



# NSF-DOE Vera C. Rubin Observatory Observations of Interstellar Comet 3I/ATLAS (C/2025 N1)

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## Abstract

We report on the observation and measurement of astrometry, photometry, morphology, and activity of the interstellar object 3I/ATLAS, also designated C/2025 N1 (ATLAS) with the NSF-DOE Vera C. Rubin Observatory. Comet 3I/ATLAS, the third known interstellar object, was discovered on UT 2025 July 1. Rubin Observatory had coincidentally collected images of the object’s region of the sky during routine commissioning. Facilitated by Rubin’s high resolution and large aperture, we successfully recovered object detections from Rubin observations spanning UT 2025 June 21 (10 days before discovery, when 3I/ATLAS was 4.5 au from the Sun) through the date of discovery, and we acquired additional images through UT 2025 July 20 as part of commissioning. We measure on-sky locations of 3I/ATLAS in Rubin *ugrizy* bands, with a typical precision of  $\sim 70$  mas, and briefly describe the reason this is coarser than our measured static source astrometric precision of  $\sim 3$  mas in Rubin images. We measure *grizy* magnitudes of 3I/ATLAS photometry at  $\sim 0.01$  mag precision, detecting no short-term photometric variability above 0.01 mag. We derive an estimated near-nucleus dust-to-nucleus scattering cross-sectional ratio of  $\eta \gtrsim 13$  on UT 2025 July 2 based on Rubin photometry and an upper limit nucleus size computed from Hubble Space Telescope observations. We find Rubin colors of  $g - r = (0.657 \pm 0.013)$  mag,  $r - i = (0.235 \pm 0.018)$  mag,  $i - z = (0.147 \pm 0.042)$  mag, and  $z - y = (0.047 \pm 0.052)$  mag. These data represent the earliest observations of this object by a large ( $\gtrsim 8$  m class) telescope and illustrate the type of measurements (and discoveries) Rubin’s Legacy Survey of Space and Time will provide after it begins in early 2026.

*Unified Astronomy Thesaurus concepts:* [Interstellar objects \(52\)](#); [Comets \(280\)](#); [Comae \(271\)](#); [Comet dust tails \(2312\)](#); [Comet nuclei \(2160\)](#); [Comet origins \(2203\)](#); [Comet tails \(274\)](#)

*Materials only available in the online version of record:* [animation](#), [machine-readable table](#)

## 1. Introduction

### 1.1. Background

Interstellar objects (ISOs) are small bodies detected in the solar system but not gravitationally bound to the Sun. They are presumed to be passing through our planetary system but to have originated in exoplanetary systems in our Galaxy. Studies of these objects can reveal the bulk compositions and surface processing of extrasolar planetesimals, as well as the dynamical footprints of the planetary systems that ejected them (A. Moro-Martín 2022; D. Z. Seligman & A. Moro-Martín 2022; D. Jewitt & D. Z. Seligman 2023; A. Fitzsimmons et al. 2024). However, our knowledge of this population remains sparse, as only three have been identified: 1I/‘Oumuamua (G. V. Williams et al. 2017), 2I/Borisov (G. Borisov et al. 2019), and now, 3I/ATLAS (Figure 1), discovered on UT 2025 July 1 (L. Denneau et al. 2025).

The first ISO, 1I/‘Oumuamua, discovered in 2017 October, did not show any visible coma or outgassing (D. Jewitt et al. 2017; K. J. Meech et al. 2017; Q. Z. Ye et al. 2017; D. E. Trilling et al. 2018), yet the object exhibited significant nongravitational acceleration (M. Micheli et al. 2018; ‘Oumuamua ISSI Team et al. 2019) and an unusually large

light-curve amplitude indicating an elongated or flattened, tumbling shape (M. T. Bannister et al. 2017; M. Drahus et al. 2017; M. M. Knight et al. 2017; M. J. S. Belton et al. 2018; B. T. Bolin et al. 2018; W. C. Fraser et al. 2018; A. McNeill et al. 2018; S. Mashchenko 2019; D. E. Vavilov & Y. D. Medvedev 2019). 2I/Borisov, discovered in 2019 August, became the second ISO identified in our solar system. In contrast to 1I/‘Oumuamua’s visibly inert nature, 2I/Borisov displayed a pronounced dust and gas coma, making it the first interstellar comet (A. Fitzsimmons et al. 2019; D. Jewitt & J. Luu 2019; B. T. Bolin et al. 2020; 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; S. E. Deam et al. 2025; J. de León et al. 2019, 2020). Unlike other inner solar system comets, 2I/Borisov had a much higher CO/H<sub>2</sub>O abundance ratio (D. Bodewits et al. 2020; M. A. Cordiner et al. 2020).

### 1.2. 3I/ATLAS

The third ISO, 3I/ATLAS, also designated C/2025 N1 (ATLAS), was first identified on UT 2025 July 1 (L. Denneau et al. 2025) by the Asteroid Terrestrial-impact Last Alert System (ATLAS; J. L. Tonry et al. 2018). It quickly became clear that the object was of interstellar origin, with an eccentricity exceeding 6.<sup>152</sup> Numerous follow-up observers quickly identified the presence of a faint cometary tail, establishing the object as a weakly active cometary body (e.g., M. R. Alarcon et al. 2025; S. Deen et al. 2025; D. Jewitt

<sup>148</sup> DiRAC Post-doctoral Fellow.<sup>149</sup> LSST-DA Catalyst Postdoctoral Fellow.<sup>150</sup> NSF Astronomy and Astrophysics Postdoctoral Fellow.<sup>151</sup> Author is deceased.<sup>152</sup> [https://ssd.jpl.nasa.gov/tools/sbdb\\_lookup.html#/?sstr=C%2F2025%20N1](https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=C%2F2025%20N1)

& J. Luu 2025). Multifilter imaging and spectroscopy by multiple observers (A. Alvarez-Candal et al. 2025; B. T. Bolin et al. 2025; C. Champagne et al. 2025; R. de la Fuente Marcos et al. 2025; C. Opitom et al. 2025; D. Z. Seligman et al. 2025) indicated that the object had a moderately red spectral gradient of  $S' \sim 18\%/100 \text{ nm}$ , at least some of which was likely due to a dust coma given the object’s visible activity at the time of those observations.

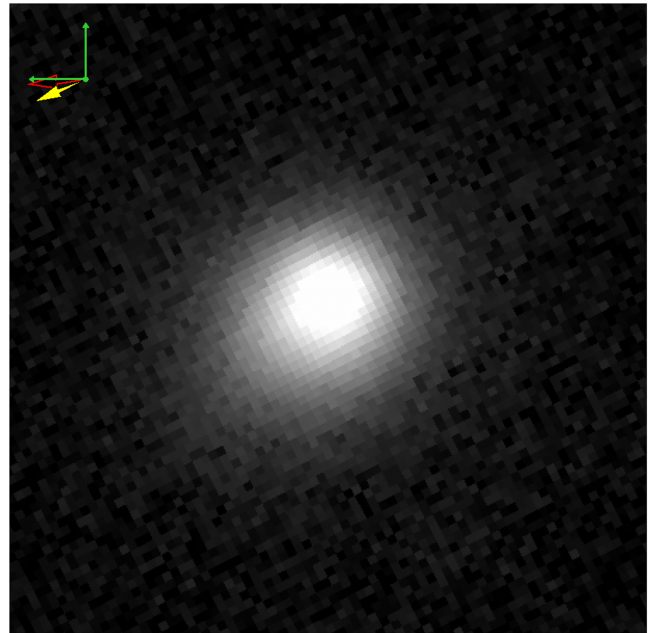
Meanwhile, no gas emission was detected in Very Large Telescope Multi Unit Spectroscopic Explorer observations on UT 2025 July 3 (C. Opitom et al. 2025), when the object was at a heliocentric distance of  $r_h = 4.47 \text{ au}$ . B. T. Bolin et al. (2025) computed 3I/ATLAS, then at  $r_H = 4.43 \text{ au}$ , had a non-nucleus-subtracted  $A(0^\circ)f\rho$  of  $280.8 \pm 3.2 \text{ cm}$  and estimated a dust mass-loss rate of  $0.1\text{--}1.0 \text{ kg s}^{-1}$ , noting that this level of activity was comparable to that of 2I/Borisov (G. P. Prodan et al. 2024) but far exceeding that of 1I/‘Oumuamua.

Nucleus measurements have also been attempted, but should be regarded with caution, given the object’s visible activity. D. Z. Seligman et al. (2025) used precovery observations obtained by the Zwicky Transient Facility (ZTF) on UT 2025 May 22 to derive a lower-limit V-band absolute magnitude of  $H_V = 12.4 \text{ mag}$ , corresponding to an upper-limit effective radius of  $r_n \sim 10 \text{ km}$ , assuming a comet-like albedo ( $p_V = 0.05$ ). However, the strongest constraint on the nucleus size to date is likely provided by D. Jewitt et al. (2025), who constrained the nucleus size to  $r \leq 2.8 \text{ km}$  based on a fit to the surface brightness distribution of the inner coma as observed by the Hubble Space Telescope (HST) on UT 2025 July 21. The discrepancy between these size estimates indicates that there was already substantial coma present at the time of those early ZTF precovery observations.

D. Z. Seligman et al. (2025) reported measured  $g' - r'$  colors from ZTF precovery data that were nearly solar, suggesting that the object’s nucleus may be less red than the ejected dust, given later observations (which include increased flux contributions from a by-then detectable coma) of redder spectral slopes for the object. However, as the ZTF multifilter observations were not simultaneous (and therefore subject to potential light-curve variability), and substantial unresolved coma is present even in those earlier data (as discussed above), these results should be regarded as uncertain.

Meanwhile, time-series observations have revealed a largely flat light curve (amplitude  $< 0.2 \text{ mag}$ ; e.g., C. Champagne et al. 2025; R. de la Fuente Marcos et al. 2025; D. Z. Seligman et al. 2025), suggesting that the object could be nearly spherical, the rotational pole could be close to the line of sight with respect to the Earth, nucleus rotational light-curve variations might be damped by a nearly steady-state coma, or a combination of all of these factors. Given that substantial coma was already present by the time 3I was discovered, however, the most likely explanation is that reported time-series photometry was dominated by relatively steady-state coma flux with minimal to no signatures of any rotational variation from the nucleus.

Based on the published data from the ATLAS survey’s discovery of 3I/ATLAS at the time, A. Loeb (2025) noted that 3I/ATLAS’s earlier estimated nucleus size of  $r_n \sim 10 \text{ km}$  implies a local number density  $n_0 \sim 3 \times 10^{-4} \text{ au}^{-3}$ , which would overproduce interstellar mass. (Note that D. Jewitt et al. 2025, with HST, later found  $0.22 < r_n < 2.8 \text{ km}$ .) To resolve



**Figure 1.** 3I/ATLAS minimum coaddition from UT 2025 July 3,  $21 \times 30 \text{ s}$   $r$ -band images acquired by NSF-DOE Vera C. Rubin Observatory. The field of view (FOV) is  $\sim 15'' \times 15''$ , with north up and east left. The antisolar (yellow arrow) and antimotion (red-outlined black arrow) directions are shown.

this mass-budget conflict, they concluded that 3I/ATLAS must either be a comet with a small nucleus ( $r_n \lesssim 0.6 \text{ km}$ ) or a rare  $\sim 10 \text{ km}$  body with  $n_0 \lesssim 5 \times 10^{-8} \text{ au}^{-3}$ . D. Z. Seligman et al. (2025) concluded that 3I/ATLAS has a number density  $n_0 \sim 10^{-3} \text{ au}^{-3}$ .

M. J. Hopkins et al. (2025) made use of Gaia DR3 and 3I/ATLAS’s orbital arc (fit as of 2025 July 3) to show 3I/ATLAS’s velocity is outside of the main moving-group structures in the Ōtautahi–Oxford ISO model, unlike those of 1I/‘Oumuamua and 2I/Borisov. 3I/ATLAS has a high velocity perpendicular to the Galactic plane, creating its unusually southern direction of approach for an ISO. They rule out any common origin with 1I/‘Oumuamua or 2I/Borisov based on kinematic exclusion, and derive a broad age range for 3I/ATLAS as most likely older than 7 Gyr, underscoring the large uncertainty in ISO age estimates (D. Marčeta & D. Z. Seligman 2023; M. J. Hopkins et al. 2025); this age is supported by the subsequent  $\sim 3\text{--}11 \text{ Gyr}$  estimate of A. G. Taylor & D. Z. Seligman (2025).

## 2. The Vera C. Rubin Observatory

The NSF-DOE Vera C. Rubin Observatory (Ž. Ivezić et al. 2019)<sup>153</sup> resides atop Cerro Pachón in Chile, hosting the 8.4 m Simonyi Survey Telescope (B. Stalder et al. 2024). It is equipped with the 3.2 gigapixel Legacy Survey of Space and Time (LSST) Camera (LSSTCam; SLAC National Accelerator Laboratory & NSF-DOE Vera C. Rubin Observatory 2025; A. Roodman et al. 2024), which covers a  $9.6 \text{ deg}^2$  field of view (FOV sampled at  $0.2''$  per pixel to a depth of  $m_r \sim 24$  with a 30 s exposure. Rubin Observatory (site code X05) will begin LSST, an ambitious 10 yr imaging survey of the southern sky, in early 2026. Ž. Ivezić et al. (2019) provided an overview of

<sup>153</sup> <https://rubinobservatory.org>

Rubin and LSST, including the science drivers that led to its specific configuration. During its main survey, LSST will obtain observations from near-UV to near-IR (*ugrizy* band-passes) with approximately 30 s exposures, imaging the entire visible southern sky repeatedly every few nights. F. B. Bianco et al. (2022) provided a more detailed overview of the survey strategy.

Rubin Observatory, which began acquiring images with the full LSSTCam in 2025 April, was in its commissioning period, carrying out science validation (SV) observations, until the end of 2025 (see C. Claver et al. 2025). During this period, data quality and acquisition rate were variable. Summit systems, including the Active Optics System, were still being refined, and observing procedures, such as interrupts for target of opportunity (ToO; Figure A3), were still being tested. Not all data products that will be available during LSST are currently available. In particular, the SV survey has not yet progressed far enough to have sufficient images available to create templates for difference imaging across its footprint.

The SV survey began limited operations on 2025 June 20, running for approximately 50% of the available nightly telescope time and covering approximately 1447 deg<sup>2</sup>. This first night of the SV survey coincidentally covered the position of 3I/ATLAS—the first detection of 3I/ATLAS (and any ISO) with Rubin (Figure 2 (a)). This observation along with the following nights (UT 2025 June 21–24) provide the earliest high-resolution, deep observations of 3I/ATLAS and a unique opportunity to study its brightness and morphology at larger distances before its perihelion passage (UT 2025 October 29).

### 3. Observations

In order to search for 3I/ATLAS in Rubin data, we derived interpolated and extrapolated 3I/ATLAS positions from the ephemeris provided by the JPL Scout service (D. Farnocchia et al. 2016)—while 3I/ATLAS was on the Minor Planet Center (MPC) Near-Earth Object Confirmation Page with the designation A11pl3Z. We executed this once for the date/time of every LSSTCam and LSST Commissioning Camera (LSSTComCam; SLAC National Accelerator Laboratory & NSF-DOE Vera C. Rubin Observatory 2024) visit from the Rubin exposure table, which includes science and non-science (e.g., engineering) images. For each visit, we checked to see if 3I/ATLAS was within  $\sim 9^\circ$  of any of the pointing (boresight) center on-sky coordinates. In addition, we used the available astrometric data from Scout before UT July 2 to re-fit the orbit using the orbit fitting software *Layup*. These solutions were used to propagate 3I/ATLAS’s ephemerides to all LSSTCam visits using the survey simulation software *Sorcha* (M. J. Holman et al. 2025; S. R. Merritt et al. 2025) and the publicly available *lsstcam\_20250930* cadence simulation (C. Claver et al. 2025; L. P. Guy et al. 2025).

For the *Sorcha* simulations, we generated a synthetic 3I/ATLAS, adopting this best-fit set of orbital elements together with the slope-inferred colors (measured colors were not yet available) in Section 5.3.3, an absolute magnitude  $H_r = 12.5$ , and a phase curve parameter  $G = 0.15$ . Given the uncertainty in how 3I/ATLAS sublimation and dust production vary with changing heliocentric distances at the time of writing, we made no attempt to model the flux enhancement from reflected sunlight by 3I/ATLAS’s coma/tail and model 3I/ATLAS’s apparent brightness as an airless nonactive body.

