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THE DOUBLE ASTEROID REDIRECTION TEST (DART): EXPECTED CHANGES TO THE HELIOCENTRIC ORBIT OF (65803) DIDYMOS

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Launched on November 23, 2021, NASA's Double Asteroid Redirection Test (DART) is set to impact the moonlet of the (65803) Didymos binary asteroid system in Fall of 2022. The aim of NASA's first dedicated planetary defense technology demonstration, DART, is to uncover how much momentum is imparted onto an asteroid during a kinetic impact at hyper velocity (6km/s) by altering the mutual orbit of the binary system. Predictions for the momentum transfer during a kinetic impact range substantially, due to the fact that ejecta are coming off the target in addition to the momentum imparted by the DART spacecraft. Ejecta that are escaping the gravitational pull of the asteroid cause a momentum enhancement characterized by the momentum enhancement factor, β. Momentum carried away by the ejecta not only affects the mutual orbit of the Didymos pair, but also the heliocentric orbit of the entire Didymos system. Since the Didymos system has close approaches with the Earth over the next century, we investigate how possible changes in the heliocentric orbit of the Didymos system affect close approach distances between the binary asteroid and the Earth. Our predictions are based on the exact launch date and likely arrival conditions for the DART spacecraft and show that future encounters with the Didymos system do not pose a significant hazard. We also show that instantaneous momentum transfer models that neglect the "low thrust" caused by slower ejecta can influence the accuracy of post deflection impact risk assessments.

INTRODUCTION

The Asteroid Impact and Deflection Assessment (AIDA) mission is an international effort to demonstrate and understand the effects of asteroid deflection via a kinetic impactor. It consists of NASA's Double Asteroid Redirection Test (DART),[1] and the European Space Agency's Hera mission.[2] DART is the first ever test of planetary defense capabilities destined to impact Dimorphos, the secondary asteroid in the (65803) Didymos binary asteroid system on September 26, 2022. Comprised of an orbiter with two cube-sat companions, Hera will follow in 2026 to study the Didymos system as well as the crater caused by DART in depth.

Understanding the effects of a hypervelocity impact on an asteroid is important because of two reasons. First, hypervelocity impacts in low gravity environments are fundamentally different from experiments that can be conducted on Earth. For one, the cratering process on a rubble-pile asteroid takes minutes, not mere seconds.[3,4] Two, due to their very nature, the momentum exchange for an impact on a rubble pile asteroid is different because of the racks and particles that are kicked off the surface can escape the system. These ejecta particles contribute to the total deflection (Δv) of the asteroid due to the impact, which is characterized through the momentum enhancement factor, or the "beta" factor. In its simplest form, β is defined as

$$\beta = \frac{m_{DART}}{m_{dim}} \frac{v_{DART}}{\Delta v_{dim}}, \tag{1}$$

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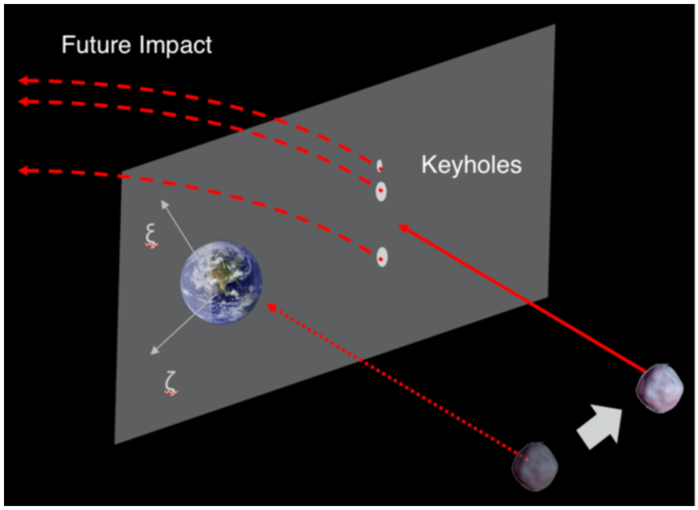


Figure 1: Illustration of keyholes on an asteroid-Earth close approach b-plane.

where β is the local momentum enhancement parameter, m_{DART} and m_{dim} are the masses of the DART spacecraft and Dimorphos, respectively, Δv_{dim} is the change in the velocity of Dimorphos, and v_{DART} is the impact velocity of the DART spacecraft relative to its target.[5] As the DART impact happens in a binary asteroid system, the local system β is calculated using the mass of the secondary asteroid Dimorphos as shown in equation (1). Only ejecta leaving the gravitational sphere of influence of Dimorphos with respect to Didymos contribute to the momentum transfer and, thus, the system β.

