



The JUPITER ICy moons Explorer Lunar-Earth Gravity Assist (LEGA): Overview

Claire Vallat¹, Olivier Witasse², Nicolas Altobelli¹, Angela Dietz³, Miriam Aberasturi⁴, Clement

5 Aldebert³, Rafael Andres⁵, Arnaud Boutonnet³, Frank Budnik³, Thomas Cornet¹, Marc Costa⁴

¹European Space Agency, ESAC, Camino Bajo del Castillo, s/n, 28692 Villafranca del Castillo, Madrid, Spain

²European Space Agency, ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands

³European Space Agency, ESOC, Robert-Bosch-Straße 5, 64293 Darmstadt, Germany

⁴Starion España SLU for ESAC/ESA, Camino Bajo del Castillo, s/n, 28692 Villafranca del Castillo, Madrid, Spain

10 ⁵SSC Space for European Space Agency at ESAC, Camino Bajo del Castillo, s/n, 28692 Villafranca del Castillo, Madrid, Spain

Correspondence to: Claire Vallat (Claire.Vallat@esa.int)

Abstract. The European Space Agency's JUPITER ICy moons Explorer (JUICE), launched in April 2023, aims to assess the potential habitability of Jupiter's icy moons—Ganymede, Europa, and Callisto—while investigating the Jovian system as a whole. During its cruise phase, JUICE performed in August 2024 the first-ever combined Moon–Earth gravity assist (LEGA), a critical milestone for optimizing its trajectory toward Jupiter. Beyond its navigation objectives, this unique event provided an exceptional opportunity for in-flight calibration and validation of the scientific payload under known Earth environment. Despite significant operational constraints, all instruments were operated. The Moon flyby enabled precise calibration of remote sensing instruments, radar testing and in situ measurements of the Moon's environment while within the Earth's magnetotail, as well as the detection of a spacecraft outgassing event observed by multiple instruments and sensors. The subsequent Earth flyby complemented these efforts through atmospheric, magnetospheric, and radiation belt observations. These measurements confirmed the excellent performances of the JUICE instruments and demonstrated the mission's capability to deliver high-quality scientific data already during cruise. This campaign represents a key step in preparing for nominal operations at Jupiter while providing valuable scientific results.

25 1 Introduction

The JUPITER ICy moons Explorer (JUICE) is the European Space Agency's first large-class mission under the Cosmic Vision 2015–2025 program. The spacecraft was launched in April 2023 and is currently travelling toward Jupiter, where it is expected to arrive in July 2031 following an eight-year cruise through interplanetary space.



30 The mission is designed to assess the potential for habitable conditions on the Jupiter’s icy moons Europa, Callisto, and Ganymede, while also examining the Jovian system as a whole and the complex interactions that occur within it. Ganymede, the largest moon in the Solar System, is the primary focus of JUICE because of its suitability as a natural laboratory for the study of icy bodies and ocean worlds as well as the presence of its intrinsic magnetic field. Observations of Europa and Callisto will also enable comparative studies across the Galilean satellite system. After Jupiter Orbit Insertion, JUICE will
35 spend more than 3 years in orbit around Jupiter and perform 36 flybys of Ganymede (11), Callisto (23) and Europa (2) before entering in orbit around Ganymede for an additional year towards the end of 2034, first on an elliptical orbit and circular orbit at 5000km altitude, before going down to 500km and 200km.

JUICE is equipped with ten advanced scientific instruments dedicated to geophysical (RIME, GALA, 3GM), in-situ (JMAG, PEP, RPWI), and remote-sensing investigations (JANUS, MAJIS, SWI, UVS), along with the Planetary Radio
40 Interferometer and Doppler Experiment (PRIDE) and a radiation monitor (RADEM). It also hosts two (redundant) navigation cameras (NAVCAM) and two monitoring cameras (JMC), the former primarily being used for navigation and public relations purpose, while the latter was initially included to monitor the correct deployment of the solar arrays and some of the JUICE appendices after launch. (Witasse et al, 2026, submitted)

During its long cruise phase, JUICE follows a complex interplanetary trajectory involving 4 gravity assists. The first one was
45 a double one, with the spacecraft flying by both the Moon and the Earth within 24 hours, between the 19th and the 20th of August 2024 (Boutonnet et al, 2024).

This combined Moon-Earth gravity assist has been a major navigation milestone to implement JUICE’s trajectory to Jupiter within the available delta-v budget. This is the first implementation ever of this type of double Gravity Assist Manoeuvre and its successful completion was top priority for the JUICE Project (Dietz et al, this issue).

50 Gravity assist flybys are also essential for critical calibration of the instruments, operational modes testing, and checking anomalies for preparing corrective measures when needed, in preparation for adequate instruments science performances at Jupiter. Moreover, the extensive volume of data gathered during this period significantly enhanced public engagement, while also demonstrating that JUICE can deliver very high-quality scientific data throughout its long cruise phase.

2 Setting the scene of LEGA

55 2.1 Timeline

Event	Time (UTC or w.r.t Closest Approaches)
Start of navigation campaign	2024-07-08
Trajectory Correction Manoeuvre	2024-07-22 (ECA -4weeks)
Roll around -Xsc to point +Zsc to Moon	ECA – 3days