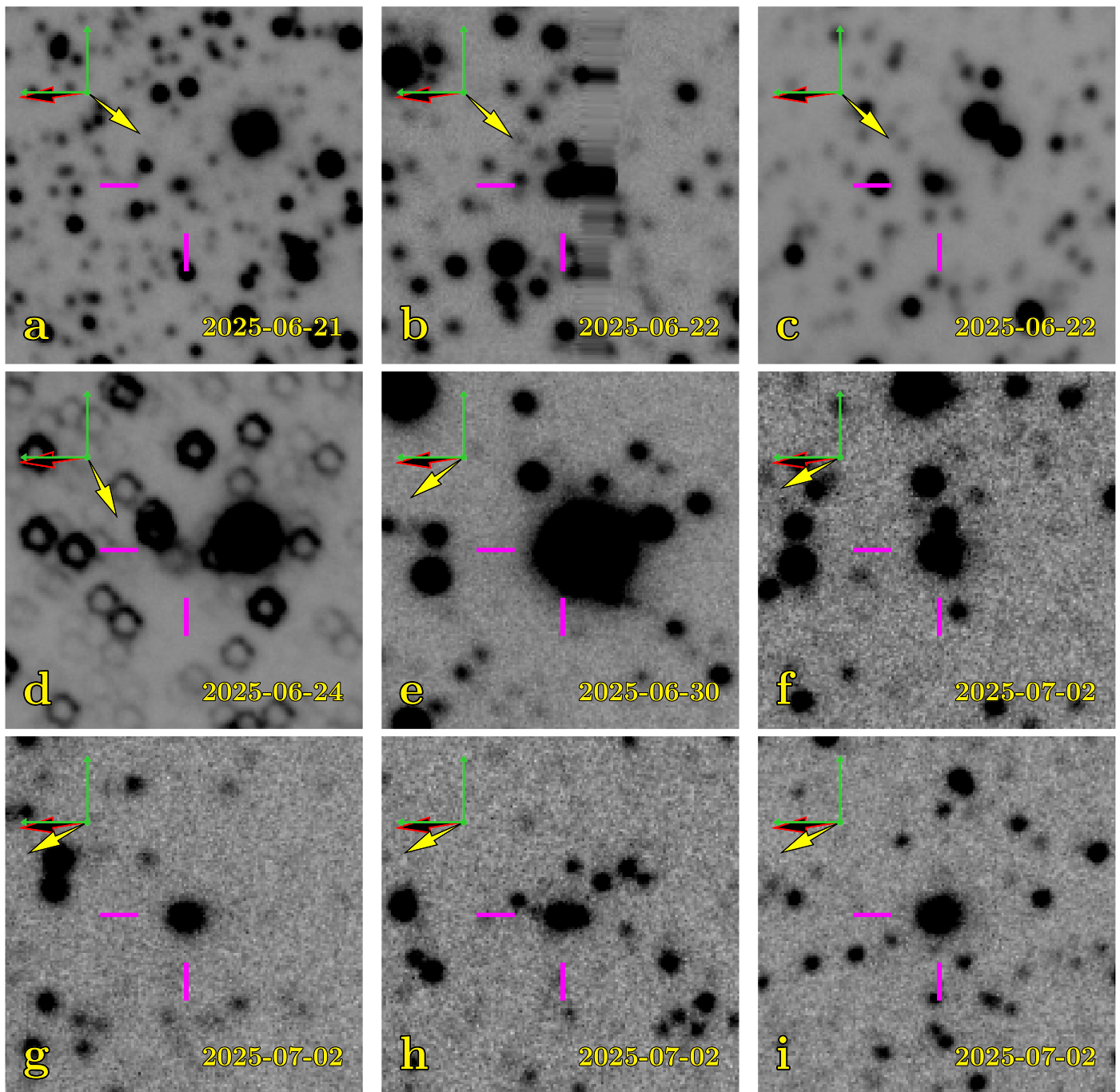
This configuration successfully reproduces all existing SV detections, and the cumulative sky-map of these detections is shown in Figure 3 (an animation is available). When the simulation was extended forward using the actual SV cadence, incorporating weather losses, maintenance downtime, and the evolving on-sky geometry of 3I/ATLAS relative to Rubin, *Sorcha* shows that 3I/ATLAS does not enter any further accessible SV pointings after UT 2025 July 20. Both methodologies used here to identify 3I/ATLAS therefore confirm that all recoverable appearances of 3I/ATLAS in the SV data have already been obtained.

In total, we identified nine SV observations that serendipitously contained 3I/ATLAS within detector bounds between UT 2025 June 21 and UT 2025 July 2 (the serendipitous observations time span), although several of these detections are significantly blended with background sources (Figure 2). An additional 32 images (Figure A1) were acquired on UT 2025 July 3 during camera calibration procedures, where a composite image constructed from these data is shown in Figure 1. That sequence was a planned part of test operations for that night, but—noticing the opportunity—the Observing Specialist shifted the telescope pointing to coincide with 3I/ATLAS’s position. Additional images were acquired over the next week, some as part of ToO testing (Figure A2). A concerted ToO test with 3I/ATLAS was carried out on UT 2025 July 13 that resulted in over 35 images spanning numerous filters (Figure A3). Several additional nights of observations serendipitously captured 3I/ATLAS between the following night (UT 2025 July 14), with the final images acquired UT 2025 July 20 (Figure A4).

Details of all observations, including information about observing geometry, are summarized in Table 1, where we note that, unless stated otherwise, all date/times are given in UTC. Rubin Observatory records observations in Temps Atomique International (TAI), which does not account for leap seconds. Throughout this manuscript, TAI is UTC + 37 s for all stamps; additional Rubin time information is available in J. Hobbitt & A. Thebo (2022). In all cases, we used comparison observations of the areas of the sky where 3I/ATLAS was detected at times when the object was absent to verify the correct identification of each candidate detection.

### 4. Data Processing

Rubin’s observing facilities are designed to be supported by a largely automated data management system (M. Jurić et al. 2017). Once the LSST survey begins, products enabling solar system science, including moving object detection, image differencing, astrometry, photometry, and morphological classification (e.g., “extendedness”), will be automatically available on minute-to-daily timescales. Further details on the LSST algorithms and pipelines are provided in Rubin Observatory Science Pipelines Developers (2025) and J. Bosch et al. (2018). Their present performance on LSSTComCam data, which is similar to LSSTCam but smaller in scale, is summarized in Vera C. Rubin Observatory (2025). Detailed information on expected data products can be found in the LSST Data Products Definition Document (M. Jurić et al. 2023) or a summary by M. Graham (2022).

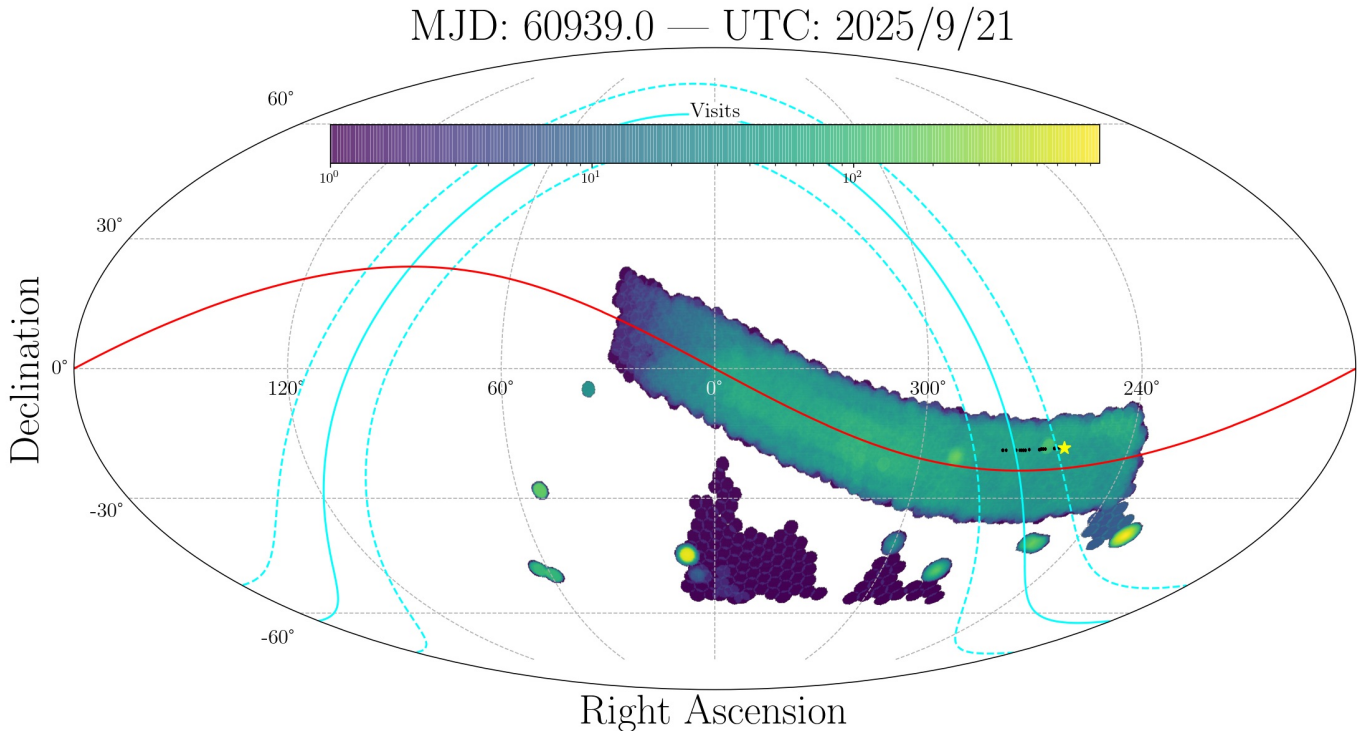


**Figure 2.** Gallery of serendipitous observations of 3I/ATLAS from the NSF-DOE Vera C. Rubin Observatory. All images are  $30'' \times 30''$  and have been reprojected so that north appears up, and east appears to the left (green arrows). The antisolar (yellow, black-outlined arrow) and antimotion (black, red-outlined arrow) directions are indicated. All dates and times are Temps Atomique International (TAI). (a) 2025 June 21 08:11:32. (b) 2025 June 22 02:32:47. An area of roughly vertical saturation masking can be seen near the center of the frame; 3I/ATLAS is not within the masking, but the nearby blended star is. (c) 2025 June 22 03:07:49. (d) 2025 June 24 03:07:46. The image was unintentionally out of focus. (e) 2025 June 30 02:26:26. 3I/ATLAS is adjacent to the saturated star at the center. (f) 2025 July 2 00:44:25. (g) 2025 July 2 01:20:33. (h) 2025 July 2 02:31:16. (i) 2025 July 2 03:33:02.

At the time of 3I/ATLAS’s discovery, only a portion of this system had been deployed and verified. This includes the data acquisition and storage system (allowing Rubin to take and store the images and image metadata) and an automated “Nightly Validation” pipeline supporting daily data reduction for quality assurance purposes that includes instrumental signature removal, World Coordinate System (WCS) determination, and detection of isolated bright ( $>20\sigma$ ) sources. Calibration production pipelines (e.g., for generating and

applying biases, darks, flats, etc.) have also been commissioned. While Rubin’s solar system pipelines have recently been demonstrated with Rubin First Look<sup>154</sup> showcase observations, they were not yet active when 3I/ATLAS was discovered, as it was too early into the SV survey for sufficient data to be available to enable image differencing and, consequently, moving object detection.

<sup>154</sup> <https://rubinobservatory.org/news/rubin-first-look>



**Figure 3.** Sky-map of the final science validation (SV) observations distributions of 3I/ATLAS. The SV here is simulated from recorded pointings already enacted at the time of writing and nominal operations thereafter. The black points represent individual observations of 3I/ATLAS, with the yellow star highlighting its final observation in the SV in UT 2025 July 20. The red solid line marks the ecliptic plane, and the solid and dashed blue lines mark the galactic plane and  $\pm 10^\circ$  from the plane, respectively. (This static figure represents the final frame of an animation available, showing the progression of 3I/ATLAS detections during the nominal SV. Each frame of the animation represents one additional night of observations, with the `HEALPy` sky-map updated accordingly. The plot title updates to reflect the night of each observation, and new black points appear as previous observations and are added to the map. The yellow star moves with each frame, representing the most up-to-date observation of 3I/ATLAS within the SV. The total duration of the animation is  $\sim 28$  s.)

(An animation of this figure is available in the [online article](#).)

For this reason, much of our data reduction in this work has been carried out with custom pipeline runs, custom configurations, with occasional custom-written software to backfill for features not yet commissioned or unavailable for other reasons at the time of 3I/ATLAS’s appearance. In particular, much of our analysis was conducted on science images (rather than difference images) and relied on the Rubin deblender (P. Melchior et al. 2018) to mitigate confusion in crowded regions. As the location of 3I/ATLAS was sufficiently well constrained, we only calibrated images for the  $4k \times 4k$  CCD detector where the object was expected to be, rather than the entire 188 array of detectors that is active in a typical commissioning visit.

For the data presented here, we specifically removed instrument signatures (flats, darks, and biases) from the raw images, fit and subtracted the sky background, computed the WCS solution using the Gaia DR3 catalog, and photometrically calibrated the images. We also ran a dedicated `SingleFrameDetectAndMeasure` LSST pipeline task to detect, deblend, and measure all sources with significance  $> 5\sigma$ . As the fields with 3I/ATLAS were fairly crowded, this task frequently failed to converge due to overly large blends resulting from numerous overlapping sources. This was a software element that had not yet been fully tuned at this stage of Rubin commissioning, and has since been greatly improved as a result of this work. When successful, the measurements of detected sources include both astrometry (centroids) and photometry (both point-spread function, PSF, and aperture

fluxes). Because of the special challenges presented by the data analyzed here, and also to better understand what specialized automated data handling may be required in similar situations in the future, we also performed a more customized photometric analysis (described in detail in Section 5.3.1) to maximize the quality of our 3I/ATLAS-specific results. An example of a successful processing run, including the appearance of a deblended source footprint, is shown in Figure 4.

## 5. Analysis and Results

### 5.1. Astrometry

The Rubin science pipeline stack has not yet been optimized for analyses of crowded fields. As a result, we developed a small custom centroid and magnitude extractor to handle the case of 3I/ATLAS. Our code derives positions by extracting cutouts of  $30 \times 30$  pixels centered at the nominal position of an object and obtaining windowed centroid measurements (XWIN and YWIN) following a procedure analogous to that of the `SEXTRACTOR` (E. Bertin & S. Arnouts 1996) package. These measurements are then translated to celestial coordinates using the full image WCS fitted by the LSST pipelines.

To validate our measurement code, in addition to using it to analyze 3I/ATLAS, we also apply it to stars in images for which the Rubin detection and measurement task successfully obtained a solution, as well as to known asteroids in all images. The star centroids are in excellent agreement with the