However, a significant fraction of ejecta also escape the gravitational influence of the entire Didymos system leading to a change in the heliocentric orbit. This can be modeled via an additional heliocentric beta parameter, $\beta_{\odot}$. The latter characterizes the change in velocity of the entire system's barycenter with the total system mass. This leads us to another reason why understanding the momentum transport in kinetic impacts is of vital importance : gravitational keyholes. Keyholes are regions on the gravitational scattering plane (b-plane) such that if an asteroid were to pass a keyhole on one close approach, it would be bound to return on an Earth-impacting trajectory at a future date (Figure 1). Uncertainties in the momentum delivery during a kinetic impact could make it impossible to ensure the long-term success of an orbit deflection mission.

In this article we investigate the likely change in the heliocentric orbit of the Didymos system caused by the DART impact. To this end we track the dynamical behavior of simulated ejecta and analyzing their contribution to the momentum exchange. This information is then used in combination with a high fidelity solar system propagator to analyze future encounters between the Didymos system and the Earth.

DYNAMICAL EVOLUTION OF EJECTA PARTICLES

In order to realistically assess the influence of ejecta on the momentum transport following a kinetic impact, we simulated the dynamics of 50,000 pseudo-particles that represent actual particles with similar characteristics. The ejecta particles released due to a hypervelocity impact on an asteroid's surface were initialized using previously developed power-law scaling relationships.[6] These initial ejecta states are primarily a function of the target asteroid's material properties as well as the physical properties of the impactor. The velocity and mass of these ejecta particles can be written as

$$\begin{aligned} \frac{v(x)}{U} &= C_1 \left[\frac{x}{a} \left(\frac{\rho}{\delta} \right)^{\nu} \right]^{(-1/\mu)}, \\ \frac{M(<x)}{m} &= \frac{3k}{4\pi} \frac{\rho}{\delta} \left[\left(\frac{x}{a} \right)^3 - n_1^3 \right], \end{aligned} \tag{2}$$

for an impactor of radius a, mass m, velocity U, and bulk density δ. Additionally, $v(x)$ is the speed of the ejecta launched at a distance x from the impact location and $M(< x)$ is the mass ejected within a distance x of the impact site. C_1, k, n_1, μ, and ν are all target material dependent constants and ρ is the bulk density of the target at the impact site.

