



POLITECNICO MILANO 1863

Reverse Engineering of Juno Mission Homework 1

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Group 5

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Notation

MAG	Magnetometer	JEDI	Jupiter Energetic-particle Detector Instrument
HGA	High Gain Antenna	JADE	Jovian Auroral Distribution Experiment
ΔV	Velocity budget	UVS	Ultraviolet Spectrograph
DSN	Deep Space Network	JIRAM	Juno Infra-Red Auroral Mapper
LEOP	Launch and early orbit phase	EGA	Earth Gravity Assist
SECO	Second engine cut off	JOI	Jupiter Orbit Insertion
L+	Time after launch	DSM	Deep Space Manoeuvre
PJ	Perijove number	PRM	Period Reduction Maneuver
MWR	Microwave Radiometer	GSO	Gravity Science Orbit

Change log	
Paragraph	Modification
section 3	Drivers are modified and made more specific for Juno mission.
section 6	ConOps introduction and analysis updated.
section 8	Specific information is added to the description.

1 Introduction

Juno is a NASA spacecraft orbiting Jupiter. Built by Lockheed Martin and operated by NASA, it was launched by an Atlas V551 on the 5th of August 2011. After 5 years, during which many maneuvers occurred, including an Earth flyby, Juno entered a polar orbit around Jupiter and started its observation, which lasts to this day. Its aim is to study the planet to understand its composition and evolution, analyzing its gravitational and magnetic fields and its atmosphere dynamics. The mission should have ended in 2017, but it is still ongoing^[1] and it will end with a de-orbit that will destroy the spacecraft into the planet's atmosphere to avoid contaminating the environment.

2 High level goals

Through an analysis of the mission and payload, the main goals of the mission can be highlighted.

1. How did Jupiter form and influence the solar system?^{[2][3]}

Since Jupiter is the biggest planet of the solar system, it has influenced the formation of all other planets. Its composition has remained unchanged ever since, making it like a time capsule: understanding how and where it formed could give knowledge on Earth and the whole solar system's origin, evolution and characteristics.

2. What's Jupiter's deep structure?^{[3][4]}

One important aspect of the mission is the analysis of Jupiter's deep structure through the measurement of radiations, magnetic and gravitational fields. This allows to comprehend whether or not the planet has a solid nucleus, if so how large it is, and to analyze the supposed layer of metallic hydrogen, compressed so much that it loses its electrons creating a conducting layer. Moreover, Juno will possibly reveal if Jupiter is rotating as a solid body or if the rotating interior is made up of concentric cylinders.

3. What's the structure of Jupiter's atmosphere?^{[3][5]}

One of the mission's goals is to study the composition and dynamics of Jupiter's atmosphere, composed by stripes and dots made of different gasses and vapors, including water, whose percentage has to be defined. A significant aspect of the analysis is the great red spot, a swirling mass of gas bigger than Earth, which resembles a hurricane but is very different in the way it works. The movement of stripes and dots is dictated by the weather, characterized by lighting and thunderstorms, which are observed by Juno.

4. What do auroras look like and what are the physical processes generating them?^{[3][5]}

Juno's orbit is designed to be polar, to allow the observation of Jupiter's poles and the analysis of its auroras, representative of the interaction between charged particles and the atmosphere. Studying this phenomenon allows a better understanding of the atmospheric composition and the magnetic field's structure and extension.

5. What do the poles look like?^[3]

One of Juno's side goals is the observation of Jupiter's poles, which had never been possible before because of the absence of a polar orbiting spacecraft. This also increments the public's involvement in the mission.

3 Mission drivers

The drivers of a mission are identified as critical requirements that lead completely or partly the design process of one or more subsystems. Being Juno an interplanetary mission starting from a distance of around 1 AU, with a final nominal distance from the Sun of 5.2 AU, and operating in an highly radiation intense environment, the following drivers have been identified:

1. Insertion on Jupiter's orbit^{[1][3][6][7]}

One of the most critical phases to achieve the mission purpose is the insertion in Jupiter's orbit. The criticality is related to the high complexity of lowering the energy to get captured by the planet. To slow down and enter Jupiter's orbit, the spacecraft has to perform a delicate maneuver, otherwise it flies off into space thus science mission fails. As a matter of fact, Juno's engines shall fire at the right moment in the correct direction for the required amount of time.

