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THE "ASTEROID NODAL INTERSECTION MULTIPLE ENCOUNTERS" (ANIME) CUBESAT MISSION: SCIENCE AND PLANETARY PROTECTION

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ABSTRACT

The "Asteroid Nodal Intersection Multiple Encounters" (ANIME) mission concept has been developed in response to the 2020 Italian Space Agency call for ideas for future CubeSat missions. ANIME aims to explore three near-Earth asteroids (NEAs), encountering them during their passages through the orbital nodes. With a nominal launch in late 2026, the 12U ANIME spacecraft will flyby Potentially Hazardous Asteroids (391211) 2006 HZ51 and (450300) 2004 QD14 in June 2027 and December 2027, respectively, and then rendezvous in August 2028 with 2000 SG344. This NEA is classified among the more dangerous asteroids in JPL and ESA risk lists, with multiple potential collision solutions with our planet during the course of the next century. It is also considered an excellent target for future human exploration thanks to its accessibility. Besides their relevance in terms of planetary protection, all of our targets present peculiar and yet unexplored size and physical regimes, hence highlighting the potential of ANIME and CubeSat technology in general for reconnaissance missions to NEAs. In particular, the 40-metre 2000 SG344 is an order of magnitude smaller than previously visited asteroids: ANIME will allow us to constrain the formation scenario and internal structure (monolithic vs. cohesive vs. rubble pile) of such, still unexplored, tens-of-metres bodies.

1 INTRODUCTION

The details of planetary accretion physics still remain unclear, as planetesimal growth becomes increasingly difficult when the size of colliding objects approaches one metre, with binding energies declining and relative velocities increasing: neither gravity nor cohesive viscous forces can easily explain the hierarchical accretion of centimetre-size grains into kilometre-size asteroids. A number of mechanisms have been invoked to overcome such physical barriers, including streaming and gravitational instabilities in the protoplanetary disk, assuming different levels of turbulence and solid-gas coupling [e.g.: 1,2,3].

The proximity of near-Earth asteroids (NEAs) allows us to discover and study small bodies about two-to-three orders of magnitude smaller than in the asteroid main belt (i.e., down to metre-size objects), hence to shed light on accretion mechanisms that took place in the primordial solar system. Indeed, investigating how a tens-of-metres asteroid behaves, and whether it is a solid block or an aggregate, can provide crucial information on how cohesion works in such a low-gravity environment, which was also experienced by planetesimals of the same size during planetary formation. Noteworthy, collisional evolution models suggest that the energy range of impacts generating the current asteroid population was generally not high enough to strongly alter the composition of the material constituting the colliding bodies [e.g., 4].

The investigation of the physical nature of NEAs is also compelling in view of the potential hazard they pose to mankind, with more or less catastrophic impact events occurring during the history of our planet [e.g., 5]. Potentially Hazardous Asteroids (PHAs) are by definition those NEAs with absolute magnitude $H \leq 22$ (i.e., with diameter greater than about 140 m) and Earth Minimum Orbit Intersection Distance (MOID) ≤ 0.05 au, and can cause extensive and large-scale damage on impact. However, smaller objects still deserve particular attention, as they have the highest statistical likelihood of impact, and can produce a catastrophe at a local/regional scale [e.g., 6]. Indeed, eight out of the ten top-ranked NEAs in the ESA Risk List[1] at the time of this writing (April 2021) have estimated diameter ≤ 60 metres.

Space exploration of solar system small bodies over the past 30 years represented a huge step forward in our understanding of planetary sciences. Each of the previous space missions dedicated to these bodies brought unexpected discoveries and opened new research scenarios; there is no reason to doubt that so far we have only seen the tip of the iceberg. In this regard NEAs represent very privileged targets, considering their striking diversity in terms of physical properties and periodic close approaches with our planet [e.g., 7].

In this paper we introduce the "Asteroid Nodal Intersection Multiple Encounters" (ANIME) mission concept, which has been developed in response to the 2020 Italian Space Agency (ASI) call for ideas for future CubeSat missions. ANIME aims to explore three NEAs, selected by virtue of their peculiar and yet unexplored size and physical regimes, as well as their relevance in terms of planetary protection. Thanks to an optimized trajectory, the targets are encountered during their passages through their orbital nodes, as detailed in the next section.

