# Report on Asteroid 2011 AG5 Hazard Assessment and Contingency Planning

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This report provides results from a preliminary analysis of a potentially hazardous asteroid scenario carried out at the Jet Propulsion Laboratory during the period from March 26 – April 26, 2012.

## Introduction

Extensive analysis of the current orbit parameters of 2011AG5 shows that it currently has a 1-in-500 chance of impacting the Earth on February 5, 2040. With an estimated diameter (based on an average albedo) of about 140 meters and a calculated impact velocity of 15 kilometers (km) per second, the asteroid would release about 100 megatons of energy should it impact. In order for the asteroid to impact Earth, it will have to pass through a small 365-km-wide region in space (called a "keyhole"), 1.8 million km from Earth, during a close Earth encounter on February 3, 2023. The trajectory of 2011 AG5 as currently understood does not indicate that the asteroid will pass through this keyhole, but the current extent of uncertainty involved with our knowledge of 2011 AG5's trajectory does allow for a passage through the keyhole, with a 1-in-500 chance. If 2011 AG5 should pass through the keyhole, the orbit change caused by the encounter would put the asteroid on a precise 17:10 resonant return to Earth (17 Earth orbits and 10 asteroid orbits about the Sun), leading to an Earth collision on February 5, 2040.

Near-Earth asteroid 2011 AG5 was discovered on January 8, 2011 at Mt. Lemmon, Arizona as part of the NASA-sponsored Catalina Sky Survey, a component of NASA's Near-Earth Object (NEO) Observation Program. Archival, pre-discovery astrometric data from images taken by the NASA-sponsored Pan-STARRS NEO survey prior to the asteroid's official discovery extended the observation data arc back to November 8, 2010. The asteroid was most recently observed on September 21, 2011, but has since been unobservable due to its faintness and proximity to the Sun's position in the sky as observed from Earth.

The orbit of 2011 AG5 about the Sun is shown in Fig. 1, along with its position on May 1, 2012 and the orbits and positions of the Earth and Mars, all projected into the ecliptic plane (the plane of the Earth's orbit). The asteroid's orbital plane is inclined only slightly to the ecliptic plane – by less than 4 degrees. Orbits that cross one another in a diagram like this do not necessarily intersect in three-dimensional space, but in the case of 2011 AG5, the asteroid's orbit does intersect the Earth's orbit in three dimensions, at the point indicated.

It is important to note that, to date, 2011 AG5 has only been observed through about half of its 625-day orbit, and as a result, its orbital motion is not known well enough to predict its position accurately decades from now. Figure 2 shows the predicted situation on Feb. 5, 2040 at 3:50 UTC, zoomed in at the orbital intersection point, and projected into the ecliptic plane, as in Fig. 1. We can predict that the Earth will be at the indicated intersection point at that moment, and we can predict that the nominal position of the asteroid will be nearby, but the uncertainty in the asteroid's predicted position (shown in red) is large, spanning a long narrow region along the asteroid's orbit. The tiny segment of the asteroid's uncertainty region that intersects the Earth maps to a line across the Earth's southern hemisphere – passing through the central region of South America.

When 2011 AG5 emerges from the daytime sky and is observed again, its orbit will be recalculated and its orbital motion will become much better defined. The uncertainty in the asteroid's predicted position in 2040 will then shrink, and in all likelihood, the probability of Earth impact will drop to essentially zero. But there is a small chance that the nominal predicted position in 2040 could get even closer to the Earth, in which case the impact probability could rise to as high as 10-15%.

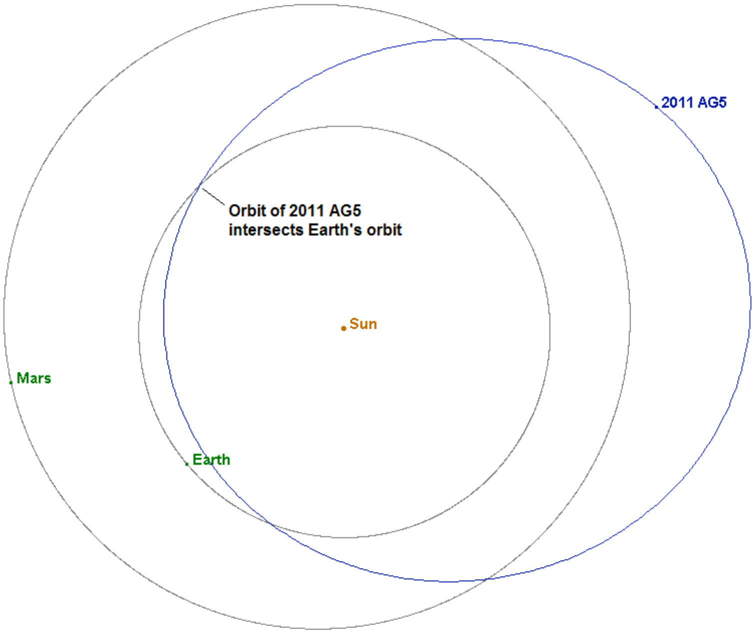

Figure 1. The orbits about the Sun of asteroid 2011 AG5, Earth and Mars, showing their positions on May 1, 2012, and the location at which the asteroid's orbit intersects the Earth's orbit in 3 dimensions.

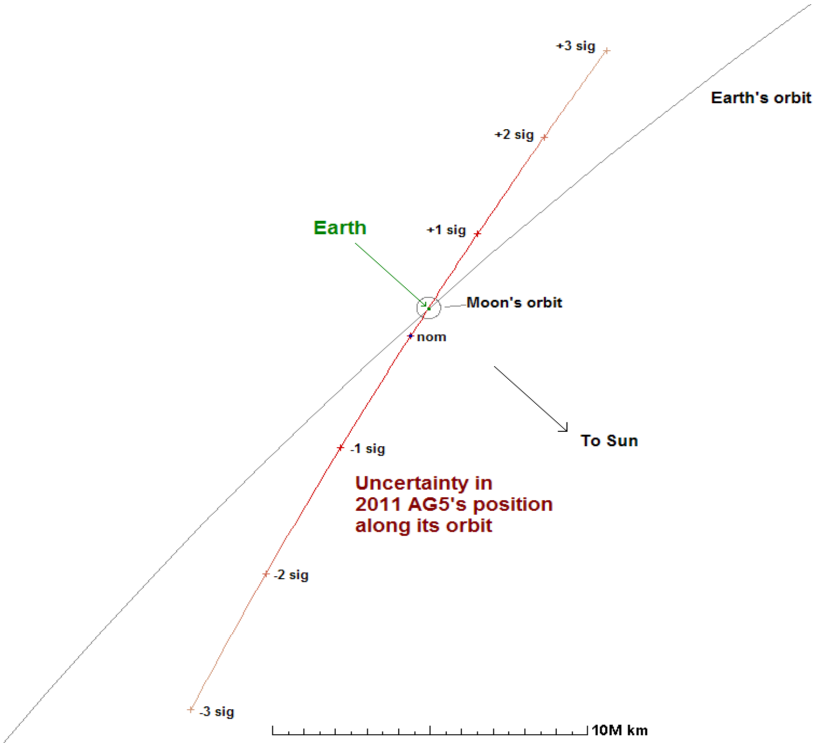

Figure 2. A close-up of the orbital intersection point on February 5, 2040, showing the Earth's position (in green) and the large uncertainty in the asteroid's predicted position (long red line along the asteroid's orbit). The nominal predicted position of the asteroid is shown ("nom"), as are the ±1, 2 and 3-sigma uncertainty positions.