2. Surviving in the Jupiter environment^{[1][2][8]}

The Juno mission shall orbit around Jupiter. The sunlight received by the planet is 25 times less than the one received by Earth, furthermore Jupiter is characterized by an enormous magnetic field which is nearly 20,000 times as powerful as Earth's field and huge intensity of radiations. As a matter of fact, Juno shall benefit the usage of thermal blankets as well as radiation-shielded electronics vault, avoid to fly over the most of Jupiter's high-radiation regions and increase the tech-quality of cells by composing solar arrays and increasing panels' area.

3. Maintaining communication during the journey and the science operations^{[6][9]}

Due to the huge distance and high interferences caused by the jovian radiation field and interplanetary radiations, communication and data handling shall be considered as a driver. Referring to the Juno's high level goals, the mission success requires collecting science data and safely transmitting back to Earth. To ensure the latter, Juno

shall include a flight processor designed to operate in a strong radiation environment and support an amount of total instruments throughput sufficient for the payload suite. Relatively to the second purpose, Juno shall establish communication with ground station alongside gathering scientific intel via a HGA that supports X-band communications with Earth for command uplink and science data and telemetry downlink. Communications with Juno shall be accomplished by NASA's Deep Space Network Station. Juno shall also include low and medium gain communication system to provide continuous communication, even when the HGA is not pointing towards Earth.

4 Functional analysis

Functional analysis is performed in order to identify the functionalities that the spacecraft must perform during the mission. The identified functionalities are schematized in [Figure 1](#).



Figure 1: Functional analysis for Juno mission

5 Main mission phases

The Juno mission was divided into five phases: LEOP, Cruise, Jupiter approach and insertion, Science Operations and De-orbit.

1. LEOP

Following the launch from Cape Canaveral, the spacecraft entered a low Earth parking orbit.^[6] Afterwards Juno was injected in an interplanetary trajectory and was separated from its upper stage after SECO-2 at time L+54 min. The solar panels deployment was performed about five minutes after the spacecraft separation, and it took approximately five minutes.

2. Cruise

The cruise had a duration of about five years, during which two deep space manoeuvres, multiple minor corrections and an Earth fly-by were performed. All manoeuvres will be better described in [section 8](#). This phase also included instruments testing and verification, to ensure they were functioning properly and ready for the usage during the mission.

3. Jupiter approach and insertion

This phase began four days before the start of orbit insertion manoeuvre and ended one hour after the start of the orbit insertion manoeuvre. The latter occurred at closest approach to Jupiter and slowed the spacecraft down enough to let it be captured by Jupiter in a 53-days period orbit. The Jupiter orbit insertion burn was performed by the Leros 1-b main engine, and it lasted 30 minutes. After the burn, the spacecraft was in a polar orbit around Jupiter. The 53-days orbit provided substantial propellant savings with respect to the direct insertion in the operational orbit.

4. Science operations

The Juno polar and highly eccentric orbit was designed to facilitate the close-in measurements and to minimize the time spent in the Jupiter radiation belts. During this phase all the science operations, in different attitudes, are being performed.

5. De-orbit

The de-orbit phase will occur during the final orbit of the mission. The latter was designed to satisfy NASA's planetary protection requirements and ensure that Juno doesn't impact any of Jupiter's moons. A de-orbit burn will be performed, placing the spacecraft on a trajectory towards Jupiter inner and denser layer of the atmosphere where it will burn up.

6 ConOps

The Mission ConOps serve as a roadmap for planning and executing a mission. The trajectory correction maneuvers, the communications science operations and data transfer are not continuous operations as shown in [Figure 2](#), but are performed throughout the shown time interval. The mission was extended from 2018 until 2021 in order to achieve the principal goals guaranteeing the security of instruments. Moreover a second extension was approved to obtain more insight about Jupiter that will last up until September 2025.