2 TARGET SELECTION AND INTERPLANETARY TRAJECTORY

The reference ANIME mission profile envisages a departure in late 2026, and performs two NEA fly-bys and then a rendezvous with a third asteroid in a total time-frame of less than two years. The target selection process starts from the identification of asteroids that have a nodal passage in the proximity of the Earth in the mission time-frame, characterized in terms of radial and angular positions with respect to the Earth and expected relative velocity.

[1] https://neo.ssa.esa.int/risk-list

Among a preliminary list of about 1500 NEAs, asteroid 2000 SG344 is identified as the final rendezvous target of ANIME, due to a number of appealing properties:

- An estimated diameter of about 40 metres (assumed from its absolute magnitude H=24.7), i.e. an order of magnitude smaller than previously explored asteroids, which will allow us to constrain the latest theories about planetary system formation scenarios;
- A very high ranking in the ESA Risk List (3rd, at the time of this writing), with multiple potential impact solutions existing in the course of the next century;
- A very accessible orbit, earning the 1st ranking (at the time of this writing) in the NASA NHATS[2] list of potential targets for future human exploration.

Fly-by targets are then determined based on the comparison of nodal encounter and spacecraft position along the rendezvous trajectory; the number of suitable targets is rather large and the final selection converged to PHAs (391211) 2006 HZ51 and (450300) 2004 QD14. The former has an equivalent diameter of 410 ± 90 m and an albedo of 0.42 ± 0.23 [8], while the latter has an equivalent diameter of 143 (-24/+49) m and an albedo of 0.37 (-0.18/+0.20) [9]. We emphasize that both of these asteroids present higher surface albedos than those of all asteroid targets of previous space missions. Moreover, 2004 QD14 would become the second smallest asteroid ever visited by a space mission, at an intermediate scale between our rendezvous target 2000 SG344 and the 330-m Itokawa explored by JAXA Hayabusa (the smallest asteroid ever visited up to present), further boosting the scientific return of ANIME.

The reference mission profile (presented in Table 1 and Fig. 1) has a total ΔV of 1.05 km/s and a propellant consumption of 1.04 kg (out of the available 1.5 kg). The thrust of the selected propulsion system (cf. Section 3) is of 1 mN, with a specific impulse Isp equal to 2100 s. The available power is assumed to vary with the inverse square of the distance from the Sun, with constant efficiency and specific impulse: for the reference trajectory, available power ranges from 60 to 75 W, well within the thruster capabilities (55-80 W). A 90% duty cycle is introduced, and the used thrust is 0.9 times the available thrust. The duty cycle is reduced to 70% during the fifteen days before fly-bys and rendezvous. A further 7% thrust reduction is considered for additional margin. Possible departure dates range from September to November 2026, with November 2026 being the best compromise in terms of mission duration and propellant consumption.

Table 1: Reference ANIME mission profile: timeline and relative velocities at encounters.

Body	Earth	2006 HZ51	2004 QD14	2000 SG344
Date	24/11/2026	19/6/2027	12/12/2027	24/8/2028
V_{rel} (km/s)	0	9.72	10.31	0

