Icarus 421 (2024) 116225

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Research Paper

ASTERIA — Thermal inertia evaluation of asteroid Didymos

Bojan Novaković [a,b,*], Marco Fenucci [c,d]

[a] Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía s/n., Granada, 18008, Spain
[b] Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16, Belgrade, 11000, Serbia
[c] ESA ESRIN/PDO/NEO Coordination Centre, Largo Galileo Galilei, 1, Frascati (RM), 00044, Italy
[d] Elecnor Deimos, Via Giuseppe Verdi, 6, San Pietro Mosezzo (NO), 28060, Italy

ARTICLE INFO

Keywords:
Small solar system bodies (1469)
Asteroids (72)
Near-earth objects (1092)
Asteroid surfaces (2209)
Asteroid didymos

ABSTRACT

Asteroid Didymos, recently targeted by the NASA DART mission, is also planned to be visited by the ESA Hera mission. The main goal of the DART mission was to impact Dimorphos, the small satellite of Didymos, which was accomplished in September 2022. This collision altered the Didymos–Dimorphos system, generating a notable quantity of ejecta that turned Dimorphos into an active asteroid, with some ejecta potentially settling on the surfaces of both components. This prompts the investigation into the extent of post-impact surface alterations on these bodies, compared to their original states. The purpose of this study is to independently evaluate the pre-impact thermal inertia of Didymos. We employed ASTERIA, an alternative to conventional thermophysical modeling, to estimate the surface thermal inertia of Didymos. The approach is based on a model-to-measurement comparison of the Yarkovsky effect-induced drift on the orbital semi-major axis. These results, alongside existing literature, enable an evaluation of the impact-induced alterations in Didymos's thermal inertia. Our nominal estimate with a constant thermal inertia model stands at $\Gamma = 211^{+81}_{-55}$ J m^{-2} K^{-1} s$^{-1/2}$, while assuming it varies with the heliocentric distance with an exponent of -0.75 thermal inertia of Didymos is found to be 258^{+94}_{-63} J m^{-2} K^{-1} s$^{-1/2}$. Subsequent verification confirmed that this result is robust against variations in unknown physical parameters. The thermal inertia estimates for Didymos align statistically with values reported in the literature, derived from both pre- and post-impact data. The forthcoming Hera mission will provide an opportunity to further corroborate these findings. Additionally, our results support the hypothesis that the thermal inertia of near-Earth asteroids is generally lower than previously expected.

1. Introduction

The near-Earth binary asteroid (65803) Didymos was recently the target of the NASA DART (Double Asteroid Redirection Test) mission (Cheng et al., 2018). The main aim of the mission, impacting Didymos's accompanying body Dimorphos, was accomplished on 2022 September 26, 23:14 UTC. The impact altered the binary system's orbital period from 11.92 h to 11.37 h, proving that kinetic impacts are a viable method of diverging an asteroid orbit and, therefore, can also be applied for planetary defense purposes (Daly et al., 2023; Thomas et al., 2023). For an overview of the achievements of the DART mission and related investigations we direct readers to a recent paper by Chabot et al. (2024).

Further enhancement of the ability to protect our planet crucially depends on how well we understand the consequences of the DART impact experiment. For instance, in the case of small objects such as Dimorphos, the impact likely occurred in the strength-dominated regime, where the physical properties of the surface play a significant role in the crater formation process (e.g. Benz and Asphaug, 1999).

Thermal inertia gauges the resistance of a material to temperature changes and can indicate the particle size of regolith (e.g. Gundlach and Blum, 2013; Schorghofer et al., 2024), or the porosity of rocks and boulders (Grott et al., 2019; Sakatani et al., 2021). Therefore, it serves as a valuable property that characterizes small bodies surfaces.

The impact on Dimorphos also generated ejecta, boosting the momentum by a factor of 3.6 ± 0.2 (Cheng et al., 2023) and effectively transforming it into an artificial active asteroid (Graykowski et al., 2023; Li et al., 2023). A part of the ejecta may or may not be deposited on Didymos (see, e.g. Rossi et al., 2022; Ferrari et al., 2022, and references therein). This raises the question of whether a significant deposit of material at the surface of Didymos has occurred, and if so, whether it changed the surface thermal inertia of Didymos.

1.1. Pre- and post-impact surface properties of Didymos

What do we know about the pre- and post-impact Didymos' surface properties?

* Corresponding author at: Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16, Belgrade, 11000, Serbia.
E-mail address: bojan.novakovic@matf.bg.ac.rs (B. Novaković).

https://doi.org/10.1016/j.icarus.2024.116225
Received 22 April 2024; Received in revised form 18 July 2024; Accepted 19 July 2024
Available online 22 July 2024

Physical properties of the Didymos system before and after the DART impact were studied by Lin et al. (2023), using photometric observations. The authors found variations in taxonomic classification from S-complex (pre-impact) to C- and back to S-complex (post-impact). These variations are likely caused by contamination from the ejecta. This implies that the properties of the ejecta from Dimorphos could be somewhat different from those of the material of Didymos surface. Therefore, accumulation of the ejecta on Didymos surface might change its properties.

Gray et al. (2023) performed polarimetric observations of the Didymos–Dimorphos system, spanning a period from about one month before to almost four months after the impact. This allows the authors to determine the polarimetric behavior of the system in its original state (pre-impact) and its changes following the impact of the DART spacecraft (post-impact). Gray et al. found a drop in polarization in the post-impact measurements. They explained this as being, at least partly, due to the ejection of smaller particles than those present at the surface before the impact.

Moreno et al. (2023) analyzed the ejecta dust properties and evolution by applying Monte Carlo models to ground-based and Hubble Space Telescope observations of the Didymos–Dimorphos system, taken after the impact. Among other results, Moreno et al. show that up to 1.5×10^6 kg of material fell back on the surfaces of both Dimorphos and Didymos in the first 20 days following the impact. Some of this material may have settled permanently on the surface of both binary system components.

Still, according to Polishook et al. (2023), near-infrared spectral observations of the Didymos system taken before the impact and after the ejecta dissipated show no signs of the spectral features changes. The authors suggested that both Didymos and Dimorphos are made of the same silicate material, and interpreted this as a support for a binary asteroid formation theory that includes the breaking up of a single body due to rotational fission. Polishook et al. also suggested that only a negligible amount of non-weathered material was ejected from Dimorphos subsurface, suggesting that Dimorphos originates from weathered material ejected from Didymos surface.

The results described above significantly increase our understanding of the Didymos–Dimorphos system. Still, these findings also leave some uncertainties about which changes occurred on the surface of Didymos following the DART impact on Dimorphos and, if they happened, to what degree. Better data and more precise answers in this respect are expected from the forthcoming ESA Hera mission, which aims to characterize the DART impact outcome (Michel et al., 2022).

1.2. Pre- and post-impact surface thermal inertia of Didymos

The post-impact thermal inertia of Didymos has been recently estimated by Rivkin et al. (2023), using data from the James Webb Space Telescope obtained after the impact. Based on mid- and near-infrared observations, the authors estimated the post-impact thermal inertia values at 260 ± 30 and 290 ± 50 J m^{-2} K^{-1} s$^{-1/2}$, respectively.

The pre-impact thermal inertia of Didymos has also been recently estimated by Rozitis et al. (2024). The authors applied the standard procedure for thermal inertia estimation, that is fitting thermal-infrared observations of a planetary body or surface with an appropriate thermophysical model (e.g. Delbo et al., 2015; Hung et al., 2022, and references therein). Using the mid-infrared observations obtained by ESO's Very Large Telescope before the DART impact, Rozitis et al. estimated the pre-impact thermal inertia of Didymos to be 320 ± 70 J m^{-2} K^{-1} s$^{-1/2}$.

