Jupiter Icy Moons Explorer Investigation

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Abstract

This report presents an investigation of the European Space Agency's JUICE (Jupiter Icy Moons Explorer) mission from the perspective of orbital and space flight mechanics. Emphasis is placed on its complex gravity assist trajectory, orbital insertion at Jupiter, and final orbit around Ganymede.

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Chapter 1

Introduction

1.1 Mission Overview

Initially named Laplace in 2007, it was renamed the Europa Jupiter System Mission after ESA and NASA joined proposals in 2009 (Blanc et al. 2009) for a major mission to the Jupiter System. In 2011, EJSM was reformed again into an ESA-led mission to Ganymede with flybys to Europa and Callisto, named JUICE (JUpiter ICy moon Explorer) (Dougherty et al. 2011). JUICE has been selected as ESA's next large mission for launch in 2022.

1.2 Scientific and Engineering Goals

Juice, the ESA's Jupiter Icy Moons Explorer, will use a suite of remote sensing, geophysical, and in situ equipment to collect extensive studies of the giant gas planet and its three huge ocean-bearing moons, Ganymede, Callisto, and Europa.
The mission will characterize these moons as both planetary objects and potential habitats, investigate Jupiter's complex environment in depth, and examine the Jupiter system as a model for gas giants throughout the universe. Juice will reach the Jovian system in July 2031, following four gravity aids and eight years of transit. In December 2034, the spacecraft will reach orbit around Ganymede for a close-up science mission.

1.3 Importance of Orbital Mechanics

The use of orbital mechanics principles allows JUICE to:

- Reach jupiter efficiently (in terms of fuel consumption and trajectory navigation)
- Navigate around the Jovian system.
- Which in turn helps explore the icy moons Ganymede, Europa, and Callisto.

Chapter 2

Construction of the Undertaken System

2.1 Mission Architecture

2.1.1 The JUICE spaceship

The JUICE spacecraft looks almost cuboidal, with two big cross-shaped 'wings' of solar panels on either side, multiple extending booms and antennas, and a large dish-shaped antenna on one face, as shown in figure 2.1

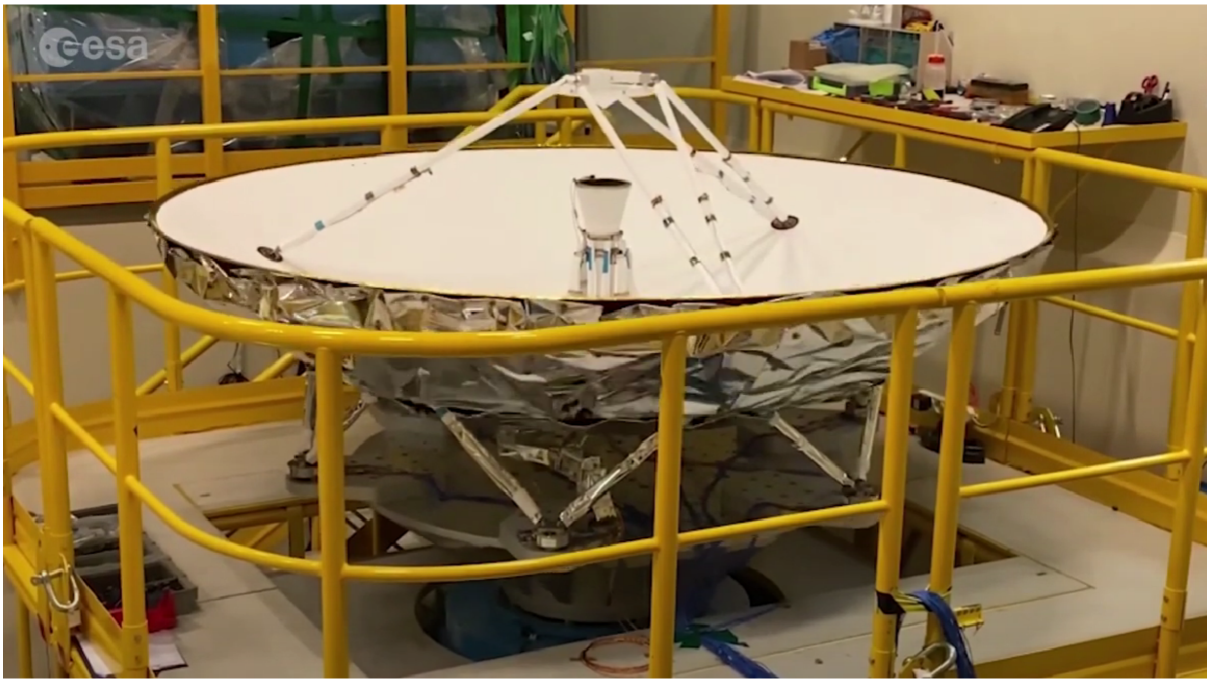


Figure 2.1: JUICE's high gain antenna (designed, produced and supplied by Thales Alenia Space) undergoing vibration tests

The spacecraft's dimensions are as follows:

- **Dimensions (stowed for launch):** 4.09 x 2.86 x 4.35 m
- **Dimensions (deployed in orbit):** 16.8 x 27.1 x 13.7 m.

With a dry mass of 2420kg + 3650kg of propellant that take up the entire tank + 280kg in instrument mass, the total mass before launch is **6350kg**.

