DEFLECTION MISSIONS FOR ASTEROID 2011 AG5[†]

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Abstract: *The recently discovered asteroid 2011 AG5 currently has a 1-in-500 chance of impacting Earth in 2040. In this paper, we discuss the potential of future observations of the asteroid and their effects on the asteroid's orbital uncertainty. Various kinetic impactor mission scenarios, relying on both conventional chemical as well as solar-electric propulsion, are presented for deflecting the course of the asteroid safely away from Earth. The times for the missions range from pre-keyhole passage (pre-2023), and up to five years prior to the 2040 Earth close approach. We also include a brief discussion on terminal guidance, and contingency options for mission planning.*

Keywords: *near-Earth object, small body, impact trajectory.*

1. Introduction

On January 8, 2011, the asteroid 2011 AG5 was discovered by the NASA-sponsored Catalina Sky Survey in an observatory north of Tucson. From the observational data, the nominal trajectory for 2011 AG5 is predicted to pass as close as 2.5 lunar distances of Earth on February 5, 2040. Uncertainty in the asteroid's position indicates that 2011 AG5 has a 1-in-500 chance of impacting Earth at this time. Should the asteroid impact Earth, it is estimated it would release roughly 100 MT of energy somewhere in the Southern hemisphere, potentially South America. The threat of 2011 AG5 impact was acknowledged by space centers around the world, where, for example, Elecnor Deimos [1] and NASA's Jet Propulsion Laboratory [2] immediately responded by investigating deflection missions to the asteroid. The results were presented along with other findings at an international workshop at NASA Goddard Space Flight Center on May 29, 2012.

The threat of impact from an asteroid or comet is genuine, and our concern extends well beyond 2011 AG5. For example, we have historical evidence in the form of craters left by asteroids and comets all over the solar system, particularly here on Earth. According to the Earth Impact Database [3], there are 183 known impact craters on Earth, including the well-known 170-km Chicxulub Crater on the Yucatan Peninsula in Mexico that is believed to have struck Earth 65 million years ago, causing the extinction of dinosaurs. As our historical evidence of impact craters builds, our eyes outward to the solar system are also improving. In July of 1994 we watched as Comet Shoemaker-Levy 9 collided with Jupiter estimated to have released more than 10^6 MT of energy [4]. A similar impact on Earth would be devastating. To date, there are nearly 9,000 known near-Earth asteroids (NEAs), where approximately 1,000 of these were discovered in the last year. Considering the number of known NEAs and our current rate of discovery for them, it is inevitable we will stumble upon many small bodies that pass very close to Earth, and even some that might be on impact trajectories with Earth. Briefly for a time in 2004, Apophis was thought to have a 2% chance of impacting Earth in 2029. Fortunately close monitoring of the asteroid indicated it would safely miss Earth by more than five Earth radii [5]. In the case that we find an asteroid that might be on an impact trajectory, it is imperative that we develop a tested and reliable method for deflecting the asteroid's course safely away from Earth.

In the 1990s, scientists and engineers around the world discussed methods for altering the course of near-Earth objects (NEOs) [6]. Later Scheeres and Schweickart [7] as well as Wie [8] more thoroughly investigated from a dynamical standpoint the feasibility of moving NEOs. Perhaps the simplest method for altering the course of an asteroid is to strike it with a kinetic impactor, similar to the method employed by Deep Impact (DI) in the collision with the Comet Tempel 1 on July 4, 2005 [9]. The concept of a kinetic impactor was also a focus of the 1st Global Trajectory Optimization Competition (GTOC) in 2005, where the goal was to assemble a sequence of planetary flybys for a low-thrust mission impacting asteroid 2001 TW229 in such a way to maximize deflection [10]. For a possible collaboration with ESA, deflection missions were investigated at NASA's Jet Propulsion Laboratory for the asteroid 2002 AT4 [11-12], based on ESA's Don Quijote concept study [13]. The missions created involved sending a rendezvous spacecraft to characterize the size, shape, composition, and rotation rate of the asteroid, followed by a kinetic impactor spacecraft that would arrive at least six months after the rendezvous spacecraft.

In this paper, we survey the mission prospects available for deflecting the course of the asteroid 2011 AG5, some of which is included in an earlier report delivered to NASA [2]. Options are presented that rely on chemical as well as solar-electric propulsion (SEP) for transporting the spacecraft to the asteroid. There are a variety of pre- and post-keyhole mission scenarios for an assortment of launch vehicles. While a nominal deflection of $10R_e$ (R_e = Earth radii) is deemed safe, we also consider missions that wait up to four years prior to the estimated Earth impact and deflections as small as $2R_e$, as well as sending multiple small impactors to deflect the asteroid. The benefits of sending an in-situ rendezvous spacecraft to arrive at the asteroid prior to impact are also addressed. In the unlikely event that future observations of 2011 AG5 indicate the asteroid is headed for the keyhole, the mission opportunities presented in this paper will be invaluable to NASA and other space agencies around the world. In the more likely case that 2011 AG5 misses the keyhole, these mission concepts remain an excellent proof-of-concept for future asteroid deflection missions.

2. Asteroid 2011 AG5

Asteroid 2011 AG5 was last observed by astronomers on September 21, 2011. From the absolute visual magnitude H = 21.8 and assuming a visual albedo p_v = 0.154, the estimated diameter of the asteroid is 140 m. Further assuming a uniform density of 2.6 g/cm^3, the mass of 2011 AG5 is approximately 4.1 x 10^9 kg. Since observations only tracked the asteroid for half its orbital period, the orbital motion is not known to the accuracy desired. However, from the observational data available, we can conclude the asteroid resides in a 0.9 x 2.0 AU orbit inclined 3.7 deg to the ecliptic. (See Fig. 1.) The period of the orbit is predicted to be 625 days, such that the asteroid is in a near perfect 17:10 resonance with Earth's orbit around the Sun. There is an Earth close approach of 4.7 lunar distances on February 3, 2023. Due to uncertainties in the asteroid's trajectory, at the 2023 close approach, 2011 AG5 has a 0.2%

chance of passing through a 365-km window, or keyhole, located roughly 1.8 million km from Earth. Should the asteroid pass through this keyhole, it will be on a trajectory that will collide with Earth on February 5, 2040. From the estimated mass of the asteroid and the predicted velocity at impact, roughly 14.7 km/s, the energy released by the impact would be 100 MT of TNT. We want to make clear that although there is a small chance of impact, the predicted nominal trajectory misses Earth by 2.5 lunar distances.

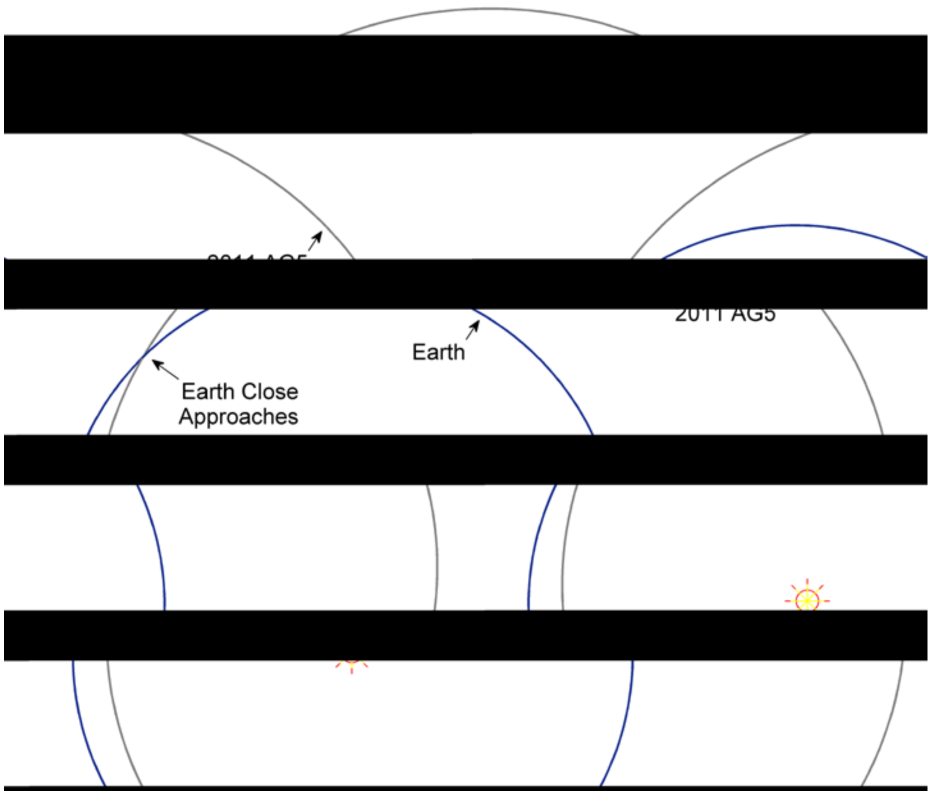

Figure 1. Heliocentric view of 2011 AG5's orbit.

