

The Physics of Cometary Anti-tails as Observed in 3I/ATLAS

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ABSTRACT

Observations of interstellar comet 3I/ATLAS at 3.8 au show an elongated coma similar to a cometary tail but pointing in the direction of the Sun. This type of anti-tail, not a result of perspective, may not have been previously observed. We explain the anti-tail as an anisotropic extension of the snow line, or survival radius of a sublimating ice grain, in the direction of the Sun. The anisotropy is due to the difference in the sublimation mass flux in the solar and perpendicular directions caused by the change in the illumination angle of the cometary surface. The stronger sublimation mass flux in the solar direction results in ice grains with larger sizes, longer sublimation lifetimes, and a snow line at a larger radial distance with respect to other directions. The observed radial surface brightness profiles as a function of illumination angle are well reproduced by a Haser-type spherical outflow with constant velocity and sublimating ice grains with angularly dependent survival lengths.

Keywords: comets (280), interstellar objects (52)

1. INTRODUCTION

Observations of the interstellar object, 3I/ATLAS, by the Hubble Space Telescope (HST) on July 21, 2025 (D. Jewitt et al. 2025) revealed a faint anti-tail in the solar direction that is not due to projection. This phenomenon, observed at a distance of 3.8 au from the Sun, is not common and possibly observed for the first time in 3I/ATLAS. The anti-tail has been confirmed in other observations (J. Tonry et al. 2025; B. T. Bolin et al. 2025). In this paper, we explain the development of an anti-tail based on simple physical models of comets.

We model the coma as a spherical outflow of sublimating grains and reproduce the observed surface brightness profiles with the survival or snow-line length, the radial distance that an ice grain persists while sublimating, varying with illumination angle. Calculated surface temperatures and grain survival times indicate that the sublimation mass flux off the cometary surface must be predominantly CO₂ as observed (C. M. Lisse et al. 2025; M. A. Cordiner et al. 2025), while the grains must be H₂O ice.

From a chain of simple calculations, we determine the maximum ice grain size and terminal velocity as a function of the illumination angle to derive the survival length, $\ell = v_\infty t_{\text{life}}$, the extent of the coma as a function of illumination angle.

2. THE ANTI-TAIL IN THE HST IMAGE

Figure 1 shows two representations of the HST data. The image (*left*) is shown with a logarithmic color transfer function. Radial profiles (*right*) are shown along directions of 10, 100, 190° with respect to the coordinate axes. The profile of 10°, in the direction of the Sun, is larger than the profiles in the two perpendicular directions at 100 and 190°. The elongation of the coma toward the Sun may be called an anti-tail since it is in the opposite direction of a typical cometary tail. None of the profiles fits a single-slope power law. Their curvature suggests an exponential decrease in the number density of reflecting ice grains with distance from the nucleus as previously mentioned (D. Jewitt et al. 2025).

