Draft version December 18, 2025
Typeset using LaTeX **twocolumn** style in AASTeX7

The Feasibility of a Spacecraft Flyby with the Third Interstellar Object 3I/ATLAS from Earth or Mars

Atsuhiro Yaginuma [1], Tessa Frincke [1], Darryl Z. Seligman [1,*], Kathleen Mandt [2], Daniella N. DellaGiustina [3], Eloy Peña-Asensio [4], Aster G. Taylor [5,†] and Michael C. Nolan [3]

[1] *Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[2] *NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA*
[3] *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.*
[4] *Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy*
[5] *Dept. of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA*

ABSTRACT

We investigate the feasibility of a spacecraft mission to conduct a flyby of 3I/ATLAS, the third macroscopic interstellar object discovered on July 1 2025, as it traverses the Solar System. There are both ready-to-launch spacecraft currently in storage on Earth, such as Janus, and spacecraft nearing the end of their missions at Mars. We calculate minimum ΔV single-impulse direct transfer trajectories to 3I/ATLAS both from Earth and from Mars. We consider launch dates spanning January 2025 through March 2026 to explore obtainable and hypothetical mission scenarios. Post-discovery Earth departures require a challenging $\Delta V \gtrsim 24$ km s^{-1} to fly by 3I/ATLAS. By contrast, Mars departures from July 2025 - September 2025 require $\Delta V \sim 5$ km s^{-1} to achieve an early October flyby — which is more feasible with existing propulsion capabilities. We discuss how existing spacecraft could be used to observe 3I/ATLAS and how spacecraft at other locations in the Solar System could be repurposed to visit future interstellar objects on short notice.

Keywords: Asteroids (72) — Comets (280) — Interstellar Objects (52) — Flyby missions (545)

1. INTRODUCTION

The discovery of 3I/ATLAS (L. Denneau et al. 2025) increases the interstellar object sample by 50%, building on the previous discoveries of 1I/'Oumuamua in 2017 (G. V. Williams et al. 2017) and 2I/Borisov in 2019 (G. Borisov et al. 2019). On 2025 July 1, the Asteroid Terrestrial-impact Last Alert System (ATLAS) survey (J. L. Tonry et al. 2018) discovered the small body A11pl3Z [1]. Fits to the ATLAS astrometry revealed that this object has a perihelion distance $q \sim 1.36$ au, orbital eccentricity of $e \sim 6.2$, inclination of $i \sim 175°$, and a hyperbolic velocity of $v_\infty \sim 58$ km s^{-1}, clearly indicating an interstellar origin. This object is only the third confirmed macroscopic interstellar object and therefore presents an unprecedented opportunity to characterize a planetesimal from outside of the Solar System.

Preliminary observations of 3I/ATLAS revealed a weakly active nucleus (D. Jewitt & J. Luu 2025; M. R. Alarcon et al. 2025; C. O. Chandler et al. 2025) with a reddened reflectance spectrum and an absolute magnitude of $H_V \sim 12$ (D. Z. Seligman et al. 2025; C. Opitom et al. 2025) although the nucleus size is uncertain (A. Loeb 2025). Its visible and near-infrared reflectance is red and featureless, matching the spectral slopes of D-type asteroid and active Centaurus (M. Belyakov et al. 2025; T. Kareta et al. 2025; R. de la Fuente Marcos et al. 2025). **High angular resolution observations from the Hubble Space Telescope WFC3 provided an upper limit on the nucleus radius of $\lesssim 2.8$ km (D. Jewitt et al. 2025). Optical and near-infrared spectra revealed a broad 2.0 μm band consistent with $\sim 30\%$ 10 μm-sized water ice grains in the coma (B. Yang et al. 2025). Observations with the *Neil Gehrels-Swift Observatory* revealed the presence of H_2O outgassing via the detection of OH emission (Z. Xing et al. 2025). Time series photometry provided evidence of a rotation period of 16.16±0.01 h and dust loss rates be-**

Email: yaginuma@msu.edu
* NSF Astronomy and Astrophysics Postdoctoral Fellow
† Fannie and John Hertz Foundation Fellow
[1] https://www.minorplanetcenter.net/mpec/K25/K25N12.html

tween 0.3 and 4.2 kg s^{-1} (T. Santana-Ros et al. 2025), while shift stack TESS pre-discoveries imply low level activity at ~ 6.4 au (A. D. Feinstein et al. 2025; J. Martinez-Palomera et al. 2025). SOAR/Goodman spectra reveal a red continuum dominated by refractory organics, with no detected of CN, C_2, or CO^+ at 4.4 au (T. H. Puzia et al. 2025). 3I/ATLAS's high excess velocity and Galactic velocity radiant imply an old kinematic age of 3–11 Gyr (A. G. Taylor & D. Z. Seligman 2025) and lower-metallically stars.

The first two interstellar objects exhibited remarkably different characteristics. 1I/'Oumuamua displayed no cometary activity (K. J. Meech et al. 2017; Q.-Z. Ye et al. 2017; D. Jewitt et al. 2017; D. E. Trilling et al. 2018) but its trajectory exhibited a significant nongravitational acceleration (M. Micheli et al. 2018). In stark contrast, 2I/Borisov displayed clear signatures of an active coma (D. Jewitt & J. Luu 2019; A. Fitzsimmons et al. 2019; Q. Ye et al. 2020; A. J. McKay et al. 2020; P. Guzik et al. 2020; M.-T. Hui et al. 2020; Y. Kim et al. 2020; G. Cremonese et al. 2020; B. Yang et al. 2021). 1I/'Oumuamua and 2I/Borisov had lower excess velocity than 3I/ATLAS, corresponding to younger kinematic ages albeit with large uncertainty (E. Mamajek 2017; E. Gaidos et al. 2017; F. Feng & H. R. A. Jones 2018; F. Almeida-Fernandes & H. J. Rocha-Pinto 2018; T. Hallatt & P. Wiegert 2020; C.-H. Hsieh et al. 2021).

The discovery of these interstellar objects has ignited significant interest in sending dedicated spacecraft to measure their properties *in situ* (e.g., D. Seligman & G. Laughlin 2018; K. Moore et al. 2021). Space-based measurements of interstellar object physical and chemical attributes — such as isotopic signatures and volatile compositions — would profoundly enhance our understanding of extrasolar systems at both broad and narrow scales. Compositional indicators such as the H_2O content — when combined with the kinematics and galactic history of a given object — can provide insight into planet and star formation rates throughout the galaxy (C. Lintott et al. 2022; M. J. Hopkins et al. 2023, 2025). On the other hand, the carbon-to-oxygen ratio of an interstellar object approximately traces its formation location in a protoplanetary disk (D. Z. Seligman et al. 2022b). Since analogous objects may be responsible for enriching short-period exoplanet atmospheres (D. Z. Seligman et al. 2022a), such data could provide insight into the delivery of volatiles and organics to exoplanets.

Many spacecraft have conducted close-range remote observations of comets and asteroids in the Solar System, such as the Deep Impact (M. F. A'Hearn et al. 2005), Giotto (R. Reinhard 1986, 1987), NEAR Shoemaker (L. Prockter et al. 2002), Rosetta (K.-H. Glassmeier et al. 2007), DART (A. F. Cheng et al. 2023), and Hera (P. Michel et al. 2022) missions. Moreover, a number of sample-return missions have delivered extraterrestrial material back to Earth, e.g., Stardust (D. Brownlee 2014; D. E. Brownlee et al. 1996), Hayabusa (M. Yoshikawa et al. 2021), Hayabusa2 (S.-i. Watanabe et al. 2017), and OSIRIS-REx (D. S. Lauretta et al. 2017).

Recently, Comet Interceptor — an ESA F-class mission — has been approved and is currently in its implementation phase (C. Snodgrass & G. H. Jones 2019; G. H. Jones et al. 2024). Designed as a flexible mission architecture, Comet Interceptor will be stationed at the Sun–Earth L2 point, awaiting the discovery of a dynamically new comet or other pristine small body to intercept. Unlike previous missions, Comet Interceptor will employ a multi-spacecraft configuration to enable simultaneous multi-point observations of the target. This mission's primary objective is to investigate a long-period comet entering the inner Solar System for the first time. However, if early warning conditions permit, it could be redirected to perform the first *in situ* exploration of an interstellar object.