2.1. Observation Opportunities

As with the 2004 threat of impact presented by Apophis, 2011 AG5 will be closely monitored in the future to more precisely determine its likelihood of impact. In Fig. 2 we provide the solar elongation, Earth range, and estimated visual magnitude versus time. Ideal observation times are available when the solar elongation is large and Earth range is small. For example, a very good viewing opportunity is available on September 26, 2013 since the brightness is at a maximum (V = 23.6) and the solar elongation is 175 deg. A list of recommended observation opportunities are provided in Table 1, including the requirements for viewing the asteroid. For the earliest opportunity listed in the table, we expect the asteroid to be only faintly visible, with imaging only possible during the morning twilight. These observations are perhaps best handled by the largest telescope available at the Keck Observatory, even so there is only a remote chance of obtaining reliable data for the asteroid. However, the 2012 observations can be used to provide Hubble Space Telescope (HST) with a star field characterization for HST observations that might be conducted in April of 2013. We understand that coordinating observations with the Keck Observatory and HST would be challenging; however, the earlier opportunities could aid in preparations for later, more favorable, apparitions and will likely indicate conclusively whether or not the asteroid is indeed headed for the 2023 keyhole.

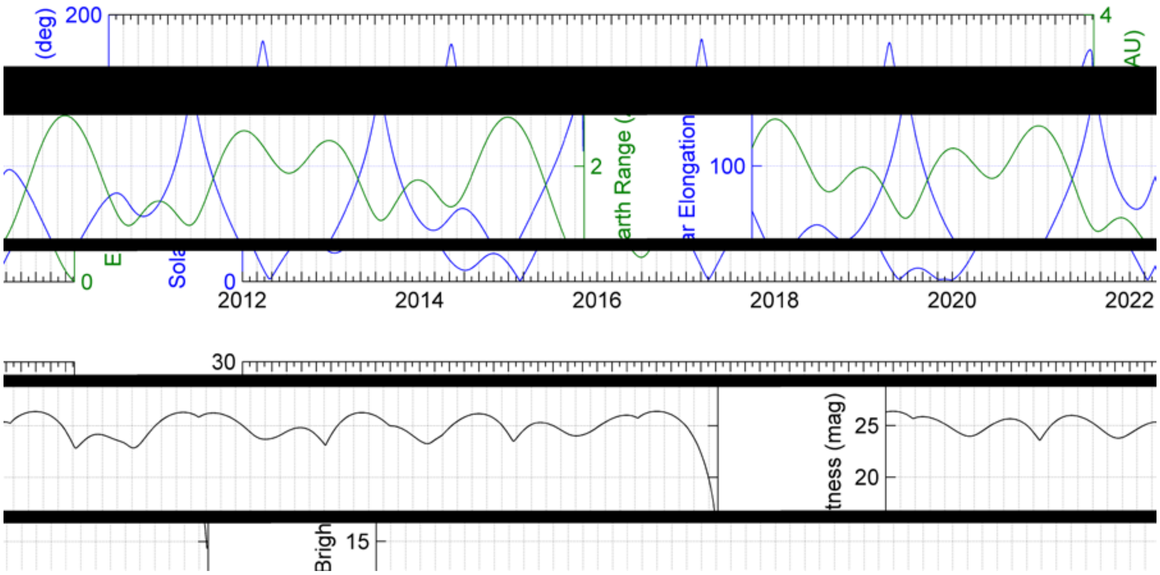

Figure 2. Time-history for solar elongation, Earth range, and brightness of asteroid 2011 AG5. Ideal viewing times for observation from Earth occur when the elongation is large and the asteroid is bright.

Table 1. Future observation opportunities available for asteroid 2011 AG5.

Date	Brightness (mag)	Solar Elongation (deg)	Description
Oct. 2012	24.5	42	Requires Keck. ‘MK012’
Apr. 2013	25.5	50	Requires HST. ‘HST 13’
Sep. 2013	23.6	175	Requires 2-4m aperture
Nov. 2015	22.9	170	Requires 2-4m aperture
June 2016	22.9	85	Requires 2-4m aperture
Sep. 2018	23.1	175	Requires 2-4m aperture
Oct. 2020	23.5	172	Requires 2-4m aperture
Feb. 2023	14.3	135	Radar Opportunity

2.2. Observation Effects on Impact Uncertainty

Given the observation opportunities available, we can predict the encounter uncertainty evolution as a function of time. (See Fig. 3.) Currently the encounter uncertainty is roughly 10 million km. With observations from the Keck Observatory starting in October 2012, we estimate the encounter uncertainty to become less than $10R_e$ by the end of this year (2012) and less than $1R_e$

by 2017 for observations with Keck or HST. As indicated in the figure, the encounter uncertainty drops to near zero in late 2021 if an in situ rendezvous spacecraft is sent to the asteroid. Assuming the observations in Table 1, Fig. 4 shows the probability of discovering 2011 AG5 will not be on an impact trajectory after all. With the Keck Observatory observations, by the end of this year, we are over 90% confident that we will be able to conclude the asteroid will in fact miss the 2023 keyhole. And we are 99% confident that by 2017 we will be able to determine that the asteroid will safely pass by Earth in 2040.

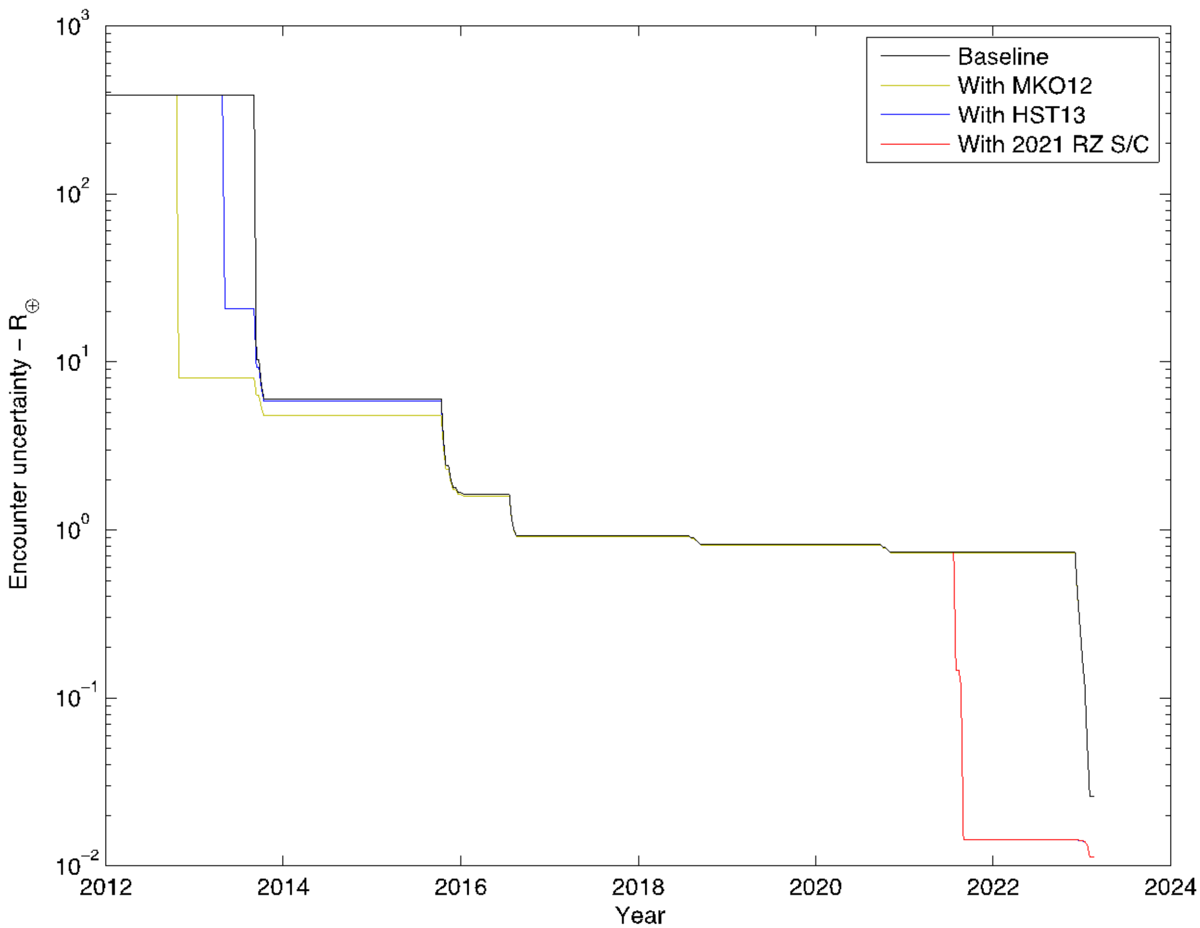

Figure 3. Time evolution of position uncertainty given the observations opportunities available for 2011 AG5. The baseline case assumes all observations listed in Table 1 after the April 2013 HST opportunity. 'MKO12' and 'HST' refers to observations augmented to the baseline with the October 2012 and April 2013 opportunities, respectively. The large drop for '2021 RZ S/C' in encounter uncertainty corresponds to sending an in situ rendezvous spacecraft to the asteroid in late 2021.