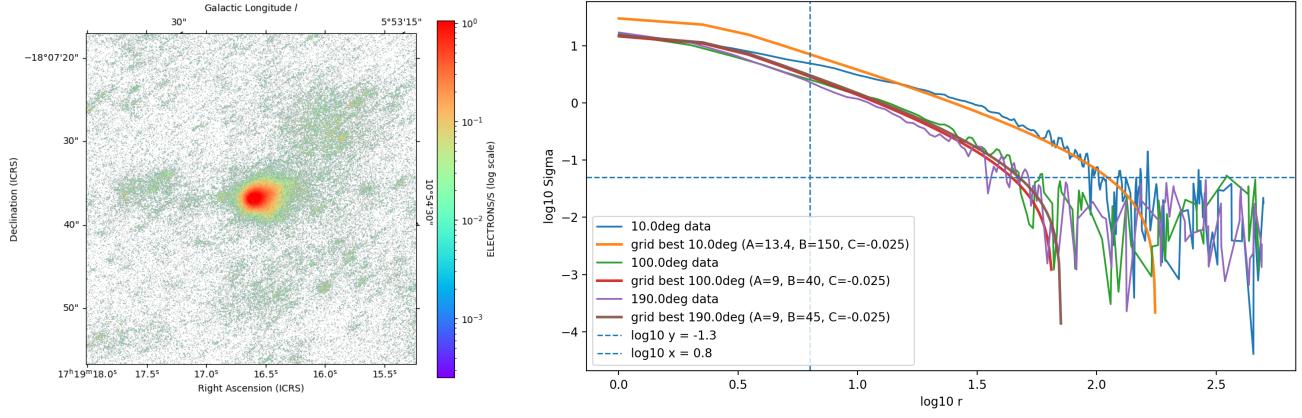


Figure 1. Left: HST image. Right: Radial profiles of the surface brightness at angles of 10° , 100° , and 190° where the angles are measured with respect to the x, y coordinate axes. The observed profiles are overlaid with fits to a model Haser-type surface brightness. The x, y axes have units of pixels ($0.04''$) and counts (electrons s^{-1}).

3. A PHYSICAL MODEL FOR THE ANTI-TAIL

We model the surface brightness profiles with a Haser-type density law (L. Haser et al. 2020) that develops from flux conservation in a constant-velocity, spherical outflow combined with destruction of the particles,

$$\frac{1}{r^2} \frac{d}{dr} [r^2 v(a) n(r, a)] = -\frac{n(r, a)}{t_{\text{life}}}. \quad (1)$$

where a is the ice grain size with lifetime t_{life} . The solution for the number density modifies the solution for a steady-state outflow by an exponential,

$$n(r, a) \propto r^{-2} \exp\left(-\frac{r}{\ell(a)}\right) \quad (2)$$

if we select a representative ice grain size to replace the ice-grain size distribution, we can use the same integral solution for the surface brightness as in the original solution of Haser developed for molecular emission. The surface brightness follows,

$$\Sigma(\rho, a) \propto \frac{Q}{4\pi v(a)\rho} 2K_0(x) \quad (3)$$

where ρ is the projected radius, Q is the mass flux of the outflow, $v(a)$ is the constant terminal velocity, K_0 is the modified Bessel function of the second kind, and $x = \rho/\ell(a)$. The horizontal dashed line on figure 1 shows the approximate noise level. The vertical dashed line is placed at three times the resolution of the HST, about 3×2 pixels. The fitting is restricted to data that lie above and to the right of the dashed lines.

The model curves that are fit to the data, give an empirical estimate for the lengths, ℓ , of the snow lines in the different directions. At a heliocentric distance of 3.8 au, the apparent length in the solar direction is 3500 km, and 1300 km in the two perpendicular directions. At this distance, the comet is moving toward both the Sun and the Earth with a projection angle of 9.6° and a foreshortening factor of 5.8. Scaling the projected radius, ρ , implies a snow-line length in the solar direction of 29,600 km.

Theoretically, we expect that the snow line or survival length of a sublimating ice grain of size a , is,

$$\ell(a) = v(a)t_{\text{life}}(a) \quad (4)$$

This suggests a process that results in a longer survival length in the sunward direction. The two factors in the survival length are the velocity of the ice grains and their survival time against sublimation.

The velocity of the ice grains is estimated with the Haser-Whipple (L. Haser 1957; F. L. Whipple 1951) model for free molecular acceleration,

$$a_d = \frac{F_{\text{drag}}}{m_d} = \frac{C_D \pi a^2 v_g J}{\rho_a a} \quad (5)$$

where C_D is the drag coefficient (~ 1); $v_g = \sqrt{8k_B T / (\pi m_g)}$ (ms^{-1}) is the gas velocity where $T < 200$ K is the surface temperature ; and J is the mass flux ($\text{kg m}^{-2}\text{s}^{-1}$) from sublimation. Integration of the acceleration with some assumptions results in the Probstein terminal velocity (M. L. Finson & R. F. Probstein 1968),

$$v_\infty \approx \sqrt{\frac{3C_D}{2}} \sqrt{\frac{v_g R_n J}{\rho_d a}} \propto J^{1/2} a^{-5/4} \quad (6)$$

where R_n is the radius of the cometary nucleus. This velocity gives us the first of the two factors in the survival length scale $\ell(a) = v_\infty(a)t_{\text{life}}$.