**Table 1**  
Table of Observations

Row	Date Midpoint (TAI)	Visit ID	Chip(s)	R.A. <sup>a</sup> (deg)	Decl. <sup>b</sup> (deg)	eRA <sup>c</sup> (arcsec)	eDec <sup>d</sup> (arcsec)	Band	Mag <sup>e</sup>	eMag <sup>f</sup>	Phase <sup>g</sup> (deg)	r <sup>h</sup> (au)
1	2025-06-21 08:11:32	2025062000620	104	276.513300	-18.755701	0.043	0.050	<i>z</i>	...	...	1.630	4.837
2	2025-06-22 02:32:47	2025062100383	38	...	...	...	...	<i>g</i>	...	...	1.470	4.812
3	2025-06-22 03:07:49	2025062100431	38	...	...	...	...	<i>r</i>	...	...	1.465	4.811
4	2025-06-24 03:07:46	2025062300417	77	...	...	...	...	<i>i</i>	...	...	1.120	4.744
5	2025-06-30 02:26:26	2025062900393	9	...	...	...	...	<i>i</i>	...	...	1.684	4.545
6	2025-07-02 00:44:25	2025070100200	119	271.447823	-18.684875	0.084	0.077	<i>i</i>	17.722	0.05	2.233	4.480
7	2025-07-02 01:20:33	2025070100248	119	271.434746	-18.684645	0.063	0.067	<i>z</i>	17.610	0.10	2.240	4.479
8	2025-07-02 02:31:16	2025070100350	119	271.409146	-18.684044	0.050	0.060	<i>z</i>	17.542	0.10	2.255	4.478
9	2025-07-02 03:33:02	2025070100399	119	271.386660	-18.683526	0.049	0.046	<i>i</i>	17.709	0.05	2.268	4.476
10	2025-07-03 01:53:12	2025070200188	6	...	...	...	...	<i>i</i>	...	...	2.557	4.445
11	2025-07-03 03:03:56	2025070200274	6	270.873594	-18.670730	0.039	0.041	<i>z</i>	...	...	2.573	4.444
12	2025-07-03 06:25:00	2025070200479	94	...	...	...	...	<i>r</i>	...	...	2.618	4.439
13	2025-07-03 06:27:17	2025070200480	94	270.798445	-18.668739	0.086	0.100	<i>r</i>	...	...	2.618	4.439
14	2025-07-03 06:32:03	2025070200481	94	270.796728	-18.668700	0.080	0.106	<i>r</i>	17.934	0.03	2.619	4.439
15	2025-07-03 06:36:22	2025070200482	94	270.795081	-18.668671	0.073	0.076	<i>r</i>	17.942	0.03	2.620	4.439
16	2025-07-03 06:48:53	2025070200483	94	270.790488	-18.668570	0.089	0.096	<i>r</i>	17.941	0.03	2.623	4.438
17	2025-07-03 06:49:27	2025070200484	94	270.790243	-18.668547	0.084	0.104	<i>r</i>	17.946	0.03	2.623	4.438
18	2025-07-03 06:50:17	2025070200485	94	270.789975	-18.668545	0.075	0.060	<i>r</i>	17.947	0.03	2.623	4.438
19	2025-07-03 06:50:52	2025070200486	94	270.789724	-18.668519	0.064	0.077	<i>r</i>	17.950	0.03	2.623	4.438
20	2025-07-03 06:51:47	2025070200487	94	270.789388	-18.668523	0.069	0.070	<i>r</i>	17.956	0.03	2.624	4.438
21	2025-07-03 06:52:21	2025070200488	94	270.789171	-18.668512	0.050	0.073	<i>r</i>	17.954	0.03	2.624	4.438
22	2025-07-03 06:53:16	2025070200489	94	270.788852	-18.668532	0.058	0.074	<i>r</i>	17.953	0.03	2.624	4.438
23	2025-07-03 06:53:51	2025070200490	94	270.788645	-18.668511	0.051	0.064	<i>r</i>	17.949	0.03	2.624	4.438
24	2025-07-03 06:54:40	2025070200491	94	270.788325	-18.668504	0.051	0.063	<i>r</i>	17.948	0.03	2.624	4.438
25	2025-07-03 06:55:15	2025070200492	94	270.788133	-18.668489	0.050	0.060	<i>r</i>	17.952	0.03	2.624	4.438
26	2025-07-03 06:58:56	2025070200493	94	270.786767	-18.668463	0.062	0.065	<i>r</i>	17.951	0.03	2.625	4.438
27	2025-07-03 06:59:30	2025070200494	94	270.786568	-18.668443	0.063	0.070	<i>r</i>	17.955	0.03	2.625	4.438
28	2025-07-03 07:00:20	2025070200495	94	270.786210	-18.668402	0.067	0.074	<i>r</i>	17.953	0.03	2.626	4.438
29	2025-07-03 07:00:54	2025070200496	94	270.786006	-18.668399	0.051	0.073	<i>r</i>	17.948	0.03	2.626	4.438
30	2025-07-03 07:01:46	2025070200497	94	270.785735	-18.668441	0.058	0.074	<i>r</i>	17.951	0.03	2.626	4.438
31	2025-07-03 07:02:20	2025070200498	94	270.785494	-18.668414	0.053	0.072	<i>r</i>	17.948	0.03	2.626	4.438
32	2025-07-03 07:07:48	2025070200499	94	270.783508	-18.668359	0.051	0.073	<i>r</i>	17.947	0.03	2.627	4.438
33	2025-07-03 07:08:22	2025070200500	94	...	...	...	...	<i>r</i>	17.962	0.03	2.627	4.438
34	2025-07-03 07:09:07	2025070200501	94	...	...	...	...	<i>r</i>	17.954	0.03	2.627	4.438
35	2025-07-03 07:09:41	2025070200502	94	...	...	...	...	<i>r</i>	17.951	0.03	2.628	4.438
36	2025-07-03 07:10:31	2025070200503	94	...	...	...	...	<i>r</i>	17.952	0.03	2.628	4.438
37	2025-07-03 07:11:05	2025070200504	94	...	...	...	...	<i>r</i>	17.956	0.03	2.628	4.438
38	2025-07-03 07:11:55	2025070200505	94	...	...	...	...	<i>r</i>	17.967	0.03	2.628	4.438
39	2025-07-03 07:12:30	2025070200506	94	...	...	...	...	<i>r</i>	17.955	0.03	2.628	4.438
40	2025-07-03 07:13:19	2025070200507	94	...	...	...	...	<i>r</i>	17.952	0.03	2.628	4.438
41	2025-07-03 07:13:53	2025070200508	94	...	...	...	...	<i>r</i>	17.952	0.03	2.628	4.438
42	2025-07-04 06:36:15	2025070300497	98	270.262204	-18.654113	0.055	0.059	<i>r</i>	...	...	2.944	4.405
43	2025-07-05 01:23:40	2025070400162	137,144	...	...	...	...	<i>y</i>	17.461	0.10	3.204	4.379
44	2025-07-05 01:56:38	2025070400210	137,144	269.827654	-18.641391	0.057	0.064	<i>y</i>	17.476	0.10	3.212	4.379
45	2025-07-06 23:53:08	2025070600062	41	...	...	...	...	<i>y</i>	...	...	3.872	4.315
46	2025-07-07 00:44:03	2025070600140	41	...	...	...	...	<i>y</i>	...	...	3.884	4.314
47	2025-07-12 01:12:32	2025071100318	42	265.854190	-18.488537	0.042	0.043	<i>i</i>	...	...	5.729	4.147

**Table 1**  
(Continued)

Row	Date Midpoint (TAI)	Visit ID	Chip(s)	R.A. <sup>a</sup> (deg)	Decl. <sup>b</sup> (deg)	eRA <sup>c</sup> (arcsec)	eDec <sup>d</sup> (arcsec)	Band	Mag <sup>e</sup>	eMag <sup>f</sup>	Phase <sup>g</sup> (deg)	r <sup>h</sup> (au)
48	2025-07-12 01:46:44	2025071100364	42	...	...	...	...	<i>z</i>	...	...	5.738	4.146
49	2025-07-12 04:39:06	2025071100563	59	265.768030	-18.484531	0.060	0.072	<i>i</i>	...	...	5.784	4.142
50	2025-07-12 05:13:58	2025071100611	59	...	...	...	...	<i>z</i>	...	...	5.794	4.142
51	2025-07-13 00:35:43	2025071200343	93	...	...	...	...	<i>r</i>	...	...	6.102	4.115
52	2025-07-13 03:13:21	2025071200518	30	265.203945	-18.457186	0.085	0.075	<i>g</i>	18.262	0.03	6.145	4.111
53	2025-07-13 03:14:43	2025071200520	3,6	...	...	...	...	<i>g</i>	...	...	6.145	4.111
54	2025-07-13 03:18:35	2025071200522	30	265.201767	-18.457068	0.056	0.060	<i>i</i>	17.389	0.05	6.146	4.111
55	2025-07-13 03:19:57	2025071200524	3,4,6,7	...	...	...	...	<i>i</i>	17.385	0.05	6.147	4.111
56	2025-07-13 03:23:44	2025071200526	30	...	...	...	...	<i>r</i>	17.675	0.03	6.148	4.111
57	2025-07-13 03:25:05	2025071200528	3,4,6,7	...	...	...	...	<i>r</i>	...	...	6.148	4.111
58	2025-07-13 03:28:52	2025071200530	30	...	...	...	...	<i>y</i>	17.204	0.10	6.149	4.111
59	2025-07-13 03:30:13	2025071200532	3,4,6,7	...	...	...	...	<i>y</i>	17.232	0.10	6.150	4.111
60	2025-07-13 03:33:59	2025071200534	30	265.195258	-18.456752	0.059	0.054	<i>z</i>	17.265	0.10	6.151	4.111
61	2025-07-13 03:38:59	2025071200538	30	...	...	...	...	<i>g</i>	18.279	0.03	6.152	4.111
62	2025-07-13 03:39:38	2025071200539	30,31	...	...	...	...	<i>g</i>	18.290	0.03	6.152	4.111
63	2025-07-13 03:44:01	2025071200542	30	...	...	...	...	<i>i</i>	17.402	0.05	6.153	4.111
64	2025-07-13 03:44:39	2025071200543	31	...	...	...	...	<i>i</i>	17.378	0.05	6.154	4.111
65	2025-07-13 03:48:58	2025071200546	30	...	...	...	...	<i>r</i>	17.637	0.03	6.155	4.110
66	2025-07-13 03:49:36	2025071200547	31	...	...	...	...	<i>r</i>	17.664	0.03	6.155	4.110
67	2025-07-13 03:53:56	2025071200550	30	...	...	...	...	<i>y</i>	17.176	0.10	6.156	4.110
68	2025-07-13 03:54:33	2025071200551	31	...	...	...	...	<i>y</i>	17.231	0.10	6.156	4.110
69	2025-07-13 03:58:53	2025071200554	30	265.184742	-18.456200	0.064	0.061	<i>z</i>	17.274	0.10	6.157	4.110
70	2025-07-13 03:59:31	2025071200555	31	...	...	...	...	<i>z</i>	17.258	0.10	6.158	4.110
71	2025-07-13 04:03:46	2025071200558	30	265.182679	-18.456142	0.075	0.074	<i>g</i>	18.268	0.03	6.159	4.110
72	2025-07-13 04:04:24	2025071200559	31	...	...	...	...	<i>g</i>	18.282	0.03	6.159	4.110
73	2025-07-13 04:08:42	2025071200562	30	...	...	...	...	<i>i</i>	17.416	0.05	6.160	4.110
74	2025-07-13 04:09:20	2025071200563	31	...	...	...	...	<i>i</i>	17.371	0.05	6.160	4.110
75	2025-07-13 04:13:34	2025071200566	30	265.178568	-18.455915	0.060	0.058	<i>r</i>	17.611	0.03	6.161	4.110
76	2025-07-13 04:14:11	2025071200567	31	265.178324	-18.455923	0.063	0.061	<i>r</i>	17.656	0.03	6.162	4.110
77	2025-07-13 04:18:26	2025071200570	30	...	...	...	...	<i>y</i>	17.132	0.10	6.163	4.110
78	2025-07-13 04:19:04	2025071200571	31	...	...	...	...	<i>y</i>	17.234	0.10	6.163	4.110
79	2025-07-13 04:23:19	2025071200574	30	...	...	...	...	<i>z</i>	17.264	0.10	6.164	4.110
80	2025-07-13 04:23:57	2025071200575	31	265.174176	-18.455696	0.061	0.063	<i>z</i>	17.257	0.10	6.164	4.110
81	2025-07-13 04:28:07	2025071200578	30	...	...	...	...	<i>g</i>	18.239	0.03	6.165	4.110
82	2025-07-13 04:28:45	2025071200579	31	...	...	...	...	<i>g</i>	18.285	0.03	6.165	4.110
83	2025-07-13 04:33:06	2025071200582	30	265.170335	-18.455511	0.054	0.058	<i>i</i>	17.411	0.05	6.167	4.109
84	2025-07-13 04:33:44	2025071200583	31	265.170039	-18.455497	0.048	0.055	<i>i</i>	17.380	0.05	6.167	4.109
85	2025-07-13 04:37:54	2025071200586	30	265.168291	-18.455395	0.055	0.062	<i>r</i>	17.582	0.03	6.168	4.109
86	2025-07-13 04:38:32	2025071200587	31	265.168023	-18.455378	0.048	0.045	<i>r</i>	17.650	0.03	6.168	4.109
87	2025-07-13 04:42:43	2025071200590	30	...	...	...	...	<i>y</i>	...	...	6.169	4.109
88	2025-07-13 04:43:20	2025071200591	31	...	...	...	...	<i>y</i>	...	...	6.169	4.109
89	2025-07-14 04:22:11	2025071300432	102	...	...	...	...	<i>i</i>	...	...	6.552	4.077
90	2025-07-14 04:56:49	2025071300480	102	...	...	...	...	<i>z</i>	...	...	6.561	4.076
91	2025-07-19 00:57:02	2025071800083	22	261.530749	-18.245460	0.053	0.057	<i>g</i>	...	...	8.488	3.916
92	2025-07-19 00:57:45	2025071800084	177	261.530413	-18.245412	0.082	0.078	<i>g</i>	...	...	8.488	3.916
93	2025-07-19 23:25:43	2025071900042	66	260.929564	-18.205121	0.042	0.044	<i>r</i>	...	...	8.868	3.885
94	2025-07-19 23:42:18	2025071900063	66	260.922118	-18.204647	0.038	0.039	<i>i</i>	...	...	8.873	3.885

**Table 1**  
(Continued)

Row	Date Midpoint (TAI)	Visit ID	Chip(s)	R.A. <sup>a</sup> (deg)	Decl. <sup>b</sup> (deg)	eRA <sup>c</sup> (arcsec)	eDec <sup>d</sup> (arcsec)	Band	Mag <sup>e</sup>	eMag <sup>f</sup>	Phase <sup>g</sup> (deg)	r <sup>h</sup> (au)
95	2025-07-20 00:05:16	2025071900088	123	260.911789	-18.203959	0.086	0.075	<i>u</i>	...	...	8.880	3.884
96	2025-07-20 03:33:14	2025071900336	173	...	...	...	...	<i>g</i>	...	...	8.939	3.880
97	2025-07-20 04:15:08	2025071900384	80	260.799042	-18.196257	0.087	0.092	<i>u</i>	...	...	8.951	3.879

**Notes.**

<sup>a</sup> Measured R.A.

<sup>b</sup> Measured decl.

<sup>c</sup> Measured R.A. uncertainty.

<sup>d</sup> Measured decl. uncertainty.

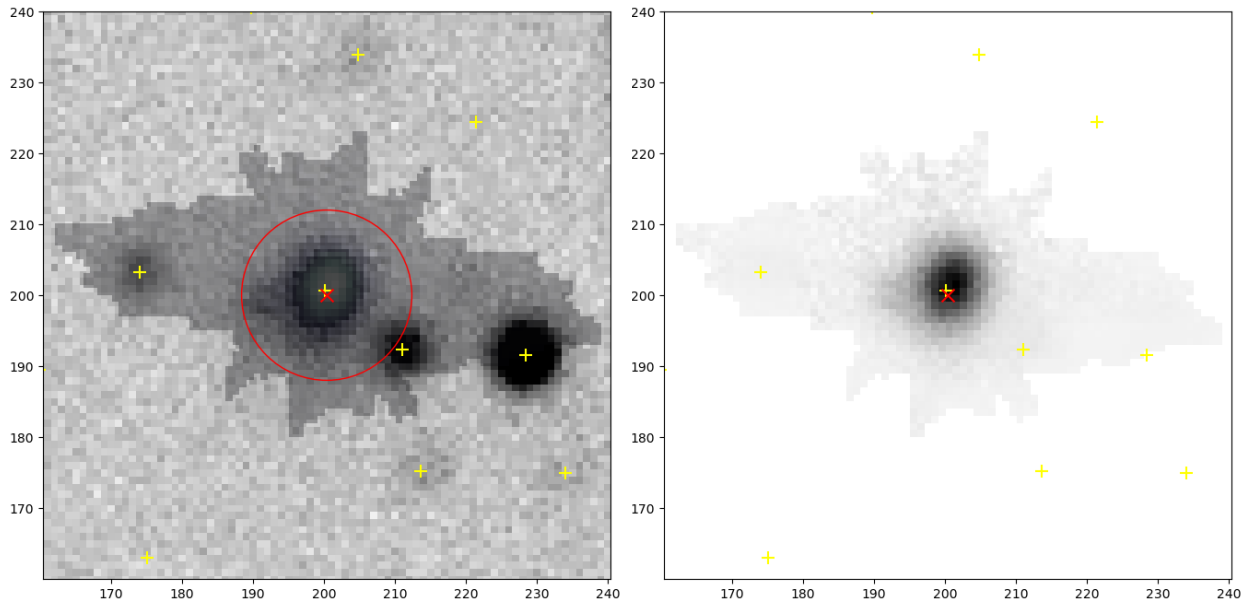
<sup>e</sup> Measured apparent aperture magnitude in specified band.

<sup>f</sup> Measured apparent aperture magnitude uncertainty in specified band.

<sup>g</sup> Solar phase angle (Sun-target-observer).

<sup>h</sup> Heliocentric distance.

(This table is available in machine-readable form in the [online article](#).)



**Figure 4.** Deblending 3I/ATLAS and background sources in a Rubin calibrated exposure (visit 2025070100200, detector 119) imaged UT 2025 July 2 00:44:25 (TAI). On the left is a cutout from a crowded field centered on 3I/ATLAS. The red ring represents the LSST Science Pipeline’s aperture photometry radius (see Section 5.3.2). In the image, 3I/ATLAS is seen nestled between four sources. The brighter three have been detected as separate and deblended (marked with yellow plus symbols). The fourth source (just to the left of 3I/ATLAS, and inside the red ring) has not. The resulting *footprint* (the dark-gray region in the left panel)—a set of pixels deemed by the deblender to contain 3I/ATLAS’s flux—is shown on the right. The deblender successfully removed the flux belonging to the three detected stars, preventing major biases in photometry and astrometry. However, the flux due to the fainter undetected star is still present. This illustrates both the power and the caveats of deblender applications: while the worst effects of crowding are mitigated, some low-level residual flux from faint blended sources likely remains.

LSST stack measurements, with maximum offsets of  $\sim 5$  mas in both R.A. and decl. For asteroids, the median difference between our measured position and the JPL Horizons-computed ephemerides is on the order of  $1\sigma$ , with an overall systematic offset of  $-20$  mas in R.A. and  $-34$  mas in decl.