The discovery of 1I/'Oumuamua and 2I/Borisov rapidly spurred development on an interstellar object mission concept. Initial studies (e.g., D. Seligman & G. Laughlin 2018) emphasized the urgency of preparing interception missions with minimal latency but determined that it was feasible to detect and reach future interstellar objects with conventional chemical propulsion. Further studies such as Project Lyra examined the feasibility of direct missions to 1I/'Oumuamua using near-term technologies, including solar Oberth maneuvers and high-energy launch architectures (A. M. Hein et al. 2019; A. Hibberd et al. 2021; A. Hibberd 2023). These analyses demonstrated that with optimized trajectories and sufficient launch energies, flyby or rendezvous missions could be viable even years after 1I/'Oumuamua's perihelion. Alternative mission design proposals include solar sail architectures capable of prolonged loitering and rapid-response interception of future interstellar objects (A. M. Hein et al. 2019; D. Garber et al. 2022; D. Miller et al. 2022), or a distributed statite cluster for high-ΔV response scenarios (D. J. Hoover et al. 2022). Evaluations of optical and autonomous navigation performance during high-velocity flybys emphasize the importance of on-board image processing and neural network guidance to maintain targeting accuracy at encounter speeds exceeding 60 km s^{-1} (D. Mages et al. 2022; B. P. S. Donitz et al. 2023). A complementary analysis focused on the tradeoffs between target detectability, spacecraft storage strategies, and imaging resolution advocated for rendezvous missions to 1I/'Oumuamua-sized targets (A. Siraj et al. 2023). **S. A. Stern et al. (2024) also investigated the feasibility of an intercept mission to an interstellar object, "Interstellar Object Explorer."** The "Bridge" New Frontiers-class flyby mission concept would intercept an interstellar object with a dedicated science payload including a guided impactor, ultraviolet/visible/infrared spectrometers, and a high-resolution camera (K. Moore et al. 2021). Additional studies explored broader science cases and mission architectures for interstellar object investigation, including rapid-response trajectories and programmatic feasibility (B. P. Donitz et al. 2021), the astrobiological relevance of interstellar objects as potential carriers of organic material and the propulsion technologies that could enable their exploration (M. Lingam et al. 2023), and the practical constraints and feasibility of near-term rendezvous missions to interstellar objects using advanced but achievable propulsion architectures (D. Landau et al. 2023).

Here, we investigate possible missions that could reasonably intercept 3I/ATLAS in the months following its July 2025 discovery. We specifically explore utilizing existing missions near Earth or Mars and consider favorable minimum distances to 3I/ATLAS. This paper is structured as follows — in Section 2, we detail an algorithm designed to determine direct transfer trajectories and launch dates. In Section 3, we calculate minimum-energy mission trajectories to 3I/ATLAS from Earth achievable in the months following its discovery. **Here, we defined minimum-energy as the trajectory requiring the lowest single-impulse ΔV.** In Section 4, we identify additional key launch dates and trajectories for a flyby mission to 3I/ATLAS from Mars. Finally, we conclude in Section 5 with a summary of our results and a final discussion of our suggestions for immediate implementation of an intercept mission with 3I/ATLAS.

2. IDENTIFICATION OF OPTIMAL TRAJECTORIES

In this section, we describe the algorithm that we implemented to find minimum-energy trajectories to 3I/ATLAS. This algorithm is based on a methodology to calculate the minimum-energy trajectory between two elliptical orbits (H. Leeghim 2013), which was later expanded to include hyperbolic trajectories in Section 4 of D. Seligman & G. Laughlin (2018).

The algorithm first solves Kepler's equations as a function of time given a departure date τ_0 that is sampled over a 400-day interval. For the remainder of this paper, a subscript of 0 denotes departure and I/T denote interceptor **(the intercepting spacecraft)** / target **(the object)**. The flight time is a free parameter in the optimization problem and is denoted by $\Delta\tau$. We obtain the target's heliocentric position from JPL Horizons and **, under the patched-conic approximation, simplify** the boundary-value problem by enforcing only the interceptor's universal variable residual. For each candidate departure and flight duration, $\Delta\tau$, we extract the interceptor's heliocentric state $(\vec{r}_{0,I}, \vec{v}_{0,I})$ **by taking the departure planet's center-of-mass position and velocity,** and compute the target's position $\vec{r}_T$ at arrival. For every pair of both (i) departure date and (ii) arrival date, we solve the minimum-energy single-impulse trajectory by applying the two-body Lambert problem using the universal variable method. With this method, the function η, which indicates how well the solution fits the Kepler's equations of motion, may be written as:

$$\begin{aligned}\eta(\chi,\tau,\vec{r}_0,\vec{v}_0) = \|\vec{r}_0\|\chi - \sqrt{GM_\odot}\Delta\tau \\ +\frac{\vec{r}_0\cdot\vec{v}_0}{\sqrt{GM_\odot}}\chi^2 C\left(\frac{\chi^2}{a}\right) \\ +\left(1-\frac{\|\vec{r}_0\|}{a}\right)\chi^3 S\left(\frac{\chi^2}{a}\right).\end{aligned} \tag{1}$$

In Equation 1, the vectors $\vec{r}_0$ and $\vec{v}_0$ are the initial position and velocity vectors of the object. The universal variable χ is defined to be $\chi \equiv \sqrt{a}E$ for elliptical orbits and $\chi \equiv \sqrt{-a}F$ for hyperbolic orbits with semi-major axis a and eccentric/hyperbolic anomaly $E/\ F$. In Equation 1, G is the gravitational constant, $M_\odot$ is the mass of the Sun, and $S(x)$ and $C(x)$ are Stumpff functions, defined as:

$$S(x) \equiv \begin{cases} \dfrac{\sqrt{x}-\sin(\sqrt{x})}{(\sqrt{x})^3}, & x>0 \text{ (elliptical)}, \\ \dfrac{1}{6}, & x=0 \text{ (parabolic)}, \\ \dfrac{\sinh(\sqrt{-x})-\sqrt{-x}}{(\sqrt{-x})^3}, & x<0 \text{ (hyperbolic)}, \end{cases} \tag{2}$$

and

$$C(x) = \begin{cases} \dfrac{1-\cos(\sqrt{x})}{x}, & x>0 \quad \text{(elliptical)}, \\ \dfrac{1}{2}, & x=0 \quad \text{(parabolic)}, \\ \dfrac{\cosh(\sqrt{-x})-1}{-x}, & x<0 \quad \text{(hyperbolic)}. \end{cases} \tag{3}$$

For the application of the universal variable formalism to Kepler's equations, Equations 2 and 3 are typically defined as functions of the variable $x = \chi^2/a$.

We calculate the numerical values of the universal variable χ by finding the roots of the transcendental equation defined by $\eta = 0$. Following this step, we use the Lagrange propagators $f(\chi)$ and $g(\chi)$ (and their time derivatives) to advance the interceptor's state to time $\tau_0 + \Delta\tau$, since

$$\vec{r}(\chi) = f(\chi)\,\vec{r}_0 + g(\chi)\vec{v}_0\,, \tag{4}$$

and

$$\vec{v}(\chi) = \dot{f}(\chi)\,\vec{r}_0 + \dot{g}(\chi)\vec{v}_0\,. \tag{5}$$

We refer the reader to the corresponding Equations 25-28 in D. Seligman & G. Laughlin (2018) for definitions of the Lagrange propagators.

Since the arrival position $\vec{r}_T$ is taken directly from Horizons, we reformulate the boundary-value problem in terms of the variable $z = \chi^2/a$. With this simplification, there is no need to solve the target's universal variable equation as described in D. Seligman & G. Laughlin (2018).

For a given interceptor state $\vec{r}_{0,I}$, $\vec{v}_{0,I}$, and $\Delta\tau$, the universal variable time-of-flight residual is given by:

$$\begin{aligned} \eta_I\big(\chi_I, \tau_0 + \Delta\tau, \vec{r}_{0,I}, \vec{v}_0 + \vec{v}_{0,I}\big) = \|\vec{r}_{0,I}\|\chi_I - \sqrt{GM_\odot}\Delta\tau \\ + \frac{\vec{r}_{0,I}\cdot(\vec{v}_0 + \vec{v}_{0,I})}{\sqrt{GM_\odot}}\,\chi_I^2\, C\left(\frac{\chi_I^2}{a}\right) \\ + \left(1 - \frac{\|\vec{r}_{0,I}\|}{a}\right)\chi_I^3 S\left(\frac{\chi_I^2}{a}\right). \end{aligned} \tag{6}$$

Rather than propagating both orbits, we require that the interceptor reaches the known target position $\vec{r}_T$, (given by Horizons) after a flight time of $\Delta\tau$. To this end, we compute the angle between the target and interceptor, $\Delta\theta$, given by:

$$\cos\big(\Delta\theta\big) = \frac{\vec{r}_T\cdot\vec{r}_I}{\|\vec{r}_T\|\,\|\vec{r}_I\|}\,. \tag{7}$$

We define a geometric coefficient:

$$A = \sin\big(\Delta\theta\big)\sqrt{\frac{\|\vec{r}_T\|\,\|\vec{r}_I\|}{1-\cos\big(\Delta\theta\big)}}\,, \tag{8}$$

which rescales the chord connecting the departure and arrival position vectors so that the universal variable time-of-flight equation properly reflects the transfer geometry.