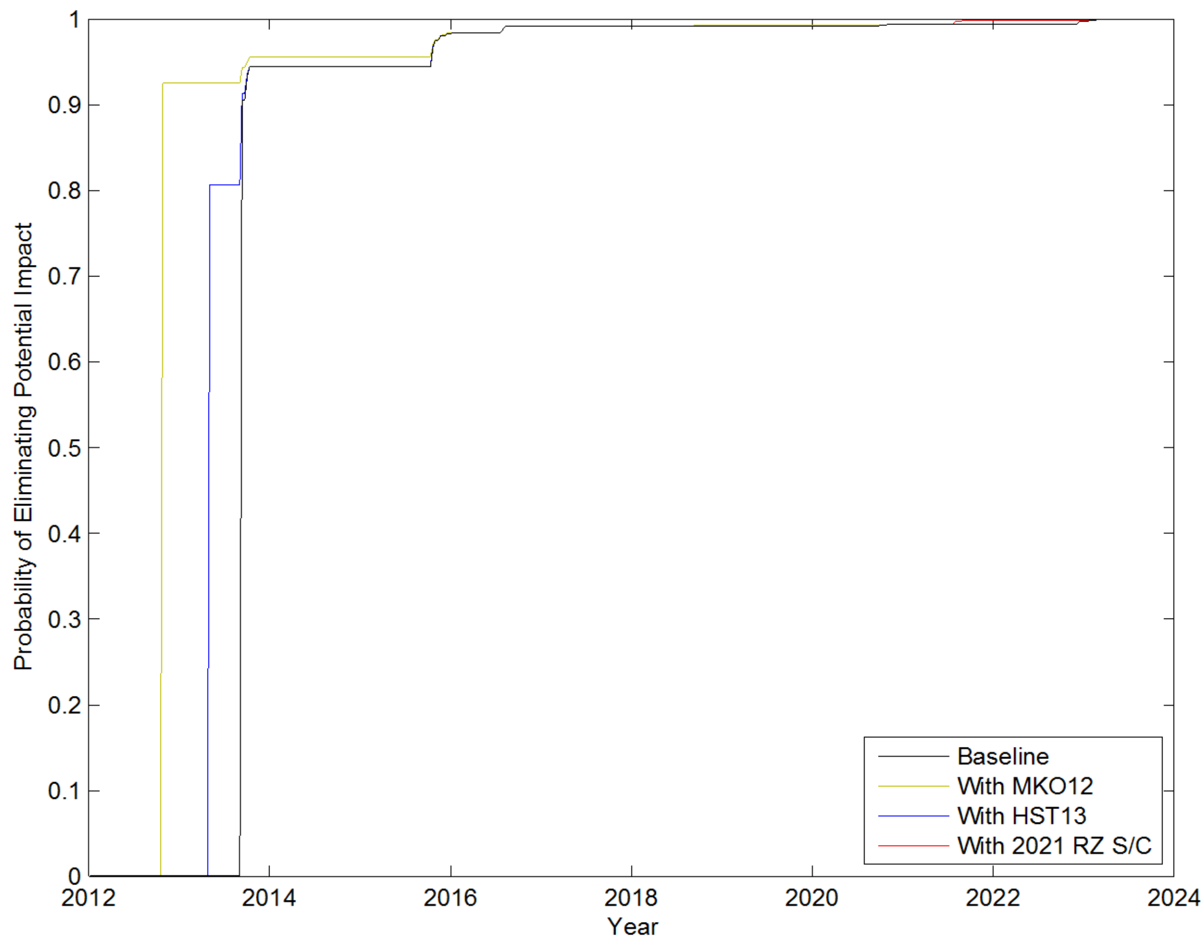

Figure 4. The probability that we will be able to rule out the 2040 impact with the coming observations.

3. Mission Design

Even though the likelihood of Earth impact in 2040 is small, the chances are still large enough for us to be concerned, and in the case that we discover 2011 AG5 is in fact headed for the 2023 keyhole, it is important to have missions in-hand so that we may respond immediately. In this section we present the mission opportunities available for deflecting 2011 AG5 with a kinetic impactor, and investigate the possibility of sending a rendezvous spacecraft ahead of time to characterize the asteroid's shape and rotation, and determine more precisely its orbit. Since it requires much less energy to deflect the asteroid if the impactor collides with the asteroid prior to the keyhole passage, we focus our attention on pre-keyhole mission opportunities. However, we also discuss post-keyhole mission opportunities.

To estimate the deflection of the asteroid, we use a trajectory for the asteroid that is on a collision course with Earth in 2040. A *b*-plane is defined according to [14], and the *b*-plane sensitivity with respect to the asteroid's velocity, for both keyhole passage and Earth impact, is computed. Then the deflection in the *b*-plane do to a change in the asteroid's velocity $\Delta\bar{v}$ is

$$\Delta\bar{b} = \frac{\partial\bar{b}}{\partial\bar{v}}\Delta\bar{v}. \tag{1}$$

The $\Delta\bar{v}$ imparted to the asteroid by the kinetic impactor spacecraft is determined from the spacecraft's hyperbolic excess velocity $\bar{v}_\infty$ according to

$$\Delta\bar{v} = \beta\,\bar{v}_\infty \frac{m}{M}, \tag{2}$$

where *m* is the spacecraft mass at impact, and *M* is the mass of the asteroid. The momentum multiplier β describes the momentum enhancement due to impact ejecta blowback. The range of possible β values runs from at least 1 (plastic collision) to 10, here we assume a conservative value $\beta = 2$. Thus, given a vector $\bar{v}_\infty$ and an impact mass *m* for the spacecraft, we can predict both the deflection in the keyhole passage *b*-plane and the deflection from Earth in 2040. For navigation purposes and terminal guidance, we seek hyperbolic excess velocities v_∞ less than 25 km/s, and preferably as low as possible while still achieving the desired deflection. The mass of the kinetic impactor is primarily driven by the launch vehicle and the method of propulsion used for transporting the spacecraft to the asteroid. For deflection missions that rely on chemical propulsion, we perform an exhaustive search of Lambert arcs between Earth and the asteroid at various epochs. We also examine the possibility of utilizing gravity assist with Mercury, Venus, Earth and Jupiter, however, in general we are interested in postponing the launch to as late as possible (to wait for observations) while still achieving the desired deflection, thus we are mostly interested in the direct launch opportunities. Then for various launch vehicles, it is straightforward to compute the deflection from Eq. 1 from the Lambert arcs.

For missions that rely on SEP for transporting the spacecraft, we use MALTO to design the trajectories [15]. Maximizing the performance index

$$J = m\,|\,\bar{v}_\infty \cdot \bar{V}\,|, \tag{3}$$

where $\bar{V}$ is the velocity of the asteroid at the time of impact, maximizes the asteroid's deflection. Equation 3 was originally provided by the organizers of the 1st GTOC [10], and is available in MALTO as a possible objective for designing SEP trajectories [16]. We found a strong correlation between maximizing *b*-plane deflection and maximizing the performance index in Eq. 3. For all trajectories designed in MALTO, we eventually compute the asteroid's deflection according to Eq. 1.

3.1. Phase-Free Analysis & Deflection Requirements

One way to maximize deflection, as indicated by Eq. 1, is to deliver as much mass as possible to the asteroid. The delivered mass is primarily limited by the performance of the launch vehicle. See Fig. 5 for injected mass provided by launch vehicles in the domain of this study, which assumes that a Star solid upper stage is available to boost performance to high C3s. As indicated in Fig. 5, the injected mass decreases with the orbital energy, or C3, provided by the launch vehicle.

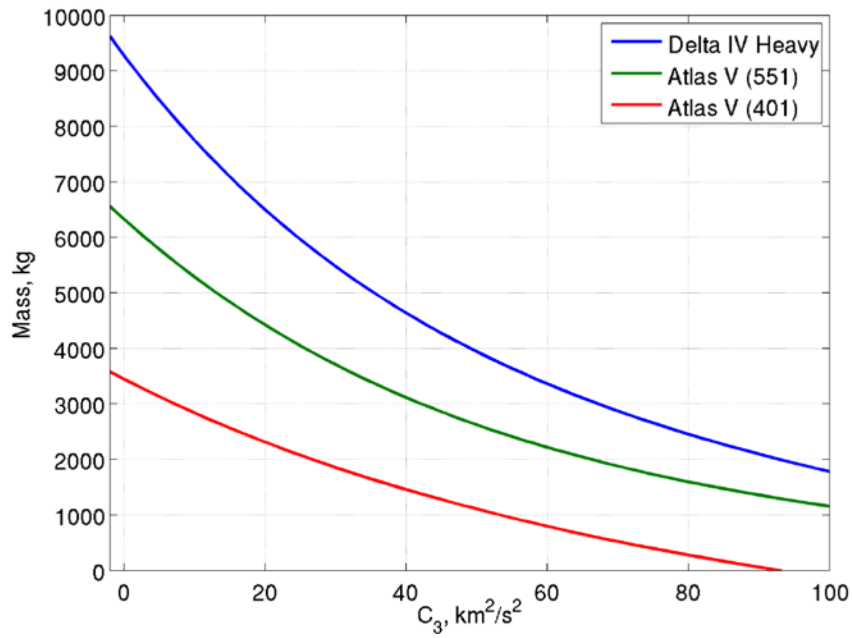

Figure 5. Injected mass versus launch C3 for various launch vehicles (28.5 deg launch declination).