## Observability Opportunities for 2011 AG5 During 2012 – 2023

In order to determine whether or not asteroid 2011 AG5 is on an impacting trajectory, we need to significantly reduce its orbital uncertainties, which we can do by making additional observations and measuring its position. The asteroid is currently on the opposite side of the Sun from the Earth and hence unobservable. Figure 3 shows the future motion of 2011 AG5, plotted in a rotating reference frame in which the Earth and Earth-Sun line are fixed. This frame makes it easy to see when the angle between the Earth-Sun line and the Earth-asteroid line (the "Solar Elongation") is sufficiently large that observations are possible. For example, when this angle is small, an object is above the horizon only in the daytime and is therefore unobservable. The figure also shows how the Earth- asteroid distance varies with time: the asteroid will of course be fainter at larger distances.

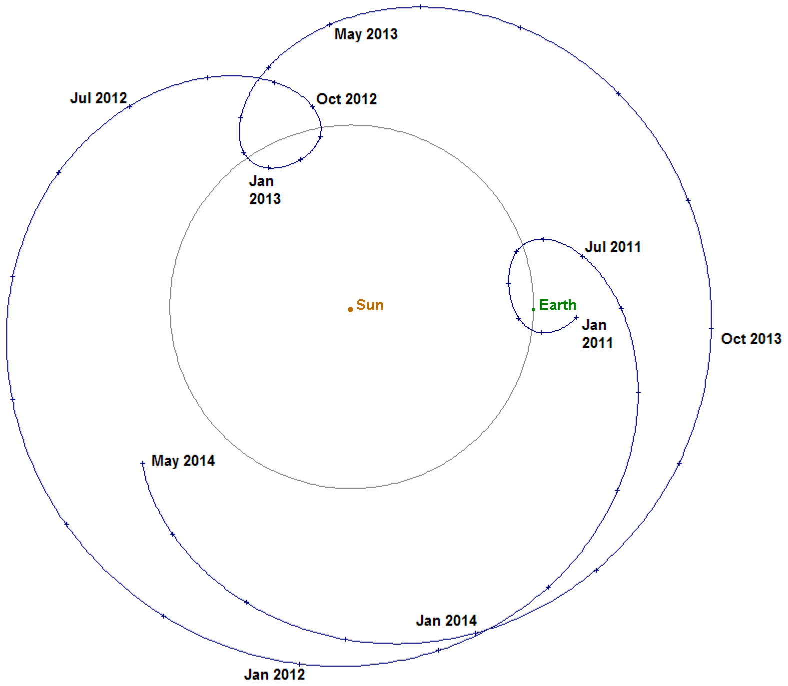

Figure 3. The motion of asteroid 2011 AG5 from discovery through May 2014, displayed in a rotating reference system in which the position of the Earth and direction of the Earth-Sun line are fixed. In October 2012, the asteroid will be only 40° from the Sun as seen from the Earth, and quite distant, whereas in October 2013 this elongation angle will be closer to 180° (near solar opposition) and the asteroid will be much closer to Earth.

Several future observing opportunities are available for 2011 AG5, some markedly more challenging than others. The following table summarizes these opportunities:

| Date | Brightness (mag) | Solar Elong. (deg) | Remarks |
|---|---|---|---|
| **Oct. 2012** | 24.5 | 42 | Requires Keck. 'MKO12' |
| **Apr. 2013** | 25.5 | 50 | Requires HST. 'HST13' |
| **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 |

The observing opportunity in 2012 is very challenging. The asteroid will be extremely faint, and imaging will only be possible during morning twilight and near the horizon. While these observations are possible to obtain, they would require very favorable observing circumstances, even utilizing the largest telescope available, at the Keck Observatory. For this reason, observations should be scheduled for a series of half-nights to ensure success. Because of the extraordinary challenge of these observations, an astronomer who has experience observing faint objects at low solar elongations with the Keck Observatory should be consulted.

The Hubble Space Telescope (HST) observation opportunity in April 2013 would require an ancillary ground-based effort in advance of the HST observing period. The HST field of view is so small that it would likely have very few catalogued astrometric reference stars, if any. The expected HST star field thus would need to be astrometrically characterized by wide-field ground-based observations in order to use the HST field stars as astrometric standards. The timing is such that the 2012 Keck opportunity discussed above, if undertaken, could logically be expanded to include the HST star field characterization. The HST observing effort would require roughly 3 orbits, spread out over a week. The details of an HST observing plan should be coordinated with an experienced HST small-body observer.

The first two opportunities in the above table would require significant efforts to arrange and approve, probably requiring direct intervention from NASA HQ. This is because such observations would have limited science value relative to the observational resources required, and proposals for what would be considered significant time on these instruments would be unlikely to succeed through the traditional Telescope Allocation Committee (TAC) process. The timeliness of these observations would be their only advantage, since they could aid preparations for observing the more favorable September 2013 apparition. If NASA were to plan the April 2013 HST observations, it would be expected to also award the Keck time in 2012. It is possible that other instruments could be used to support the HST observations. But in every case, Director's Discretionary Time (DDT) would be the required avenue for scheduling, due to the perceived lack of science value of the observations. While DDT is usually only awarded for proposals that have a response time that is too short to follow the TAC process, it would make sense in this case to request the Keck/HST DDT early in order to minimize disruption to other observing efforts.

## Orbital Uncertainty Outlook with Future Observations

It is possible to estimate the evolution of uncertainty involved with predicting the 2040 encounter as determined by the expected future tracking opportunities for 2011 AG5. We have simulated a modest return of data from the series of observational opportunities tabulated above. Figure 4 shows the resulting time history of the 2040 encounter uncertainty. We can use the estimated uncertainty to compute the maximum possible impact probability (Fig. 5) by assuming that 2011 AG5 is indeed on an impact trajectory, and we can use this information to infer the likelihood that the 2040 impact will be eliminated in the future (Fig. 6). We neglect the prediction uncertainties associated with the Yarkovsky effect (a weak nongravitational force due to thermal re-radiation). At the present time, the orbit of AG5 is too poorly constrained for this factor to affect our results significantly. As our knowledge of the orbit improves, we eventually will have to contend with the Yarkovsky effect.