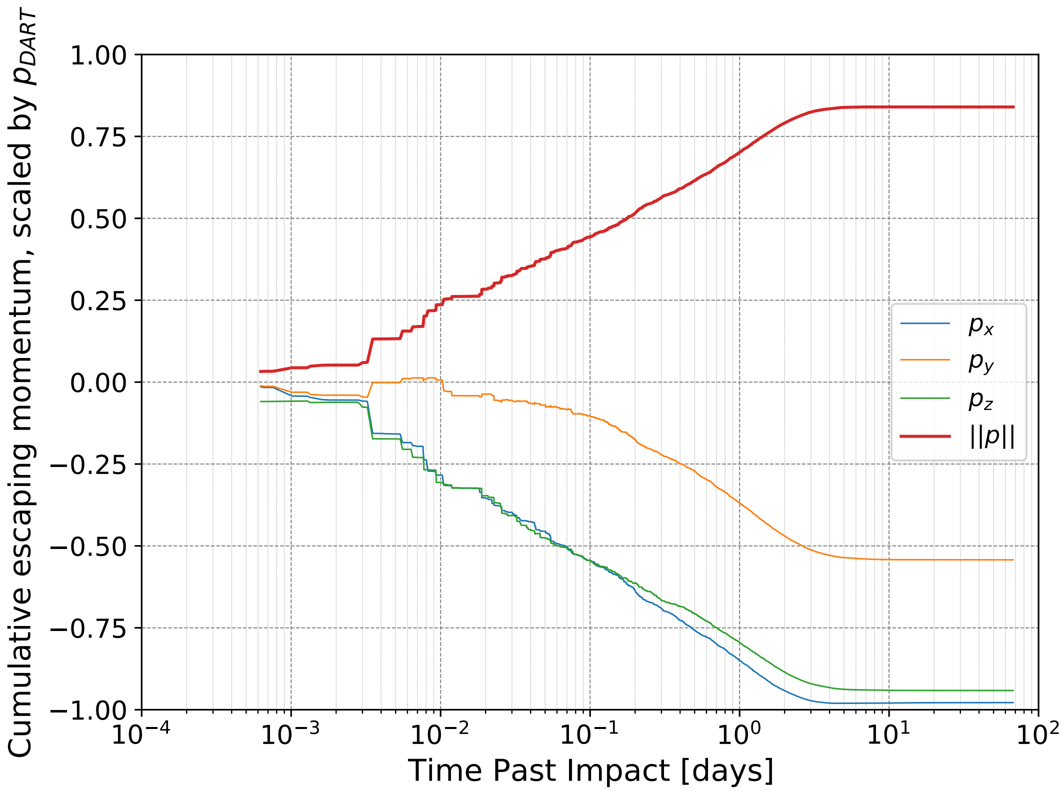


Figure 2: International Celestial Reference Frame (ICRF) components of escaping ejecta momentum scaled by DART impact momentum.

Once initialized, the pseudo-particles were propagated within the binary asteroid system to model their short-term evolution. For this propagation, detailed shape models for the asteroids are necessary since using point mass approximations this close to the system can induce significant errors in the propagated states. To this end we used radar observation-based shape models for the primary and the shape model for the secondary proposed in the DART design reference model in combination with the General Use Binary Asteroid Simulator (GUBAS).[7] GUBAS is capable of efficiently evaluating the mutual gravitational potential of the two asteroids for each ejecta particle.[*] while solving the Full Two-Body Problem (F2BP). Additionally, solar radiation pressure was added to this simulation including shadowing. The complete model was used to propagate and record the pseudo-particle states for the first 90 days after impact.

Figure 2 shows the time evolution of the cumulative escaping momentum scaled by the DART impact momentum (i.e., the second term in the $\beta_\odot$ portion of equation 3). Note that while 50% of the ejecta momentum is transferred within 5hrs of the DART impact, the rest of the momentum carried by slower ejecta takes days to escape the system. This is a novel result. In fact, the relatively slow transfer of a significant amount of ejecta momentum suggests that the previously used instantaneous ΔV model may be too simplistic to correctly describe the outcome of a kinetic impact based asteroid deflection. We will provide a more quantify assessment of this effect in the next section. Sticking to the instantaneous momentum transfer model for the

[*] https://github.com/alex-b-davis/gubas

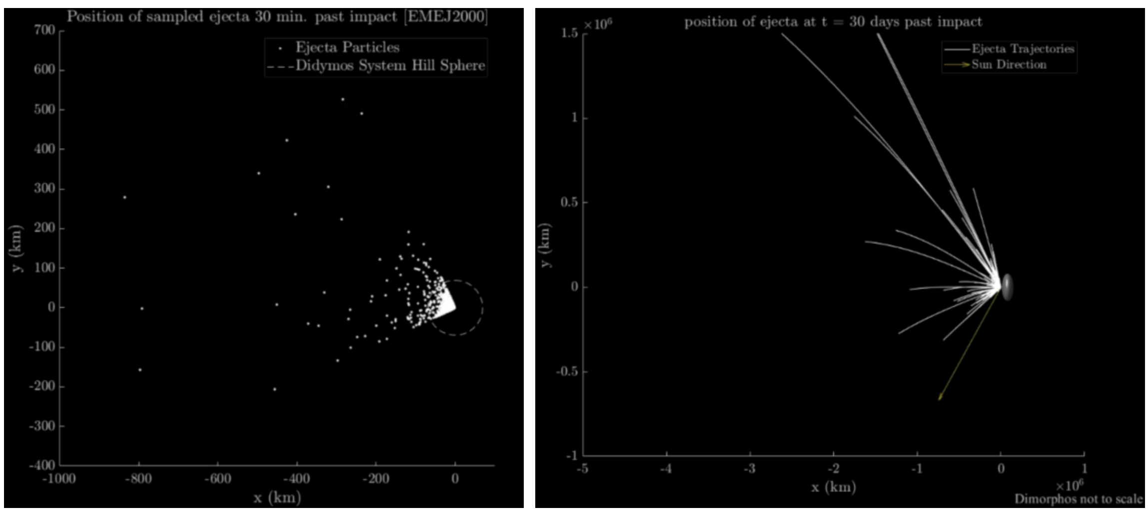
moment, we can estimate both the system beta and the heliocentric beta through the following equations

$$\beta = 1 + \frac{p_{ej,dim}}{p_{DART}} \approx 1.89,$$
$$\beta_{\odot} = 1 + \frac{p_{ej,sys}}{p_{DART}} \approx 1.84. \tag{3}$$