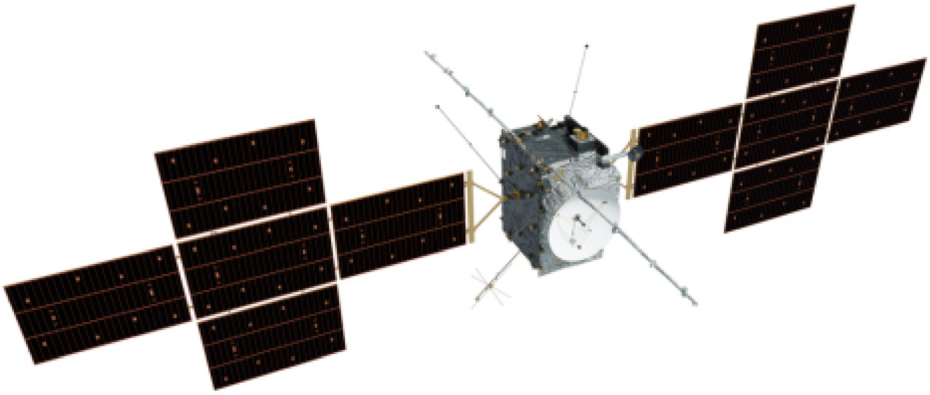


Figure 2.2: the JUICE spacecraft. Credit: ESA/ATG medialab

2.1.2 JUICE's instruments

Antennas and Booms

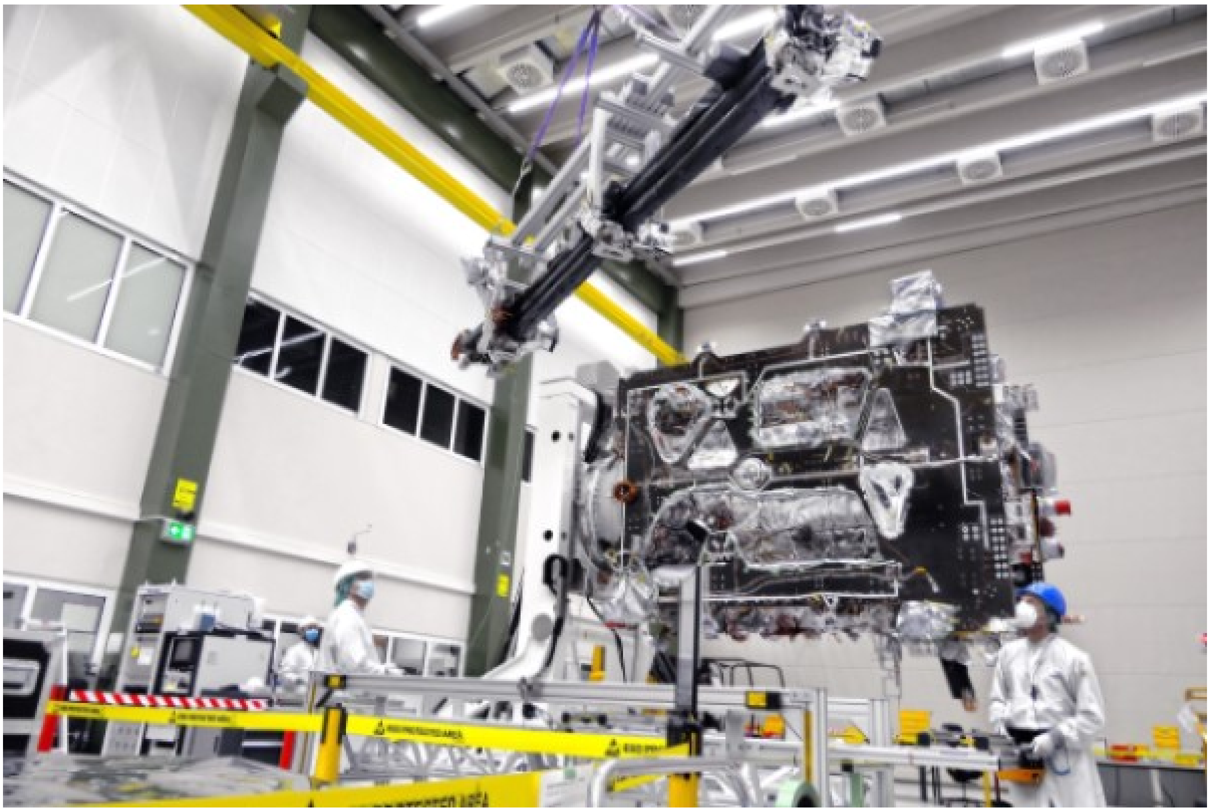


Figure 2.3: integrating the magnetometer 'arm' in Airbus, Sener

JUICE holds antennas and booms with many magnetically sensitive sensors that are placed distant from its body to avoid interference and disturbance as the instruments investigate the complexities of Jupiter's magnetism. JUICE will carry a 10.6-meter deployment boom (figure 2.4)

Figure 2.4: test-deploying JUICE's 10.6-metre boom

for its JUICE Magnetometer (J-MAG) and Radio and Plasma Wave Investigation (RPWI) instruments, as well as a 16-meter deployable antenna for its radar instrument (RIME). RPWI contains three additional electric 2.5-meter antennas (known as RWI) and a three-axis Search Coil Magnetometer (SCM), both installed on the J-MAG boom, as well as four 3-meter deployable booms. The 3-meter booms each hold a 10-cm-diameter Langmuir probe, which is tetrahedrally placed on the spacecraft's body. The other instruments will be installed on the spacecraft body, except the radio science experiment (3GM), which will be housed within.