The survival time of a spherical ice grain is proportional to its size,

$$\tau = \frac{m_g}{dm_g/dt} = \frac{\frac{4}{3}a^3\rho_d}{4\pi a^2 J} = \frac{\rho_d}{3} \frac{a}{J_d} \propto a \quad (7)$$

Here J_d is the sublimation mass flux off the ice grain. The terminal velocity and the lifetimes of the ice grains are now described as a function of the ice grain size.

Ice grain sizes are described by a power-law distribution with an index that is reliably maintained at -3.5 by fragmentation. The maximum ice grain size that can escape the gravitational pull of the nucleus is given by Whipple's maximum liftable grain size. Although this maximum size grain will not actually escape the nucleus since its terminal velocity is zero, we can use this maximum as a multiplicative factor on the sizes of ice grains across the distribution. From the balance between gravity and the drag force.

$$a_{\max} = \frac{3C_D v_g J}{4\rho_d g} \quad (8)$$

where g is the gravitational force of the nucleus, R_n is the nuclear radius, ρ_n is nuclear density, and J is the mass flux off the nucleus.

Since the terminal velocities scale as $v_\infty \propto a^{-5/4}$, and the ice grain lifetimes scale as $t_{\text{life}} \propto a$, the survival length scales as $a^{-1/4}$. The ice grain sizes and hence their lifetimes and also their terminal velocities are both related to the mass flux off the nucleus, J .

The mass flux derives from the energy balance at the surface of the nucleus (D. Prialnik 2004),

$$(1 - A) \frac{S_0}{r_H^2} \cos(\theta) = \epsilon\sigma T^4 + L_s J - k \frac{\partial T}{\partial z} \quad (9)$$

where A is the Bond (bolometric) albedo; S_0 is the solar constant at 1 au (1361 W m^{-2}); r_H is the heliocentric distance in au; $\cos(\theta)$ is the illumination factor with θ the illumination or hour angle (HA) around the nuclear circumference and $\theta = 0$ towards the Sun; ϵ is the thermal emissivity (~ 0.9); and, L_s is the latent heat of sublimation.

The left side of the equation is the power from insolation. The first term on the right side is the radiative cooling. The second is the cooling from sublimation. The third term is the heat flow by conduction from the nuclear interior required to maintain a non-zero surface temperature on the dark side of the nucleus. The solution for the diffusion equation for heat flow is obtained with a standard conduction closure approximation that depends on the thermal inertia, $\Gamma = \sqrt{\kappa\rho c_p}$ ($\text{J m}^{-2}\text{K}^{-1}\text{s}^{-1/2}$) of the nucleus (M. Delbo et al. 2015).

The mass flux has to satisfy the kinetics at the gas-solid interface described by the Hertz-Knudsen formula,

$$J(T) = \alpha \frac{m_g (P_{\text{vap}}(T) - P_\infty)}{\sqrt{m_g/(2\pi kT)}} \quad (10)$$

where $\alpha \sim 1$ is an accommodation factor.

The calculation of the mass flux, J , is a two-step procedure. The temperature for the surface is obtained from the energy balance with the HK formula for J . The mass flux is then determined for this equilibrium temperature from the HK formula.

If the nucleus is a mixture of components, then we replace the single term, LJ by the sum of terms for the several components. We consider a comet that is 80% H_2O ice and 20% CO_2 ice. Then,

$$LJ = L_{\text{H}_2\text{O}} J_{\text{H}_2\text{O}} f_{\text{H}_2\text{O}} + L_{\text{CO}_2} J_{\text{CO}_2} f_{\text{CO}_2} \quad (11)$$

We also need the thermal inertia, Γ . If $\Gamma = 25$ and $\Gamma = \sqrt{\kappa\rho c_p}$, $\rho_n = 500 \text{ g m}^{-3}$, and $c_p = 500 - 1200 \text{ J kg}^{-1}\text{K}^{-1}$, then $\kappa = (1.0 - 2.5) \times 10^{-3} \text{ W m}^{-1}\text{K}^{-1}$, reasonable numbers for comets (O. Groussin et al. 2019; J. Boissier et al. 2011).

