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AETHER: a novel scientific software for modelling dust emissions in cometary comae

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ABSTRACT

Comets are small celestial bodies generally regarded as remnants of planetary formation. Research into their properties yields important insights into the thermal evolution and compositional history of the Solar system. Three key elements can be identified in a comet: the nucleus, the coma, and the tail. The nucleus of the comet continuously emits rapidly moving molecules and dust, creating a tenuous coma that can be considered its atmosphere. Its interaction with solar radiation and the solar wind then gives rise to cometary tails. This paper proposes to the scientific community active in the field of coma modelling a novel scientific software, called Advanced Engine for Three-dimensional High-resolution Emission Rendering. Unlike the others released to date, it offers a complete, fully accessible 3D environment for researchers' studies. It is also completely open source and distributed under the GNU GPL 3.0 license, so it can be used as is or modified to suit the desired purposes by adding new features. It can also be made more stable through collaborative work, fixing any existing bugs. Its functionality has been evaluated by modelling the coma of known comets, obtaining plausible, and convincing results.

Key words: 3D – Coma – Comet – Software – Modelling – Morphology.

1 INTRODUCTION

The study of comets is a key area of astronomy and astrophysics, as these celestial bodies help us to understand more about our Solar System (C. Ceccarelli et al. 2022; E. Bergin et al. 2024). Unveiling the details of the inner coma of comets provides valuable insights into gas dynamics, dust characteristics, and the physical attributes of the nucleus, thereby enhancing our understanding of early Solar system conditions by examining processes occurring near the source before external contamination.

Numerical modelling of the coma of a comet allows the estimation of key parameters, such as the rotation period of the nucleus, the pole orientation, the location of active regions, and the terminal velocity of dust particles within jets, thereby developing a comprehensive profile of cometary structure and behaviour (D. Prialnik et al. 2004). By simulating gas and dust interactions, photochemical reactions, and jet phenomena, these models provide a more thorough understanding of the dynamic environment surrounding a comet, enabling a more accurate risk assessment for spacecraft that may encounter comets and facilitating the interpretation of data from missions such as *Rosetta* (C. Snodgrass et al. 2017).

In recent years, research on cometary coma modelling has focused on multiple aspects (Z. Sekanina 1998; M. J. Foster & S. F. Green 2007; J.-B. Vincent et al. 2010, 2013; E. Bojurova et al. 2021; F. Manzini et al. 2021, 2025; N. H. Samarasinha et al. 2023; N. Haslebacher et al. 2025; V. Kleshchonok & H. Sierks 2025). Some research aimed to improve the modelling process, which is described mathematically or demonstrated through graphical representations, often overlaid on telescope images. However, graphical models intended to simulate the features visible in telescope images are often depicted in a 2D space, lacking depth and spatial realism. When dedicated scientific software is used, it is, in most cases, proprietary; its use is restricted to individuals or small research groups and thus is not available to the research community. In most instances, when a new one is presented, neither the executable nor the code is made available. This limits widespread access and prevents researchers from leveraging these tools for their own investigations. In fact, any scientific software published as open-source has the following advantages:

(i) *reproducibility and transparency*: the source code is inspectable, promoting methodological transparency and research reproducibility. It is easier for reviewers and collaborators to verify algorithms and hypotheses;

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(ii) *community-driven innovation*: bugs and features could be fixed quickly thanks to a global community. Some tools based on this paradigm, such as Python, R, and TensorFlow, evolve rapidly thanks to this approach;

(iii) *extensibility and customizability*: the source code can be modified to accommodate new methods, experimental setups, or specific workflows. This is ideal for exploratory or cutting-edge research;

(iv) *cost and resource efficiency*: scientific software based on this approach is usually free. This can benefit research laboratories with limited funds for buying licenses or developing one internally;

(v) *long-term accessibility*: the risk of losing access to the scientific software due to discontinuity is lower. Anyone can copy and continue accessing the entire source code, even if the original developers stop supporting it.

These considerations have led the authors of this paper to develop a novel open-source scientific software solution called Advanced Engine for Three-dimensional High-resolution Emission Rendering (AETHER). It accurately simulates the morphology of anisotropic dust emissions in the cometary coma in a fully 3D environment while remaining efficient enough to run on standard hardware without excessive computational resources. To the authors' knowledge, it features the following key innovations:

(i) it is based on the cutting-edge multi-platform Godot 3D engine (J. Linietsky & A. Manzur 2014), which makes it easy to be modified through its comprehensive development environment;

(ii) its interface was developed for partial automation of repetitive operations by researchers, including the retrieval of ephemerides of the studied comet and the possibility to load/save a specific comet configuration;

(iii) it allows exploring the evolution of the coma features over time, thus allowing to refine and validate the estimation of the main parameters that generated the initial model;

(iv) not only does it provide an instant 3D view of the modelled coma of the comet from the geocentric point of view (POV), but it also allows for deep exploration by rotating it at will.

The idea is to provide the research community active in this field with a tool that can hopefully be adopted and continuously improved through collaborative efforts. This opportunity is guaranteed by the choice of the GNU General Public License (GPL) v3.0 as the publication license.

The remainder of the paper is structured as follows. Section 2 introduces some general notions on comets, aimed at helping the understanding of the scientific software features. The following Section 3 details how AETHER was created, how it works, and how researchers can use it to study a comet. Section 4 highlights some of the results obtained with AETHER on known comets. Section 5 outlines the future perspectives of AETHER based on the current version. Finally, 6 summarizes the discussion to draw objective conclusions.

2 COMETS

2.1 General notions

Comets are generally characterized by a nucleus, a coma, and one or more tails. The cometary nucleus is an irregularly shaped, solid body of a few kilometres in size, consisting of ice (frozen gases, primarily water, and carbon dioxide) with embedded dust particles, mainly in the sub-micrometre to sub-millimetre size range. The nucleus moves along a Keplerian orbit, i.e. an ellipse with the Sun at one focus, experiencing acceleration due to the gravitational force of the Sun. When a comet approaches the Sun, its surface is heated, causing the ice to sublime and release gas and dust. These emissions form a cloud around the nucleus, called the coma, that is generally visible due to sunlight scattered by dust particles. These are pushed out of the coma by solar radiation pressure, the force resulting from the exchange of momentum between photons emitted by the Sun and the surfaces of dust particles, forming a curved dust tail. The dust tail appears morphologically diffuse, white-yellowish, or slightly pink because dust grains scatter sunlight more efficiently at longer wavelengths.