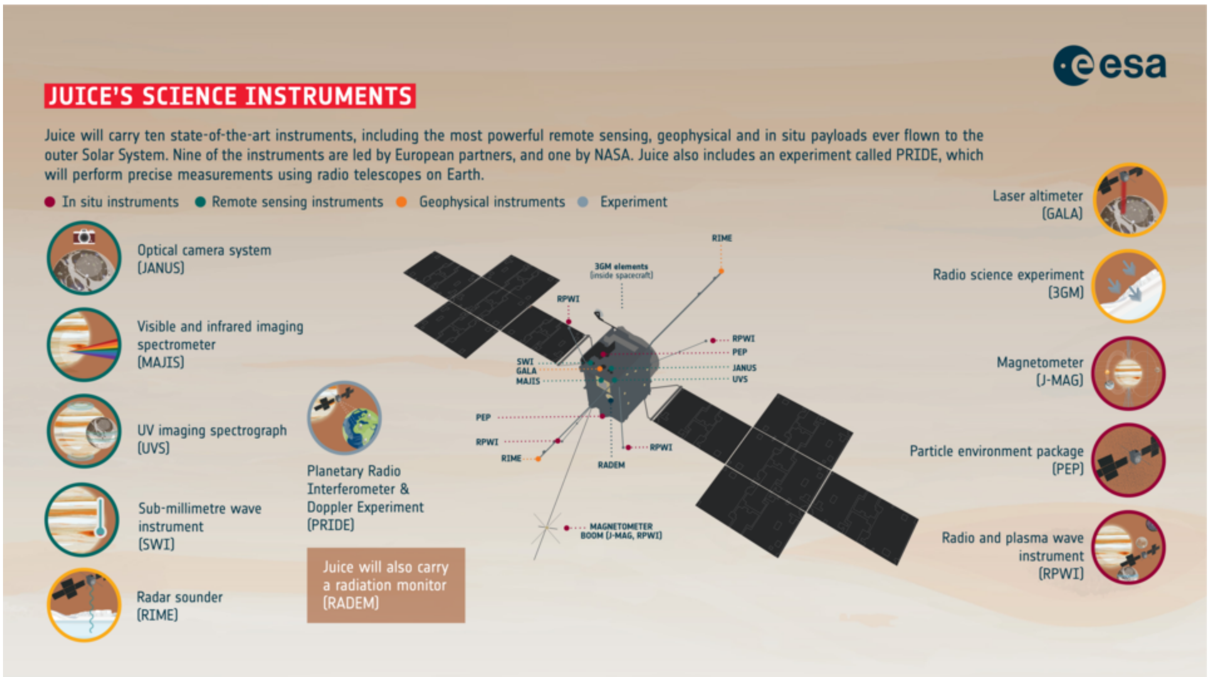


Figure 2.5: JUICE's science instruments

Instrument	Description

3GM	The Gravity & Geophysics of Jupiter and Galilean Moons radio package includes a Ka transponder, an ultrastable oscillator, and a high-accuracy accelerometer. The experiment will look at Ganymede's gravity field, the size of the interior oceans on the frozen moons, and the structure of Jupiter's neutral atmosphere and ionosphere.
GALA	The Ganymede Laser Altimeter will analyze Ganymede's tidal deformation as well as the topography of the frozen moons' surfaces.
JANUS	JANUS, an optical camera system, will examine global, regional, and local lunar characteristics and processes, as well as map Jupiter's clouds. It will have a resolution of up to 2.4 meters on Ganymede and approximately 10 kilometers on Jupiter.
J-MAG	J-MAG is the Juice magnetometer, and it is equipped with instruments to characterize the Jovian magnetic field and its interaction with Ganymede, as well as to research the frozen moons' subterranean waters.
MAJIS	MAJIS is the Moons and Jupiter Imaging Spectrometer. It will investigate cloud characteristics and atmospheric elements on Jupiter, as well as ices and minerals on the icy moon's surfaces.
PEP	PEP stands for the Particle Environment Package. It consists of a set of sensors designed to characterize the plasma environment of the Jupiter system and its ice moons.
RIME	RIME, or Radar for Icy Moon Exploration, is an ice-penetrating radar that studies the subsurface structure of icy moons down to a depth of around nine kilometers.
RPWI	The Radio and Plasma Wave Investigation (RPWI) will use a variety of sensors and probes to characterise Jupiter's radio emission and plasma environment, as well as its frozen moons.
SWI	SWI (Submillimeter Wave Instrument) will study the temperature structure, composition, and dynamics of Jupiter's atmosphere, as well as the exospheres and surfaces of the icy moons.
UVS	UVS is a UV imaging spectrograph designed to examine the composition and dynamics of the frozen moons' exospheres, the Jovian aurorae, and the composition and structure of the planet's upper atmosphere.
RADEM	RADEM is a radiation meter that will measure the amount of radiation Juice is subjected to while also being utilized for scientific purposes.
PRIDE	PRIDE will use Juice's standard telecommunication system, as well as radio telescopes on Earth, to precisely measure the spacecraft's position and velocity in order to examine Jupiter's gravity fields and the icy moons.

2.2 Mission timeline

2.2.1 Launch & Deployment

Juice was sent into orbit aboard an Ariane 5 rocket from the Guiana Orbit Centre on April 14, 2023. This was the final launch of an ESA science mission using the Ariane 5 vehicle and the rocket's second-to-last overall.

Figure 2.6: Ariane 5 launch of the ESA Juice spacecraft

Now that the rocket is in space, here is the **deployment timeline**:

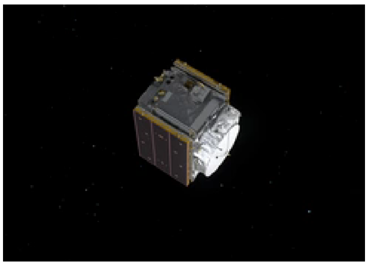
- The solar arrays will be deployed after 50 minutes, with the two 'wings' taking less than a minute to fully expand. These massive cross-shaped arrays, inspired by the design of telecommunications satellites, will ensure that Juice has enough solar energy to power all of its instruments.
- After 16 hours, the medium-gain antenna will be deployed; this antenna will connect Juice to mission controllers on Earth while Juice's larger antenna is used as a sunshield. It will also be employed during cold moon flybys, returning valuable data for the gravity experiment to interested scientists on Earth.
- After five days, the 16 m-long Radar for Icy Moons Exploration (RIME) antenna will be deployed; this instrument will make measurements that help us investigate the structure underneath the surface of Jupiter's three largest icy moons—Europa, Ganymede, and Callisto.
- After 10 days, the magnetometer boom will be deployed; at the end of this 10.6 m-long boom, Juice carries an experiment to measure magnetic fields, keeping it

away from the spacecraft's main body so that it may monitor Jupiter and its cold moons without interference from onboard instrumentation.

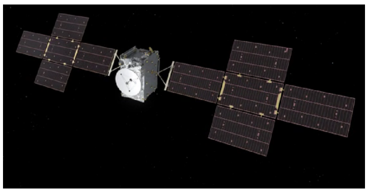
- After 12 days, the Radio Wave Instrument (RWI) antennas will be deployed as part of the Radio and Plasma Wave Investigation (RPWI), which will use a variety of sensors to investigate the radio emission and plasma environment surrounding Jupiter and its ice moons.