We then introduce the intermediate function:

$$y(z) = \|\vec{r}_T\| + \|\vec{r}_I\| + A\,\frac{z\,S(z) - 1}{\sqrt{C(z)}}\,. \tag{9}$$

With Equation 9, the time-of-flight residual can be written as defined in (H. D. Curtis 2020, Chapter 5, Eq. 5.40):

$$F(z) = \left(\frac{y(z)}{C(z)}\right)^{3/2} S(z) + A\sqrt{y(z)} - \sqrt{GM_\odot}\,\Delta\tau\,, \tag{10}$$

Root-finding on Equation 10 enforces both geometric and temporal constrains simultaneously. For a root z, the Lambert-Lagrange coefficients are

$$\begin{aligned} f_I &= 1 - \frac{y(z)}{\|\vec{r}_{0,I}\|}, \\ g_I &= A\,\frac{\sqrt{y(z)}}{\sqrt{GM_\odot}}. \end{aligned} \tag{11}$$

By substituting these values into Equations (4, 5), the required arrival position and velocity vectors can be written as:

$$\vec{r}_T = f_I\vec{r}_{0,I} + g_I\vec{v}_{0,I}, \tag{12}$$

and

$$\vec{v}_{0,I} = \frac{\vec{r}_T - f_I\vec{r}_{0,I}}{g_I}\,. \tag{13}$$

To evaluate the impulsive change in velocity ΔV required for a spacecraft to reach 3I/ATLAS, we subtract the heliocentric velocity of the departure planet from $\vec{v}_{0,I}$, so that:

$$\Delta V = \big\|\vec{v}_{0,I} - \vec{v}_h\big\|\,. \tag{14}$$

In Equation 14, $\vec{v}_h$ is the heliocentric velocity of departure planet.

We repeat the following process iteratively to solve for ΔV:

1. Choose a trial departure epoch $\tau_{0,I}$ and set a flight time $\Delta\tau$.

2. Solve the universal variable Lambert problem for that $\Delta\tau$ by finding the root z of the time-of-flight residual defined in Equation 10.

3. Compute the Lagrange coefficient using Equation 11 and propagate the interceptor state with Equations 12 and 13.

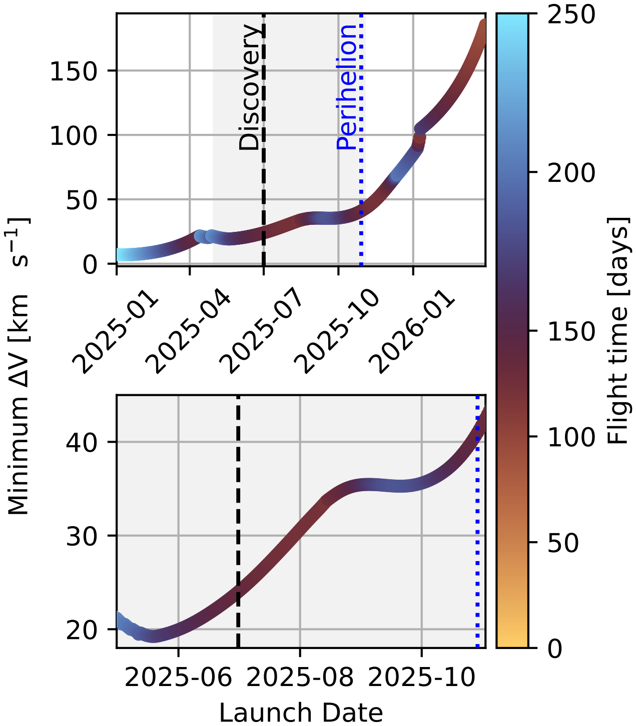

Figure 1. Direct flight ΔV values as a function of launch date for trajectories to 3I/ATLAS from Earth. The color of each point corresponds to the flight time of the mission. The upper- and lower-panels show direct flight ΔV values from 2025 January 1 – 2026 March 31 and May 1 – November 2 2025, respectively. The minimum post-discovery ΔV trajectory is 24.0 km s^{-1} on 2025 July 1 with a flight time of 137 days. Pre-discovery trajectories may have been feasible, requiring $\Delta V \sim 7$ km s^{-1} with a flight times of $\sim$250 days. The shaded region on the upper panel is the region shown in the lower panel.

4. Evaluate ΔV using Equation 14.
5. Identify the global minimum-energy trajectory from the resulting ΔV values.

It is important to note that these ΔV values only encapsulate the **hyperbolic-excess component of the** impulsive burn required to leave a circular low-Earth orbit on an escape trajectory. In other words, they do not include the **velocity needed to climb out of the departure planet's gravitational potential nor any downstream deep space maneuvers.**

Finally, we verified that this methodology accurately produced flyby trajectories. We performed numerical integrations with hypothetical massless test particles representing the spacecraft and the Sun-Earth system with the solution velocity vectors. We verified that the position of the spacecraft and target matched after the corresponding time of flight. All verification numerical simulations were performed with `REBOUND` N-body code (H. Rein & S. F. Liu 2012), the `REBOUNDx` library (D. Tamayo et al. 2020) and `MERCURIUS` (H. Rein et al. 2019).

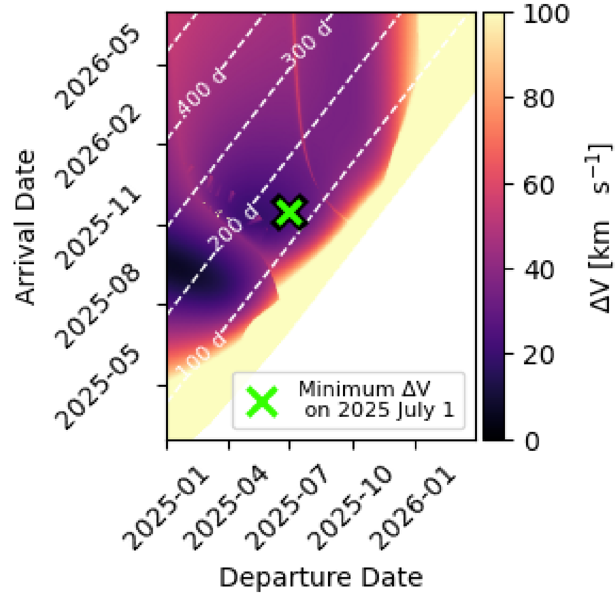

Figure 2. Mission Design Contour displaying required ΔV (0–100 km s^{-1}) across Earth departure and 3I/ATLAS arrival dates. The Red X mark indicates the minimum ΔV on discovery date, 2025 July 1.

The universal variable Lambert solver described above is a well-established solution to a two-body problem (D. Seligman & G. Laughlin 2018; H. D. Curtis 2020). Our novel contribution is not in the solver itself but in its systematic application to the evolving geometry of 3I/ATLAS and subsequent mapping of the resulting minimum ΔV to the Earth- and Mars-based launchers. This enables the identification of mission-ready intercept windows under realistic departure and arrival constraints.

3. OPTIMAL TRAJECTORIES FROM EARTH

In this section, we examine the feasibility of trajectories from the Earth to the interstellar object 3I/ATLAS. We calculate minimum-energy trajectories from Earth to 3I/ATLAS using the methodology described in Section 2.

To determine when a direct launch from Earth could be viable, we use the Earth's position as the initial launch date for a spacecraft. We then calculate the minimum ΔV required to reach 3I/ATLAS for a range of possible initial launch dates. The minimum ΔV required as a function of launch date for a direct flight

Table 1. Velocity vector information of minimum-energy trajectories to 3I/ATLAS for a variety of launch dates and locations. All listed velocities are with respect to the reference frame comoving with the orbit of the Earth.

