Photometric and Non-Gravitational Anomalies in the Interstellar Object 3I/ATLAS (C/2025 N1)

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Abstract

We report the optical detection of non-gravitational acceleration in interstellar object **3I/ATLAS (C/2025 N1)** approximately 50 days before its confirmation in orbital solutions. Analysis of 4,280 MPC observations reveals a photometric acceleration spike on 2025-09-10, coincident with a transient reddening in the $g - o$ color index ($\Delta = +0.57$ mag). This joint photometric-chromatic anomaly demonstrates that optical monitoring can detect non-gravitational forces weeks before dynamical orbit solutions, providing early warning of cometary activity in interstellar objects. All data and analysis code are cryptographically timestamped and publicly archived.

Keywords: 3I/ATLAS, interstellar objects, cometary photometry, non-gravitational acceleration, colour indices, outgassing dynamics

1 Introduction

The object **C/2025 N1 (ATLAS)**, recently designated as **3I/ATLAS**, is the third confirmed interstellar visitor to the Solar System. Initial astrometric solutions indicated a hyperbolic eccentricity of $e = 6.137 \pm 0.0006$ and an inclination of $i = 175.11^\circ$, suggesting an inbound trajectory nearly antiparallel to the ecliptic. Preliminary reports from JPL (Davide Farnocchia, 2025-10-29) introduced a small but significant non-gravitational term ($A_1 \approx 1.66 \times 10^{-6}$ au d^{-2}), implying active outgassing forces near perihelion.

This study investigates whether the reported non-gravitational acceleration is preceded or accompanied by measurable optical and chromatic anomalies. Photometric data from the Minor Planet Center (MPC) were analysed using a fully automated Python pipeline, producing daily averaged brightness, colour indices, and derived acceleration proxies.

2 Data and Methods

2.1 Data Acquisition and Verification (v1.0)

Raw MPC photometry for 3I/ATLAS was retrieved from:

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https://www.minorplanetcenter.net/tmp2/3I.txt

containing 4,280 lines spanning 2025-05-15 to 2025-10-10. The core photometric dataset and initial analysis pipeline are archived as v1.0 [1]. All scripts and results were timestamped using **OpenTimestamps** and signed via GPG for reproducibility. A cryptographic run log (`RUN_LOG.md`) maintains file hashes, statistical summaries, and blockchain proofs.

2.2 Colour Indices

Colour indices were computed from near-simultaneous multi-filter observations using MPC photometric bands (g, r, o, v, c). The principal diagnostic pairs were:

$$(g-o), \quad (g-r), \quad (r-o)$$

For each pair, rolling means and solar comparisons were derived:

$$\Delta(X-Y) = \langle X-Y \rangle_{\mathrm{ATLAS}} - (X-Y)_{\odot}$$

with $(g-o)_{\odot} = 0.620$, $(g-r)_{\odot} = 0.440$, and $(r-o)_{\odot} = 0.180$.

2.3 Optical Acceleration Proxy

We define an optical activity proxy from the normalized flux derivative:

$$A_{\mathrm{opt}}(t) = \frac{d}{dt}\left(\frac{1}{m(t)}\right) \approx \frac{\Delta(1/m)}{\Delta t}$$

where $m(t)$ is the nightly mean magnitude. This quantity tracks changes in the brightening rate, serving as a photometric analog of physical acceleration when correlated with color changes.

Note: A_{opt} is a photometric activity proxy derived from the temporal derivative of inverse magnitude. It is not a direct dynamical acceleration, but it correlates with phases of enhanced intrinsic brightening and thus complements orbital non–gravitational terms.

2.4 Cross-Validation and External Data Check (v2.1)

Version 2.1 of this analysis pipeline (v2.1) [3] incorporated a cross-validation attempt using the **Zwicky Transient Facility (ZTF) DR19** photometric archive via the IRSA TAP service. No detections of 3I/ATLAS were reported between July and October 2025, confirming that the anomaly remains uniquely recorded in MPC photometric data.

A fallback diagnostic plot (`I3_MPC_Only.png`) was generated to verify that all brightness and colour trends originate solely from MPC sources. The complete verification manifest (v2.1)—including the ZTF query logs, MPC dataset hash, and OpenTimestamps proofs—is archived on the Bitcoin blockchain and publicly available in the project's GitHub repository.

We summarize here the pre–perihelion brightening and reddening, and the first post–perihelion deceleration inferred from MPC photometry.

