC can successfully deflect 2017 PDC given a size range of 100-150 m for S, C, B, and Xc-type asteroids. Failure of a one or two NBAC-carrying spacecraft during deflection does not preclude successful deflection for a set of sizes and densities. NBAC can be used to arrest asteroid rotations through hovering spacecraft that track the asteroid in its rotating frame. We present a general formulation for angular momentum of a monolithic, single boulder asteroid considering both its rotational and orbital angular momentum. We find that while arresting the rotation for this type of asteroid, it is likely to change its orbit as well. A variety of stable and unstable asteroid rotation states for the asteroid size are used. Propellant usage and time required to fully de-spin representative asteroids will be presented. Additionally, the time required for total de-spin will be compared to the time required for partial arrest. Partial arrest of unstable spinners is possible under mission constraints for a set of asteroid sizes and densities. Additionally, total arrest can be achieved for less than 60 kg per spacecraft for a four-spacecraft NBAC system.**

TABLE OF CONTENTS

1. INTRODUCTION

JPL's Center for NEO Studies (CNEOS) [1] documents the occurrence of asteroid flybys of Earth. Since 2000, at least 1579 flybys at 5 LD (Lunar Distances) or less have occurred with at least a couple dozen asteroids having a lower bound diameter over 100m. Additionally, there have been 579 bollide events recorded since 2000. This demonstrates a need for increased monitoring of these objects, including follow-up observations to more accurately track them. In addition to deflection and monitoring, there is also need for deflection technology development. As a response to this need, NASA created the Planetary Defense Coordination Office (PDCO) (in 2016) on advice from the NASA Advisory Council (NAC) [2] to coordinate the United States' efforts for discovery and to sponsor development of deflection technologies.

Several asteroid deflection methods have been investigated. Deflection techniques are usually divided into two categories: high impulse and slow-push. The actual technique that is employed is usually driven by the time until impact. The combined kinetic-nuclear impact mission outlined by Wie [3] represents a potential high yield deflection method that can be effective at both high intercept speeds and within short-warning windows. They use two spacecraft to deflect: a kinetic impactor to create a crater and another with a nuclear explosive that aims for the crater before detonating. The material that is ejected from the surface of the asteroid acts as expelled propellant, changing the asteroid's trajectory quickly. In contrast, slow push methods such as gravity tractors from Olympio [4], Wie [5], and Mazanek *et al.* [6] and propulsive methods from Scheeres and Schweickart [7] and Bombardelli et al. [8] take years to alter the asteroid trajectory significantly, but they also provide greater trajectory control. Gravity tractors using solar sails can greatly reduce the propellant needed for the long-term station keeping at the asteroid. Olympio [4] determined an optimal duty cycle for

*AIAA Student Member
†AIAA Member
‡AIAA Associate Fellow
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coast and thrust phases achieving a deflection of $\sim$ 100km in five years, a modest deflection over a long period. Mazanek *et al.* [6] proposes using the regolith of an asteroid to increase the mass of the spacecraft in their Enhanced Gravity Tractor (EGT), decreasing the time required for deflection. This relies on the asteroid surface being populated by many boulders, which increases the uncertainty in predicting deflection time as prior knowledge of the asteroid topography may not be possible. A phased laser array which could be placed in the vicinity of Earth from Lubin *et al.* [9] may be a sustainable solution for planetary defense in a few decades. However, this concept was not evaluated for its effectiveness against tumbling asteroids, which may pose a problem for the illumination time to start sublimation. Scheeres and Schweickart [7] propose a spacecraft tethered to the asteroid that can de-spin and tug it onto a new trajectory. Tethering to an asteroid is problematic as significant knowledge about the composition is needed to design a grappling mechanism to create secure contact with the body. Bombardelli *et al.'s* [8] ion beam shepherd (IBS) uses an ion thruster to push against the asteroid. They compare this concept's efficacy to the gravity tractor. IBS presents two difficulties for implementation. At a distance of several asteroid radii from the surface, the IBS half angle would incur significant losses with an ellipsoidal asteroid. Additionally, the volatiles sputtered from the surface have the potential to travel through the ion beam and deposit back onto the spacecraft. Using multiple landers, Olds [10] determined the effectiveness of using mass drivers for the hypothetical D'Artagnon asteroid and for moving the Apophis asteroid out of the resonant-return keyhole, with analysis including such physics as the rotation rate of the asteroid. Unfortunately mass drivers require high power, which is only attainable using a nuclear reactor. Also, the landers must be well secured to the asteroid surface, something that is difficult given the loose, granular nature of these bodies.

After reviewing the existing asteroid deflection technologies, we have identified high level requirements for a new deflection technology that would avoid many of the weaknesses of the currently discussed methods. Specifically, to deflect 100-400m diameter asteroids, the method should:

1) Not require a spacecraft to mechanically attach to the asteroid,
2) Mitigate the creation of an unsafe operating environment for the spacecraft,
3) Maintain reasonable power and mass for current or near-term technology,
4) Be throttleable to evaluate deflection effectiveness and reduce errors in deflection,
5) Compare favorably with the time other slow-push methods take to deflect an asteroid,
6) Include an assessment of the risk in losing a spacecraft or thruster during a deflection campaign.

Methods that affix to asteroids invariably require prior knowledge of the asteroid composition and structural strength. These data are not widely known for the current population of Near Earth Objects (NEOs) or in the smaller subset of Potentially Hazardous Asteroids (PHAs). Therefore, either a scouting mission or a chance close flyby of Earth would be required to assess an asteroid's structure. As previously discussed, sputtered particles are an environmental danger to spacecraft. The same is true for sublimation so any method must find a way to minimize the effects these have on a spacecraft. Additionally a limit on power and mass stems from designing a mission that could be deployed in the near term and does not use low- technology readiness level (TRL) components. From an operational standpoint, EGT has fine control over altering the asteroid trajectory, something that is difficult to achieve in high impulse methods (i.e. multiple kinetic impactors). Propulsive methods can potentially offer high fidelity control as well. As the present work is aimed at contending with current slow-push methods, it must yield timescale for deflection that is similar to or better than existing concepts. Assessing the impact of a spacecraft or thruster failure on the total deflection of an asteroid is another key design requirement to understand the risk to mission success.