Launch Date	Launch Location	V_x [km s^{-1}]	V_y [km s^{-1}]	V_z [km s^{-1}]	ΔV [km s^{-1}]	Flight time [days]	Arrival Date
2025 January 10	Earth	-5.353	0.592	4.371	6.935	248	2025 September 15
2025 July 1	Earth	-8.196	22.536	-0.996	24.001	137	2025 November 15
2025 December 15	Earth	8.424	70.532	-4.082	71.151	198	2026 July 1
2025 March 6	Mars	-0.483	-0.082	1.958	2.019	212	2025 October 4
2025 July 1	Mars	-1.641	-1.033	2.959	3.538	94	2025 October 3
2025 August 10	Mars	-3.291	-1.994	4.8354	6.179	54	2025 October 3
2025 November 10	Mars	14.410	72.571	3.959	74.093	233	2026 July 1

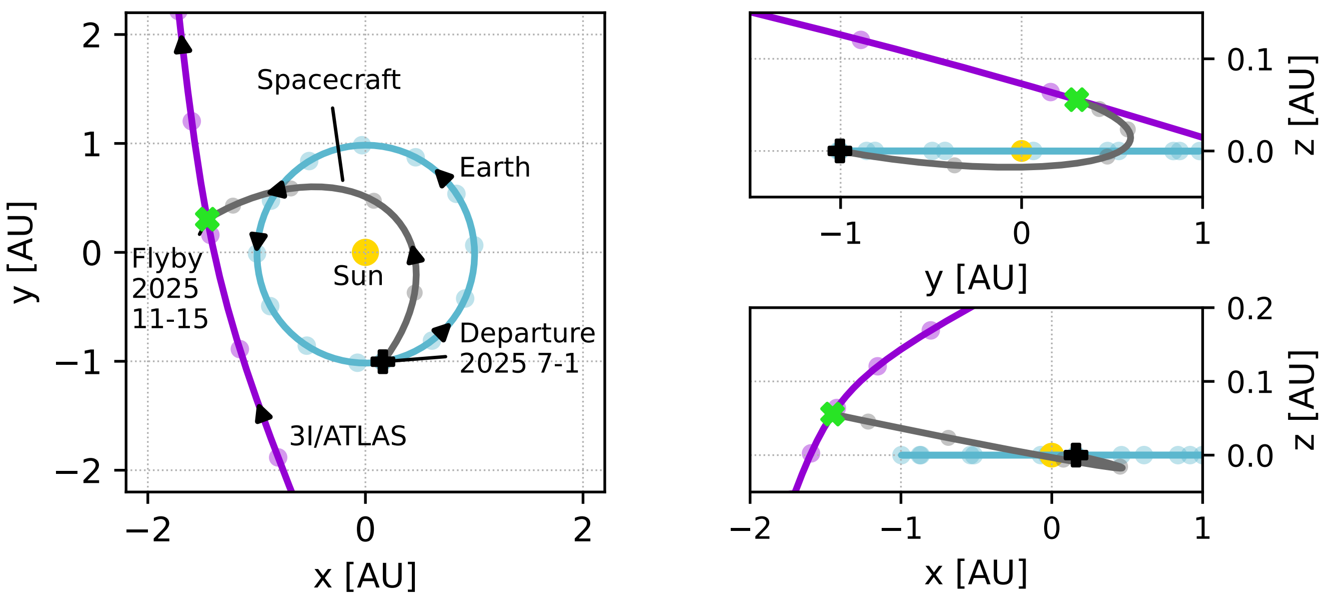

Figure 3. The orbit of a post-discovery minimum ΔV mission to 3I/ATLAS sent on 2025 July 1 from the Earth. The spacecraft would encounter 3I/ATLAS on 2025 November 15 and would require $\Delta V = 24$ km s^{-1}. The trajectory for 3I/ATLAS, Earth, and the spacecraft are plotted in purple, blue, and gray, respectively. Markers represent departure location and flyby location, and arrows show direction of each orbit/trajectory. Points on each trajectory indicate the positions of each object every 30 days.

is shown in Figure 1. The color of each point indicates the flight time for each of the corresponding trajectories. **Figure 2 shows the required ΔV across Earth departure and 3I/ATLAS arrival date.**

The minimum ΔV solution recovered after the discovery of the object technically occurs on 2025 July 1. In other words, the optimal intercept mission would have required immediate launch of a spacecraft contemporaneous with discovery. This optimal trajectory would have required $\Delta V \sim 24.0$ km s^{-1}, with a flight time of 137 days. The details of this trajectory are reported in Table 1. An orbit schematic of this hypothetical minimum-energy flyby mission is shown in Figure 3.

The energetic requirements for a direct transfer mission post-discovery gradually increase during the timespan between July and early October 2025. Specifically the ΔV value increases to ~ 35 km s^{-1} while the flight time extends to ~ 140 days. After early October 2025 — but still before perihelion — the minimum ΔV rises steeply. The minimum ΔV reaches a value of ~ 60 km s^{-1} by December 2025 and ~ 80 km s^{-1} in January 2026. Therefore, an Earth-based direct flight is significantly more attainable if a spacecraft is launched before 3I/ATLAS passes its perihelion. However, even $\Delta V = 24$ km s^{-1} for a fiducial best case mission shown in Figure 3 would be challenging for current propulsion capabilities.

A direct-transfer trajectory from Earth would have been more energetically feasible if 3I/ATLAS had been discovered earlier. Earth departures between January

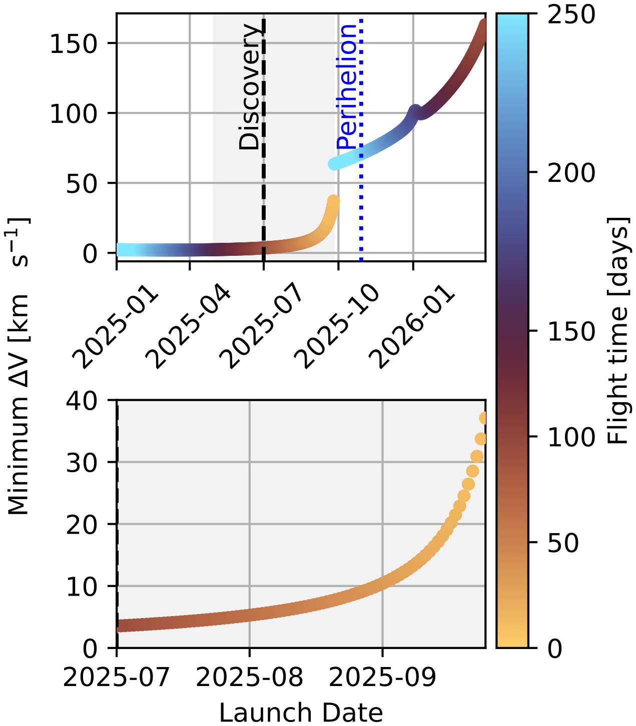

Figure 4. Similar to Figure 1, but for trajectories to 3I/ATLAS from Mars. Here, the shaded inset region is from 2025 July 1 to 2025 September 25. The minimum energy trajectory for a post-discovery mission would be launched on 2025 July 1 with a flight time of 94 days and require $\Delta V = 3.54$ km s^{-1}. Pre-discovery trajectories would have required $\Delta V \sim 3$ km s^{-1} with flight times of more than 200 days.

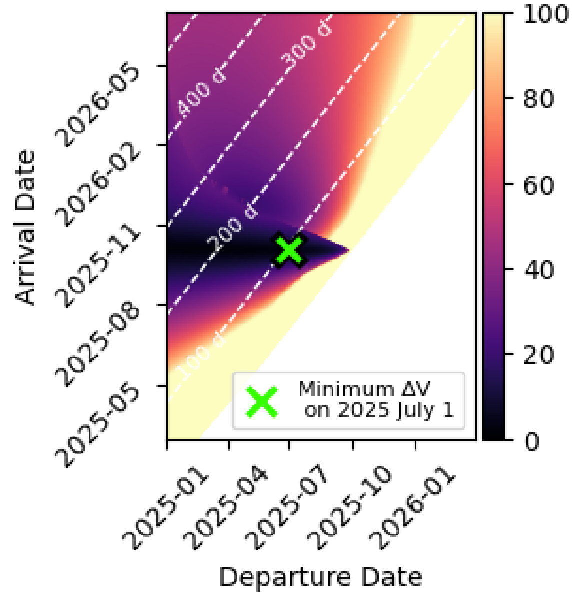

Figure 5. Similar to Figure 2, but from Mars in this case.

