# On the Delivery of DART-ejected Material from Asteroid (65803) Didymos to Earth

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## Abstract

The Double Asteroid Redirection Test (DART) spacecraft is planned to impact the secondary of the binary asteroid (65803) Didymos in 2022 to assess deflection strategies for planetary defense. The impact will create a crater and release asteroidal material, some of which will escape the Didymos system. Because the closest point of approach of Didymos to Earth's orbit is only 6 million km (about 16 times the Earth–Moon distance), some ejected material will make its way sooner or later to our planet, and the observation of these particles as meteors would increase the scientific payout of the DART mission. The DART project may also represent the first human-generated meteoroids to reach Earth and is a test case for human activity on asteroids and its eventual contribution to the meteoroid environment and spacecraft impact risk. This study examines the amount and timing of the delivery of meteoroids from Didymos to near-Earth space. This study finds that very little DART-ejected material will reach our planet, and most of that only after thousands of years. But some material ejected at the highest velocities could be delivered to Earth-crossing trajectories almost immediately, though at very low fluxes. Timing and radiant directions for material reaching Earth are calculated, though the detection of substantial numbers would indicate more abundant and/or faster ejecta than is expected. The DART impact will create a new meteoroid stream, though probably not a very dense one. However, larger, more capable asteroid impactors could create meteoroid streams in which the particle flux exceeds that naturally occurring in the solar system, with implications for spacecraft safety.

*Unified Astronomy Thesaurus concepts:* Near-Earth objects (1092); Meteor streams (1035); Asteroids (72); Space debris (1542); Space vehicles (1549)

*Supporting material:* animations

## 1. Introduction

The Asteroid Impact and Deflection Assessment mission is a partnership between NASA and ESA. The Double Asteroid Redirection Test (DART, spearheaded by NASA) will send a spacecraft to impact the secondary of the (65803) Didymos binary asteroid system, in order to determine the efficiency of kinetic impactors as a strategy for asteroid deflection. The Hera spacecraft (led by ESA) is planned to observe and characterize the impact's effects on the Didymos system (Michel et al. 2016; Cheng et al. 2018).

Envisioned as a planetary defense exercise, the project may also produce the first artificially generated meteoroids that reach Earth. The *Deep Impact* spacecraft that struck comet 9P/Tempel 1 in 2005 (A'Hearn et al. 2005) would have released a similar cloud of material but its minimum orbital intersection distance (or MOID) with Earth is over 0.5 au, a order of magnitude further than Didymos' MOID of 0.04 au, so material is not delivered as efficiently to our planet. The observation of DART-generated meteors if and when they reach us would provide additional information about the target and impact-related processes. The DART impact is also a test case in some sense for the production of asteroid-derived debris by human activity such as asteroid mining, though mining is perhaps more likely to release material at lower speeds (e.g., Fladeland et al. 2019). At the very least, it seems prudent to ask how

much material might be delivered to near-Earth space as a result of such an impact, and that is the purpose of this study.

### 1.1. Didymos' Current Orbit

The point of closest approach of Didymos' orbit to Earth's orbit (its MOID) sits currently at 0.0398 au. The Jet Propulsion Laboratory (JPL)'s Solar System Dynamics site[1] lists it as a near-Earth object (NEO, indicating that its perihelion distance lies within 1.3 au of the Sun) and a potentially hazardous asteroid (PHA, indicating that it poses at least a hypothetical danger of impact, having an Earth MOID less than 0.05 au and an absolute magnitude $H$ less than 22.0; Atkinson et al. 2000; Stokes et al. 2003).[2] The Didymos primary itself has $H = 18.2$ and a diameter of 780 m (Michel et al. 2016).

The MOID of Didymos is currently slowly decreasing over time under the gravitational perturbations of the other planets of our solar system, but it will reach a minimum value of 0.022 au in 2500 yr and then will start to increase. As a result, Didymos is not considered to be an impact threat to Earth in the near-term and has a Torino scale (Binzel 2000; Morrison et al. 2004) rating of zero.[3]

The Didymos asteroid pair consists of a primary with a diameter of 780 m and a 163 m diameter secondary; their individual centers of mass are separated by 1.18 km and their

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[1] https://ssd.jpl.nasa.gov/sbdb.cgi?sstr=Didymos; retrieved 2019 December 5.

[2] The absolute magnitude provides a measure of the asteroid size if its albedo is known. Because absolute magnitude increases as asteroid size decreases, the $H < 22$ limit corresponds to a minimum asteroid diameter of between 100 and 250 m for typical asteroidal albedos ranging from 0.25 to 0.05, respectively.

[3] https://cneos.jpl.nasa.gov/sentry/, retrieved 2019 December 12.

orbital period is 11.92 hr (Michel et al. 2016). Material released from Didymos' secondary (informally known as "Didymoon"; e.g., Michel et al. 2016) by the DART impactor can be expected to show a range of behaviors. Ejecta with speeds less than the escape speed from Didymos (about $1 \, \mathrm{m \, s^{-1}}$; Michel et al. 2016) can be expected to remain in orbit around the asteroid and/or re-impact one of the members of the binary. Ejected material that remains bound to the binary system may prove hazardous to the follow-up spacecraft Hera slated to observe the impact and has been examined by other authors (Richardson & O'Brien 2016; Michel & Yu 2017). However, this material cannot reach Earth and will not be considered here.

Ejecta released at speeds at or above $1 \, \mathrm{m \, s^{-1}}$ will mostly escape from the vicinity of Didymos and its moon, and begin to orbit the Sun. Slower material will follow a path very close to that of Didymos itself, either leading or trailing that asteroid. This material will have a MOID similar to Didymos' and so will not be able to reach Earth (at least not immediately, see Section 3). Material ejected at higher speeds will travel on orbits further from Didymos'. These particles may have MOIDs closer to Earth, and could potentially reach it. An additional complication is that for small particles (less than about 1 cm in size), radiation pressure and Poynting–Robertson drag will affect the delivery of debris to our planet.

Particles ejected from Didymos cannot impact Earth unless their MOID decreases to a sufficiently small value: for this study we will require that the MOID reach zero for an impact with Earth to be considered possible. When we are considering delivery of material to near-Earth space however, larger MOIDs will be of interest. For example, the *Planck* spacecraft (Tauber et al. 2004) currently orbits near, and the *James Webb Space Telescope* (*JWST*; Gardner et al. 2006) will soon be launched to, the Earth–Sun L2 point, which is about 0.01 au outside Earth's orbit. The *Solar and Heliospheric Observatory* spacecraft moves near the inner Earth–Sun L1 point (Domingo et al. 1995), located a similar distance inside our planet's orbit. Because these important space assets are vulnerable in principle to meteoroid impacts, we will use a MOID of 0.01 au with Earth as our boundaries for "near-Earth space." Of course, a particle with a low or zero MOID with Earth will still not necessarily impact our planet: both planet and particle must be at the point where their orbits cross at the same time and this must be checked for as well.