We are developing a new technology to be used for asteroid deflection and control through arresting its tumbling rotational motion and deflecting it from Earth. To achieve this, we use several spacecraft equipped with a neutral beam emitter that rendezvous with an asteroid, de-spinning and deflecting it over the course of years. Neutral beams are globally neutralized particle beams typically used as heating elements for fusion tokamaks. They consist of four major modules: an ion source, a gas cell, a deflection magnet, and an ion dump. In a neutral beam set-up, an ion source is fed into a target of neutral gas (gas cell). As the ions interact with neutral gas, they undergo ionization and electron capture reactions leading to a majority of neutrals in the beam. The remainder of ions are deflected via a magnetic field into an ion dump. Importantly, the magnetic field used in the deflection of the remaining ions is shielded from the neutralizer gas cell through magnetic field clamps. The emitted beam consists purely of fast moving neutrals that carry no electric charge. Using uncharged beams in proximity operations at low-gravity bodies would help mitigate the risk of regolith deposits on sensitive components due to back-flow through the beam. The Neutral Beam for Asteroid Control (NBAC) targets 100-400 m diameter asteroids with the goal of successful deflection after less than 5 years of proximity operations. According to Johnson [11], this particular size range of asteroids is estimated to be the largest population of undiscovered Near Earth Asteroids (NEAs), some of which could be PHAs. The time required for deflection via NBAC is between that of a fast action nuclear interceptor and that of a slow-push gravity tractor. Our prior work, DeCicco and Hartzell [12], provided performance metrics of power, thrust, propellant mass, and de-spin time for NBAC, considering a moderately sized ellipsoidal asteroid rotating steadily about a single axis. In that work, we calculated successful de-spin occurring within less than three years while using less than 500kg of total propellant between four spacecraft.

With a clear development path, NBAC's enabling technologies can be developed within years, not decades, and do not require any large advances in technology in terms of power, mass, or thrust. Future missions may not only seek to deflect asteroids but move them into more favorable orbits to be accessed later for their resources, as has been suggested with the Asteroid Rendezvous and Redirect Mission (ARRM) [13]. NBAC could likewise be used to arrest asteroid rotation allowing for mechanical grappling of the body. It is important to develop a large portfolio of asteroid deflection technologies that can be deployed for a wide variety of difficult missions, such as high velocity intercepts, large inclination orbits, and limited observation and characterization. NBAC has the potential to meet the requirements of a subset of these missions and provide mission designers with an additional option for medium-term deflection.

2. DEFLECTION OF HYPOTHETICAL ASTEROID 2017 PDC

The primary mission of NBAC is to provide a deflection capability that bridges the design space between slow and fast impulse methods. As a propulsive deflection method, it must follow the asteroid over a period of months to years to achieve sufficient deflection. Asteroid 2017 PDC was created for the 2017 IAA Planetary Defense Conference as a baseline asteroid for the purpose of a deflection exercise. Initial information for the asteroid placed it on a 1% chance of impact on July 21, 2027. It was estimated to be between 100m-250m in size due to the uncertainty in albedo and on an elliptical 0.88 AU x 3.60 AU orbit. The greatest deflection for hypothetical asteroid 2017 PDC is achieved by thrusting during perihelion approach all the way through perihelion. On its elliptical orbit, there are two perihelion passages (2020 and 2024) before the potential collision with Earth in 2027. The days of active deflection are equally divided into those before and after perihelion passage. Low-thrust deflection of 2017 PDC using NBAC is calculated using the General Mission Analysis Tool (GMAT). For the present study, we investigated a range of asteroid masses and deflection times for 2017 PDC and considered only gravitational forces acting on the asteroid. For when 2017 PDC was more than 1 million km from Earth, approximately the radius of Earth's sphere of influence (SOI), all planetary bodies were included as point masses for integration of the orbital dynamics equations. Point masses for Venus and Jupiter were found to be substantially important in determining the orbit of 2017 PDC. Inside Earth's SOI, Earth was the primary attractor using the JGM-2 gravity model and the Moon was included as a point mass. The initial state of 2017 PDC at Jan 1, 2018 00:00:00.000 was acquired through JPL's HORIZONS system and fed into GMAT to determine all future states. With no deflection, GMAT predicts Earth impact on July 21, 2027. During deflection, all thrust is directed through the center of mass of the asteroid along its instantaneous velocity vector in the VNB (Velocity-Normal-Binormal) frame. It is assumed that four NBAC engines producing 70 mN each are thrusting during the deflection campaign. This corresponds to each NBAC engine producing a 10 keV beam with a plasma current of 0.95A operating on argon propellant. It was found through GMAT simulations, that substantial deflection with NBAC was achieved for thrusting between 120 and 210 days before and after the perihelion approach in Sept. 2020, with diminishing returns at greater than 210 days of thrusting. We did not consider a second set of deflection maneuvers during the Feb. 2024 perihelion, because there are only minimal gains achievable with a low thrust system.