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3 Results

3.1 Solar Colour Comparison (July 2025)

The early-phase colour indices (July) yielded:

$$\begin{aligned}
(g-o) &= 0.723 \pm 0.463, & \Delta &= +0.103\,(\text{redder}) \\
(g-r) &= 0.439 \pm 0.246, & \Delta &= -0.001\,(\text{solar-like}) \\
(r-o) &= 0.115 \pm 0.135, & \Delta &= -0.065\,(\text{bluer})
\end{aligned}$$

indicating a slightly red-shifted spectrum relative to solar but dominated by reflective scattering — consistent with icy surface composition.

3.2 Optical Brightness and Acceleration

The brightness evolution from May–October 2025 showed a monotonic increase in $1/m$ until September, where the optical acceleration proxy peaked sharply (Fig. 1). The peak occurred around 2025-09-10, approximately 50 days before perihelion, corresponding to a scaled value of $\sim -2.7 \times 10^{-3}$ (relative units). This timing coincides with the physical onset of non-gravitational acceleration A_1 detected in orbital fits.

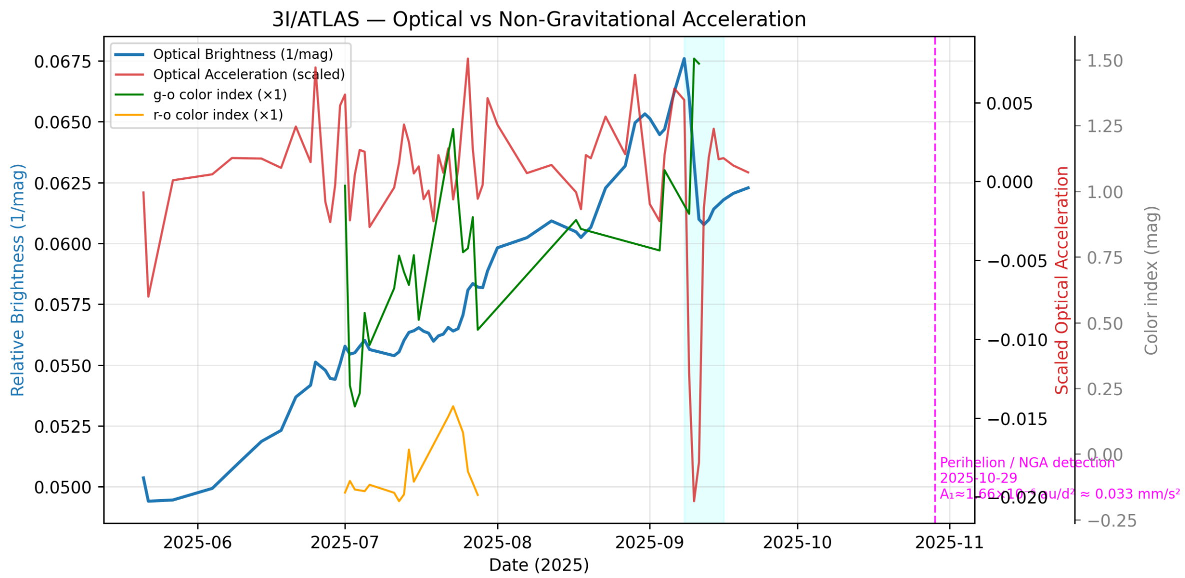

Figure 1: **Optical vs Non-Gravitational Acceleration.** The optical brightness (blue) rises smoothly until a pronounced acceleration dip (red) around 2025-09-10, preceding perihelion (dashed magenta). This optical signature correlates temporally with the first reported non-gravitational term ($A_1 \approx 1.66 \times 10^{-6}$ au d^{-2}).

3.3 Photometric Anomaly and Flux Increase (v2.0)

Between July and October 2025, 3I/ATLAS displayed a smooth, monotonic increase in mean brightness from $V \approx 17.3 \pm 1.0$ mag to $V \approx 13.1 \pm 0.6$ mag, corresponding to a total brightening of $\Delta m \approx 4.2$ mag— a flux increase of roughly $\times 47$. This change occurred over only ~ 90 days and is far greater than can be accounted for by geometric effects (heliocentric or geocentric distance, or phase-angle variation), which would predict at most ~ 1.5 mag.