The statistical compatibility of the obtained pre- (Rozitis et al., 2024) and post-impact (Rivkin et al., 2023) thermal inertia values implies that Dimorphos' ejecta likely had minimal impact on Didymos' thermal inertia. Nonetheless, the slight shift towards higher pre-impact values warrants further investigation into potential effects on thermal properties caused by ejecta.

In this work, we contribute to the topic by taking advantage of an alternative method for asteroid thermal inertia estimation recently proposed by Novaković et al. (2024) to re-evaluate the pre-impact thermal inertia of Didymos. By combining these findings with available literature values, we aim to place additional constraints on a possible difference between the pre- and post-impact thermal inertia.

2. Thermal inertia estimation by ASTERIA

The Asteroid Thermal Inertia Analyzer (ASTERIA) is a novel approach to asteroid thermal inertia estimations. It is generally based on the model-to-measurement comparison of the Yarkovsky effect-induced orbital drift. As such, ASTERIA is independent from the classical thermophysical modeling approach, and it therefore presents an alternative solution. A detailed description of the approach is beyond the scope of this paper, and it can be found in Novaković et al. (2024, see also Fenucci et al. (2021, 2023a)), while the corresponding code is freely available (Fenucci et al., 2023b).

Note that the ASTERIA framework, fundamentally grounded in the analysis of the Yarkovsky effect, is tailored for the study of single bodies. However, it can still be effectively used for binary systems. In fact, the Yarkovsky effect of a binary asteroid measured from astrometry corresponds to that acting on the center of mass of the system. On the other hand, if the mass ratio of the system is small enough (∼0.01 for the Dimorphos–Didymos system, assuming the two components have the same density), the Yarkovsky-induced drift predominantly reflects the influence on the primary body (Vokrouhlický et al., 2015). Therefore, it is safe to compare the modeled Yarkovsky effect acting on the primary body to the measured drift of the center of mass of the system. This was further substantiated by results from Novaković et al. (2024), demonstrating that the ASTERIA model retains its efficacy in binary systems, effectively accounting for the Yarkovsky effect on the primary and, by extension, to the system as a whole.

The ASTERIA model has been demonstrated to provide reliable thermal inertia estimations if certain conditions are met. In particular, along with the orbital parameters, Yarkovsky drift and rotation period, at least the albedo and diameter of an object need to be known, as outlined in Novaković et al. (2024). In the case of Didymos, these requirements are not only met, but supplemented with additional relevant data, making Didymos a suitable candidate for applying the ASTERIA model.

To accurately estimate the thermal inertia of Didymos using ASTERIA, it is essential to select appropriate input parameters and an appropriate model of the Yarkovsky effect. To this purpose, we identified a nominal set of input parameters and a model that are most suitable to get accurate estimate of Didymos' pre-impact thermal inertia. Additionally, to ensure the robustness of our nominal results, we have conducted analyses using alternative sets of input parameters and models.

2.1. Nominal input parameters of the model

In our nominal case, we used JPL's solution #204 (see Table 2), where the Yarkovsky effect related parameter A_2 was determined with a signal-to-noise ratio (SNR) of 16. Note that this solution includes astrometry taken after the impact, although our goal is to assess Didymos's pre-impact thermal inertia. Considering that the arc of post-impact observations used for orbit determination is too short to influence the Yarkovsky effect's detection significantly, we assume that the determined A_2 value is representative of the pre-impact Didymos orbit. Accordingly, changes in the A_2 parameter with respect to previous JPL solutions (see solution #181, Table 2) are due to the higher accuracy of the orbit solution #204, which includes radar and occultation measurements.

Physical parameters of Didymos used as the nominal settings are summarized in Table 1. Additionally, the model non-sphericity parameter derived from the ratio of the ellipsoid axes is determined to be 1.03.

Note, however, that we used the density distribution of S-type asteroids (see Novaković et al., 2024, Table 2) for the density, without using any determination from the known literature. In contrast, we analyze how the density value may affect the results in Section 2.1.2.

We include constraints in the obliquity according to the value established by Naidu et al. (2024). Though in our original ASTERIA model (Novaković et al., 2024) the population-based distribution of obliquity is used as input, we consider this constraint to increase the accuracy of the thermal inertia estimate. For the heat capacity and emissivity, which are unmeasured on asteroid Didymos, we based our values on analogous measurements from meteorites. We adopted a heat capacity value of $C = 600$ J kg^{-1} K^{-1}, drawing on findings by Opeil et al. (2020). For emissivity, we used a value of $\epsilon = 0.9$, in line with Rozitis et al. (2024).

While the absolute magnitude H is listed among the physical parameters, it was not employed in the model since they it is redundant when both albedo and size are known. However, we included it for reference purposes.

2.1.1. Thermal inertia estimates with the nominal settings

To determine the thermal inertia of Didymos with the nominal set of input parameters, we employed two different Yarkovsky effect models implemented within ASTERIA. The first model assumes a constant thermal inertia along Didymos' orbit. However, Didymos' orbital eccentricity value of $e \sim 0.38$ may be large enough to cause thermal inertia variations due to temperature changes along the trajectory. To accommodate this potential variability, we introduced a second model that adjusts thermal inertia along the orbit in relation to the heliocentric distance.

An important point to emphasize is that the thermal inertia values for Didymos reported here are derived from orbit-average computations, corresponding to the object's average heliocentric distance, which is approximately 1.6 astronomical unit (au). This distinction is irrelevant when assuming constant thermal inertia, as the results are considered independent of heliocentric distance. However, this detail becomes crucial in the variable thermal inertia model (see below).

Constant thermal inertia model

The ASTERIA is first used with the constant thermal inertia model and nominal settings explained above. In this case, the thermal inertia of Didymos is estimated at $\Gamma = 211^{+81}_{-55}$ J m^{-2} K^{-1} s$^{-1/2}$. We consider this value our nominal estimate for the constant thermal inertia model.

The thermal inertia of asteroids, mainly those covered by particulate regolith, may be sensitive to temperature variations (Rozitis et al., 2018). As Cambioni et al. (2021) found that the surfaces of S-type asteroids can efficiently produce particulate regolith due to thermal cracking and micrometeorite bombardment, the model incorporating thermal inertia variable with heliocentric distance may be more suitable for the asteroid Didymos. Nevertheless, it is important to note that our estimate with the constant thermal inertia model is statistically consistent with the pre- and post-impact results reported by Rozitis et al. (2024) and Rivkin et al. (2023).

Variable thermal inertia model

The variable thermal inertia model has one additional free input parameter, namely, the exponent α of a scaling formula $\Gamma = \Gamma_0 r^\alpha$, where Γ_0 represents the baseline thermal inertia at a distance of 1 au, and r is the heliocentric distance expressed in au.

Therefore, in what follows, for all the results obtained with the variable thermal inertia model, the Γ_0 value that represents the baseline thermal inertia at a distance of 1 au will be reported.

The theoretically predicted value of α is -0.75 (Delbo et al., 2015), and we formally accepted the corresponding estimate as our nominal result for the variable thermal inertia case. Still, the thermal inertia variations with heliocentric distance could differ for different asteroids (Rozitis et al., 2018). Therefore, it is not a priori clear what value of exponent α should be used. To account for the unknown exponent α, we used several values from the interval between 0 and -2, based on the finding by Rozitis et al. (2018).