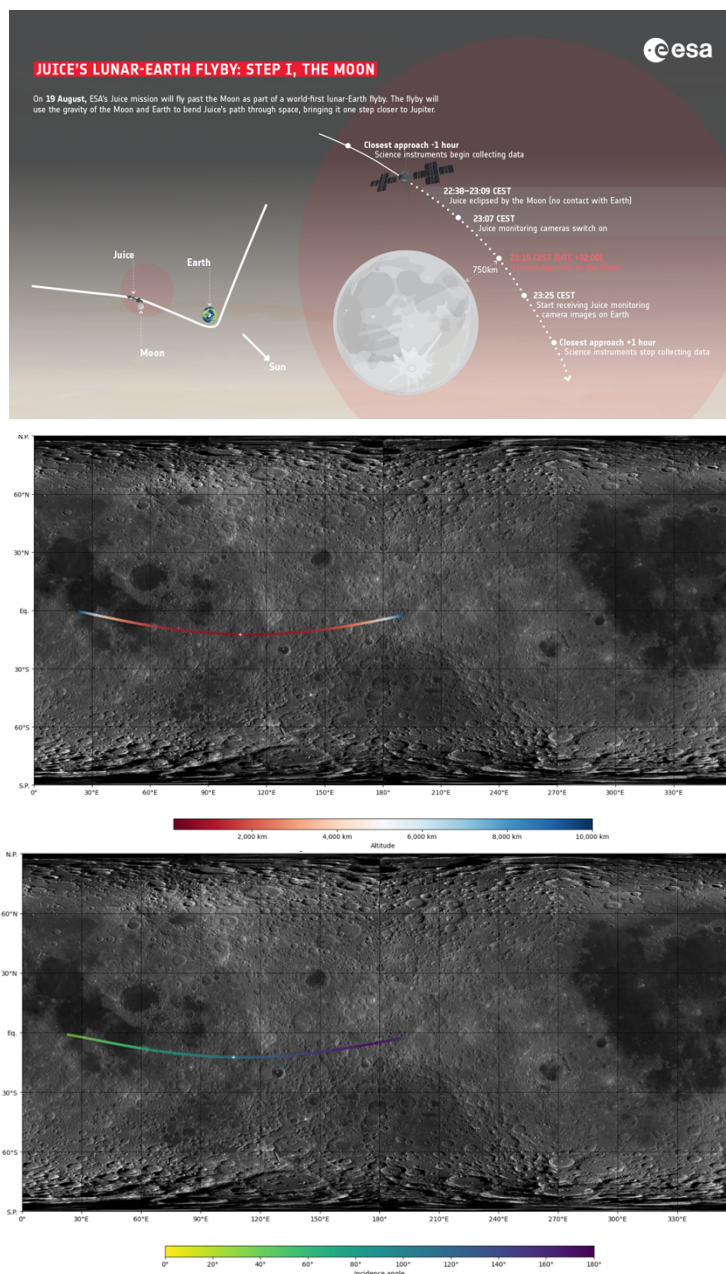
Moon flyby observations start	2024-08-19T20:15 UTC (MCA -1hour)
Eclipse start	2024-08-19T20:36 UTC
Eclipse end	2024-08-19T21:08 UTC
Closest Approach Moon (MCA)	2024-08-19T21:15 UTC
Moon flyby observations end	2024-08-19T22:15 UTC (MCA +1hour)
Roll around -Xsc to ensure ~30min of Earth visibility on +Zsc before closest approach	2024-08-20T09:56 UTC (ECA -12 hours)
Earth flyby observations start	2024-08-20T17:56 UTC (ECA -4 hours)
Closest Approach Earth (ECA)	2024-08-20T21:56 UTC
Roll around -Xsc to keep +Z at angular distance of ~5 deg from Earth direction	2024-08-20T23:56 UTC (ECA +2hours)
Full 360 degrees roll around -Xsc	ECA+2d and 6h
Earth flyby observations end	2024-08-23T21:56 UTC (ECA +3 days)
Trajectory Correction Manoeuvre	2024-08-27T19:00 UTC (~ECA + 1week)
Earth-Moon farewell image	2024-09-09T09:51:00 UTC

Table 1: Summary of the main operational events for the LEGA. +Zsc is the spacecraft Nadir deck. -Xsc is where the HGA that acts as a sunshield during hot cruise phase is located. ECA: Earth Closest Approach ; MCA: Moon Closest Approach.

2.2 Geometry

The Moon flyby occurred on the 19th August 2024, followed by the Earth flyby about 24 hours later. Given the constraints associated with such key navigation activities and the very limited time to perform measurements, a careful prioritisation of payload operations had to be planned. In addition, all payload and facility instruments (JMC, NAVCAM, RADEM) could operate during those 2 days.

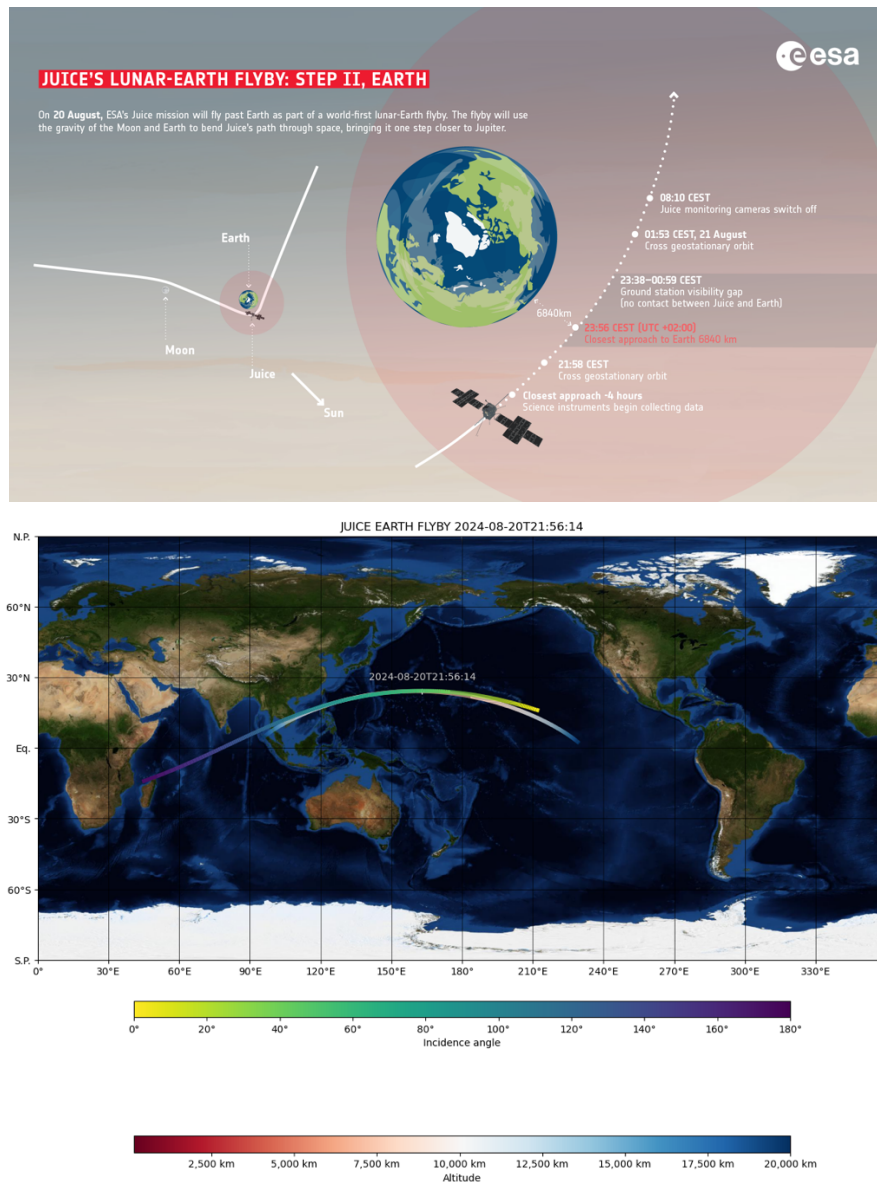
JUICE approached the Moon from the non-illuminated side. The closest approach occurred on 19/08/2024 at 21:14:54.681 UTC, at an altitude of 752 km and with a solar phase angle of 110 deg. The spacecraft was aligned with the Moon, Earth and Sun with a very low Sun-spacecraft-Earth angle (see Fig. 1).