While typically R.A. offsets can be attributed to errors in the timing for moving objects (the timing for Rubin is well established; J. Hohlitt & A. Thebo 2022), and effects such as differential chromatic refraction can cause shifts in both R.A. and decl., our analysis does not show similarly prominent biases when comparing the offset between 3I/ATLAS and the other asteroids. The systematic shift is also present on the subset of images successfully measured with the LSST Science Pipelines, whose performance has been extensively tested as part of the LSST Data Preview 1 (DP1) release (Vera C. Rubin Observatory 2025). In particular, DP1 demonstrated that the LSST Commissioning Camera achieved residuals of the order of 5 mas for high signal-to-noise ratio (SNR) sources, consistent with the limits of atmospheric turbulence; a similar performance is expected here for LSSTCam.

#### 5.1.1. Rubin Astrometric Calibration

To evaluate the apparent bias we observed in LSSTCam’s astrometry, we verified the Rubin pipeline-derived source positions in two complementary ways: static-source position validation and measurement of moving objects.

First, we assessed whether we could accurately determine the positions of static sources. Using catalogs derived from difference imaging produced as part of the SV commissioning efforts, we compared the positions of known quasars in Rubin data with the well-established Quiaia quasar catalog (K. Storey-Fisher et al. 2024). Since quasars are

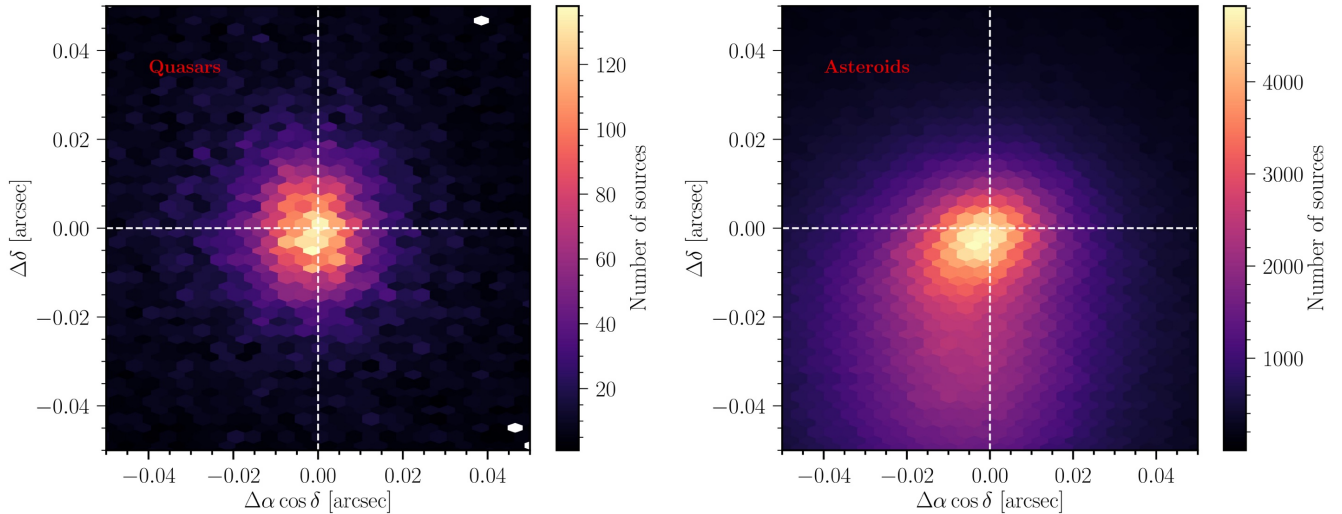
photometrically variable, they appear in difference images, thus proving to be ideal sources for this experiment.

We applied a simple positional crossmatch between the sources detected in each difference imaging catalog to the quasars, and considered only sources whose on-sky separation was  $d \leq 0''.5$ , as any larger positional difference indicates a potential mismatch. The result was a catalog of approximately 65,000 identified sources (Figure 5, left panel). We find that  $\langle \Delta\alpha \cos \delta \rangle = -2.6$  mas and  $\langle \Delta\delta \rangle = -0.6$  mas, indicating an excellent agreement between these two independent catalogs.

Next, we assessed whether our asteroid measurements were equally well calibrated. We used data from 2.5 million observations of roughly 200,000 unique, previously known asteroids that were measured by the LSST solar system association pipeline during SV efforts. We queried their positions as determined by the JPL Horizons ephemeris service at the midpoint time of each Rubin image taken of each asteroid (Figure 5, right panel). As with the quasars, we only considered sources with  $d \leq 0''.5$ , where we have  $\langle \Delta\alpha \cos \delta \rangle = -8.5$  mas and  $\langle \Delta\delta \rangle = -21.7$  mas. This analysis reveals a small but measurable bias in these asteroid measurements. The Rubin offsets reported here are below the noise floor of Section 5.1.2; further characterization of these offsets will be left to a future publication and is beyond the scope of this work.

#### 5.1.2. Curated Astrometric Measurements

We manually produced our own bespoke, curated astrometric measurements (rows of Table 1 with reported positions) from a subset of the available images, following a traditional, nonpipeline astrometry approach. We first identified viable images by visually inspecting each exposure and rejecting those where 3I/ATLAS was (1) notably involved (blended)



**Figure 5.** Two-dimensional histograms of the astrometric residuals between Rubin observations of objects matched to the Quiaia quasar catalog (left panel) and Rubin observations of known asteroids with positions derived by the JPL Horizons ephemeris service (right panel). In both cases, the color scale indicates the number of sources per bin, and the dashed lines intersect at the origin.

with nearby background sources, (2) very close to the edge of the array (i.e., chip boundary), or (3) contaminated by obvious artifacts (e.g., scattered light).

We produced  $600 \times 600$  pixel ( $\sim 126'' \times 126''$ ) image cutouts centered on the object’s ephemeris position. We astrometrically solved these images using all Gaia DR3 sources down to magnitude  $G = 21.0$  via a quadratic polynomial model fit. We rejected Gaia sources showing residuals  $> 0.2''$  from the solution since they were likely contaminated by other nearby blended sources, especially at times when 3I/ATLAS was crossing crowded fields near the galactic center.

We measured the position of 3I/ATLAS on each cutout using a Gaussian PSF fit following the “zero-aperture astrometry correction” technique (D. J. Tholen & S. R. Chesley 2004; D. Farnocchia et al. 2021). We repeated the fit with five different circular apertures, with radii ranging from 2–6 pixels, and linearly extrapolated to the theoretical location of a 0 pixel aperture, in both R.A. and decl.

Following the methodology outlined in D. Farnocchia et al. (2022), we assigned an astrometric uncertainty to each measured position. For stellar sources, the D. Farnocchia et al. (2022) approach is designed to provide conservative uncertainty estimates. However, for cometary objects, the non-Gaussian nature of the target’s PSF can cause a slight underestimation of the object centroid component of the error budget. The reduced  $\chi^2$  from the orbit fitting in Section 5.2 indicates that the assigned errors are, nevertheless, realistic and properly capture the intrinsic astrometric noise.

## 5.2. Orbit Determination

To assess the impact of our curated astrometric measurements of 3I/ATLAS, we compute a new orbit solution using all available astrometry up to perihelion (2025 October 29) and perform a residual analysis using the Gauss-Radau Small-body Simulator (GRSS; R. Makadia et al. 2025). GRSS is a user-friendly, open-source Python package with a C++ binding for high-precision propagation and orbit fitting of small bodies in the solar system. Astrometric measurements of asteroids by

other observatories are commonly weighted according to the P. Vereš et al. (2017) scheme, and astrometry catalogs are debiased as suggested in S. Eggl et al. (2020). However, since 3I/ATLAS shows clear signs of cometary activity, a conservative astrometric rejection scheme must be used to reduce the effects of any centroiding and timing errors in the astrometry. The results of this orbit fit are presented in Figure 6. The LSST astrometry is conservatively weighed at  $0.25''$  for orbit determination. The estimation leads to a reduced chi-squared,  $\chi^2_\nu = 0.1$  (see Figure 6), indicating a successful (albeit conservative) fit.

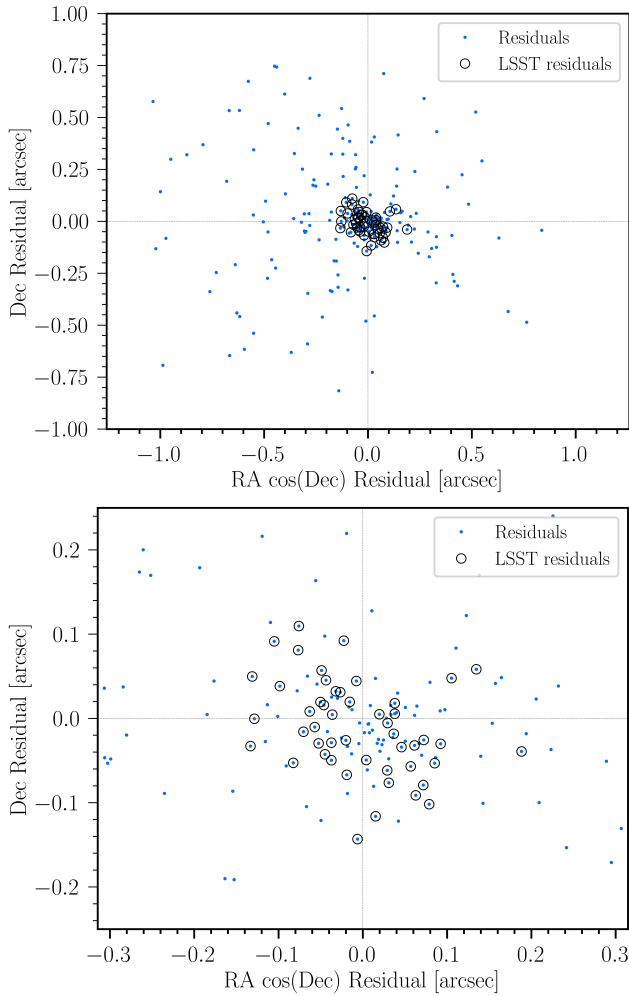
For the LSST observations, the post-fit residuals in R.A. are  $-5 \pm 70$  mas, and those in decl. are  $-10 \pm 55$  mas, indicating that the curated LSST astrometry fits very well with respect to their uncertainties. The somewhat linear trend in the residuals is aligned with the direction of the tail and is a manifestation of the extended nature of 3I/ATLAS. It is important to note that the spread in the residuals is only a fraction of the measurement uncertainty and, therefore, is not statistically significant. Conversely, if all available astrometry at the MPC is accepted at face value with a weight of  $1''$ , the LSST residuals in R.A. are  $211 \pm 176$  mas, and those in decl. are  $-197 \pm 91$  mas. This more than one-order-of-magnitude increase in the residuals highlights the dangers of ill-weighted astrometry in the orbit determination process, especially for extended objects such as 3I/ATLAS.

No evidence of significant nongravitational acceleration can be found with a pre-perihelion dataset alone, but we note that an orbit solution containing post-perihelion data will need nongravitational accelerations as part of the estimate.

## 5.3. Photometry

### 5.3.1. Photometric Measurements

As described in Section 4, the LSST pipeline performs automated photometric analyzes, but, due to the special challenges presented by the 3I/ATLAS data reported in this work, we also conducted a more customized photometric analysis. We report photometry in an aperture of exactly  $3''.0$  radius ( $\sim 15$  pixels), measured using our custom difference



**Figure 6.** Astrometric residuals of 3I/ATLAS based on data available at the Minor Planet Center (MPC) up until 2025 October 29. Top panel: residuals in R.A. scaled by  $\cos(\text{Dec})$  vs. residuals in decl. Points corresponding to residuals from LSST measurements are marked with rings around them. Bottom panel: zoomed-in view of the top panel.

imaging and subtracting a sky background based on the clipped mean in an annulus from  $6''.0$ – $8''.0$ . This nonpipeline approach is necessary for several reasons, including the pipeline’s limited performance on crowded fields (which is actively being improved) and the need to avoid self-subtraction of real flux from 3I/ATLAS. For each science image, we check for images suitable for template creation by requiring that the exposures (1) be in the same band as the science image, (2) show a similar PSF (and on-detector position, when possible), and (3) have acquisition times sufficiently separated in time (e.g., several minutes) such that 3I/ATLAS would be at least two aperture radii ( $6''$ ) from its location on the science image.

Prior to image subtraction, we used bilinear interpolation to resample the science and template-creation images onto a consistent astrometric grid using stereographic projection with celestial north up and a pixel size of exactly  $0''.2$ . For each science image, we constructed a clipped median stack of all template-creation images that met the above criteria. We matched the template image PSF to the science image by convolving with an optimized kernel (C. Alard & R. H. Lupton 1998) composed of basis functions that involved

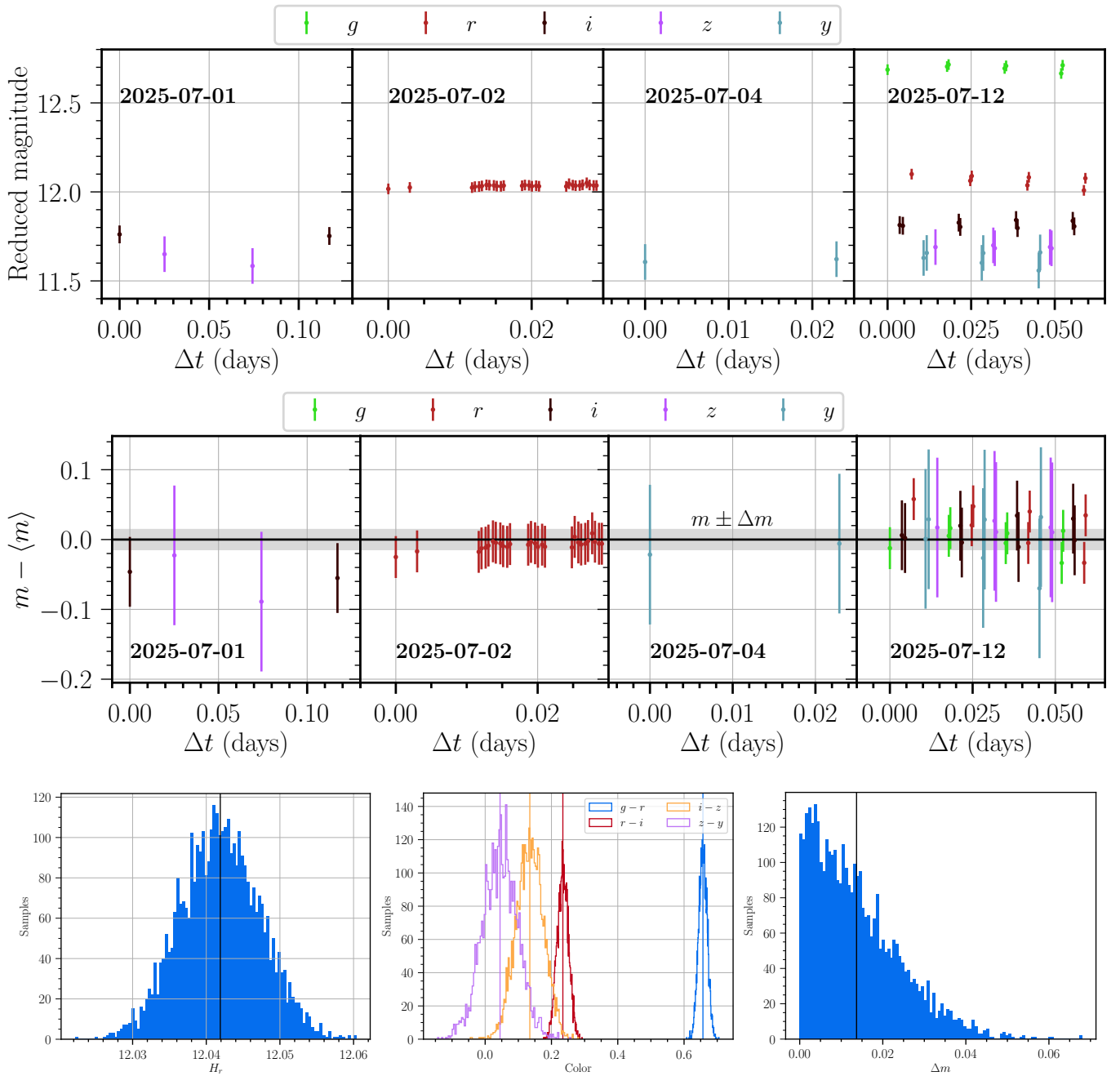
Gaussians with  $\sigma$  equal to 4.0, 2.0, and 1.0 pixels ( $0''.8$ ,  $0''.4$ , and  $0''.2$ ) multiplied by polynomials up to fourth, fourth, and fifth order, respectively. We did not attempt photometry for any science image that had no corresponding template-creation images, or when 3I/ATLAS fell on a background source too bright for adequate subtraction.

