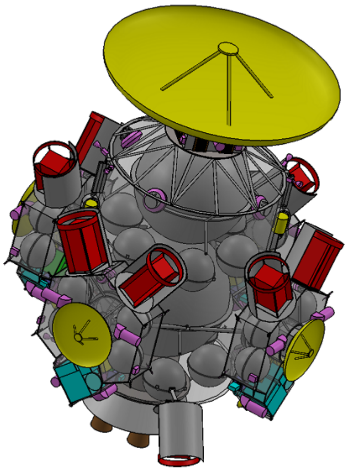
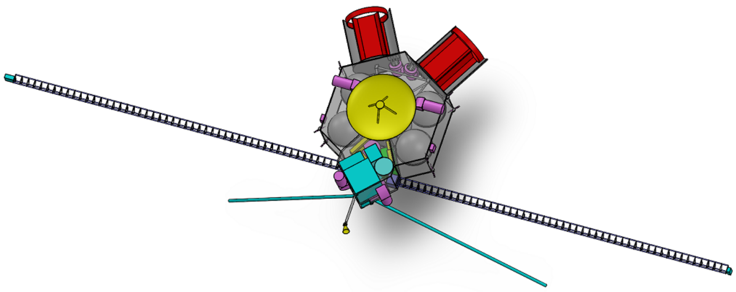
Space Mission Analysis and Design Course
Department of Aerospace Engineering
Academic Year 2020-2021





JOVIAN ENVIRONMENT MULTISCALE ANALYSIS

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Quick Facts

Mission Name

JOLLY spacecrafts will analyse Jupiter's magnetosphere, atmosphere and Galilean moons. This is why the mission was named Jovian environment multiscale analysis, gathered in the acronym JOLLY, that in Italian is related to a polyvalent card, therefore with different purposes.

Scientific Objectives

- Characterize the radiation environment, by maximising spatial data acquisition with particular attention to the low latitude regions in the Jupiter - Io distance band;
- Analyze the large and short scale variation in the radiation environment;
- Perform Jovian atmosphere 3D mapping;
- Investigate the Jupiter - Sun interaction.

High Level Requirements

- In situ science shall occur in distributed locations in the Jovian magnetosphere, both internal and external;
- 3D data collection shall occur in proximity of both magnetic and inert moons;
- The interaction with Jupiter atmosphere and Io volcanism should be analysed;
- The space segment should be distributed in the Jovian system, with a lifetime at planet higher than 2 years.

Spacecraft

Two designs will be used in the mission:

J-CARE (JOLLY-Cargo And RElay for telecommunications): it is the cargo that deploys the M&As and after it will be used as a relay for telecommunications.

Dimensions: 6.5 m high, 2.6 m in diameter.

Weight: 10476 kg at launch, consisting of 3276 kg of spacecraft, 3600 kg of fuel and 3600 kg of oxidizer.

M&As (Master & Agents): these are the four spacecraft that will form the science analysing system.

Dimensions: 0.57 m high, 2.9 m max width.

Weight: 702 kg at launch, consisting of 486 kg of spacecraft, 216 kg of propellant.

Launch Vehicle

Type: SLS Block II (core stage with four Liquid Engines with two Solid Rocket Boosters, upper stage with four RL10-C-1)

Height: 117 meters

Mission Milestones

Launch: **2032.09.23**
Venus flyby: 2032.12.03
First Earth flyby: 2033.04.01
Second Earth flyby: 2034.08.24
Arrival at Jupiter: 2039.04.28

Begin Magnetosphere analysis: 2039.12.25
Begin moon analysis phase: 2042.1.28
EOM: **2043.09.05**

Program

JOLLY mission investment is approximately 3.65€ billion in total. This cost includes spacecraft development and production, scientific payloads, launch services, mission operations and relay support for 11 years.

Jupiter at a Glance

The Jovian environment can be considered as a miniaturized Solar System and its study can give precious insights about the understanding of exoplanetary systems. Furthermore, its strong magnetic field gives rise to an enormous magnetosphere and many of its satellites interact with it, generating a series of coupling phenomena that can be studied only in this specific system.

Radiations

The radiation level in the Jovian environment is one of the highest in the Solar System, due to the combination of several effects. The strong magnetic field together with an ion source represented by Io, the innermost of the main satellites, creates a radiation belt made of very energetic ions trapped in a similar way to the ones in the Van Allen belts around Earth. In these zones, the radiation intensity is extremely high, shortening electronic components lifespan and jeopardizing related missions, unless proper countermeasures are adopted.