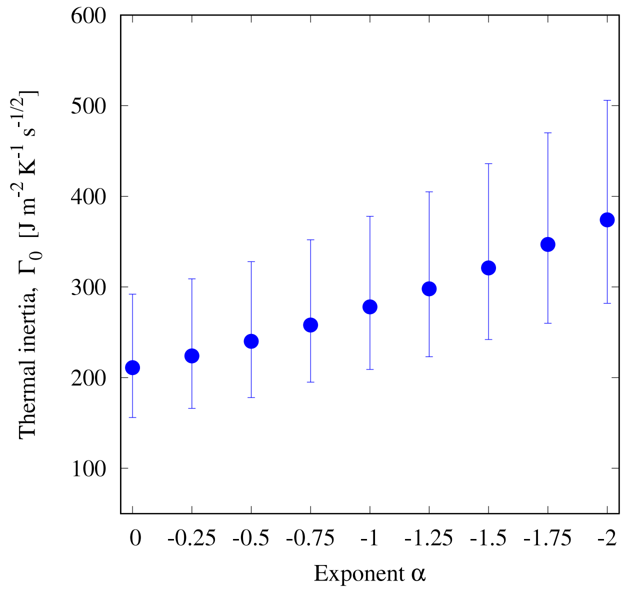

Fig. 1. Thermal inertia estimates for asteroid Didymos with the model assuming thermal inertia variable with heliocentric distance. The results for different values of scaling exponent α are shown. Note that the $\alpha = 0$ case corresponds to the constant thermal inertia model, while the most commonly used value is $\alpha = -0.75$.

The obtained Didymos' thermal inertias are shown in Fig. 1. It should be noted here that the constant thermal inertia model corresponds to the $\alpha = 0$ case. The plot clearly reveals the sensitivity of the result to the exponent α. The estimates range from 224^{+85}_{-58} J m^{-2} K^{-1} s$^{-1/2}$ (for $\alpha = -0.25$), to 374^{+132}_{-92} J m^{-2} K^{-1} s$^{-1/2}$ (for $\alpha = -2$). For $\alpha = -0.75$, the thermal inertia of Didymos is estimated to 258^{+94}_{-63} J m^{-2} K^{-1} s$^{-1/2}$.

2.1.2. Alternative input parameters

Although our results for nominal parameters align with the values reported in the literature, we also investigated how using other reasonable values of input parameters might potentially affect our conclusions. In particular, we tested different values for density, the magnitude of the Yarkovsky effect, heat capacity, and emissivity. Unless otherwise stated, we employed the constant thermal inertia model in all alternative parameter tests. In this case, the results should be compared to $\Gamma = 211^{+81}_{-55}$ J m^{-2} K^{-1} s$^{-1/2}$. However, when referring to a single result from the variable thermal inertia model, it denotes the baseline thermal inertia Γ_0 obtained with an exponent of $\alpha = -0.75$, and the reference value is $\Gamma_0 = 258^{+94}_{-63}$ J m^{-2} K^{-1} s$^{-1/2}$.

The role of density

In our above analysis we considered the population based density of rocky S-type asteroids. While this is a reasonable assumption for Didymos, it is important to quantify how much this may affect the estimated thermal inertia. Keeping all the parameters from the nominal model, but using the density value of $\rho = 2400 \pm 300$ kg m^{-3} from Daly et al. (2023) yields a thermal inertia estimation of 207^{+90}_{-61} J m^{-2} K^{-1} s$^{-1/2}$. Similarly, using the density of $\rho = 2790 \pm 280$ kg m^{-3} from Chabot et al. (2024), Rozitis et al. (2024), results in a thermal inertia of 203^{+88}_{-57} J m^{-2} K^{-1} s$^{-1/2}$.

These values are statistically the same as those obtained with the nominal set of parameters, indicating that the estimated thermal inertia of Didymos is relatively insensitive to variations in the density, provided that their values are consistent with those of S-type asteroids.

Table 1
Physical parameters of asteroid (65803) Didymos.

Parameter	Value	Reference
Absolute magnitude, H	18.16 ± 0.06	Rozitis et al. (2024)
Diameter, D	730 ± 17 m	Barnouin et al. (2024)
Best-fit ellipsoid, $a \times b \times c$	819 × 801 × 605 m	Barnouin et al. (2024)
Bulk density, ρ	2790 ± 140 kg m^{-3}	Naidu et al. (2024)
Obliquity, γ	167.7 ± 0.5 deg	Naidu et al. (2024)
Rotation period, P	2.2600 ± 0.0001 h	Thomas et al. (2023)
Geometric albedo, p_V	0.17 ± 0.01	Rozitis et al. (2024)
Emissivity, ϵ	0.9	Adopted
Heat capacity, C	600 J kg^{-1} K^{-1}	Opeil et al. (2020)

Table 2
Orbital parameters of asteroid (65803) Didymos.

JPL solution 181	
Semi-major axis, a	1.644268882 ± 1.56 × 10^{-9} au
Eccentricity, e	0.383882802 ± 2.75 × 10^{-9}
Inclination, i	3.407768167 ± 1.32 × 10^{-6} deg
Parameter, A_2	(−1.8858 ± 0.7226) × 10^{-14} au d^{-2}
Observation Arc	1996-Apr-11 to 2021-Feb-05
Epoch	2457380.5 JD
JPL solution 204	
Semi-major axis, a	1.642665058 ± 2.72 × 10^{-10} au
Eccentricity, e	0.383264789 ± 1.33 × 10^{-10}
Inclination, i	3.414150730 ± 1.61 × 10^{-8} deg
Parameter, A_2	(−1.0423 ± 0.0649) × 10^{-14} au d^{-2}
Observation Arc	1996-Apr-11 to 2023-Jan-21
Epoch	2460200.5 JD

The alternative values of heat capacity and emissivity

We recall that the ASTERIA model is only weakly sensitive to the choice of the heat capacity parameter, and using other reasonable values should not significantly change the results. Nevertheless, Opeil et al. also found that the heat capacity increases with increasing temperatures, and therefore it is higher for near-Earth asteroids. For this reason, we also performed simulations assuming $C = 1000$ J kg^{-1} K^{-1}. Based on meteorite measurements, Ostrowski and Bryson (2019) suggested higher emissivity values than 0.9. Therefore, we also run simulations for emissivity of 0.984, as we used this value in our original ASTERIA model (Novaković et al., 2024).

Using the larger heat capacity of $C = 1000$ J kg^{-1} K^{-1} did not change our nominal result, while using the emissivity of $\epsilon = 0.984$ marginally increased it to 215^{+85}_{-56} J m^{-2} K^{-1} s$^{-1/2}$.

The alternative orbit solution

We used JPl's orbit solution #204 in our nominal case. However, as explained in Section 2.1, strictly speaking, it also includes post-impact observations, which means the resulting thermal inertia may not purely reflect pre-impact conditions. We explored the potential outcomes using an orbit solution based solely on pre-impact data to address this.

Accordingly, we employed JPL's orbit solution #181 (Table 2), which indicated a more substantial Yarkovsky effect but had a significantly lower SNR. Our findings show that solution #181 leads to a higher estimate of Didymos' thermal inertia. Specifically, when combined with the physical parameters from our nominal settings, the thermal inertia values were calculated as $\Gamma = 304^{+290}_{-99}$ J m^{-2} K^{-1} s$^{-1/2}$ under a constant thermal inertia model, and 357^{+271}_{-98} J m^{-2} K^{-1} s$^{-1/2}$ under a variable thermal inertia model.

It is crucial to highlight that the larger uncertainties associated with these thermal inertia estimates directly result from the lower SNR in the Yarkovsky drift detected in JPL solution #181. This emphasizes the influence of data quality on the accuracy of our thermal inertia calculations.

Thermal inertia estimates with the minimal set of input parameters

In this part, we revisited the estimation of Didymos' thermal inertia employing the minimal set of input parameters identified by Novaković et al. (2024) as sufficient for ASTERIA to yield trustworthy outcomes. The primary goal of this is to additionally validate ASTERIA's ability to accurately estimate the thermal inertia with limited input data. Thus, the significance of the results lies in their methodological implications rather, than their specific values. The minimum necessary set of input parameters for a reliable estimation is obtained simply by replacing Didymos' obliquity value with the population-based obliquity distribution (Tardioli et al., 2017). In this analysis, we applied both constant and variable models of ASTERIA's thermal inertia.