and June would have required $\Delta V \sim 10$ km s^{-1}, with a flight time of approximately 150–200 days. A launch on 2025 January 10 would require only a minimum ΔV of 6.94 km s^{-1} with a flight time of 248 days, which may have been within the reach of modern spacecraft. **J. P. Sanchez & C. Snodgrass (2025) demonstrated that a complementary deep-space maneuver (DSM) study for the European Space Agency Comet Interceptor mission (CI) could intercept 3I/ATLAS on 2025 November 7 after an $\sim$ 825 days of flight time. This would require departing the Sun-Earth L_2 halo orbit on 2023 August 2 with a hyperbolic departure velocity of 2.8 km s^{-1} and performing a 685 m s^{-1} mid-course burn.** It is worth noting that in a recent and complimentary analyses, A. Hibberd et al. (2025) identified an optimal trajectory from Earth to 3I/ATLAS. They calculated a minimum energy trajectory launched in 2024 July 19 for a rendezvous 2025 October 18. **That trajectory assumes a single impulsive ΔV burn.**

4. OPTIMAL TRAJECTORIES FROM MARS

Mars has been a high-priority planetary science target for multiple space agencies, including NASA and the ESA, for several decades. A typical mission starts with the "prime mission", which is designed to achieve the originally-funded objectives. Once a prime mission is completed, if the spacecraft can continue operating for a longer period of time, extended missions can be approved with additional science goals. As a spacecraft approaches the end of its operational life (e.g., running out of fuel) an end-of-mission maneuver is designed to safely dispose of the spacecraft. This end-of-mission maneuver can also be used to achieve additional objectives beyond the spacecraft's initial design capabilities. For example, the Cassini spacecraft was disposed of by sending the spacecraft into Saturn's atmosphere, taking *in situ* measurements that could not be accomplished during the active mission and which resulted in major scientific achievements (S. G. Edgington & L. J. Spilker 2016). Additionally, the Rosetta mission ended its life by descending to the surface of its target comet 67P/Churyumov-Gerasimenko and making observations directly at the surface (A. Accomazzo et al. 2017; M. A. Barucci & M. Fulchignoni 2017).

At this time, several spacecraft currently in orbit around Mars are approaching their end-of-life (M. H. Carr 1996). If the required ΔV is small, one of these spacecraft could de-orbit from Mars and conduct a flyby of 3I/ATLAS. Such a maneuver would be a potentially

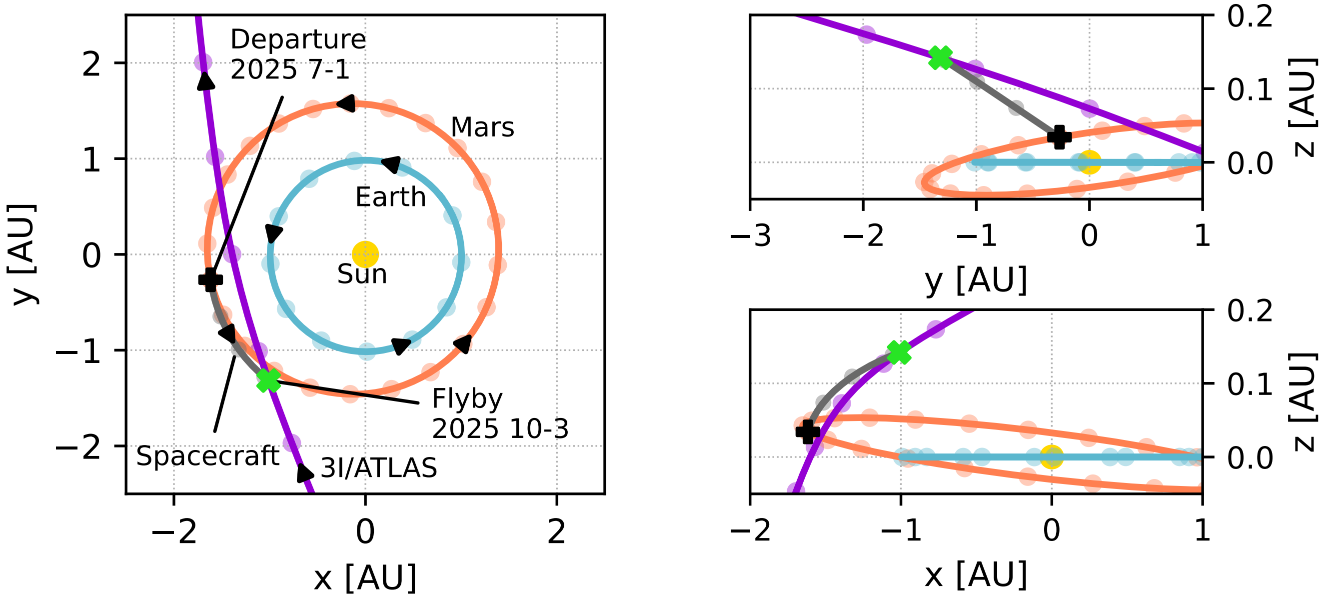

Figure 6. Similar to Figure 3, except for a minimum ΔV mission to 3I/ATLAS post-discovery, sent on 2025 July 1 from Mars. This hypothetical trajectory requires a $\Delta V \sim 4$ km s^{-1} and a time of flight of 94 days.

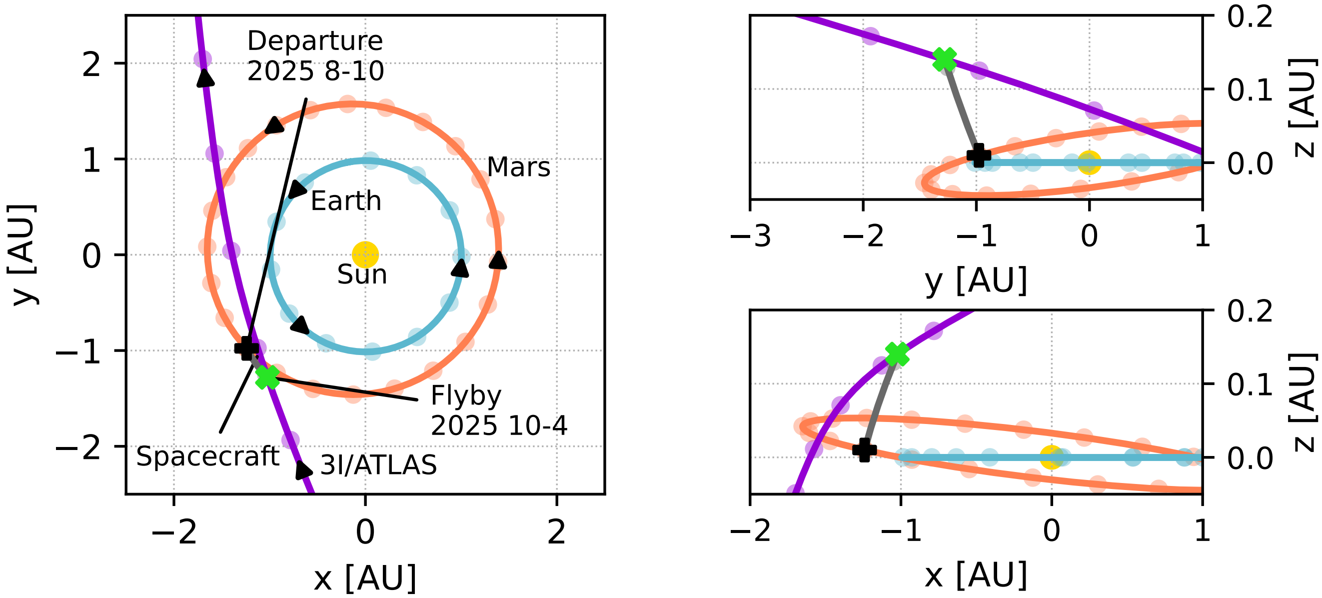

Figure 7. Similar to Figure 3, except for a minimum-energy mission to 3I/ATLAS sent from Mars on 2025 August 10. Such a mission would require a $\Delta V \sim 6.5$ km s^{-1} and performs a flyby on 2025 October 4 with a time of flight of 54 days.

high impact end-of-mission scenario for an end-of-life spacecraft. In this section, we assess whether trajectory designs from Mars to 3I/ATLAS may be energetically feasible. Although we consider generic trajectories, our results can be applied to existing spacecraft. We once again use the algorithm discussed in Section 2 to calculate the minimum-energy trajectories between 3I/ATLAS and Mars.

In Figure 4, we show the minimum ΔV required for such a mission. The minimum ΔV of 2.02 km s^{-1} occurs for a launch on 2025 March 6 (four months prior to discovery), with flight time of 212 days. The first post-discovery opportunity also occurs contemporaneously with discovery and would have required a ΔV of 3.54 km s^{-1} on 2025 July 1. A mission with this trajectory would arrive on 2025 October 3, three months after discovery, with its 94 days in transit. This optimal mission would fly by 3I/ATLAS during its closest approach to Mars. **In Figure 5, we show the required ΔV as a function of the Mars departure date and 3I/ATLAS arrival date.** In Figure 6, we show the orbit of this minimum-energy post-discovery mission. For detailed information regarding these trajectories, see Table 1. After discovery, the required ΔV for flyby climbs gradually, yet remains at $\Delta V \leq 10$ km s^{-1} through 2025 August 30.