Here, $p_{ej,dim}$ is the cumulative momentum of the ejecta particles that escape the gravitational pull of Dimorphos alone. Similarly, $p_{ej,sys}$ is the momentum of the particles that end up leaving the whole system and contribute to the heliocentric orbit changes. Escape is defined as crossing the Hill sphere of the Didymos system, the radius of which can be written using the heliocentric distance, mass of the system, and the Sun's mass as

$$r_H = r\sqrt[3]{\frac{m_{sys}}{3M_{\odot}}}. \tag{4}$$

In this suite of simulations, $\beta \approx \beta_{\odot}$. This is not always the case, however, as the amount of fast ejecta depends on the physical parameters of the target such as surface strength and porosity.[8] Figure 3 shows a snapshot of these ejecta particles around the system 30 minutes after impact, where some have already escaped the system, and another 30 days after impact, where most particles that would escape the system have done so.



(a) (b)

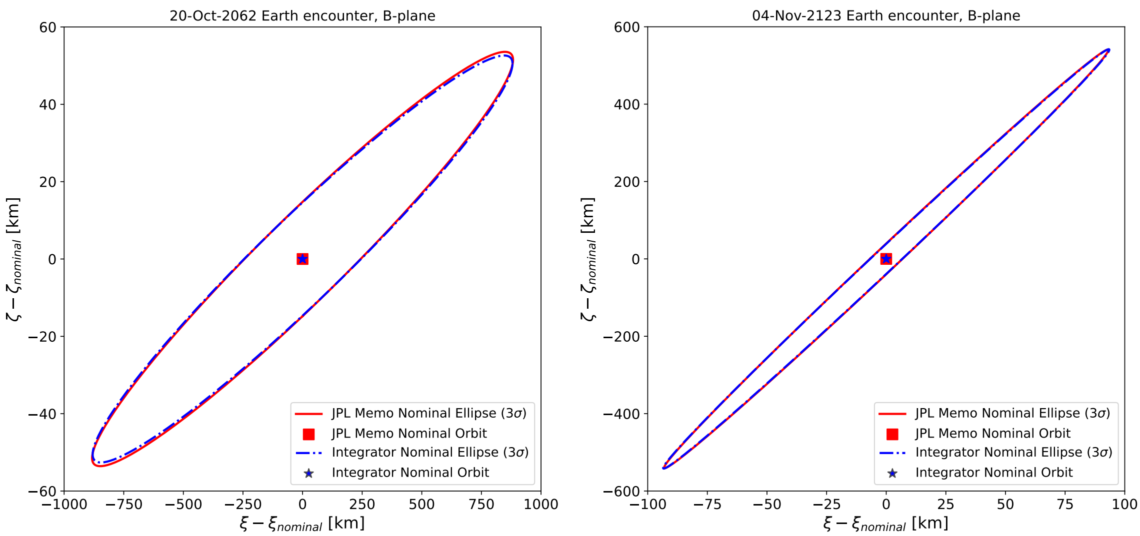
Figure 3: Ejecta particle evolution, (a) 30 minutes and (b) 30 days after impact showing particles escaping the system. The asteroid is not shown to scale.

POST–IMPACT PROPAGATION TO CLOSE APPROACHES

Equipped with a more realistic momentum transfer model, we analyzed the likely changes DART would cause in future Didymos-Earth close approaches. This was done using a newly developed high fidelity solar system propagator based on a 15$^{\text{th}}$-order Gauss-Radau integrator. To validate our propagator, a prior study of potential post-DART changes was used to compare the uncertainty ellipses on the b-plane.[9] Said study was based on JPL orbit solution 134 for the Didymos system*. Figure 4 compares the ellipses generated by the propagator used in this study to the previous results generated at JPL. Both projections of the nominal orbit and uncertainty ellipsoids onto the 2062 b-plane are in excellent agreement.