We photometrically calibrated our astrometrically resampled images using Pan-STARRS DR2 data obtained from the VizieR catalog service (F. Ochsenbein et al. 2000). Calibrating large-aperture photometry is challenging in dense fields with no isolated stars. We avoided calibration stars brighter than magnitude 15.5 (15.0 in the  $g$  band) due to concerns about saturation and nonlinearity. Subject to these maximum brightness constraints, we experimented using calibration sets in different magnitude ranges, from broad and faint (e.g., mag 18.0 to 15.5) to narrow and bright (mag 16.0 to 15.5). The calibration changed systematically as the mean magnitude of the calibration stars increased, indicating that contamination within our  $3''$  photometric aperture may have persisted even in the brightest magnitude range.

The problem was most pronounced in the reddest bands ( $z$  and  $y$ ), as the fields are most crowded in these bands. To address this problem, we performed an alternative calibration without clipping applied to the background calculation—i.e., we deliberately included stellar flux in the “sky” measurement to statistically remove a mean density of background stars from the photometric aperture. We calculated the median photometric calibration in flux space rather than magnitude space to avoid problems from occasional negative fluxes that may result from this approach. Using this method, the calibration still changed systematically with the magnitude of the calibration stars, but now with the opposite sign—an expected result that may be caused by clustering of the brighter stars. Both methods appeared to converge (from opposite directions) toward a similar calibration as we increased the mean brightness of the stars being used, with  $\sim 0.05$  mag agreement for bluer bands. For the  $z$  and  $y$  bands in the densest fields, the disagreement was still  $\sim 0.20$  mag for the brightest cohort of stars. Hence, we take the average of the two calibration methods as our final calibration, and report approximately half the difference as our systematic error: 0.03 mag in the  $g$  and  $r$  bands, 0.05 mag in  $i$ , and 0.10 mag in  $z$  and  $y$ . The internal consistency of our photometry makes it clear that systematic errors dominate the random error in every case, so we have not attempted to rigorously quantify the latter.

### 5.3.2. Photometric Variability

The sequence of observations taken on UT 2025 July 3 gave us a unique opportunity to measure the variability of 3I/ATLAS on approximately minute timescales. We applied the Bayesian methodology of P. H. Bernardinelli et al. (2023) to the fluxes from Section 5.3. We assumed every measurement at time  $\mu$  and band  $b$  had a flux measurement  $f_{\mu,b} = \langle f_b \rangle [1 + Ah(\phi_\mu)]$ , where  $\langle f_b \rangle$  is the object’s mean flux at band  $b$ ,  $A$  is its light-curve semi-amplitude, and  $h(\phi)$  is a time-varying function with phase  $0 \leq \phi \leq 1$ . We marginalized over  $\phi$  for each visit, thus assuming that the object was seen at a random point of its light curve, which, for simplicity, we used  $h(\phi) = \sin(2\pi\phi)$ . In practice, this procedure yields a statistically rigorous Monte Carlo sampling of the probability distribution of the object’s mean flux and its variability



**Figure 7.** Top panels: the two horizontal panels show time-series photometry of 3I/ATLAS taken on four different nights and in the LSST *grizy* bands. The top panel shows the reduced magnitude (where distance to the observer and the Sun is subtracted), while the bottom panel shows the same value, but where the mean magnitude per band is also subtracted, i.e., any excess scatter is due to light-curve variations. The gray shaded area in the bottom panel represents the 68% region of the estimated variability  $\langle \Delta m \rangle$ . Bottom-left panel: probability distribution of the mean magnitude yielded by this procedure, with the vertical line indicating the mean measurement  $\langle H_r \rangle = 12.042 \pm 0.005$  mag. Bottom-center panel: probability distribution of the color pairs  $g - r$ ,  $r - i$ ,  $i - z$  and  $z - y$ . The mean value (vertical line) is indicated; all values are summarized in Table 2. Bottom-right panel: the probability distribution of the peak-to-peak light-curve amplitude (in magnitudes)  $\Delta m \equiv 2.5 \log_{10}[(1 + A)/(1 - A)]$  for the flux measurements over this time span, with  $\langle \Delta m \rangle = 0.014 \pm 0.010$ .

without detailed modeling of its light curve (e.g., phase folding or shape modeling). We present the results of this analysis in the bottom panel of Figure 7. Our photometry is consistent with  $A$  on the order of 6%. This means that we can exclude variations larger than  $\approx 0.1$  mag in the timescale of these observations. Incidentally, this also demonstrates good photometric stability of the Rubin system even in such a crowded field and for a moving source.

While techniques such as difference imaging (C. Alard & R. H. Lupton 1998; B. Zackay et al. 2016; N. Sedaghat &

A. Mahabal 2018) would be ideal to extract the photometry of this object, at the time these images were acquired, there were few visits in each of these fields (including those with the object). Because of this, high-quality templates are more challenging to construct and may not yield image differences that improve upon the measurements presented above. The UT 2025 July 3 data include 28  $r$ -band observations of 3I/ATLAS within an hour (see Figure 7), which can also be challenging due to the potential for self-subtraction, as the object moves  $\lesssim 1$  PSF across two pairs of visits. Another option, which we

**Table 2**  
Solar, Predicted, and Measured Colors

Color	Solar	3I/ATLAS <sup>a</sup>	3I/ATLAS <sup>b</sup>
$(u - g)_{\text{LSST}}$	1.154	1.384	...
$(g - r)_{\text{LSST}}$	0.436	0.677	$0.657 \pm 0.013$
$(r - i)_{\text{LSST}}$	0.112	0.299	$0.235 \pm 0.018$
$(i - z)_{\text{LSST}}$	0.011	0.147	$0.147 \pm 0.042$
$(z - y)_{\text{LSST}}$	0.009	0.125	$0.047 \pm 0.052$

**Notes.**

<sup>a</sup> Expected colors in LSST filters for 3I/ATLAS assuming a spectral gradient of  $S' = 18\%$ .

<sup>b</sup> Our measured colors of 3I/ATLAS.

leave for future work, would be to explore techniques such as scene modeling photometry (e.g., P. H. Bernardinelli et al. 2023), which can measure the target at multiple images while simultaneously accounting for contamination of background sources.

### 5.3.3. Colors

Here, we derive 3I/ATLAS colors using a model that leverages the previously measured object slope and directly from our own measurements. First, recalling that D. Z. Seligman et al. (2025) and C. Opitom et al. (2025) independently reported spectral gradients of  $S' \sim 18\%/100$  nm for 3I/ATLAS (Section 1.2), we use this spectral gradient to compute equivalent colors for the object in the LSST *ugrizy* filter set (which differs from the SDSS filter system). Using the `spectroscopy` module<sup>155</sup> in `sbgpy` and effective central wavelengths for LSST filters from the LSST website,<sup>156</sup> we compute colors for 3I/ATLAS for each filter pair given a spectral gradient of  $S' = 18\%/100$  nm (normalized at the central wavelength of the *g'*-band filter, 480.69 nm) and report these in Table 2. For reference, in the same table, we also show solar colors in LSST filters that were computed from an R. L. Kurucz (1993) model spectrum of the Sun for use in the computation of the object's colors from its spectral gradient.

## 5.4. Morphology

### 5.4.1. Overview

To study 3I/ATLAS's morphology, we first construct contour plots of detections from UT 2025 June 21 at 08:11:33 and UT 2025 July 2 at 03:33:02, where the object was largely isolated from background sources (Figure 8). On June 21, the target appeared somewhat extended in the east–west direction, the direction of its apparent nonsidereal motion. Therefore, this morphology may have been due to trailing (of 3I/ATLAS) in these sidereally tracked images. On July 2, the object appeared to have a notably extended and asymmetric coma, with a position angle (PA) at  $\sim 290^\circ$  east of north, very nearly opposite the direction of the projected antisolar vector PA. In other words, rather than pointing away from the Sun, as is most commonly the case, the tail appeared to be pointing toward the Sun. To more quantitatively analyze the morphology of 3I/ATLAS, we first perform a radial surface brightness profile analysis (Section 5.4.2), followed by an

analysis of one-dimensional surface brightness profiles measured perpendicular to the direction of the object's motion (Section 5.4.3). Finally, we discuss 3I/ATLAS's apparent sunward tail in Section 5.4.4.

### 5.4.2. Radial Surface Brightness Profile Analysis

We perform a radial profile analysis of 3I/ATLAS (Figure 9) when it was relatively isolated from background sources, despite the object transiting a crowded field. We carried out our analyzes with  $600 \times 600$  pixel ( $120'' \times 120''$ ) cutouts extracted via the Rubin Science Platform and `astropy`'s `Cutout2D` function, preserving an adequate WCS for the purpose (e.g., matching to Gaia stars). The two 3I/ATLAS-isolated images were from UT 2025 June 21 and UT 2025 July 2.

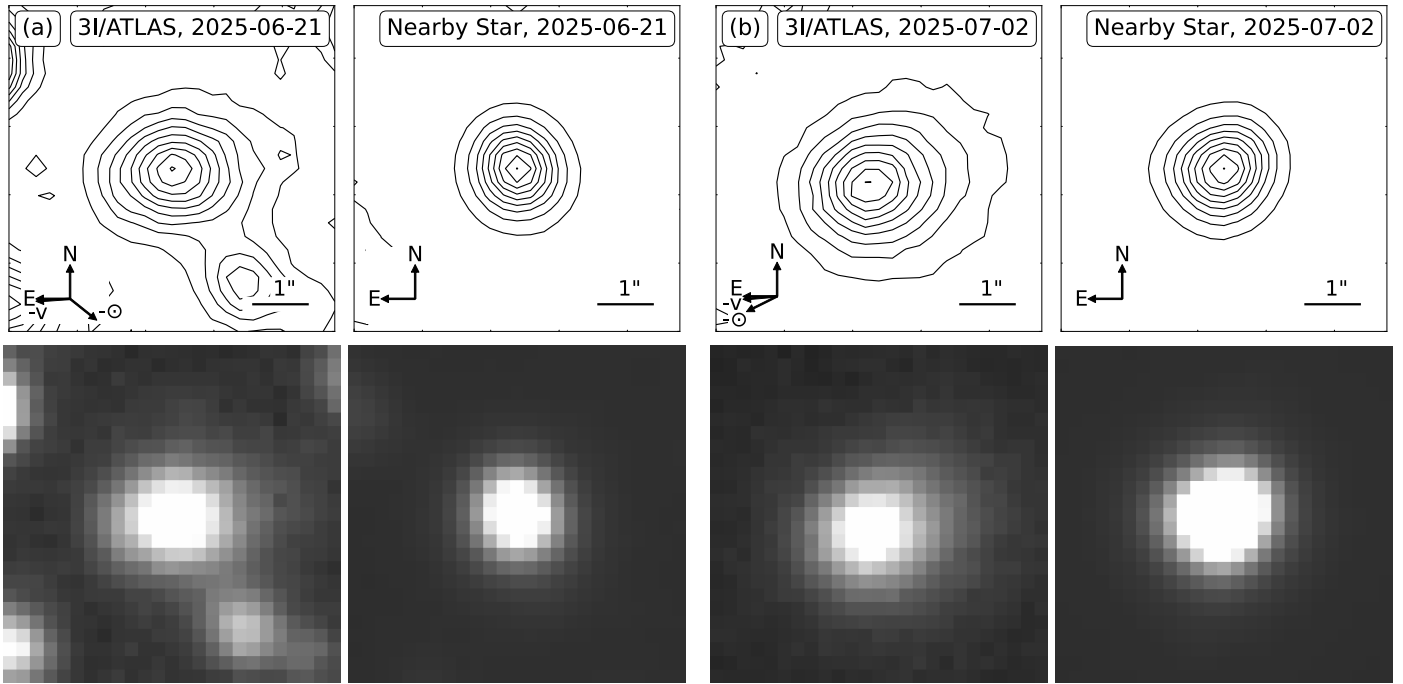
For each image, we prescribe an aperture sufficient to capture all of the flux of 3I/ATLAS discernible from the background (or noise floor; see below); these were 20 and 30 pixels ( $4''$  and  $6''$ ), respectively. We also randomly selected several background stars throughout the field, also in relative isolation, though the field was sufficiently crowded that only a handful of isolated stars were usable. Larger cutouts might have provided additional stars; however, proximate stars are more likely to conform to the same general shape, given that some data were acquired during engineering time. We summed the flux of 3I/ATLAS and the field stars in concentric radial annuli.

In Figure 9 we show the azimuthally averaged radial profile of the reflected light from 3I/ATLAS to show the PSF compared to that of nearby field stars. The excess of the radial profile compared to that of the nearby stars is indicative of cometary activity. However, the Rubin LSST images are not tracking the motion of 3I/ATLAS, and the exposure time of each image is 30 s. Therefore, there will be both trailing loss and smearing of the radial profile with respect to that of the comparison star. To quantify the magnitude of the effect, we first consider the object's apparent sky rates of motion of  $\sim 60''/\text{hr}$  (UT 2025 June 21, Table 1) and  $\sim 75''/\text{hr}$  (UT 2025 July 2). Thus, in each exposure, the object had moved  $\sim 0.5$  (2.5 pixels) and  $\sim 0.625$  (3.125 pixels), respectively. At first glance, this appears to be comparable in magnitude to the offset between the comparison star and the 3I/ATLAS profile (see the region between 0.5 and 7.5 pixels in Figure 9, top panel). However, we note that the smearing of the profile should *only* operate along the direction of motion. Should there be just a trailing starlike nucleus with no coma, we should see at least a few data points representing pixel intensities of 3I/ATLAS that lie along the stellar PSF curve (belonging to pixels lying perpendicular to the motion). We do not see such points, which strongly support the presence of a coma.

These images were fully processed by the LSST Science pipelines (Rubin Observatory Science Pipelines Developers 2025) and, consequently, should have already had their background values subtracted. However, (a) commissioning is ongoing, and (b) crowded fields have proven challenging due to the absence of discernible background (i.e., little to no area on the sky without one or more sources in the field). In the case of our two isolated images, the June 21 image underwent background subtraction that resulted in appreciable “negative flux,” and the July 2 image still had some background flux measurable in our aperture.

<sup>155</sup> <https://sbgpy.readthedocs.io/en/stable/sbgpy/spectroscopy/index.html>

<sup>156</sup> <https://rubinobservatory.org/for-scientists/rubin-101/instruments>



**Figure 8.** Contour plots (top row; using 10 logarithmically spaced contour levels ranging from the peak value of each image to the average background level in each image) of LSST images (bottom row) of 3I/ATLAS (left panel) and a nearby (within  $1''$  of the target) reference field star from the same image (right panel) from (a) UT 2025 June 21 and (b) UT 2025 July 2, centered on the target. The FOV of each panel is  $5'' \times 5''$ . North (N), east (E), and the PAs of the antisolar vector ( $-v$ ) and negative heliocentric velocity vector ( $-v$ ) as projected on the sky are indicated as labeled. Corresponding grayscale images on which each contour plot is based are shown below each contour plot.

To address the discrepant background levels, we fit a polynomial function to each set of measurements and derive a limit determined by the inflection point (i.e., where the curve reaches its floor). For UT 2025 June 21, 3I/ATLAS had an apparent radial extent of 11.75 pixels ( $2.35''$ , or  $\sim 6, 520$  km). On UT 2025 July 2, the extent was 18.64 pixels  $\approx 3.73'' \approx 9384$  km. These should be considered very conservative lower limits as the object appeared nearly head-on, so the tail could have extended far along the  $z$ -axis (as projected on the sky).

#### 5.4.3. One-dimensional Surface Brightness Profile Analysis

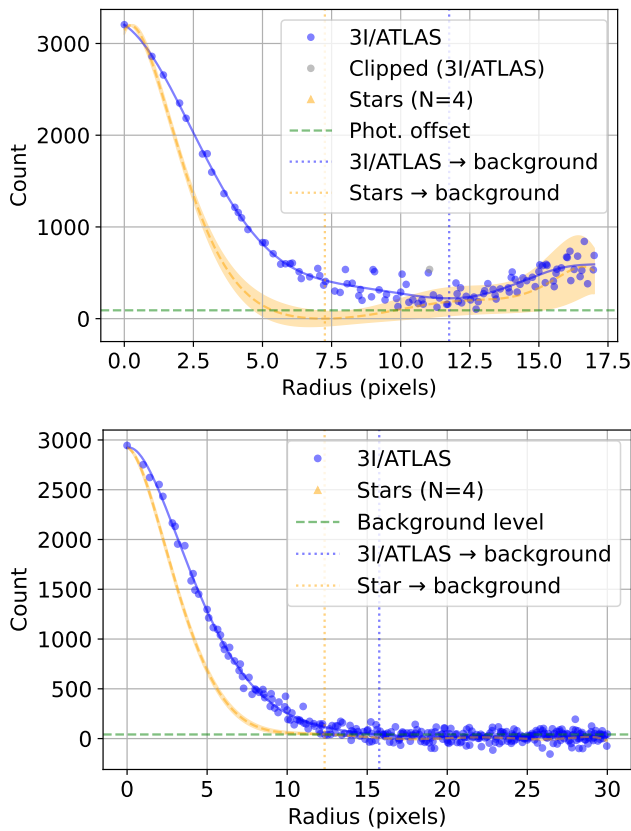
In an effort to specifically quantitatively characterize the amount of coma present on these different dates, following J. X. Luu & D. C. Jewitt (1992) and H. H. Hsieh & D. Jewitt (2005), we performed an analysis in which we compare one-dimensional surface brightness profiles of the comet, as measured perpendicularly to the direction of apparent nonsidereal motion, to those of template field stars with varying amounts of synthetically added spherically symmetric and steady-state coma. This follows an  $r^{-1}$  radial surface brightness profile, where  $r$  is the angular distance from the photocenter as projected on the sky. In this modeling analysis, coma levels were parameterized by  $\eta = C_c/C_n$ , where  $C_c$  and  $C_n$  were the total scattering cross sections from the coma and nucleus (assuming that both have the same effective albedos), respectively, where we used a reference photometry aperture of  $r_{\text{phot}} = 5''5$  for measuring these fluxes.