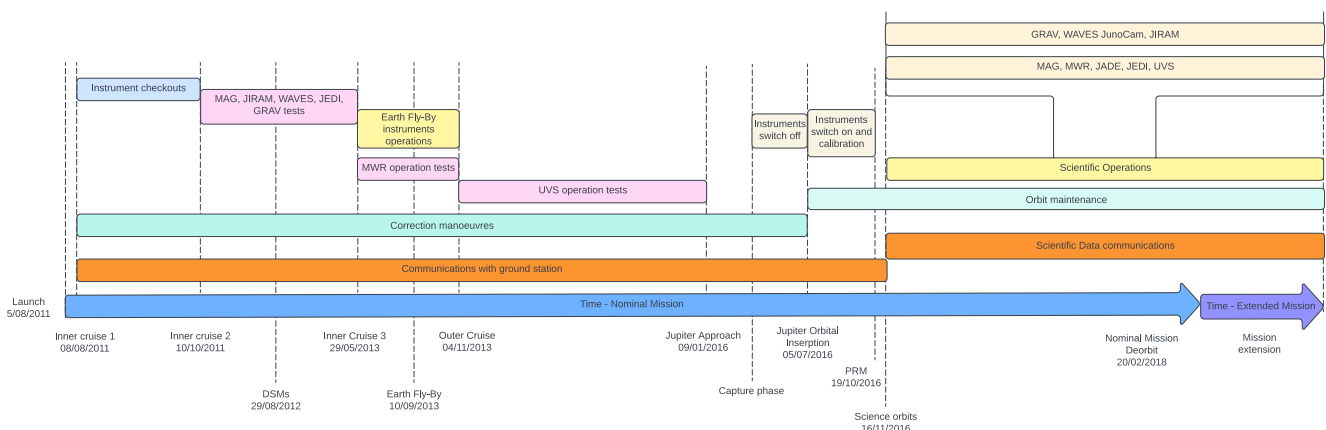


Figure 2: Conceptual Operations, time not in scale^{[2][6][10][11]}

7 Payload analysis

7.1 Instruments overview

As previously described in [section 2](#) the mission scientific goals are quite numerous and diverse. Thus, to achieve all of them, the payload consists of several instruments, nine to be precise, covering a wide spectrum of experimentation. In its entirety the payload has a mass of around 174 kg and consumes approximately 125 W of power excluding the Gravity science experiment.^[7] Here we have a brief overview of all the singular instruments where, unless otherwise specified, only the sensors are mounted on the exterior of the spacecraft, while all the relevant electronics are located inside the radiation vault.