The orbit solution for Didymos was since updated and the rest of the results shown in this study used solution 147. As solution 147 contains more observations, uncertainty ellipses are smaller than shown in

*JPL Small Body Database Browser (SBDB) https://ssd.jpl.nasa.gov/sbdb.cgi?sstr=didymos



(a) (b)

Figure 4: Integrator validation for future Didymos-Earth close approach uncertainty ellipses

Figure 4. An integration start date of 27 March 27 2012 was used for 10,000 Monte Carlo clones over a span of 120 years. The expected value for the DART impact time of 26 September 2022 was used with a relative velocity of $6.14 \mathrm{km/s}$ for each clone. Two close approaches were detected, one on 20 October 2062 and another on 04 November 2123, and this matches the close approach data provided by JPL*.

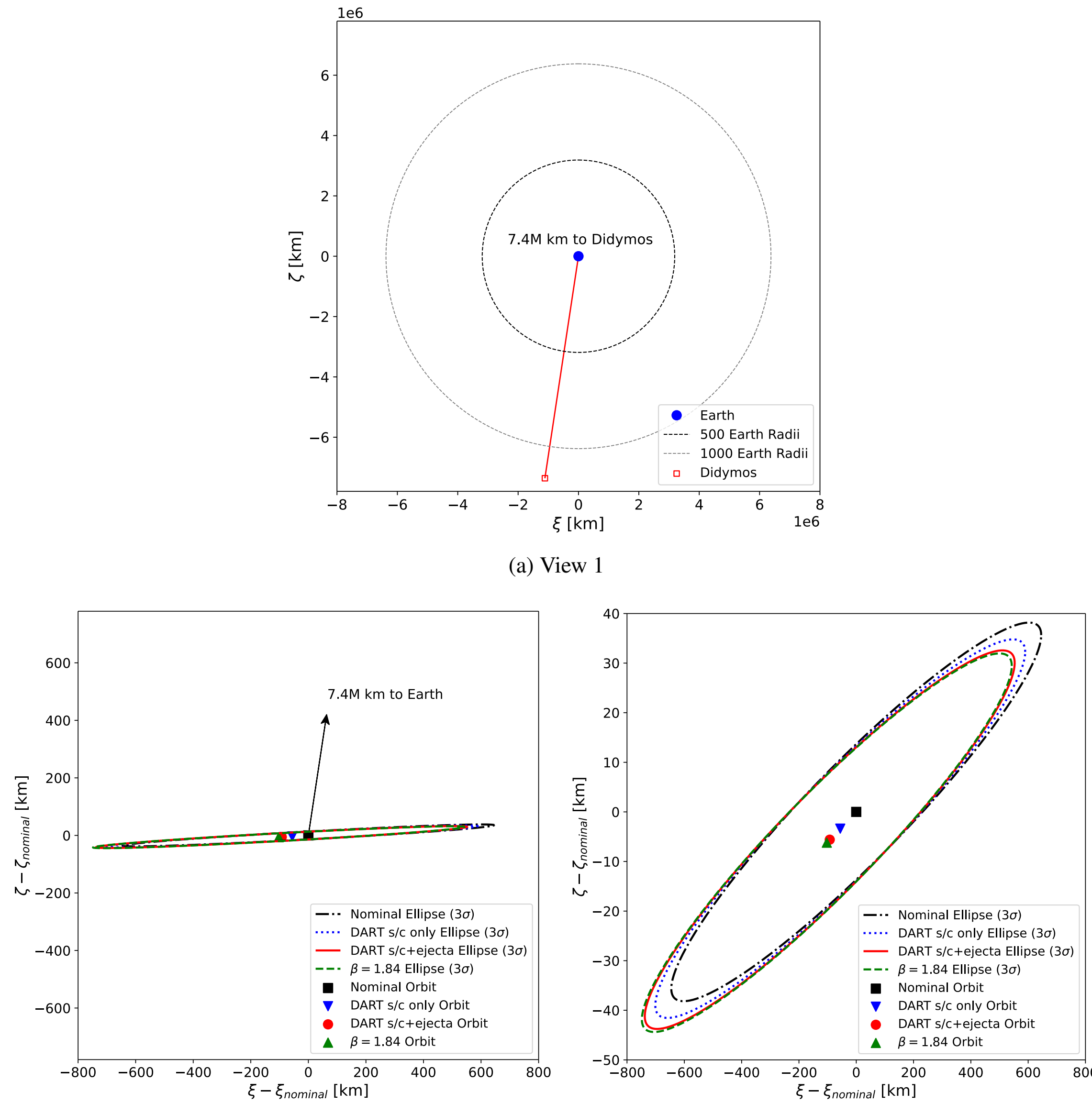
Two numerical experiments were conducted based on the ejecta dynamical simulations. The effect of DART on the heliocentric orbit of Didymos was studied using (a) the $\beta_\odot$ value from equation 3 and (b) the time series data of individual ejecta particles crossing the Hill sphere of the system. In terms of the heliocentric changes, this corresponds to two different cases, (a) where $\beta_\odot$ is applied instantaneously as a multiplier to the DART impact momentum exchange at the time of impact and (b) the higher fidelity, DART spacecraft and ejecta case, where escaping particles impart momentum at their corresponding time of escape.