The constant model estimated the thermal inertia at 202^{+79}_{-52} J m^{-2} K^{-1} s$^{-1/2}$, whereas the variable model yielded an estimate of 255^{+86}_{-57} J m^{-2} K^{-1} s$^{-1/2}$. These results align with those derived from the nominal set of parameters, reaffirming that the this minimal set of input parameters suffices for ASTERIA to assess thermal inertia reliably.

3. Summary and discussion

Let us first briefly address the limitations of the ASTERIA model and the additional complexities related to the Yarkovsky effect that were not included in our analysis. Two primary factors in this regard are (i) the nonlinearity of boundary conditions for heat conduction at the surface and (ii) the anisotropy of thermal emission from the surface due to surface roughness ("thermal beaming").

Nonlinearity effects tend to reduce the theoretically predicted semi-major axis drift rate da/dt within the relevant range of thermal inertia values, with a drop factor between 0.7 and 0.9 (Čapek, 2007). Conversely, thermal beaming effects generally increase the semimajor axis drift rate by a factor of 1.1 to 1.5 (Rozitis and Green, 2012, see also Müller et al. (2014)). Therefore, fortunately, these two effects tend to compensate for each other. Although some residual effects may persist in specific cases, their overall impact should be limited. In this respect, it is worth mentioning that, despite the modeling issues discussed above, the cross-validation of ASTERIA with thermophysical modeling results performed on ten well-characterized near-Earth asteroids plus asteroid Bennu shows full consistency of the results (Novaković et al., 2024).

Another possible limitation is the dependence of the result of surface thermal inertia variations with latitude. Although this aspect can be included in the ASTERIA, the relevant information for Didymos is unavailable, preventing us from including it in the model. Nevertheless, suppose the level of potential variations is not much larger than in the case of asteroid Bennu (Rozitis et al., 2020), the impact on the result should be limited to a few percent (Novaković et al., 2024).

Our study aimed to obtain an independent estimate of the pre-impact thermal inertia of the Didymos–Dimorphos binary asteroid system. The results of Didymos' thermal inertia estimates are summarized in Fig. 2. Our nominal analysis yields Didymos thermal inertia of $\Gamma = 211^{+81}_{-55}$, and 258^{+94}_{-63} J m^{-2} K^{-1} s$^{-1/2}$, obtained from the constant and the variable thermal inertia model, respectively. These estimates align well with the existing literature.

We also obtained results for different values of input parameters. We found that, as long as the input parameters are in a reasonable range compatible with the known physical properties, they show minimal impact on the resulting thermal inertia.

The only exception is when an older orbit solution #181 is used. It yielded larger thermal inertia, more in line with results by Rozitis et al. (2024), but with a significantly larger uncertainty due to a low SNR detection of the Yarkovsky effect.

Specifically, increasing the non-gravitational acceleration parameter for a factor of about 1.8 resulted in thermal inertia of $\Gamma = 304$ J m^{-2} K^{-1} s$^{-1/2}$, more than 40% larger than in the nominal orbit case. However, the latter estimate is associated with large uncertainties,

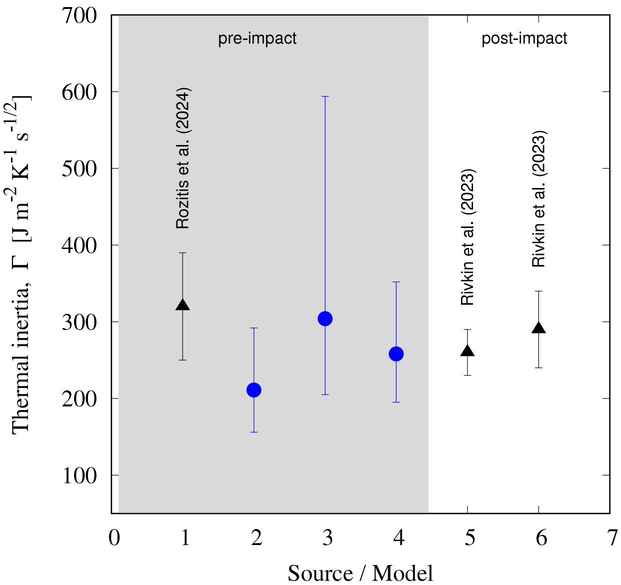

Fig. 2. Thermal inertia estimates for asteroid Didymos. The blue circles show the results obtained in this work using the ASTERIA. The black triangles are literature values, as indicated in the plot. The plot is divided into two segments, corresponding to pre-impact and post-impact data assessments. The x-axis denotes the sources and models used for these estimations: (1) Rozitis et al. (2024), (2) ASTERIA (constant thermal inertia, orb. sol. #204), (3) ASTERIA (constant thermal inertia, orb. sol. #181), (4) ASTERIA (variable thermal inertia, $\alpha = -0.75$, orb. sol. #204), (5) Rivkin et al. (2023) (mid-infrared), and (6) Rivkin et al. (2023) (near-infrared).

mainly due to the considerable uncertainty in the non-gravitational acceleration parameter A_2, as determined from this orbit solution.

The results obtained using the thermal inertia variable with heliocentric distance show a clear dependence on the exponent of the scaling relation. The resulting thermal inertia Γ_0 at 1 au is the lowest for exponent $\alpha = 0$ (equivalent to the constant thermal inertia model) and increases as the exponent goes from 0 to -2. This implies that, if the thermal inertia of Didymos changes with heliocentric distance, knowing the exponent α is crucial for proper estimation.

On the other hand, supposing the thermal inertia estimates obtained by Rivkin et al. (2023) are appropriate reference values, our results suggest that the thermal inertia of Didymos changes with an exponent α likely between -0.75 and -1.25. The upper bound aligns well with the value of $\alpha = -1.37 \pm 0.14$ found by MacLennan and Emery (2021). This might further suggest that the larger estimate of 290 ± 50 J m^{-2} K^{-1} s$^{-1/2}$ by Rivkin et al. (2023) is closer to the real thermal inertia of Didymos.

Technically, the thermal inertia estimates we obtained are statistically consistent with pre- and post-impact results as reported by Rozitis et al. (2024) and Rivkin et al. (2023). Combining all these results supports the hypothesis that the impact event on Dimorphos did not significantly affect Didymos' surface thermal inertia. Therefore any changes to Didymos' thermal inertia were either negligible or within the detection limits of current terrestrial observational techniques. However, further verification of these findings is required. This will likely be facilitated by the upcoming ESA Hera mission, scheduled to visit the system in late 2026.

In this respect, it is worth mentioning that thermophysical models tailored for binary systems such as Didymos–Dimorphos may further improve our knowledge of the system's thermal inertia. Such models are already under development (Kanamaru et al., 2023), but their full potential will be realized only once data from the Hera mission is available.

In a broader context, our findings regarding the thermal inertia of Didymos contribute to the accumulating evidence that many small near-Earth asteroids exhibit lower-than-expected thermal inertia. For example, the global thermal inertia of (162 173) Ryugu was estimated to be $\Gamma = 225 \pm 45$ J m^{-2} K^{-1} s$^{-1/2}$ (Shimaki et al., 2020), and for asteroid (101 955) Bennu, it was approximately $\Gamma = 300 \pm 30$ J m^{-2} K^{-1} s$^{-1/2}$ (Rozitis et al., 2020). Moreover, Bennu was found to host boulders with even lower thermal inertia (Ryan et al., 2024). A study by Fenucci et al. (2021) reported significantly low thermal inertia of $\Gamma \lesssim 150$ J m^{-2} K^{-1} s$^{-1/2}$ for the rapidly rotating asteroid (499 998) 2011 PT, and similar findings were observed for the small, fast-rotating near-Earth asteroid 2016 GE1, with estimates around $\Gamma \simeq 100$ J m^{-2} K^{-1} s$^{-1/2}$ (Fenucci et al., 2023a). Preliminary data from the Hayabusa2 extended mission targeting asteroid 1998 KY26 also indicate very low thermal inertia (Petković et al., 2021). These studies collectively suggest that many small near-Earth asteroids, regardless of their taxonomic classification, tend to have low surface thermal inertia.