Extending on work by DeCicco and Hartzell [12], we investigate partial failure of NBAC and how it affects mission success. Possible failure modes for NBAC range include a failure of GNC and grid failure in the accelerator. Failure of the GNC would make the spacecraft uncontrollable as NBAC requires operation of two thrusters with the spacecraft positioned such that one is directing towards the asteroid for deflection and the other is used for station keeping to maintain close proximity. The advantage of electric propulsion is the high achievable specific impulse owing to the high velocities in a gridded system. Degradation and failure of these grids would leave NBAC as a low specific impulse cold gas thruster. To evaluate the impact of this failure, we set a time in the GMAT script for which the effective thrust on the asteroid is lowered. For example, from 280 mN on a 240 day deflection campaign with a single thruster failure after 25% of the thrusting time, the thrust is lowered to 210 mN on day 60. Comparing a zero-failure, 25% failure of a single thruster, and 25% failure of two thrusters in Fig. 1, we observe the effect of an early stage failure for low-thrust deflection of 2017 PDC. Given that there is only one perihelion passage that is advantageous for deflection with NBAC, the losses incurred from failure could not be effectively recovered through deflection during the Feb 2024 perihelion passage. For a 420 day deflection campaign, the deflection attained for a 1×10^9 kg asteroid with a double thruster failure after 25% of the mission decreases from a radius of 14500 km to 10000 km (a 31 % decrease). There is also a shift in the asteroid mass that can be successfully deflected by NBAC due to these failures. Under a no failure scenario, NBAC can deflect a 3.8×10^9 kg asteroid, but this falls to 2.3×10^9 kg, a 39% reduction, for a failure of the two thrusters 25% of the way into the deflection mission. This decrease, while severe, highlights the need to act upon asteroids early for deflection missions.

Even with a 50% failure of the thrusting capability early in the mission, NBAC's use of a electric propulsion derivative propulsion system is still able to deflect some smaller asteroids that could cause an airburst event or in the rare case, impact the surface. Airbursts can cause weak structures to fail, windows to shatter, and result in minor or severe injuries. Both the Chelyabinsk and Tunguska events exhibited a significant amount of damage to the ground without being major cratering events.

In Scheeres *et al.* [14] and Carry [15], asteroid densities for several classes are given with a wide range in density and macroporosity, signifying the lack of understanding related to asteroid structure. Macroporosity in asteroids is usually specified over a wide range as asteroids can either be a loose collection of boulders held together by cohesive dust or a monolithic single-body structure. Scheeres *et al.* [14] note that the data are biased toward binary asteroids and asteroids visited by spacecraft. There is no large survey of sub-kilometer asteroids at present, so we assume that they have similar densities to their larger counterparts. We use the densities from Scheeres *et al.* [14], shown in Table 1, for our analysis relating uncertainties in asteroid composition to deflection performance.

Table 1. Densities of asteroid classes (Scheeres *et al.*)

Class	Density (g/cm^3)	Variance (g/cm^3)
S	2.72	$\pm$ 0.54
C	1.33	$\pm$ 0.58
B	2.38	$\pm$ 0.45
Xc	4.86	$\pm$ 0.81

S-type asteroids are fairly bright stony asteroids composed of iron and silicates. C-type asteroids are carbonaceous chondrites with a dark albedo and among the most common of the asteroid spectral types with several different subclasses. B-types such as Bennu, the target for the OSIRIS-REx mission, are made of silicates and have a higher albedo. Finally Xc asteroids are a class of X-group asteroids that have a higher density and likely have metallics although there is limited information on this spectral class. The S, C, and B types have overlapping densities with the Xc being the outlier.

In Fig. 2, we plot the deflection for the 420-day deflection mission for a given size and density of the asteroid and for specific asteroid radii show the density uncertainties from Scheeres *et al.* [14]. Additionally, we examine the worst case scenario of a single thruster and a double thruster failure 25%

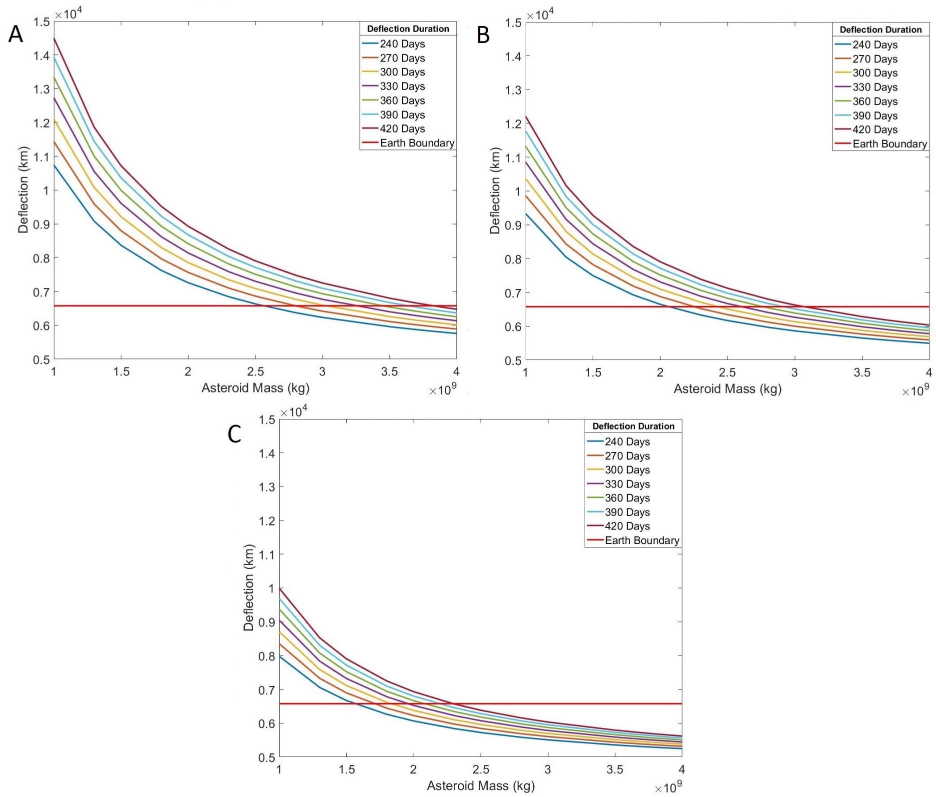

Figure 1. Effect of NBAC thruster failure on deflection performance for 2017 PDC deflecting over a single useful perihelion passage. A): Achievable deflection for operation of the four NBAC thrusters for the entire duration of the mission time. B): Failure of a single thruster after 25% of the mission duration. C): Failure of two thrusters after 25% of the mission duration.