Figure 5 shows summary plots of the 20 October 2062 close approach. The momentum delivered by the DART spacecraft alone would deflect Didymos by about $56 \mathrm{km}$ in the 2062 b-plane. Using an instantaneous ejecta momentum transfer model where the impact is simulated using a single impulse, the total deflection is $103 \mathrm{km}$. However, if the impulses delivered by each escaping ejecta pseudo-particle are considered, the total deflection is lower at about $93 \mathrm{km}$. Due to the relatively large close approach distance of 7.4 million km between Didymos and the Earth in 2062 as well as the absence of key-holes in the vicinity of the nominal orbit, no significant increase in the impact hazard of Didymos as a consequence of DART could be detected.

For the 04 November 2123 close approach (not shown) the DART spacecraft's contribution to the shift of the Didymos system on the 2123 b-plane is at about $35 \mathrm{km}$. The single-impulse momentum transfer model suggests the Didymos system is deflected by about $64 \mathrm{km}$. Once again, for the case where the escaping particles impart momentum at their corresponding time of escape, the deflection is slightly lower at $58 \mathrm{km}$. Similar to the close approach in 2062, no significant increase in the impact hazard of Didymos due to DART was found.

Results with increased $\beta_\odot$ of 5 and 10 (not shown) to cover unexpectedly large ejecta momentum transfers suggest that the overall change in the orbit of the Didymos system is small enough to allow for a linearization of the effect of DART on the position of Didymos on the 2062 b-plane. Hence, even larger values of $\beta_\odot$ would not lead to a future collision with the Earth.

*JPL Small Body Database Browser (SBDB) https://ssd.jpl.nasa.gov/sbdb.cgi?sstr=didymos



(a) View 1

(b) View 2

(c) View 3

Figure 5: 20 October 2062 Didymos-Earth Close Approach uncertainty ellipses for various cases of the DART impact.

CONCLUSION

We discussed the heliocentric changes to the (65803) Didymos system due to the kinetic impact caused by the DART spacecraft on the secondary asteroid Dimorphos. Updated post-DART b-plane maps were generated for the Didymos-Earth close approaches in October 2062 and November 2123. Our results suggest that the likely maximum b-plane deflection caused by DART will be around 100 kilometers. Even for a substantially larger than expected momentum transfer, the b-plane deflection remained in the linear regime. Therefore, we conclude that the DART mission will most likely not alter the heliocentric orbit of the Didymos binary asteroid system to an extent that puts it on a collision course with the Earth.

Finally, we found that there was a small but significant difference between modeling the impact using the

$\beta_{\odot}$ value at the time of impact and modeling the impact as barycentric impulses when the ejecta particles escape the system. These differences are on the order of a few kilometers. Such differences could prove significant for future deflection missions if the asteroid in question passes close to keyholes during an encounter with the Earth.[10] Since keyholes can be on the order of a few hundred meters, modeling the ejecta impulses at individual escape times could be essential to conduct successful kinetic impactor based asteroid deflection missions.

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REFERENCES

[1] A. F. Cheng, A. S. Rivkin, P. Michel, J. Atchison, O. Barnouin, L. Benner, N. L. Chabot, C. Ernst, E. G. Fahnestock, M. Kueppers, P. Pravec, E. Rainey, D. C. Richardson, A. M. Stickle, and C. Thomas, "AIDA DART asteroid deflection test: Planetary defense and science objectives," *Planetary and Space Science*, Vol. 157, 2018, pp. 104–115, 10.1016/j.pss.2018.02.015.