Neutral gas species in the coma can be ionized by solar ultraviolet (UV) radiation and interact with the solar wind, a stream of charged particles composed mainly of protons and electrons. The resulting magnetic fields in the coma sweep the ions out of the coma into a long and straight ion tail. Because one of the most common ions, CO^+, emits strongly at blue wavelengths, the ion tail often appears blue.

2.2 Cometary emissions

The release of dust particles from the cometary nucleus surface exposed to the Sun is a complex process driven by gas sublimation, which drags the grains into the circumnuclear environment. Processes such as acceleration, fragmentation, and collisions play a dominant part in the first kilometres (km) above the nucleus. In particular, the dust emissions can be isotropic, i.e. released uniformly in all directions from the entire nucleus surface, or anisotropic, i.e. unevenly distributed because ejected from localized sources. The dust environment around the nucleus is conventionally divided into three main regions (R. Marschall et al. 2020):

(i) the *coupled coma region*, where the dust dynamics is dominated by local forces connected to the nucleus (gas drag and nucleus gravity);

(ii) the *transitional coma region*, where the dust has decoupled from the gas, and the motion of the small particles is driven by solar gravity and radiation pressure, and by the terminal velocity the dust acquired from the gas drag, while large particles are bound in the gravitational field of the nucleus;
(iii) the *dust tail and trail*, within which the dust particles are governed by solar forces only.

In the *coupled coma region*, dust particles are accelerated by gas drag from sublimating ice on the nucleus surface or from discrete active sources up to a height of approximately ten times the nuclear radius, at which point drag vanishes. Fragmentation of large particles occurs predominantly within the coupled coma (S. Merouane et al. 2016; F. Moreno et al. 2017). The gravitational attraction of the comet nucleus is negligible, given its small size.

In the *transitional coma region*, the dust particles are then exposed to two forces: the radiation pressure $F_{\rm rad}$ and the solar gravity $F_{\rm grav}$:

$$F_{\rm rad} = \frac{Q_{pr}}{c}\frac{L_s}{4\pi r^2}\frac{\pi d^2}{4}; \; F_{\rm grav} = \frac{GM}{r^2}\rho\frac{\pi d^3}{6}, \tag{1}$$

where L_s and M are the luminosity and mass of the Sun, c is the speed of light, G is the gravitational constant, r is the Sun-comet distance, d is the diameter of the grain (assumed spherical), and ρ is the mean grain density. Q_{pr} is the scattering efficiency for radiation pressure and is proportional to d, wavelength, and the index of refraction of the grain material. The two forces act in the same direction, but in the opposite sense, so that the net force is a central force that varies as r^{-2}, implying that the trajectory of the dust particles will still be a Keplerian orbit around the Sun, but with an effective gravitation reduced by the factor $(1-\beta)$ (M. L. Finson & R. F. Probstein 1968; J. A. Burns et al. 1979; J. Agarwal et al. 2024):

$$F_{\rm total} = F_{\rm rad} - F_{\rm grav} = F_{\rm grav}(1-\beta), \tag{2}$$

where the β parameter is the ratio of the radiation force to the gravitational force:

$$\beta = \frac{F_{\rm rad}}{F_{\rm grav}}. \tag{3}$$

When a small dust particle is released from the nucleus of a comet, radiation pressure immediately comes into play, and the β of the particle assumes a finite value. If $\beta < 1$, the net force is attractive and so an elliptic, parabolic, or hyperbolic orbit is possible, depending on the orbital energy. If $\beta > 1$ (as in the case of small and sparse dust particles), only hyperbolic orbits occur (C. M. Birkett 1988). The trajectories of the dust particles emitted from the comet surface are therefore not only determined by their initial emission velocity, but are mainly influenced by the coefficient β, which, in turn, is strongly related to dust diameter, density, and albedo. In practice, β values > 1 are uncommon, so radiation pressure forces rarely exceed the force of gravity.

2.3 Modelling the dust motion

The modelling process in AETHER focuses on the dynamics of dust particles ejected from discrete active areas within the transitional coma region relative to the nucleus of the comet. AETHER has been designed to reproduce coma features on the thousand-kilometre scales observed in telescopic images, therefore it considers only processes occurring in the transitional coma, and neglects gas drag and the gravity of the nucleus, which act within the innermost coupled coma, as well as weaker forces such as the Poynting–Robertson effect and the Lorentz force, which are typically excluded from calculations of cometary dust dynamics (J. Agarwal et al. 2024). As both the dust particles and the nucleus are affected by the Sun's gravitational force within the same reference frame, it is not necessary to include solar gravitational acceleration in the analysis of particle motion. Therefore, in the models, solar radiation pressure is the sole force governing the trajectories of dust particles. Based on this, the motions of the dust grains emitted at velocity v, and their positions relative to the nucleus at any observation time t can be easily determined.

Three main reference frames and coordinate systems are used in the modelling, all of which are right-handed [Navigation & A. I. F. (NAIF) 2023]. They will be discussed in the following sections.

2.3.1 A geocentric reference frame

This is a geocentric system of sky plane coordinates. Y_g is a vector that points towards the Observer (Earth), X_g is parallel to the Earth's equatorial plane, and x increases from right (west) to left (east) for an Observer looking at the sky. Z_g forms the right-hand set and completes the orthogonal system, pointing northward in projection. It is assumed that the $x-z$ plane corresponds to the plane of the sky and to the image plane.

This is the default view in AETHER, showing the comet as seen from Earth. The orientation of the spin axis and the position of the Sun, which determine the extent of insolation of the nucleus, are consistent with this view.

2.3.2 A body-fixed reference frame

The centre of this frame coincides with the nucleus centre, the main plane ($X_{\rm com}$, $Y_{\rm com}$) is the equatorial plane of the comet, $Z_{\rm com}$ is orthogonal to $X_{\rm com}$, $Y_{\rm com}$, and points to the positive pole of the nucleus, aligned with the spin axis. The locations of the active sources and the initial position of the emitted dust particles are defined in latitude and longitude in this body-fixed frame.