- **Magnetometer (MAG):** As the name implies its objective is to accurately measure Jupiter's magnetic field, achieved by employing two flux-gate magnetometers, a scalar helium magnetometer and two star cameras. All the sensors are mounted on the magnetometer boom, located at the end of one of the solar array wings to reduce the interference from the spacecraft itself. Even then the presence of two magnetometers allows to subtract this contribution from the measurement.
- **Microwave Radiometer (MWR):** It consists of six antennas which measure six different frequencies (600 MHz, 1.2 GHz, 2.4 GHz, 4.8 GHz, 9.6 GHz and 22 GHz) in order to investigate the Jovian atmosphere below the visible external layer. A key objective of this analysis is also the determination of the abundance of water inside the planet. The antennas are mounted on two sides of the hexagonal prism that constitutes the main body of the spacecraft, relying on its spin to survey Jupiter.
- **Gravity science:** It's quite a unique instrument as it's composed both by a space and a ground elements, which mainly consists with the telecommunication systems of both the spacecraft and ground stations. This is because this experiment is based on measuring the doppler shift in the returning signal from Juno which, allows to characterize Jupiter's gravitational field. Thus the instrument can't really be separated from the telecommunication hardware, which is the reason why its weight and power requirement were omitted in the previously shown totals.
- **Jupiter Energetic-particle Detector Instrument (JEDI):** It detects high energy electrons and ions present in the Jovian magnetosphere, which are discriminated by composition. Each sensor is characterized by six electron and six ion viewing directions that together cover a $160^\circ \times 12^\circ$ field of view. In total three sensors are present on Juno, two arranged to obtain an almost complete 360° view perpendicular to the spacecraft spin axis, while the third one is instead aligned with it to achieve a full scan of the sky over one spin period. As the JEDI sensors are self-contained units no electronic hardware is present within the radiation vault.
- **Jovian Auroral Distribution Experiment (JADE):** It detects low energy electrons and ions with the same goal of characterizing the magnetosphere as JEDI. The instrument comprises of three identical electron energy per charge analyzers (JADE-E) and a single ion mass spectrometer (JADE-I). The electron sensors are located on the three sides of the spacecraft that do not house the solar arrays pointing outwards, to again obtain a complete view normal to the spin axis. The spectrometer field of view, instead, contains the spin axis and like the third JEDI sensor it scans all the sky over a full rotation.
- **Ultraviolet Spectrograph (UVS):** This instrument images and measures the spectrum of the Jovian aurora in order to understand its morphology and source. The chosen ultraviolet range of $68 \div 210$ nm covers all of the most important UV emissions from the aurora, mainly the H Lyman series and longer wavelengths from hydrocarbons. The sensor is mounted on the side of Juno, relying once more on the spinning of the spacecraft to achieve a full sweep of the planet.
- **Radio and Plasma Waves (Waves):** Its objective is to study both components of the electromagnetic field generated by plasma and radio waves inside the polar regions of Jupiter's magnetosphere to understand its interaction with the atmosphere and magnetic field. To detect the electric component a V-shaped dipole antenna is used, while for the magnetic component a much smaller magnetic search coil is employed. Both sensors cover a vast range of frequencies, namely from 50 Hz up to 40 MHz.
- **Visible-spectrum Camera (JunoCam):** It's designed to provide highly detailed color images of Jupiter to help and support public engagement of the mission without any real scientific purpose. The instrument is thus only comprised of the camera itself, mounted on the side of the spacecraft, and all the necessary electronics which, given the less critical objective and relaxed radiation tolerance requirements, aren't housed in the radiation vault.
- **Juno Infra-Red Auroral Mapper (JIRAM):** It's an infrared imager and spectrometer that studies the Jovian atmosphere in the $2 \div 5 \mu\text{m}$ range complementing both the atmospheric and magnetospheric experiments. This instrument is also completely housed outside of the radiation vault since it is a late addition after mission selection, reason for both the relaxed radiation requirements and less than ideal positioning of the sensor on the aft deck of the spacecraft.

All the instruments and their positions can be seen in Figure 3.