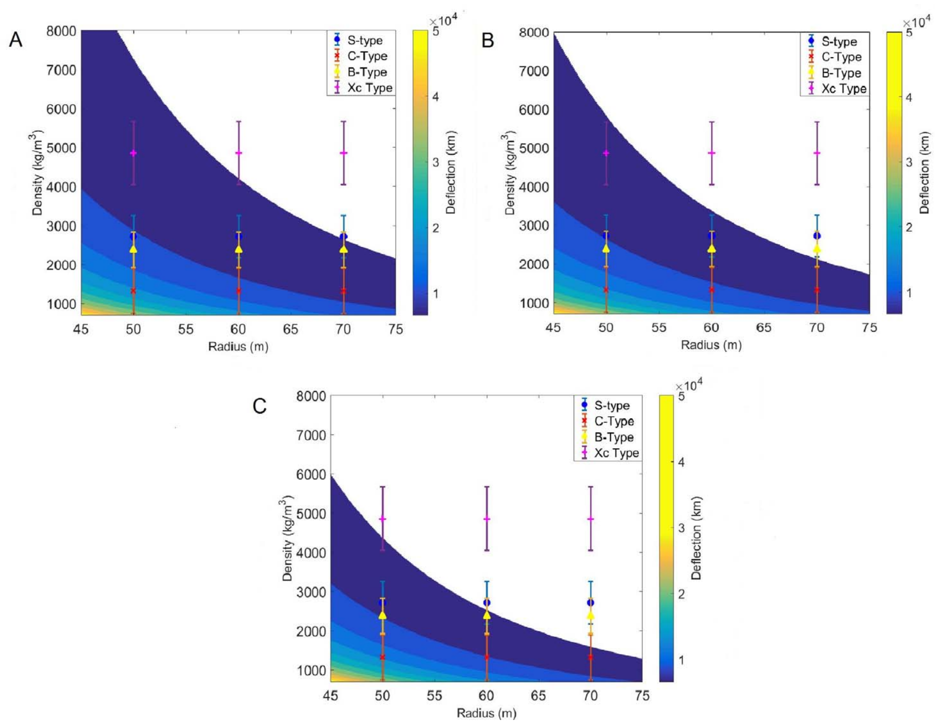

Figure 2. Unknowns in the spectral class of the asteroid incur uncertainty in the total deflection during a campaign with NBAC. White regions denote insufficient deflection given a 200km altitude miss distance from Earth. A): Assuming constant operation of the four thrusters during the entire 420 day deflection campaign. B): Failure of a single thruster 25% into the 420 day deflection mission. C): Failure of two thrusters 25% into the 420 day deflection mission.

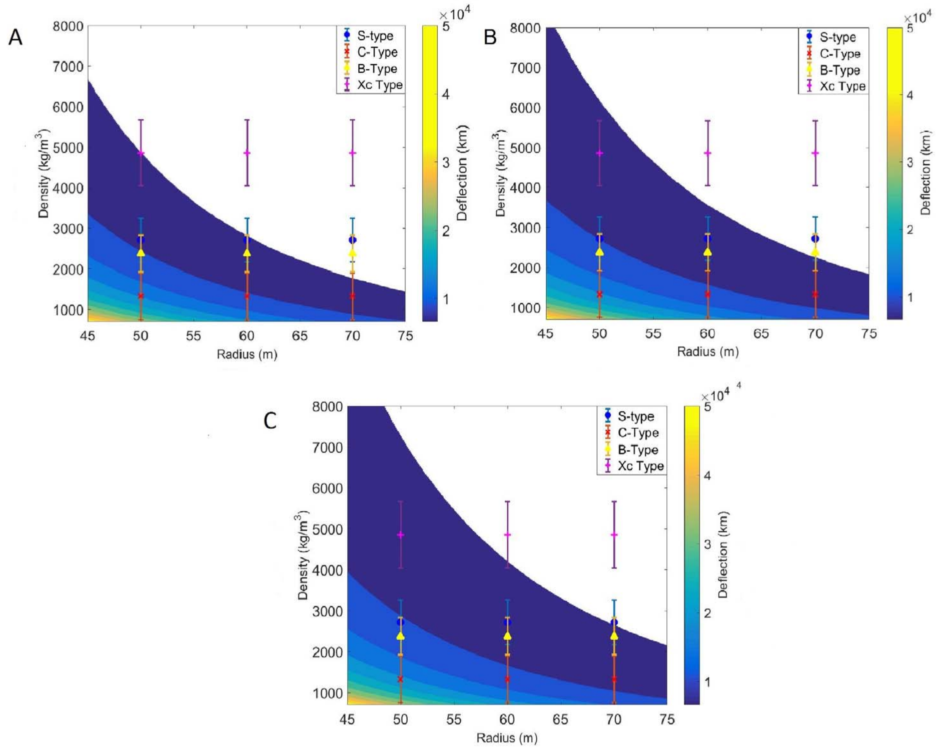

Figure 3. Impact of thrusting duration on deflection achieved as a function of radius and density for: A): 240 days, B): 330 days, and C): 420 days of thrusting.

into the deflection mission. As mentioned before, the bulk density varies with macroporosity and composition of these bodies thus varying the mass and the achievable deflection.

