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Astrometry with Interplanetary Spacecraft: Determination of the Non-Gravitational Accelerations of the Interstellar Object 3I/ATLAS

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ABSTRACT

Here, we report on the results of adding 6 observations from 2 interplanetary spacecraft to the orbit determination of 3I/ATLAS, the third known Interstellar Object (ISO). These observations, from vantage points and times impossible with terrestrial instruments, reduce the formal errors on the non-gravitational acceleration parameters formal errors by 20% to 40% compared to solutions using just the terrestrial data available from May-Dec. 2025. Using these data we find significant non-gravitational accelerations (NGAs) in the 3I/ATLAS trajectory, with a vector magnitude scaled to 1 au of (89.3 $\pm$ 4.6) $\times 10^{-9}$ au day^{-2}, and a time offset (ΔT) of -34.60 $\pm$ 2.62 days (i.e., an acceleration peaking $\sim$one month before perihelion). This leads to a rough mass estimate for 3I/ATLAS of 44 million tons in early August, 2025, equivalent to a CO_2 dominated nucleus radius $r_n \lesssim 374$ m.

Keywords: Exocomets (2368) – Interstellar objects (52) — Comet dynamics (2213)

1. INTRODUCTION

ISO orbit determination provides important scientific information about both the origin of ISOs, from their kinematics, and their nuclear properties, from their acceleration (M. Micheli et al. 2018). T. M. Eubanks et al. (2025) suggested that these determinations be improved by observations by interplanetary spacecraft, which was done for 3I/ATLAS with initial results being presented here.

2. NON-GRAVITATIONAL ACCELERATIONS

Outgassing thrust from sublimating CO, CO_2, and H_2O can cause noticeable cometary NGAs (B. G. Marsden et al. 1973), commonly modeled by constant parameters times a scaling term, g(r), dependent on the heliocentric distance r(t), with g(1 au) = 1. The solve-for parameters are A_i, where $i = 1, 2, 3$ denote radial, transverse and perpendicular to the orbital plane accelerations, respectively. The 3I coma is CO_2 dominated (M. A. Cordiner et al. 2025), and we g(r) $\propto \frac{1}{r^2}$, as this is more appropriate for CO_2. The fit model also allows for a time offset ΔT to g(r(t)), yielding g'(r(t)) = g(r(t + ΔT)) and shifting the peak outgassing to before or after perihelion, depending on the sign of ΔT

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(S. R. Chesley & D. K. Yeomans 2005).

Table 1 provides *Find_Orb* solutions for all three known ISOs using Minor Planet Center Database results. These all show significant in-plane accelerations, while 3I/ATLAS also has a strongly significant out of plane (A_3) acceleration, possibly providing information on the inclination of its rotation pole. While there is insufficient 1I data to meaningfully estimate ΔT, and the 2I/Borisov ΔT estimate is consistent with zero, the 3I/ATLAS solutions also produce a significant ΔT adjustment, and the variation between different solutions is significantly reduced.

	Data	NGAs				χ^2
		A_1	A_2	A_3	ΔT	
		10^{-9} au day^{-2}	10^{-9} au day^{-2}	10^{-9} au day^{-2}	day	
1I	M	245.5 ± 8.0				941.7 (1 d.f.)
1I	E	169.4 ± 25.7	-60.0 ± 20.0	15.38 ± 5.97		59.0 (3 d.f.)
1I	E	139.7 ± 85.4	-48.0 ± 27.7	13.0 ± 8.0	6.68 ± 18.50	8.4 (4 d.f.)
2I	E	35.90 ± 2.20	21.28 ± 4.48	-4.18 ± 1.59		295.8 (3 d.f.)
2I	E	35.44 ± 2.22	24.20 ± 5.62	-1.27 ± 3.37	-23.4 ± 21.2	260.0 (4 d.f.)
3I	E	-46.48 ± 4.42	113.39 ± 7.23	-5.26 ± 0.36		574.7 (3 d.f.)
3I	E+P	6.00 ± 3.30	97.40 ± 7.15	-5.79 ± 0.36		451.8 (3 d.f.)
3I	E+TGO	8.34 ± 3.58	60.54 ± 6.92	-7.13 ± 0.35		489.4 (3 d.f.)
3I	E+P+TGO	16.95 ± 3.17	66.76 ± 6.71	-6.90 ± 0.35		522.4 (3 d.f.)
3I	E	-22.82 ± 4.55	92.21 ± 6.32	-4.11 ± 0.22	-34.00 ± 3.99	650.1 (4 d.f.)
3I	E+P	-20.89 ± 3.21	86.33 ± 4.12	-4.28 ± 0.19	-30.60 ± 2.51	1137.5 (4 d.f.)
3I	E+TGO	-25.89 ± 4.43	94.50 ± 4.35	-4.06 ± 0.19	-37.10 ± 2.80	1158.6 (4 d.f.)
3I	E+P+TGO	-23.10 ± 3.71	86.19 ± 3.74	-4.26 ± 0.18	-34.60 ± 2.62	1286.7 (4 d.f.)