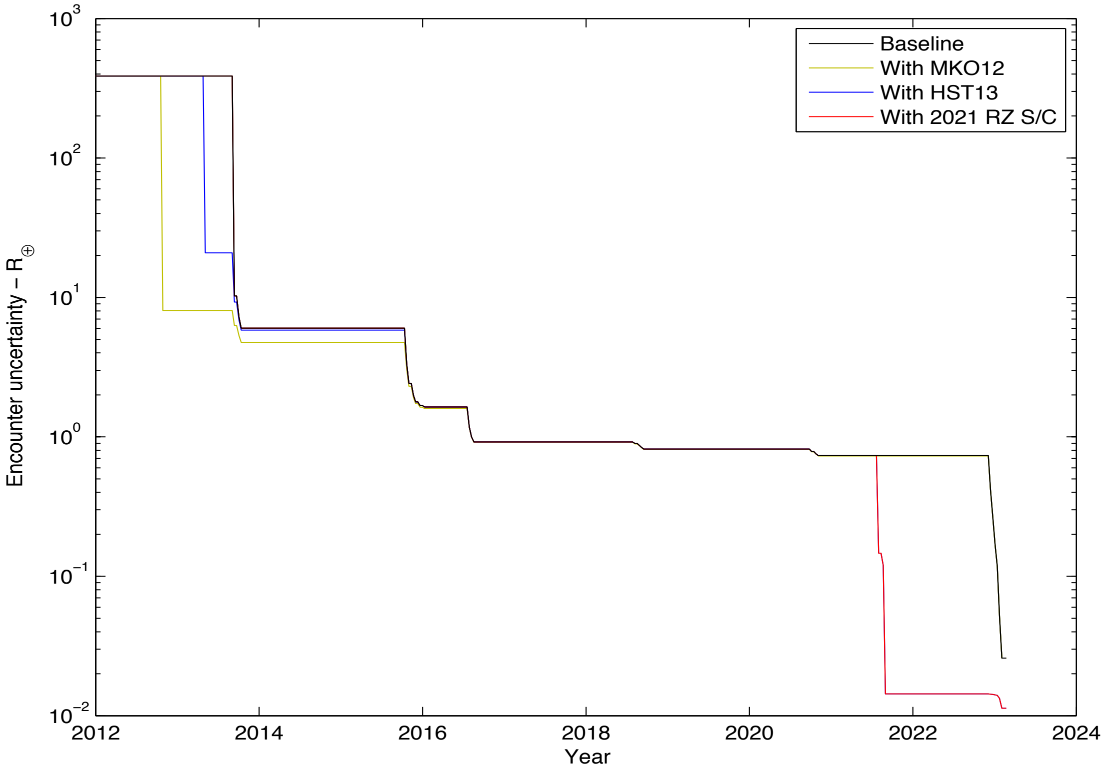

Figure 4. Time-history prediction of 2011 AG5's position uncertainty for the 2040 encounter, in Earth radii. The baseline case assumes ground-based optical observations in 2013, 2015, 2016, 2018, 2020 and 2023, collected by our routine NEO network assets. For the "MKO12" case, the baseline observations are augmented with Mauna Kea Observatory observations (i.e., Keck Observatory) starting in 2012. For the "HST13" case, the baseline observations are augmented with 2013 Hubble Space Telescope observations. In addition, the dramatic improvement seen in 2021 is the result of spacecraft tracking data and optical asteroid observations allowed by a rendezvous spacecraft in situ with the asteroid ("With 2021 RZ S/C"). The encounter uncertainty is defined here as the semimajor axis 1-sigma uncertainty ellipse in the 2040 b-plane (which is defined in the next section).

Conclusions resulting from Fig. 4 include:

- 2012 or 2013 observations should reduce the asteroid 2040 Earth encounter uncertainty from the current ~400 Earth radii down to 5-6 Earth radii.
- Further observations in 2015-2020 reduce this uncertainty down to ~1-2 Earth radii.
- Ground-based optical and radar observations in Feb. 2023 reduce this uncertainty to ~0.03 Earth radii, and an in-situ rendezvous spacecraft

arriving in 2021 can reduce the 2040 asteroid position uncertainty down to less than 0.02 Earth radii (~130 km).

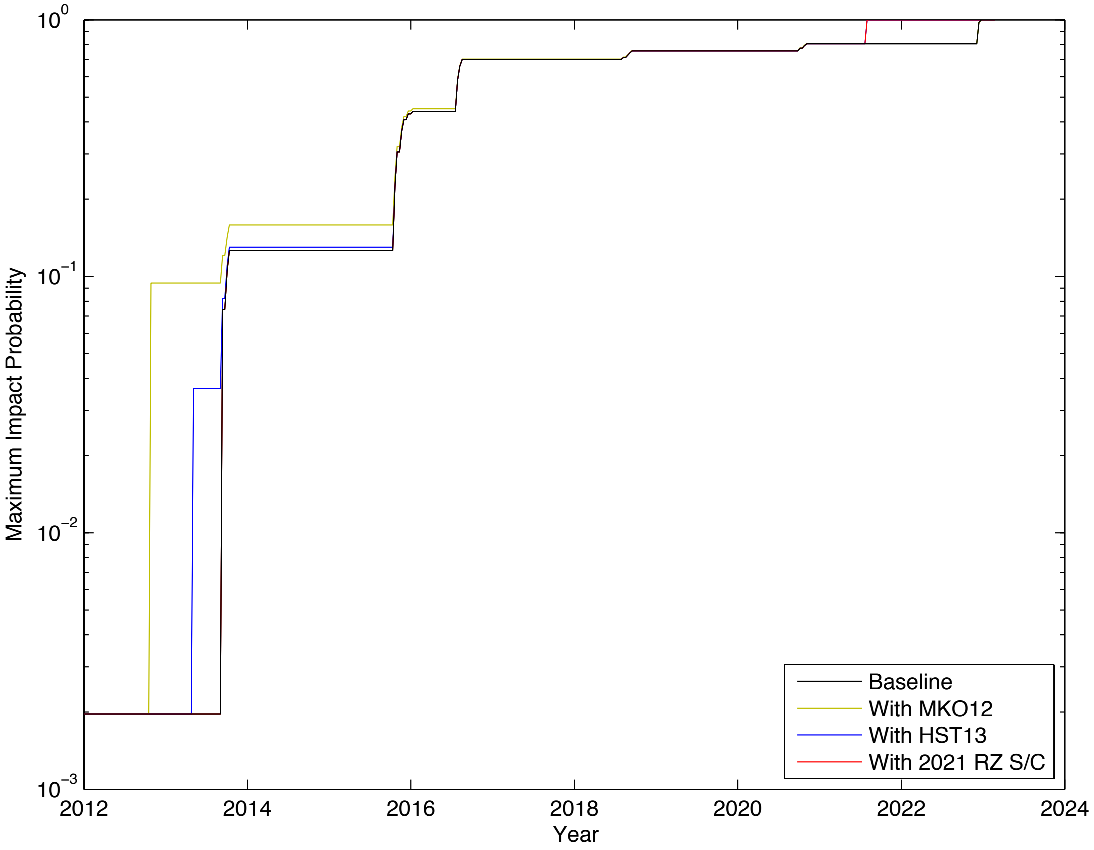

Figure 5. The maximum impact probability for 2011 AG5, assuming it is on an impact trajectory. The same cases seen in Fig. 4 are also represented here. For example, Keck Telescope observations made in October 2012 could increase the impact probability from 0.002 (1 in 500) to about 0.1 (1 in 10), if the asteroid were on a 2040 Earth impact trajectory.

Conclusions resulting from Fig. 5 include:

- Assuming the asteroid is on an Earth impacting trajectory, the 2012 – 2013 observations could raise the impact probability to about 10-15%.
- In this scenario, observations in 2015 – 2016 could raise the maximum impact probability of an actual impactor to around 70%.