With increased rate of Yarkovsky detections (see e.g. Bedini and Tommei, 2024), and the development of automated procedures for detecting the Yarkovsky effect, such as the one at the ESA NEO Coordination Centre (Fenucci et al., 2024), the applicability of the ASTERIA model will be extended to many new objects, opening new possibilities for asteroid thermal inertia estimations. As shown by Novaković et al. (2024), this will be especially important for small objects, where required input data for thermophysical modeling is generally unavailable.

In the case of potential deflection or exploration missions, a reliable Yarkovsky detection would be necessary from both pre- and post-deflection orbit to enhance the possibility of detecting thermal inertia alternations using solely ASTERIA. To achieve this, we underscore the significance of performing pre- and post-deflection occultation measurements,[1] which provide high-precision astrometric positions, allowing Yarkovsky detection from shorter observational arcs.

CRediT authorship contribution statement

Bojan Novaković: Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Marco Fenucci:** Writing – review & editing, Validation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors appreciate the support from the Planetary Society STEP Grant, made possible by the generosity of The Planetary Society' members. This research was also partly supported by the Science Fund of the Republic of Serbia, GRANT No 7453, Demystifying enigmatic visitors of the near-Earth region (ENIGMA). BN acknowledges support from the project PID2021-126365NB-C21 (MCI/AEI/FEDER, UE) and from the Severo Ochoa grant CEX2021-001131-S funded by MCI/AEI/10.13039/501100011033.

[1] In a slightly different context, the importance of occultation measurements was also outlined by Makadia et al. (2024).

References

Barnouin, O., Ballouz, R.L., Marchi, M., et al., 2024. Nature Commun. submitted for publication.

Bedini, L., Tommei, G., 2024. New Yarkovsky drift detections using astrometric observations of NEAs. Exp. Astron. 57 (4), http://dx.doi.org/10.1007/s10686-024-09925-z.

Benz, W., Asphaug, E., 1999. Catastrophic disruptions revisited. Icarus 142, 5–20. http://dx.doi.org/10.1006/icar.1999.6204, arXiv:astro-ph/9907117.

Cambioni, S., Delbo, M., Poggiali, G., Avdellidou, C., Ryan, A.J., Deshapriya, J.D.P., Asphaug, E., Ballouz, R.L., Barucci, M.A., Bennett, C.A., Bottke, W.F., Brucato, J.R., Burke, K.N., Cloutis, E., DellaGiustina, D.N., Emery, J.P., Rozitis, B., Walsh, K.J., Lauretta, D.S., 2021. Fine-regolith production on asteroids controlled by rock porosity. Nature 598, 49–52. http://dx.doi.org/10.1038/s41586-021-03816-5.

Čapek, D., 2007. Thermal Effects in Physics and Dynamics of Small Bodies of the Solar System. (Ph.D. thesis). Charles University, Faculty of Mathematics and Physics Astronomical Institute, Prague.

Chabot, N.L., Rivkin, A.S., Cheng, A.F., Barnouin, O.S., Fahnestock, E.G., Richardson, D.C., Stickle, A.M., Thomas, C.A., Ernst, C.M., Daly, R.T., Dotto, E., Zinzi, A., Chesley, S.R., Moskovitz, N.A., Barbee, B.W., Abell, P., Agrusa, H.F., Bannister, M.T., Beccarelli, J., Bekker, D.L., Syal, M.B., Buratti, B.J., Busch, M.W., Bagatin, A.C., Chatelain, J.P., Chocron, S., Collins, G.S., Conversi, L., Davison, T.M., DeCoster, M.E., Deshapriya, J.D.P., Eggl, S., Espiritu, R.C., Farnham, T.L., Ferrais, M., Ferrari, F., Föhring, D., Fuentes-Muñoz, O., Gai, I., Giordano, C., Glenar, D.A., Gomez, E., Graninger, D.M., Green, S.F., Greenstreet, S., Hasselmann, P.H., Herreros, I., Hirabayashi, M., Husárik, M., Ieva, S., Ivanovski, S.L., Jackson, S.L., Jehin, E., Jutzi, M., Karatekin, O., Knight, M.M., Kolokolova, L., Kumamoto, K.M., Küppers, M., Forgia, F.L., Lazzarin, M., Li, J.Y., Lister, T.A., Lolachi, R., Lucas, M.P., Lucchetti, A., Luther, R., Makadia, R., Epifani, E.M., McMahon, J., Merisio, G., Merrill, C.C., Meyer, A.J., Michel, P., Micheli, M., Migliorini, A., Minker, K., Modenini, D., Moreno, F., Murdoch, N., Murphy, B., Naidu, S.P., Nair, H., Nakano, R., Opitom, C., Ormö, J., Owen, J.M., Pajola, M., Palmer, E.E., Palumbo, P., Panicucci, P., Parro, L.M., Pearl, J.M., Penttilä, A., Perna, D., Petrescu, E., Pravec, P., Raducan, S.D., Ramesh, K.T., Ridden-Harper, R., Rizos, J.L., Rossi, A., Roth, N.X., Rozek, A., Rozitis, B., Ryan, E.V., Ryan, W.H., Sánchez, P., Santana-Ros, T., Scheeres, D.J., Scheirich, P., Senel, C.B., Snodgrass, C., Soldini, S., Souami, D., Statler, T.S., Street, R., Stubbs, T.J., Sunshine, J.M., Tan, N.J., Tancredi, G., Tinsman, C.L., Tortora, P., Tusberti, F., Walker, J.D., Waller, C.D., Wünnemann, K., Zannoni, M., Zhang, Y., 2024. Achievement of the planetary defense investigations of the double asteroid redirection test (dart) mission. Planet. Sci. J. 5 (49), http://dx.doi.org/10.3847/PSJ/ad16e6.

Cheng, A.F., Agrusa, H.F., Barbee, B.W., Meyer, A.J., Farnham, T.L., Raducan, S.D., Richardson, D.C., Dotto, E., Zinzi, A., Corte, V.Della., Statler, T.S., Chesley, S., Naidu, S.P., Hirabayashi, M., Li, J.Y., Eggl, S., Barnouin, O.S., Chabot, N.L., Chocron, S., Collins, G.S., Daly, R.T., Davison, T.M., DeCoster, M.E., Ernst, C.M., Ferrari, F., Graninger, D.M., Jacobson, S.A., Jutzi, M., Kumamoto, K.M., Luther, R., Lyzhoft, J.R., Michel, P., Murdoch, N., Nakano, R., Palmer, E., Rivkin, A.S., Scheeres, D.J., Stickle, A.M., Sunshine, J.M., Trigo-Rodriguez, J.M., Vincent, J.B., Walker, J.D., Wünnemann, K., Zhang, Y., Amoroso, M., Bertini, I., Brucato, J.R., Capannolo, A., Cremonese, G., Dall'Ora, M., Deshapriya, P.J.D., Gai, I., Hasselmann, P.H., Ieva, S., Impresario, G., Ivanovski, S.L., Lavagna, M., Lucchetti, A., Epifani, E.M., Modenini, D., Pajola, M., Palumbo, P., Perna, D., Pirrotta, S., Poggiali, G., Rossi, A., Tortora, P., Zannoni, M., Zanotti, G., 2023. Momentum transfer from the DART mission kinetic impact on asteroid Dimorphos. Nature 616, 457–460. http://dx.doi.org/10.1038/s41586-023-05878-z, arXiv:2303.03464.