Aside from increasing the impactor mass, maximum deflection also occurs when v_∞ is large and directed along or against $\overline{V}$, as well as for earlier impacts, to allow the effect of the impact to grow with time. To maximize the change in the asteroid's orbital energy, an ideal time to deflect the asteroid is to strike it at the earliest perihelion possible. The angle between the incoming hyperbolic asymptote and the Sun-asteroid line, or the approach phase, is roughly 90 deg for striking the asteroid at perihelion. For terminal guidance and targeting, smaller approach phases are desired, preferably 90 deg or less. Recall the orbit of 2011 AG5 is significantly inclined with respect to the ecliptic (roughly 3.7 deg). Therefore we also expect that colliding with the asteroid near an ascending or descending node will result in higher v_∞s and larger impactor masses (since propellant mass is not used for the plane change). Perhaps the best deflection opportunity is at the ascending node, since it is also near perihelion.

Rather than maximizing deflection, for this study we are interested in the latest possible mission opportunity that safely deflects the asteroid from the Earth in 2040. For a deflection that occurs at perihelion, the impactor will likely be on a lower energy trajectory so that $\bar{v}_\infty$ is in opposite direction of $\bar{V}$ (the asteroid collides with the impactor by over-taking it). The result of the impact would be to decrease the asteroid's orbital period. In order to avoid falling into a secondary keyhole, in [2] we show that for impactors that decrease the asteroid's orbital period, safe deflections occur between 1,500-8,000 km of the keyhole, or miss distances of 8-44 Earth radii in 2040. Therefore, the goal is to find the lastest possible mission opportunity that deflects the asteroid $10R_e$ away from the Earth in 2040, or equivalently 2,000 km from the 2023 keyhole. For post keyhole mission analyses we allow the deflection to be as low as $2R_e$.

Since the desired deflection is known, Eqs. 1-3 are used to gain a better understanding of the trade space between m and v_∞. To maximize J in Eq. 3, we assume $\bar{v}_\infty$ is either along or against $\bar{V}$, and allow the magnitude to vary from 5 km/s to 25 km/s. From Eqs. 1 and 2 we compute the mass m necessary to achieve deflections of $10R_e$ and $2R_e$. This mass should be interpreted as the minimum required mass to achieve the given deflection and at the specified $\bar{v}_\infty$. The results are plotted in Fig. 6. The large mass requirement roughly 17 years prior to the potential 2040 Earth impact corresponds to when the asteroid is passing through the keyhole (i.e., Earth collision cannot be avoided for deflections that occur in the keyhole). From Fig. 6, it is apparent that a mission striking the asteroid at the perihelion prior to the keyhole passage (June 2021) would require at least a 1,000-kg impactor with $v_\infty = 10$ km/s. This mass is well within the capability of the Atlas V (401), as indicated in Fig. 5. Alternatively, for a 5,000-kg impactor spacecraft, that might be launched with an Atlas V (551), with $v_\infty = 15$ km/s we can wait all the way to 0.9 years prior to the keyhole passage (March 2022) and still achieve the deflection of $10R_e$. For post-keyhole deflections of $10R_e$, it is possible to wait up to 6.7 years prior to the projected Earth collision (March 2033), where the mass of the impactor should be at least 7,600 kg with $v_\infty = 15$ km/s. If the desired deflection is only $2R_e$, it is in theory possible to wait up to 1.6 years before the Earth impact (July 2038), and the impactor mass should be 6,000 kg and $v_\infty = 15$ km/s. As indicated by Fig. 5, the Delta IV Heavy is the only launch vehicle capable of delivering these masses for post-keyhole mission deflections. We want to stress that while Fig. 6 gives us intuition of the trade space between m and v_∞, depending on orbit phasing and launch vehicle requirements, ultimately trajectories may or may not exist for these masses and v_∞s. However, Fig. 6 is useful for determining an upper bound on the latest possible time to deflect the asteroid.

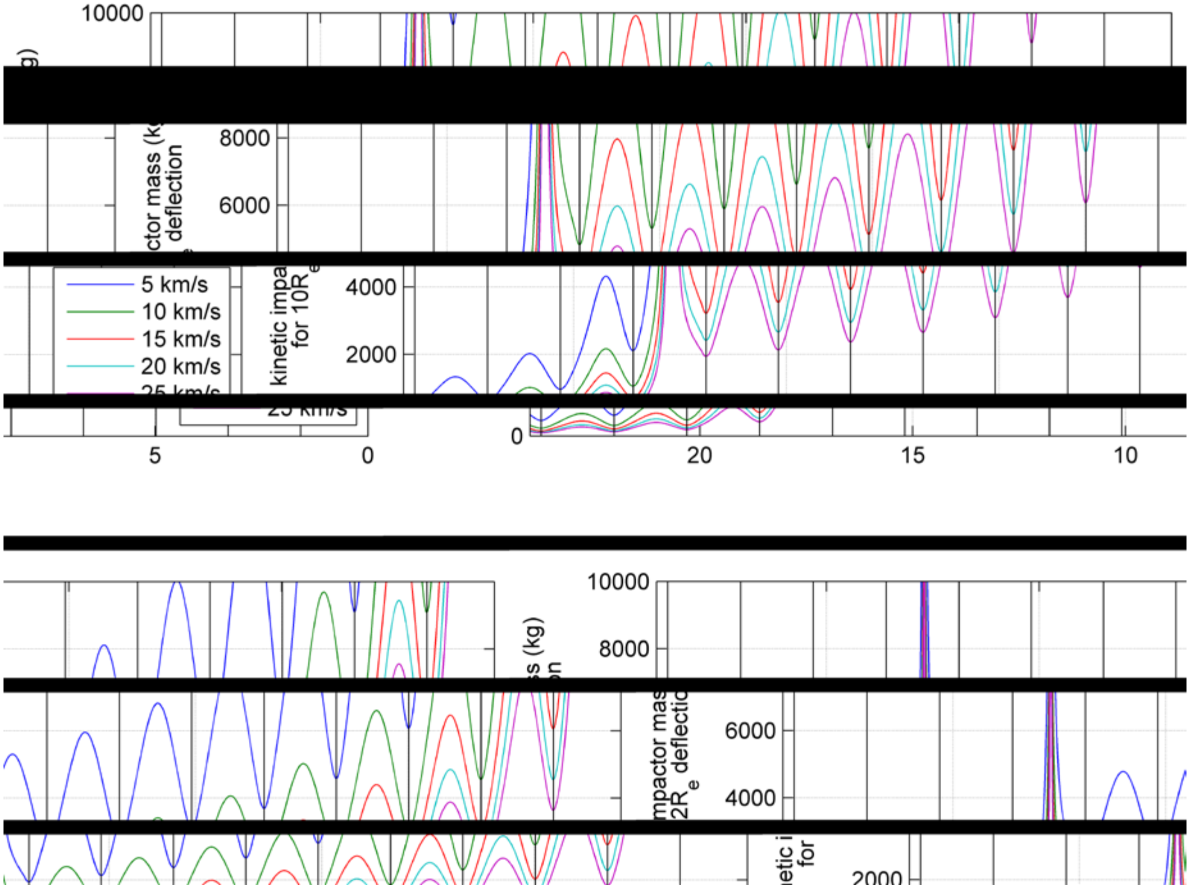

Figure 6. Minimum required mass for $10R_e$ (top) and $2R_e$ (bottom) deflections in years before potential 2040 Earth impact, black vertical lines correspond to 2011 AG5 perihelia.

3.2. Chemical Options

A near exhaustive search for all options that rely on chemical propulsion is performed. For the pre-keyhole investigation, we scan through every combination of launch date and arrival date from mid-2017 to 2023, allowing for up to two gravity assists with either Mercury, Venus, Earth, Mars, or Jupiter. The solutions are the Lambert arcs between the bodies at the various epochs. The primary launch vehicle considered is the Atlas V (401), where the C3 declinations are limited to ±28.5 deg. Post-launch maneuvers, including the insertion Δv for the rendezvous spacecraft, are modeled with a liquid bi-propellant system (specific impulse of 323 s) and the velocity is decremented according to the rocket equation.

The results of our search for pre-keyhole deflection mission opportunities are provided in Fig. 7. Only trajectories with approach phases less than 90 deg and deflections of $2R_e$-$12R_e$ are plotted in Fig. 7. The mission options are colored by deflection distance from Earth in 2040. From the figure, we can conclude that there are many opportunities for deflecting the asteroid prior to the keyhole passage, however, we are particularly interested in the red islands, as they correspond to deflections of approximately $10R_e$. For a nominal mission strategy, we select the latest possible launch, or launch in early 2020. The kinetic impactor spacecraft arrives at the asteroid in mid-2021, or 1.7 year prior to the keyhole passage. The trajectory is plotted in Fig. 8, where it is apparent that the impact occurs at the ascending node of 2011 AG5's orbit, exactly one orbital revolution prior to the keyhole passage.