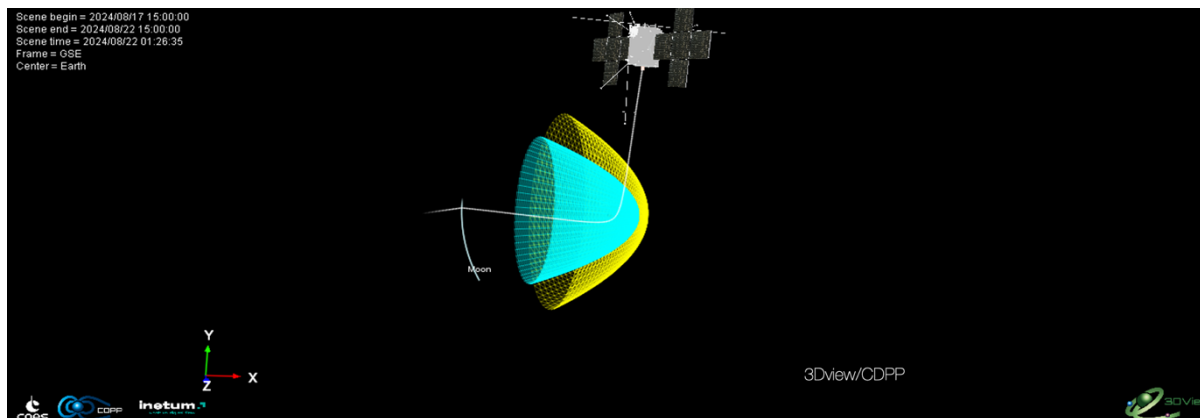
70 **Figure 1: Overview of the Moon flyby on the 19th August 2024. Top panel shows the main operational events, viewed from the Solar System South pole (credits: ESA). The bottom panels show a map projection of JUICE ground track with altitude [km] and spacecraft +Z (nadir) axis target intersection with Sun incidence angle [deg]. The incidence angle is measured between the outward normal (zenith direction) at the surface point and the direction from the surface point to the illuminator. This plot was generated with the planetary coverage tool (Seignovert et al, 2025)**



The Earth Closest Approach occurred roughly 24 hours later, on the 20th of August 2024, at 21:56:13.637 UTC, at an altitude of 6839 km above Southeast Asia and with a solar phase angle of 47.7 degrees (See Fig. 2).



80 **Figure 2: Overview of the Earth flyby on the 20th August 2024. Top panel shows the main operational events (credits: ESA). The bottom panel shows a surface map with the projection of JUICE ground track colour coded with altitude [km] and the projection of spacecraft +Z axis target intersection colour coded with Sun incidence angle [deg]. The incidence angle is measured between the outward normal (zenith direction) at the surface point and the direction from the surface point to the illuminator. This plot was generated with the planetary coverage tool (Seignovert et al, 2025)**



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Figure 3: Overview of the JUICE trajectory in GSE coordinate system between the 17th and the 22d of August 2024. Earth magnetopause is shown in blue and bow shock in yellow. Visualization generated with the 3DView tool from the Centre de Données de la Physique des Plasmas (CDPP). (Genot et al, 2018)

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The plot in Figure 3 represents the JUICE trajectory in the Geocentric Solar Ecliptic (GSE) frame, X_{GSE} indicating the Sun direction. JUICE is arriving from the far magnetotail and approaching Earth from the night side.

The Moon Closest Approach is occurring while the Moon is in the magnetotail (trajectory part on the left). While approaching and departing from Earth, JUICE also flew over the outer and inner radiation belts (not shown). A few hours after Earth Closest Approach, JUICE crossed the magnetopause (light blue) and the bow shock (yellow) before exiting in the Solar wind.

95 2.3 Payload instrument operations constraints

The limited observations time (especially during the Moon gravity assist), coupled with rapidly changing geometry conditions, required a careful and precise scheduling of the various payload observations. In addition, this period also presented several challenging operational constraints that are briefly described below.

2.3.1 Navigation

100 Gravity assists being key manoeuvres for the mission success, they require robust operations strategy for navigation and trajectory correction manoeuvres (TCM) (Dietz et al, this issue). TCM slots are scheduled at Closest approach -4weeks, -2weeks, -1week and +1week. In addition, to cope with the unlikely case where the latest orbit determination and trajectory optimisation reveals that Jupiter would not be reached within the given mission constraints (or with a prohibitive Delta-v penalty), an emergency Trajectory Correction Manoeuvre (eTCM) is scheduled a few hours before the actual flyby. For
105 LEGA, two of those were scheduled: one 6 hours before the Moon Closest Approach, and one 4 hours before Earth Closest



Approach. To interfere as little as possible with this strategy, it was therefore considered as an acceptable risk to operate payloads exclusively during the following time periods:

- Between +/- 1 hour around the Moon closest approach
- from - 4 hours to + 3 days around Earth closest approach.

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In practice, before the Moon closest approach, only the TCM planned at -4 weeks has been used. After the Earth closest approach, the TCM at +1week was executed, although it has been decided to split the manoeuvre in two smaller corrections, the second one planned much later (on 1/1/2025) to optimize the correction (Dietz et al, this issue).