- The four Langmuir probes will be deployed between 13 and 17 days following launch; they are also part of the RPWI, and their primary goal is to give critical information about the plasma environment surrounding Jupiter's frozen moons.

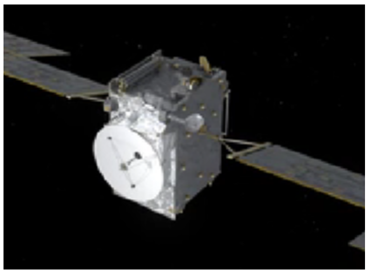
The following figure 2.7 shows an impression of how the deployment sequence will look:



(a) Post-separation with the rocket



(b) Solar arrays deployed

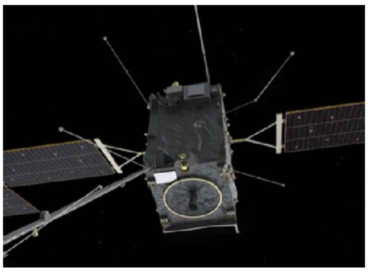


(c) Medium gain antenna deployment

(d) RIME antenna deployment

(e) Magnetometer boom deployed

(f) RWI antennas deployed



(g) Four Langmuir Probes deployed

Figure 2.7: JUICE spacecraft deployment sequence

So the satellite finally develops into what's shown in figure 2.8:

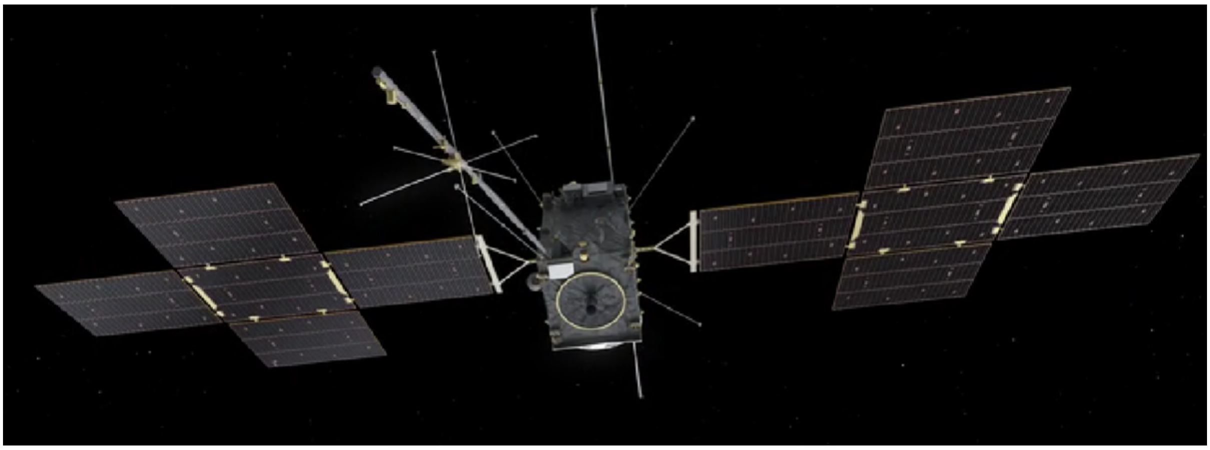


Figure 2.8: Fully deployed JUICE spacecraft

2.3 Trajectory and Gravity Assist Maneuvers

2.3.1 Gravity Assist

The basic idea behind gravity assist maneuvers is that a close flyby of a planet can be utilized to alter the spacecraft's direction of motion and give it a noticeable speed boost if the spacecraft's route is correctly planned.
Consider a two-body problem; the concept seems counter-intuitive at first because it seems to violate the law of conservation of energy; how can there be a velocity boost Δv when the satellite should have the same (magnitude) velocity all throughout the maneuver?

Assuming the flyby's will be unpowered, we can safely assume the trajectory will be hyperbolic and symmetric. We consider first the center of the planet as the reference frame; we clearly see (figure 2.9) that

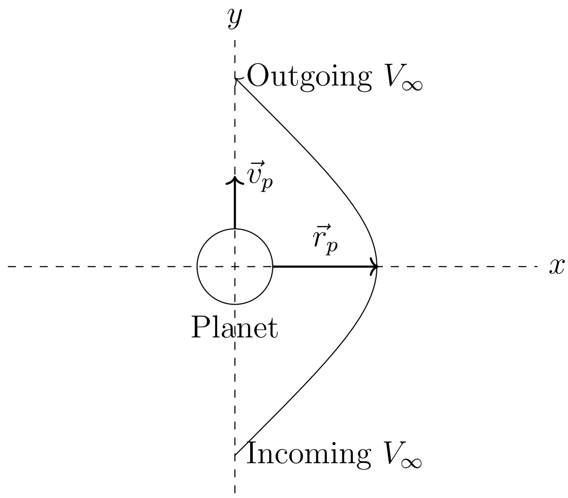


Figure 2.9

The planet is stationary w.r.t. the frame of reference. The specific mechanical energy

$$\epsilon = \frac{v^2}{2} - \frac{\mu}{r}$$

tells us that as the satellite approaches the planet, the potential energy gets converted to kinetic energy, therefore resulting in a gain in speed, and once the satellite surpasses the planet, the process is reversed.
That means the satellite returns to the same speed it initially had but with a different velocity vector.