Figure 2 shows the solutions for each of the pure species and for the mixture. The rapid sublimation of CO₂ cools the surface of the mixture and keeps the temperature of the H₂O too cool for sublimation as previously noted (C. M. Lis et al. 2025). The gas coma is then dominated by CO₂ as observed. Aside from the left-right symmetry, there is a 1-1 relationship between the temperature and the hour angle.

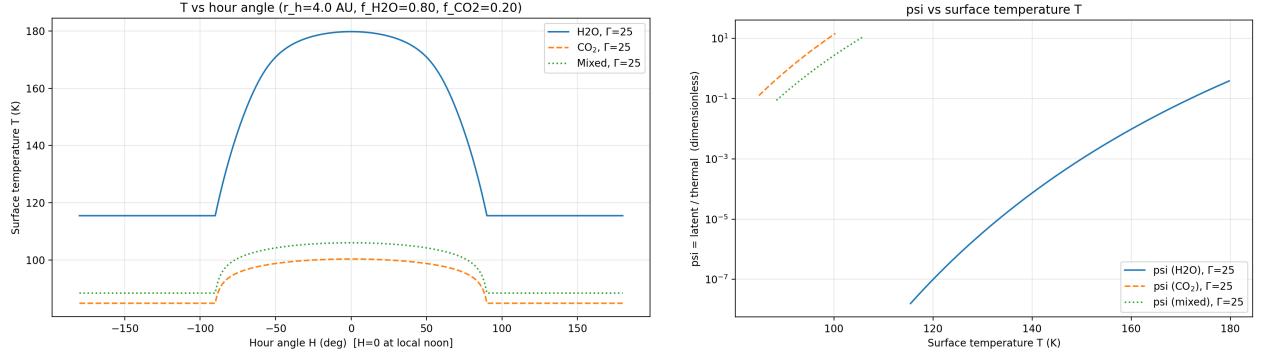


Figure 2. (Left) Surface temperature of the nucleus as a function of angle for H₂O, CO₂, and mixed 80% H₂O 20% CO₂. (Right) Ratio ψ (equation 16)

The thermal response time scale may be estimated as,

$$\tau(T) = \frac{\Gamma \sqrt{P/\pi}}{4\epsilon\sigma T^4 + \sum f_i L_i dJ/dT} \quad (12)$$

The response time varies from a minimum of 170 s at HA=0 to 3.7 hr at HA=90.0 both shorter than the 16 hour observed rotation period (T. Santana-Ros et al. 2025; R. de la Fuente Marcos et al. 2025), validating the approximation of an equilibrium temperature.

The solution for the mass flux has two limiting cases depending on whether the cooling is dominated by radiation or sublimation. If $\epsilon\sigma T^4 \ll (1-a)S_0r^{-2}$, then radiative losses are negligible and most of the solar energy goes into sublimation. Ignoring conduction, the energy-limited mass flux is,

$$J_E \approx \frac{(1-a)S_0}{Lr_H^2} \cos \theta. \quad (13)$$

In this case, the mass flux is independent of temperature.

If the sublimation is limited not by the available energy but by the kinetics at the interface, then $J \approx J_H K$ given by the HK formula. The dependence on T is more complex since the saturation vapor pressure is given by the Clausius-Clapeyron equation,

$$P_{\text{vap}} \approx P_0 \exp(-L/RT). \quad (14)$$

In this case J has a strong, exponential dependence on temperature, $J \sim T^{-1/2} \exp(-L/RT)$.

We can determine whether the nuclear surface is in the energy or kinetic-limited regime as a function of angle or temperature for a given composition. Define the radiative temperature,

$$T_{\text{rad}} = (F_{\text{abs}}/\epsilon\sigma)^{1/4} \quad (15)$$

where F_{abs} is the absorbed solar flux. For each species define the function,

$$\psi_i = \frac{f_i L_i J_i(T_{\text{rad}})}{F_{\text{abs}}}. \quad (16)$$

If $\Sigma_i \psi_i \gg 1$: energy limited – sublimation cooling dominates $T < T_{\text{rad}}$. J independent of surface T .