[2] https://cneos.jpl.nasa.gov/nhats/

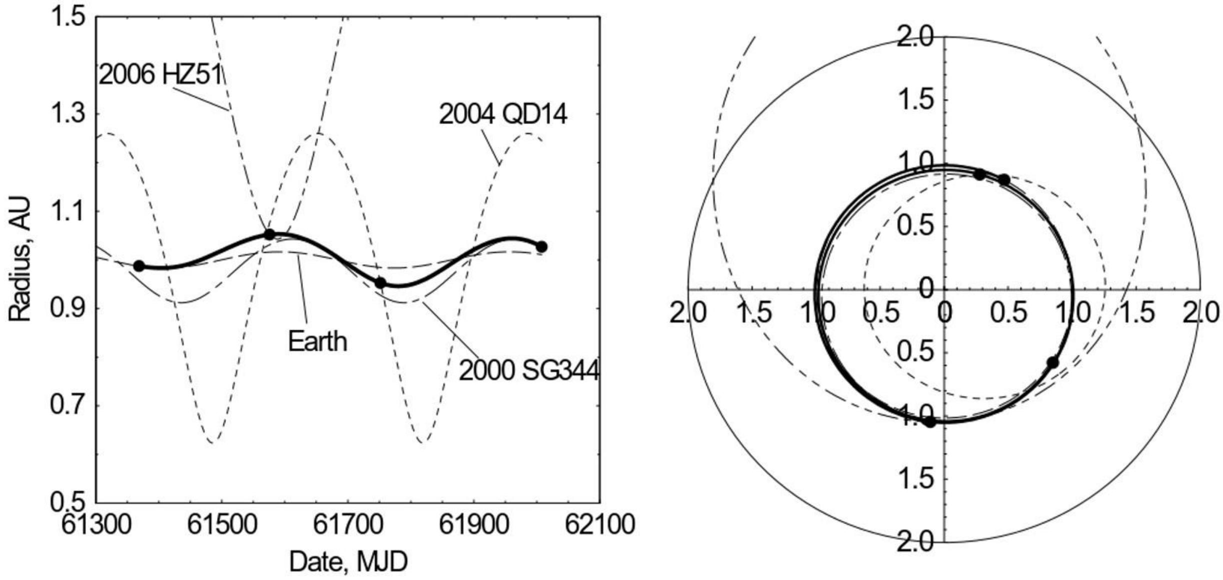

Figure 1: Reference ANIME trajectory (in bold), with respect to the orbits of the Earth (medium dashes) and of the three target asteroids: 2006 HZ51 (short-short-medium dashes), 2004 QD14 (short dashes), and 2000 SG344 (short-long dashes).

2.1 Mission concept flexibility

With respect to the reference mission profile, several alternative fly-by targets exist (1997 NC1, 2000 RS11, 2005 SE71, 2008 UL90, 2003 SD220: all of them being PHAs) implying minimal changes in the propellant requirements and keeping departure date and final asteroid unchanged. Rendezvous with 2008 SG344 can also be attained with departure moved up to October-December 2025 or pushed back to late 2027 - early 2028. New fly-by asteroids must be sought and preliminary results show that several targets could be well suited (e.g., 2008 TZ3 and 2000 QK130 for earlier departure and 2001 WN5 and 2013 EM20 for later departure). In addition, several small-size NEAs presenting intriguing physical characteristics offer rendezvous opportunities for alternative mission scenarios in case the departure date is not suited for a mission to 2000 SG344. The ample propellant margin guarantees flexibility in terms of departure date changes, strategies for escape from Earth sphere of influence (depending on the launch opportunities and orbit provided by the launcher), target selection, and provides manoeuvre capabilities after rendezvous with the final target.

3 SPACECRAFT AND OPERATIONS CONCEPT

The 12U ANIME spacecraft has an initial wet mass of 19.55 kg, including margins at component level (in the 5-20% range) and a further 20% margin at system level. Commercial Off-The-Shelf (COTS) components are considered (Table 2) to exploit the modularity and flexibility of the CubeSat standard. Most of them have successfully flown on multiple missions in the Earth orbital environment (Technology Readiness Level 9), and the configuration design takes into account a proper shielding of the most critical components against radiation issues.

The rationale used to define the proposed preliminary configuration (Fig. 2) considers the following constraints imposed by the other subsystems:

- Deployable solar arrays to satisfy the Electric Propulsion Unit power requirements;
- Deployable reflect array antenna placed to avoid interference with the solar array panels and to avoid occultation of the instruments' Field of View (FoV);
- The payload and the star trackers are oriented to avoid FoV occultation and limit Sun disturbance, maximizing the power generated;
- Electric Propulsion Unit centred with respect to the 12U structure to avoid the misalignment of the thrust vector;
- Symmetric configuration to keep constant at the most the principal inertia axis as well as to avoid spurious torques.