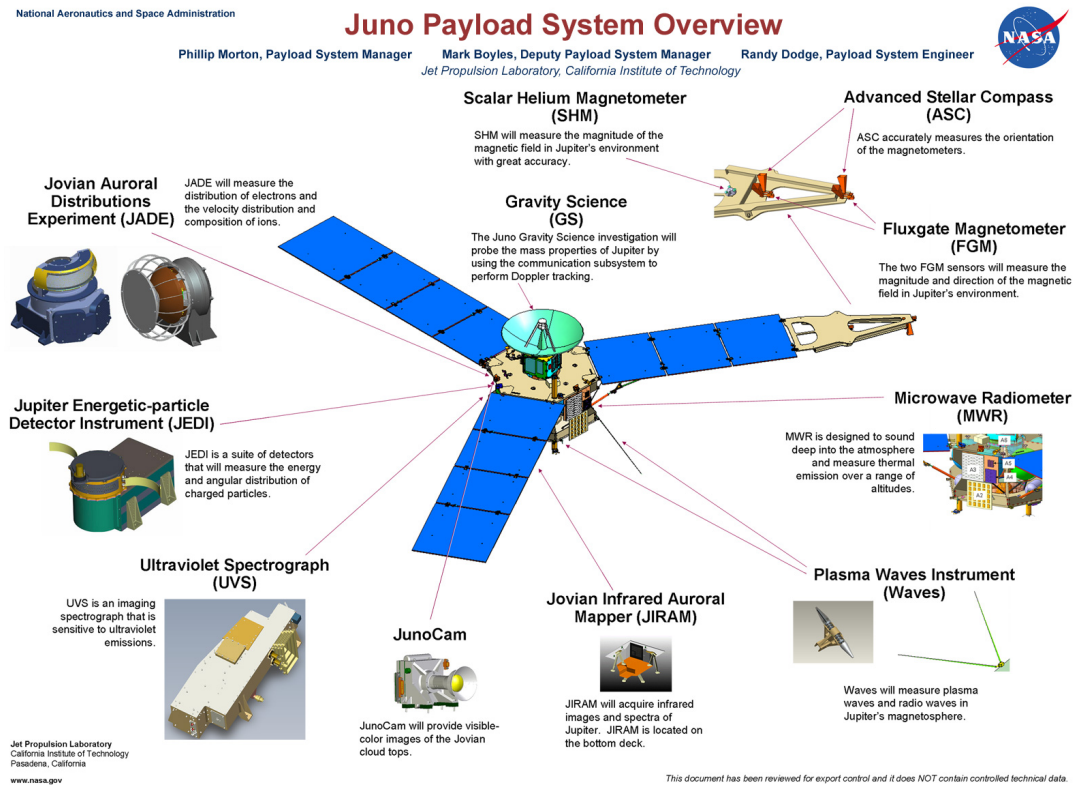


Figure 3: Positioning of the instruments on the spacecraft

7.2 Payload and Goals correlation

There is a notable overlap in the main objectives of the payload instruments, both in the sense that multiple ones collaborate towards a single scientific goal, but also in the sense that a single instrument can address multiple goals. All of these relations are exemplified in Table 2.

Guiding questions	Science objectives	Measurements objectives
How did Jupiter form and influence the solar system?	Determine Jupiter's inner composition	Composition analysis: MWR
What's Jupiter's deep structure?	Analyze gravitational and magnetic field, measure water abundance in the planet	Gravitational field analysis: Gravity science Magnetic field analysis: MAG Water abundance measurements: MWR
What's the structure of Jupiter's atmosphere?	Analyze atmospheric composition and dynamics	Atmospheric composition determination: MWR Atmospheric dynamics study: JIRAM
What do auroras look like and what are the physical processes generating them?	Image auroras, study interactions between atmosphere and magnetic field, characterize the magnetosphere in the polar regions	Imaging auroras: UVS, JIRAM Atmosphere-magnetic field interaction: JIRAM Characterize the magnetosphere: Waves, JADE, JEDI

Table 2: Mission goals and instrument objectives correlation

It can be noted that the JunoCam instrument doesn't appear in the table since it's not part of the scientific goals of the mission, as previously mentioned in its description.

7.3 Payload and Phases/ConOps correlation

Another high-level correlation can be highlighted between the mission phases/ConOps and the activities of the payload as shown in Table 3.^[6]

Mission phases	Payload activities
LEOP	Mag boom is deployed together with solar arrays
Cruise	Instruments checks are performed regularly and the high gain antenna (used for Gravity science) is calibrated and aligned
Jupiter approach and insertion	Final instruments checks are carried out together with some initial scientific observations of Jupiter
Science operations	Complete nominal operation of the payload with observations divided between Gravity science passes (Earth pointing) and MWR passes (Nadir pointing)
De-orbit	No planned payload operations

Table 3: Mission phases/ConOps and Payload activities correlation

8 Mission analysis

8.1 Launch and cruise

The spacecraft was launched into orbit with an Atlas V 551 Rocket from Cape Canaveral. The actual launch date belonged to a 21-day time window limited by a number of events and their timings such as the Deep Space Maneuvers, the Earth Flyby, the Jupiter Insertion and the science orbits. The adopted transfer strategy allowed for significant reduction in ΔV with respect to a direct transfer between Earth and Jupiter.