### 1.2. Ejecta

The DART impact is expected to produce a final crater of size around 10 m in diameter on Didymoon with $10^4$–$10^5$ kg of mass escaping ($\sim 0.01\%$ of the secondary's mass; Stickle et al. 2015). Larger ejected masses and larger craters (even exceeding 100 m diameter on the 163 m diameter moon) are possible, though less likely, and the precise outcome depends on the unknown strength, porosity, and other physical properties of Didymoon. Other Didymoon-specific simulations of the impact show ejecta speeds approaching the impactor speed (expected to be $6 \, \mathrm{km \, s^{-1}}$; Cheng et al. 2018) in some cases, though the bulk of material is released at much lower (several to hundreds of $\mathrm{m \, s^{-1}}$) speeds (Richardson & O'Brien 2016; Raducan et al. 2019; Stickle et al. 2020). We note that the cratering produced by *Deep Impact* proved difficult to interpret. Fast-moving ejecta implied acceleration due to expanding gases, probably from volatiles (Holsapple & Housen 2007) that

are less likely to be present in Didymoon. As a result, the *Deep Impact* experiment does not provide strong constraints on the ejecta expected from DART.

Here we will examine three specific ejection speeds: 10, 100, and $1000 \, \mathrm{m \, s^{-1}}$. These are chosen to span the range between the lowest speeds that can escape ($\gtrsim 1 \, \mathrm{m \, s^{-1}}$) and the highest expected ejection speeds. These speeds reach somewhat higher than typical of the cometary ejection processes (tens to hundreds of $\mathrm{m \, s^{-1}}$; Whipple 1951; Crifo 1995; Jones 1995), which create most meteoroid streams.

Particle sizes examined in this study have diameters of 10, $100 \, \mu\mathrm{m}$, 1 mm, and 1 cm. For a traditional power-law size distribution, larger particles would be less common, but it is not clear if that is a good assumption for Didymoon. Some asteroids, such as (25143) Itokawa, (162173) Ryugu, and (101955) Bennu, have abundant cm and larger sized particles on their surface (Fujiwara et al. 2006; Lauretta et al. 2019; Watanabe et al. 2019). On the other hand, the spinning-top shape of the Didymos primary (Cheng et al. 2018) indicates Didymoon may be made of particles lifted from it by centrifugal forces, a process that could favor fine particles. We do not assume a particular size distribution here. Our largest particle size of 1 cm is chosen because particles larger than this will evolve dynamically in the same way, as radiation effects are negligible at these sizes on the timescales considered here. Particles smaller than $10 \, \mu\mathrm{m}$ may be produced in substantial quantities, but they are not modeled here because they almost undetectable with current meteor techniques. Optical meteor systems typically see millimeter-sized particles, while meteor patrol radars like the Canadian Meteor Orbit Radar (Jones et al. 2005) can typically see particles down to masses of $10^{-8}$ kg (Blaauw et al. 2011), which corresponds to a $200 \, \mu\mathrm{m}$ diameter at our assumed density. Particles smaller than $10 \, \mu\mathrm{m}$ are also well below the usual threat limit to spacecraft set by NASA's Meteoroid Environment Office of $10^{-9}$ kg or $100 \, \mu\mathrm{m}$ diameter at our assumed density (Moorhead et al. 2015).

As for the DART impact timing, that is not yet set. Planned for "late September" (Michel et al. 2016), more recent work (Cheng et al. 2018) lists "October 5." The impact will most likely occur near Didymos' closest approach to Earth, which the JPL website gives as 2022 October 4. Here we will take our baseline scenario to be an impact date of 2022 October 1 at 00:00 UT but will examine other dates as well.

## 2. Methods

The dynamics of the particles were simulated with the RADAU15 (Everhart 1985) algorithm with an accuracy parameter of $10^{-12}$. The baseline impact date calculations were verified by repeating them with the Wisdom–Holman (Wisdom & Holman 1991) algorithm modified to handle close approaches by the hybrid method Chambers (1999), with a time step of two days or less. The differences between the two were negligible, and we report on the RADAU15 results here. The particles were simulated in a solar system, which includes the Sun and all eight planets (the Moon was not simulated independently but its mass was included at the Earth–Moon barycenter) with their initial positions derived from the JPL DE405 ephemeris. The orbit of Didymos was obtained from the JPL Solar System Dynamics website.[4] These orbital elements

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[4] https://ssd.jpl.nasa.gov/sbdb.cgi, retrieved 2019 November 2.

**Table 1**
The Orbital Elements (J2000) of Didymos from JPL Horizons

| $a$ (au) | 1.644267944704789 |
|---|---|
| $e$ | 0.3840204904781526 |
| $i$ (°) | 3.408561576582074 |
| $\Omega$ (°) | 73.20707875073758 |
| $\omega$ (°) | 319.3188820727824 |
| $M$ (°) | 124.6176912105528 |

**Note.** The semimajor axis, $a$; eccentricity, $e$; inclination, $i$; longitude of the ascending node, $\Omega$; argument of perihelion, $\omega$; and mean anomaly, $M$, at 2458600.5 (2019 April 27.0) TDB.

(see Table 1) were advanced to the desired date of the impact to be simulated.

Ejecta were modeled as massless particles released from a spherical shell located 1 km from Didymos with relative velocity directions chosen randomly on the sphere. Though the release of ejecta will primarily be in a cone aligned along the impact vector rather than spherical, that impact vector is not yet known. Our choice encompasses all impact geometries for simplicity and completeness. However, the impact is planned for the Earth-facing side and this will increase the flux of particles delivered directly to us (see Section 3.1.1), though impact location is not expected to have significant effect on the long-term evolution of the meteoroid stream. DART's target Didymoon orbits 1.18 km from the center of the primary, which is why the 1 km release distance was chosen, though this offset has little effect. The orbital speed of Didymoon ($\approx$0.2 m s$^{-1}$) is negligible for our simulations, as is the gravity of both asteroid components, and these are ignored. One thousand particles are released for each size/impact date/ejection speed combination.