If $\Sigma_i \psi_i \ll 1$: kinetic limited – radiation dominates $T \approx T_{\text{rad}}$ and $J \sim T^{-1/2} \exp(L_i/RT)$.

Figure 2 (right) shows that ψ crosses the critical value for CO_2 and for the mixture, but remains < 1 for H_2O for almost the full range of surface temperatures.

Figure 3 shows the length of the snow line as a function of hour angle for three different ice grain sizes. The maximum ice grain size, which has an outward velocity of zero by definition, represents the maximum ice grain size for the distribution of sizes and decreases with hour angle due to the diminishing sublimation mass flux. The factor a_{frac} , shown in the legend represents a multiplier on the maximum ice grain size at each hour angle chosen to result in a representative ice grain size near the wavelength of optical light. Ice grains of this size dominate the total scattering cross-section. The snow line, $\ell(a, T_s)$ is longest toward the Sun and falls off with hour angle and surface temperature. Therefore, the coma should be extended toward the Sun as observed.

The curves for the snow line have the same functional dependence on hour angle as the maximum ice grain size and the sublimation mass flux of CO_2 . All are well-fit by a cosine function implicating the illumination angle in the energy balance as the dominant effect on the length of the snow line.

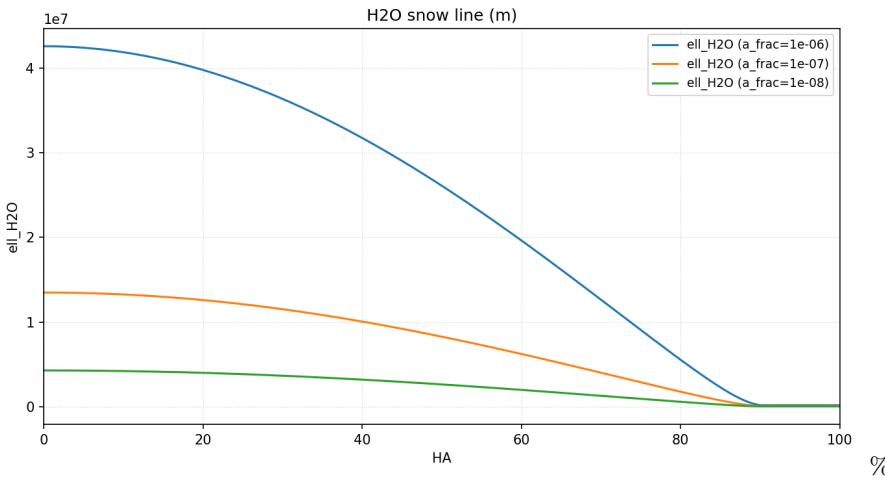


Figure 3. Snow line for water ice as a function of nuclear hour angle for three sizes of ice grains.

4. CONCLUSIONS

We compare simple physical models of cometary coma with observations from the Hubble Space Telescope. The Haser-type outflow solution with exponential destruction (equations 1 - 3) provides good fits to the observed surface brightness profiles in the solar and perpendicular directions, indicating that the sublimation of ice grains in the coma, driven by the sublimation mass flux of CO_2 gas from the nucleus, determines the observed curvature of the profiles and the angular anisotropy.

Within a spherical model, the anti-tail emerges naturally as a consequence of anisotropic illumination. We find that the angular dependence of the characteristic length scale for the destruction is primarily due to the illumination angle of the cometary surface which affects the sublimation mass flux of CO_2 gas off the cometary surface. The mass flux determines both the terminal velocity of the ice grains and the maximum size in the grain size distribution and therefore the characteristic survival length of the ice grains in the outflow.

The development of an observable anti-tail depends on a favorable combination of cometary composition and solar insolation that both affect the sublimation mass flux off the cometary surface as well as the destruction of the ice grains by sublimation. In particular, the total scattering cross-section should be dominated by volatile ice grains. The sublimation mass flux and radiation pressure should not be so large as to create a traditional cometary tail, both indicating that an anti-tail is more likely to be observed at larger heliocentric distances. This in turn requires high-angular-resolution observations, such as those of the HST. As 3I/ATLAS approaches the Sun, the physical conditions and shape of the coma will change.

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