Consider a different setup where we take the reference frame to be from the sun's center. This means that now, the planet itself is moving with a velocity v_p w.r.t. the sun. We modify our previous setup by taking that into account (figure 2.10)

A portion of this planet's momentum around the Sun is transferred to the satellite during the flyby orbit. The spaceship will gain momentum when it intercepts a planet if it is ahead of it; conversely, it will lose momentum if it is running behind the planet. The planet loses the same amount of momentum that the satellite does, according to the law of conservation of energy. However, because of the enormous mass of the celestial body in comparison to the man-made satellite, the satellite experiences a significant increase in velocity while the planet experiences a negligible change in velocity.
The initial velocity V

$$V^2 = \mu \left(\frac{2}{r} - \frac{1}{a} \right) \tag{2.1}$$

can be found by orbital energy conservation (2.1) In this equation, r represents the planet's distance, an its semi-major axis, and μ its gravitational constant. The hyperbolic excess velocity, V_∞, is calculated by letting $r \to \infty$, resulting in (2.2)

$$V_\infty = \sqrt{\frac{\mu}{a}} \tag{2.2}$$

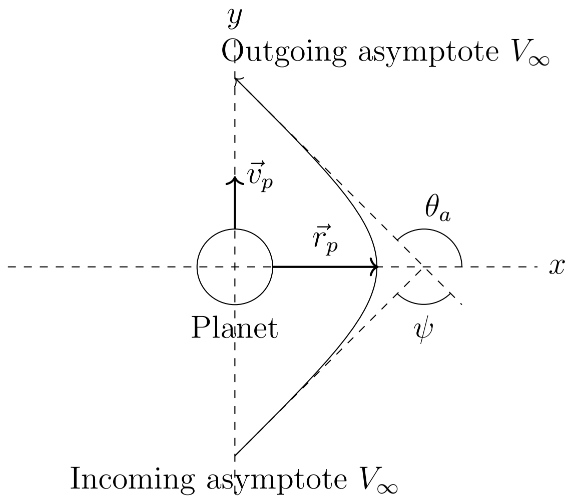


Figure 2.10

θ_a, the true anomaly, computed as:

$$\theta_a = \arccos\left(-\frac{1}{e}\right) \tag{2.3}$$

where

$$e = 1 + \frac{V_\infty^2 r_p}{\mu} \tag{2.4}$$

is known as the eccentricity.

We can express the change in direction ψ using the parameters above as:

$$\frac{\psi}{2} = \theta_a - \frac{\pi}{2} = \arcsin\left(\frac{1}{e}\right) \tag{2.5}$$

Therefore, we can write the change in velocity as

$$\Delta V = 2V_\infty \sin\left(\frac{\psi}{2}\right) = \frac{2V_\infty}{e} \tag{2.6}$$

Now we have to express the planet's and satellite's velocity vectors as (2.7) & (2.8)

$$\vec{V_P} = (V_P \cos\theta_P)\vec{e_x} + (V_P \sin\theta_P)\vec{e_y} \tag{2.7}$$

$$\vec{V_S} = (V_S \cos\theta_S)\vec{e_x} + (V_S \sin\theta_S)\vec{e_y} \tag{2.8}$$

The initial hyperbolic excess velocity V_∞ (2.9) in planet frame corresponds to the spacecraft's relative velocity vector to the planet.

$$\vec{V_\infty} \approx \vec{V_{S/P}} = \vec{V_S} - \vec{V_P} \tag{2.9}$$

To calculate the approach velocity, use the vector's absolute value (—V_∞—). In our coordinate system, the initial approach angle (θ_i) is determined by the relative velocity vector.

$$\theta_i = \arctan\left(\frac{V_\infty(y)}{V_\infty(x)}\right) \tag{2.10}$$

again, using (2.4) and (2.5), we can calculate the hyperbola eccentricity e and direction change ψ of the trajectory. To compute the departure angle (2.11), simply add the change in direction to the approach angle.

$$\theta_f = \theta_i + \psi \tag{2.11}$$

The departure angle can be used to calculate the new components of the spacecraft velocity (2.12), as the speed at the start of the gravity assist maneuver is the same as the speed at the end.

$$\overrightarrow{V_\infty}' = (V_\infty \cos\theta_f)\overrightarrow{e_x} + (V_\infty \sin\theta_f)\overrightarrow{e_y} \tag{2.12}$$

The heliocentric final spacecraft velocity is calculated by adding the planet's velocity:

$$\overrightarrow{V_S}' = \overrightarrow{V_\infty}' + \overrightarrow{V_P} \tag{2.13}$$

Taking the magnitude of that vector —V_s'— gives us a realistic value of the velocity gain of the spacecraft, while $\Delta V = V_s' - V_s$ is the velocity gain by direction and speed change.

2.3.2 Trajectory

Before arrival to Jupiter, JUICE will perform 4 gravity assist maneuvers, and it's timeline is as follows:

- August 2024: Lunar-Earth gravity assist (a novel double flyby).
- August 2025: Venus gravity assist.
- September 2026: Earth gravity assist.
- January 2029: Earth gravity assist.
- July 2031: Arrival at Jupiter.

It will also pass through the asteroid belt twice.

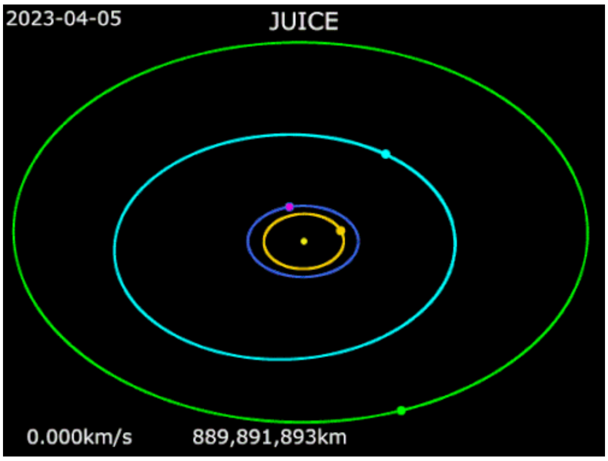


Figure 2.11: This figure shows the trajectories of important bodies in the solar system relevant to JUICE:
The center is the sun,
the yellow-orange system is Venus
the dark blue line is earth
light blue is the 223 Rosa asteroid
Green is Jupiter

Current location of JUICE as of 13 April 2025

As of now, JUICE has (figure 2.12):

- Been launched (14th of April 2023)
- Performed a Lunar flyby at 777km (first gravity assist, 19th August 2024)
- Performed an Earth flyby at 6861km (second gravity assist, 20th August 2024)
- Been en route to perform a venus flyby at 5081km (third gravity assist, at around 18th August 2025)