2.3.3 A cometocentric reference frame

This new reference frame is obtained through a rotation of the body-fixed reference system about the Y and Z axes, so that the X-axis is oriented towards the Sun. The spatial positions of dust particles are expressed within the new reference frame, wherein coordinates are referenced to the nucleus, designated as the origin. Within the transformed frame, the motion of each dust particle is characterized by acceleration exclusively along the X-axis, which corresponds to the Sun–comet direction. In contrast, displacement along the Y and Z axes follows a linear relationship with velocity and time. This separation of dynamic components facilitates detailed and precise modelling of particle trajectories in the cometary environment. The motion of a dust particle within this frame is determined as follows:

$$\begin{aligned} x(t) &= x_0 + v_{0,x}t - \frac{1}{2}a_0t^2 \\ y(t) &= y_0 + v_{0,y}t \\ z(t) &= z_0 + v_{0,z}t \end{aligned} , \qquad (4)$$

where x_0, y_0, and z_0 define the initial position of the particle (i.e. the origin on the nucleus), v_0 is the initial velocity, and a_0 is the acceleration given to the particle by solar radiation pressure. The value of the acceleration can be easily calculated as follows:

$$a = \frac{3L_s(1+A)}{8\pi c d \rho r^2}, \qquad (5)$$

where A is the albedo of the dust grains ($= 0$ for a blackbody that absorbs all incident radiation and $= 1$ for a body that reflects all incident radiation), and d is the diameter of the dust grains; thus, the acceleration is determined by the size and density of the particles, and smaller particles will be subject to greater acceleration.

The positions of dust grains are then converted back from cometocentric to sky-plane coordinates, allowing the positions of the grains relative to the nucleus to be computed and plotted on the model to account for line-of-sight effects. AETHER performs these rotations in the background and is only concerned with the calculations of the dust particle trajectories, while the geocentric view of the nucleus in the main viewport is not affected.

3 ADVANCED ENGINE FOR 3D HIGH-RESOLUTION EMISSION RENDERING (AETHER)

3.1 Game engine choice

The first problem the author of this paper focused on when creating AETHER was deciding which game engine to use (D. Gobbi 2025). There are currently several game engines available, of which unity and unreal engine are undoubtedly the most well-known. The choice to use Godot for this project, however, is due to the fact that the authors of this paper, like the original Godot creators and many other open-source software developers, wanted to create tools freely available to the community that everyone could contribute to. Godot is, in fact, a MIT-licensed, open-source, cross-platform game engine developed for 2D and 3D applications. For these reasons, it has over time attracted a steadily growing community of users and engine developers.

AETHER is primarily written in GDScript, a Python-like scripting language developed specifically for Godot. However, Godot also supports C++ and C#, and all of these languages can be used together for the same project, even for AETHER.

3.2 Graphical user interface

The Graphical User Interface (GUI) of AETHER is organized into three main tabs:

(i) *Settings*: shown in Fig. 1, is divided into two panels:

(a) the left one is dedicated to parameter input; it allows to import the orbital elements of a comet, which are summarized in Table 1, and the main ephemeris data from the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) Horizons On-Line Ephemeris System[1] by simply entering the name of the comet and a date (or a date range with time intervals of days or hours).

(b) the right one displays the retrieved ephemeris data, which can be exported as a.csv file.

(ii) *Model*: shown in Fig. 2, is organized into three main panels:

[1] https://ssd.jpl.nasa.gov/horizons/

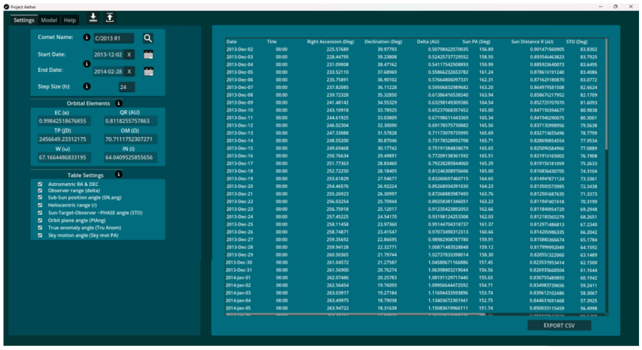

Figure 1. The AETHER settings tab.

Table 1. Main orbital elements of a comet.

Parameter	Definition
Semimajor axis (a)	Defines the size of the orbit as half the longest diameter of the ellipse.
Eccentricity (e)	Describes the shape of the orbit. $e = 0$ corresponds to a circular orbit, while values approaching 1 indicate increasingly elongated ellipses.
Inclination (i)	The angle between the orbital plane and the ecliptic.
Longitude of the ascending node (Ω)	The angle from a fixed reference direction (e.g. the vernal equinox) to the point where the orbit passes upward through the reference plane (ascending node).
Argument of periapsis (ω)	The angle from the ascending node to the perihelion, measured in the orbital plane.
True anomaly (ν)	The angle between the direction of perihelion and the current position of the body, as seen from the focus of the ellipse (i.e. the Sun).

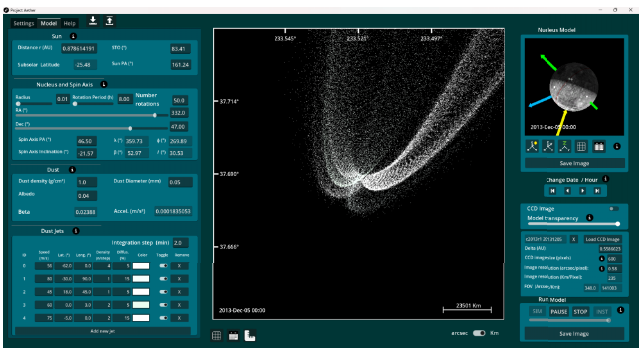

Figure 2. The AETHER model tab.

(a) left panel: contains separate input boxes for defining the parameters related to the Sun position, comet nucleus, dust properties, and active regions.

(b) central panel: contains the main viewport, where the model is displayed.

(c) right panel: includes controls for entering data related to the telescopic image, configuring the parameters required to compute the model scale, changing the date, adjusting the transparency of the model over the telescopic image, and running the model. At the top of the interface, a dedicated frame displays a model of the nucleus.

(iii) *Help*: shown in Fig. 3, it contains general information on how to use AETHER.