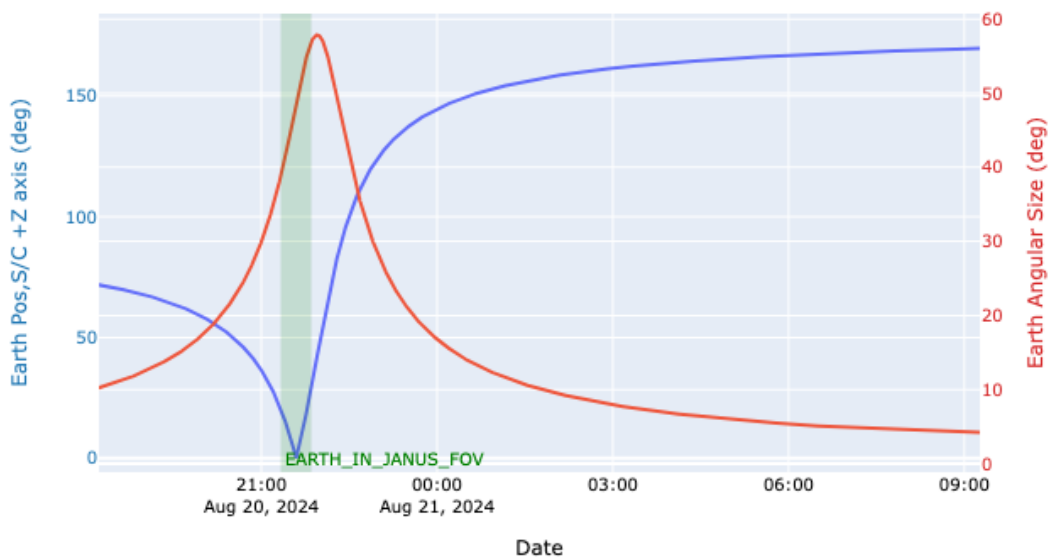
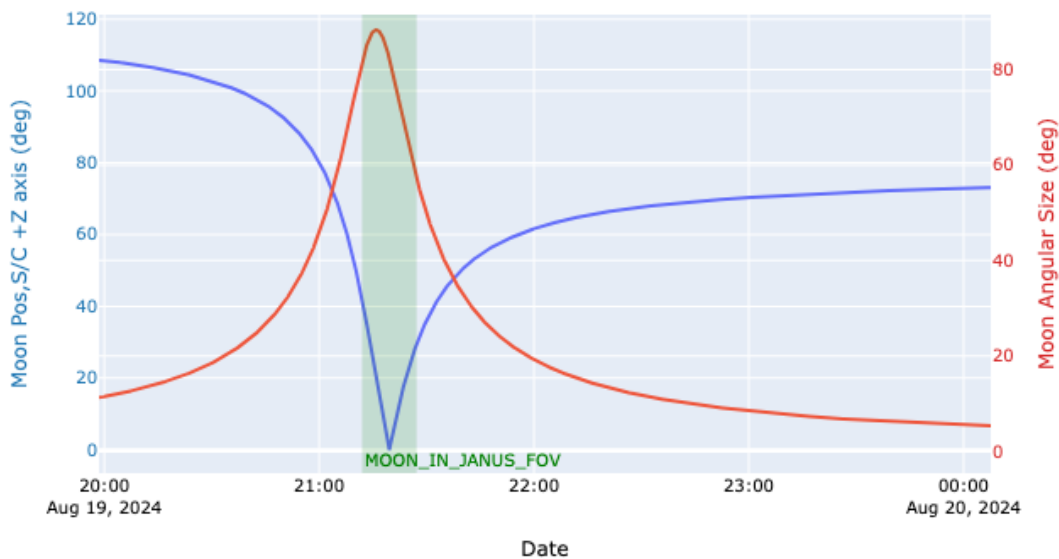
2.3.2 Eclipse

115 Coming from the night side, JUICE had to enter in eclipse shortly before the Moon Closest Approach. The eclipse lasted 32 minutes and finished less than 7 minutes before the closest approach point.

2.3.3 Attitude

120 At such low heliocentric distances, strong thermal constraints apply on JUICE (Sarri et al., 2026). Below 1.34 AU from the Sun, the spacecraft attitude is limited as its High Gain Antenna (HGA) is used as a heat shield and should not depart from this orientation. The flexibility in setting the spacecraft attitude is therefore limited to a rotation around the spacecraft to Sun direction while keeping the High Gain antenna always pointing to the Sun.

125 To maximize the observations time and conditions, a rotation angle strategy (around the HGA to Sun orientation) has been selected to ensure that the Spacecraft +Zsc axis (nadir deck) intercepts the Moon (resp. Earth) disc for as long as possible. This ensured around 15min of the +Zsc interception with the Moon surface (around closest approach), and ~30min of the +Zsc interception with the Earth surface (until a few minutes before closest approach). The transition between the two configurations was planned ~12 hours after the Moon Closest Approach.



130 **Figure 4: up: Moon angular size as seen from JUICE (in red) and angular separation between Moon centre and +Zsc (in blue). When this angular separation reaches 0, the spacecraft is pointing nadir. Bottom: same plot for the Earth. The green background indicates when the target is within the JANUS science camera field of view, showing that Earth was not in the camera FoV at Earth closest approach.**



2.3.4 Thermal configuration of instruments

135 Some instruments require a thermal stabilisation before science acquisition, and this period can extend to several hours. Given the limited operations time allowed during the Moon flyby, specific non-nominal thermal regulation strategies had been put in place to ensure that those instruments would be in an acceptable range when starting their observations.

2.3.5 Interferences with RIME

140 The Moon flyby was the only opportunity during cruise for the radar instrument to characterise precisely electromagnetic interferences with the probe’s subsystems in the radar band (central frequency at 9 MHz), using the echo bounced from the surface of the Moon. To disentangle from possible other interferences sources, RIME was allocated eight minutes to measure alone, while other instruments were either switched off or set to a so-called ‘quiet’ mode. This period started from an altitude of 1000km inbound and ended shortly before the Terminator crossing towards the illuminated side of the surface, when remote sensing instruments resumed their observations.