For measuring one-dimensional surface brightness profiles, we rotated images of 3I/ATLAS and a selected well-isolated field star in each image to align the direction of motion horizontally in the image frame, where in this case, the nonsidereal motion of 3I/ATLAS was very nearly exactly

west to east on June 21 and July 2, and so the orientations of the rotated images are virtually identical to those of the images in Figure 2 and contour plots in Figure 8. We then averaged pixel values over horizontal rows over the entire widths of the object and reference stars, and subtract sky background sampled from nearby areas of blank sky. Object and model profiles were then normalized to unity at their peaks and plotted together (Figure 10) to search for the closest matching model profile to each object profile.

Adding synthetic coma using the method described above has less of an effect on surface brightness profile cores than it does on profile wings; of course, however, the profiles are more impacted by noise farther from a particular source's photocenter. As such, we focus on examining the deviation of the comet profile close enough to the center where the signal is relatively strong, profiles vary relatively smoothly, and the  $r^{-1}$  coma profile assumption used in our model is more likely to be true, but far enough away that the model profiles using different coma levels show visible separation from one another. For profile plots on both dates, this range of interest is approximately  $0.4''$  to  $0.7''$  from the photocenter.

We find that coma is clearly present for 3I/ATLAS in the June 21 08:11:33 image (Figure 10(a)) at a level of  $\eta \sim 2.0 \pm 0.5$ , where the uncertainty is estimated based on visually identifying the synthetic coma profiles that bound the comet profile. Meanwhile, we find an approximate coma level of  $\eta \sim 2.5 \pm 0.5$  for the July 2 03:33:02 image (Figure 10(b)), indicating that the coma may have increased slightly over the 11 days between the two observations (although we also note that the coma level estimates are also consistent within their estimated uncertainties between the two dates). That said, we also see a larger extension of the surface brightness profile on the north side of the comet, which is corroborated by the

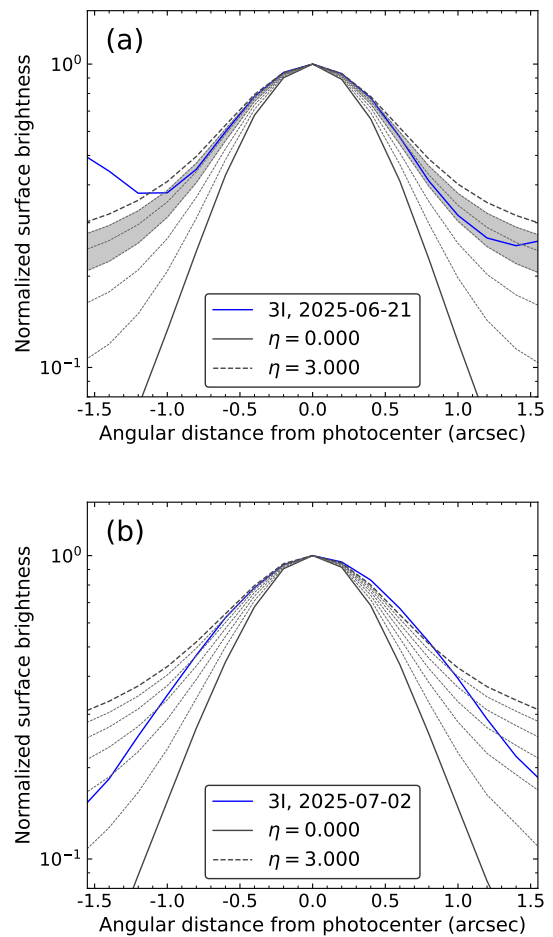


**Figure 9.** Radial profile measurements of 3I/ATLAS (blue circles) and a set of four vetted comparison stars (yellow shaded region), along with polynomial fits (solid blue line and dashed yellow line, respectively). Data points beyond  $3\sigma$  from the polynomial fit were clipped (gray markers, when present), and the function was re-fit. The signal floor is indicated by a horizontal green dashed line. Vertical dashed lines indicate the radial extent of 3I/ATLAS (blue) and the mean of the comparison stars fit (yellow). Top panel: 2025 June 21. Coma extent at 11.75 px:  $\sim 6520$  km.  $r_H = 4.834$  au. The signal floor is below zero flux, so a photometric offset has been applied to the fit. Bottom panel: 2025 July 2. Coma extent at 18.64 px:  $\sim 9,380$  km.  $r_H = 4.476$  au. The residual background signal was measurable, so additional background subtraction was incorporated into the measurements.

visible asymmetry of the comet in its contour plot from that date (Figure 8(b)). As such, we consider the estimated increase in coma level of  $\Delta\eta \sim 0.5 \pm 0.5$  between June 21 and July 2 to be a lower limit.

#### 5.4.4. Tail Analysis

As noted by several observers (D. Jewitt & J. Luu 2025; M. R. Alarcon et al. 2025; D. Z. Seligman et al. 2025; B. T. Bolin et al. 2025; C. Opatom et al. 2025), 3I/ATLAS is observed to exhibit a short sunward-pointing tail in imaging data obtained since its discovery. Cometary dust tails typically extend away from the Sun in three-dimensional space due to radiation pressure acting on dust grains, and thus, this morphology for 3I is not the nominal expectation. However, an antisolar dust tail can appear on the sunward side of a comet nucleus as projected on the sky given certain viewing geometries, while actual sunward dust tails can be produced by nonisotropic dust emission. Notably, the latter is not without precedent among distant active bodies, where T. L. Farnham et al. (2021) reported a similar sunward enhancement in comet C/2014 UN<sub>271</sub> (Bernardinelli-Bernstein), which they interpreted as the result of the slow ejection

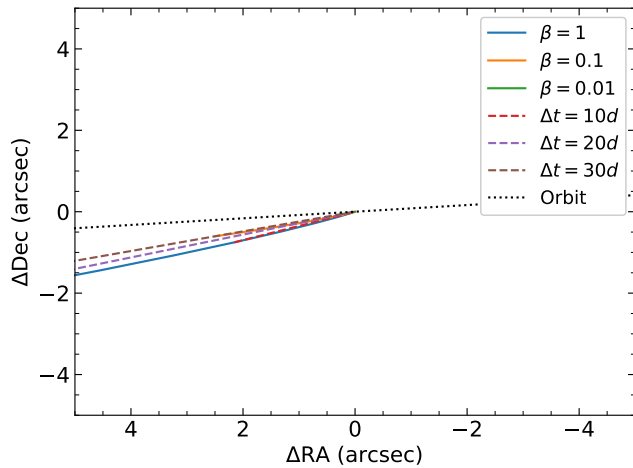


**Figure 10.** One-dimensional surface brightness profiles (measured perpendicular to the direction of apparent nonisidereal motion) of 3I/ATLAS (solid blue lines) and seeing-convolved model nuclei with linearly spaced coma levels (i.e.,  $\eta_i = 0.5(i - 1)$ ) ranging from  $\eta = 0$  (solid black lines) to  $\eta = 3$  (dashed black line, with profiles corresponding to intermediate  $\eta$  values shown as dotted black lines) for data from (a) UT 2025 June 21, and (b) UT 2025 July 2. Estimated uncertainty regions, i.e., the regions bound by the model profiles adjacent to the best-matching model profile in each panel, are shaded in gray.

of relatively large dust particles predominantly from the sunlit hemisphere.

Simple Finson–Probstein–style dust modeling (M. J. Finson & R. F. Probstein 1968a; M. L. Finson & R. F. Probstein 1968b) carried out using the `SynGenerator` class<sup>157</sup> in `sippy` (M. Mommert et al. 2019) to generate and plot syndynes and synchrones for 3I/ATLAS shows that, for isotropic dust emission (which is typically assumed), any dust tail should have a PA of  $\sim 100^\circ$  east of north (Figure 11). This nominally rules out the tail’s sunward direction (PA  $\sim 290^\circ$ ) as a viewing geometry effect and implies instead that it is the result of anisotropic dust emission (e.g., H. H. Hsieh et al. 2011; T. L. Farnham et al. 2021; H. H. Hsieh et al. 2025), specifically with an average direction in the orbit plane (which is close to the ecliptic plane), given the sunward tail’s approximate orientation along the direction of heliocentric motion. Although the sunward feature observed in 3I/ATLAS is broadly consistent with anisotropic dust emission, such a morphology can also arise from gas jets, as observed in comets like C/1996 B2 (Hyakutake), where strong sunward CN and

<sup>157</sup> <https://sippy.readthedocs.io/en/latest/sippy/dynamics.html#dust-syndynes-and-synchrones>



**Figure 11.** Synchrone-syndyne grid for 3I/ATLAS on UT 2025 July 2 for isotropic dust emission. The position of the object is at the center of the plot (at  $\Delta R.A. = \Delta \text{decl.} = 0''$ ), where (essentially overlapping) solid colored lines correspond to syndynes, along which particles of specified sizes should be found (where particle sizes are parameterized by  $\beta$ ; particle radii,  $a$ , in microns, are approximately given by  $a = \beta^{-1}$ ), dashed colored lines correspond to synchrones, along which particles ejected at specified times should be found (synchrones shown for 10, 20, and 30 days prior to the current epoch), and the dotted black line shows the projection of the orbital plane on the sky.

$C_2$  emissions were detected in narrowband images (A. V. Rodionov et al. 1998). CN detection at 3I/ATLAS’s distances during our observations ( $\sim 5$  to  $\sim 4$  au) would be very exceptional (M. F. A’Hearn et al. 1995), however, and optical spectroscopy of 3I/ATLAS as of 2025 July 30 has not detected any gas (A. Alvarez-Candal et al. 2025; C. Opatom et al. 2025).

We note that the implication of anisotropic dust emission close to the ecliptic plane raises the possibility of a nearly in-plane rotation pole, since the time-averaged direction of a nonequatorial jet is equivalent to the direction of the nearest rotation pole (e.g., see H. H. Hsieh et al. 2011). Such geometry could, in principle, allow for pole-on viewing orientations with respect to the Earth (e.g., M. W. Buie et al. 2018), which would in turn be consistent with only minor light-curve variations being reported for 3I/ATLAS thus far in this work (Section 5.3.2) and by others (e.g., D. Z. Seligman et al. 2025). That said, the small light-curve ranges observed thus far could also be partially or even entirely due to the damping effects of a steady-state coma on the observable light-curve variations of an underlying rotating nucleus (e.g., H. H. Hsieh et al. 2011). Finally, it is important to keep in mind that the detailed geometry of dust emission depends critically on nucleus shape. Small cometary nuclei are frequently irregular or contact binary objects, often characterized by deep concavities capable of producing focused sunward jets. For example, in comet 67P/Churyumov-Gerasimenko, such topography-induced sunward jets were well documented by Rosetta (e.g., X. Shi et al. 2018). Without knowledge of 3I/ATLAS’s nucleus shape, no firm conclusion on the physical cause of its coma morphology can be drawn.

### 5.5. Nucleus Analysis

The well-isolated July 2 03:33:02 detection of 3I/ATLAS (see Figure 8(b)) had a measured  $i$ -band aperture magnitude of  $m_i = 17.633 \pm 0.006$  as measured in a circular aperture with a

radius of  $3''/4$  (17 pixels, or 8600 km at the geocentric distance of the comet). We note that this value differs slightly from the aperture magnitude reported for that detection in Table 1 given the slightly different aperture sizes used for the photometry listed in the table ( $3''/0$  for all measurements) and for the customized measurement discussed here.

On July 2, 3I/ATLAS had a heliocentric distance of  $r_h = 4.48$  au, a geocentric distance of  $\Delta = 3.47$  au, and a solar phase angle of  $\alpha = 2.3$ . In order to estimate the object’s nucleus size, we first compute a reduced magnitude,  $m(1, 1, \alpha)$ , i.e., normalizing the measured apparent aperture magnitude to  $r_h = \Delta = 1$  au using

$$m_i(1, 1, \alpha) = m_i(r_h, \Delta, \alpha) - 5 \log(r_h \Delta). \quad (1)$$

Given that the nucleus and dust are expected to have different phase darkening behaviors, we then partition this reduced magnitude into its nucleus and dust components using the coma level estimated from our surface brightness profile analysis for July 2 of  $\eta = 2.5 \pm 0.5$ , where the nucleus is assumed to account for  $1/(3.5 \pm 0.5)$  of the observed flux, and the dust coma is assumed to account for  $2.5/(3.5 \pm 0.5)$  of the observed flux. This results in a nuclear magnitude of  $m_{i,n}(1, 1, \alpha) = 13.04 \pm 0.16$  and a dust coma magnitude of  $m_{i,d}(1, 1, \alpha) = 12.04 \pm 0.16$ .

Adopting Jupiter-family comet (JFC) nuclei as a potentially reasonable proxy for the nucleus of 3I/ATLAS, we use the median linear phase coefficient and standard deviation of  $\beta = 0.046 \pm 0.017$  mag deg $^{-1}$  found from measurements of a large sample of JFC nuclei by R. Kokotanekova et al. (2017). Correcting for  $\alpha = 2.3$  therefore results in an absolute magnitude of  $H_{i,n} = m_{i,n}(1, 1, 0) = 12.93 \pm 0.16$ .

Meanwhile, we use the Schleicher–Marcus phase function<sup>158</sup> (sometimes also referred to as the Halley–Marcus phase function; D. G. Schleicher & A. N. Bair 2011; D. G. Schleicher et al. 1998; J. N. Marcus 2007) for determining the phase darkening correction of the dust component of this observation, finding that the expected observed flux at  $\alpha = 2.3$  is 0.91 of the expected observed flux at  $\alpha = 0^\circ$ . We therefore obtain  $H_{i,d} = m_{i,d}(1, 1, 0) = 11.94 \pm 0.16$ .

Lastly, we combine the distance- and phase-corrected magnitudes of 3I/ATLAS’s nucleus and dust components using

$$m_{i,\text{tot}} = -2.5 \log \left( 10^{-0.4m_{i,n}(1,1,0)} + 10^{-0.4m_{i,d}(1,1,0)} \right) \quad (2)$$

obtaining a total absolute magnitude of  $m_{i,\text{tot}}(1, 1, 0) = 11.57 \pm 0.12$ . We note that the above calculations assume that the dust coma is optically thin, and utilize the `uncertainties` python package for the calculation and propagation of uncertainties.<sup>159</sup>

In order to estimate 3I/ATLAS’s nucleus size from the absolute magnitude found above, we first convert the  $i$ -band absolute magnitude to the  $r$  band using the object’s measured  $(r - i)_{\text{LSSST}}$  color (Table 2), obtaining  $H_{r,n} = H_{i,n} + (0.235 \pm 0.018) = 13.16 \pm 0.16$ . We then compute an equivalent V-band absolute magnitude,  $H_{V,n}$ , using

$$H_{V,n} = H_{r,n} + 0.73(V - R) - 0.088 \quad (3)$$

<sup>158</sup> <https://asteroid.lowell.edu/comet/dustphase.html>

<sup>159</sup> <https://pythonhosted.org/uncertainties/>

from K. Jordi et al. (2006), where we use  $V - R = (0.333 \pm 0.008)$  based on measured colors reported in Section 5.3.3, and assume that the difference between  $r'$  and  $r_{\text{LSST}}$  is negligible for the purposes of this calculation. We obtain  $H_{V,n} = (13.32 \pm 0.16)$  mag, or  $\sim 1$  mag fainter than the  $H_V$  value ( $H_V > 12.4$ ) estimated by D. Z. Seligman et al. (2025) based on ZTF precovery data. Finally, we can estimate the effective nucleus radius using

$$r_n = \left( \frac{2.24 \times 10^{22}}{p_V} \times 10^{0.4(m_{\odot,V} - H_V)} \right)^{1/2} \quad (4)$$

where we use  $m_{\odot,V} = -26.71 \pm 0.03$  for the apparent  $V$ -band magnitude of the Sun (J. Hardorp 1980) and assume a  $V$ -band geometric albedo of  $p_V = 0.05$  (typical of reddened comet nuclei; M. M. Knight et al. 2024). We find  $r_n = (6.6 \pm 0.5)$  km, about two-thirds of the previous nucleus size upper-limit estimate by D. Z. Seligman et al. (2025). Given that this nucleus size is based on a coma-to-nucleus ratio that we expect to be underestimated, we regard this result as an upper limit to 3I/ATLAS's true nucleus size, where this has since been confirmed by D. Jewitt et al. (2025). They constrained the nucleus size to  $r \leq 2.8$  km based on a fit to the surface brightness distribution of the inner coma as observed by HST on UT 2025 July 21. Later (post-perihelion), the nucleus was measured to be  $1.3 \pm 0.2$  km (M.-T. Hui et al. 2026).