For example, for the no failure scenario a 60m radius S-type asteroid could be deflected from 7300 km to 9000 km from the Earth's center, both extremes representing successful deflection but with a fair amount of variance. However, in the case of a 70m radius asteroid with no failures, a density up to 2.65 g/cm^3 could be tolerated but the upper ends of S-type and B-type and all Xc-type asteroids would not be successfully deflected. The failure of two thrusters early in the campaign reduces the capability to deflect B, S, and Xc types to a 60m radius asteroid. Even with these failures, NBAC demonstrates that in the majority of cases, C-type asteroids will be successfully deflected over this size range. A four thruster NBAC architecture is able to handle a variety of asteroid spectral types and sizes with some tolerance in asteroid uncertainty. Additional thrusters could potentially close the gap for larger, more dense asteroids.

In Fig. 3 we plot the effect of thrusting duration on the amount of achievable deflection as a function of asteroid radius and density. Increasing from 240 to 330 days of thrusting allows for all spectral types at a 50m radius and the S, C, and B types at the 60m radius to be successfully deflected. However, further increases in capability are modest increasing from 330 days to 420 days due to the true anomaly approaching $\pm 90^o$ for the thrusting cycle. At deflection durations greater than 420 days there are diminishing returns for total deflection of 2017 PDC. Even with these modest gains, the majority of 70m radius S-type asteroids could be deflected with a 420 day deflection. The 420 day campaign would use more propellant, but it would provide better range of deflection and more flexibility for spacecraft issues that may arise. The nominal 240 day deflection duration with no failures is more successful than a 420 day campaign with two thrusters failing after 25% of the mission. This presents an option in whether we design the mission to attempt a larger deflection with 420 days of thrusting and risk two failures or whether we design for a shorter deflection campaign with less time for failures to occur. In designing an NBAC deflection campaign, Figs. 2 and 3 show the important relationship between asteroid spectral types, thruster failure, and deflection time to successfully steer an asteroid from an Earth collision. With no assumed prior knowledge about an asteroid's composition, it is important to know what spectral types NBAC could deflect for a relatively short warning asteroid impact. Under the current NBAC design, it is difficult for the fleet of spacecraft to deflect a X-type asteroid 2017 PDC within the only good perihelion thrusting window. To mitigate that risk, longer deflection durations should be considered to deflect of X-type asteroids.

3. Arresting the Rotation of 2017 PDC

Stabilizing the rotation of an asteroid is one of the major goals for NBAC. Though stabilization or full arrest of the asteroid, we can increase the strength of the asteroid. We can also decrease the difficulty for future spacecraft to either land or latch onto the asteroid to tug it into a more favorable orbit. We discuss the dynamics of asteroid control, estimations of asteroid spin rate and unstable criteria, and NBAC's performance for total and partial arrest of asteroid rotation. Nothing is known about 2017 PDC's rotational state at the time of discovery, given that very limited arcs have been observed in this hypothetical scenario. In DeCicco and Hartzell [12], we derived a total angular momentum description (both rotational and orbital) for a rotating asteroid

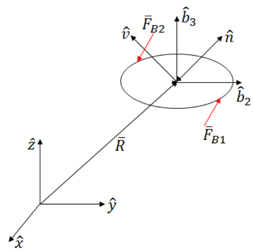

Figure 4. Schematic showing the body ($\hat{b}$), VNB ($\hat{v}, \hat{n}$), and inertial reference frames used to describe asteroid motion. It is evident that as forces are applied in the body frame, so long as they are balanced on the moment arms, no net $\bar{F}$ will alter the asteroid orbital trajectory.

under an external torque noting that $\dot{\bar{\bar{I}}}_B = 0$ as the body tensor is aligned with the principle axis (shown in Fig 4):

$$\begin{aligned}\dot{\bar{H}}^I_{TOT} =& (\bar{R} \times \dot{\bar{V}})^I + \bar{\bar{C}}_{IV}[\bar{\tau}_B + \bar{\omega}_{B/V} \times (\bar{\bar{I}}_B \bar{\omega}_{B/V}) + \\ & \bar{\omega}_{V/I} \times \bar{H}^V_{ROT}] + \dot{\bar{\bar{C}}}_{IV} \bar{H}^V_{ROT}\end{aligned} \tag{1}$$

where $\bar{R}$ is the position vector in the inertial frame, $\dot{\bar{V}}$ is the velocity vector in the inertial frame, $\bar{\tau}_B$ is the torque, $\bar{\omega}_{B/V}$ is an angular velocity of the asteroid with respect to the VNB frame, $\bar{\bar{I}}_B$ is the inertia tensor in the body-fixed frame, $\bar{\omega}_{V/I}$ is the angular velocity in the VNB frame with respect to the inertial frame, $\bar{H}^V_{ROT}$ is the total angular momentum in the VNB frame, and $\bar{\bar{C}}_{IV}$ is the transform tensor from the VNB frame to the inertial frame.

From the above equation we then define $\dot{\bar{V}}_I$ through the classical two-body orbital description with a force applied, $\bar{F}_{Bi}$ in the body-frame:

$$\dot{\bar{V}}_I = \frac{-\mu}{|\bar{R}^3_I|}\bar{R}_I + \bar{\bar{C}}_{IV}\bar{\bar{C}}_{VB}\sum_i \frac{\bar{F}_{Bi}}{m_A} \tag{2}$$

where μ is the gravitational parameter, $\bar{\bar{C}}_{VB}$ is the transform tensor from the body frame to the VNB-frame, and m_A is the mass of the asteroid. If the spacecraft are positioned at opposite ends of the asteroid as shown in Fig. 4, then $\sum_i \bar{F}_{Bi} = 0$. If we are able to maintain such a configuration about the asteroid during the de-spin maneuver, then there should be little to no effect on the orbit of the asteroid during that period. However, in practice, this will be difficult to maintain so it is important to know the spacecraft positions relative to one another determine how they affected the asteroid's orbit. One advantage of NBAC is that since it is a propulsive method, it is possible to correct any errors during either phase of asteroid control.