145 3 Activities

3.1 Moon flyby

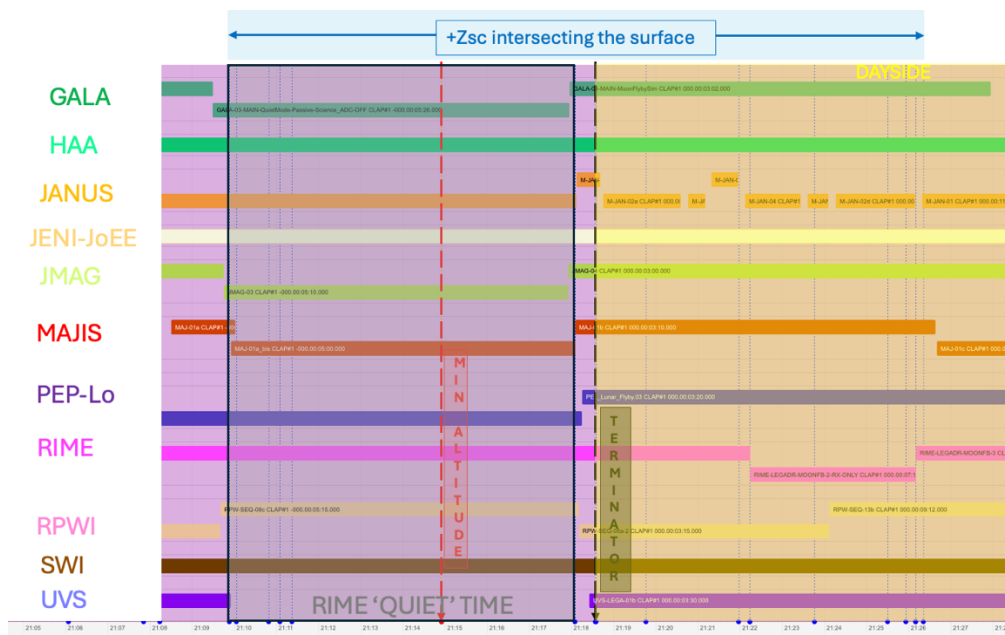


Figure 5: Overview of the scientific instruments’ activities timeline covering 20 minutes around the Moon Closest Approach. Top blue background indicates when the +Zsc intersecting the Moon surface, yellow indicates that JUICE is observing on the dayside.



150 **Grey background indicates the period where all instruments had to use a so-called ‘quiet’ mode not to disturb the RIME characterisation test.**

The Moon provides a great proxy for Jupiter moons’ flyby operations as it provides a first operational benchmark for the instrument to check their performances using Earth and the Moon as real targets.

155 3.1.1 Remote sensing instruments (JANUS, MAJIS, SWI, UVS)

The characteristics of specific lunar regions of the Moon in the visible and near IR are well known from observations by lunar orbiters, and this has been extremely useful for remote sensing calibrations.

The Moon is an airless body that can be used as reflectance standard to check the instrumental radiometric calibration function and is useful to understand instrument response and post-processing techniques for the remote sensing instruments.

160 (Agostini et al, this issue; Tubiana et al, this issue; Langevin et al, this issue; Poulet et al, this issue)

Combined observations were also scheduled to estimate boresight alignment and instrument co-alignment which may have slightly changed after launch.

165 During the Moon flyby, MAJIS was able to provide local coverage of the lunar surface down to about 130 meters from the visible up to the thermal infrared range. The obtained spectrum allowed to retrieve information on the composition and the physical properties of the observed regions. MAJIS could therefore detect mafic minerals (some associated to fresh excavated materials) and measure thermal emission and emissivity variations on the Moon (Zambon et al, this issue; Tosi et al, this issue). Thermal emission and reflectance radiations due to seas or “maria” and lunar highlands could also be observed.

170 The observations acquired by the JANUS camera, although primarily devoted to calibrations, could allow provide high quality scientific data to support geological and spectrophotometric analysis of the surface, like e.g. the Langrenus crater (Lucchetti et al, this issue).

In the UV, the Moon provided a great opportunity during cruise to determine the effective area of the UV spectrograph at EUV wavelengths (<100 nm) since stars do not provide enough signal at these wavelengths and Earth has variable atmospheric emissions that complicate the interpretation of results (Molyneux et al, this issue).

175 The Moon also provided an excellent opportunity to verify the science observations strategies of the heterodyne spectrometer (SWI) and that are relevant for the Ganymede/Europa/Callisto observations (Cavalié et al, this issue), as well as an interesting extended target for in-flight characterization of the antenna pointing and beam characterization (Moreno et al, this issue).



3.1.2 In-situ instruments (JMAG, RPWI, PEP)

180 During the flyby, the Moon was located well within Earth's magnetotail, in the magnetic lobes. JUICE approached the Moon from the wake side (LaMoury et al, this issue). The extended lunar wake structure within Earth's magnetosphere could therefore be sampled by the plasma environment package.

In situ instruments (magnetometer, plasma environment package, radio plasma wave instrument (Wahlund et al, 2025)) could also test specific operational modes in preparation for the Jupiter phase, like e.g. passive sub-surface radar operations using the Radio Wave Instrument and taking advantage of the proximity of the Earth as a radio source (Auroral Kilometric Radiation emissions).

3.1.3 Geophysics instruments (RIME, GALA, 3GM, PRIDE)

Given the cruise trajectory geometry and the instruments operational range, the Moon flyby was the only opportunity until 2032 to get a signal back from a target surface for the ice penetrating radar (RIME) radar as well as to test laser altimeter (GALA) measurement.

190 Although GALA experienced an unexpected reboot during operations that prevented it to acquire data during the flyby, the ice penetrating radar (RIME) returned high quality echoes of the Moon surface enabling to check how the spacecraft noise affects the performance of the instrument. Based on the data collected, the team developed an algorithm to best process the data.

195 The High Accuracy Accelerometer (part of the 3GM experiment) measured the spacecraft's dynamics response to Moon gravity gradient and other non-gravitational perturbations. The calibrated data show excellent agreement with theoretical models, confirming the instrument's accuracy (DeFilippis et al, this issue).