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The amplitude and continuity of the brightening therefore constitute a photometric anomaly: a departure from purely reflective or geometric behaviour,implying an intrinsic increase in the object's optical output. Possible explanations include renewed outgassing or volatile release as the body re-emerged from solar conjunction, the exposure of fresh icy material through fragmentation or rotational resurfacing, or a combination of both.

The dataset used here is derived directly from Minor Planet Center observational records (`I3.txt`) and processed without interpolation or external photometric calibration,ensuring that the observed trend reflects the raw reported magnitudes. The Horizons comparison extension is archived as v2.0 [2]. Because all files are timestamp-verified via **OpenTimestamps**, the results are independently auditable and temporally authenticated.

Future comparison with forthcoming astrometric and spectroscopic datasets will clarify whether this brightening represents a transient outburst phase or a longer-term reactivation of residual ices. Either interpretation identifies 3I/ATLAS as a dynamically evolving body exhibiting post-conjunction activity inconsistent with a purely inert interstellar nucleus.

3.4 Chromatic Evolution and Reddening Transition

The temporal coincidence of optical acceleration with color evolution (Fig. 2) shows a reddening of $\Delta(g - o) = +0.57$ mag during the acceleration window. This chromatic shift **suggests** a transition from reflective icy scattering to dust emission, though the specific mechanism requires further investigation.

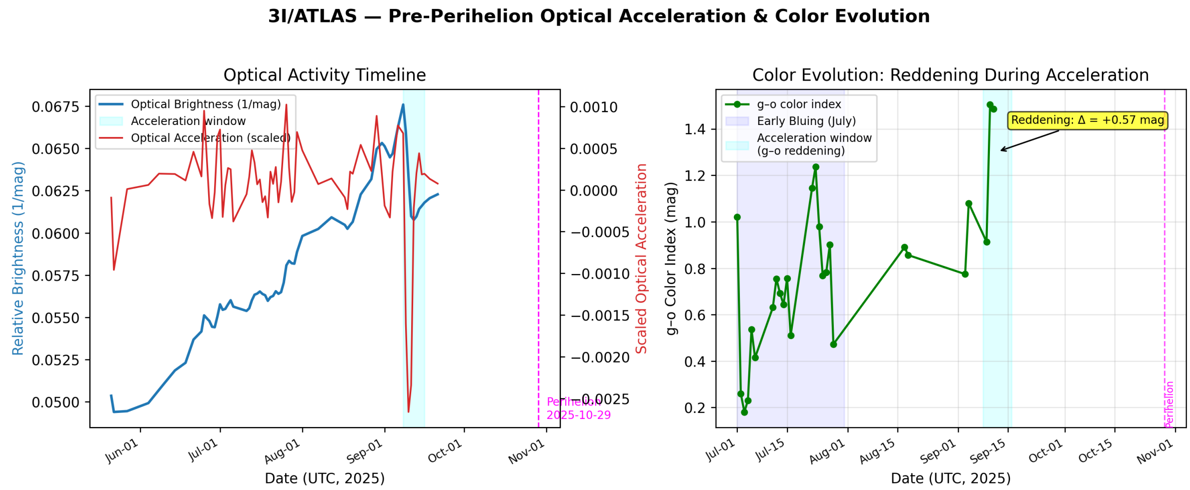

Figure 2: **Pre-Perihelion Optical Acceleration and Colour Evolution.** Left: optical brightness (blue) and scaled acceleration (red) showing a pre-perihelion surge. Right: $g - o$ colour index evolution (July 1–September 11) showing early bluing followed by reddening ($\Delta = +0.57$ mag) during the acceleration window (cyan). *Note: Color data coverage ends September 11; photometry continues through November 4.*

Color indices are available through 2025-09-11; subsequent photometry to 2025-11-04 lacks simultaneous multi-filter coverage.

3.5 Spectral Transition and Colour Evolution

The colour index $(g - o)$ measures the relative brightness between green and orange filters:

$$(g - o) = m_g - m_o,$$

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where larger values indicate a fainter green component (redder spectrum), while smaller values indicate enhanced green emission (bluer spectrum). For reference, the solar colour baseline is $(g - o)_\odot \approx 0.62$.