To determine the range of spin rates for the distribution of asteroid sizes for 2017 PDC, we use data sets from the JPL Small-Body Database. In Fig. 5, we plot asteroids for which there are rotational period data. Within the 100-250 m range, there is limited information on spin rates owing to the difficulty in determining such properties. For an asteroid with a diameter $\simeq$ 150 m, we can expect a rotation period anywhere between 0.3 hr to 51 hr, the faster of which is likely to be a monolithic, singular boulder.

Discussion in Scheeres and Schweickart[7] suggests that there is a spin rate limit for rubble-pile asteroids, above which they will disassemble. This limit is evident in the sharp cutoff seen in Fig. 5 for rotation rates faster than about two hours, above where there are only a couple of stray asteroids. Often spin rate data are obtained via light curves so there is still some bias in the data towards Main Belt asteroids since there have been more frequent, longer periods of observation for this population. However, the initial data from NEAs suggest that they follow the same clustering in size and rotation rate so we can be confident in the current data in establishing unstable criteria. Thus we establish our boundary for stable asteroids to be at this cutoff of approximately 2 hrs, above whichvrubble pile asteroids risk disassembly.

For de-spin, we assume a roughly spherical asteroid rotating about a singular axis at some steady rate w_0 with no external accelerations. In our calculations, we filter the results for time to de-spin 2017 PDC by those that take longer than a half period for the asteroid and further by those that can not be deflected by at least a 200 km altitude to Earth at closest approach. We use the same four-thruster NBAC system operating at 0.28 N of combined thrust.In Fig. 6 we show the calculated time to de-spin asteroids rotating faster than the break-up limit, slowing the rotation rate these by 25 %. With asteroids having rotation periods at a tenth of an hour, the NBAC system is not suitable to slow their rotation. However, half hour rotators could be moderately slowed, even though their rotation would not be fully arrested. While Fig. 6 shows that it is difficult to partially de-spin these unstable asteroids, there is a design space for NBAC to reduce the angular momentum of the asteroid. For a 50 m asteroid, the NBAC system can arrest a half hour rotator with $\rho \leq 2$ g/cm^3 and an hour rotator with $\rho \leq 3$ g/cm^3. While NBAC is designed for a moderately low current, a higher current version could yield a larger impact on these fast rotators.

Full de-spin of asteroids can be achieved with those rotating in the normal, stable range (2hr period or greater) for asteroids of this size range. In Fig. 7 we present the time for total arrest of stably rotating asteroids which could also be successfully deflected. The limit of de-spin for a half orbital period severely limits the range of faster rotators than can be fully arrested, but it does not affect cases where the rotation period is 10 hrs or greater. The 2.5 hr rotator, near the stability limit, can be completely de-spun for an asteroid radius of 50 m with a $\rho \sim 2$ g/cm^3. Recalling from Table 1 that this is in the range of C and B-type asteroids. Full arrest of the rotation is not necessarily required and much of the benefit for increasing the strength of the rubble pile and decreasing the difficulty for attachment on the asteroid could be achieved by simply halving the period (Fig. 8). In this case, asteroids with a rotation periods of 5hrs or greater could have their periods slowed to 10 hrs with no affect on the range of asteroids able to be then deflected. The faster 2.5 hr rotator has significantly more options in the case of achieving a successful partial arrest and deflection for a 50 m radius asteroid in the density range of S, C, B, and Xc-type asteroids.

Using the full NBAC system means that the propellant mass is equally subdivided amongst the spacecraft to control the asteroid. In Fig. 9, we can achieve total de-spin for wide range of asteroid sizes using less than 60 kg of argon propellant per spacecraft. This helps to reduce the size of each spacecraft as the tank size to hold the propellant will likewise

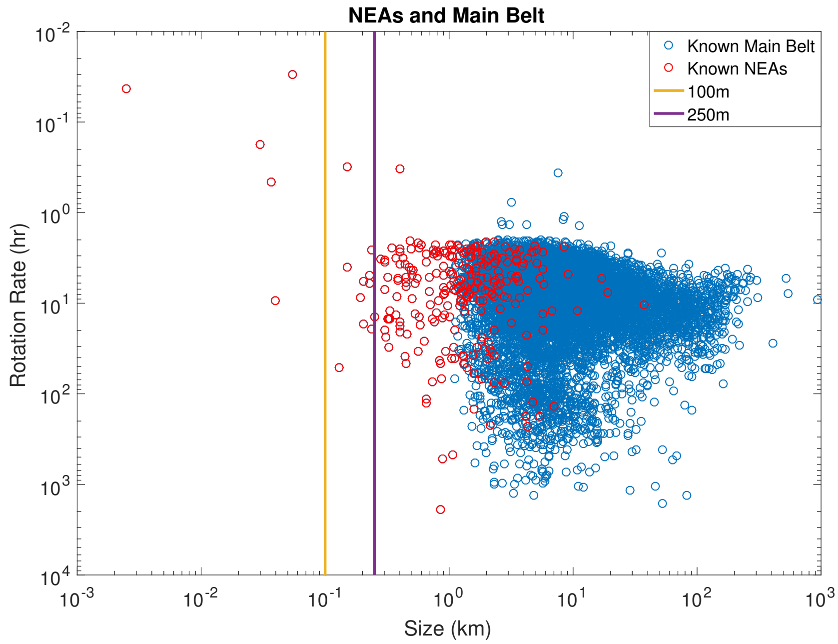

Figure 5. Known rotation rates obtained from the JPL Small Body Database, there is little data on asteroids in the 100-250 m size range.