The effect of radiation pressure and Poynting–Robertson drag are included. Each particle is assigned diameter $d$, which defines its $\beta$ parameter (the ratio of radiation to gravitational forces) according to an expression derived from that of Weidenschilling & Jackson (1993):

$$\beta = \frac{1.14 \times 10^{-3}}{\rho d},$$

where $d$ is the particle diameter in meters, and $\rho$ is the assumed density in kg m$^{-3}$ that we take to be the bulk density of the Didymos system, 2100 kg/m$^{-3}$ (Michel et al. 2016; Cheng et al. 2018). Since Didymos is an Sq spectral type, associated with ordinary chondrite meteorites (densities of 3600–3900 kg m$^{-3}$; Britt et al. 2002), our choice of density may be low. If this is the case, the dynamics of the simulations presented here all remain correct, except that the particles correspond to somewhat different sizes or masses. For example, if the actual particle density was double that assumed, the mass quoted for a particular size particle would have to be increased by a factor of 2 or the diameter for a given mass particle would have to be increased by a factor of $2^{1/3} \approx 1.3$.

Because the results are found to be somewhat sensitive to the timing of the impact, we examined impacts on 2022 October 1 (baseline), then at intervals of $\pm 1$ month and $\pm 3$ months, and then an impact at the asteroid's aphelion (2023 November 10).

## 3. Results and Discussion

The dispersion time $T$ for the material to spread around the mean orbit depends primarily on the ejection speed. For 1000 m s$^{-1}$ ejection, $T \lesssim 10$ yr (see, e.g., Figure 3(b)), for 100 m s$^{-1}$ ejection, $20 < T < 200$ yr, and for 10 m s$^{-1}$ ejection, $150 < T < 500$ yr. Since the dispersion timescale is much shorter than the time it takes for the particle MOID to get close to Earth in most cases, we can estimate the delivery time for meteoroids to near-Earth space as being the time it takes for the MOID to drop to a suitable value. Those cases where the ejecta is not fully dispersed will be called out specifically when they arise.

The time evolution of the MOIDs for the baseline case is shown in Figure 1. The figure includes the lowest and highest MOID values, or rather we will take the "lowest" and "highest" values here to mean the 1st and 99th percentile values. This excludes the 10 truly lowest and highest MOIDs of the 1000 simulated particles in each case. This choice is made because, while a spherical distribution of ejecta velocities produces a meteoroid stream with a well-defined elliptical cross section (see Figure 3(a) later), over time a few particles are scattered widely by close planetary encounters, and their inclusion would produce deceptive results. Here we are interested in when the bulk of the ejected population might reach Earth, not rare heavily perturbed particles.

From Figure 1, it is clear that for particles with the range of speeds and sizes chosen, none are delivered immediately to Earth and many of them will never reach us (at least not on the 10,000 yr timescale examined here), though this is not true of all impact times. The smallest simulated particles (10 $\mu$m) reach us first, after 1000–2000 yr. Their different evolution is a result of the effects of radiation forces, which affect the orbits of these small particles strongly immediately upon release, and they do not follow the orbit of their parent asteroid as closely as larger particles. In particular, their MOIDs immediately after release differ from those of other particles because radiation pressure counteracts solar gravity substantially as particle size diminishes. Effectively, radiation pressure's radial outward force means that small particles behave as if the Sun's mass were reduced, and thus they have larger orbits for the same initial velocity (see, e.g., the animation of Figure 3(b)). As a result, particles' with different sizes may have different initial MOIDs, even though they are all on orbits released from the same point at the same speed.

Larger particles are much less affected by radiation pressure, closely follow the dynamical evolution of Didymos itself, and do not reach near-Earth space. The exception is for the highest ejection speeds simulated, 1000 m s$^{-1}$. Here the orbital dispersion caused by the higher ejection speed brings meteoroids of all sizes just barely into near-Earth space in 1500–2000 yr (Figure 1(c)).

Figure 2 shows the effect of a change in time of the impact by one month. The overall result is much like that of the baseline impact date. Our smallest 10 $\mu$m particles arrive in about 2000 yr, while larger ones are delayed or do not reach near-Earth space at all on these time frames. The only exception is the case of the highest ejection speeds for an impact on 2022 September 1. Here the particles are widely enough dispersed to have MOIDs intersecting Earth almost immediately.