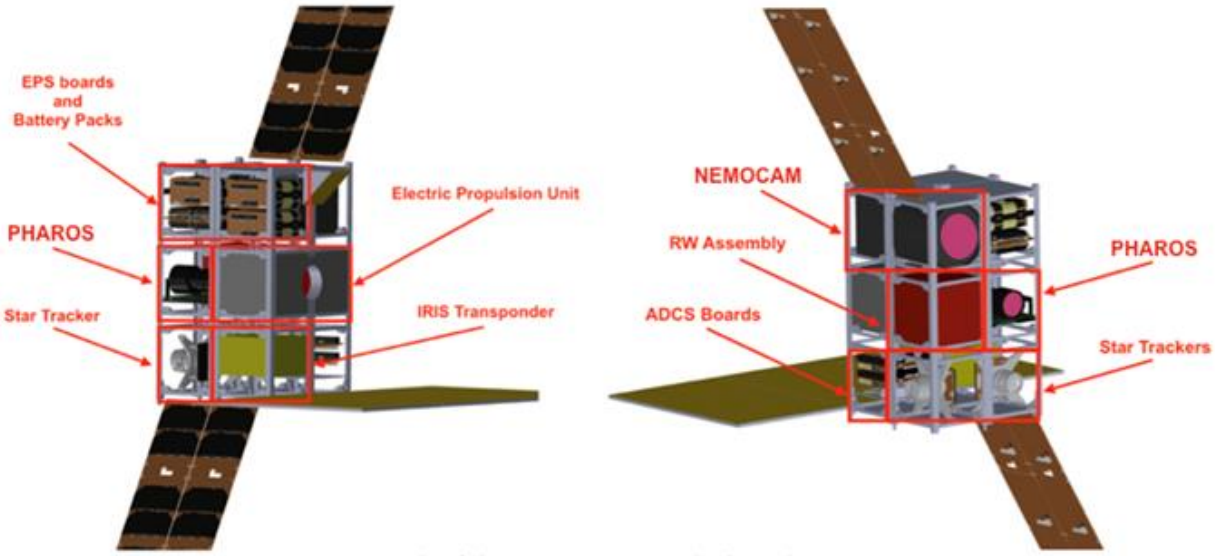

Figure 2: Detail of the ANIME CubeSat components. The design of the deployable solar arrays (not fully shown) includes 7 panels with 12 cells each, for a total available power of 84 W. An increase to 9 panels would imply minimal modifications in the spacecraft design. The reflect array antenna is composed by three equivalent reflectors with a surface of 2Ux3U each, for a total reflective area after deployment of 6Ux3U.

Table 2: Components considered for the main relevant subsystems in the preliminary design of ANIME, to be eventually updated during further study phases also depending on ongoing technological developments.

Component	TRL	Notes
Attitude Determination and Control Subsystem		
DOCK-ADCS	9	TRL acquired in LEO
OBC-ADCS	9	TRL acquired in LEO

IMU	9	TRL acquired in LEO
Reaction Wheels	9	TRL acquired in LEO
Star Tracker	9	TRL acquired in LEO
Propulsion Subsystem		
Electric Propulsion Unit	8	Will fly in deep space environment in 2021 (Lunar IceCube and LunaH-Map onboard NASA Artemis I)
Electrical Power Subsystem		
DOCK-EPS	9	TRL acquired in LEO
Power Distribution Unit	9	TRL acquired in LEO
Array Conditioning Unit	9	TRL acquired in LEO
Battery Pack	9	TRL acquired in LEO
Solar cells	9	TRL acquired in LEO
On-Board Data Handling Subsystem		
DOCK-OBDH	9	TRL acquired in LEO
OBC-OBDH	9	TRL acquired in LEO
Telemetry, Tracking & Control Subsystem		
Transponder	9	Flown on NASA/JPL MarCO
Deployable Antenna	9	Flown on NASA/JPL MarCO
Structure & Configuration Subsystem		
12-Unit CubeSat Structure	7	Structures by the same supplier with a smaller form factor are flight heritage
Deployer	9	Flight Heritage since 2014 both European and USA launchers
Release Mechanism	9	TRL acquired in LEO