Cheng, A.F., Rivkin, A.S., Michel, P., Atchison, J., Barnouin, O., Benner, L., Chabot, N.L., Ernst, C., Fahnestock, E.G., Kueppers, M., Pravec, P., Rainey, E., Richardson, D.C., Stickle, A.M., Thomas, C., 2018. AIDA DART asteroid deflection test: Planetary defense and science objectives. Planet. Space Sci. 157, 104–115. http://dx.doi.org/10.1016/j.pss.2018.02.015.

Daly, R.T., Ernst, C.M., Barnouin, O.S., Chabot, N.L., Rivkin, A.S., Cheng, A.F., Adams, E.Y., Agrusa, H.F., Abel, E.D., Alford, A.L., Asphaug, E.I., Atchison, J.A., Badger, A.R., Baki, P., Ballouz, R.L., Bekker, D.L., Bellerose, J., Bhaskaran, S., Buratti, B.J., Cambioni, S., Chen, M.H., Chesley, S.R., Chiu, G., Collins, G.S., Cox, M.W., DeCoster, M.E., Ericksen, P.S., Espiritu, R.C., Faber, A.S., Farnham, T.L., Ferrari, F., Fletcher, Z.J., Gaskell, R.W., Graninger, D.M., Haque, M.A., Harrington-Duff, P.A., Hefter, S., Herreros, I., Hirabayashi, M., Huang, P.M., Hsieh, S.Y.W., Jacobson, S.A., Jenkins, S.N., Jensenius, M.A., John, J.W., Jutzi, M., Kohout, T., Krueger, T.O., Laipert, F.E., Lopez, N.R., Luther, R., Lucchetti, A., Mages, D.M., Marchi, S., Martin, A.C., McQuaide, M.E., Michel, P., Moskovitz, N.A., Murphy, I.W., Murdoch, N., Naidu, S.P., Nair, H., Nolan, M.C., Ormö, J., Pajola, M., Palmer, E.E., Peachey, J.M., Pravec, P., Raducan, S.D., Ramesh, K.T., Ramirez, J.R., Reynolds, E.L., Richman, J.E., Robin, C.Q., Rodriguez, L.M., Roufberg, L.M., Rush, B.P., Sawyer, C.A., Scheeres, D.J., Scheirich, P., Schwartz, S.R., Shannon, M.P., Shapiro, B.N., Shearer, C.E., Smith, E.J., Steele, R.J., Steckloff, J.K., Stickle, A.M., Sunshine, J.M., Superfin, E.A., Tarzi, Z.B., Thomas, C.A., Thomas, J.R., Trigo-Rodríguez, J.M., Tropf, B.T., Vaughan, A.T., Velez, D., Waller, C.D., Wilson, D.S., Wortman, K.A., Zhang, Y., 2023. Successful kinetic impact into an asteroid for planetary defence. Nature 616, 443–447. http://dx.doi.org/10.1038/s41586-023-05810-5, arXiv:2303.02248.

Delbo, M., Mueller, M., Emery, J.P., Rozitis, B., Capria, M.T., 2015. Asteroid Thermophysical Modeling. University of Arizona Press, Tucson, pp. 107–128.

Fenucci, M., Micheli, M., Gianotto, F., Faggioli, L., Oliviero, D., Porru, A., Rudawska, R., Cano, J.L., Conversi, L., Moissl, R., 2024. An automated procedure for the detection of the Yarkovsky effect and results from the ESA NEO coordination centre. Astron. Astrophys. 682, A29. http://dx.doi.org/10.1051/0004-6361/202347820, arXiv:2311.10175.

Fenucci, M., Novaković, B., Marčta, D., 2023a. The low surface thermal inertia of the rapidly rotating near-Earth asteroid 2016 GE1. Astron. Astrophys. 675, A134. http://dx.doi.org/10.1051/0004-6361/202346160, arXiv:2306.07693.

Fenucci, M., Novaković, B., Marčeta, D., Pavela, D., 2023b. Fenu24/d-neas: Asteria v1.0.0. http://dx.doi.org/10.5281/zenodo.8365840.

Fenucci, M., Novaković, B., Vokrouhlický, D., Weryk, R.J., 2021. Low thermal conductivity of the superfast rotator (499998) 2011 PT. Astron. Astrophys. 647, A61. http://dx.doi.org/10.1051/0004-6361/202039628, arXiv:2101.04399.

Ferrari, F., Raducan, S.D., Soldini, S., Jutzi, M., 2022. Ejecta formation, early collisional processes, and dynamical evolution after the DART impact on Dimorphos. Planet. Sci. J. 3, 177. http://dx.doi.org/10.3847/PSJ/ac7cf0.

Gray, Z., Bagnulo, S., Granvik, M., Cellino, A., Jones, G.H., Kolokolova, L., Moreno, F., Muinonen, K., Muñoz, O., Opitom, C., Penttilä, A., Snodgrass, C., 2023. Polarimetry of Didymos-Dimorphos: Unexpected long-term effects of the DART impact. http://dx.doi.org/10.48550/arXiv.2311.13483, arXiv e-prints, arXiv:2311.13483 arXiv:2311.13483.

Graykowski, A., Lambert, R.A., Marchis, F., Cazeneuve, D., Dalba, P.A., Esposito, T.M., O'Conner Peluso, D., Sgro, L.A., Blaclard, G., Borot, A., Malvache, A., Marfisi, L., Powell, T.M., Huet, P., Limagne, M., Payet, B., Clarke, C., Murabana, S., Owen, D.C., Wasilwa, R., Fukui, K., Goto, T., Guillet, B., Huth, P., Ishiyama, S., Kukita, R., Mitchell, M., Primm, M., Randolph, J., Rivett, D.A., Ryno, M., Shimizu, M., Toullec, J.P., Will, S., Yue, W.C., Camilleri, M., Graykowski, K., Janetzke, R., Janke, D., Kardel, S., Loose, M., Pickering, J.W., Smith, B.A., Transom, I.M., 2023. Light curves and colours of the ejecta from Dimorphos after the DART impact. Nature 616, 461–464. http://dx.doi.org/10.1038/s41586-023-05852-9, arXiv:2303.05548.

Grott, M., Knollenberg, J., Hamm, M., Ogawa, K., Jaumann, R., Otto, K.A., Delbo, M., Michel, P., Biele, J., Neumann, W., Knapmeyer, M., Kührt, E., Senshu, H., Okada, T., Helbert, J., Maturilli, A., Müller, N., Hagermann, A., Sakatani, N., Tanaka, S., Arai, T., Mottola, S., Tachibana, S., Pelivan, I., Drube, L., Vincent, J.B., Yano, H., Pilorget, C., Matz, K.D., Schmitz, N., Koncz, A., Schröder, S.E., Trauthan, F., Schlotterer, M., Krause, C., Ho, T.M., Moussi-Soffys, A., 2019. Low thermal conductivity boulder with high porosity identified on C-type asteroid (162173) Ryugu. Nat. Astron. 3, 971–976. http://dx.doi.org/10.1038/s41550-019-0832-x.

Gundlach, B., Blum, J., 2013. A new method to determine the grain size of planetary regolith. Icarus 223, 479–492. http://dx.doi.org/10.1016/j.icarus.2012.11.039, arXiv:1212.3108.

Hung, D., Hanuš, J., Masiero, J.R., Tholen, D.J., 2022. Thermal properties of 1847 WISE-observed asteroids. Planet. Sci. J. 3 (56), http://dx.doi.org/10.3847/PSJ/ac4d1f, arXiv:2201.05164.

Kanamaru, M., Okada, T., Senshu, H., Demura, H., Hirata, N., Horikawa, Y., Tommei, G., 2023. Thermophysical model development for hera mission to simulate non-gravitational acceleration on binary asteroid. http://dx.doi.org/10.48550/arXiv.2309.03458, arXiv e-prints, arXiv:2309.03458, arXiv:2309.03458.