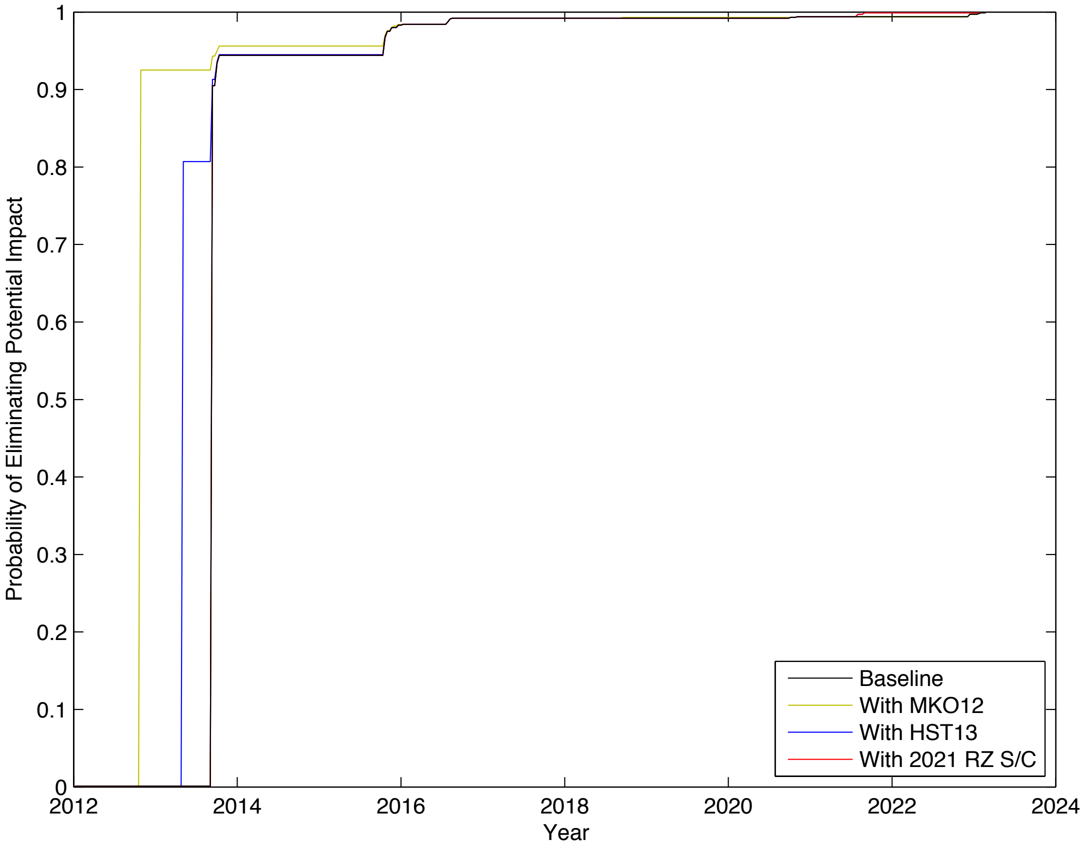

Figure 6. The probability that the 2040 potential impact will be ruled out (at $<10^{-6}$ probability of impact) in the coming years.

Conversely, we can use the estimated remaining uncertainty to compute the likelihood the impact potential will be eliminated (Fig. 6) by the modest observation data returns.

Conclusions from Fig. 6 include:

- The 2012 – 2013 observations have a 95% probability of eliminating the 2040 potential impact altogether.
- With the addition of 2015 – 2016 observations, this likelihood increases to about 99%.

## Deflection Mission Analyses

In the remainder of this report we make the assumption that 2011 AG5 is indeed headed for Earth impact in 2040, and examine options for deflecting the asteroid away from the impact trajectory. Many viable mission options exist for carrying out a pre-keyhole deflection campaign for 2011 AG5, using either chemical or solar electric propulsion (SEP). Many viable mission options also exist for carrying out a post-keyhole deflection well after the 2023 keyhole passage. While much further study would be required to design optimal pre- and post- keyhole rendezvous and impact missions, our analysis demonstrates that numerous viable deflection mission options are available. In the unlikely event that observations made in September 2013 show a significant increase in 2011 AG5's Earth impact probability, there is still sufficient time to plan and carry out a successful deflection campaign.

Our studies focus on a kinetic impactor spacecraft, which would impact the asteroid with enough mass and at a high enough velocity to change the asteroid's trajectory so that it misses the Earth by a wide margin in 2040. Most of our analyses focus on pre-keyhole deflections, which prevent the asteroid from passing through the keyhole in 2023, but we also examine options for deflecting the asteroid after its keyhole passage. Both chemical and solar electric propulsion (SEP) options are considered, and some viable mission concepts take advantage of planetary gravity assists. Additional constraints assumed for the mission analysis studies included the following:

- The kinetic impact spacecraft approach phase angle should be as small as possible, preferably 90° or less, to facilitate terminal targeting. We note that optimizing deflection efficiency usually leads to phase angles around 90°.
- The momentum multiplier ($\beta$), a parameter that describes the rather uncertain momentum enhancement factor due to impact ejecta blowback, was taken as a conservative value of 2. The significant uncertainty associated with $\beta$ leads to a corresponding uncertainty in the predicted deflection.
- The diameter of the asteroid was assumed to be 140 meters and its bulk density was taken as 2600 kg/m$^3$, leading to an asteroid mass $M= 4 \times 10^9$ kg.

To provide early confirmation of a successful deflection and to ease the terminal guidance challenges for the impactor, an in-situ rendezvous spacecraft should be in close proximity with the asteroid (on-station) at least a few months before the kinetic impactor arrives. The rendezvous spacecraft would facilitate the impactor mission by characterizing the asteroid's size, shape, composition and rotation, as well as providing astrometric data on the asteroid's position in space. The targeting accuracy of the impactor would be improved with a rendezvous spacecraft. Hence, viable mission opportunities were investigated that included a rendezvous spacecraft that would precede, by two months or more, the arrival of the impactor spacecraft.

In the following discussion of deflection distances, we express the effects of a deflection as changes measured in the "b-plane", rather than changes in physical miss distances. The b-plane is defined as the plane passing through the Earth's center and orthogonal to the incoming asymptote of the hyperbolic, geocentric asteroid trajectory. It is a standard tool for astrodynamics calculations involving close planetary encounters, both for spacecraft and small solar system bodies, primarily because it removes the nonlinearities associated with gravitational focusing. A trajectory's position in the b-plane is the point at which its incoming asymptote intersects the b-plane, relative to the Earth's center. Since a trajectory's position in the b-plane does not include gravitational focusing, its distance from the Earth's center must be significantly more than 1 Earth radius to avoid a collision: for 2011 AG5, the b-plane distance must be >1.54 Earth radii. Figure 7 shows how miss distances for 2011 AG5 vary with b-plane distances.

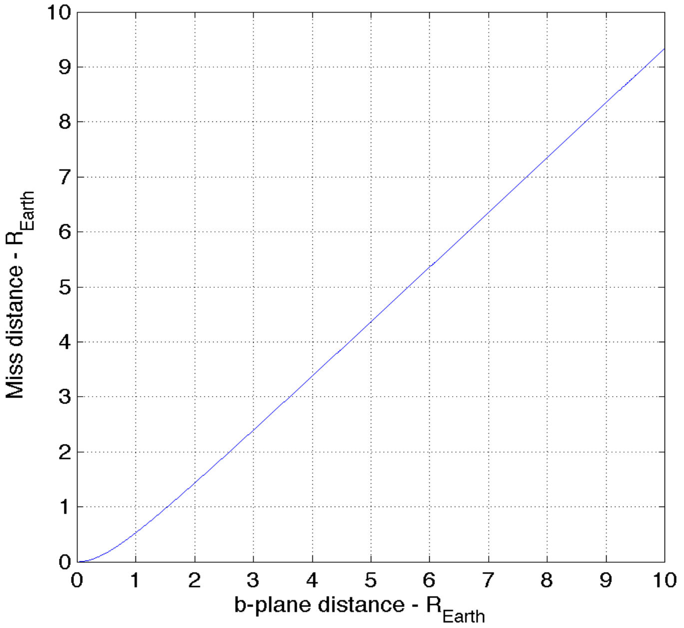

Figure 7. The geocentric miss distance vs. b-plane distance for 2011 AG5.

## Desired Deflection Distance

There are a number of considerations in determining the desired deflection distance. First among them is to ensure that the entire post-impact uncertainty region misses the Earth. For this reason, we have selected the conservative value of 2 for the momentum enhancement factor β that arises from the additional momentum provided by the asteroid impact ejecta flying off the asteroid's surface. The range of possible values for β runs from at least 1 (plastic collision) to perhaps 5-10. There is an additional uncertainty in the assumed mass of 2011 AG5, which could be off by as much as a factor of ~3-4. Thus it makes sense to carry a safety factor of at least 5 in our targeted deflection distance, and therefore deflection distances in the range of 10 - 20 Earth radii should be sufficient to allow for the largest sources of uncertainty.