Adopting the nucleus size upper limit found by D. Jewitt et al. (2025) as the true nucleus size for the purposes of the following analysis, we can estimate the potential mass-loss rate,  $\dot{M}$ , from  $\eta$  using

$$\dot{M} = \frac{(1.1 \times 10^{-3}) \pi \rho_d \bar{a} \eta r_{\text{obj}}^2}{p r_h^{0.5} \Delta} \quad (5)$$

(J. X. Luu & D. C. Jewitt 1992), where  $\rho_d$  is the average bulk dust grain density,  $\bar{a}$  is the weighted mean grain radius,  $r_{\text{obj}}$  is the object's effective radius,  $p = 5''$  is the angular photometry radius in arcseconds, and  $r_h = 4.48$  au and  $\Delta = 3.47$  au are the heliocentric and geocentric distances in astronomical unit on July 2. We keep in mind that if we use  $r_{\text{obj}} \sim 2.8$  km instead of our originally calculated  $r_{\text{obj}} \sim 6.6$  km, we obtain  $\eta \sim 13$  instead of our originally calculated  $\eta \sim 2.5$  (on July 2). In addition to the uncertainty on our nucleus size estimate, there are currently no useful empirical constraints on  $\rho_d$  and  $\bar{a}$ . While  $\rho_d$  may vary by a factor of a few among different materials,  $\bar{a}$  dominates the uncertainty as it can vary by several orders of magnitude (e.g., from micron to millimeter scales or larger). For illustration, for arbitrary assumptions of  $\rho = 1000 \text{ kg m}^{-3}$  and  $\bar{a} = 1 \mu\text{m}$ , we obtain  $\dot{M} \sim 10 \text{ kg s}^{-1}$ , but  $\bar{a} = 10 \mu\text{m}$  would result in  $\dot{M} \sim 100 \text{ kg s}^{-1}$ . Constraints on particle sizes (which may vary with heliocentric distance), e.g., via detailed dust modeling, will be critical for deriving more realistic mass-loss rates for 3I/ATLAS in the months following these reported observations, as it becomes more active.

For reference, we also calculate the  $A(\alpha = 0^\circ) f \rho$  parameter (hereafter,  $Af\rho$ ; M. F. A'Hearn et al. 1984), which is frequently used to parameterize the dust content of cometary comae, and

is given by

$$A(\alpha = 0^\circ) f \rho = \frac{(2r_h \Delta)^2}{\rho_{ap}} 10^{0.4[m_{\odot} - m_d(r_h, \Delta, 0)]}, \quad (6)$$

where  $r_h$  is in astronomical unit,  $\Delta$  is in centimeters,  $\rho_{ap}$  is the physical radius in centimeters of the photometry aperture used to measure the magnitude of the comet at the distance of the comet,  $m_{\odot}$  is the apparent magnitude of the Sun at  $\Delta = 1$  au in the same filter used to observe the comet, and  $m_d(r_h, \Delta, 0)$  is the phase-angle-corrected (to  $\alpha = 0^\circ$ ) apparent magnitude of the dust with the flux contribution of the nucleus (assuming the nucleus size upper limit from D. Jewitt et al. 2025) subtracted from the measured total magnitude. For this calculation, the nucleus contribution to the flux is calculated assuming a linear phase function and median linear phase coefficient from a sample of JFC nuclei from R. Kokotanekova et al. (2017), and the nucleus-subtracted magnitude of the dust is corrected to  $\alpha = 0^\circ$  using the Schleicher–Marcus phase function as discussed above. Using parameter values specified above, we compute  $Af\rho = (334 \pm 13)$  cm based on our  $i_{\text{LSST}}$ -band detection on UT 2025 July 2, which is slightly larger than the  $i'$ -band  $Af\rho = (288 \pm 5)$  cm value (using a photometry aperture with a radius of  $4''$ , or about 10,000 km at the distance of the comet) reported by B. T. Bolin et al. (2025).

## 6. Discussion

### 6.1. Discoverability of 3I/ATLAS

The SV survey is intended to behave much like the operations LSST survey strategy. In the SV survey, observations are typically obtained in pairs of exposures separated by approximately 30 minutes, as is the case in the operations survey. However, the SV survey is attempting to gather on the order of 1–2 yr worth of operations LSST images (about 150 exposures) within 2–3 months of commissioning time. To achieve this goal, the pointings within the main SV footprint are generally covered every night, rather than every few nights as in the operations survey. Additionally, the primary SV survey footprint is much smaller than the full LSST footprint. The primary SV survey covers a region along the ecliptic plane, stretching across a wide variety of galactic latitudes, including the Galactic plane itself. This provides tests of pipelines in both crowded and less-dense fields, as well as the maximum opportunity to commission the solar system linking pipelines.

The SV survey is both similar and dissimilar to the nominal upcoming LSST (baseline\_v4.0; L. Jones et al. 2025; P. Yoachim 2025) during comparable periods (i.e., between May and August, centered on 3I's discovery). The SV footprint is much more compact, predominantly following the ecliptic plane, with the exception of the deep drilling fields. While the exact frequency and quality of images may differ, both SV and LSST provide relatively uniform coverage over the regions of sky included.

An early simulation of the entire SV survey period was released alongside C. Claver et al. (2025). This simulation was created by the Feature Based Scheduler (E. Naghib et al. 2019; P. Yoachim et al. 2025a), much as the baseline operations survey is simulated. As the SV survey progresses, these simulations are updated by including information about

exposures acquired to date, obtained from the LSST Consolidated Database (K. T. Lim 2025), alongside attempts to improve the fidelity of the observatory model. The already-acquired exposure information is fed into the scheduler, then the simulation is continued for the remainder of the SV period. One such simulation was created containing the pointing history of the SV survey as of the start of observing on UT 2025 July 14 ('sv\_20250714'), which was used to evaluate both the likelihood of acquiring 3I/ATLAS in already-acquired visits and the possibility of future detections.

We used the ISO survey simulation framework outlined in R. C. Dorsey et al. (2025) to simulate the probabilistic observability of 3I/ATLAS in the LSST SV survey. We simulate 10,000 clones, each sampled from the covariance matrix of 3I/ATLAS's orbit (retrieved from JPL Horizons on 2025 July 15), and assess which SV pointings would have observed an object of similar absolute magnitude and color (Table 2), applying the LSST solar system processing criteria for moving object discovery. For this analysis, we use the preliminary value of  $H_r \sim 12.5$  for 3I/ATLAS that was available at the time of this analysis. As anticipated, all clones were detected and subsequently discovered within the SV survey: the apparent magnitude of 3I/ATLAS ( $m_r \sim 18$  mag) is 5 mag brighter than the median limiting magnitude of LSST in the  $r$  band (S1). For 95% of the clones, the first successful observation occurred on UT 2025 June 21 (MJD 60847.155), and discovery occurred  $\sim 13$  days later, on UT 2025 July 4 (MJD 60860.998). None of the clones were discovered earlier than UT 2025 July 2 (the date of discovery by ATLAS). This simulation demonstrates that had the SV begun 2 weeks earlier and pipelines run as in LSST, then LSST may have indeed discovered 3I/ATLAS prior to ATLAS.

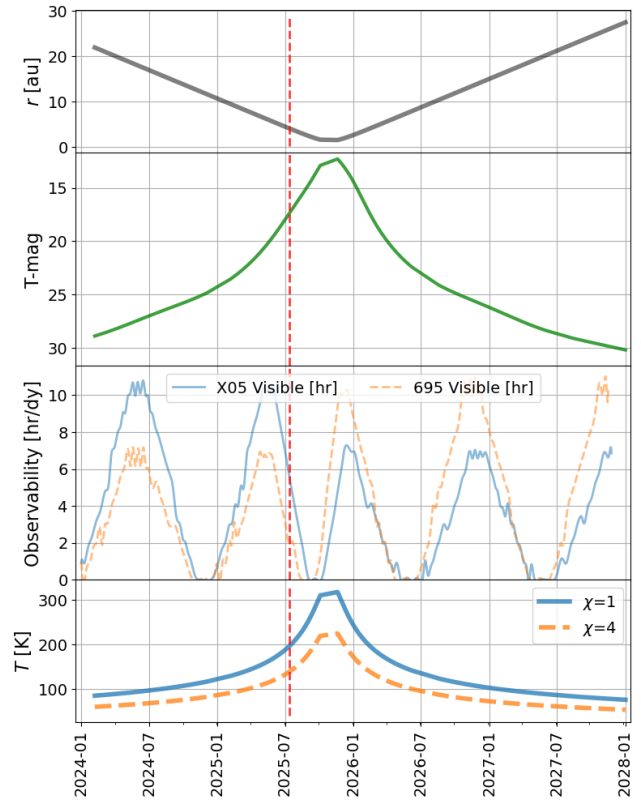
### 6.2. Thermophysical Modeling

To get a general sense of the rate of temperature change for an airless body at a given distance, we make use of a simple thermophysical model, following H. H. Hsieh et al. (2015) and C. O. Chandler et al. (2020), whereby a body's heliocentric distance as a function of temperature is given by

$$R(T) = \sqrt{\frac{F_{\odot}(1-A)}{\chi[\epsilon\sigma T^4 + Lf_D\dot{m}_S(T)]}} \text{ au.} \quad (7)$$

Here,  $F_{\odot} = 1360 \text{ W m}^{-2}$  is the solar flux at 1 au,  $A = 0.05$  is the assumed Bond albedo,  $\epsilon = 0.9$  is the assumed infrared emissivity of the ice,  $T_{\text{eq}}$  is the equilibrium temperature,  $\sigma = 5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$  is the Stefan–Boltzmann constant,  $L$  is the latent heat of sublimation,  $f_D$  is the “diffusion barrier factor” accounting for emission blocked by overlaying material like regolith,  $\dot{m}_S(T)$  is the mass-loss rate as illustrated in C. O. Chandler et al. (2020). The parameter  $\chi$  captures rotational and axial-tilt effects on insolation:  $\chi = 1$  corresponds to a “slab” perpetually facing the Sun (resulting in maximum heating),  $\chi = \pi$  to a rapid rotator with zero tilt, and  $\chi = 4$  is the value we adopt for an isothermal, fast-rotating body in thermodynamic equilibrium.

Figure 12 shows the results of this modeling, along with several other metrics useful for understanding the discovery and future observations of 3I/ATLAS. 3I/ATLAS was at its peak observability (number of hours at night that an object is above the horizon) during 2025 June, and it will be less observable from NSF-DOE Vera C. Rubin Observatory during



**Figure 12.** 3I/ATLAS metrics plotted vs. time from UT 2024 January 1 to UT 2028 January 1. The vertical dashed red line indicates UT 2025 July 12; this is the date elements were retrieved from JPL Horizons (J. D. Giorgini et al. 1996). The  $r$  [au] panel indicates the heliocentric distance of 3I/ATLAS. The T-mag panel indicates the JPL Horizons-computed total magnitude of 3I/ATLAS; T-mag should be considered a *very* rough estimate, and is included here to provide a general sense of expected brightness behavior rather than a quantitative or predictive tool. The Observability [hr/day] panel describes the number of nighttime hours 3I/ATLAS spends above the horizon for a given UT night at the specified observatory. Kitt Peak National Observatory (695) and Rubin Observatory (X05) are chosen as representative Northern and Southern Hemisphere sites, respectively. The  $T$  [K] panel provides a simple temperature estimate for a representative airless body, where  $\chi = 4$  represents the isothermal case (e.g., fast-rotator) and  $\chi = 1$  corresponds to the “flat slab” scenario, which is the thermophysical extreme. These lines are to provide context only and do not represent actual temperatures on 3I/ATLAS.

perihelion passage as compared to Northern Hemisphere sites. We also note that 3I/ATLAS becomes too bright (i.e., saturates LSSTCam) for Rubin to observe in any filter except possibly for  $u$  and  $y$  (solar system objects are typically much fainter in these filters) until roughly 2026 July.

### 6.3. Implications for the ISO Luminosity Function

The estimated nuclear size of 3I/ATLAS ( $13.32 \pm 0.16$  mag,  $13.16 \pm 0.16$  mag,  $12.93 \pm 0.16$  mag) from LSST photometry has important implications for the size-frequency distribution (SFD) of the galactic population of ISOs. The detections of 1I/'Oumuamua and 2I/Borisov as significantly smaller ISOs ( $r \sim 100$  m and  $r \sim 400$  m, respectively) implied an intrinsically steep SFD ( $q_s \sim 3-4$ ; D. Jewitt et al. 2020), which would agree with historical nondetections of ISOs in solar system surveys. This constraint is consistent with other small-body populations within the solar system, from the “primordial” (e.g., large hot classical Kuiper Belt objects; J.-M. Petit et al. 2023) to the more

collisionally evolved (e.g., main-belt asteroids; A. Alvarez-Candal & J. Licandro 2006). However, as 3I/ATLAS has an absolute magnitude much lower than either of its predecessors, its discovery strongly disfavors a steep slope, instead favoring slopes  $q_s \lesssim 3$  (R. C. Dorsey et al. 2025). This apparent contradiction can be resolved by instead considering that the intrinsic ISO SFD, which is cumulative across all donor planetary systems, is likely not parameterized by a single slope power law. It is rather a piecewise function of several such power laws with “breaks”—forming a “wavy” SFD—similar to that demonstrated in our own solar system (W. F. Bottke et al. 2023). If the latter, 3I/ATLAS provides the first evidence to begin constraining the shape of the ISO population SFD.

## 7. Summary and Conclusions

We report the analysis of the third interstellar object (ISO), 3I/ATLAS, obtained from images taken during commissioning of the Rubin Observatory, from UT 2025 June 20 to UT 2025 July 20, coinciding with the start of the Observatory’s science validation (SV) survey. At the time of these observations, although only a portion of the data analysis and management system was deployed and verified, we obtained science-quality photometric and astrometric measurements via a combination of deploying Rubin data management software and bespoke and/or manual techniques. Even in a state of early commissioning, our analysis shows that Rubin Observatory is already capable of delivering high-grade science photometric and astrometric observations of solar system small bodies.

Below, we summarize our key findings:

1. Rubin images clearly show the ISO 3I/ATLAS with a dust coma, indicative of activity. These observations provide the earliest high-resolution evidence of detected cometary activity.
2. We detect no short-term photometric variability, constraining apparent brightness variations of 3I/ATLAS to  $<0.1$  mag on timescales of a week.
3. Rubin multifilter photometry is consistent with previous observations in the literature, with significantly smaller error bars. We report measured colors of  $g - r = (0.657 \pm 0.013)$  mag,  $r - i = (0.235 \pm 0.018)$  mag,  $i - z = (0.147 \pm 0.042)$  mag, and  $z - y = (0.047 \pm 0.052)$  mag.
4. In Rubin’s observations leading up to (and including) the discovery of 3I/ATLAS, the coma’s radius appeared to increase slightly over the 11 days from  $\sim 6520$  km (UT 2025 June 21) to  $\sim 9380$  km (UT 2025 July 2) as measured from azimuthally averaged radial profiles. We estimate an increase in coma level of  $\Delta\eta \sim 0.5$  between 2025 June 21 and 2025 July 2, which we assume to be a lower limit for several reasons, including that 3I/ATLAS was observed nearly head-on (very low phase angle) and the tail could have extended far along the  $z$ -axis, as projected on the sky.
5. We obtain a lower-limit  $V$ -band absolute magnitude of  $H_V = 13.32 \pm 0.16$  mag and an equivalent upper-limit effective radius of  $(6.6 \pm 0.5)$  km for the nucleus, assuming a spherically symmetric steady-state coma, which we note is substantially larger than a later HST-derived nucleus size upper limit of  $r \leq 2.8$  km. Using the HST-derived nucleus size, we estimate a near-nucleus

dust-to-nucleus scattering cross-sectional ratio of  $\eta \gtrsim 13$  for 3I/ATLAS on UT 2025 July 2. We estimate a mass-loss rate ranging from 10–100 kg s<sup>−1</sup>, depending on the grain sizes assumed to dominate, and we compute  $Af\rho = (315 \pm 15)$  cm for data obtained on UT 2025 July 2.