The sharp rise and gap in ΔV around October 2025 coincides with the closest approach between Mars and 3I/ATLAS, which occurs on 2025 October 3. **Mars and 3I/ATLAS are closely aligned before their trajectories cross in the XY plane, as shown in Figures 6 and 7. Therefore, a near-tangent transfer only requires leaving before the crossing and plane change maneuvers, resulting in low ΔV. After the orbits cross and the distance between Mars and 3I/ATLAS increases, a flyby requires significantly larger ΔV, causing the sharp rise seen in Figure 4.**

The optimum trajectories sent prior to the closest approach have flight times such that the flyby occurs close in time to 2025 October 3. In Figure 7, we show the trajectory for a launch on 2025 August 10, 41 days after discovery, which demonstrates one of possible Mars departure scenarios. On the other hand, even the optimal trajectories after the close approach date would require significantly more ΔV to perform a flyby.

These results suggest that an intercept or flyby from Mars would require less ΔV than an Earth-based mission. **This advantage is due primarily to orbital phasing. At the perihelion, Mars is closely aligned with 3I/ATLAS orbital longitude, while Earth is nearly 180° out of phase, making an Earth-based intercept far more ΔV intensive.** A hypothetical Mars-based mission to 3I/ATLAS would have ΔV requirements within the performance envelope of modern spacecraft propulsion systems. Therefore, such a Mars-based flyby mission could be feasible.

5. DISCUSSION

In this paper, we calculated minimum-energy trajectories from both Earth and Mars to the interstellar object 3I/ATLAS. Given the current state of spacecraft propulsion technology, a spacecraft flyby of 3I/ATLAS would be more feasible if launched from Mars rather than Earth.

Our calculations show that post-discovery Earth departures likely demand ΔV values beyond the capabilities of available spacecraft. However, had 3I/ATLAS been discovered before July 1, a mission launched from Earth would have required $\Delta V \sim 7$ km s^{-1}, within the envelope of current spacecraft technologies. This fact underscores the critical impact of discovery time on the feasibility of deep-space missions.

On the other hand, Mars departures require substantially less ΔV. For example, a pre-discovery flyby on 2025 March 6 (four months prior to discovery) could reach 3I/ATLAS with just $\Delta V = 2.02$ km s^{-1} while a launch on the discovery date of 2025 July 1 would require $\Delta V \sim 4$ km s^{-1}. These ΔV values likely fall within the maneuvering envelope of current Mars orbiters, making it possible to re-target one for a close flyby of 3I/ATLAS.

There are a variety of spacecraft currently orbiting Mars that are nearing their end of life — Mars Reconnaissance Orbiter (R. W. Zurek & S. E. Smrekar 2007), MAVEN (B. M. Jakosky et al. 2015), Mars Odyssey (R. S. Saunders et al. 2004), Mars Express (A. Chicarro et al. 2004; A. F. Chicarro 2007), ExoMars Trace Gas Orbiter (A. C. Vandaele et al. 2015) and others. These spacecraft collectively carry a wide range of imaging cameras, spectrometers, *in situ* instrumentation, and communications and operation tools. Repurposing these missions as interstellar interceptors would offer valuable scientific data, especially since they may be able to reach interstellar objects that are inaccessible from Earth. While repurposing Earth-observing missions is also possible, these spacecraft are generally de-orbited during their end-of-life phase and have less maneuvering capability, limiting their use as interstellar interceptors. **Beyond Mars orbiters, opportunistic geometries with existing deep-space spacecraft may also enable intercepts. A. Loeb et al. (2025) propose using *Juno* (S. J. Bolton et al. 2017) during 3I/ATLAS's March 2026 Jupiter approach.**

The Janus spacecraft mission (D. J. Scheeres et al. 2021), part of NASA's SIMPLEx program, consists of two identical 12 U CubeSats, designed to fly by binary asteroids. Each carries JCam, a visible/infrared imager capable of capturing meter-scale resolution images and thermal data. Janus could have potentially performed its 10 km s^{-1} flyby of 3I/ATLAS **at 50 km distance** if we had launched it within the first few days after discovery since it is one of the ready-to-launch spacecraft. This close encounter would allow Janus to collect detailed images and thermal data, helping us to understand 3I/ATLAS's shape, rotation, and dust activity.

Although a flyby may not be feasible, NASA's OSIRIS-APEX (D. N. DellaGiustina et al. 2023) could be assigned to observe 3I/ATLAS from the spacecraft's existing trajectory using the PolyCam and MapCam imagers (B. Rizk et al. 2018). Observations with the Eight Color Asteroid Survey (ECAS) b, v, w, and x filters onboard the OSIRIS-APEX MapCam instrument (D. N. DellaGiustina et al. 2018) would provide valuable data characterizing 3I/ATLAS. MapCam could acquire narrow-band photometry from the near-ultraviolet through the near-infrared, constraining the spectral slope and broad surface composition of 3I/ATLAS (D. R. Golish et al. 2021; D. N. DellaGiustina et al. 2023). The viable observation windows are late September and mid-November of 2025. Although late September offers the advantage of pre-perihelion observations, preferable for comet characterization, it coincides with an OSIRIS-APEX Earth Gravity Assist (D. N. DellaGiustina et al. 2023), making additional spacecraft activities during this period potentially risky. By mid-November, the solar elongation of 3I/ATLAS increases rapidly, and observations could likely be conducted once the elongation exceeds 35–40 degrees. A spacecraft like OSIRIS-APEX can provide valuable photometric data at a distance, obtaining unique observation geometries in the absence of atmospheric effects.

In addition, higher-resolution imagery could resolve any dust plumes or jets coming off the surface of 3I/ATLAS, further characterizing its mass-loss rate. By viewing the object at different phase angles, the albedo of the object can be constrained (assuming that we can resolve the nucleus). Finally, a simple infrared measurement would indicate how the surface of 3I/ATLAS responds to thermal forcing, enabling further characterization of its surface properties. Together, these results would allow for estimates of nucleus size, composition, rotation, and activity level.

Even if no existing spacecraft performs a flyby of 3I/ATLAS, the discovery and apparition provide a tangible example for a future interstellar object mission. The NSF-DOE Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) should identify more interstellar objects in the near future (A. Moro-Martín et al. 2009; N. V. Cook et al. 2016; T. Engelhardt et al. 2017; D. J. Hoover et al. 2022; D. Marčeta 2023; R. C. Dorsey et al. 2025). If we station fueled spacecraft at key locations (e.g., Earth orbit, Mars orbit, the Earth-Sun Lagrange points) we could direct these craft to fly by a newly discovered interstellar object with short notice. If equipped with narrow-band cameras and sufficient maneuvering capability for small trajectory changes, these fueled spacecraft could execute fast flybys or continuous brightness monitoring of interstellar objects immediately after discovery. Such measurements would provide critical information regarding the composition, rotational state, and activity of interstellar objects beyond the capabilities of ground-based instruments alone. The data provided by such a mission would provide unprecedented insights into the interstellar object population, and in turn, the history of planet formation throughout the Galaxy.

ACKNOWLEDGMENTS

We thank the anonymous reviewer for insightful comments and constructive suggestions that strengthened the scientific content of this manuscript.

We thank Shannon Curry, Adina Feinstein, Karen Meech, James Wray, Abraham Loeb, Adam Hibberd, Devin Hoover, and Qicheng Zhang for helpful conversations.

D.Z.S. is supported by an NSF Astronomy and Astrophysics Postdoctoral Fellowship under award AST-2303553. This research award is partially funded by a generous gift of Charles Simonyi to the NSF Division of Astronomical Sciences. The award is made in recognition of significant contributions to Rubin Observatory's Legacy Survey of Space and Time. A.Y. and T.F. also acknowledge support from NSF grant number AST-2303553. A.G.T. acknowledges support from the Fannie and John Hertz Foundation and the University of Michigan's Rackham Merit Fellowship Program. E.P.-A. acknowledges support by the Italian Space Agency (ASI) within the LUMIO project (ASI-PoliMi agreement n. 2024-6-HH.0). K.E.M. acknowledges support from the NASA ROSES Discovery Data Analysis Program (DDAP). D.N.D. and M.C.N. acknowledge support under NASA contract NNM10AA11C.