3.1 Payload

NEMOCAM (Near Earth Multiple Objects CAMera), the main scientific instrument onboard ANIME, is an off-the-shelf modified Ritchey-Chrétien telescope derived from the Simera Sense TriScape 100 camera, which acquired a TRL 9 in the Earth orbital environment. Considering the maximum ionizing dose accepted by the camera (25 krad) and the mission profile of ANIME (cf. Section 2), a ~1.5 mm enclosure of aluminium or polyethylene will be added to shield both the NEMOCAM Sensor Unit and Control Electronics. NEMOCAM is a colour snapshot imager with a FoV of 2.22° across track and 1.70° along track, covering the 400-670 nm spectral range with an RGB Bayer filter. NEMOCAM stays in focus from infinity to 10 km and provides images through a 12.6-megapixel CMOS image sensor, with a spatial resolution of 0.95 m at a distance of 100 km from the target.

PHAROS (Potentially Hazardous Asteroids and Rendezvous ObServer), the secondary payload onboard ANIME, is the off-the-shelf GECKO catadioptric camera from SCS Space. Besides having acquired a TRL 9 in LEO space, the GECKO imager (renamed LUKE, Liciacube Unit Key Explorer) is one of the two scientific cameras onboard ASI/LICIACube, the Light Italian Cubesat for Imaging of Asteroids [10]. LICIACube is a 6U cubesat, part of the NASA/DART (Double Asteroid Redirection Test) mission, that has the main goal to impact (in 2022) Dimorphos, the secondary member of the (65803) Didymos binary asteroid system. PHAROS is a colour snapshot imager with a FoV of 5.0° (across track), covering the 390-680 nm spectral range with an RGB Bayer filter. PHAROS provides images with a 2.2-megapixel CMOS image sensor. The camera stays in focus from infinity to 400 m, having a spatial resolution of 7.8 m at a distance of 100 km from the target.

3.2 Fly-by and rendezvous trajectories design

Performance and constraints of the fly-bys are measured in terms of maximum resolution achieved (from payload properties), and maximum spin rate and acceleration (from reaction wheels limitations), as a function of fly-by speed and distance from the target. Given the high-speed and short-time nature of the fly-bys, gravitational effects from the targets, and major perturbation sources, can be neglected. Feasible fly-by regions (Fig. 3) are found to be mainly determined by spin rate (rather than spin acceleration) limits, evaluated considering a spacecraft rotation along its minimum inertia axis (0.25 kg m^2): considering the expected fly-by speeds of 2006 HZ51 and 2004 QD14 (cf. Table 1), a minimum distance of 49 km and 52 km respectively is required (a distance of 55-60 km is advisable, taking all of the uncertainties into account). Figure 3 also shows the expected maximum spatial scale of NEMOCAM images, which is around 0.7 m/px for both fly-bys.

The rendezvous phase around 2000 SG344 has a nominal duration of 2 months. Operations will foresee maneuvered transfers around the target, e.g. slow fly-by branches connected through holding points, taking into account the target gravity and main perturbations. Such kind of trajectories will allow a far-range (~10 km) phase for safe acquisition of target information (e.g., shape, spin) and global mapping of the surface (at spatial resolution of about 10 cm/px with NEMOCAM), and then a closer-range phase for higher-resolution imaging (up to 3.1 cm/px with PHAROS) and radio science, through a gradual sequence of intermediate orbits to be optimised during the activity.