3.3 Studying a comet with AETHER

AETHER is designed to model, at the typical scale of ground-based telescopic images, coma features produced by anisotropic dust emission from discrete active sources on the nucleus. The 3D modelling engine behind AETHER enables estimation of the dust emissions of the comet to be studied based on various parameters. It is important to specify that modelling is conducted through a trial-and-test process, which is often complex and time-consuming. To avoid getting lost in random, unlikely solutions or false positive results, it must necessarily be preceded by an appropriate processing of the telescopic images and a thorough analysis of the visible coma features, as well as of the data on the comet available in the literature, to narrow as much as possible the plausibility ranges of the

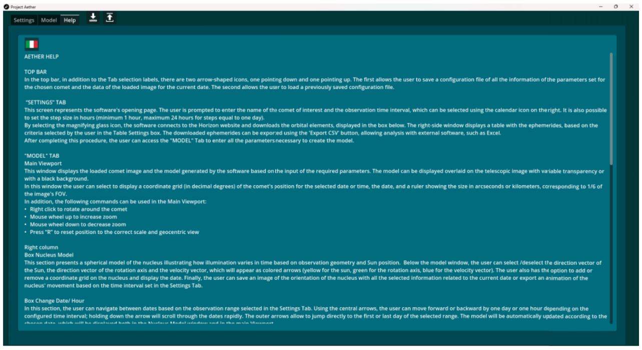

Figure 3. The AETHER help tab.

nucleus and dust parameters that will be used to build the model. It is always recommended to proceed step by step. Using the Settings and Model tabs, it is possible to define multiple inputs, as detailed in the following sections.

3.3.1 Geometric conditions of the observation

Most of the information describing the position of the studied comet with respect to the Earth and the Sun is retrieved automatically from JPL Horizons, but some parameters must be entered manually.

The first parameters required by AETHER are the resolution and the field of view (FOV) of the telescopic image, which are used to compute the model scale. To this end, the first ephemeris imported from JPL Horizons is the delta, i.e. the distance of the comet from Earth in astronomical units (AU). The FOV of the image (in arcseconds and in km) is then automatically calculated by the scientific software based on it and on manual input of the resolution of the telescopic image (in arcseconds/pixel) and of the number of pixels of the image side (which, for convenience, is useful to be square). This is important to ensure that the model in the viewport is drawn with the same scale as the image.

AETHER also needs to know, for the chosen date(s), the position of the comet and the Sun, as well as the distance between the Sun and the cometary nucleus. This allows it to compute the extent of insolation of the active sources on the nucleus and the magnitude of the radiation pressure force acting on dust emissions. This information is obtained directly from JPL/Horizon. In particular, the following parameters are retrieved:

(i) *Right ascension (RA) and Declination (Dec)*: are the coordinates of the comet, defining its position in space for each date.
(ii) *Sun position angle* (PA): it ranges from 0° to 360° and defines the direction of the Sun projected onto the sky plane as seen from Earth. It is measured counterclockwise from the celestial north towards the east;
(iii) *Sun-target-observer* (STO): is the phase angle between the Sun, the comet (Target), and the Observer (the Earth); it ranges from 0° to 180°, where 0° corresponds to a position of the Sun behind the Observer, 90° to a position lying on the sky plane, and 180° to a position on the opposite side of the Observer, illuminating the hidden hemisphere of the comet nucleus;
(iv) r: is the distance of the comet from the Sun, normally expressed in AU. For calculations, it is converted to km.

3.3.2 Cometary nucleus

The Model tab allows to set the inputs that characterize the nucleus, which are the following:

(i) orientation of the axis of rotation;
(ii) rotation period and number of rotations;
(iii) location of the active dust-emitting source(s) on the nucleus in latitude and longitude.

For simplicity, the nucleus is always assumed to be spherical. The spin-axis orientation significantly influences the direction and pattern of dust and gas emissions. As the comet rotates, different surface regions are exposed to solar radiation at different times, which in turn affects ice sublimation and jet formation. For this reason, accurately modelling the spin-axis orientation is crucial for accurately simulating the trajectories of particles emitted from the surface of a comet. It is also important to define the north pole of the spin axis, as this defines the direction of rotation (counterclockwise), which can significantly affect the morphology of the coma.

The orientation of the spin axis of a comet in space is conventionally defined by the RA and Dec equatorial coordinates to which the positive (north) pole is directed. However, in our geocentric reference frame, it is intended to show the nucleus as seen by an Earth-based Observer (or a telescope image). Two angles define the spin axis orientation:

(i) *PA*: it ranges from 0° to 360° and defines the direction of the spin axis projected onto the sky plane. It is measured counterclockwise from the celestial north toward the east.

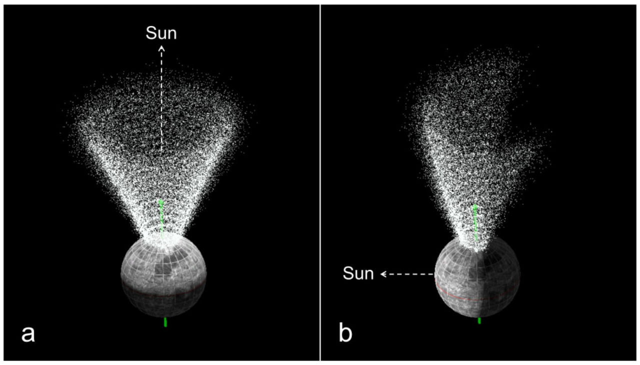

Figure 4. Schematic representation of a dust cone model generated with AETHER. A discrete source is placed at latitude $+70^\circ$; the spin axis (indicated by the green arrow) has the positive pole inclined 30° towards the Observer. Panel (a): the Sun is in the north, almost on the plane of the sky, thus the source is always illuminated, and the emission is continuous and forms a full cone. Panel (b): the Sun is in the east, the source is illuminated only for half a rotation of the nucleus, the emission is quasi-continuous and forms a semicone. The central axis of the cone coincides with the axis of rotation of the cometary nucleus. The size of the nucleus is not to scale but is exaggerated for purely demonstrative reasons.