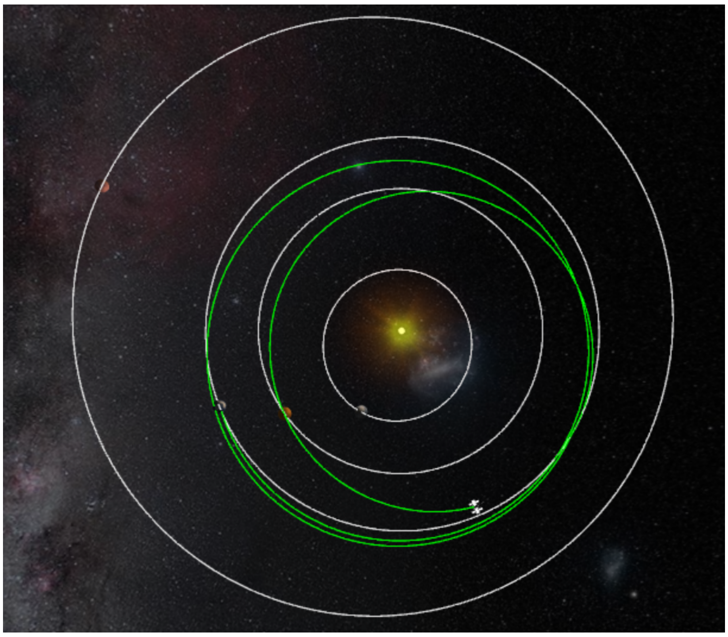


Figure 2.12

After the Venus flyby, we have 2 more lunar-Earth flybys before finally arriving at Jupiter.

Therefore, the full trajectory looks like (Figure 2.13):

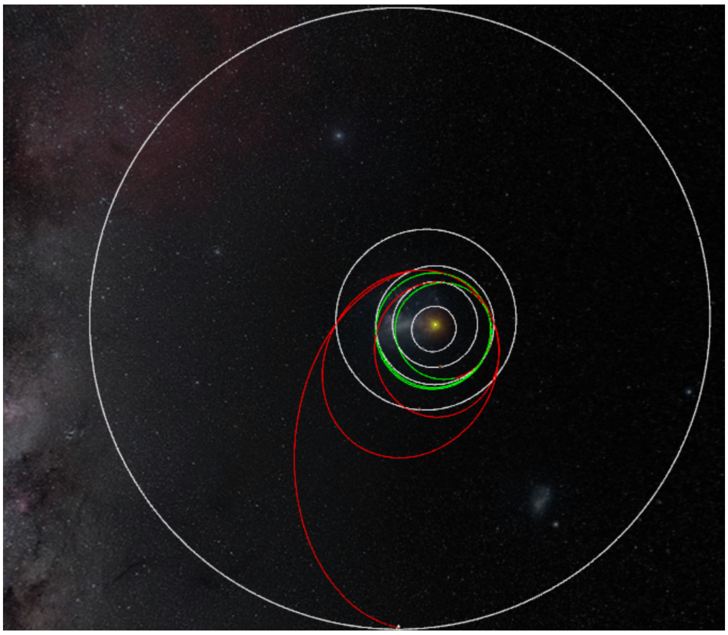


Figure 2.13

Post arrival at jupiter

Upon arrival at Jupiter, JUICE will perform the Jupiter Orbit Insertion (JOI) maneuver (Figure 2.14).

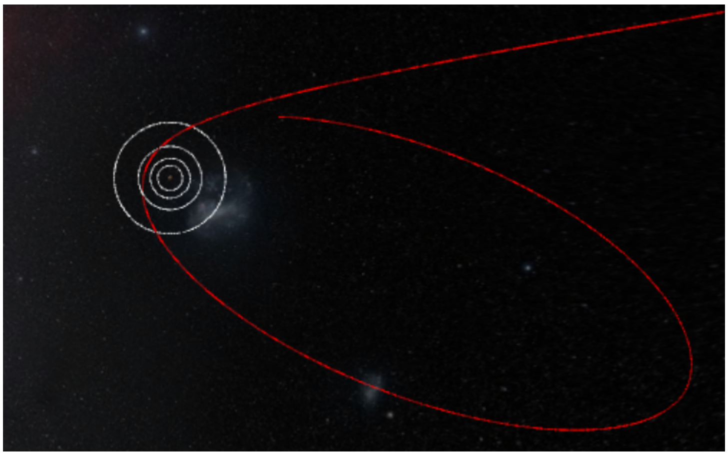


Figure 2.14: Arrival and first ellipse into the Jupiter system $\Delta v = 952 m/s$

Followed by multiple Ganymede flybys to decrease orbital period T. Following that is the 1st flyby to Callisto (Figure 2.15).

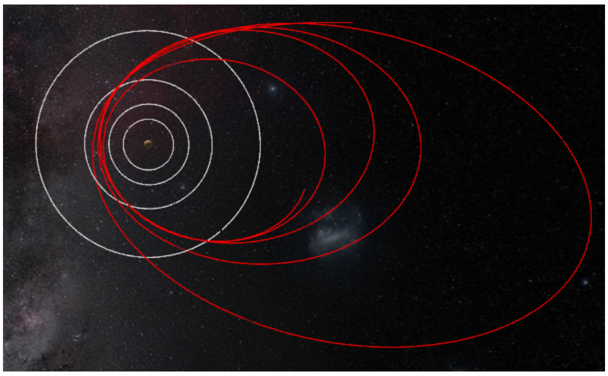


Figure 2.15: Energy Reduction phase, $\Delta v = 27 m/s$

Then starts the Europa phase in 2032 where 2 Europa flybys followed by another Callisto flyby ($\Delta v = 30 m/s$).

Then, for scientific research reasons, another 6 flybys to Callisto and Ganymede to increase inclination i by 22 deg ($\Delta v = 13 m/s$).