The spacecraft was powered three days prior to the scheduled launch, allowing all required pre-flight inspections and check-ups, concerning the operational status and integrity of both the spacecraft and the launch vehicle. Following the launch, after booster separation, Juno was put in a low Earth parking orbit thanks to a first burn of the Centaur upper stage. Afterwards, at time L+645 s, via a second burn given by the same stage, Juno entered an heliocentric trajectory. Solar arrays were deployed and initial checks on the instruments were performed at this time. This procedure is fundamental in order to provide enough electrical power to the spacecraft to perform initial check on its health. The specific trajectory followed by Juno is called "2 + dV-EGA", which means that the spacecraft will perform an Earth gravity assist at around two years after launch. During the initial cruise various correction maneuvers were performed: the main ones being the two DSMs needed to place Juno on the correct path to achieve the planned fly-by. DSMs were performed near the apocentre, located farther away from the Sun than Mars' orbit, causing the spacecraft to pass as close as 0.88 AU before approaching Earth. During the approach to perform the fly-by, attitude corrections were performed to protect the spacecraft by the incoming radiation from the Sun. The fly-by around Earth occurred on the 10th of September 2013 and puts the spacecraft on its final trajectory to Jupiter. Particularly, the fly-by gave the spacecraft 7.3 km/s, avoiding a fire-up of the Leros 1-b main engine of Juno. A last correction maneuver was performed to refine Juno's trajectory.^{[4][6][12][13][14]}

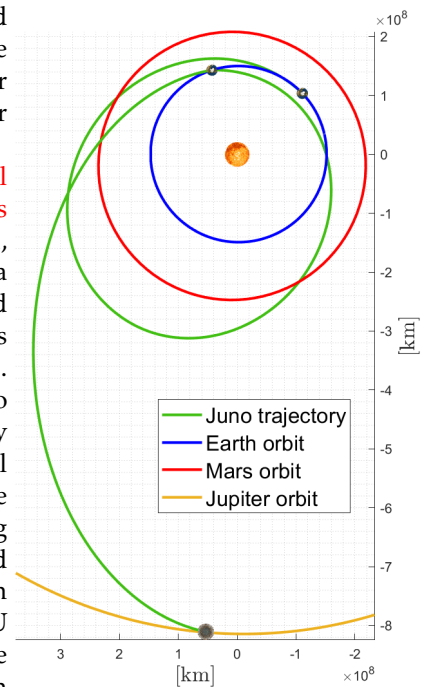


Figure 4: Juno's trajectory from ecliptic north pole

8.2 Jupiter approach and insertion

After the flyby, Juno spent 791 days on its last interplanetary leg in which no significant maneuvers nor scientific operations were conducted. Jupiter approach lasted a further 178 days, during which calibration, validation of the on board instruments and telecommunications checks were accomplished. Initial science observations of Jupiter's distant environment were also performed.

JOI, which was obtained through a main engine burn, was made at the closest approach to Jupiter: this moment is called PJ-0, indicating the first passage at the perijove of Juno. The targeted point for this maneuver is at an altitude of

4200 km, calculated above the 1-bar level of Jupiter. **JOI burn was timed to happen in the area of minimum magnetic field strength, reducing the risk of hardware damage during such a critical manoeuvre.** The spacecraft is left on a highly elliptical 53-days period around Jupiter with an inclination of 90° ($\pm 10^\circ$). Additional clean-up maneuvers were planned to correct the trajectory. The attitude during JOI phase, as the spacecraft was slowing down, was such that the HGA was not pointing Earth, constraining communications to low tones, only meant to send information about the completion or failure of the events. After 50 hours from PJ-0 all instruments were successfully powered up and started to perform nominal science operations.

8.3 Science operations and extended mission

The nominal science orbit, with a period of 14-days, had to be achieved via a PRM at PJ-02. This orbit had been chosen for many reasons:

- it allowed to avoid Jupiter's strongest radiation belts
- enabled near Sun pointing to generate enough electrical power and granted Earth communications via HGA
- it provided the closest possible approach of the instruments to Jupiter's clouds
- it allowed, thanks to Jupiter's oblateness, to scan the whole planet with only 32 orbits obtaining a resolution of 11.25° .