We also examined the case of the impact occurring three months early or later or at the asteroid's aphelion distance (2023 November 10). These cases are much less likely for
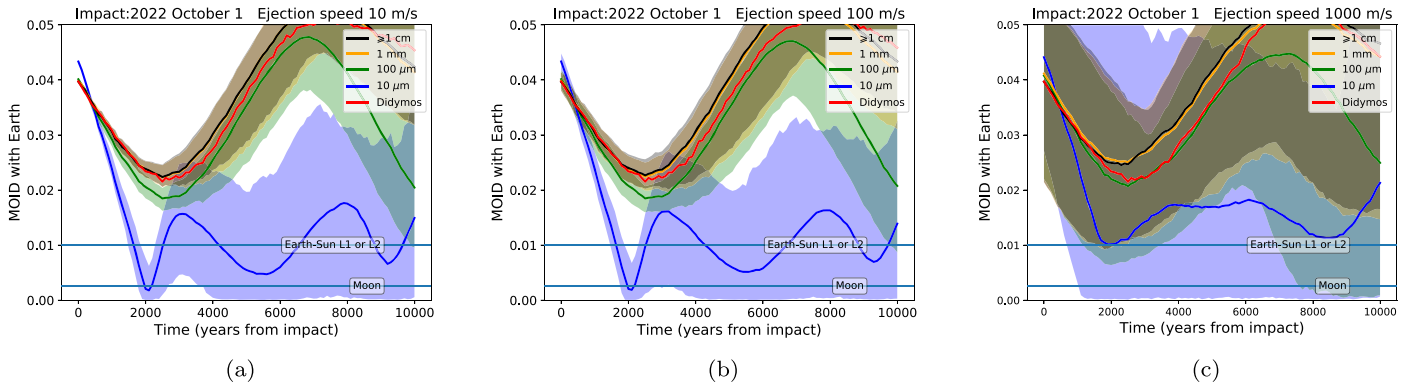
**Figure 1.** Evolution of the MOIDs of the simulated DART-ejected debris in the case of an impact on 2022 October 1. The median value of the MOIDs is shown by a solid line, while the shaded areas indicate the highest and lowest values. The MOID of Didymos itself is shown in red.
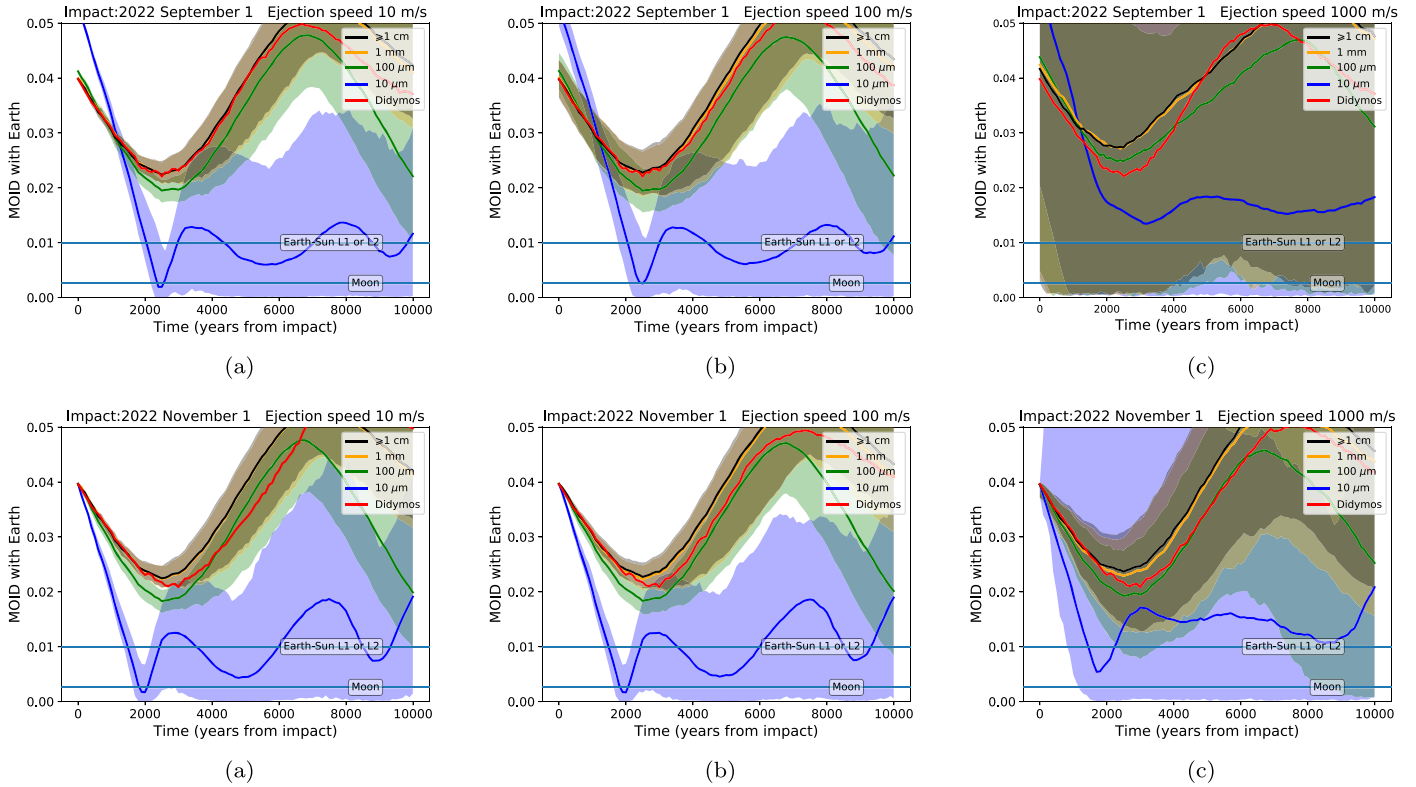


**Figure 2.** Evolution of the MOIDs of the simulated DART-ejected debris in the case of an impact on 2022 September 1 or 2022 November 1. See Figure 1 for more details.

operational reasons, as the asteroid is farther from Earth and thus the impact is more difficult to observe, but are examined for completeness. The results in these cases qualitatively resemble those of the 2022 September 1 impact and are shown in Figure 5 (see the Appendix). The 10 $\mu$m particles arrive after thousands of years, while larger particles may not arrive at all, except in the case of the highest ejection speeds where the MOIDs almost immediately reach low values.

The differences between the scenarios can be understood broadly in terms of how close the DART impact occurs to the Didymos–Earth MOID. This is because the ejecta particles, once released, travel on (essentially) Keplerian ellipses and so necessarily return to the point of impact, regardless of their ejection velocities. So, though the ejecta moves out on diverging heliocentric orbits after the impact, the closed nature

of these orbits brings them back to converge on the impact point again. As a result, the meteoroid stream has its smallest cross section at the impact point. And when the impact occurs near the Didymos–Earth MOID, the resulting meteoroid stream is therefore narrowest at its closest point of approach to Earth's orbit (see, e.g., the animation of Figure 3(b)).

Perhaps counterintuitively, an impact *farther* from the Earth–Didymos MOID can more easily produce a debris stream that has *smaller* MOIDs with respect to Earth and therefore takes a *shorter* time to be perturbed onto orbits that can reach our planet. Since Earth reaches its MOID with Didymos in early November,[5] impact scenarios closer to this date produce debris streams that take longer to reach Earth.