REFERENCES

Accomazzo, A., Ferri, P., Lodiot, S., et al. 2017, Acta Astronautica, 136, 354, doi: 10.1016/j.actaastro.2017.03.027

A'Hearn, M. F., Belton, M. J. S., Delamere, W. A., et al. 2005, Science, 310, 258, doi: 10.1126/science.1118923

Alarcon, M. R., Serra-Ricart, M., Licandro, J., et al. 2025, The Astronomer's Telegram, 17264, 1

Almeida-Fernandes, F., & Rocha-Pinto, H. J. 2018, MNRAS, 480, 4903, doi: 10.1093/mnras/sty2202

Barucci, M. A., & Fulchignoni, M. 2017, A&A Rv, 25, 3, doi: 10.1007/s00159-017-0103-8

Belyakov, M., Fremling, C., Graham, M. J., et al. 2025, arXiv e-prints, arXiv:2507.11720. https://arxiv.org/abs/2507.11720

Bolton, S. J., Lunine, J., Stevenson, D., et al. 2017, SSRv, 213, 5, doi: 10.1007/s11214-017-0429-6

Borisov, G., Durig, D. T., Sato, H., et al. 2019, Central Bureau Electronic Telegrams, 4666, 1

Brownlee, D. 2014, Annual Review of Earth and Planetary Sciences, 42, 179, doi: 10.1146/annurev-earth-050212-124203

Brownlee, D. E., Burnett, D., Clark, B., et al. 1996, in Astronomical Society of the Pacific Conference Series, Vol. 104, IAU Colloq. 150: Physics, Chemistry, and Dynamics of Interplanetary Dust, ed. B. A. S. Gustafson & M. S. Hanner, 223

Carr, M. H. 1996, Water on Mars (Oxford University Press)

Chandler, C. O., Bernardinelli, P. H., Jurić, M., et al. 2025, arXiv e-prints, arXiv:2507.13409. https://arxiv.org/abs/2507.13409

Cheng, A. F., Agrusa, H. F., Barbee, B. W., et al. 2023, Nature, 616, 457, doi: 10.1038/s41586-023-05878-z

Chicarro, A., Martin, P., & Trautner, R. 2004, in ESA Special Publication, Vol. 1240, Mars Express: the Scientific Payload, ed. A. Wilson & A. Chicarro, 3–13

Chicarro, A. F. 2007, Highlights of Astronomy, 14, 334, doi: 10.1017/S1743921307010903

Cook, N. V., Ragozzine, D., Granvik, M., & Stephens, D. C. 2016, ApJ, 825, 51, doi: 10.3847/0004-637X/825/1/51

Cremonese, G., Fulle, M., Cambianica, P., et al. 2020, Astrophysical Journal Letters, 893, L12, doi: 10.3847/2041-8213/ab8455

Curtis, H. D. 2020, Orbital Mechanics for Engineering Students, 4th edn. (Oxford, England; Cambridge, MA: Butterworth-Heinemann)

de la Fuente Marcos, R., Licandro, J., Alarcon, M. R., et al. 2025, arXiv e-prints, arXiv:2507.12922. https://arxiv.org/abs/2507.12922

DellaGiustina, D. N., Bennett, C., Becker, K., et al. 2018, Earth and Space Science, 5, 929, doi: 10.1029/2018EA000382

DellaGiustina, D. N., Nolan, M. C., Polit, A. T., et al. 2023, The Planetary Science Journal, 4, 198, doi: 10.3847/PSJ/acf75e

Denneau, L., Siverd, R., Tonry, J., et al. 2025, MPEC

Donitz, B. P., Castillo-Rogez, J. C., & Matousek, S. E. 2021, in 2021 IEEE Aerospace Conference (50100), 1–12, doi: 10.1109/AERO50100.2021.9438142

Donitz, B. P. S., Mages, D., Tsukamoto, H., et al. 2023, in 2023 IEEE Aerospace Conference, 1–9, doi: 10.1109/AERO55745.2023.10115554

Dorsey, R. C., Hopkins, M. J., Bannister, M. T., et al. 2025, arXiv e-prints, arXiv:2502.16741, doi: 10.48550/arXiv.2502.16741

Edgington, S. G., & Spilker, L. J. 2016, Nature Geoscience, 9, 472, doi: 10.1038/ngeo2753

Engelhardt, T., Jedicke, R., Vereš, P., et al. 2017, Astronomical Journal, 153, 133, doi: 10.3847/1538-3881/aa5c8a

Feinstein, A. D., Noonan, J. W., & Seligman, D. Z. 2025, arXiv e-prints, arXiv:2507.21967, doi: 10.48550/arXiv.2507.21967

Feng, F., & Jones, H. R. A. 2018, Astrophysical Journal Letters, 852, L27, doi: 10.3847/2041-8213/aaa404

Fitzsimmons, A., Hainaut, O., Meech, K. J., et al. 2019, Astrophysical Journal Letters, 885, L9, doi: 10.3847/2041-8213/ab49fc

Gaidos, E., Williams, J., & Kraus, A. 2017, RNAAS, 1, 13, doi: 10.3847/2515-5172/aa9851

Garber, D., Friedman, L. D., Davoyan, A., et al. 2022, Experimental Astronomy, 53, 945, doi: 10.1007/s10686-022-09835-y

Glassmeier, K.-H., Boehnhardt, H., Koschny, D., Kührt, E., & Richter, I. 2007, Space Science Reviews, 128, 1, doi: 10.1007/s11214-006-9140-8

Golish, D. R., DellaGiustina, D. N., Li, J. Y., et al. 2021, Icarus, 357, 113724, doi: 10.1016/j.icarus.2020.113724

Guzik, P., Drahus, M., Rusek, K., et al. 2020, Nature Astronomy, 4, 53, doi: 10.1038/s41550-019-0931-8

Hallatt, T., & Wiegert, P. 2020, Astronomical Journal, 159, 147

Hein, A. M., Perakis, N., Eubanks, T. M., et al. 2019, Acta Astronautica, 161, 552, doi: https://doi.org/10.1016/j.actaastro.2018.12.042

Hibberd, A. 2023, Acta Astronautica, 211, 431, doi: 10.1016/j.actaastro.2023.06.029

Hibberd, A., Crowl, A., & Loeb, A. 2025, arXiv e-prints, arXiv:2507.12213. https://arxiv.org/abs/2507.12213

Hibberd, A., Perakis, N., & Hein, A. M. 2021, Acta Astronautica, 189, 584, doi: 10.1016/j.actaastro.2021.09.006

Hoover, D. J., Seligman, D. Z., & Payne, M. J. 2022, Planetary Science Journal, 3, 71, doi: 10.3847/PSJ/ac58fe

Hopkins, M. J., Bannister, M. T., & Lintott, C. 2025, The Astronomical Journal, 169, 78, doi: 10.3847/1538-3881/ad9eb3

Hopkins, M. J., Lintott, C., Bannister, M. T., Mackereth, J. T., & Forbes, J. C. 2023, The Astronomical Journal, 166, 241, doi: 10.3847/1538-3881/ad03e6

Hsieh, C.-H., Laughlin, G., & Arce, H. G. 2021, Astrophysical Journa, 917, 20, doi: 10.3847/1538-4357/ac0729

Hui, M.-T., Ye, Q.-Z., Föhring, D., Hung, D., & Tholen, D. J. 2020, Astronomical Journal, 160, 92, doi: 10.3847/1538-3881/ab9df8

Jakosky, B. M., Lin, R. P., Grebowsky, J. M., et al. 2015, SSRv, 195, 3, doi: 10.1007/s11214-015-0139-x

Jewitt, D., Hui, M.-T., Mutchler, M., Kim, Y., & Agarwal, J. 2025, arXiv e-prints, arXiv:2508.02934. https://arxiv.org/abs/2508.02934

Jewitt, D., & Luu, J. 2019, Astrophysical Journal Letters, 886, L29, doi: 10.3847/2041-8213/ab530b

Jewitt, D., & Luu, J. 2025, The Astronomer's Telegram, 17263, 1

Jewitt, D., Luu, J., Rajagopal, J., et al. 2017, Astrophysical Journal Letters, 850, L36, doi: 10.3847/2041-8213/aa9b2f

Jones, G. H., Snodgrass, C., Tubiana, C., et al. 2024, Space Science Reviews, 220, doi: 10.1007/s11214-023-01035-0

Kareta, T., Champagne, C., McClure, L., et al. 2025, arXiv e-prints, arXiv:2507.12234. https://arxiv.org/abs/2507.12234