Li, J.Y., Hirabayashi, M., Farnham, T.L., Sunshine, J.M., Knight, M.M., Tancredi, G., Moreno, F., Murphy, B., Opitom, C., Chesley, S., Scheeres, D.J., Thomas, C.A., Fahnestock, E.G., Cheng, A.F., Dressel, L., Ernst, C.M., Ferrari, F., Fitzsimmons, A., Ieva, S., Ivanovski, S.L., Kareta, T., Kolokolova, L., Lister, T., Raducan, S.D., Rivkin, A.S., Rossi, A., Soldini, S., Stickle, A.M., Vick, A., Vincent, J.B., Weaver, H.A., Bagnulo, S., Bannister, M.T., Cambioni, S., Bagatin, A.Campo., Chabot, N.L., Cremonese, G., Daly, R.T., Dotto, E., Glenar, D.A., Granvik, M., Hasselmann, P.H., Herreros, I., Jacobson, S., Jutzi, M., Kohout, T., Forgia, F.La., Lazzarin, M., Lin, Z.Y., Lolachi, R., Lucchetti, A., Makadia, R., Epifani, E.Mazzotta., Michel, P., Migliorini, A., Moskovitz, N.A., Ormö, J., Pajola, M., Sánchez, P., Schwartz, S.R., Snodgrass, C., Steckloff, J., Stubbs, T.J., Trigo-Rodríguez, J.M., 2023. Ejecta from the DART-produced active asteroid Dimorphos. Nature 616, 452–456. http://dx.doi.org/10.1038/s41586-023-05811-4, arXiv:2303.01700.

Lin, Z.Y., Vincent, J.B., Ip, W.H., 2023. Physical properties of the Didymos system before and after the DART impact. Astron. Astrophys. 676 (A116), http://dx.doi.org/10.1051/0004-6361/202245629.

MacLennan, E.M., Emery, J.P., 2021. Thermophysical investigation of asteroid surfaces. I. Characterization of thermal inertia. Planet. Sci. J. 2, 161. http://dx.doi.org/10.3847/PSJ/ac1591, arXiv:2103.08371.

Makadia, R., Chesley, S.R., Farnocchia, D., Naidu, S.P., Souami, D., Tanga, P., Tsiganis, K., Hirabayashi, M., Eggl, S., 2024. Measurability of the heliocentric momentum enhancement from a kinetic impact: The double asteroid redirection test (dart) mission. Planet. Sci. J. 5 (38), http://dx.doi.org/10.3847/PSJ/ad1bce.

Michel, P., Küppers, M., Bagatin, A.C., Carry, B., Charnoz, S., de Leon, J., Fitzsimmons, A., Gordo, P., Green, S.F., Hérique, A., Juzi, M., Karatekin, Ö., Kohout, T., Lazzarin, M., Murdoch, N., Okada, T., Palomba, E., Pravec, P., Snodgrass, C., Tortora, P., Tsiganis, K., Ulamec, S., Vincent, J.B., Wünnemann, K., Zhang, Y., Raducan, S.D., Dotto, E., Chabot, N., Cheng, A.F., Rivkin, A., Barnouin, O., Ernst, C., Stickle, A., Richardson, D.C., Thomas, C., Arakawa, M., Miyamoto, H., Nakamura, A., Sugita, S., Yoshikawa, M., Abell, P., Asphaug, E., Ballouz, R.L., Bottke, W.F., Lauretta, D.S., Walsh, K.J., Martino, P., Carnelli, I., 2022. The ESA hera mission: Detailed characterization of the DART impact outcome and of the binary asteroid (65803) Didymos. Planet. Sci. J. 3 (160), http://dx.doi.org/10.3847/PSJ/ac6f52.

Moreno, F., Bagatin, A.C., Tancredi, G., Li, J.Y., Rossi, A., Ferrari, F., Hirabayashi, M., Fahnestock, E., Maury, A., Sandness, R., Rivkin, A.S., Cheng, A., Farnham, T.L., Soldini, S., Giordano, C., Merisio, G., Panicucci, P., Pugliatti, M., Castro-Tirado, A.J., Fernández-García, E., i, Pérez-García., Ivanovski, S., Penttila, A., Kolokolova, L., Licandro, J., Muñoz, O., Gray, Z., Ortiz, J.L., Lin, Z.Y., 2023. Characterization of the ejecta from the NASA/DART impact on Dimorphos: Observations and Monte Carlo models. Planet. Sci. J. 4 (138), http://dx.doi.org/10.3847/PSJ/ace827, arXiv:2307.10086.

Müller, T.G., Hasegawa, S., Usui, F., 2014. (25143) Itokawa: The power of radiometric techniques for the interpretation of remote thermal observations in the light of the Hayabusa rendezvous results*. Publ. Astron. Soc. Japan 66 (52), http://dx.doi.org/10.1093/pasj/psu034, arXiv:1404.5842.

Naidu, S.P., Chesley, S.R., Moskovitz, N., Thomas, C., Meyer, A.J., Pravec, P., Scheirich, P., Farnocchia, D., Scheeres, D.J., Brozovic, M., Benner, L.A.M., Rivkin, A.S., Chabot, N.L., 2024. Orbital and physical characterization of asteroid Dimorphos following the DART impact. Planet. Sci. J. 5 (74), http://dx.doi.org/10.3847/PSJ/ad26e7.

Novaković, B., Fenucci, M., Marčta, D., Pavela, D., 2024. ASTERIA-asteroid thermal inertia analyzer. Planet. Sci. J. 5 (11), http://dx.doi.org/10.3847/PSJ/ad08c0, arXiv:2311.03479.

Opeil, C.P., Britt, D.T., Macke, R.J., Consolmagno, G.J., 2020. The surprising thermal properties of CM carbonaceous chondrites. Meteorit. Planet. Sci. 55, E1–E20. http://dx.doi.org/10.1111/maps.13556.

Ostrowski, D., Bryson, K., 2019. The physical properties of meteorites. Planet. Space Sci. 165, 148–178.

Petković, V., Fenucci, M., Novaković, B., 2021. The extended Hayabusa2 mission target 1998 KY26: another small super-fast rotator with low thermal inertia.. In: European Planetary Science Congress. EPSC2021–390, http://dx.doi.org/10.5194/epsc2021-390.

Polishook, D., DeMeo, F.E., Burt, B.J., Thomas, C.A., Rivkin, A.S., Sanchez, J.A., Reddy, V., 2023. Near-IR spectral observations of the Didymos system: Daily evolution before and after the DART impact indicates that Dimorphos originated from Didymos. Planet. Sci. J. 4 (229), http://dx.doi.org/10.3847/PSJ/ad08ae, arXiv:2311.00421.

Rivkin, A.S., Thomas, C.A., Wong, I., Rozitis, B., de León, J., Holler, B., Milam, S.N., Howell, E.S., Hammel, H.B., Arredondo, A., Brucato, J.R., Epifani, E.M., Ieva, S., Forgia, F.La., Lucas, M.P., Lucchetti, A., Pajola, M., Poggiali, G., Sunshine, J.N., Trigo-Rodríguez, J.M., 2023. Near to mid-infrared spectroscopy of (65803) Didymos as observed by JWST: Characterization observations supporting the double asteroid redirection test. Planet. Sci. J. 4 (214), http://dx.doi.org/10.3847/PSJ/ad04d8, arXiv:2310.11168.

Rossi, A., Marzari, F., Brucato, J.R., Corte, V.Della., Dotto, E., Ieva, S., Ivanovski, S.L., Lucchetti, A., Epifani, E.Mazzotta., Pajola, M., Poggiali, G., Zinzi, A., Liciacube Team, 2022. Dynamical evolution of ejecta from the DART impact on Dimorphos. Planet. Sci. J. 3 (118), http://dx.doi.org/10.3847/PSJ/ac686c.