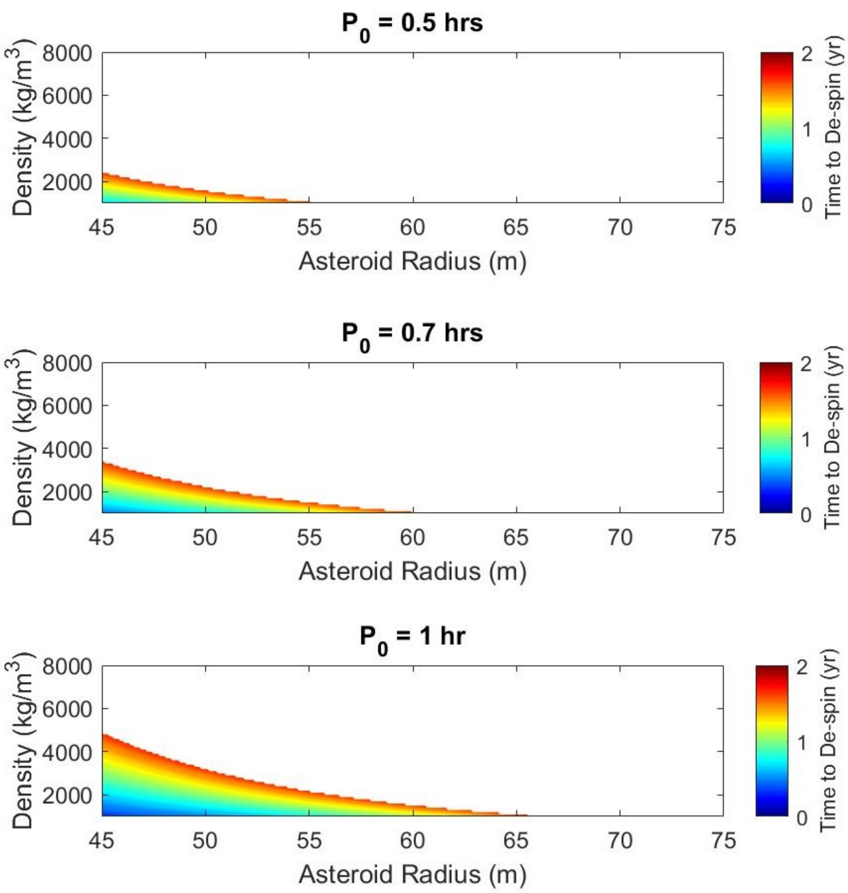

Figure 6. Time to partially de-spin fast rotating asteroids by 25 % of the rotational rate within half an orbital period of 2017 PDC.

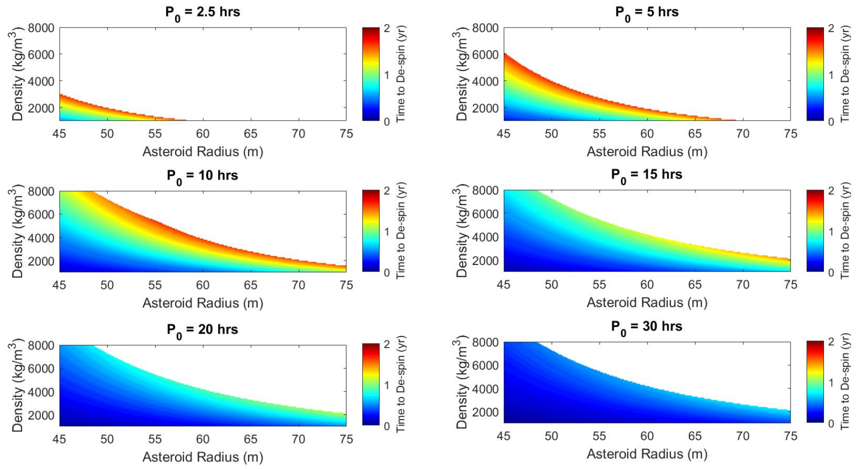

Figure 7. Time to toally de-spin 2017 PDC as a function of asteroid density and radius for initial rotation periods of 2.5 hrs to 30 hrs. Larger rotation periods ($\geq$ 10 hrs) can be easily de-spun and deflected without being limited by the de-spin time criteria.

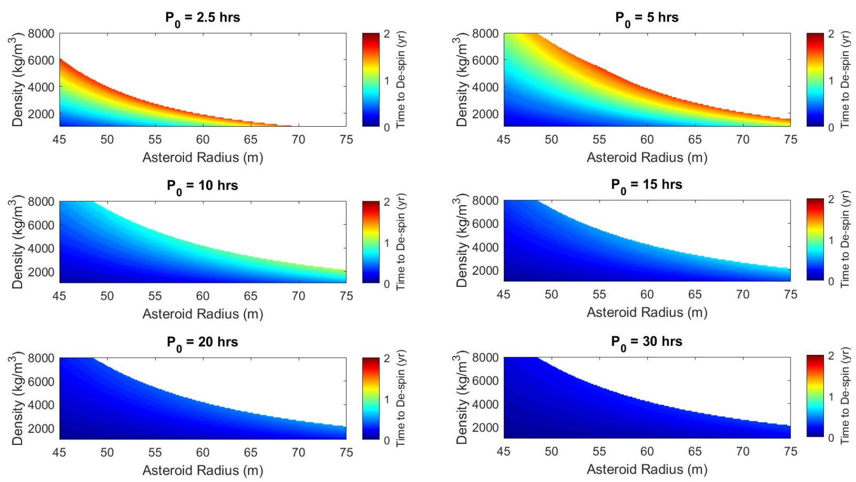

Figure 8. Time to halve the asteroid rotation rate as a function of asteroid density and radius for rotation periods of 2.5 to 30 hrs can be achieved in less than a half period for many asteroids.