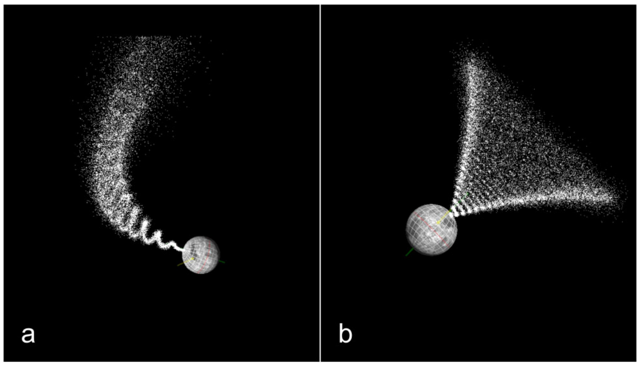

Figure 5. Panel (a): Example of a curvilinear pattern of a collimated dust emission from a source located at high latitude; the source is always illuminated, thus the emission is continuous and forms a narrow spiral, which is soon pushed back by radiation pressure. Panel (b): A dust emission from a source located at mid latitude produces a large cone that, when projected on the plane of the sky, takes a fan-shaped pattern. The aperture angle of the cone indicates the co-latitude of the source; the edges of the cone appear more condensed due to a perspective effect. The size of the nucleus is not to scale but is exaggerated for purely demonstrative reasons.

(ii) *Inclination*: it ranges from -90° to $+90^\circ$ and defines the angle between the spin axis and the sky plane as seen by the Observer. It provides a measure of how much the spin axis is tilted with respect to the Observer's line of sight.

AETHER computes these two angles from the equatorial RA/Dec coordinates of the comet and the RA/Dec coordinates of its pole. While AETHER automatically imports the former from JPL Horizons for a given date, the latter are often not known. The orientation of the spin axis can be estimated by analysing the morphology of dust emissions from the cometary nucleus, mainly based on the observation that dust ejected from a discrete active area forms a conical pattern (if the emission is continuous, Fig. 4a) or a partial cone (if the emission is intermittent due to the diurnal cycle, Fig. 4b) as the source spins around the rotation axis. The edges of the cone, defined by the material ejected in the area of the cone farthest from its axis, are more condensed than the central region due to a perspective effect. The apex of the emission cone coincides with the centre of the spherical nucleus, and the axis of the emission cone coincides with the rotation axis, while the aperture angle of the cone indicates the co-latitude of the source (Z. Sekanina 1987, 1998).

The emission cone model can produce a variety of dust structure morphologies, which are determined by the Sun–Comet–Earth geometry. Although they are not intended to provide a physically realistic representation of dust emission from a cometary nucleus, the test models shown in Figs 4, 5, and 6 provide a schematic illustration of the projected morphology of such structures on the plane of the sky. Depending on the latitude of the emission source and the spin axis orientation, these features may appear as collimated jets, spirals, shells, or fan-like structures. Assuming that the projected position of the spin axis is located between the edges of the emission cone, its orientation can be inferred by measuring the *PA* of the axis of the cone (often identified by the peak luminosity along the structures) and then, through an iterative approach, by varying the *PA* incrementally on the nucleus until the model provides the most accurate representation of the observed dust structures across all observation dates.

As shown in the right part of Fig. 2, a dedicated window in the upper right of the Model tab displays a close-up 3D view of the nucleus, the spin axis (green arrow), the velocity vector (cyan arrow), and the direction to the Sun (yellow arrow). This allows the user to get a real-time view of the axis orientation and of the extent of insolation of the nucleus following any change in the *RA*/*Dec* coordinates

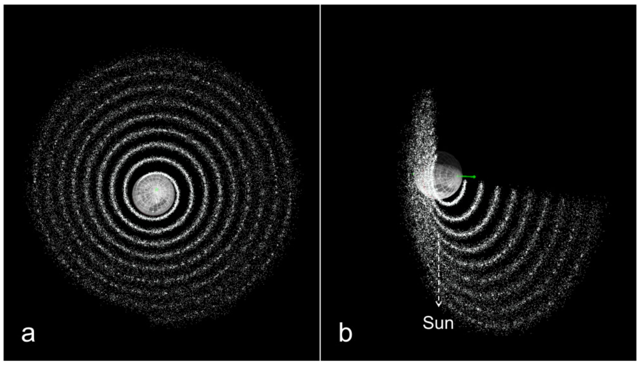

Figure 6. Example of a spiral pattern of a collimated dust emission from a source located at near-equatorial latitude. Panel (a): the spin axis points towards the Observer and the Sun; the source is always illuminated, thus the emission is continuous and forms a full spiral. Panel (b): the Sun is in the south, the source is illuminated only for half a rotation of the nucleus, the emission is quasi-continuous and forms a half-spiral. The spin axis is tilted 60° away from the line of sight, and the half-spiral is visible in the form of shells. The size of the nucleus is not to scale but is exaggerated for purely demonstrative reasons.

of the pole or in the date/time. It is possible to toggle each axis on or off, to display the grid pattern on the nucleus, and to show the current date if the ephemeris data has been imported. This view also allows for saving an image of the nucleus model.

3.3.3 Dust emissions

The last information necessary to compute the model for the desired comet, always to be entered in the AETHER's Model tab, is the positions of the active areas on the nucleus and the parameters that characterize the dust emissions.

The location of active sources is defined by their cometo-centric latitude and longitude. Dust jets are assumed to be radially emitted from the active regions. In fact, it has been shown that dust follows free-radial outflow beyond about six average comet radii, and that beyond this distance, fragmentation and gravitationally bound particles are negligible processes in determining the optically scattered light distribution in the coma (S.-B. Gerig et al. 2018).

AETHER allows inserting as many active sources as needed, each with a different associated emission velocity. For each active source that is added, the following inputs are required:

(i) *dust emission speed* (in $\mathrm{m\,s^{-1}}$), assumed to correspond to the terminal velocity reached in the transitional coma, after the dust decouples from the gas;
(ii) *latitude and longitude* of the source;
(iii) *particles emitted per step*, which determines how many dots per area unit should be plotted.
(iv) *diffusion* of the emission, i.e. how broadly the dust grains are dispersed around the central trajectory;
(v) *colour*, a graphic parameter useful for distinguishing the emissions from different active sources; the active regions are shown on the nucleus model as small dots of the same colour as set here.

Each source can be toggled to simplify the model view when more than one source has been entered or deleted.

It is then necessary to specify a final additional parameter, applicable to all sources in the integration phase, that specifies the frequency (in minutes) at which each source emits dust.