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[5] The close approach between Earth and Didymos on 2022 October 4 mentioned in Section 1.2 occurs near, but not exactly at, the MOID.
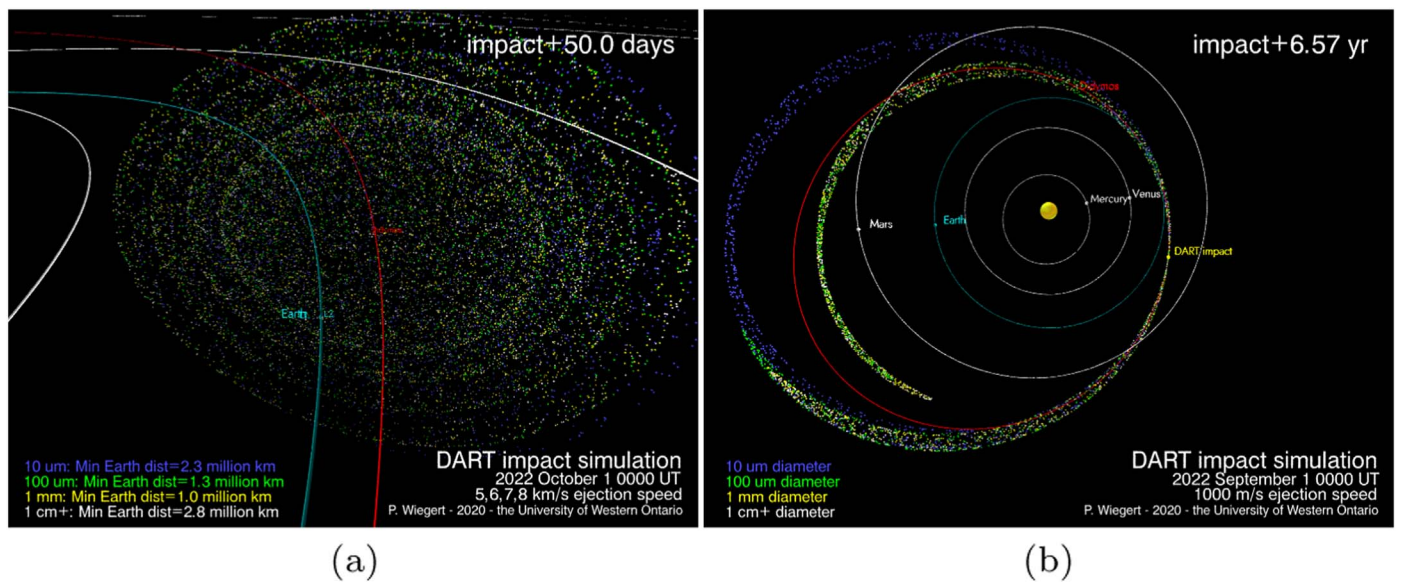
**Figure 3.** Panel (a): the dispersal of ejecta at 5, 6, 7, and 8 km s$^{-1}$ from a 2022 October 1 impact. Panel (b): the dispersal of ejecta at 1000 m s$^{-1}$ from a 2022 September 1 impact. See the text for more details.

(Animations (a and b) of this figure are available.)

What does it take to get particles to Earth quickly at the nominal 2022 October 1 impact date? Additional simulations done with higher ejection velocities show that all sizes will begin to arrive 15–30 days after the DART impact, but only at ejection speeds of 6 km s$^{-1}$ or more. These are discussed in more detail later in Section 3.1.1, but if Didymos ejecta were observed in near-Earth space soon after impact, that would indicate that the ejection speeds are higher than expected or that some other unmodeled process is at work.

What happens in the case of the 2022 September 1 impact where ejection speeds reach 1000 m s$^{-1}$? When does this material arrive at Earth? All sizes except 10 $\mu$m arrive two years later when Didymos returns to the closest approach, and this will be detailed in Section 3.1.2.

### 3.1. Fluxes

In addition to whether or not material reaches Earth, there is the question of how much. The amount of material delivered is extremely low, but for completeness, we estimate the flux. To do this in detail would require a knowledge of the amount, size distribution, and velocity distribution of the ejecta, which are not well known. Instead we will adopt two simplistic models here, which will hopefully capture the essential details without entangling them too much with assumptions about the ejecta production process.

In our first "nominal" model, we will assume that 1% of the mass of ejecta produced in the creation of a 10 m diameter crater is converted entirely into particles of the size and ejection velocity being discussed. This is certainly an overestimate of the amount of material expected when discussing larger, faster moving particles and an underestimate for smaller and/or slower-moving particles.

For our second "edge-case" model, we will assume that 1% of all the mass of Didymoon is converted entirely into particles of a particular size and ejection velocity. Such catastrophic scenario is extremely unlikely, but we consider it here for two reasons. First, simulated impacts have produced craters over 100 m in diameter on the 150 m diameter moon (Stickle et al. 2015), though for

admittedly less probable asteroid properties. Second, the kinetic energy of the DART impactor (assuming a 300 kg mass impacting at 6 km s$^{-1}$; Michel et al. 2016; Cheng et al. 2018) exceeds the gravitational binding energy of Didymoon as well as its orbital potential energy with its primary by one to two orders of magnitude, so there is no strong physical constraint against such an ejection event. Though unlikely, the edge-case scenario is designed to capture the result of unusual asteroid properties or other as-yet-unexplored eventualities, e.g., navigation malfunction resulting in an oblique impact; that might create much more debris than expected. However, even in this extreme case, very little material ever reaches Earth.

For our nominal case, 1% of the mass of a half-sphere of diameter 10 m is converted into $N$ particles of diameter $d$, where

$$N_{\text{nominal}} \approx \frac{0.01}{2}\left(\frac{10 \text{ m}}{d}\right)^3 = 5 \times 10^9 \left(\frac{d}{1 \text{ mm}}\right)^{-3}, \qquad (1)$$

while for the edge-case scenario,

$$N_{\text{edge}} \approx 0.01\left(\frac{163 \text{ m}}{d}\right)^3 = 4.3 \times 10^{13} \left(\frac{d}{1 \text{ mm}}\right)^{-3}, \qquad (2)$$

where we have taken the secondary's diameter to be 163 m (Michel et al. 2016). We will concentrate on a particle diameter of 1 mm because these are typical of sizes routinely detected by meteor sensors on Earth and the low arrival speeds of DART-produced meteors at Earth mean that most meteor detection systems will have difficulty detecting smaller particles. Of course, the simple nature of our adopted size model means that numbers reported at millimeter sizes can be scaled easily to any other desired ejecta model.

#### 3.1.1. Impact on 2022 October 1, Direct Arrival

Though an ejection speed of even 1000 m s$^{-1}$ does not deliver ejecta directly to Earth, additional simulations with faster ejecta show that it can reach our planet at speeds of

$6 \, \mathrm{km \, s^{-1}}$ or higher. A simulation of ejecta released at 5, 6, 7, and $8 \, \mathrm{km \, s^{-1}}$ is shown in Figure 3(a). In this case, debris arrives directly from Didymos and is roughly uniformly distributed on an expanding sphere. As a result, the flux $f$ is given approximately by

$$f \approx \frac{\alpha N}{4\pi R^2 \Delta t} \approx 3 \times 10^{-18} N \left(\frac{\alpha}{2}\right) \left(\frac{R}{0.1 \text{ au}}\right)^{-2}$$
$$\times \left(\frac{\Delta t}{10 \text{ days}}\right)^{-1} \mathrm{km^{-2} \, hr^{-1}}, \tag{3}$$

where $N$ is the number of particles produced at the ejection velocity in question, $R$ is the Earth–Didymos distance when the debris reaches our planet ($\sim$0.1 au at 15–30 days after 2022 October 1), and $\Delta t$ is the time the shell of ejecta takes to cross near-Earth space, about 10 days. The parameter $\alpha$ is one over the fraction of the sphere into which material is ejected. Our simulations assumed uniform spherical ejection to allow for all ejection directions to be assessed, but in practice, the impact will release material only into a half-sphere ($\alpha = 2$, adopted here) or perhaps an even narrower cone ($\alpha > 2$). The nominal flux at Earth under these conditions is $\sim 10^{-8} \, \mathrm{km^{-2} \, hr^{-1}}$, or for the edge-case, $\sim 10^{-4} \, \mathrm{km^{-2} \, hr^{-1}}$.