The PRIDE experiment successfully tracked the JUICE mission spacecraft during its 2024 lunar and Earth flybys using Very Long Baseline Interferometry (VLBI) radio telescopes, with Doppler measurements closely matching model predictions and providing valuable data on the Earth's ionosphere and space weather (Molera Calves et al, this issue)

3.1.4 The outgassing event

During the Moon flyby, the ESA Flight Dynamics team found out discrepancies between the ground-predicted reaction wheel levels and the reconstructed values from telemetry. While the prediction accounts for solar radiation pressure and gravity gradient torque, converting the residuals into spacecraft frame torque reveals the excess (i.e., unmodelled) torque (see Figure 6). The dominant contribution appears around the spacecraft +Y axis, peaking at roughly 6 mNm about seven minutes after closest approach to the Moon. Possible sources included thermal or Moon albedo forces, spacecraft outgassing, or inaccuracies in ground spacecraft parameters, such as inertia, which would propagate into reaction wheel level prediction errors. At this time, the spacecraft's cold +X side was illuminated by Moon albedo (see Figure 7 and 8), consistent with these



210 effects. In parallel, Orbit Determination estimates a parasitic Δv of about 0.3 mm/s (constrained along +X) shortly after the lunar closest approach.

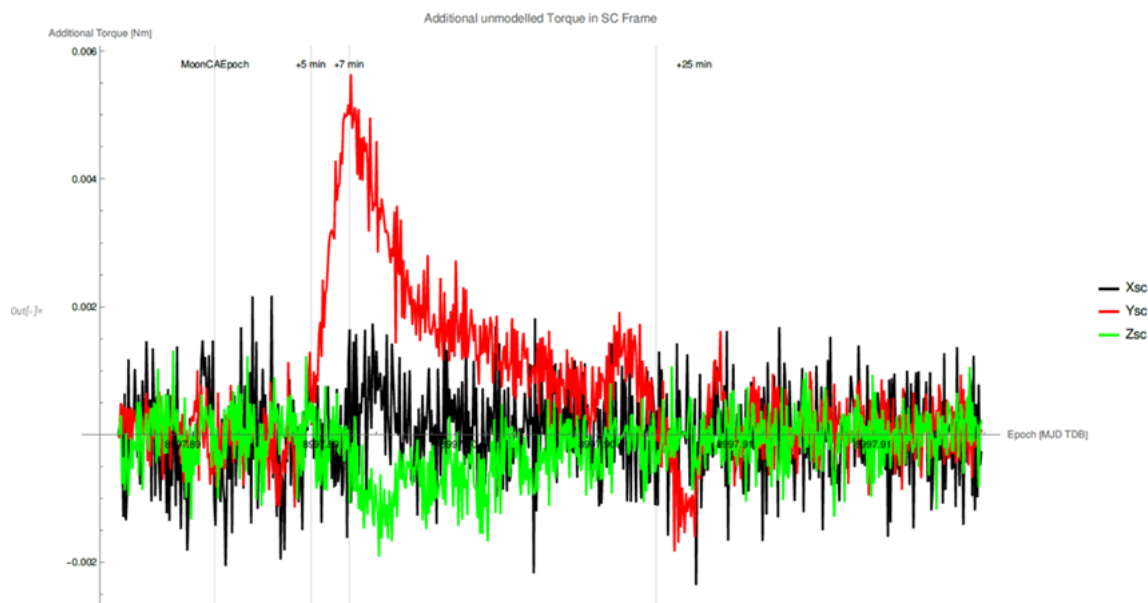
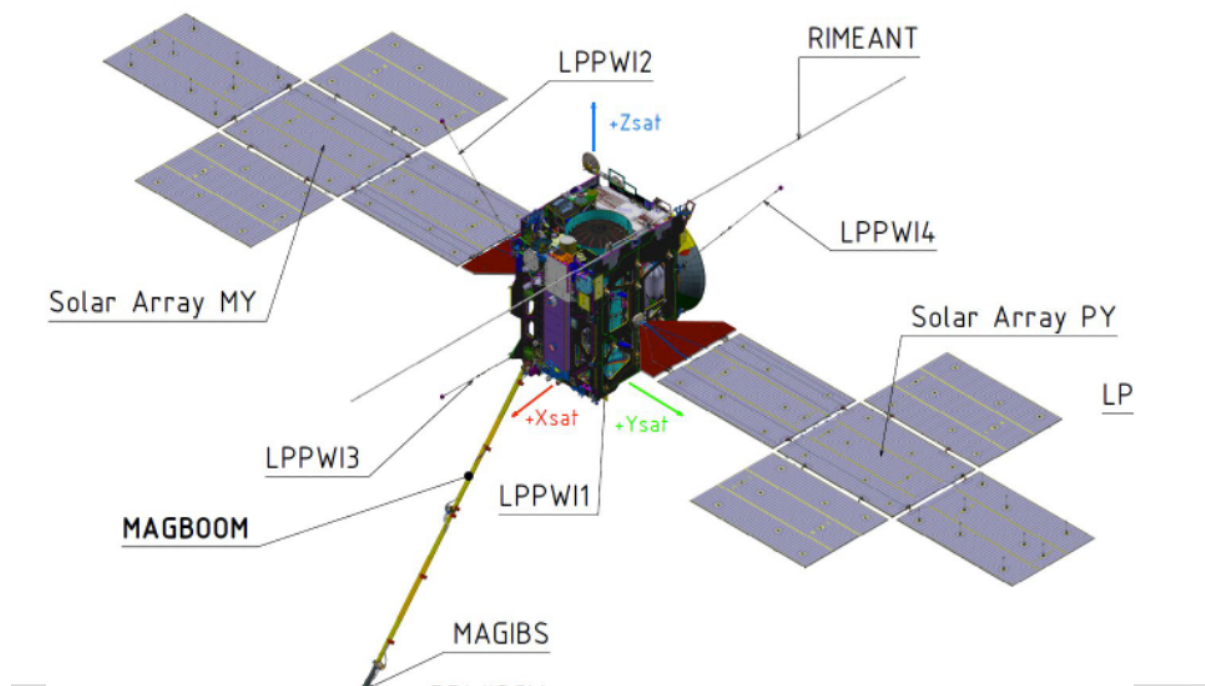


Figure 6: Spacecraft unmodeled torques, showing a dominant contribution around the +Y axis, peaking at roughly 6 mNm seven minutes after closest approach to the Moon. This observation is interpreted as an outgassing event.