Dust can be characterized using the following parameters:

(i) *albedo*, which introduces a minor correction to the calculated beta value, as well as to the acceleration due to the interaction between radiation pressure and emission velocity. It is usually set between 0.03 and 0.05 (B. J. Buratti et al. 2016);
(ii) *diameter*, defined by taking into account the known range (usually between 1 μm and 1 mm, although there may also be smaller or larger particles) according to the power law of the dust size distribution (G. Rinaldi et al. 2017);
(iii) *density*, defined by considering a plausible range of size/density pairs for specific values of the β parameter, which defines the properties and dynamics of dust. Typical values are comprised between 0.3 and 3.0 $\mathrm{g\,cm^{-3}}$ (M. Fulle et al. 2018).

AETHER then calculates the β value and the acceleration, which are shown just below the entered parameters. Since diameter and density are both in the denominator of the calculation of β, they are closely related to each other. The best combination is found by trial-and-test, and the final choice is based on the resulting model.

A current limitation of the software is that it can use only one dust size at a time. However, a possible workaround is to generate models, each with a different dust size, and combine them into a single final model. Validating dust parameters is a very complex task. To reach a reasonable estimate of the dust parameters, the following approaches (which may also be used in combination) can be used:

(i) given the approximate relation between the β parameter and the dust particle radius, $\beta \simeq 1/a$, and the dependence of terminal emission velocity on dust size and density, $v = \beta^{0.5}$ (F. Moreno 2022), testing several β values within a defined range can yield multiple size–density combinations, with the corresponding emission velocities, that produce very similar models. A model can therefore be constrained by selecting the limited set of β values that best reproduce the observed coma morphology. Differences among the acceptable solutions are generally modest, affecting secondary features such as the dot density of smaller particles or the visibility of corkscrew-shaped structures instead of diffuse jets at higher velocities, without substantially altering the overall size, shape, or curvature of the emissions. Conversely, unsuitable particle sizes or velocities would produce an immediately evident mismatch with the structures observed in telescopic images;

(ii) the dust size distribution in a typical cometary coma, observed between the perihelion and the equinoxes, is described by a power law with coefficients between -2 and -4 (A.-C. Levasseur-Regourd et al. 2018). The lower the coefficient, the greater the relative contribution of small particles. For values < -3, the coma will be optically dominated by micrometre-sized particles due to the combined effects of the power law and wavelength-dependent scattering efficiency. Larger particles are underrepresented because of the steep power-law distribution, whereas very small particles scatter light inefficiently because their sizes are much smaller than the observing wavelength. As a result, both size extremes contribute only weakly to the total radiance, and micrometre-sized grains provide the dominant optical signal. A size range consistent with the estimated power-law index, optionally verified with a simple Monte Carlo model, can therefore provide a robust estimate of the prevailing grain sizes.

3.4 Running the model

Once all needed parameters have been entered, AETHER calculates the acceleration and trajectory of the dust particles based on the forces acting on them: emission velocity and solar radiation pressure, which is calculated based on the characteristics of the dust, the distance from the Sun, and the angles between the active sources and the Sun's direction. The acceleration equation considers all these elements, which vary over time due to the rotation of the nucleus, which, in turn, changes the exposure of active areas to sunlight. Subsequently, AETHER plots a graph of dots in the main viewport that simulate dust emissions over the specified number of rotations of the nucleus. In the viewport, it is also possible to toggle the date, the RA/Dec coordinates, and a ruler indicating a 1/6 FOV measurement, either in arcsecs or km.

3.5 Evaluation of the generated model

The accuracy of the obtained model is evaluated by visually comparing it with the telescope images loaded in the main viewport, displayed as an underlying layer. The alignment between the numerical model and the morphology of the observed coma structures is evaluated by adjusting its transparency against the underlying telescope image. It is therefore partly dependent on the operator's subjectivity (as with other similar software).

Model parameters are typically refined through an iterative procedure in which simulated outputs are compared with observational images until an acceptable agreement is obtained. A more rigorous validation requires generating time-dependent coma models from image sequences acquired at multiple epochs along an observing arc spanning weeks to months. This approach enables the temporal evolution of the cometary morphology to be constrained and tests whether the adopted model parameters consistently reproduce changes in the dust environment under the varying geometries of the apparition.

3.6 Implementation details

In 3D environments and in AETHER, the Sun is often approximated as a directional light source emitting an infinite number of parallel rays that cover the entire scene. Because of this definition, this type of illumination is usually position-invariant, but not rotation-invariant. Furthermore, there is no attenuation due to the infinite number of rays. The Sun's orientation in AETHER is defined by the *STO* and the *PA*, both of which are derived directly from the ephemeris for a specific date or specified by the user.

As previously mentioned, in AETHER the nucleus of the comet is depicted as a sphere. This simplification can be considered acceptable if it takes into account the fact that, for most known comets, the shape of the nucleus is unknown, even if it is assumed to be mostly irregular. For a few comets whose nucleus shape is known, this information was obtained via dedicated space missions (H. U. Keller & E. Kührt 2020).

The reference frame of the comet is assumed to be concordant with the right-handed Godot coordinate system (OpenGL standard), where $+X$ is to the right, $+Y$ is up, and $+Z$ points forward (off-screen). This is aligned with the body-fixed reference frame described in Section 2.3.2, where, however, it is Y, and not Z, that points toward the positive pole of the nucleus. This rotates based on the manually entered rotation period.

In AETHER, the emission sources become active when illuminated by sunlight, and dust is emitted from them radially with respect to the nucleus centre. Then, their trajectories are computed in a cometocentric reference frame, which is obtained by rotating the X-axis so that it is parallel to the direction of the Sun, and the dust motion is influenced by the solar radiation pressure $F_{\rm rad}$ as defined in Section 2.3.3.

3.7 Cameras

The AETHER's camera is designed to orbit the comet nucleus so as to analyse the coma in 3D. It is orthogonal by default, meaning the projection rays are parallel and perpendicular to the image plane. It is possible to rotate the nucleus in any position by holding down the *right mouse button* and dragging freely. The zoom level, i.e. the distance of the camera from the nucleus of the comet, can be adjusted by clicking the *mouse wheel*. The camera position and orientation can be set to the initial state, corresponding to the view of the comet from Earth and at the correct scale as the telescopic image, by pressing the *R* key.

3.8 Performance optimization

As scientific software, AETHER is not computationally complex, except for the part related to calculating dust particle motion. If not properly optimized, this part could represent a performance bottleneck for the scientific software. During development, considerable time was devoted to improving its performance. The following strategies were therefore adopted.