For comparison, the background sporadic meteor flux at millimeter sizes is $0.18 \pm 0.04 \, \mathrm{km^{-2} \, hr^{-1}}$ (Campbell-Brown & Braid 2011) as measured by video meteor techniques, while a weak meteor shower might be two orders of magnitude less, e.g., the 2016 Camelopardalids (Campbell-Brown et al. 2016). So the DART-produced fluxes are certainly low: could they be detected?

A typical meteor radar or camera has an effective collecting area of $\sim$1000 km$^2$ (Weryk & Brown 2004). So in the nominal case, such a meteor detection system would see perhaps one meteor from Didymos during the 10 days in question, and even in the edge-case scenario, it would only see tens of meteors over that time span. Clearly, any detectable meteor activity at Earth would indicate both exceptionally fast and exceptionally abundant ejecta.

As the impact takes place below the ecliptic plane with Didymos rising toward its ascending node, any directly delivered meteors arrive from southerly radiant directions. The high ejection speeds, together with their low velocities relative to Earth ($4$–$12 \, \mathrm{km \, s^{-1}}$, peaking at 9), result in a very broad radiant extending for tens of degrees centered roughly at R.A. $= 0°$ and decl. $= -50°$. These meteors will be fainter than usual for their size due to the rapid drop in ionization production (Jones 1997; DeLuca et al. 2018) and light production (Subasinghe & Campbell-Brown 2018) by meteors at such low speeds.

The calculations above ignore gravitational focusing, which increases the effective cross section of Earth by a factor of $1 + (v_{esc}/v)^2$, where $v$ is the meteoroid arrival speed, and $v_{esc}$ is the escape speed of Earth ($\approx 8 \, \mathrm{km \, s^{-1}}$). Though the low arrival speed means that gravitational focusing is not completely negligible, it only increases the fluxes determined above by a factor $\approx$2.

### 3.1.2. Impact on 2022 September 1, Arrival Two Years Later

Next we consider the flux of $1000 \, \mathrm{m \, s^{-1}}$ ejecta released during an impact on 2022 September 1. This material disperses quickly along the orbit and arrives at Earth at about the same time as Didymos' close approach in 2024, as can be seen in Figure 3(b).

To calculate the flux, we will assume that the particles have dispersed uniformly around their orbit (as is evident from Figure 3(b)) and occupy a toroidal volume $V$ around their mean orbit such that $V \approx 2\pi a A$, where $a$ is Didymos' semimajor axis ($\approx$1.64 au), and $A$ is the stream cross sectional area. The area $A$ is computed from an ellipse fitted to a cross section of the simulated stream at its closest approach to Earth's orbit. Then the particle number density, $n$, is just $N/V$ and the flux is $n v_{rel}$, where $v_{rel}$ is the relative velocity of the meteoroids to Earth, $\approx 5 \, \mathrm{km \, s^{-1}}$.

For all particle sizes at $1000 \, \mathrm{m \, s^{-1}}$ ejection speed, the cross section is $\approx 3 \times 10^{-3} \, \mathrm{au^2}$, and the nominal flux at Earth is $\sim 10^{-9} \, \mathrm{km^{-2} \, hr^{-1}}$. This is an order of magnitude below that determined for direct arrival in Section 3.1.1, and even for our edge-case scenario, a detector with an effective collecting area of $1000 \, \mathrm{km^2}$ would see $\lesssim$1 mm sized meteor per day. As a result, it is not expected that this extremely weak meteor activity will be detected.

For completeness, we note that any meteoroids that do reach Earth will be accelerated by Earth's gravity to an in-atmosphere speed of $12 \, \mathrm{km \, s^{-1}}$ and would arrive from a broad geocentric radiant in the vicinity of R.A. $= 295°$ and decl. $= -40°$. These meteors will also be fainter than typical for their sizes both in radar and optical meteor systems due to their low speeds (see Section 3.1.1).

### 3.1.3. Flux in the New Meteoroid Stream

Most of the debris from a DART impact will not arrive at Earth but will disperse into a meteoroid stream near Didymos' orbit. What flux can a spacecraft flying through this stream expect? We estimate this by the same technique used in Section 3.1.2. For consistency, we will use the stream cross section determined from the simulations at the Earth MOID and the same relative velocity ($5 \, \mathrm{km \, s^{-1}}$) considered earlier, but a more correct determination would require considering the specific speed and position of the spacecraft as it crosses the stream. The predicted fluxes for the nominal case assuming a $10 \, \mathrm{m \, s^{-1}}$ ejection speed, which produces the highest flux values, are shown in Figure 4.

The figure shows that at millimeter sizes, the nominal flux will be $\sim 10^{-5} \, \mathrm{km^{-2} \, hr^{-1}}$ initially and will drop over time as the stream evolves. This is still quite low, though orders of magnitude higher than the fluxes discussed earlier. The increased flux is a result of a smaller cross section, resulting from the lower ejection speed. The initial cross section at the Earth MOID for $10 \, \mathrm{m \, s^{-1}}$ ejection speeds is $\lesssim 10^{-7} \, \mathrm{au^2}$ for all particle sizes, about four orders of magnitude smaller than in the $1000 \, \mathrm{m \, s^{-1}}$ ejection case, and producing a $10^4$ increase in the meteoroid flux. This demonstrates that low-speed ejecta, which will be far more abundant, may be of more long-term concern. It is also relevant to the design of asteroid mining operations that may inadvertently or deliberately release debris at low speeds and that could create dense meteoroid streams in their vicinity.