Table 1. NGAs The 1I/'Oumuamua M solution is from (M. Micheli et al. 2018), while solutions here used 111 of 113 observations from 2017 Oct. 18 to 2018 Jan. 2 with root mean square (rms) residuals of 0.11". The 2I/Borisov solution used 2117 of 2788 observations from 2019 Mar. 17 to 2020 Apr. 28 with rms residuals of 0.11", and the full 3I/ATLAS solution used 4194 of 4836 observations from May 8 to Dec. 1, 2025 with an rms residual 1.49". The E data set includes all ground based optical data plus astrometry from the TESS and HST satellites, P represents the E data plus 2 Psyche points, on Sep. 8, and Oct. 29, and TGO the E data plus 4 Trace Gas Orbiter data points on Oct. 3; the errors assigned to these spacecraft measurements are 20", 0.25", 2" and 4", respectively.

3. ESTIMATION OF THE 3I/ATLAS MASS

The presence of significant NGAs permits derivation of the mass of 3I/ATLAS (A. Sosa & J. A. Fernández 2009), by:

$$Ma = \frac{dM}{dt} v, \tag{1}$$

where a is the magnitude of the NGA, $\frac{dM}{dt}$ the total rate of mass loss due to outgassing and v the velocity of these gases, which depends on the molecular mass of the principal gas being ejected (CO_2 for 3I/ATLAS)

$$v = \zeta \left(\frac{8kT}{\pi m} \right)^{\frac{1}{2}}, \tag{2}$$

with k being the Boltzmann Constant, T is the temperature in Kelvin, m the molecular mass of the gas, here 7.38×10^{-26} and ζ a constant $\sim 0.5 - 0.6$, yielding $v \sim 155$ m s^{-1}.

JWST observations in early Aug. 2025 (M. A. Cordiner et al. 2025) yield $\frac{dM}{dt} \sim 150$ kg s^{-1} at 3.3 au from the Sun, assuming an inverse-square production rate. From Table 1 (row 6) $a = 8.9 \times 10^{-8}$ au day^{-2} on 2025 Sep 24, at 1.8 au from the Sun. Adjustment for Sun-3I distance gives $a \sim 2.6 \times 10^{-8}$ au day^{-2} (i.e. $\sim 5.3 \times 10^{-7}$ m s^{-2}). From equation 1:

$$M \sim 4.4 \times 10^{10} \text{ kg}, \tag{3}$$

or 44 million metric tons. Comet density estimates are in the range 200 - 600 kg m^{-3} (M. Tatsuuma et al. 2024), implying a 3I nuclear radius of 260 to 374 m.

4. DISCUSSION

Our calculation of the 3I radius, 260 m $< r_{3I} <$ 374 m, is within the limits on 3I's size determined by D. Jewitt et al. (2025) from Hubble observations, 220 m $< r_{3I} <$ 2.8km. The nuclear radius of the previous interstellar comet 2I/Borisov was estimated to be 200 m $< r_{2I} <$ 500 m (D. Jewitt et al. 2020), comparible in size to our 3I/ATLAS radius estimate.

5. CONCLUSIONS

We find that the astrometry of ISO 3I/ATLAS reveals significant NGA in all three components of its acceleration, and also a significant shift in the time of peak acceleration, implying a 3I/ATLAS mass of ∼44 million tons. The results shown here will be substantially improved by the addition of five additional spacecraft data sets acquired in Oct. and Nov., 2025, but not yet processed.

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Software: *Find_Orb* (B. Gray 2022)

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