As indicated by Fig. 9, there are also many options for a rendezvous spacecraft for the Atlas V (401) launch vehicle. In Fig. 9 the color corresponds to delivered mass. A typical spacecraft with the appropriate instruments is in the 500-1,000 kg range. As a baseline mission scenario, we select a trajectory option for a 1,000-kg rendezvous spacecraft that arrives at the asteroid a few months prior to the launch of the impactor spacecraft. In this way the rendezvous spacecraft can be used to strengthen the case for launching the impactor spacecraft by more precisely determining the orbit of 2011 AG5. The trajectory for the rendezvous spacecraft is plotted along with the impactor spacecraft in Fig. 8, and the relevant mission parameters for both spacecraft are tabulated in Table 2. In Table 2 and the following itinerary tables, the v_∞ angle is the angle between $\bar{v}_\infty$ and $\bar{V}$, where a near 180 deg angle corresponds to impacts with the asteroid that decrease its heliocentric orbital energy.

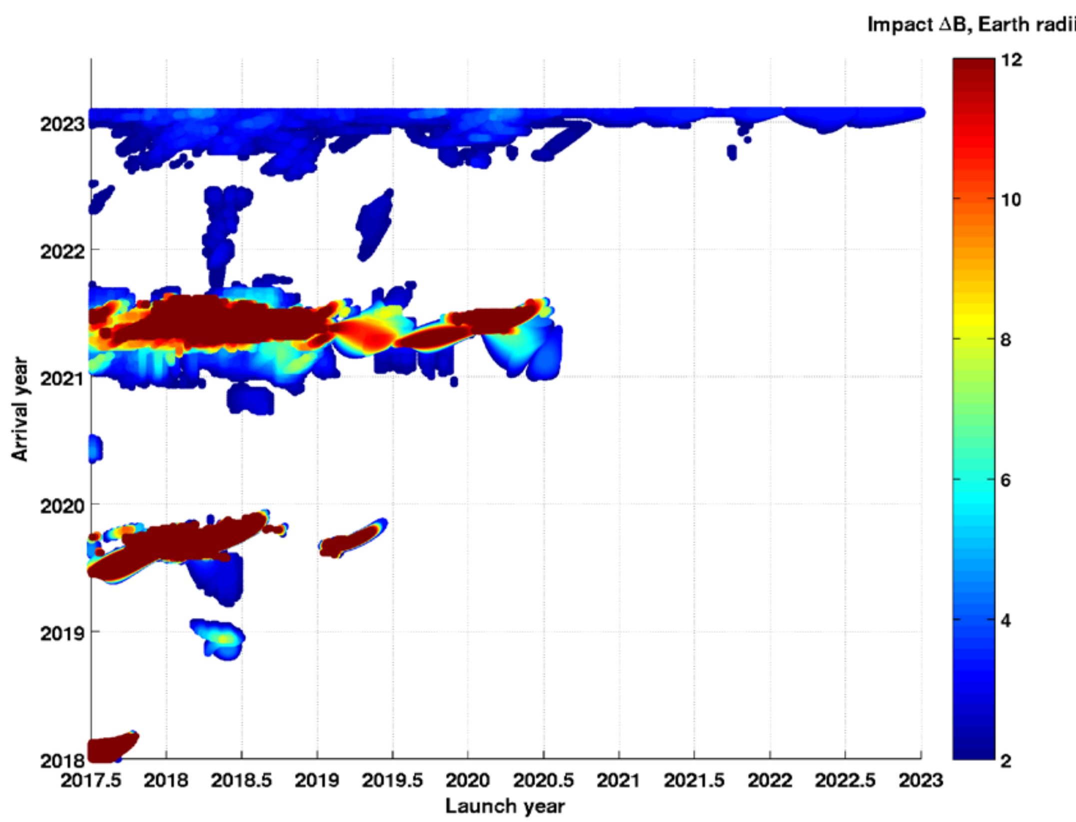

Figure 7. Results for scan of trajectories from Earth launch with Atlas V (401) in the range mid-2017 to 2023 arriving at 2011 AG5 before the 2023 keyhole passage. Colors indicate *b*-plane deflection of the asteroid for the potential 2040 Earth impact.

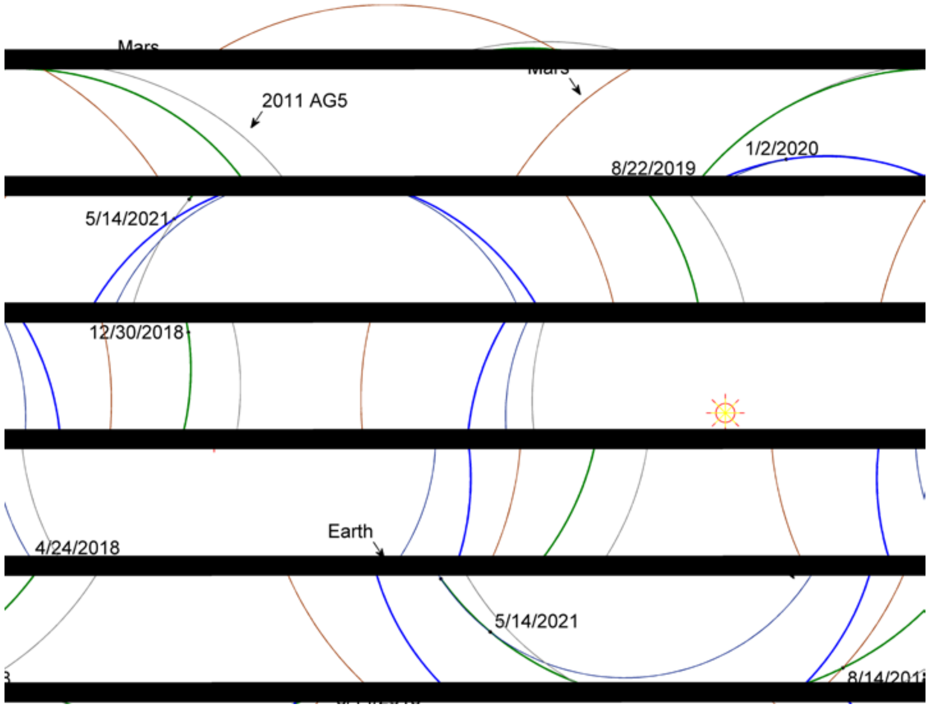

Figure 8. Pre-keyhole chemical mission, corresponding itinerary is in Table 2.

Table 2. Itinerary for pre-keyhole chemical mission for both Impactor Spacecraft (IS) and Rendezvous Spacecraft (RS).

Date	Event	Description
24 Apr. 2018	RS Launch	Atlas V (401) C3 = 26.3 km^2/s^2 Declination = -26.3 deg Launch Mass = 2,015 kg
14 Aug. 2018	RS Mars Gravity Assist	Flyby Altitude = 500 km v_∞ = 9.71 km/s
30 Dec. 2018	RS Deep-Space Maneuver	Δv = 0.76 km/s
22 Aug. 2019	RS Orbit Insertion	Approach Phase = 86.5 deg Δv = 0.86 km/s Spacecraft Mass = 1,194 kg Flight Time = 484 day
2 Jan. 2020	IS Launch	Atlas V (401) C3 = 6.1 km^2/s^2 Declination = -5.3 deg Launch Mass = 3,043 kg
5 May 2021	IS Impact	Approach Phase = 12.0 deg v_∞ = 12.53 km/s v_∞ Angle = 109.8 deg Spacecraft Mass = 3,043 kg Flight Time = 498 day Est. Deflection = 10.9R_e

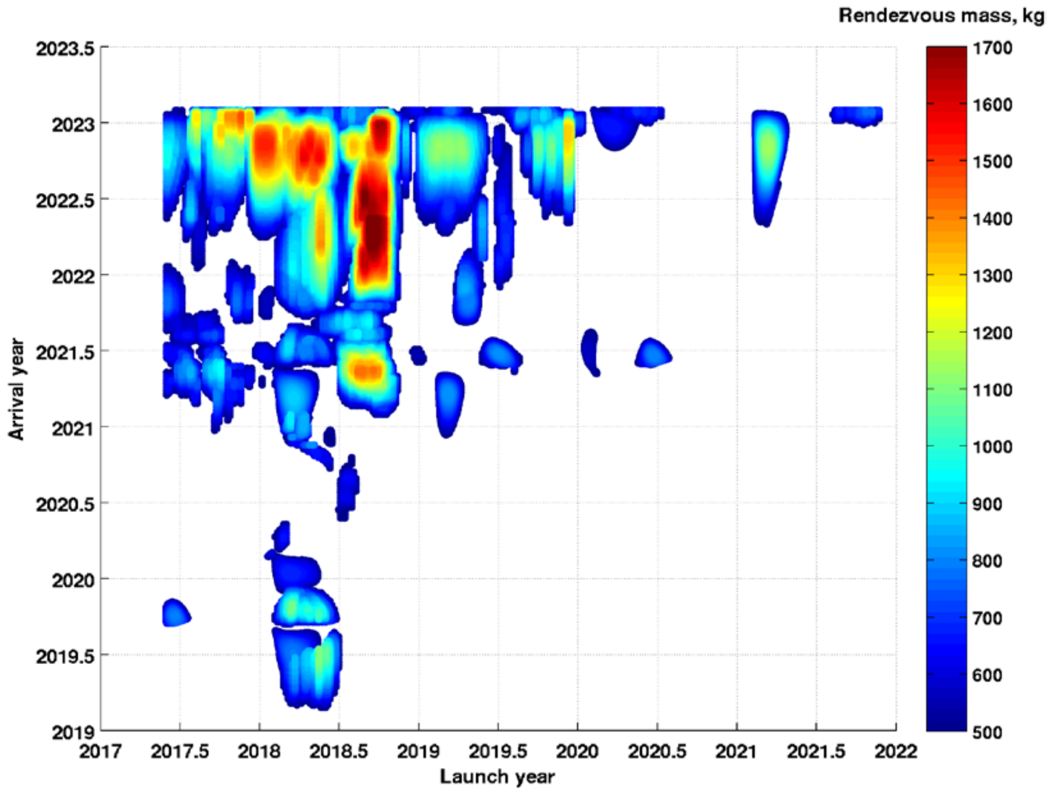

Figure 9. Options for sending 500-1700 kg rendezvous spacecraft to 2011 AG5 prior to the impactor spacecraft. The rendezvous spacecraft would provide useful information about the asteroid and more precisely determine its orbit for terminal guidance.