3.8.1 Particle shape

Instead of representing each particle using a complex spherical mesh, they are represented as PointMesh[2], i.e. rectangles of constant size. This system is typically used for particle systems, but it can also render billboarded sprites.

3.8.2 Particle drawing

In the early development phases, an individual node was used to draw each particle. Such a strategy resulted in a high number of drawing calls and significant per-node overhead. To reduce this overhead, it was decided to group all particles generated by an emitter into a single node, so they could be drawn in a single call after their positions are updated. Specifically, each emitter has its own MultiMeshInstance3D[3], which manages the particles emitted by the source. This approach allows tens of thousands of particles to be emitted efficiently while maintaining complete control of each particle.

3.8.3 Dust emission

Two approaches were analysed to verify whether a source is active: one based on raycasting and the other on a scalar product calculation. The initial approach was to use raycasting to verify occlusions between the emitter and the light source. Although rigorous, this approach requires significant computational power. An alternative approach was therefore considered, based on the assumption of sphericity of the nucleus and the absence of self-shadowing. In this approach, the scalar product of the Sun's direction and the normal to the emission point is calculated. A positive result implies that the angle between the two vectors is less than 90 deg and that the emission zone is therefore active. Otherwise, the emission zone is considered inactive and will consequently not emit any dust. This approach was found to be about 1.5 times faster (execution time of 20 μs versus 30 μs) than its raycasting counterpart.

3.8.4 Additional performance optimization techniques

Some Godot features have been turned off to reduce central processing unit (CPU) and graphics processing unit (GPU) workloads, as they have no concrete visual impact on the modelling and do not enrich the final result. This has significantly improved the execution time of the scientific software.

(i) The same material was used for all particles.
(ii) Shadow calculations for particles were disabled.
(iii) Although GDScript supports dynamic typing, meaning that a variable can change its type during execution, only static typing was used, which enforces type consistency, allows for further optimizations during execution, and reduces the likelihood of runtime errors.

3.9 Publication license

As mentioned previously, AETHER is completely open source and is published under the GNU GPL 3.0 license. The releases and source code are freely downloadable both from the official site[4] and from the official GitHub repository.[5]

[2] https://docs.godotengine.org/en/stable/classes/class_pointmesh.html
[3] https://docs.godotengine.org/en/stable/classes/class_multimeshinstance3d.html
[4] https://astronomy.polito.it/aether/.
[5] https://github.com/PoliTO-Astronomy/AETHER-Godot.

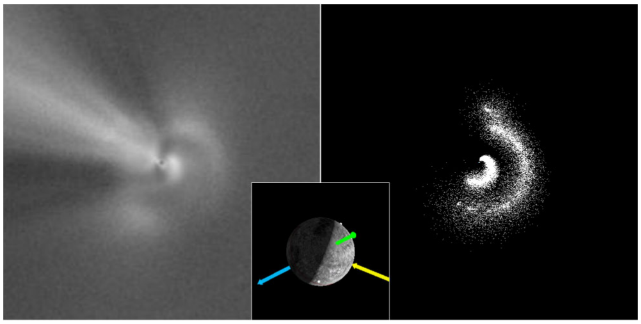

Figure 7. Left: close-up image of the coma of comet C/2020 F3 (NEOWISE) taken on 2020 July 24, showing a pair of concentric spirals. The comet was at only 0.67 AU from the Sun. FOV is 120 000 km: the numerical model of the coma shows a synthetic reproduction of the shells with one single rotation of the nucleus by placing two dust-emitting areas at mid and low latitudes, respectively, but at almost opposite longitudes. The inset shows the orientation of the spin axis (green arrow), the velocity vector (cyan arrow), the direction of the Sun (yellow arrow), and the extent of insolation over the active areas (marked by white dots) on the same date.

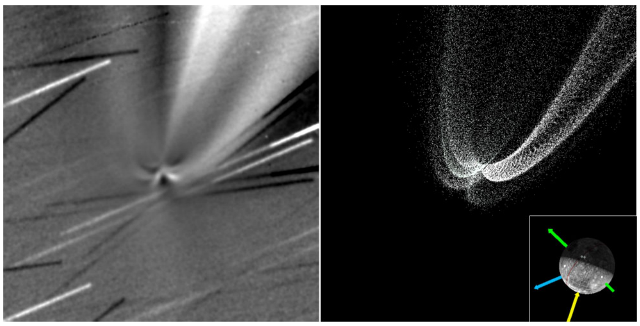

Figure 8. Left: image of comet C/2013 R1 (Lovejoy) taken at the Stazione Astronomica di Sozzago on 2013 December 5, processed with $1/\rho$ and Larson-Sekanina 15° digital filters. FOV is 165 000 km. Right: numerical model of the coma showing a synthetic reproduction of the telescope image by placing five dust-emitting areas on the nucleus. The inset shows the orientation of the spin axis (green arrow), the velocity vector (cyan arrow), the direction of the Sun (yellow arrow), and the extent of insolation over the active areas on the same date.

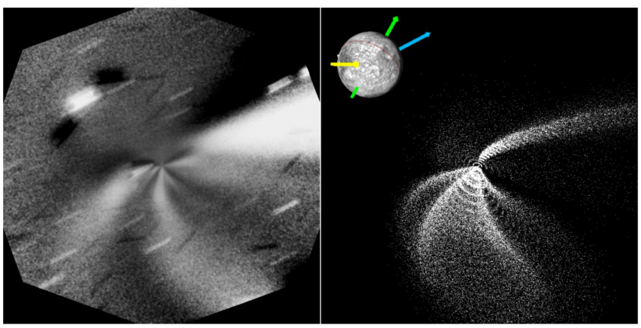

Figure 9. Left: image of comet 67P (Churyumov-Gerasimenko) taken with the 1.8-m Copernico telescope at the Asiago Astrophysical Observatory on 2021 December 30, processed with $1/\rho$ and Larson-Sekanina 20° digital filters. FOV is 104 000 km. Right: numerical model of the coma showing a synthetic reproduction of the telescope image by placing two dust-emitting areas close to each other at low latitudes on the nucleus. The dust emission in the upper part of the model is a neck-line tail or a dust trail. The inset shows the orientation of the spin axis (green arrow), the velocity vector (cyan arrow), the direction of the Sun (yellow arrow), and the extent of insolation over the active areas on the same date.