During science operations, two types of orbits should have been performed, differing in terms of spacecraft orientation: MWR passes, which required nadir pointing of Juno's spin plane in order to let the radiometers scan directly the planet, and GSOs, designed to align HGA with Earth.

However, due to a malfunctioning of an helium tank valve, Juno entered Safe Mode for 13.5 hours and PRW was discarded. This change showed the robustness of the designed capture orbit. It was in fact possible to conduct science operations on this longer path with only minor changes: the disposal of the spacecraft had to be moved from 2017 to 2021 to allow the completion of the 35 orbits. Moreover, the 53-days orbit required a slight plane change (from 90° to 105°) between PJ-22 and PJ-23 to avoid a solar eclipse since the batteries are only suited for the 19 minutes eclipse during the Earth fly-by.

The so conducted mission was scheduled to end on July 2021 but the conditions of the spacecraft and the remaining fuel on board allowed to extend the mission by other 42 orbits for 5 more years of mission. During the nominal phases, the PJ had been shifted northwards, so during the extended phase a series of close passes of Jupiter's north polar cyclones occurred. Furthermore, flybys of Ganymede, Io and Europa are performed in addition to an analysis of the faint rings of the observed planet.^[1]

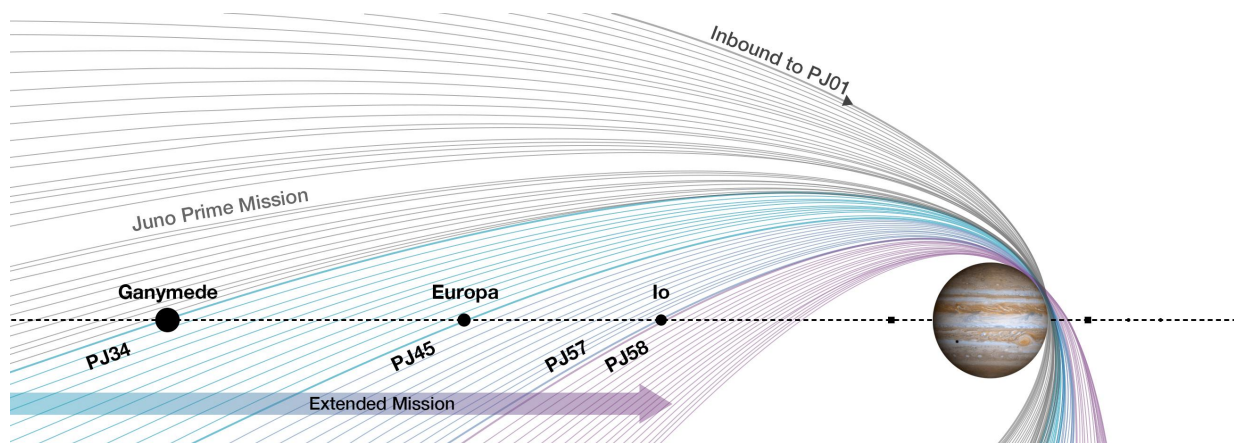


Figure 5: Orbits around Jupiter

8.4 Mission disposal

Under the planetary protection requirements, Juno is designed to de-orbit itself after the extended mission succeeds. **In this phase, it may be necessary to establish communication with the ground station, hence an alignment between the HGA boresight and the spin-axis, to ensure that data is transmitted at adequate downlink rates.** The dose of radiations absorbed during the lifetime of the spacecraft won't allow for safe operations. The de-orbit maneuver is supposed to begin with an apocentre burn, slowing down Juno by 75 m/s, enough to lower its perijove in the atmosphere of Jupiter. The dense gas layers will cause the spacecraft to disintegrate.

De-orbiting the spacecraft, now planned in 2025, will eliminate the possibility of contamination of Jupiter and its Moons' environment, especially to avoid unreliable results from the planned ESA Juice mission, expected to enter Jupiter's orbit in 2031.^{[10][11]}

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