Since post-keyhole missions for deflecting the asteroid require significantly more energy, we use the Delta IV Heavy and again analyze the latest possible opportunities for deflecting the asteroid. The results of our search are presented in Fig. 10, where recall that only approach phases less than 90 deg and deflections of $2R_e$-$12R_e$ are included in the plot. The horizontal islands correspond to impacts near perihelion, where impacting the asteroid any place else yields deflections less than $2R_e$. From Fig. 10, the latest possible launch that achieves a deflection of $10R_e$ is in 2025, whereas launch opportunities are available all the way up to early 2036 for deflections as low as $2R_e$. We also investigate post-keyhole options for a rendezvous spacecraft with an Altas V (401), we found there are many opportunities. In Fig. 12 we present a potential post-keyhole mission for a $10R_e$ deflection, including a rendezvous spacecraft, and the relevant mission parameters are summarized in Table 3.

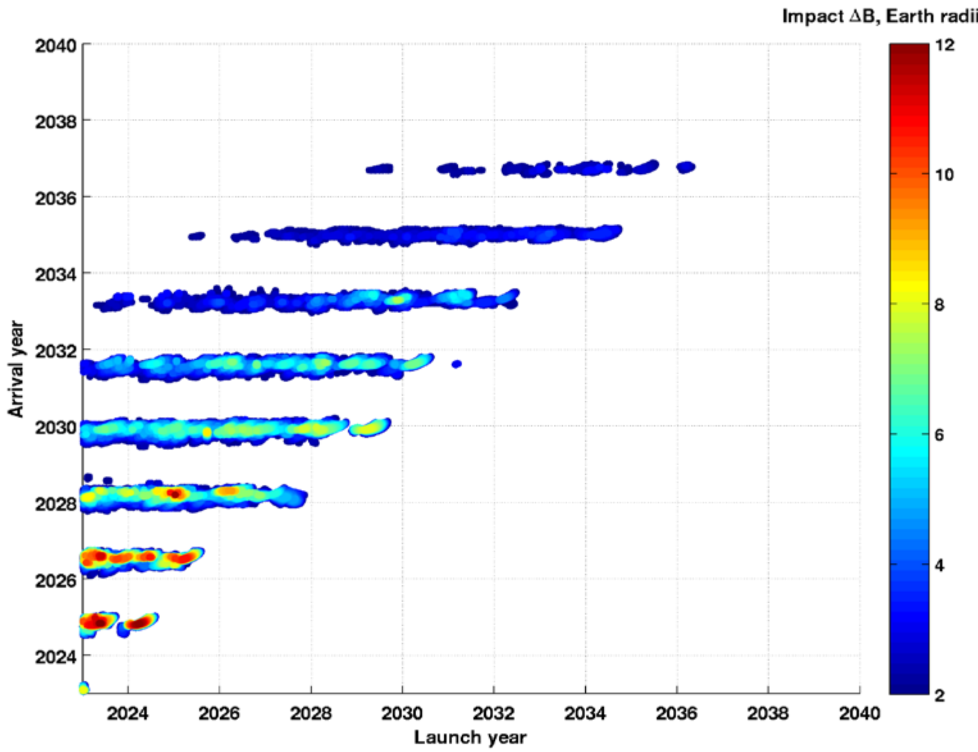

Figure 10. Post-keyhole deflection options for the Delta IV Heavy launch vehicle. The latest launch date that achieves $10R_e$ deflection is in 2025.

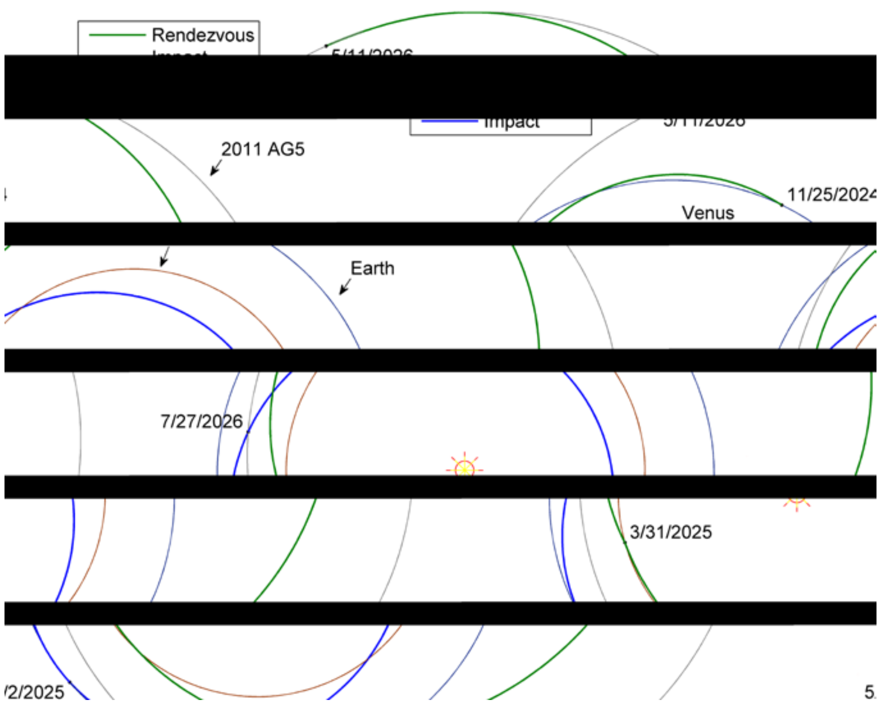

Figure 11. Post-keyhole chemical mission, corresponding itinerary is in Table 3.

Table 3. Itinerary for post-keyhole chemical mission for Impactor Spacecraft (IS) and Rendezvous Spacecraft (RS).

Date	Event	Description
25 Nov. 2024	RS Launch	Atlas V (401) $C3 = 26.5\ km^2/s^2$ Declination = 25.2 deg Launch Mass = 2,008 kg
31 Mar. 2025	RS Venus Gravity Assist	Flyby Altitude = 300 km $v_\infty = 7.54$ km/s
2 May 2025	IS Launch	Delta IV Heavy $C3 = 21.9\ km^2/s^2$ Declination = 5.8 deg Launch Mass = 6,273 kg
11 May 2026	RS Orbit Insertion	Approach Phase = 87.0 deg $\Delta v = 2.18$ km/s Spacecraft Mass = 1,010 kg Flight Time = 532 day
27 July 2026	IS Impact	Approach Phase = 38.5 deg $v_\infty = 14.16$ km/s v_∞ Angle = 132.2 deg Spacecraft Mass = 6,273 kg Flight Time = 451 day Est. Deflection = $10.0R_e$

3.3. Solar-Electric Propulsion Options

Designing trajectories that rely on solar-electric propulsion (SEP) for transporting the spacecraft to the asteroid is significantly more challenging. Since the problem of low-thrust is infinite dimensional, it is challenging to obtain a complete picture of the design space. To cope with these challenges, we resort to local optimization methods to find best case point designs, and compute multiple solutions by sampling different phasing for the initial guesses. The software used to design the trajectories is MALTO [15], where the objective function Eq. 3 was activated for designing the optimization. The SEP impactor has four BPT-4000s engines, operating in the high-Isp configuration and with a 90% duty cycle. The input power of the SEP system from the arrays is roughly 20 kW. There are many options for deflecting the asteroid both post- and pre-keyhole, however, only a few of the options found are presented here (see Table 4). In order to build-up energy relative to the asteroid in a short period of time, the pre-keyhole opportunities in Table 4 also use gravity assist. Earlier launches (in late 2018) can deflect the asteroid by more than $80R_e$ using the Atlas V (551) launch vehicle. Since deflections of only 10Re are necessary, the launch date is delayed and new trajectories are computed that arrive at the asteroid's perihelion one orbital period later. The latest possible opportunity prior to the key-hole passage for deflecting the asteroid at least $10R_e$ in 2040 corresponds to a launch in August 2020. In Fig. 12, we present a possible mission to the asteroid that utilizes this impactor spacecraft, and the corresponding mission itinerary and relevant mission parameters are available in Table 5. In terms of deflecting the asteroid prior to the keyhole passage, we found SEP performance to be comparable to chemical propulsion.