Another important consideration is that, following a successful deflection and miss in 2040, the asteroid should not end up on a trajectory which impacts the Earth sometime soon after 2040. These "secondary" impact possibilities can be mapped back to their associated keyholes in the 2023 b-plane in order to assess whether there are particular deflection directions and distances that would be preferred. Figure 8 presents just such a “keyhole map” for 2011 AG5. The post-2023 minimum geocentric distance through the year 2100 is plotted for over 100,000 variant trajectories, each with essentially the same orbit as 2011 AG5, but slightly different b-plane positions in 2023. Points plotted below the dotted line represent Earth impacting trajectories. The 365-km width of the primary 2040 keyhole is clearly seen at the center, but it is also clear that there are more than a dozen secondary keyholes in close proximity to the primary 2040 keyhole. These secondary keyholes are small, the widest being less than 100 meters in width, and decreasing the closer they get to the primary keyhole, down to widths of less than 1 meter. Of course, the secondary keyholes have correspondingly smaller impact probabilities, currently of order $10^{-8}$. There are two wider secondary keyholes well outside the range of this plot: a 700m-wide keyhole for 2047 at abscissa value -8,000 km on the left, and a 2.2-km-wide keyhole for 2045 at abscissa +12,000 km on the right.

We conclude that there are “safe harbor” zones in the 2023 b-plane that run from −8,000 km to −1,500 km on the left and +2,000 km to +12,000 km on the right in Fig. 8. These zones should be the targeted regions for the deflection. In terms of miss distances in 2040, these safe harbors correspond to deflections of 8-44 Earth radii from an impactor that slows the asteroid and 11-66 Earth radii from an impactor that increases the asteroid velocity. The celestial mechanics of the 2011 AG5 deflection strongly favor the former case, where the impact causes the asteroid to slow down slightly, lose kinetic energy and decrease orbital period.

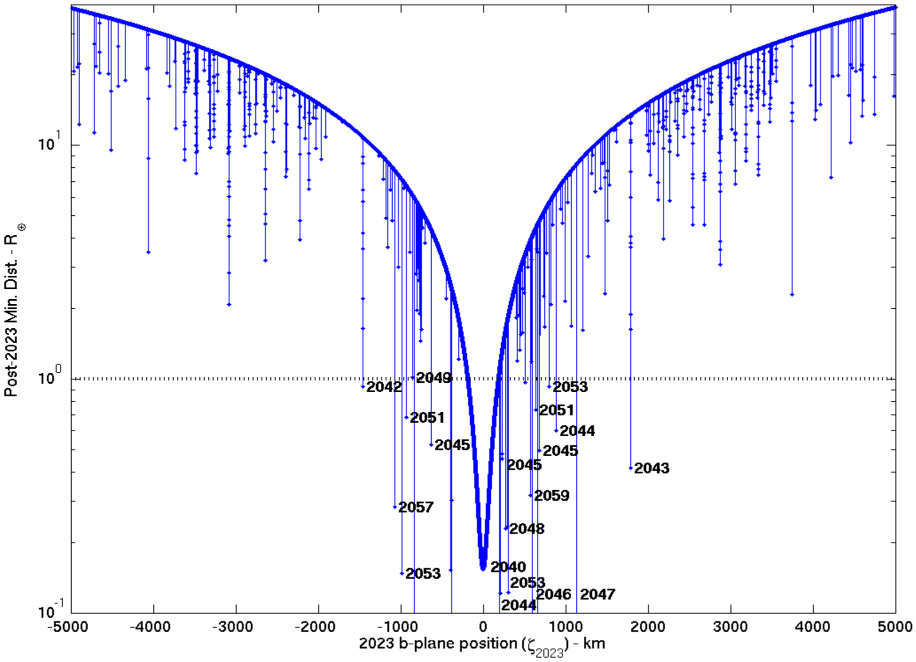

Figure 8. A “keyhole map” for 2011 AG5 in the 2023 b-plane. The vertical axis shows the post-2023 minimum geocentric distance for each trajectory, through the year 2100. Any point below the dotted line represents an Earth impact, with the

year of the impact noted (up to the year 2060). Zero on the x-axis is at the 2040 impact solution, and the 365-km wide keyhole associated with the 2040 impact is clearly seen. Nearby are secondary returns to Earth that could be spawned by the 2040 encounter.

## 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, 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 determined the spacecraft's orbit relative to the comet and performed 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, enabling 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 they would have to deal with 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 might not be as favorable. However, these challenges could 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 could turn faster and implement maneuvers more quickly. Software improvements could 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° to avoid unfavorable approach lighting conditions and kept approach velocities at a level similar to that of DI.

## Rendezvous and Impactor Mission Options Using Chemical-only Propulsion

Our first analysis of possible deflection mission options for 2011 AG5 was restricted to missions using only conventional chemical propulsion systems, and with the goal of deflecting the asteroid before its 2023 keyhole passage.

Our approach to finding viable impactor missions was to perform a grid scan of every combination of launch date and arrival date, over the period from mid-2017 through 2023. The trajectory scan also included sequences of one or two flybys, where gravity assist bodies from Mercury to Jupiter were considered. The key parameters from the trajectory search were launch energy ($C_3$), deep space and flyby ΔV values, and the arrival relative velocity ($V_\infty$). The departure mass for each trajectory was computed from the launch vehicle performance curves given by Fig. 9, which assumes that a Star solid upper stage is available to boost performance at high values of $C_3$. The launch vehicle performance was also limited to launch declinations of ±28.5°. (If the launch declination exceeded this bound, the spacecraft was assumed to launch to a $C_3$ of $-2$ km$^2$/s$^2$, perform a maneuver at apogee to reorient the orbit for high declination, and perform a second maneuver at perigee to escape.) All post-launch trajectory ΔV values were modeled using a bi-propellant system with Isp of 323 s, and the total spacecraft mass after each maneuver was reduced according to the rocket equation.

The same approach was used for finding viable rendezvous mission options, except that an additional final rendezvous ΔV was applied at arrival.

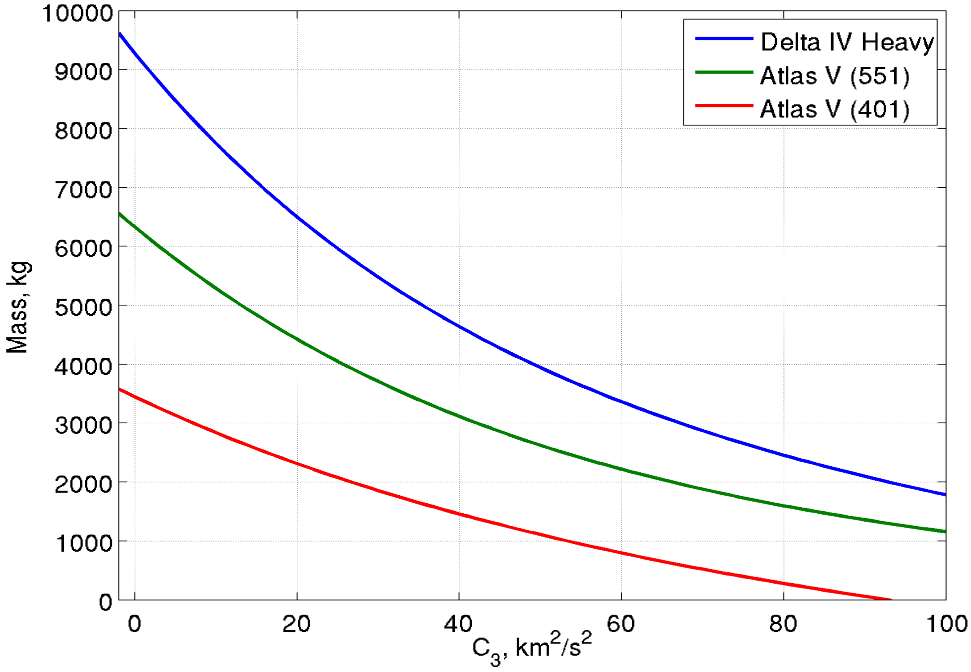

Figure 9. Launch mass as a function of $C_3$ for various launch vehicles.