In our edge-case scenario, the initial flux of millimeter-sized material in the stream would actually exceed that associated with weak meteor showers by a factor of 100, reaching levels comparable to the background sporadic meteoroid flux at Earth (this scenario corresponds to the 1 mm line in Figure 4, multiplied by $N_{edge}/N_{nominal} \approx 10^4$). Though the risk to
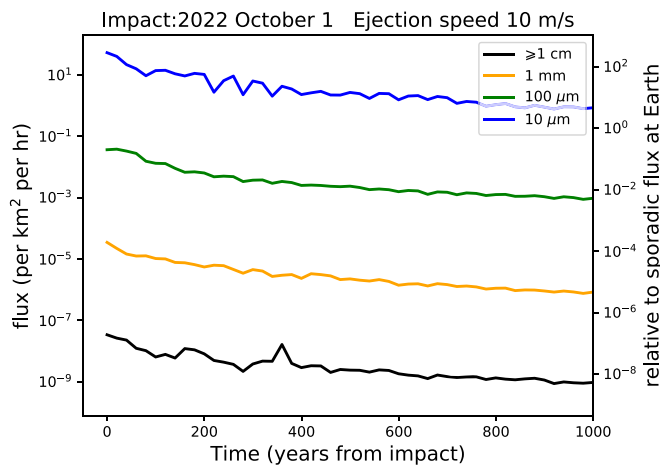
**Figure 4.** Estimated flux near Didymos' orbit at its MOID with Earth for the nominal ejected mass at a 10 m s$^{-1}$ ejection speed. The right-hand $y$-axis gives the flux relative to the sporadic meteoroid flux at Earth of 0.18 per km$^2$ per hour (Campbell-Brown & Braid 2011).

spacecraft even in this case remains low, it is conceivable that DART or, perhaps more likely, future more ambitious planetary defense tests will result in the production of meteoroid streams where the debris fluxes exceed those naturally occurring within the solar system. These streams carry implications for the safety of spacecraft that need to cross them, and though associated risks are likely to be initially very low, they will undoubtedly increase with time much as has the orbital debris problem in low Earth orbit.

We note that the flux values of Figure 4 assume the particles' are fully dispersed around the stream's mean orbit. This dispersion takes longer in the case of low ejection speeds ($\approx$250 yr for all particle sizes at 10 m s$^{-1}$ ejection speed). As a result, the flux will initially be higher along some portions of Didymos' orbit and lower in others. Determining the actual debris flux encountered by a spacecraft crossing the stream in the near-future, such as the Hera spacecraft planned to observe the effects of the DART impact, would require a more detailed study than is done here.

## 4. Conclusions

Debris ejected by the DART impact on Didymoon may reach Earth in small numbers. Ejecta can reach Earth directly within 15–30 days after impact if the ejection speeds reach 6 km s$^{-1}$, though these speeds are higher than expected. The debris cloud will subsequently spread out into a meteoroid stream. The baseline DART impact date of 2022 October 1 does not produce a stream that crosses Earth's orbit, at least not

immediately, though its dynamical evolution will eventually bring some of the debris to near-Earth space after thousands of years.

Other impact dates can place material onto orbits that immediately cross that of Earth, though only at high (1000 m s$^{-1}$) ejection speeds, and only a very small amount of the ejecta is expected to reach our planet.

The meteoroid stream produced by the impact remains primarily in the vicinity of Didymos' orbit. The stream's cross section is larger for larger ejection speeds; as a result, low-speed ejecta, expected to be relatively abundant, produce a denser meteoroid stream. Though it is unlikely to occur in the case of the DART impact, future human asteroid operations such as planetary defense tests or asteroid mining, could conceivably produce debris streams whose meteoroid particle content rivals or exceeds naturally occurring meteoroid streams. Streams initially emplaced far from Earth may reach near-Earth space after hundreds or thousands of years, and thus require some long-term planning. Though such a stream would have to be quite dense and contain a large number of decameter or larger class asteroids to be dangerous to the Earth's surface, a much lower density of small particles could be inconvenient or detrimental to some space operations. *JWST* has a large vulnerable mirror and future space telescopes are likely to be even more ambitious and sensitive. The *Gaia* spacecraft attitude control system already has to deal with natural meteoroid impacts (Serpell et al. 2016), as does the Laser Interferometer Space Antenna (LISA) Pathfinder's (Thorpe et al. 2019). Though one is tempted to dismiss the problem as negligible at this time, it is reminiscent of the problem of space debris in low Earth orbit. Neglected initially, we are now reaching a point where we may be denied the full use of valuable portions of near-Earth space because of orbital debris build-up. Much future expense and risk could be averted if the same story does not unfold with asteroidal debris production.

## Appendix
## Other Impact Dates

Results for cases of the impact occurring three months earlier or later or at the asteroid's aphelion distance are shown in Figure 5.
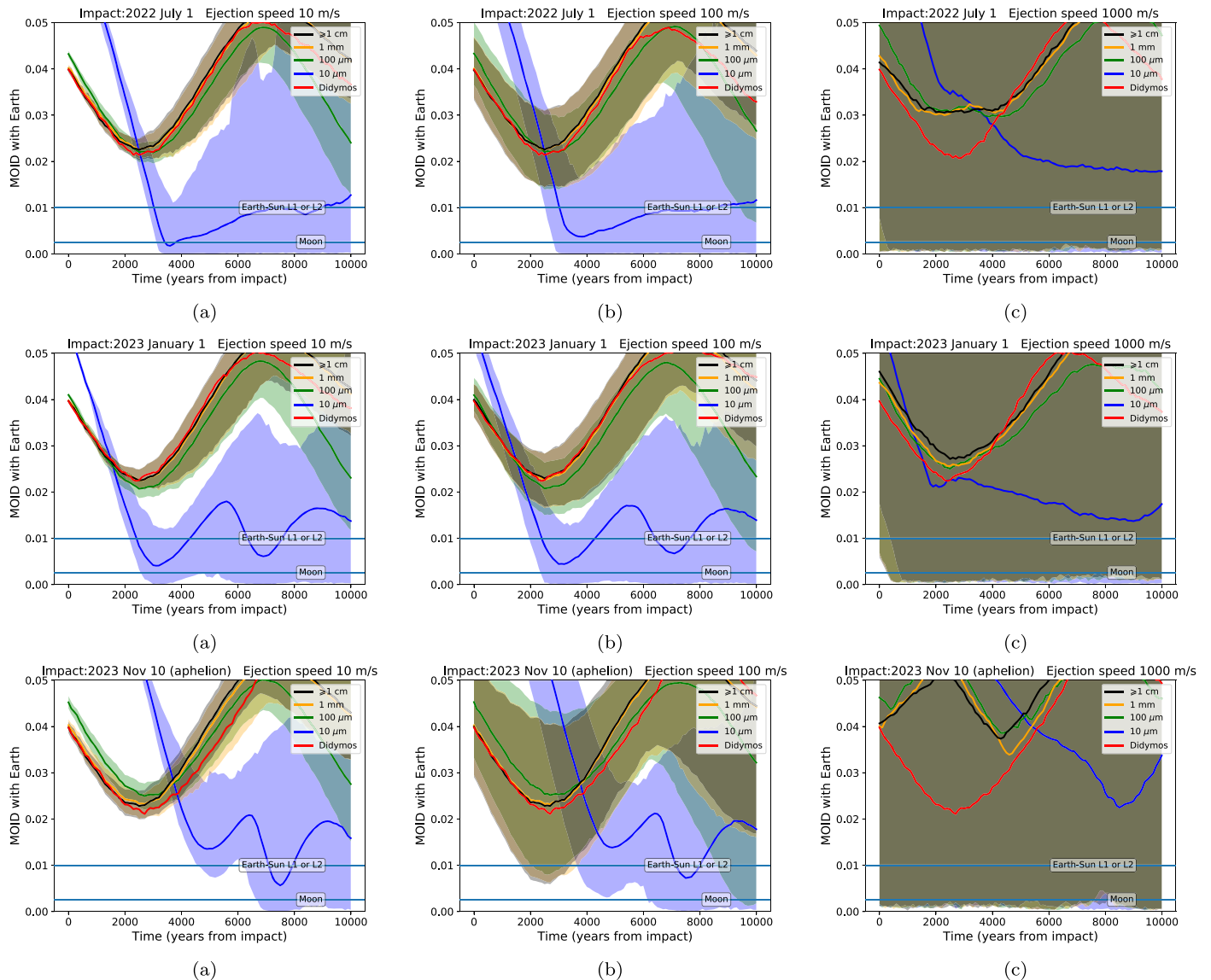
**Figure 5.** Evolution of the MOIDs of the simulated DART-ejected debris in the case of an impact on dates three months on either side of the nominal date of 2022 October 1 (2022 July 1 and 2023 January 1), as well as at Didymos' subsequent aphelion (2023 November 10). See Figure 1 and the text for more details.