After that, an orbital transfer to Ganymede ($\Delta v = 60 m/s$) takes place by a series of gravity assists,
which starts the Ganymede phase in which JUICE will enter a 12 day orbit after performing a propulive brakes ($\Delta v = 614 m/s$).

Chapter 3

Design of the System

3.1 Mission Analysis

The mission has been divided into 2 major parts, being the interplanetary transfer & the change to a trajectory tied to Ganymede during Jupiter's scientific phase. In both situations, the trajectories were optimized to demand the lowest Δv. Additionally, the mission trajectory is optimized throughout the Jupiter phase while taking into account the spacecraft's radiation exposure in the Jupiter radiation environment (avoidance of excessively low orbits near Jupiter). Additionally, numerous inclined revolutions about Jupiter and two flybys of Europa were provided at a low Δv cost. Consequently, the mission phases listed below are identified:

1. Interplanetary transfer (cruise) (7.6–9 years)
2. Nominal science phase
   a. Jupiter equatorial phase #1 and transfer to Callisto (12 months)
   b. Europa flybys ($\sim$ 1 month)
   c. Jupiter high inclination orbit/Callisto flybys (6 months)
   d. Jupiter equatorial phase #2 and transfer to Ganymede (9 months)
   e. Ganymede phases (9.5 months)
      i. 1st elliptical phase
      ii. High altitude circular orbit (GCO-5000)
      iii. 2nd elliptical phase
      iv. Low altitude circular orbit (GCO-500)

3.1.1 Launch

There were several good opportunities to launch JUICE during 2022, 2023, 2024, and 2025. The one in 2022, however, was particularly favorable because it had an interplanetary cruise duration of 7.4 years instead of 9 years; in the Venus flyby, the spacecraft would be 0.64 AU away from the sub.

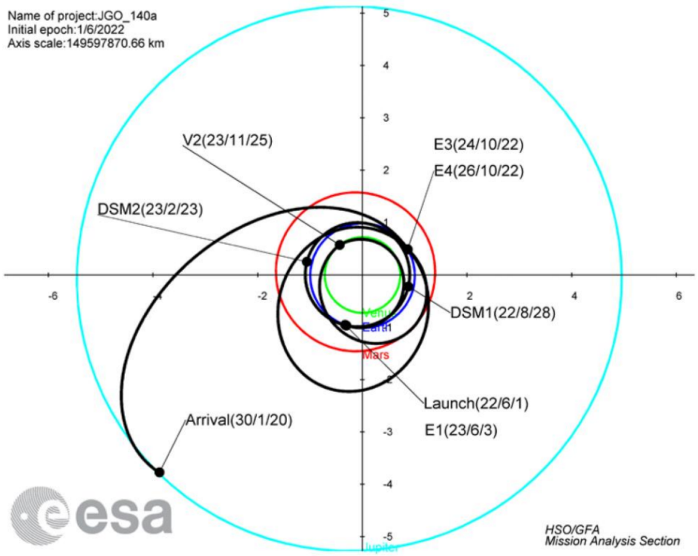


Figure 3.1: 7.4 year interplanetery transfer opportunity at 01/06/2022

3.1.2 Jupiter equitorial phase

In order for the spacecraft to be captured into Jupiter's orbit, it needs a V_∞ range from 5.59 km/s to 5.82 km/s.

A 400-kilometer Ganymede gravity assist will come before the JOI maneuver. A trade-off between the radiation dose, which rises as the spacecraft approaches Jupiter, and the Δv gain, which improves as the spacecraft approaches Jupiter, led to the selection of the distance from Jupiter at JOI. Following this trade-off, the Ganymede gravity assist (G1, Figure 3.2) reduces Δv by around 300 m/s before to JOI.

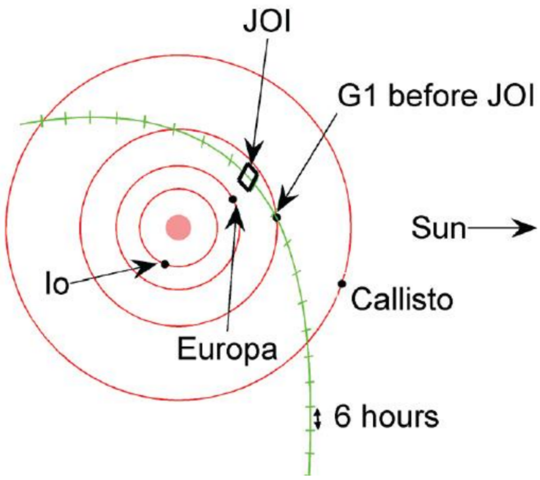


Figure 3.2

Following the JOI, Ganymede injects the spacecraft into a 38:1 resonant orbit (Figure 3.3, 272 days). A Perijove Raising Manoeuvre (PRM) is executed at apojove. By bringing the perijove closer to the orbit of the next Ganymede swing-by (G2), the perijove raise lowers the arrival velocity.

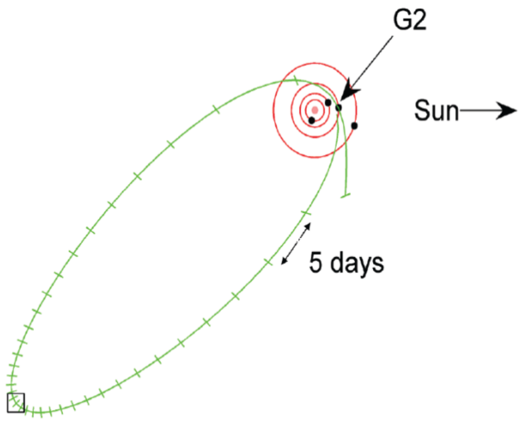


Figure 3.3

This increases the effectiveness of Ganymede's subsequent gravity assistance. Additionally, a larger perijove lowers the radiation dose during subsequent trips near Jupiter.

3.1.3 Inclined Orbit phase

The spacecraft achieves a maximum magnetic latitude of 26 deg and a maximum inclination of 22 deg with this series of six flybys. The 7:8 resonant orbit with Callisto is the highest inclined, allowing for 117 days of maximum inclination exploration of the Jupiterian environment and polar areas. The orbit inclination's progression during this time is depicted in Figure 3.4.