For the impactor mission options, the deflection ΔV applied to the asteroid was calculated from the trajectory arrival relative velocity $V_\infty$ and the arrival mass m of the impactor, using the momentum transfer equation $\Delta V=\beta\ V_\infty\ m/M$, with $\beta=2$. The resulting asteroid velocity deflection in the 2040 Earth-encounter b-plane was calculated using a pre-computed matrix of partial derivatives relating b-plane position to change in velocity (a 2 x 3 matrix) tabulated at daily increments beginning 25 years before potential impact. The sensitivity of the miss distance at Earth to the size of the velocity deflection ΔV was verified independently using the MONTE institutional orbit determination software.

As shown in Fig. 10, a large number of pre-keyhole impactor missions are available, assuming use of an Atlas V 401 launch vehicle (the lowest performance of the Atlas V family). Shown in color are those missions with 2040 b-plane deflections of at least 2 Earth radii and encounter phase angles less than 90°. Cases with deflection greater than 12 Earth radii are all assigned the same shade of red. As discussed above, the desired deflection distance should be in the range of 8-44 Earth radii. We note that more capable launch vehicles are available (Fig. 9), and so the lower performing cases could be enhanced by a launcher upgrade.

The set of viable pre-keyhole rendezvous missions, again assuming the Atlas V 401 launch vehicle, are shown in Fig. 11. The color indicates the rendezvous mass, which for a typical spacecraft with appropriate instruments, would be in the range 500-1000 kg.

Figures 10 and 11 identify ample opportunities to characterize the asteroid with a rendezvous spacecraft prior to the arrival of the impactor spacecraft. From Fig. 10, the l*atest* impactor launch that provides a sizable asteroid deflection is in the first half of 2020, less than three years before the keyhole passage. A representative impactor trajectory is shown in Fig. 12 and tabulated below. Similarly, from Fig. 11, the *earliest* date that a spacecraft with sufficient mass could rendezvous with the asteroid is in the middle of 2019, which provides ample time to investigate the object before the launch of the impactor several months later. A representative rendezvous trajectory is given in Fig. 13 and tabulated below.

| | Rendezvous S/C | Impactor S/C |
|---|---|---|
| Launch Date | 4/24/2018 | 1/2/2020 |
| Launch Vehicle | Atlas V 401 | Atlas V 401 |
| C3 ($km^2/s^2$) | 26.3 | 6.1 |
| Launch Mass (kg) | 2015 | 3060 |
| Time of Flight (days) | 484 | 498 |
| Approach Phase (deg.) | 86 | 12 |
| Arrival Date | 8/22/2019 | 5/14/2021 |
| Arrival Vel. (km/s) | 0.9 | 12.5 |
| Arrival Mass (kg) | 1194 | 3060 |
| ΔV (mm/s) | — | 19 |
| 2040 Deflection ($R_{Earth}$) | — | 11 |

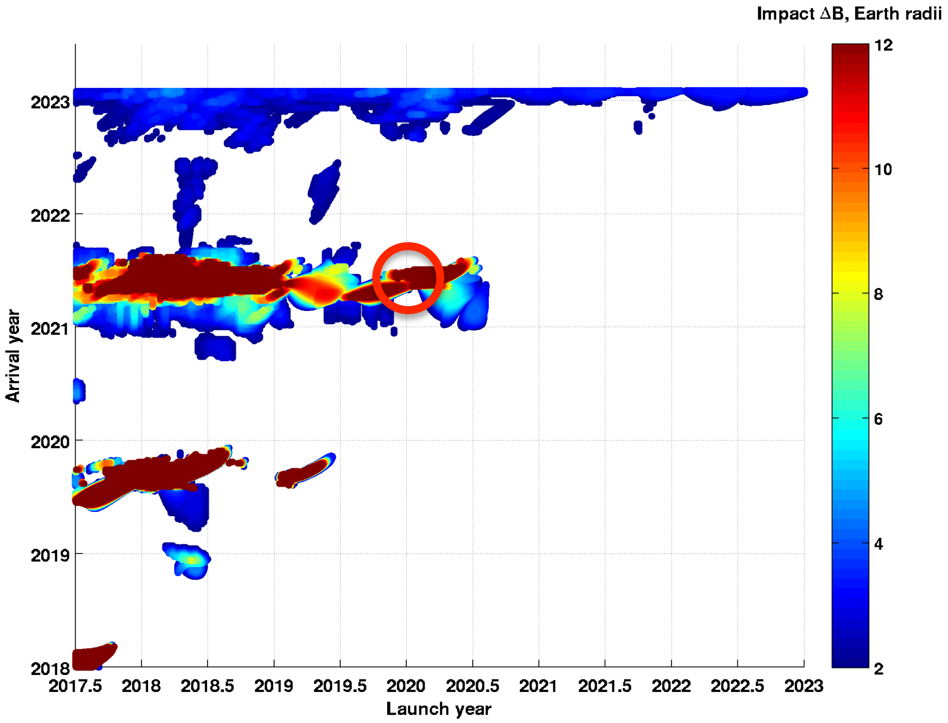

Figure 10. The 2040 b-plane deflection magnitudes for viable deflection missions, assuming the capability of an Atlas V 401 launch vehicle. The colors indicate the deflection achieved in 2040 for each pair of launch and arrival dates. The example discussed in the text and shown in Fig. 12 is marked with a red circle.

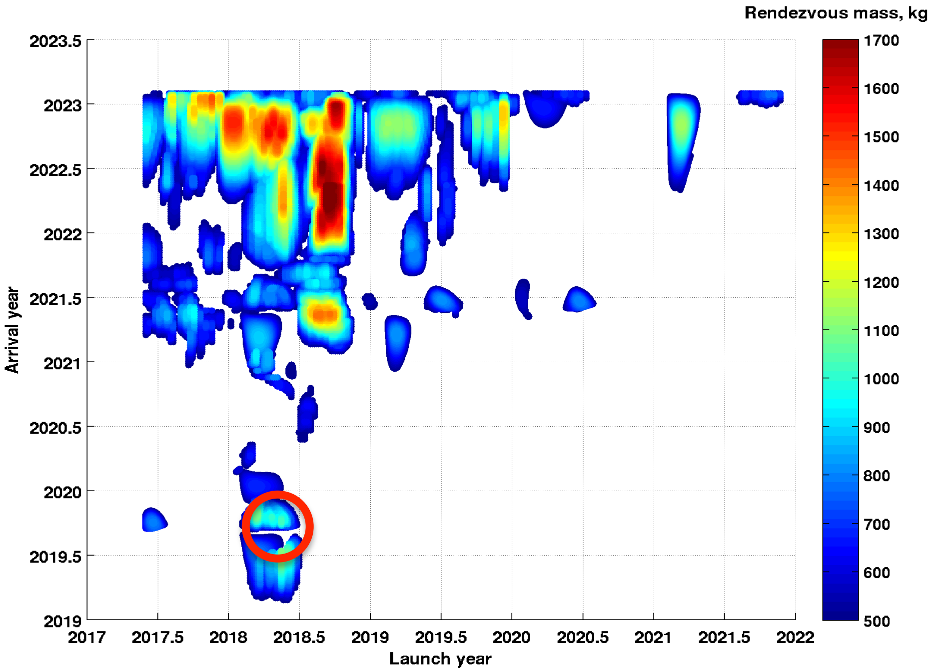

Figure 11. This plot demonstrates the variety of pre-keyhole rendezvous mission opportunities using the Atlas V 401 launch vehicle. The color indicates the arrival mass of the rendezvous spacecraft for each pair of launch and arrival dates. The example discussed in the text and shown in Fig. 13 is marked with a red circle.