215 **Figure 7: Sketch showing the nomenclature for the JUICE spacecraft faces.**

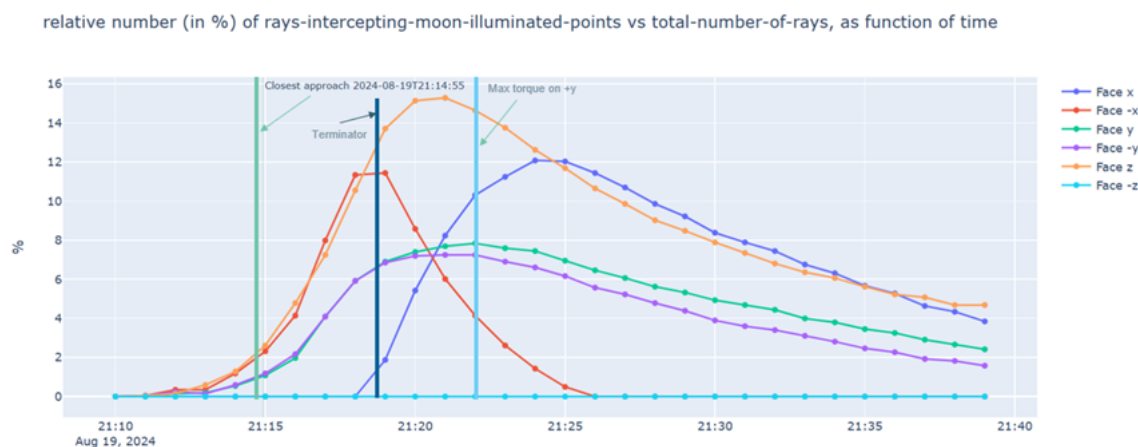


Figure 8: Estimation of the illumination of each spacecraft faces by the moon. Vertical bars indicate closest approach (green), terminator (dark blue), and the time of the maximum torque on +x (pale blue).

220 This outgassing event is reported in De Filippis et al., this collection. The SWI instrument detected water vapor around the spacecraft, confirming the reports from reaction wheel and accelerometer analyses. It is very important to document this event to properly analyse the JUICE data set acquired during this flyby (e.g. Schläppi, B., et al. 2010, 2014; Xie et al., 2017; Fraenz et al, 2024). In the case of the Moon, it is particularly useful in the context of the study of a Lunar water cycle (e.g. Benna et al., 2019; Hodges et al. 2022).

3.2 Earth flyby

225 The Earth provided an excellent extended source for calibrations, complementary to the Moon due to its different characteristics, like e.g. radiance and radiance variability. (Agostini et al, this issue).

During the gravity assist, atmospheric absorption features, thermal brightness, and icy cloud properties could be measured, while cloud variability provides a useful diagnostic of atmospheric dynamics, as demonstrated in Hueso et al (this issue).

230 For the UV spectrograph, the use of emission lines (O, H, He, N₂, O+...) helped to determine extended source spectral resolution and plate scale across the bandpass. The UV emissions from Earth's atmosphere provided an especially good test of the plans for JUICE-UVS to observe Ganymede's UV aurora and other atmospheric features. (Molyneux et al, this issue).

235 The Earth's atmosphere was observed and used to validate the MAJIS instrument performance. Major species such as carbon dioxide and water vapor, as well as ozone and other trace gases, were clearly identified in the infrared spectra, demonstrating the excellent spectral and radiometric performances of the instrument (Guerlet et al, this issue). Terrestrial lightning event could also be detected by MAJIS (D'Aversa et al, this issue). Comparison with PRISMA data demonstrated its calibrated



hyperspectral performance and confirmed MAJIS ability to retrieve atmospheric and surface spectral signatures. (Oliva et al, this issue).

During the flyby, SWI could detect hundreds of molecules in Earth's atmosphere, including water and CHNOPS elements (carbon, hydrogen, nitrogen, oxygen, phosphorous and sulphur) (Jarchow et al, this issue), also revealing spatial information, like a variation of ozone over the South Pole region.

Finally, the ice penetrating radar (RIME) was operated in listen-only mode to measure radio signals generated by terrestrial transmissions (natural and manmade), providing useful measurement for calibration.

3.3 Magnetosphere

On its path, JUICE encountered various plasma populations, from the low energy plasmasphere to the ring current to the harsh radiations' belts environment (Zeroual et al, this issue). On the outbound part of the flyby, JUICE crossed the magnetopause and the bow shock, providing a great sampling of the different plasma regions around Earth. (Fraenz et al, Stenberg et al, Brandt et al, LaMoury et al, this issue)

In addition, flying through the magnetosphere gave the opportunities to detect particles coming from different direction than the Solar Wind, where JUICE is spending most of its cruise phase, allowing to calibrate different sectors of the plasma package units (Fraenz and al, this issue, Stenberg et al, this issue).

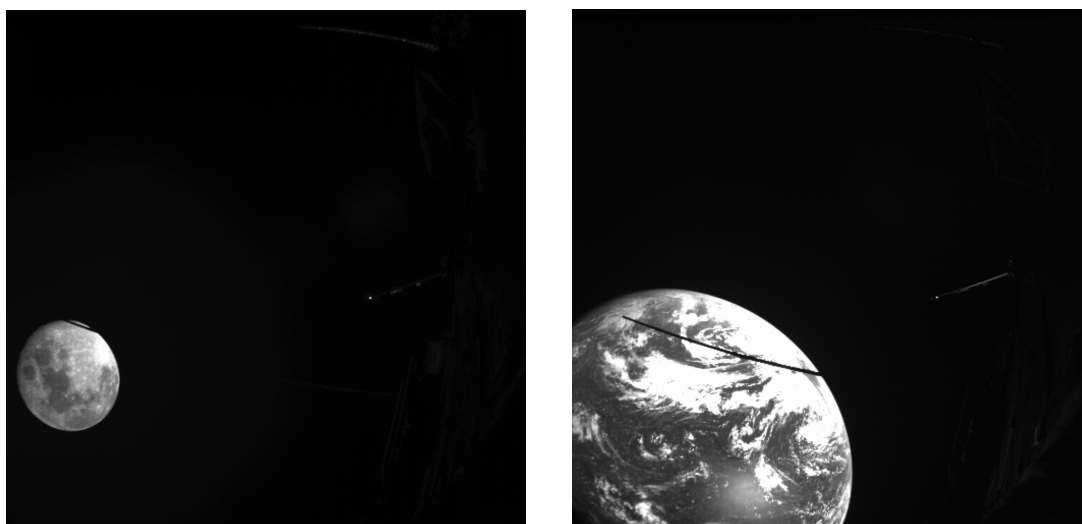
Parallel measurements of the in-situ instruments (RPWI, JMAG and PEP) provided good conditions for cross calibration, like e.g. calibration of plasma parameters, cross calibration of different fields at different frequencies, ExB calibration against ion flux, known plasma & plasma wave environment amplitudes, phases and sources. In particular, the spacecraft potential as derived by RPWI is used as an input/constraint for interpreting PEP measurements at low energy. (Fraenz and al, Stenberg et al, this issue)

For the ring current and the (nightside) plasma sheet, the flyby gave an excellent calibration opportunity since the in-situ environment has been monitored by different spacecraft in the past (Stenberg et al, this issue). In addition, energetic atoms emitted by charged particles that interact with hydrogen gas coming from Earth's atmosphere could be captured (Brandt et al, this issue).