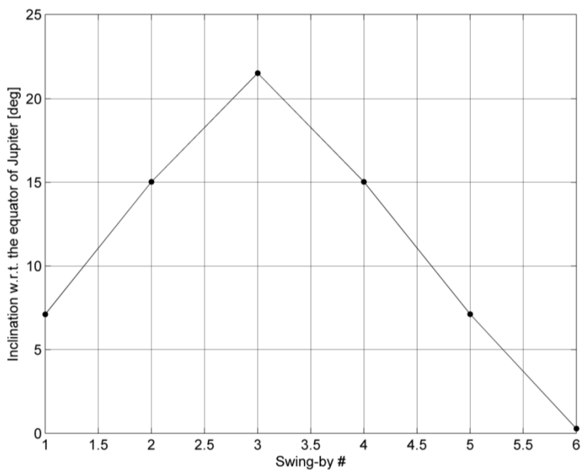


Figure 3.4

3.1.4 Ganymede orbital phases

The following factors limit the Ganymede orbital phase:

- The need to prevent eclipses on near-polar operating orbits. For low altitudes, the angle (or "β-angle") between the Sun's direction and the orbit plane must get larger (for example, ¿ 60° for a circular orbit at 500 km).
- Jupiter's perturbations that affect the orbit's eccentricity based on the pericenter's position relative to the ascending node (it increases when the pericenter's argument is near 50° or 230° and lowers when it is near 140° or 320°).

3.2 Spacecraft design requirements

3.2.1 Radiation mitigation

The advantages of units shielding one another have been taken into account and assessed using in-depth radiation transport models. At the exterior of every unit, the necessary radiation tolerance was set at 50 krad.

3.2.2 Power

A worst case solar intensity of 46 W/m^2. This corresponds to a solar array with an area of 100 m^2.

3.2.3 Thermal

Only electrical heating will be supplied; radiators will be used to achieve passive thermal control. Also multilayer insulation covering the entire spacecraft for jupiter's cold conditions.

3.2.4 Propulsion

a significant number of propellant tanks will need to be included in the spacecraft architecture.

3.2.5 Communications

Capability of transmitting atleast 1.4Gb of data daily.

3.2.6 Attitude and Orbital control subsystem

Momentum wheels will be used to provide the attitude, with the assistance of an offloading propulsion system. Offloading will take place outside of the windows for science observation.

3.2.7 Avionics

To allow for enough flexibility to allow the spacecraft to be oriented in accordance with the requirements of the science instrumentation and buffer the data for later downlink, a storage facility for several days' worth of science data will be added.

3.2.8 Mechanisms

The subsurface radar boom, the magnetometer boom, the RPWI antennae, the solar panels, and the solar array driving mechanisms are examples of mechanisms. The appendices, including stray light avoidance cones, will be positioned so that their deployment may be done separately and that they don't obstruct the field of view of the optical and particle instruments.

3.2.9 Launcher

Ariana 5 ECA Launcher from Kourou.

Chapter 4

Self-Reflection and Potential Enhancements

4.1 What worls well

A lot of milestones have been achieved by JUICE since its launch on April 14, 2023. The critical deployment of the 100 m^2 solar arrays went off without a hitch, ensuring the spacecraft has the power it needs for its long journey and science operations. The science instruments have had their moments too—like the ultraviolet spectrograph (UVS) snagging its first UV data in 2023, proving they're ready to tackle the Jovian system. The lunar-Earth flybys, starting with the double flyby in August 2024, have been a win, giving the team a chance to test and calibrate the instruments while tweaking the trajectory perfectly. Even when the RIME antenna jammed, the engineering team jumped on it, firing up two actuators to fix it right away—showing how quick thinking can keep things on track. So far, JUICE has nailed every milestone, setting it up for a solid scientific journey if it keeps this momentum.

4.2 Improvements

There's still room to squeeze more out of JUICE, depending on how much propellant is left and how the solar arrays hold up. If conditions allow, extending the mission to drop into an even lower orbit around Ganymede—say, down to 200 km—could give us sharper data on its surface and subsurface, maybe even pinning down the extent of its ocean. Looking ahead, future missions like this could crank up the comms game with higher data rates, letting us pull down more detailed observations faster—imagine getting real-time streams of Jupiter's storms or Ganymede's ice cracks. Radiation's a beast out there, so researching tougher shielding materials could make spacecraft last longer and protect the gear better; JUICE is solid at 50 krad tolerance, but pushing that limit could be a game-changer. Adding some smarter autonomous navigation could also cut down on ground control babysitting—think of it handling gravity assists or orbit tweaks on its own, especially when signals take 40 minutes each way. If JUICE's health checks out, stretching the mission to swing by more moons or dive deeper into Jupiter's atmosphere could milk every last drop of science from it. And why not go bigger? .

Conclusions

The Jupiter Icy Moons Explorer (JUICE) mission embodies a remarkable fusion of orbital mechanics and spacecraft engineering, designed to unravel the secrets of Jupiter and its icy moons. This report has detailed how JUICE's intricate trajectory, leveraging four gravity assist manoeuvres, optimises fuel efficiency to reach the Jovian system by July 2031. Upon arrival, the spacecraft's carefully planned orbital insertions and flybys of Ganymede, Europa, and Callisto will enable comprehensive scientific investigations into their subsurface oceans, surface features, and potential habitability. The spacecraft's design—equipped with radiation shielding, a massive 100 m^2 solar array, and a suite of advanced instruments—demonstrates the engineering prowess required to operate in Jupiter's harsh environment. As JUICE progresses through its mission phases, from the equatorial Jupiter orbits to the final Ganymede orbital phase, it promises to deliver data that will deepen our understanding of gas giants and their moons, not just within our solar system but as archetypes for exoplanetary systems. The mission's success to date, marked by flawless deployments and gravity assists, underscores its potential to achieve these ambitious goals, setting a benchmark for future interplanetary exploration.

References

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