4 COMET MODELLING TEST RESULTS

A series of comprehensive tests was conducted on a variety of comets, which included both hypothetical and real examples. Among the comets studied were those with simpler morphologies, such as a single polar jet – examples include 19P and 81P (V. Oldani et al. 2023, 2024) – as well as comets exhibiting more complex features resulting from multiple jets, such as C/2020 F3 (NEOWISE) F. Manzini et al. (2021), C/2013 R1 (Lovejoy) F. Manzini et al. (2025), and 67P/Churyumov-Gerasimenko (Figs 7, 8, and 9). The primary purpose of these tests was to verify the accuracy and reliability of the generated models across several key aspects. The evaluation focused on:

(i) ensuring the correct import of geometric conditions for each comet;
(ii) assessing the scale of the model in comparison to telescope images;
(iii) confirming the computed spin axis orientation in the model is consistent with existing published data (where available) or with the entered RA/Dec coordinates;
(iv) determining the location of active areas and analysing the extent of insolation relative to geometric conditions and axis orientation;
(v) evaluating the plausibility of dust size, density, and emission velocity values, ensuring they fall within known and accepted ranges.

In this respect, comet 67P, shown in Fig. 9, represented a particularly suitable case for model validation, since most of the key input parameters used in the modelling procedure were already known from the *Rosetta* mission. This made it possible to compare the model input parameters and the resulting modelled morphology with quantities measured *in situ* by the spacecraft. This applied in particular to the spin-axis pole coordinates, the rotation period of the nucleus, and the possible locations of the main active regions. In addition, extensive constraints on the dust size distribution were available. The validation of the model was therefore based on a comparatively robust framework, because the modelled results could be compared with observational constraints and with measurements acquired directly by *Rosetta*.

The test models of comets 19P, 81P, C/2020 F3 (NEOWISE), and C/2013 R1 (Lovejoy) were not only compared with telescope images to verify their accuracy, but they were also evaluated alongside models produced in the past by another proprietary scientific software (see the respective cited publications for details), which has previously been used multiple times to model both the same comets and others, providing an additional benchmark for validation and consistency.

5 CURRENT STATE OF AETHER AND FUTURE DEVELOPMENTS

One of the standout benefits of AETHER, compared to most scientific software available to date, is its fully interactive 3D environment for analysing the coma of a comet, equipped with numerous features to minimize repetitive tasks and speed up the modelling process. Additional features that are currently in an early development phase include:

(i) modification of the modelling process from a static approach – which is only based on the geometry at a specific date – to a dynamic methodology. The updated framework would incorporate the influence of changes in observation geometry resulting from the comet's motion along its orbit throughout the simulation period, thereby providing a more precise calculation of the trajectories of the emitted dust according to Keplerian dynamics;
(ii) the option of entering multiple values or a range for dust size and density, enabling exploration of broader dust particle distributions and yielding a more realistic representation of observed phenomena;
(iii) real-time model updates following any parameter adjustment, offering users immediate feedback regarding their modifications, though this may necessitate increased computational resources;
(iv) the ability to select from a range of 3D nuclear shapes, from spheres to more irregular geometries, could facilitate more accurate simulations of coma structures influenced by surface topography;
(v) support for incorporating periodic changes in the orientation of the spin axis, such as precessional effects, which may impact coma evolution during observation campaigns;

Many other minor changes are being implemented, including improvements to the GUI and a detailed user guide. All of these improvements aim to make AETHER easier to use and create a more comprehensive scientific software.

The application of modelling to coma structures and its subsequent extrapolation to characterize the physical properties of the comet involve certain intrinsic limitations. Notably, the modelling procedure does not directly estimate parameters related to dust or active regions from images. Rather, model variables – whose values may not be determinable beforehand – are estimated through iterative trial-and-error simulations of dust jets, based on plausible initial hypotheses drawn from analysis of the telescope images. This process is inherently complex and typically requires significant time and effort to develop a reliable model. Automating this process could dramatically accelerate researchers' work, making it an attractive direction for future development. For example, automating the model selection process could reduce the analysis time from several weeks to just a few hours. A possible implementation could involve integrating a Monte Carlo algorithm (J.-F. Crifo et al. 2005; F. Moreno 2022) that generates a series of models, exploring a wider range of combinations of key variables (such as spin axis coordinates or dust properties), rather than relying on single values at a time. This would involve automatically selecting the best-fitting model, objectively evaluating its quality and correspondence with telescope images using statistical and mathematical criteria rather than a subjective visual assessment. These advanced features could prove invaluable for researchers.

In many cases, only a few input parameters are known, and sometimes none are available. This makes modelling inherently uncertain and calls for caution when drawing conclusions, particularly when the required parameters are poorly constrained or when low-resolution telescopic images prevent a detailed preliminary analysis of the coma morphology. None the less, modelling remains a useful tool when it is supported by careful image analysis and by a critical assessment of the adopted parameters. Although no model can precisely determine nucleus properties, or the exact dust particle sizes, it can still provide meaningful constraints on the main physical properties of a comet.

With AETHER, our main aim is to provide freely accessible software for both users and programmers, while offering a framework with the potential to progressively overcome some of these limitations in current and future versions. For example, the existing 3D visualization already represents a useful advance, as it enables multidimensional exploration of coma phenomena and may improve the understanding of their development.

6 CONCLUSIONS

This article presents a new scientific software called AETHER, designed to help researchers study the properties of the comet coma. It provides a fully interactive 3D environment for coma analysis, with numerous features to accelerate studies and reduce repetitive tasks. One major advantage of AETHER is its open-source and cross-platform nature, which enables researchers to use it as-is or tailor it to their specific requirements.

Although its development required significant effort, there remains substantial potential for further enhancements to make it even more powerful and user-friendly. By providing clear explanations of both AETHER's strengths and its current challenges, the authors hope to support an open and constructive dialogue with other researchers. Regular updates on new features and remaining obstacles will foster transparency and encourage community engagement in the ongoing progress of the scientific software.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

The AETHER source code and related builds are freely available on GitHub at https://github.com/PoliTO-Astronomy/AETHER-Godot. AETHER is released under the GNU GPL 3.0 license. The latest builds are also available at https://astronomy.polito.it/aether/.

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