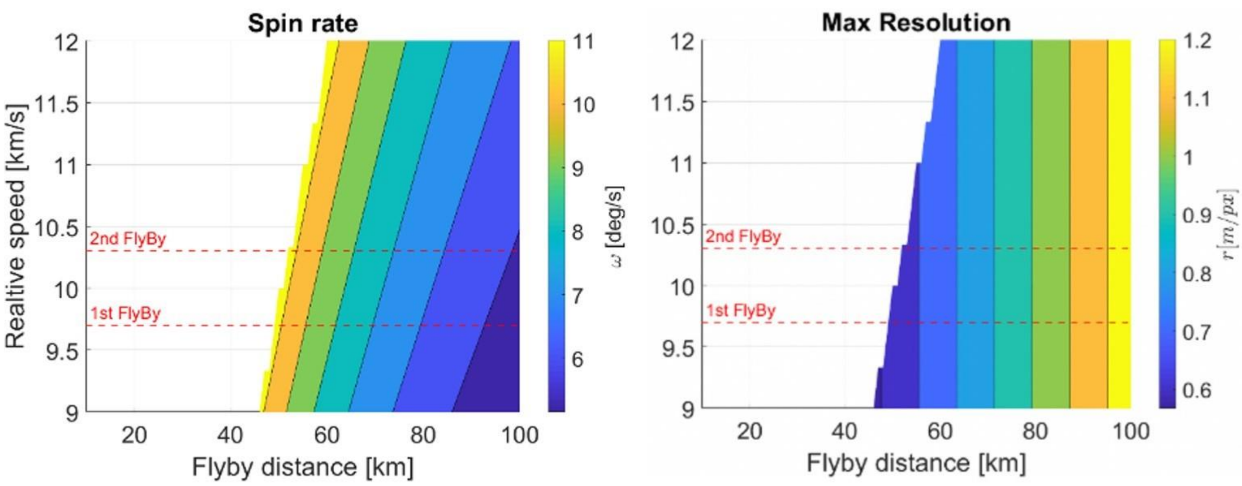

Figure 3: Feasible fly-by regions in terms of maximum spin rate (left) and maximum resolution achievable during the fly-by (right), as a function of fly-by distance and speed. Dashed horizontal red lines indicate the expected fly-by speeds of 2006 HZ51 (1st fly-by) and 2004 QD14 (2nd fly-by).

4 SCIENTIFIC RETURN

4.1 Imaging science

Both fly-by target PHAs 2006 HZ51 and 2004 QD14 will be imaged with NEMOCAM at the decimetre-scale (cf. Sec. 3.2). This will allow us to study their cratering size-frequency distribution (SFD), hence deriving their surface ages [e.g., 11], and their boulder SFD [e.g., 12], therefore analysing the formation and degrading processes that occurred and are still occurring on their surfaces [e.g., 13]. Thanks to geological detailed analyses of the different units identifiable on the asteroids both from texture [e.g., 14], as well as from colours [e.g., 15], their rubble pile vs. monolithic nature will be investigated. The wider-FoV images of PHAROS acquired during the fly-bys will be mostly used for safety recognition and to detect potential satellites of the two asteroids or ejected particles.

Besides the above scientific objectives mentioned for fly-by targets, the centimetre-scale images of rendezvous target 2000 SG344 will also provide the possibility to identify fractures on its surface and/or boulders, allowing the identification and discrimination of ongoing processes affecting this body, such as thermal fracturing [e.g., 16], space weathering [e.g., 17] and micrometeorite bombardment [e.g., 18]. Given the 2000 SG344 small size (~40 m), the multiple NEMOCAM acquisitions will help in understanding if the YORP effect [e.g., 19] is spinning up the object's rotation or decelerating it, hence estimating the induced heliocentric radial drift and refining the possible impact solutions with the Earth. Moreover, the 3D reconstruction of the entire surface, providing a high-resolution shape model able to evaluate the elevation and gravitational slopes [e.g., 20], coupled with the mass estimate derived through radio science (cf. Sec. 4.2), will lead to the first density measurement of such a small asteroid. The PHAROS camera will be used for proximity navigation (down to a distance of 400 m) to support both radio science investigation and surface characterization at higher resolution than NEMOCAM (up to 3.1 cm/px) during the close-range campaign around 2000 SG344.