Table 4. Pre- and post-keyhole (grey) impactor SEP missions and deflection (yellow).

Launch Vehicle	Atlas V (551)	Atlas V (551)	Atlas V (401)	Atlas V (551)	Delta IV Heavy	Atlas V (551)
Launch Date	9/1/18	9/1/18	7/20/20	8/29/20	3/21/27	3/6/35
C3 (km^2/s^2)	11.9	17.7	14.1	34.8	6.6	19.9
Launch Mass (kg)	5,118	4,246	2,611	3,363	8,272	4,436
Gravity Assist	Venus 12/7/18	Earth 3/8/19	Venus 12/29/20	Venus 1/13/21	-	-
Arrival Date	10/8/19	9/19/19	8/14/21	9/6/21	12/6/29	10/4/36
v_∞ (km/s)	12.7	17.3	9.1	9.1	20.4	19.0
Approach Phase (deg)	50.9	42.5	85.0	89.5	34.5	54.6
Arrival Mass (kg)	4,176	2,948	2,025	2,334	5,909	2,977
Flight Time (day)	402	383	390	374	991	578
Deflection (R_e)	87	80	14	13	10	2

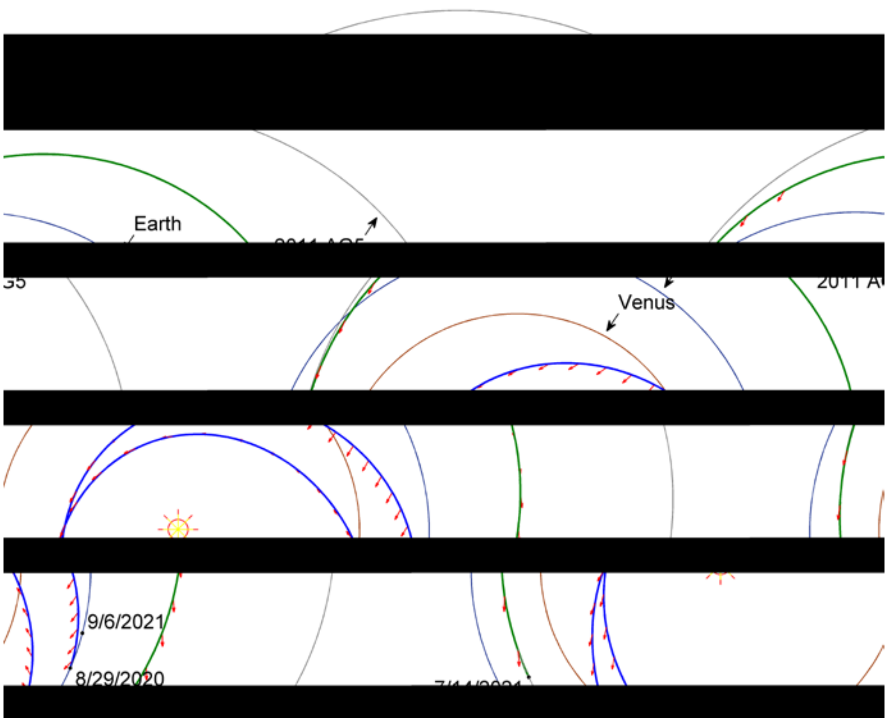

Figure 12. Pre-keyhole SEP mission, corresponding itinerary is in Table 5.

Due to the long time span between the keyhole passage and potential asteroid impact, SEP might prove more useful than chemical for later missions (i.e., between 2027-2036). With SEP there is an option of trading flight time for increased impactor mass or relative velocity, and exploiting the higher efficiency of the SEP system over the launch vehicle to build-up energy with respect to the asteroid. Although these trajectories require more years to fly, they ultimately allow for later launches than any of the options available for chemical propulsion. There are numerous spiral-type trajectories where the impactor is launched into an orbit interior to the Earth's, and the perihelion is slowly reduced while keeping the aphelion at roughly 1 AU. In Table 4 we present the latest possible option found for a $10R_e$ deflection using the Delta IV Heavy launch vehicle. This option launches roughly two years after the last chemical option in Fig. 10, and arrives at the asteroid four years later. The latest option for deflecting the asteroid $2R_e$ can be found in the last column of Table 4, and a possible mission that uses this trajectory is presented in Fig. 13 and Table 6. This option launches with an Atlas V (551) a year before the last chemical option for the Delta IV Heavy, and arrives at the asteroid a few years earlier; however, there is a significant reduction in the launch vehicle size with SEP. Chemical options do not exist that are capable of launching this late with the Atlas V (551) while still deflecting the asteroid at least $2R_e$.

Table 5. Itinerary for pre-keyhole SEP mission for Impactor Spacecraft (IS) and Rendezvous Spacecraft (RS).

Date	Event	Description
21 May 2020	RS Launch	Atlas V (401) C3 = 4.3 km^2/s^2 Declination = -27.2 deg Launch Mass = 3,174 kg
29 Aug. 2020	IS Launch	Atlas V (551) C3 = 34.8 km^2/s^2 Declination = -16.8 deg Launch Mass = 3,363 kg
13 Jan. 2021	IS Venus Gravity Assist	Flyby Altitude = 1,531 km v_∞ = 17.22 km/s
14 July 2021	RS Rendezvous	Total Δv = 5.47 km/s Spacecraft Mass = 2,405 kg Flight Time = 420 day
6 Sept. 2021	IS Impact	Total Δv = 7.21 km/s Approach Phase = 89.5 deg v_∞ = 9.07 km/s v_∞ Angle = 155.9 deg Spacecraft Mass = 2,334 kg Flight Time = 374 day Est. Deflection = $13.4R_e$

For the rendezvous spacecraft, the size of the SEP is reduced to two BPT-4000 engines, for a baseline 10 kW SEP system. The trajectories for the rendezvous spacecraft are also designed in MALTO, where the performance index is changed to maximize the delivered mass. In general there are many pre- and post-keyhole options for rendezvousing with the asteroid, some of which are included in Table 7. For the mission scenarios presented in this section, an option for the rendezvous spacecraft is selected from Table 7 so that the spacecraft arrives at least three months prior to the impactor spacecraft to sufficiently characterize the asteroid and aid in navigation. Of course, any of the chemical rendezvous trajectories from Fig. 9 can be used in lieu of a rendezvous SEP spacecraft and be combined with one of the SEP impactor spacecraft options presented in Table 4.

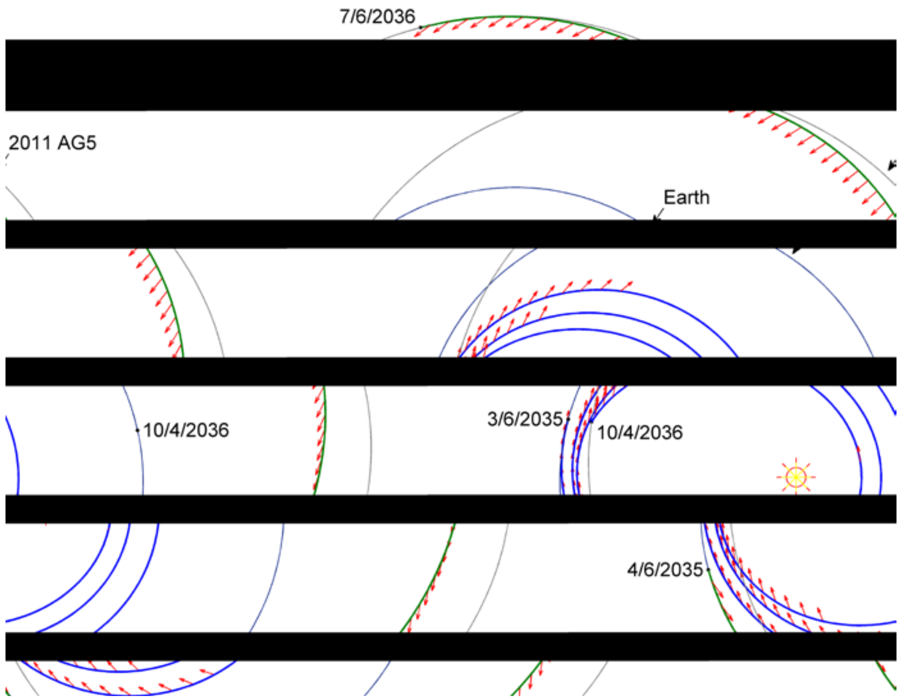

Figure 13. Post-keyhole spiraling SEP mission, corresponding itinerary is in Table 6.

Table 6. Itinerary for post-keyhole SEP mission for Impactor Spacecraft (IS) and Rendezvous Spacecraft (RS).

Date	Event	Description
6 Mar. 2035	IS Launch	Atlas V (551) C3 = 19.9 km^2/s^2 Declination = 21.1 deg Launch Mass = 4,436 kg
6 Apr. 2035	RS Launch	Atlas V (401) C3 = 4.9 km^2/s^2 Declination = -14.1 deg Launch Mass = 3,134 kg
6 July 2036	RS Rendezvous	Total Δv = 6.68 km/s Spacecraft Mass = 2,234 kg Flight Time = 457 day
4 Oct 2036	IS Impact	Total Δv = 7.87 km/s Approach Phase = 54.6 deg v_∞ = 18.98 km/s v_∞ Angle = 150.8 deg Spacecraft Mass = 2,977 kg Flight Time = 578 day Est. Deflection = 2.1R_e

Table 7. Selection of pre- and post-keyhole (grey) rendezvous options.