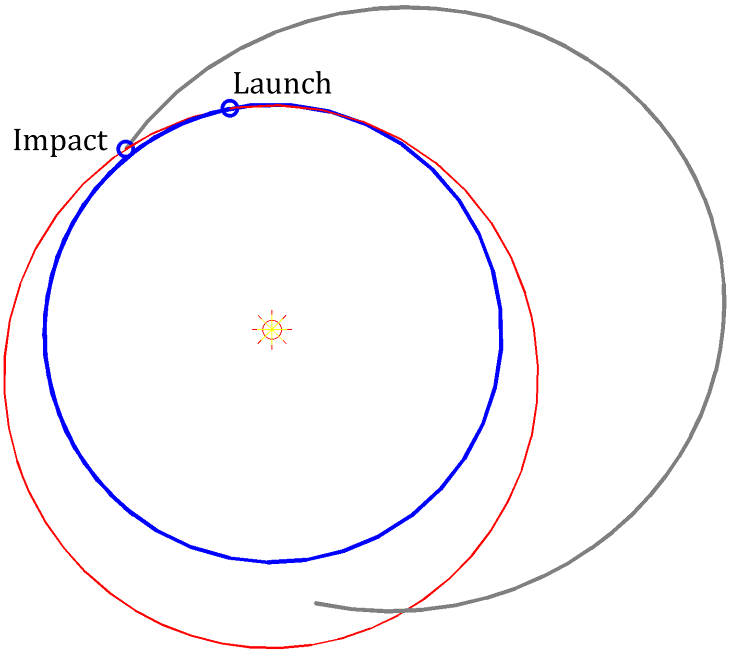

Figure 12. The pre-keyhole impactor trajectory for the case tabulated above and marked in Fig. 10. The Earth's orbit is shown in blue, the orbit of 2011 AG5 is gray, and the spacecraft trajectory is red.

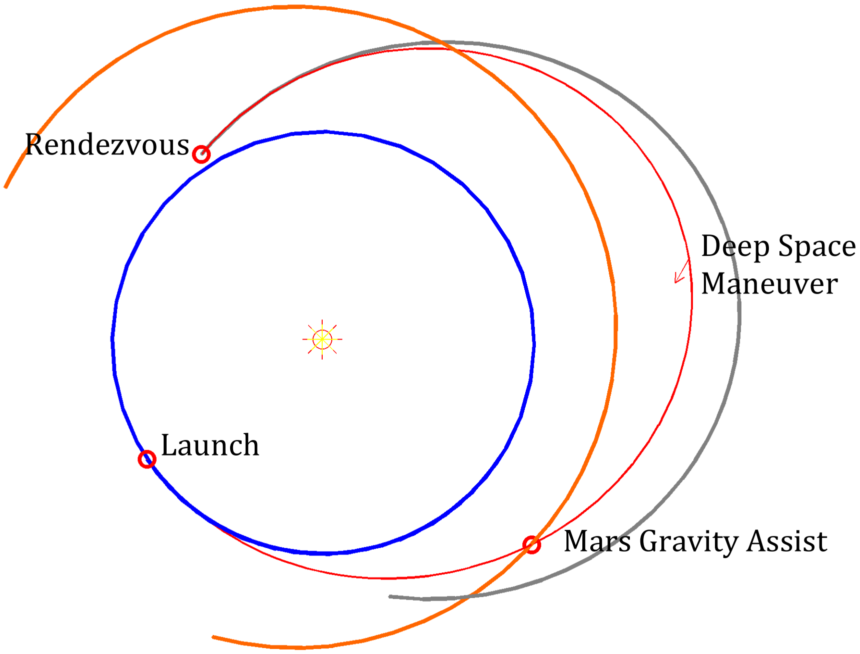

Figure 13. The pre-keyhole rendezvous trajectory for the case tabulated above and marked in Fig. 11. The Earth's orbit is shown in blue, the orbit of Mars is orange, the orbit of 2011 AG5 is gray, and the spacecraft trajectory is red.

## Rendezvous and Impactor Mission Options Using SEP

The options for pre-keyhole deflection missions using solar electric propulsion (SEP) technology are comparable with the above results provided for the chemical propulsion. SEP mission option studies assumed configurations with either two or four 5 kW engines (BPT – 4000 Hi Isp, 90% duty cycle) and various Atlas V launcher configurations. Both rendezvous and impactor missions were studied. Among many options available, we have identified early launch opportunities (mid-2018) for both mission types, which we label “Rendezvous A” and “Impactor A.” Similarly, we have identified late launch opportunities (mid-2020), which we label “Rendezvous B” and “Impactor B.” The relevant mission parameters for these options are tabulated below. Both impactor missions utilize a Venus gravity assist.

| | Rendezvous A | Rendezvous B | Impactor A | Impactor B |
|---|---|---|---|---|
| Launch Date | 9/1/2018 | 5/29/2020 | 9/1/2018 | 8/29/2020 |
| Launch Vehicle | Atlas V 551 | Atlas V 551 | Atlas V 551 | Atlas V 551 |
| C3 ($km^2/s^2$) | 68.1 | 11.0 | 11.9 | 34.8 |
| Launch Mass (kg) | 1666 | 4262 | 5118 | 3363 |
| SEP Power (kW) | 10 | 20 | 20 | 20 |
| Time of Flight (days) | 628 | 404 | 402 | 374 |
| Approach Phase (deg.) | — | — | 50.9 | 89.5 |
| Arrival Date | 5/21/2020 | 7/7/2021 | 10/8/2019 | 9/6/2021 |
| Arrival Vel. (km/s) | 0 | 0 | 12.7 | 9.1 |
| Arrival Mass (kg) | 1001 | 3087 | 4176 | 2334 |
| $\Delta V$ (mm/s) | — | — | 27 | 11 |
| 2040 Deflection ($R_{Earth}$) | — | — | 65 | 11 |

The Impactor A mission is among the most effective options; however, it arrives before the earliest SEP rendezvous, although after the chemical rendezvous option discussed above. With the configuration studied, a deflection of 65 Earth radii in 2040 is possible with Impactor A. This is certainly more than is desired, but the implication is that the mission could be scaled down to a lower power usage, lower mass and smaller launch vehicle in order to tailor the mission to the desired deflection. In the same way, the delivered momentum of Impactor B could be tuned up or down as desired.

Given that it is advantageous to wait as long as possible before launching missions as part of a deflection campaign, the Impactor B option is clearly superior. Moreover, both of the listed rendezvous missions would reach the asteroid before the Impactor B mission, allowing the rendezvous mission to support the impact and measure the deflection. An important point is that Rendezvous A arrives ~3 months before the Impactor B launch, leaving time for the rendezvous mission to rule out the possibility of Earth impact through high precision tracking of the asteroid. This advance information could eliminate the need for the impactor mission in time for its launch to be cancelled.

In terms of deflecting the asteroid prior to the keyhole passage, we found SEP to be comparable to chemical propulsion. Both options provide many possibilities for pre- as well as post- keyhole deflection missions.

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. Although these trajectories require more years to fly, the benefit from postponing launch outweighs the increased flight time. For an example scenario, a SEP spacecraft launches in towards the Sun and further decreases perihelion over multiple heliocentric revolutions, while keeping aphelion at ~1 AU. The desired effect is to slowly build-up relative velocity before impacting the asteroid. Furthermore, if high impact velocities are undesirable for navigation purposes, a larger mass can be delivered by leveraging the efficiency of the SEP system.

## Mission Development Timeline Assumptions 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 a 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.

## Post-Keyhole Rendezvous and Impactor Options

In a scenario where a pre-keyhole deflection attempt is unsuccessful, whether due to an incomplete deflection or a mission failure, many post-keyhole deflection alternatives are available. While more challenging by a factor of ~50, they are still possible with current launch vehicles, and aided by the fact that there would still be up to 17 years time before impact. For example, assuming a Delta IV heavy launch vehicle, viable post-keyhole missions designed to deflect the asteroid 8 Earth radii or more before the 2040 Earth encounter could be carried out with launches as late as 2030 (see Fig. 14). Numerous post-keyhole, precursor rendezvous missions also could be carried out with current launch vehicles, including the Atlas V 401 (see Fig. 15).