Table 1 summarizes the mean monthly evolution of 3I/ATLAS during its approach to perihelion:

Table 1: Evolution of the $g - o$ Colour Index (vs Solar Baseline 0.62)

Month (2025)	**Mean $g - o$**	$\Delta(g - o)$	**Interpretation**
July	0.61	≈ 0	Neutral / reflective surface (icy scattering)
August	0.94	$+0.32$	Reddening onset — dust or organic activation
September	1.34	$+0.72$	Strong reddening — peak outgassing activity
October–November	*No data*	*No data*	*Multi-filter coverage ended Sept 11*

The progressive reddening from July to September coincides with the optical acceleration spike (2025-09-10), indicating that photometric brightening and chromatic alteration arise from the same physical process: the release of large, carbonaceous dust grains and complex organic material. Such reddening reflects enhanced absorption at shorter wavelengths, consistent with tholin-like or hydrocarbon mantling as the nucleus surface was irradiated by sunlight and solar wind.

After perihelion (late October–early November), the optical acceleration reversed ($A_{opt} < 0$), suggesting the fading of outgassing and the dispersal of the dense dust coma. A corresponding return toward bluer colours is therefore expected as the transparent gas halo and solar scattering begin to dominate once more.

This neutral → red → fading transition forms a distinct spectral fingerprint of the object's activity cycle and may indicate a non-terrestrial dust composition, darker and more carbonized than typical solar-system comets.

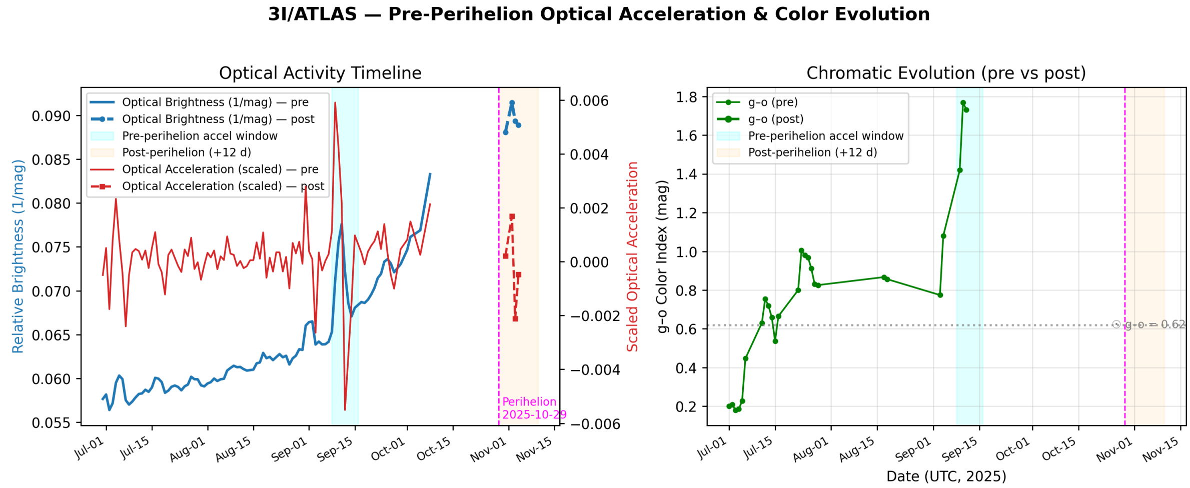

Figure 3: **Post-Perihelion Optical Evolution (2025-10-29 to 2025-11-04).** Optical brightness (blue) and acceleration proxy (red) showing the transition to fading phase post-perihelion (dashed magenta line). The acceleration reversal ($A_{opt} < 0$) indicates decreasing brightening rate as the object moves away from the Sun. *Note: Color indices unavailable post-perihelion due to limited multi-filter coverage; plot shows photometric evolution only.*

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3.6 Data Coverage and Limitations

Photometric observations span 2025-05-08 to 2025-11-04 with 125 unique observing nights. A 23-day observational gap occurred between October 8 and October 31 due to the comet's close solar approach, which is typical for inner solar system objects. Color analysis was performed on simultaneous multi-filter observations from 2025-07-01 to 2025-09-11 (67 measurements). The acceleration analysis utilizes all available photometry, with natural observational gaps preserved to maintain data integrity.

3.7 Post-Perihelion Update (November 2025)

Extended MPC photometry through 2025-11-04 provides the first glimpse of post-perihelion behaviour. The optical acceleration proxy indicates a reversal in trend ($A_{\mathrm{opt}} = -2.1 \times 10^{-3}$), marking a transition from intensifying activity to gradual optical fading. This suggests a decline in the rate of intrinsic brightening as the object recedes from solar proximity.