Launch Vehicle	Atlas V (401)	Atlas V (551)	Atlas V (401)	Atlas V (551)	Atlas V (401)	Atlas V (401)
Launch Date	3/16/18	9/1/18	5/21/20	5/29/20	3/1/28	4/6/35
C3 (km^2/s^2)	5.7	68.1	4.3	11.0	4.0	4.9
Launch Mass (kg)	3,088	1,666	3,174	4,262	3,193	3,134
Arrival Date	5/21/20	5/21/20	7/14/21	7/7/21	9/7/29	7/6/36
Arrival Mass (kg)	2,466	1,000	2,405	3,087	2,496	2,234
Flight Time (day)	796	628	420	404	554	457

3.4. Possible Microsat Deflection Mission

One option that has been unexplored by previous researchers is the possibility of using multiple microsats to deflect an asteroid. At the Jet Propulsion Laboratory, new thruster technology capable of specific impulses in excess of 5,000 s and with thrusts as high as 30 mN is in development. The thrusters, called Micro-Fluidic Electrospray Propulsion (MEP), use high electric fields to extract and accelerate charged particles from the solid state indium propellant. The projected dry mass for a single MEP module can be as low as 100 grams.

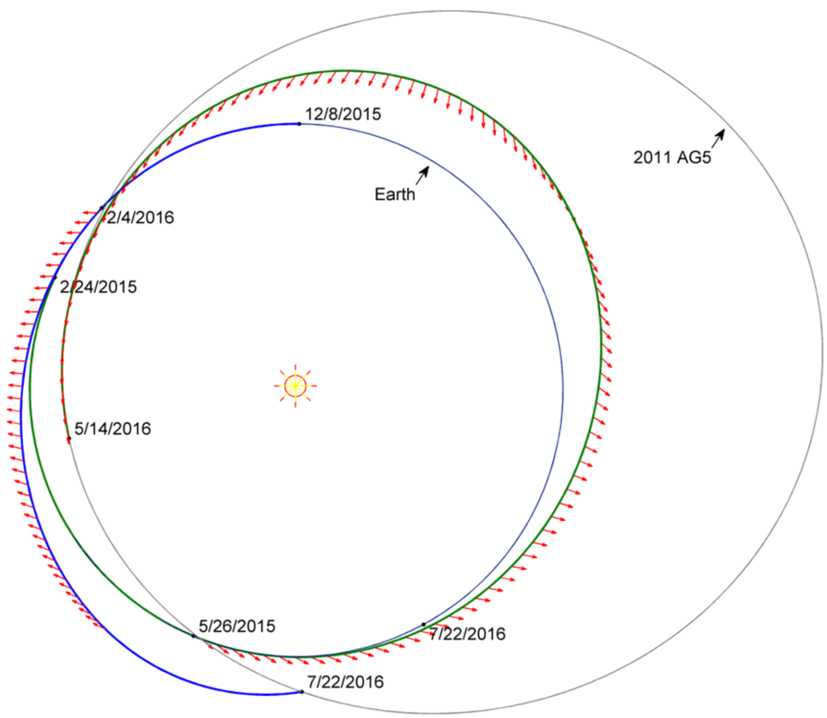

Figure 14. Machine Gun microsat mission for deflecting 2011 AG5, rendezvous spacecraft (green) and 15 kinetic impators (blue) sequentially impacting the asteroid achieve deflection greater than 10R_e in the 2040 Earth *b*-plane.

A potential microsat mission scenario that utilizes MEP thruster capability is presented in Fig. 14. A single 95-kg rendezvous spacecraft equipped with one 50 W MEP module piggybacks to geostationary orbit (GEO) in February 2015, where it takes roughly 95 days to spiral to escape, and 1.2 years to rendezvous with the asteroid 2011 AG5. Then, in late 2015, 15 160-kg impactor spacecraft also piggyback to GEO. The impactor spacecraft utilize three MEP modules and are powered at 100 W. After 50 days of spiraling around the Earth to escape and 220 days of interplanetary travel, the spacecraft arrive at 2011 AG5 and sequentially impact it, each contributing a change of $1R_e$ in the 2040 b-plane, so that the net deflection is $15R_e$. We call this approach a Machine Gun mission, since the precision targeting of the asteroid for impact can be enhanced as the spacecraft are dispatched to the asteroid. Due to the projected low cost for each spacecraft, we allow the possibility for the first few spacecraft to miss impacting the asteroid, and are used for tuning the course of the remaining spacecraft to ensure that at least 10 of them will impact. We expect the overall cost of the mission to be significantly cheaper than the cost of the missions discussed in the previous sections, and we note that a microsat simply rendezvousing with the asteroid to gather information about 2011 AG5 is a significant return in itself for such a small cost.

4. Impactor Terminal Guidance Considerations

A key component of a kinetic-impactor deflection mission is the technical challenge of hitting a small asteroid at high velocity. Fortunately, the Deep Impact (DI) mission [9], which impacted the 6-km comet Tempel 1 in July 2005 at a velocity of 10.5 km/s, has shown that such a scenario is feasible. The primary technology that enabled the impact is the closed-loop onboard autonomous navigation system, or AutoNav. For DI, AutoNav on the Impactor spacecraft was used to determine its own orbit relative to the comet and perform maneuvers to guide it to a lit area on the comet's surface. The onboard capability reduced the turnaround time for controlling the trajectory to minutes and seconds, as opposed to hours or days; this is what enabled the accuracy needed to hit the target. The same technology was also used on the DI Flyby spacecraft to view the impact, as well as on other comet missions (Deep Space 1, Stardust, Stardust-NExT, and EPOXI) to perform closed-loop nucleus tracking through their respective encounters.

The asteroid deflection missions discussed in this report would not have to deal with an obscuring cloud of cometary dust and gas but there would be additional challenges beyond those faced by DI. These challenges include the possibility of a much greater approach velocity, a target diameter perhaps two orders of magnitude smaller, and approach lighting conditions that may not be as favorable. However, these challenges can be overcome with only modest improvements or changes to AutoNav and/or the spacecraft, rather than expensive new technologies. Necessary hardware modifications would include cameras with longer focal lengths and higher sensitivities to image the smaller objects at large distances, faster processors to speed up computations, and more nimble spacecraft that can turn faster and implement maneuvers more quickly. Software improvements include upgrades to AutoNav for ease of use (for example, in updating late-breaking parameters), faster image processing techniques, and improved orbit determination filter performance for greater accuracy. Many of these changes have already been prototyped, and none require expensive new development work.

Mission scenarios could also be modified to increase the chances of success. For example, maneuvers could be implemented as late as a few minutes before impact (DI executed its last maneuver 12.5 minutes prior to impact). We have also narrowed the search for deflection missions to have approach phases of less than 90 deg to avoid unfavorable approach lighting conditions and kept approach velocities at a level similar to that of DI.

5. Mission Timeline and Contingencies

While there are many options at hand and the choice of an optimal deflection strategy would require more study, it is worth considering the deflection mission development timeline, taking as hypothesis that 2011 AG5 is indeed on a collision trajectory. We assume that Mission Phase A/B would require 24 months, and would take place from late 2013 through late 2015 for both the rendezvous and impactor mission options. Phase C/D for both missions, assumed to require 30-36 months, would initiate at the beginning of 2016 at which time the impact probability could be ~50%. These are routine mission development timelines, achieved many times in the last two decades for Planetary Science Discovery and New Frontiers class missions. A rendezvous mission could then be launched in late 2018, arriving in mid-2020. This mission would serve as a beacon to confirm or eliminate the 2040 impact possibility before the launch of the deflection mission in late 2020. In the event that the Earth collision is confirmed or in the event of a failure of the rendezvous spacecraft, the impactor mission could still launch as scheduled, reaching the asteroid in mid-2021. The deflection could be confirmed by the rendezvous spacecraft or as a result of combined ground-based optical and radar observations in 2023.

6. Conclusion

There is a small chance that the asteroid 2011 AG5 will impact Earth in 2040. In the next few years, there are many options for observing the asteroid, and we are 99% confident that by 2017 we will confirm the asteroid will safely pass by Earth in 2040. In the small but unlikely chance we find that the asteroid is headed for the 2023 keyhole, we have developed numerous mission strategies for deflecting the asteroid with a kinetic impactor. In general, the pre-keyhole deflection missions require much less energy for moving the asteroid in the 2040 Earth *b*-plane. However, mission opportunities exist for deflecting the asteroid all the way up to five years prior to the projected impact date. While we find SEP comparable to chemical in terms of deflecting the asteroid prior to the keyhole passage, the longer post-keyhole time span allows for SEP missions to utilize the efficiency of the SEP system and allow for later impact dates. There are many opportunities for deflecting the asteroid, and we are confident the technology exists for the kinetic impactor mission should the need arise.

8. Acknowledgement

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