Kim, Y., Jewitt, D., Mutchler, M., et al. 2020, Astrophysical Journal Letters, 895, L34, doi: 10.3847/2041-8213/ab9228

Landau, D., Donitz, B., & Karimi, R. 2023, Acta Astronautica, 206, 133, doi: 10.1016/j.actaastro.2023.02.021

Lauretta, D. S., Balram-Knutson, S. S., Beshore, E., et al. 2017, Space Science Reviews, 212, 925, doi: 10.1007/s11214-017-0405-1

Leeghim, H. 2013, Celestial Mechanics and Dynamical Astronomy, 115, 1, doi: 10.1007/s10569-012-9448-5

Lingam, M., Hein, A. M., & Eubanks, T. M. 2023, Acta Astronautica, 212, 517, doi: 10.1016/j.actaastro.2023.07.030

Lintott, C., Bannister, M. T., & Mackereth, J. T. 2022, The Astrophysical Journal, 924, L1, doi: 10.3847/2041-8213/ac41d5

Loeb, A. 2025, arXiv e-prints, arXiv:2507.05881, doi: 10.48550/arXiv.2507.05881

Loeb, A., Hibberd, A., & Crowl, A. 2025, arXiv e-prints, arXiv:2507.21402, doi: 10.48550/arXiv.2507.21402

Mages, D., Landau, D., Donitz, B., & Bhaskaran, S. 2022, Acta Astronautica, 191, 359, doi: 10.1016/j.actaastro.2021.11.012

Mamajek, E. 2017, Research Notes of the American Astronomical Society, 1, 21, doi: 10.3847/2515-5172/aa9bdc

Martinez-Palomera, J., Tuson, A., Hedges, C., et al. 2025, arXiv e-prints, arXiv:2508.02499. https://arxiv.org/abs/2508.02499

Marčeta, D. 2023, Astronomy and Computing, 42, 100690, doi: 10.1016/j.ascom.2023.100690

McKay, A. J., Cochran, A. L., Dello Russo, N., & DiSanti, M. A. 2020, Astrophysical Journal Letters, 889, L10, doi: 10.3847/2041-8213/ab64ed

Meech, K. J., Weryk, R., Micheli, M., et al. 2017, Nature, 552, 378, doi: 10.1038/nature25020

Michel, P., Küppers, M., Bagatin, A. C., et al. 2022, Planetary Science Journal, 3, 160, doi: 10.3847/PSJ/ac6f52

Micheli, M., Farnocchia, D., Meech, K. J., et al. 2018, Nature, 559, 223, doi: 10.1038/s41586-018-0254-4

Miller, D., Duvigneaud, F., Menken, W., Landau, D., & Linares, R. 2022, Acta Astronautica, 200, 242, doi: 10.1016/j.actaastro.2022.07.053

Moore, K., Courville, S., Ferguson, S., et al. 2021, Planetary and Space Science, 197, 105137, doi: https://doi.org/10.1016/j.pss.2020.105137

Moro-Martín, A., Turner, E. L., & Loeb, A. 2009, Astrophysical Journa, 704, 733, doi: 10.1088/0004-637X/704/1/733

Opitom, C., Snodgrass, C., Jehin, E., et al. 2025, arXiv e-prints, arXiv:2507.05226, doi: 10.48550/arXiv.2507.05226

Prockter, L., Murchie, S., Cheng, A., et al. 2002, Acta Astronautica, 51, 491, doi: 10.1016/S0094-5765(02)00098-X

Puzia, T. H., Rahatgaonkar, R., Carvajal, J. P., Nayak, P. K., & Luco, B. 2025, arXiv e-prints, arXiv:2508.02777. https://arxiv.org/abs/2508.02777

Rein, H., & Liu, S. F. 2012, A&A, 537, A128, doi: 10.1051/0004-6361/201118085

Rein, H., Hernandez, D. M., Tamayo, D., et al. 2019, MNRAS, 485, 5490, doi: 10.1093/mnras/stz769

Reinhard, R. 1986, in Field, Particle and Wave Experiments on Cometary Missions, ed. K. Schwingenschuh, W. Riedler, & J. Ortner, 119–142

Reinhard, R. 1987, Journal of Physics E Scientific Instruments, 20, 700, doi: 10.1088/0022-3735/20/6/029

Rizk, B., Drouet d'Aubigny, C., Golish, D., et al. 2018, Space Science Reviews, 214, 26, doi: 10.1007/s11214-017-0460-7

Sanchez, J. P., & Snodgrass, C. 2025, Research Notes of the AAS, 9, 207, doi: 10.3847/2515-5172/adf4c4

Santana-Ros, T., Ivanova, O., Mykhailova, S., et al. 2025, arXiv e-prints, arXiv:2508.00808, doi: 10.48550/arXiv.2508.00808

Saunders, R. S., Arvidson, R. E., Badhwar, G. D., et al. 2004, SSRv, 110, 1, doi: 10.1023/B:SPAC.0000021006.84299.18

Scheeres, D. J., McMahon, J. W., Bierhaus, E. B., et al. 2021, in 7th IAA Planetary Defense Conference, 55

Seligman, D., & Laughlin, G. 2018, The Astronomical Journal, 155, 217, doi: 10.3847/1538-3881/aabd37

Seligman, D. Z., Becker, J., Adams, F. C., Feinstein, A. D., & Rogers, L. A. 2022a, ApJL, 933, L7, doi: 10.3847/2041-8213/ac786e

Seligman, D. Z., Rogers, L. A., Cabot, S. H. C., et al. 2022b, PSJ, 3, 150, doi: 10.3847/PSJ/ac75b5

Seligman, D. Z., Micheli, M., Farnocchia, D., et al. 2025, arXiv e-prints, arXiv:2507.02757, doi: 10.48550/arXiv.2507.02757

Siraj, A., Loeb, A., Moro-Martín, A., et al. 2023, Journal of Astronomical Instrumentation, 12, 2340001, doi: 10.1142/S2251171723400019

Snodgrass, C., & Jones, G. H. 2019, Nature Communications, 10, 5418, doi: 10.1038/s41467-019-13470-1

Stern, S. A., Protopapa, S., Freeman, M., et al. 2024, Planet. Space Sci., 241, 105850, doi: 10.1016/j.pss.2024.105850

Tamayo, D., Rein, H., Shi, P., & Hernandez, D. M. 2020, MNRAS, 491, 2885, doi: 10.1093/mnras/stz2870

Taylor, A. G., & Seligman, D. Z. 2025, arXiv e-prints, arXiv:2507.08111. https://arxiv.org/abs/2507.08111

Tonry, J. L., Denneau, L., Heinze, A. N., et al. 2018, PASP, 130, 064505, doi: 10.1088/1538-3873/aabadf

Trilling, D. E., Mommert, M., Hora, J. L., et al. 2018, Astronomical Journal, 156, 261

Vandaele, A. C., Neefs, E., Drummond, R., et al. 2015, Planet. Space Sci., 119, 233, doi: 10.1016/j.pss.2015.10.003

Watanabe, S.-i., Tsuda, Y., Yoshikawa, M., et al. 2017, Space Science Reviews, 208, 3, doi: 10.1007/s11214-017-0377-1

Williams, G. V., Sato, H., Sarneczky, K., et al. 2017, Central Bureau Electronic Telegrams, 4450, 1

Xing, Z., Oset, S., Noonan, J., & Bodewits, D. 2025, arXiv e-prints, arXiv:2508.04675. https://arxiv.org/abs/2508.04675

Yang, B., Meech, K. J., Connelley, M., & Keane, J. V. 2025, arXiv e-prints, arXiv:2507.14916, doi: 10.48550/arXiv.2507.14916

Yang, B., Li, A., Cordiner, M. A., et al. 2021, Nature Astronomy, doi: 10.1038/s41550-021-01336-w

Ye, Q., Kelley, M. S. P., Bolin, B. T., et al. 2020, Astronomical Journal, 159, 77, doi: 10.3847/1538-3881/ab659b

Ye, Q.-Z., Zhang, Q., Kelley, M. S. P., & Brown, P. G. 2017, Astrophysical Journal Letters, 851, L5, doi: 10.3847/2041-8213/aa9a34

Yoshikawa, M., Kawaguchi, J., Fujiwara, A., & Tsuchiyama, A. 2021, in Sample Return Missions: The Last Frontier of Solar System Exploration, ed. A. Longobardo (Elsevier), 123–147, doi: 10.1016/B978-0-12-818330-4.00006-9

Zurek, R. W., & Smrekar, S. E. 2007, Journal of Geophysical Research (Planets), 112, E05S01, doi: 10.1029/2006JE002701