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IS THE ANTI-TAIL OF 3I/ATLAS COMPOSED OF MACROSCOPIC NON-VOLATILE OBJECTS?

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ABSTRACT

I suggest that the teardrop shape of the coma in post-perihelion images of 3I/ATLAS is a result of a large number of macroscopic non-volatile objects that separated from it as a result of its non-gravitational acceleration away from the Sun.

1. INTRODUCTION

High-resolution imaging of the interstellar object 3I/ATLAS with the Hubble Space Telescope (HST) on July 21, 2025 showed a sunward anti-tail with an apparent 2:1 elongation in the plane of the sky (Jewitt et al. 2025a). The small misalignment angle $\alpha \sim 10^\circ$ between the line-of-sight and the comet-Sun axis, increases the three-dimensional axis ratio by a geometric factor of $\sim 1/(\sin\alpha) = 5.76$. Other observations (Sierra-Ricart et al. 2025; Cordiner et al. 2025; Chandler et al. 2025) confirmed this feature as the most definite instance of a sunward anti-tail that is not a conventional cometary tail - commonly pushed away from the Sun by solar radiation and wind but sometimes displaying a portion that appears to point toward the Sun due to viewing perspective.

An earlier paper (Keto & Loeb 2025) that I co-authored suggested that the anti-tail seen on July 21 at a heliocentric distance of 4 AU can be explained by a coma model where the scattering is dominated by volatile ice grains with lifetimes long enough to travel the extent of the observed anti-tail, but short enough that the grains are destroyed by sublimation before solar radiation pressure sweeps them into a conventional tail on the opposite side of the comet. In this case, the nucleus must be rotating slowly enough that the surface temperature responds quickly to the illumination angle, so that the mass flux from the sunward surface exceeds that from the rest of its surface by a factor sufficient to produce the observed sunward elongation.

Here, I consider an alternative interpretation of the anti-tail, associated it with scattering by a swarm of macroscopic non-volatile object that are not affected by the solar radiation pressure or the solar wind. This alternative model is motivated by the latest post-perihelion data on 3I/ATLAS.

During the month of November 2025, post-perihelion images of the interstellar object 3I/ATLAS showed a tear-drop shape of its coma with an anti-tail extension of about an arcminute towards the Sun (Jewitt & luu 2025). This feature was also apparent in the second HST image taken of 3I/ATLAS on November 30, 2025, where the sunward extension of the sunward anti-tail is apparent out to a distance of $\sim 6 \times 10^4$ km from the nucleus[1].

On December 1, 2025, the JPL Horizons tracking of 3I/ATLAS reported[2] a non-gravitational acceleration. Its radial component - normalized at a heliocentric distance of 1 au to $A_1 = 7.2(\pm 2.1) \times 10^{-8}$ au d^{-2}, amounts to a small fraction $\Delta = 2.4 \times 10^{-4}$ of the gravitational acceleration from the Sun.

JPL Horizons scales the non-gravitational acceleration inversely with the square of the heliocentric distance (assuming CO_2 sublimation interior to 5 au), exactly as the Sun's gravitational acceleration. This means that the ratio between the two accelerations remains constant along the orbit of 3I/ATLAS.

[1] https://science.nasa.gov/blogs/3iatlas/2025/12/04/nasas-hubble-space-telescope-revisits-interste

[2] https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=3I%2FATLAS&view=VOP

2. DYNAMICS

The dominant component of the non-gravitational acceleration is in the radial direction away from the Sun. A simple way to incorporate it into the dynamics is to consider 3I/ATLAS as accelerating in response to a slightly reduced mass of the Sun, by a fraction of Δ.

If 3I/ATLAS is surrounded by a swarm of macroscopic non-volatile objects that do not share its non-gravitational acceleration, then these objects will tend to be closer to the Sun relative to 3I/ATLAS, because 3I/ATLAS is pushed away from the Sun relative to the objects through its non-gravitational acceleration. As long as these objects are much larger than micron-scale dust particles, the solar radiation pressure and solar wind will have a negligible effect on their dynamics.

Energy per unit mass is a conserved constant of motion in trajectories shaped by the Sun's gravity. However, the trajectory of 3I/ATLAS has a slightly smaller gravitational binding energy because of the reduction in the effective mass of the Sun by the non-gravitational acceleration.

If the objects started at the same velocity and position as 3I/ATLAS, then they would have a surplus in gravitational binding energy by a fraction of Δ relative to 3I/ATLAS. However, they would have the same binding energy and track 3I/ATLAS if they move at the same velocity and are displaced from its heliocentric distance by a fraction Δ.

At the current separation of 3I/ATLAS from the Sun of 2.7×10^8 km as of December 1, 2025, the displacement would imply that the objects are closer to the Sun than 3I/ATLAS by about 6.5×10^4 km if they overlapped (e.g. as a result of being broken off) at perihelion. This displacement corresponds to an angular separation of $\sim 0.8'$ in the sky at the current distance of 3I/ATLAS from Earth, ~ 1.9 au. This angular separation is comparable to the sunward elongation of the teardrop glow around 3I/ATLAS in recent images (Jewitt & luu 2025).

As long as the objects are made of refractory elements with no volatiles and do not experience non-gravitational acceleration from mass loss as a result of the solar illumination, they should maintain an anti-tail geometry - pointing always towards the Sun relative to 3I/ATLAS and converging to its location at perihelion.

3. IMPLICATIONS

A large swarm of objects could have a much larger surface area than that of 3I/ATLAS, even if the total mass in them is a small fraction of the mass of 3I/ATLAS. For example, 10^{12} similar objects carrying a total fraction of merely 10^{-3} of the mass of 3I/ATLAS would amount to a total surface area that is 10^2 times larger than that of 3I/ATLAS (since surface area scales as radius squared whereas mass scales as radius cubed). This swarm would create the appearance of a coma that reflects 99% of the sunlight in the glow around 3I/ATLAS. This is consistent with the fraction of light in the coma within the image of 3I/ATLAS taken by the Hubble Space Telescope on July 21, 2025 (Jewitt et al. 2025b).

As long as the non-gravitational acceleration of 3I/ATLAS scales inversely with the square of heliocentric distance, the spatial extent of the objects would be of order Δ times the heliocentric distance of 3I/ATLAS, always pointing towards the Sun. This model predicts that the teardrop shape towards the Sun will maintain its angular shape in the coming months.

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