[2] P. Michel, M. Kueppers, H. Sierks, I. Carnelli, A. F. Cheng, K. Mellab, M. Granvik, A. Kestilä, T. Kohout, K. Muinonen, A. Näsilä, A. Penttila, T. Tikka, P. Tortora, V. Ciarletti, A. Hérique, N. Murdoch, E. Asphaug, A. Rivkin, O. Barnouin, A. C. Bagatin, P. Pravec, D. C. Richardson, S. R. Schwartz, K. Tsiganis, S. Ulamec, and O. Karatekin, "European component of the AIDA mission to a binary asteroid: Characterization and interpretation of the impact of the DART mission," *Advances in Space Research*, Vol. 62, No. 8, 2018, pp. 2261–2272, 10.1016/j.asr.2017.12.020.

[3] M. Arakawa, T. Saiki, K. Wada, K. Ogawa, T. Kadono, K. Shirai, H. Sawada, K. Ishibashi, R. Honda, N. Sakatani, Y. Iijima, C. Okamoto, H. Yano, Y. Takagi, M. Hayakawa, P. Michel, M. Jutzi, Y. Shimaki, S. Kimura, Y. Mimasu, T. Toda, H. Imamura, S. Nakazawa, H. Hayakawa, S. Sugita, T. Morota, S. Kameda, E. Tatsumi, Y. Cho, K. Yoshioka, Y. Yokota, M. Matsuoka, M. Yamada, T. Kouyama, C. Honda, Y. Tsuda, S. Watanabe, M. Yoshikawa, S. Tanaka, F. Terui, S. Kikuchi, T. Yamaguchi, N. Ogawa, G. Ono, K. Yoshikawa, T. Takahashi, Y. Takei, A. Fujii, H. Takeuchi, Y. Yamamoto, T. Okada, C. Hirose, S. Hosoda, O. Mori, T. Shimada, S. Soldini, R. Tsukizaki, T. Iwata, M. Ozaki, M. Abe, N. Namiki, K. Kitazato, S. Tachibana, H. Ikeda, N. Hirata, N. Hirata, R. Noguchi, and A. Miura, "An artificial impact on the asteroid (162173) Ryugu formed a crater in the gravity-dominated regime," *Science*, Vol. 368, No. 6486, 2020, pp. 67–71, 10.1126/science.aaz1701.

[4] E. G. Fahnestock *et al.*, "Pre-Encounter Predictions of DART Impact Ejecta Behavior and Observability," *Planetary Science Journal*, 2022, in preparation.

[5] A. Stickle, J. Atchison, O. Barnouin, A. Cheng, D. Crawford, C. Ernst, Z. Fletcher, and A. Rivkin, "Modeling Momentum Transfer from Kinetic Impacts: Implications for Redirecting Asteroids," *Procedia Engineering*, Vol. 103, 2015, pp. 577–584. Proceedings of the 2015 Hypervelocity Impact Symposium (HVIS 2015), 10.1016/j.proeng.2015.04.075.

[6] K. R. Housen and K. A. Holsapple, "Ejecta from impact craters," *Icarus*, Vol. 211, No. 1, 2011, pp. 856–875, 10.1016/j.icarus.2010.09.017.

[7] A. B. Davis and D. J. Scheeres, "Doubly synchronous binary asteroid mass parameter observability," *Icarus*, Vol. 341, 2020, p. 113439, 10.1016/j.icarus.2019.113439.

[8] R. Makadia, S. D. Raducan, E. G. Fahnestock, and S. Eggl, "Heliocentric effects of the DART mission on the (65803) Didymos binary asteroid system," *Planetary Science Journal*, 2022, in prep.

[9] S. R. Chesley and S. Eggl, "Post-Deflection Impact Risk Assessment of DART Mission," *JPL IOM 392-18-003*, 2018, 10.5281/zenodo.1435957.

[10] S. R. Chesley, D. Farnocchia, M. C. Nolan, D. Vokrouhlický, P. W. Chodas, A. Milani, F. Spoto, B. Rozitis, L. A. Benner, W. F. Bottke, M. W. Busch, J. P. Emery, E. S. Howell, D. S. Lauretta, J.-L. Margot, and P. A. Taylor, "Orbit and bulk density of the OSIRIS-REx target Asteroid (101955) Bennu," *Icarus*, Vol. 235, 2014, pp. 5–22, 10.1016/j.icarus.2014.02.020.