If SEP is used, numerous spiral-type trajectories are possible where the impactor is launched into an orbit interior to the Earth's, and the perihelion is slowly reduced while keeping the aphelion at ~ 1 AU. This is an attractive concept. As an example, using a Delta IV Heavy launch vehicle, a SEP spacecraft (mass = 8273 kg) could be launched on 2027 March 21 with an impact on 2029 December 6 (s/c mass = 5909 kg) at a relative velocity of 20.4 km/s. The resulting impulse would provide a deflection of 10.4 Earth radii in February 2040. An Earth deflection of over two Earth radii would be possible with an Atlas V 551 launch of a 4436 kg SEP spacecraft as late as March 2035. In this case, arrival would be October 4, 2036, with a relative velocity of 19 km/s. In order to keep deflection energies at a level where the result may be more predictable, e.g., avoiding fragmentation of the asteroid, late deflection efforts may require more than one impactor mission.

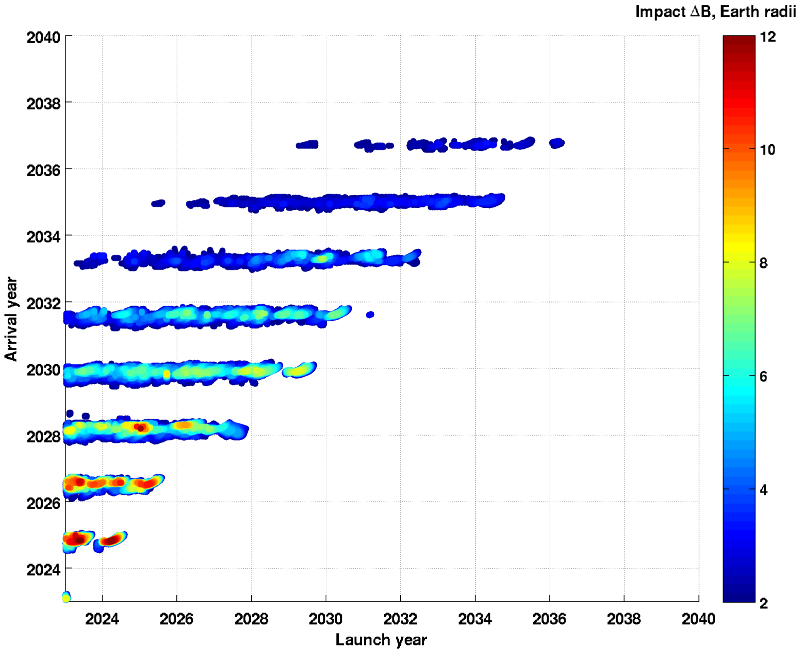

Figure 14. This plot presents the chemical propulsion mission options for post-keyhole deflections using a Delta IV Heavy launch vehicle and constraining the approach phase angle to less than 90°. The deflection distance in Earth radii is given for each pair of launch and arrival dates.

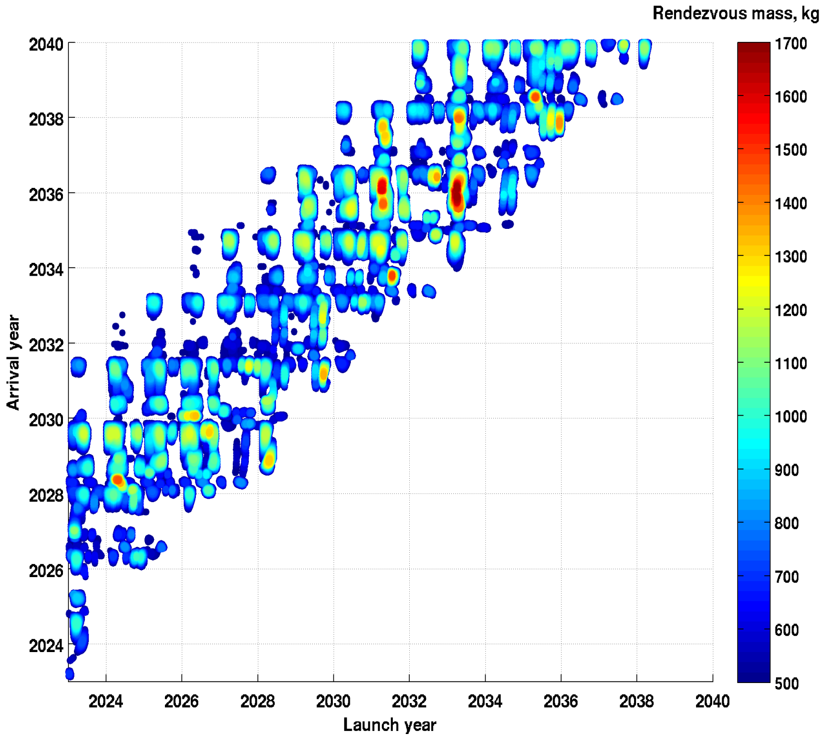

Figure 15. Post-keyhole rendezvous opportunities using the Atlas V 401 launch vehicle and chemical propulsion. The mass of the rendezvous spacecraft is given for each pair of launch and arrival dates.

## Summary of Principal Findings

- Currently, the probability that asteroid 2011 AG5 will impact the Earth in February 2040 is 1/500. If the impact occurs, the energy release will be on the order of 100 MT.
- The impact can occur only if the asteroid first passes through a 365-km keyhole in space during the February 2023 Earth close approach.
- The asteroid is currently unobservable, but when it becomes easily observable again in late 2013, its position uncertainty at the 2040 Earth-encounter will drop from its current value of ~400 Earth radii down to 5-6 Earth radii. Further observations expected in 2015-2020 will reduce this uncertainty down to ~1-2 Earth radii.
- The 2013 observations have a 95% chance of eliminating the 2040 impact possibility, while further observations in 2015-2016 have a ~99% chance of eliminating the potential impact.
- Conversely, if the asteroid really is on an Earth impacting trajectory, the 2013 observations could cause the impact probability to rise to 10% - 15%, and the observations in 2015 – 2016 could cause it to rise further, to ~70%.
- A kinetic impactor spacecraft is an effective means of deflecting 2011 AG5 to avert an Earth collision. It is desirable to also have an in-situ rendezvous spacecraft on station at least a few months before the deflection, to characterize

the object and ease the targeting challenges for the impactor spacecraft and to provide early confirmation of the magnitude of the deflection.

- Many viable mission options exist for carrying out a pre-keyhole deflection campaign for 2011 AG5, using either chemical or solar electric propulsion (SEP), with launches in the 2018-2020 timeframe. Details of several such missions are outlined in this report. There is no need to use the same type of propulsion (chemical vs. SEP) for both the rendezvous and impactor missions.
- One example impactor mission launches in 2020 on an Atlas V 401 launch vehicle and deflects the asteroid in mid-2021, applying a velocity change to the asteroid of about 2 cm/s. This is sufficient not only to deflect the asteroid out of the 2023 keyhole and prevent the 2040 Earth impact, but also to move the asteroid ~10 Earth radii away at the 2040 encounter.
- Many viable mission options also exist for carrying out a post-keyhole deflection using existing launch vehicles and launch dates in the 2027 – 2035 timeframe, well after the 2023 keyhole passage. Details for a few of these missions are provided in this report.
- While much further study would be required to design optimal pre- and post-keyhole rendezvous and impact missions, this short study has demonstrated that numerous viable deflection mission options are available in the event that the 2011 AG5 really is on a trajectory leading to a 2040 Earth impact.
- In the unlikely event that observations made in September 2013 show a significant increase in the Earth impact probability, there is still sufficient time to plan and carry out a successful deflection campaign.