Rozitis, B., Green, S.F., 2012. The influence of rough surface thermal-infrared beaming on the Yarkovsky and YORP effects. Mon. Not. R. Astron. Soc. 423, 367–388. http://dx.doi.org/10.1111/j.1365-2966.2012.20882.x, arXiv:1203.1464.

Rozitis, B., Green, S.F., Jackson, S.L., Snodgrass, C., Opitom, C., Müller, T.G., Kolb, U.C., Chesley, S.R., Daly, R.T., Thomas, C.A., Rivkin, A.S., 2024. Pre-impact thermophysical properties and the Yarkovsky effect of NASA DART target (65803) Didymos. Planet. Sci. J. 5 (66), http://dx.doi.org/10.3847/PSJ/ad23eb.

Rozitis, B., Green, S.F., MacLennan, E., Emery, J.P., 2018. Observing the variation of asteroid thermal inertia with heliocentric distance. Mon. Not. R. Astron. Soc. 477, 1782–1802. http://dx.doi.org/10.1093/mnras/sty640.

Rozitis, B., Ryan, A.J., Emery, J.P., Christensen, P.R., Hamilton, V.E., Simon, A.A., Reuter, D.C., Asad, M.Al., Ballouz, R.L., Bandfield, J.L., Barnouin, O.S., Bennett, C.A., Bernacki, M., Burke, K.N., Cambioni, S., Clark, B.E., Daly, M.G., Delbo, M., DellaGiustina, D.N., Elder, C.M., Hanna, R.D., Haberle, C.W., Howell, E.S., Golish, D.R., Jawin, E.R., Kaplan, H.H., Lim, L.F., Molaro, J.L., Munoz, D.P., Nolan, M.C., Rizk, B., Siegler, M.A., Susorney, H.C.M., Walsh, K.J., Lauretta, D.S., 2020. Asteroid (101955) Bennu's weak boulders and thermally anomalous equator. Sci. Adv. 6, eabc3699. http://dx.doi.org/10.1126/sciadv.abc3699.

Ryan, A.J., Rozitis, B., Munoz, D.Pino., Becker, K.J., Emery, J.P., Nolan, M.C., Bernacki, M., Delbo, M., Elder, C.M., Siegler, M., Jawin, E.R., Golish, D.R., Walsh, K.J., Haberle, C.W., Bennett, C.A., Edmundson, K.L., Hamilton, V.E., Christensen, P.R., Daly, M.G., Lauretta, D.S., 2024. Rocks with extremely low thermal inertia at the OSIRIS-REx sample site on asteroid bennu. Planet. Sci. J. 5 (92), http://dx.doi.org/10.3847/PSJ/ad2dff.

Sakatani, N., Tanaka, S., Okada, T., Fukuhara, T., Riu, L., Sugita, S., Honda, R., Morota, T., Kameda, S., Yokota, Y., Tatsumi, E., Yumoto, K., Hirata, N., Miura, A., Kouyama, T., Senshu, H., Shimaki, Y., Arai, T., Takita, J., Demura, H., Sekiguchi, T., Müller, T.G., Hagermann, A., Biele, J., Grott, M., Hamm, M., Delbo, M., Neumann, W., Taguchi, M., Ogawa, Y., Matsunaga, T., Wada, T., Hasegawa, S., Helbert, J., Hirata, N., Noguchi, R., Yamada, M., Suzuki, H., Honda, C., Ogawa, K., Hayakawa, M., Yoshioka, K., Matsuoka, M., Cho, Y., Sawada, H., Kitazato, K., Iwata, T., Abe, M., Ohtake, M., Matsuura, S., Matsumoto, K., Noda, H., Ishihara, Y., Yamamoto, K., Higuchi, A., Namiki, N., Ono, G., Saiki, T., Imamura, H., Takagi, Y., Yano, H., Shirai, K., Okamoto, C., Nakazawa, S., Iijima, Y., Arakawa, M., Wada, K., Kadono, T., Ishibashi, K., Terui, F., Kikuchi, S., Yamaguchi, T., Ogawa, N., Mimasu, Y., Yoshikawa, K., Takahashi, T., Takei, Y., Fujii, A., Takeuchi, H., Yamamoto, Y., Hirose, C., Hosoda, S., Mori, O., Shimada, T., Soldini, S., Tsukizaki, R., Ozaki, M., Tachibana, S., Ikeda, H., Ishiguro, M., Yabuta, H., Yoshikawa, M., Watanabe, S., Tsuda, Y., 2021. Anomalously porous boulders on (162173) Ryugu as primordial materials from its parent body. Nat. Astron. 5, 766–774. http://dx.doi.org/10.1038/s41550-021-01371-7.

Schorghofer, N., Ghent, R., Aye, K.M., 2024. Lunar grain size determination based on surface temperatures using ensembles of thermal model parameters. Icarus 407, 115771. http://dx.doi.org/10.1016/j.icarus.2023.115771.

Shimaki, Y., Senshu, H., Sakatani, N., Okada, T., Fukuhara, T., Tanaka, S., Taguchi, M., Arai, T., Demura, H., Ogawa, Y., Suko, K., Sekiguchi, T., Kouyama, T., Hasegawa, S., Takita, J., Matsunaga, T., Imamura, T., Wada, T., Kitazato, K., Hirata, N., Hirata, N., Noguchi, R., Sugita, S., Kikuchi, S., Yamaguchi, T., Ogawa, N., Ono, G., Mimasu, Y., Yoshikawa, K., Takahashi, T., Takei, Y., Fujii, A., Takeuchi, H., Yamamoto, Y., Yamada, M., Shirai, K., Iijima, Y.i., Ogawa, K., Nakazawa, S., Terui, F., Saiki, T., Yoshikawa, M., Tsuda, Y., Watanabe, S.i, 2020. Thermophysical properties of the surface of asteroid 162173 Ryugu: Infrared observations and thermal inertia mapping. Icarus 348, 113835. http://dx.doi.org/10.1016/j.icarus.2020.113835.

Tardioli, C., Farnocchia, D., Rozitis, B., Cotto-Figueroa, D., Chesley, S.R., Statler, T.S., Vasile, M., 2017. Constraints on the near-Earth asteroid obliquity distribution from the Yarkovsky effect. Astron. Astrophys. 608, A61. http://dx.doi.org/10.1051/0004-6361/201731338.

Thomas, C.A., Naidu, S.P., Scheirich, P., Moskovitz, N.A., Pravec, P., Chesley, S.R., Rivkin, A.S., Osip, D.J., Lister, T.A., Benner, L.A.M., Brozović, M., Contreras, C., Morrell, N., RoZek, A., Kušnirák, P., Hornoch, K., Mages, D., Taylor, P.A., Seymour, A.D., Snodgrass, C., Jørgensen, U.G., Dominik, M., Skiff, B., Polakis, T., Knight, M.M., Farnham, T.L., Giorgini, J.D., Rush, B., Bellerose, J., Salas, P., Armentrout, W.P., Watts, G., Busch, M.W., Chatelain, J., Gomez, E., Greenstreet, S., Phillips, L., Bonavita, M., Burgdorf, M.J., Khalouei, E., Longa-Peña, P., Rabus, M., Sajadian, S., Chabot, N.L., Cheng, A.F., Ryan, W.H., Ryan, E.V., Holt, C.E., Agrusa, H.F., 2023. Orbital period change of Dimorphos due to the DART kinetic impact. Nature 616, 448–451. http://dx.doi.org/10.1038/s41586-023-05805-2, arXiv:2303.02077.

Vokrouhlický, D., Bottke, W.F., Chesley, S.R., Scheeres, D.J., Statler, T.S., 2015. The Yarkovsky and YORP Effects. University of Arizona Press, pp. 509–532.