The exposition of JUICE to higher energy particle magnetosphere populations has been useful for calibration with a high SNR. High energy particles from the radiation belts at Jupiter are expected to generate background noise in the situ particles sensors. The combination of in-situ particle measurements and ENA imaging provides complementary views of the radiation belts, linking local plasma properties with their global spatial distribution in the inner magnetosphere (Brandt et al, this issue). Since the radiation monitor (RADEM) is continuously ON during cruise, it could also provide precise measurements while crossing the radiations belts (Pinto et al, this issue). First ENA images of Earth's magnetosphere from JENI during the Lunar-Earth Gravity Assist also revealed the radiation belts and hot plasma populations of the inner magnetosphere and confirmed the instrument's capability for future operations (Dialynas et al, this issue).



As JUICE flew past Earth, RPWI could detect radio bursts from the northern and southern lights (auroras) as well as radio emissions from electrons surrounding the planet flying close to the RPWI antennas. Solar Type II emission produced by electrons flying from the Sun were also detected and could be used to determine the noise floor and sensitivity of the Radio Wave Instrument.



275 **Figure 9: Partially processed images of the Moon (left) and Earth (right) taken by the Juice Monitoring Camera (JMC) a few minutes after the Moon and Earth Closest approach, on the 19th and 20th of August. CREDIT: ESA/Juice/JMC.**

3.4 Farewell

Less than 3 weeks after the Earth flyby, on the 9th of September 2024, JUICE performed a last set of farewell observations, from about 5.65 millions km. Both the NAVCAM and the JANUS camera obtained a stunning snap of the Earth Moon system from far.

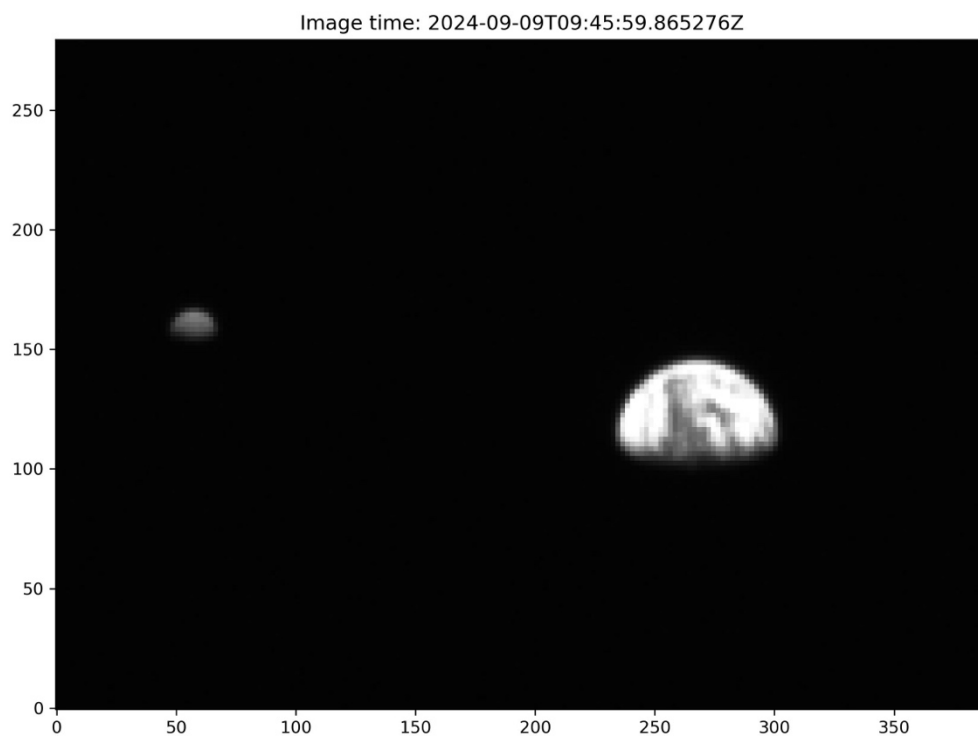


Figure 10: Farewell raw image acquired by the JUICE NAVigation CAMera on the 9th Sept 2024. Zoomed imaged (140 lines x 195 samples with bilinear interpolation of factor 2). CREDIT: ESA/Juice/NavCam.

This was also the opportunity for the laser altimeter GALA to calibrate its receiver and infer the instrument boresight
285 alignment, using passive observations of reflected Earth light. (Nishiyama et al, this issue)

All data acquired during this period by the JUICE monitoring cameras (JMC), as well as by the radiation monitor RADEM
are publicly available in the Planetary Science Archive (psa.esa.int).



4 Conclusions

The first double gravity assist of Moon and Earth on the 19th and 20th of August 2024 provided a unique opportunity for the
290 JUICE payload to calibrate the instruments in preparation for the nominal science phase, confirming the instrument
performances and acquiring excellent scientific data. Despite the complex set of constraints applicable to such mission
phases, the payload and facility instruments were able to operate. Thanks to the two flybys' geometry, Earth and Moon
provided excellent calibration targets, being large, bright and already well-characterized. The plasma environment
encountered by JUICE also allowed to sample different plasma regimes, a key aspect to validate or adjust the calibration of
295 the in-situ instruments before the nominal phase. With two more Earth flybys during cruise as well as two payload checkouts
per year, the JUICE instruments will be able to complete their necessary calibration activities and acquire additional valuable
science measurements before arriving at Jupiter.

Acknowledgements

300 JUICE is a mission under ESA leadership with contributions from its Member States, NASA, JAXA and the Israel Space
Agency. It is the first Large-class mission in ESA's Cosmic Vision programme. The RADEM data, as well as the images
acquired by the Juice Monitoring Camera (JMC) data are publicly available on the Planetary Science Archive (psa.esa.int).

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