6. If the Rubin solar system processing pipelines had been processing the commissioning data in real time, our modeling shows that there were sufficient SV observations to identify 3I/ATLAS as a moving object.
7. Analysis of the derived astrometry suggests that for bright high signal-to-noise ratio (SNR) and extended active small bodies, the combination of Rubin’s large aperture and LSSTCam’s pixel scale is less impacted by asymmetrical coma, providing precise positions for deriving accurate orbital parameters.
8. Positional measurements with Rubin are highly precise (of order 3 mas) when evaluating Gaia quasars, but a notable ( $\sim 20$  mas) decl. offset caused by external factors comprises roughly 25% of the positional uncertainty for 3I/ATLAS, with the balance due to the cometary nature of the object.

The spatial number density of ISOs remains poorly constrained, with forthcoming surveys expected to significantly advance our understanding of this population. Given its large étendue, the Legacy Survey of Space and Time (LSST) is expected to play a major role in this endeavor, with R. C. Dorsey et al. (2025) estimating that it will identify  $\sim 5$ – $50$  ISOs over its nominal 10 yr lifetime. The discovery of a third macroscopic body originating from outside of our solar system by the Asteroid Terrestrial-impact Last Alert System (ATLAS) lends further credence to this view, providing tantalizing evidence that a large reservoir of similar bodies may exist within reach of the discovery capabilities of Rubin (N. V. Cook et al. 2016; T. Engelhardt et al. 2017; D. Marčeta & D. Z. Seligman 2023; R. C. Dorsey et al. 2025). If this is correct, we are about to enter a decade of large-scale discoveries, follow-up, and characterization of this exciting new population.

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*Facilities:* Rubin:Simonyi (LSSTCam).

*Software:* astropy (Astropy Collaboration et al. 2013, 2018, 2022), astrometry.net (D. Lang et al. 2010), astroquery (A. Ginsburg et al. 2019), ChatGPT (coding; OpenAI 2023), find\_orb (B. Gray 2022), Grammarly, GRSS (R. Makadia et al. 2025), JPL Horizons (J. D. Giorgini et al. 1996), Layup,<sup>160</sup> Matplotlib (J. D. Hunter 2007), numba (S. K. Lam et al. 2015), NumPy (C. R. Harris et al. 2020), OverLeaf, pandas (J. Reback et al. 2022), PyTorch (A. Paszke et al. 2019), rubin\_scheduler (E. Naghib et al. 2019; P. Yoachim et al. 2025a), rubin\_sim (R. L. Jones et al. 2014; P. Yoachim et al. 2025b), SAOImageDS9 (W. A. Joye 2006), SCARLETT (P. Melchior et al. 2018), SciPy (P. Virtanen et al. 2020) Siril,<sup>161</sup> SkyBot (J. Berthier et al. 2006), sbpy (M. Mommert et al. 2019), Sorcha (S. R. Merritt et al. 2025; M. J. Holman et al. 2025), uncertainties (version 3.0.2), a python package for calculations with uncertainties by E. O. Lebigot.<sup>162</sup>

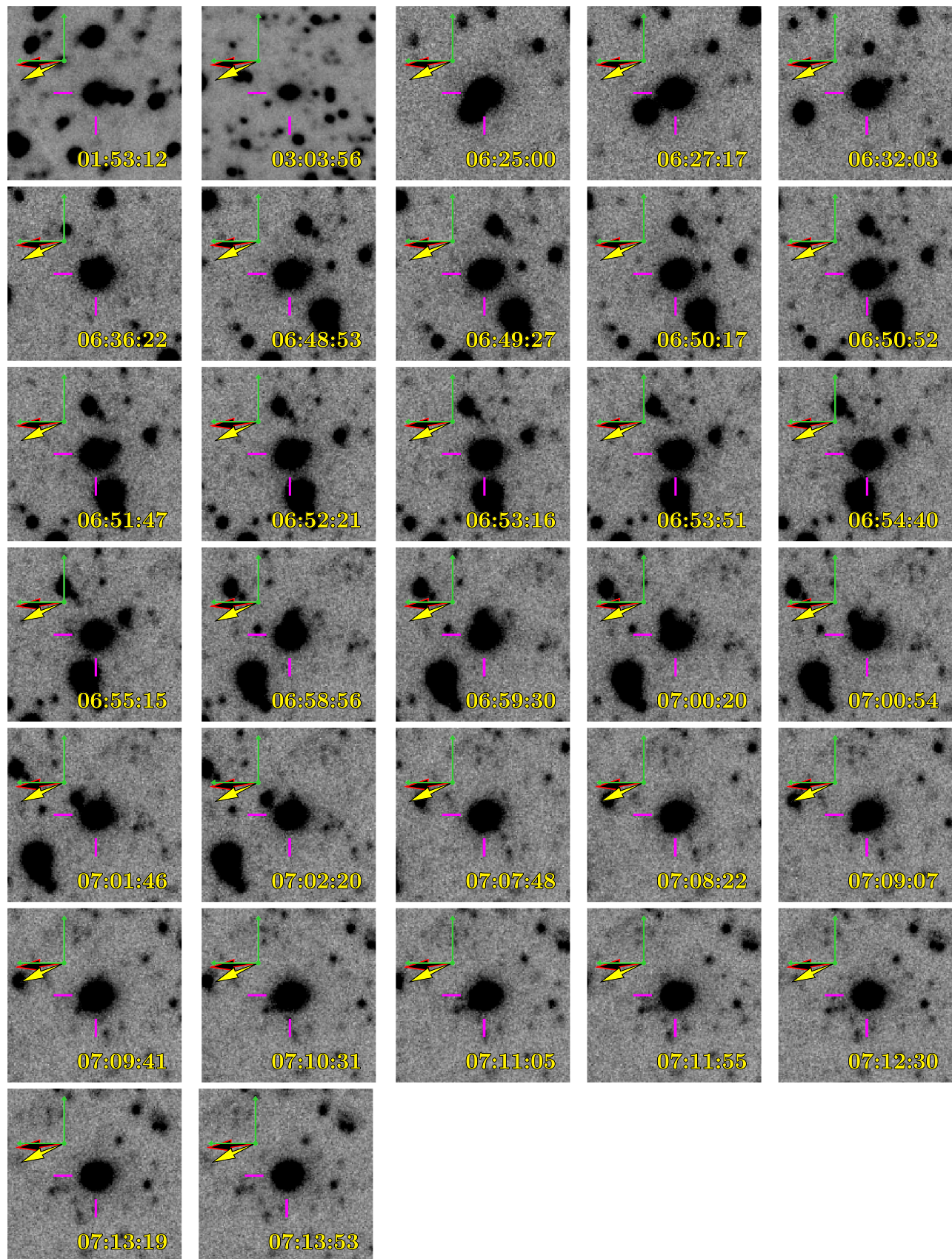
## Appendix

This appendix shows additional images of 3I/ATLAS from NSF-DOE Vera C. Rubin Observatory, in Figures A1, A2, A3, and A4; the first (precovery) gallery can be found in Figure 2. All images were produced by initially following the methods outlined in C. O. Chandler et al. (2024). We also reprojected images such that north is up and east is left (Rubin images are acquired at varying rotation angles) and mosaicked the images for cases where more than one chip was in the FOV. In all cases, the on-sky positions were provided by the JPL Horizons ephemeris service.

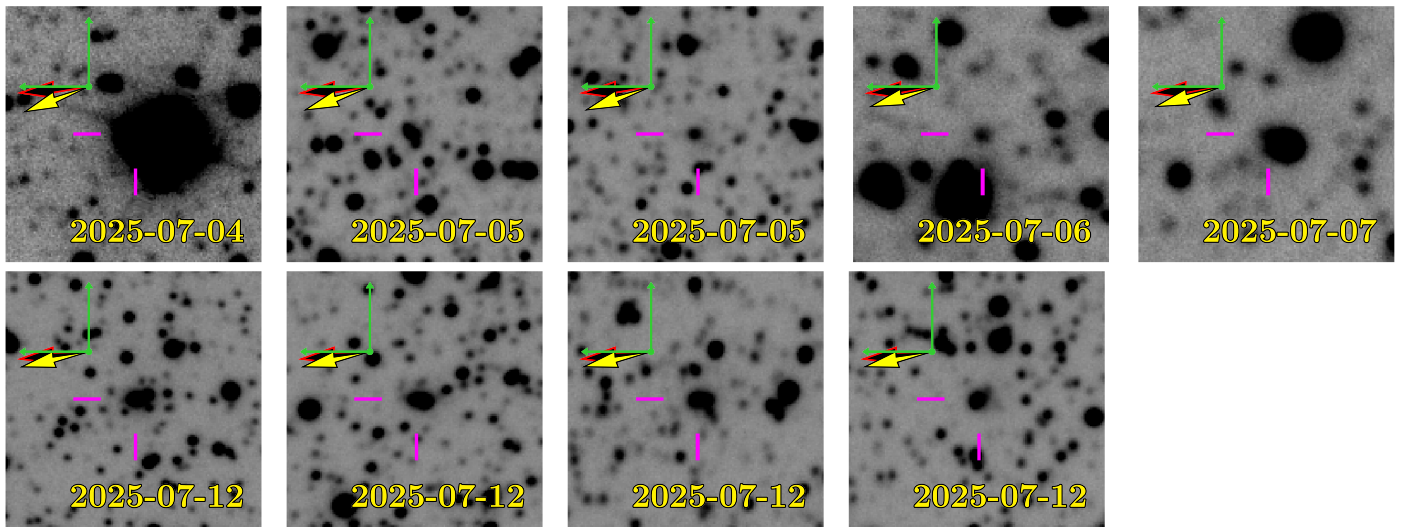
<sup>160</sup> <https://github.com/Smithsonian/layup>

<sup>161</sup> <https://siril.org>

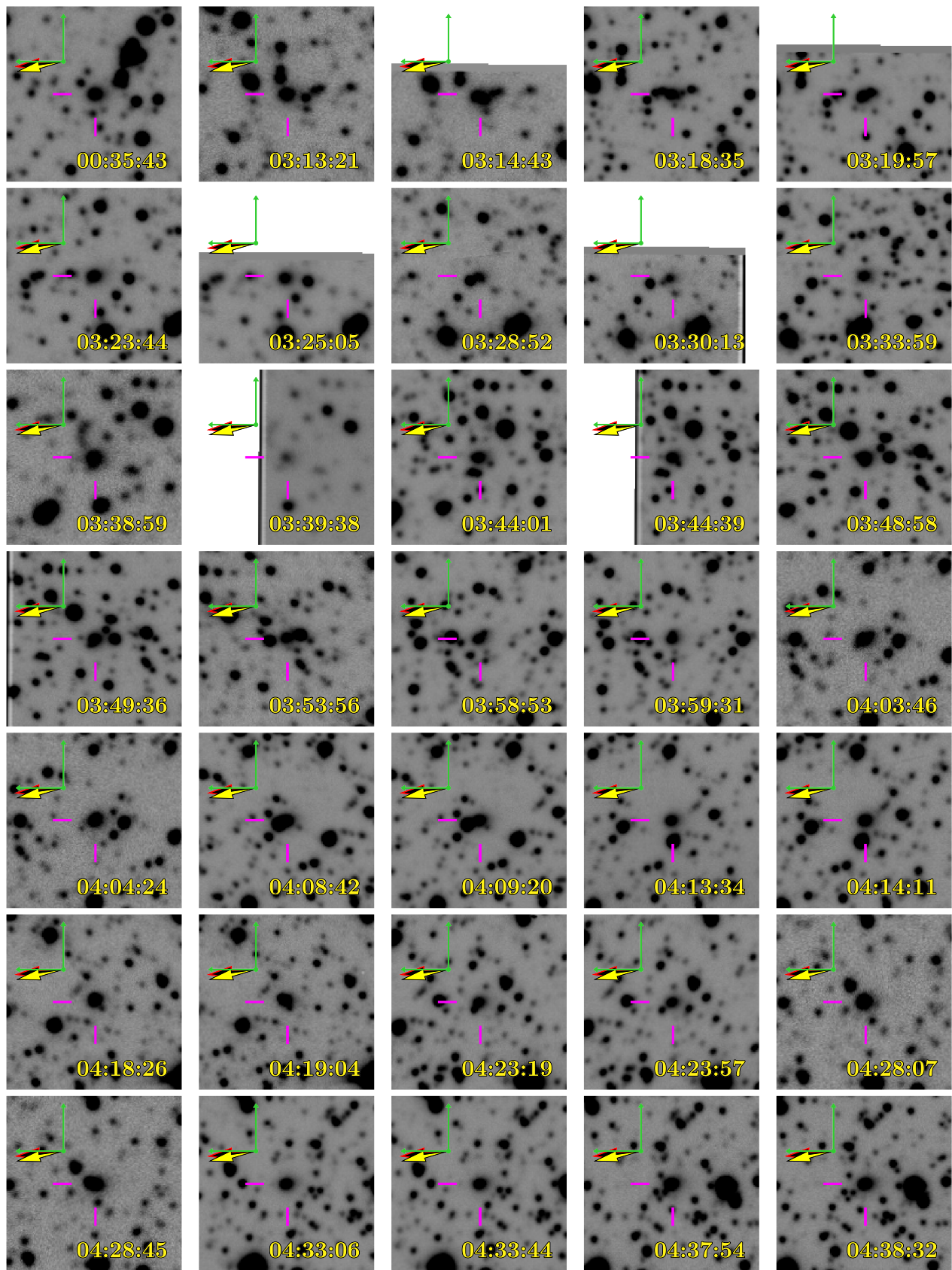
<sup>162</sup> <http://pythonhosted.org/uncertainties/>



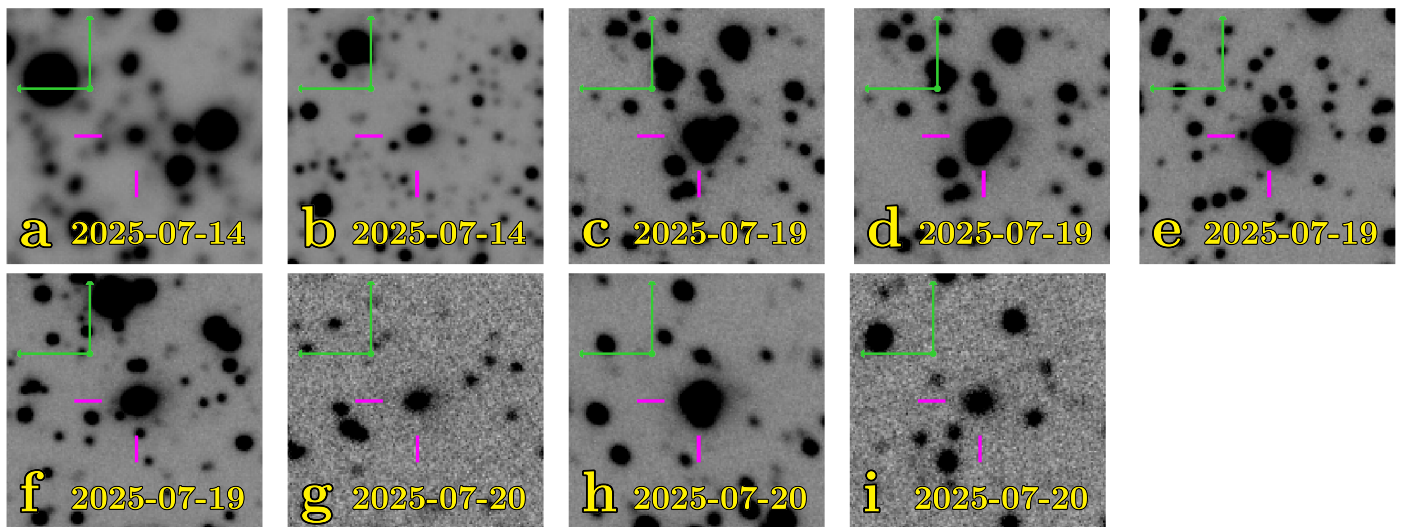
**Figure A1.** 3I/ATLAS (centered and indicated by magenta ticks) imaged on UT 2025 July 3 by the NSF-DOE Vera C. Rubin Observatory as a part of commissioning. All images are 30 s *r*-band exposures with north up and east left (green arrows), and the antisolar  $\ominus$  (yellow arrow) and antimotion  $\rightarrow v$  (red-outlined black arrow) vectors shown inset at the top-left. The TAI exposure midpoint times are given.



**Figure A2.** 3I/ATLAS (center, indicated by magenta ticks) observations after UT 2025 July 3 and before the target of opportunity (ToO) of UT 2025 July 13. North is up, and east is left (green arrows), with the antisolar (yellow arrow) and antismotion (black arrow with red outline) shown.



**Figure A3.** 3I/ATLAS (center, indicated by magenta ticks) ToO observations from UT 2025 July 13. North is up, and east is left (green arrows), with the antisolar (yellow arrow) and antimotion (black arrow with red outline) shown.



**Figure A4.** 3I/ATLAS (center, indicated by magenta ticks) serendipitous observations from UT 2025 July 14 onward. North is up, and east is left (green arrows), with the antisolar (yellow arrow) and antimotion (black arrow with red outline) shown.

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
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