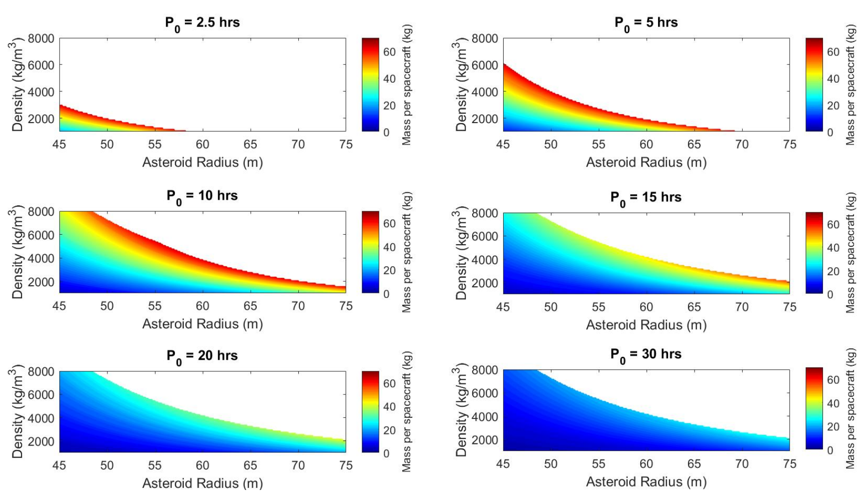

Figure 9. Propellant mass per spacecraft required to totally arrest the rotation of an asteroid using a four thruster NBAC system operating with a 10 keV beam and producing 280 mN total thrust. Many asteroid types can be completely de-spun with less than 60 kg of propellant.

be smaller. It also helps for redundancy in the swarm should a spacecraft or multiple spacecraft fail. As we approach longer rotation periods ($P_0 \geq 20$ hrs), many solutions require less than 40 kg of propellant per spacecraft. It is also worthwhile to attempt total de-spin of an asteroid so that a separate, future spacecraft could attach a cable and tow the asteroid to a more favorable orbit.

4. Conclusions

The Neutral Beam for Asteroid Control (NBAC) could be used effectively against the hypothetical asteroid 2017 PDC. Our failure analysis shows that thruster failure reduces the range of asteroid types and sizes where NBAC would be successful in a deflection mission. NBAC can handle a variety of asteroid spectral classes, deflecting them to over 200 km from an Earth impact. With 50% of the thrusters failing in a 420 day mission after 25% of the mission has elapsed, NBAC can deflect S, B, C, and some Xc types of asteroids. NBAC employing multiple spacecraft is a resilient mission architecture for asteroid deflection. Having multiple spacecraft reduces the probability of system down-time during the deflection campaign. NBAC is also suited for slowing or arresting the rotation of some asteroids. Investigating unstable spinning asteroids ($P_0 \leq 2$ hrs), there are some solutions for partial arrest of these bodies within a half orbital period. Halving the rotation rate for stable rotators and not reducing the subset of deflection capable missions is possible for asteroids with $P_0 \geq 5$ hrs. Additionally, these asteroid rotation arrest missions can be accomplished, in many cases, for less than 60kg of argon propellant showing the utility of NBAC as a means to de-spin asteroids for other spacecraft that could later tow it into a more favorable orbit.

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Biography

__Anthony J. DeCicco__ received his B.S. and M.S. degrees in Mechanical engineering from WPI in 2014. He is currently working on his PhD in Aerospace Engineering at UMD. He has worked on impact resistant composite overwrapped pressure vessels at NASA MSFC, spacecraft charging modeling at Johns Hopkins APL, and future propulsion concepts at NASA MSFC. His research focuses on asteroid deflection and the development of neutral beam propulsion to control small asteroids.

__Christine M. Hartzell__ received her Ph.D. in Aerospace Engineering Sciences from the University of Colorado at Boulder in 2012. She was a Postdoctoral Fellow with the Keck Institute for Space Studies at the California Institute of Technology, where she studied granular media. She is currently an Assistant Professor of Aerospace Engineering at the University of Maryland. Her research focuses on dust motion on airless bodies for the purpose of understanding the evolution of these bodies and improving the design of spacecraft to explore them.

Robert B. Adams *received both a B.S. and M.S. in Mechanical Engineering from the UA at Birmingham. He has also received a M.S. in Aerospace Engineering and Ph.D. (Mechanical Engineering) from the UA in Huntsville. He also completed most of the requirements for a M.S. in Nuclear Engineering from the UT in Knoxville. Dr. Adams has taught classes in fluid mechanics, propulsion and aircraft, and spacecraft design at UA - Huntsville and in launch vehicle design at NASA-MSFC. Before joining NASA Dr. Adams has served as a flight controller and has served as principal investigator for several new propulsion concepts.*

Kurt A. Polzin *(SM'11) received the B.S. (*summa cum laude*) degree in aeronautical and astronautical engineering from Ohio State University, Columbus, OH, USA, in 1999, and the Ph.D. degree from Princeton University, Princeton, NJ, USA. He has been a Propulsion Research Scientist with the Propulsion Research and Development Laboratory, NASA's George C. Marshall Space Flight Center, Huntsville, AL, USA, since 2004, where he is currently the Technical Lead of Electric Propulsion.*

Dr. Polzin is currently an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He is the AIAA Southeast Regional Director and is a member of the AIAA Electric Propulsion Technical Committee. He was the Technical Chair of the 2013 International Electric Propulsion Conference (IEPC) held at George Washington University, Washington, DC, USA. He was a Guest Editor of an IEEE Transactions on Plasma Science *Special Issue on Plasma Propulsion (Vol. 43, No. 1, 2015).*