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## References

A'Hearn, M. F., Belton, M. J. S., Delamere, W. A., et al. 2005, Sci, 310, 258
Atkinson, H., Tickell, C., & Williams, D. 2000, Rep. Task Force on Potentially Hazardous Near Earth Objects (Washington, DC: NSS) https://space.nss.org/media/2000-Report-Of-The-Task-Force-On-Potentially-Hazardous-Near-Earth-Objects-UK.pdf
Binzel, R. P. 2000, P&SS, 48, 297
Blaauw, R. C., Campbell-Brown, M. D., & Weryk, R. J. 2011, MNRAS, 412, 2033
Britt, D. T., Yeomans, D., Housen, K., & Consolmagno, G. 2002, in Asteroids III, ed. W. F. Bottke, Jr. et al. (Tucson, AZ: Univ. Arizona Press), 485
Campbell-Brown, M. D., Blaauw, R., & Kingery, A. 2016, Icar, 277, 141
Campbell-Brown, M. D., & Braid, D. 2011, in Meteoroids: The Smallest Solar System Bodies, ed. W. J. Cooke et al. (Washington, DC: NASA), 304
Chambers, J. E. 1999, MNRAS, 304, 793
Cheng, A. F., Rivkin, A. S., Michel, P., et al. 2018, P&SS, 157, 104
Crifo, J. F. 1995, ApJ, 445, 470
DeLuca, M., Munsat, T., Thomas, E., & Sternovsky, Z. 2018, P&SS, 156, 111

Domingo, V., Fleck, B., & Poland, A. I. 1995, SSRv, 72, 81
Everhart, E. 1985, ASSL, 115, 185
Fladeland, L., Boley, A. C., & Byers, M. 2019, arXiv:1911.12840
Fujiwara, A., Kawaguchi, J., Yeomans, D. K., et al. 2006, Sci, 312, 1330
Gardner, J. P., Mather, J. C., Clampin, M., et al. 2006, SSRv, 123, 485
Holsapple, K. A., & Housen, K. R. 2007, Icar, 187, 345
Jones, J. 1995, MNRAS, 275, 773
Jones, J., Brown, P., Ellis, K. J., et al. 2005, P&SS, 53, 413
Jones, W. 1997, MNRAS, 288, 995
Lauretta, D. S., Dellagiustina, D. N., Bennett, C. A., et al. 2019, Natur, 568, 55
Michel, P., Cheng, A., Küppers, M., et al. 2016, AdSpR, 57, 2529
Michel, P., & Yu, Y. 2017, EPSC, 11, 82
Moorhead, A. V., Koehler, H. M., & Cooke, W. J. 2015, NASA Meteoroid Engineering Model Release 2.0, Tech. Rep. NASA/TM-2015-218214 (Washington, DC: NASA) https://ntrs.nasa.gov/search.jsp?R=20150021449
Morrison, D., Chapman, C. R., Steel, D., & Binzel, R. P. 2004, in Mitigation of Hazardous Comets and Asteroids, ed. M. J. S. Belton et al. (Cambridge: Cambridge Univ. Press), 353
Raducan, S., Davison, T., & Collins, G. 2019, P&SS, 180, 104756
Richardson, J. E., & O'Brien, D. P. 2016, AAS Meeting Abstract, 48, 329.06
Serpell, E., Milligan, D., Marie, J., & Collins, P. 2016, in Proc. Meteoroids 2016 Meeting (Noordwijk: ESA), https://www.cosmos.esa.int/documents/653713/1000951/01_ORAL_Serpell.pdf/bd245d85-0b58-476f-bb8a-d4259b6bb7d3

Stickle, A. M., Atchison, J. A., Barnouin, O. S., et al. 2015, AAS Meeting Abstract, 47, 312.14
Stickle, A. M., Syal, M. B., Cheng, A. F., et al. 2020, Icar, 338, 113446
Stokes, G., Yeomans, D., Bottke, W., et al. 2003, Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters, SDT Rep. 2003 (Washington, DC: NASA) https://cneos.jpl.nasa.gov/doc/neoreport030825.pdf
Subasinghe, D., & Campbell-Brown, M. 2018, AJ, 155, 88

Tauber, J. A., ESA Scientific Collaboration, & Planck Scientific Collaboration 2004, AdSpR, 34, 491
Thorpe, J. I., Slutsky, J., Baker, J. G., et al. 2019, ApJ, 883, 53
Watanabe, S., Hirabayashi, M., Hirata, N., et al. 2019, Sci, 364, 268
Weidenschilling, S. J., & Jackson, A. A. 1993, Icar, 104, 244
Weryk, R. J., & Brown, P. 2004, EM&P, 95, 221
Whipple, F. L. 1951, ApJ, 113, 464
Wisdom, J., & Holman, M. 1991, AJ, 102, 1528