4.2 Radio science

During the rendezvous operations, the mass of 2000 SG344 will be estimated by measuring the deflection of the spacecraft's trajectory caused by the gravitational interaction with the asteroid, through some low-altitude, low-velocity, fly-bys [e.g., 21]. Any detection of possible density anomalies would further help to constrain the asteroid composition and formation processes. Range and range-rate measurements are carried out using the onboard radio tracking system. Assuming the median asteroid values for the unknown albedo [e.g., 22] and density [e.g., 23], the expected mass of 2000 SG344 is of the order of $\approx 10^8$ kg. Considering a pericentre radius of 1 km and a pericentre velocity of 3 cm/s, it is possible to derive a relative uncertainty in the mass estimation of ~20%. As a first approximation, the uncertainty decreases with the square root of the number of fly-bys, e.g. obtaining a relative uncertainty of ~10% after 4 low-altitude fly-bys. A better performance can also be obtained with a reduction of pericentre radius and/or velocity. Multiple fly-by geometries will allow to disentangle the gravitational and non-gravitational accelerations acting on the spacecraft, and in particular the solar radiation pressure that represents a non-negligible perturbation, due to the very low mass of the asteroid.

Moreover, by knowing the spacecraft's state relative to the asteroid, ranging measurements with the Earth are useful to better determine the heliocentric orbit of 2000 SG344, hence to accurately assess its future impact solutions with our planet. Methods and tools adopted in the radio science experiment can be also used to perform operational navigation during the entire ANIME mission.

4.3 Theoretical modelling

Optical and radio science measurements obtained by ANIME will constrain the input parameters for numerical simulations that we will perform following two approaches: (i) streaming instability [e.g., 24] as a mechanism to form planetesimals overcoming the "meter-size barrier" (cf. Sec. 1), and (ii) N-body simulations of gravitational collisions of km-sized boulders [e.g., 25].

The streaming instability is most applicable for particles from 1 mm to 10 m in size. For such size range the coagulation is no longer efficient, as the collisions are so fast (with relative velocities greater than 100 m/s) that lead to the destruction of the colliding particles. Streaming instability orientates the particles having them locally concentrated along the Keplerian flow direction [26], thus favouring "gentle" collisions to form bodies up to the decametre-scale bodies. The following growth of such objects up to km-sized planetesimals is more likely governed by local agglomeration. Once the planetesimals are formed, gravity starts to play a dominant role and the coupling with the gas becomes negligible: planetesimals grow to protoplanets through gravitational interactions that can be treated as a N-body problem. The investigation of the 40-m-size 2000 SG344 (density, boulder size distribution, etc.) will be fundamental for the fine-tuning of such groups of simulations.

Therefore, the ANIME theoretical modelling efforts will allow us to constrain the formation scenario and internal structure of 2000 SG344 and similar, still unexplored, asteroids in the tens-of-meters size range.

5 CONCLUSIONS

The ANIME mission concept has been developed in response to the 2020 ASI call for ideas for future CubeSat missions, successfully passing (together with other proposals) the technical and scientific screening. We proposed a 50-month development plan (from phase A to phase D) and 24-month operations (phase E), following the European Cooperation for Space Standardization (ECSS) standards. The total financial budget of the ANIME mission is evaluated in the order of some tens of MEuro, leaving out launch costs but including ground antennas and personnel (A-to-F phases) costs.

With a nominal launch in late 2026, the 12U ANIME spacecraft will flyby PHAs (391211) 2006 HZ51 and (450300) 2004 QD14 in mid/late 2027, and then rendezvous in September 2028 with the 40-m-size, “high impact risk” asteroid 2000 SG344. However, we highlight that the definitive choice of NEAs to be visited can be easily updated at a further stage of study phases, also considering the current and near-future exponential growth of discoveries of NEAs. This gives ANIME a huge flexibility, as the mission scenario can be easily adapted to varying constraints (launch date, mission architecture, etc.).

ANIME is meant to be the first ever mission that can address questions about the monolithic vs. cohesive vs. rubble pile aggregation structure of small (tens-of-metres) asteroids, and shed light on the formation scenarios suggested in the literature so far. Furthermore, ANIME will provide essential information to increase our capacity of mitigating the asteroids’ threat of collision with the Earth. Incidentally, the obtained characterization of the chosen targets will help to assess the potential exploitation of the asteroidal mineral resources in the near future. ANIME will also offer the opportunity to technological solutions currently under development to fill the gap to face a deep space environment.

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