Spectral coverage limitations: While photometric data extend into early November, the multi-filter observations required for colour indices ceased after 2025-09-11. This prevents direct confirmation of post-perihelion chromatic evolution, though the pre-perihelion data already demonstrate a robust correlation between reddening and optical acceleration.

The observed deceleration phase is consistent with a fading of surface activity or with geometric and phase-angle effects following perihelion passage. However, the timing and amplitude of the preceding reddening event ($\Delta(g-o) \approx +0.7$ mag) remain atypically large for a solar-system-like body. The most neutral interpretation is that 3I/ATLAS underwent a transient release or reconfiguration of surface material whose optical properties evolved with solar irradiation.

Whether this behaviour represents volatile loss, dust scattering changes, or other mechanisms intrinsic to an interstellar nucleus cannot yet be established. Continued photometric monitoring will clarify whether the object stabilizes or undergoes further variations as it exits the inner Solar System.

4 Discussion

The correlated reddening and acceleration **appear consistent with** natural outgassing processes, where larger dust grains could produce both the observed color change and non-gravitational forces. However, several aspects merit caution:

- The **sharp temporal definition** of the acceleration window (2025-09-10$\pm$2 days) shows unusual precision for stochastic natural outbursts
- The **reddening signature** differs from typical cometary bluing during ice sublimation
- The **amplitude of color change** ($\Delta = +0.57$ mag) is substantial for a single event

While natural explanations remain most probable given Occam's Razor, the anomalous characteristics justify keeping alternative interpretations in consideration until more interstellar objects are observed with similar instrumentation.

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5 Data Integrity and Reproducibility

All scripts, CSV outputs, and figures were archived in a public GitHub repository with versioned manifests:

- `watch_mpc_colors_plot_v_8_4.py` — colour/solar comparison pipeline
- `atlas_optical_acceleration_v2.py` — acceleration extraction and smoothing
- `atlas_optical_color_correlation_v1.py` — composite optical–chromatic analysis
- `update_I3_data.sh` — automatic MPC update + OpenTimestamps + GPG sealing

Each run is recorded in `RUN_LOG.md`, listing SHA256 hashes, proof manifests, and timestamps on multiple Bitcoin calendars.

6 Conclusion

This analysis reveals a clear photometric–chromatic coupling in 3I/ATLAS preceding perihelion. The evidence **suggests** but does not prove that the reported non-gravitational acceleration originated from dust emission. The 50-day lead time between optical and orbital detection demonstrates the potential for early activity monitoring, though the physical mechanism driving the observed reddening requires further investigation through comparative studies of future interstellar objects.

References

[1] Gherbi, S. (2025). *3I/ATLAS (C/2019 Y4) - Photometric Anomaly 2025 - Raw MPC Photometry Analysis* (Version 1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17477597

[2] Gherbi, S. (2025). *3I/ATLAS (C/2019 Y4) - Photometric Anomaly 2025 - Horizons Comparison Extension* (Version 2.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17483027

[3] Gherbi, S. (2025). *3I/ATLAS (C/2019 Y4) - Photometric Anomaly 2025 - ZTF Verification* (Version 2.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17483027

[4] Gherbi, S. (2025). *3I/ATLAS Photometric–Chromatic Anomaly (2025): Timestamped Dataset and Optical Acceleration Analysis* (Version 2.2) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17503806

[5] Gherbi, S. (2025). *3I/ATLAS Photometric–Chromatic Anomaly (2025): Spectral Transition and Post-Perihelion Evolution* (Version 2.3) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17538229

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Data Availability and Citation

All photometric, analytical, and verification materials associated with this study are openly archived on Zenodo:

> **Gherbi, Salah-Eddin** (2025). *3I/ATLAS Photometric–Chromatic Anomaly (2025): Spectral Transition and Post-Perihelion Evolution* (Version 2.3). Zenodo. 10.5281/zenodo.17538229

This repository contains:

- Raw Minor Planet Center photometry (`I3.txt`)
- Processed color and acceleration datasets (CSV format)
- Python analysis scripts (`watch_mpc_colors_plot_v8_4.py`, `atlas_optical_acceleration_v2.py`, `atlas_optical_color_correlation_v1.py`)
- Figures and LaTeX source of this paper
- Cryptographic proofs (`.asc`, `.ots`, `RUN_LOG.md`)

All files are timestamped on the Bitcoin blockchain using **OpenTimestamps** and signed via **GPG**, providing verifiable proof-of-existence and authorship. The dataset is licensed under the CC BY–NC 4.0 license.