Magnetosphere

If it were visible, the Jovian magnetosphere would be the largest object in the sky. The strong internal magnetic field of Jupiter (whose equatorial surface strength is approximately ten times the one of the Earth) is generated deeply within the rotating core of the planet and it is tilted by 9.7° with respect to its rotation axis, similar to the one on the Earth. The dimension of the magnetosphere is strongly affected by the solar activity, going from 45 to 100 $R_{♃}$ (where $R_{♃} = 71{,}492$ km is the radius of Jupiter).

Atmosphere

The atmosphere of Jupiter provides the most accessible example of a giant gaseous planet, an archetype for astrophysical objects that appear to be commonplace beyond our Solar System. It also provides a planetary-scale laboratory for the investigation of the fluid-dynamic processes governing planetary atmospheres and oceans. Although primarily composed by hydrogen and helium, Jupiter also contains small amounts of heavier elements (CH_4, PH_3, NH_3, H_2S, H_2O). Moreover, the ratio of helium to hydrogen in the deep atmosphere is about the same as in the Sun. Belts and zones are stable cloud formations. Their width and color might vary with time, but the semi-regular pattern can be seen up to a latitude of 50°. The color of the polar areas is similar to the one of the belts. The belts are reddish or brownish and inside them the motion of the gas is downward. On the contrary, the gas flows upward in the white zones, where there are clouds which are slightly higher and have a lower temperature than those in the belts.

Rings and Dust Environment

Jupiter's ring system is faint and consists mainly of micron-sized dust. It is composed principally by four main components, which are a thick inner torus of particles known as the *halo ring* (extended from 1.29 to 1.71 $\mathrm{R}_{♃}$), a relatively bright and thin ($< \sim 30$ km) *main ring* between 1.71 and 1.80 $\mathrm{R}_{♃}$, that shows a rich fine structure, and two wide, thick and faint outer *gossamer rings* extending up to 3.16 $\mathrm{R}_{♃}$. When orbiting at low latitudes and distances from Jupiter, the probes have to pay an increased attention to eventual impacts with bodies belonging to these rings and belts.

Moons

The main satellites of Jupiter are four: Io, Europa, Ganymede, and Callisto (Galilean moons), very diverse with respect to their chemical compositions, surfaces, internal structures, evolution and degrees of interaction with the planet.

State of the Art

JOLLY ambitious concept is to merge two different classes of missions: planetary mission around Jupiter and Magnetospheric 3D mapping. This paragraph presents a brief description of these past (or future) missions.

Jovian Missions

The exploration of Jupiter, and in general of the Jovian system, has begun in the 1970s with Pioneer 10 and 11 and Voyager 1 and 2. The expeditions started with the arrival of Pioneer 10 in 1973, which became the first spacecraft to cross the asteroid belt and fly past Jupiter. It was followed one year later by Pioneer 11; these probes discovered the magnetosphere of Jupiter and took the first close-up pictures. In the same decade Voyager 1 and 2 visited the planet too, analysing the moons of the system and discovering in particular the volcanic activity of Io and Jupiter's faint rings. Ulysses swung-by Jupiter in 1992. The next mission was then Cassini-Huygens in 2000 which took very detailed images of the atmosphere of Jupiter on its way to neighboring Saturn, as New Horizons did on its quest for Pluto and the Kuiper Belt, that passed by Jupiter in 2007.

JUNO mission, designed by NASA, was launched in 2011 by Atlas V551 with five SRBs and CENTAUR upper stage.
Among its multiple objectives, JUNO is studying the formation and evolution of Jupiter, as well as its gravitational, magnetic and electric fields. Indeed, it will improve our understanding on the solar system's beginnings by revealing the origin and evolution of Jupiter.

JUICE mission is an ongoing project designed by ESA; the proposed year for the launch is June 2022 (or August 2023) and Ariane-5 ECA will be the used launcher. The main goal of the mission is to explore the entire Jovian system, with particular attention to the potentially habitable moons (i.e. Europa, Callisto and Ganymede). Io in particular will not be studied in depth, but more distant observations will be carried out for its volcanism.

Europa-Clipper mission concept is predicated on the developed capability to obtain global-regional coverage of Europa via a complex network of fly-bys while in Jupiter orbit. The mission is programmed for the 2025 and a SLS will be employed.
The overall goal of the mission is indeed to investigate the habitability of Europa. The current concept of the Europa-Clipper mission includes 45 fly-bys of Europa at altitudes varying from 2700 km to 25 km.

Magnetospheric Missions

MMS is a NASA mission launched in 2015 with ATLAS V 421 Launch Vehicle (two Solid Rocket Boosters and single engine Centaur). This mission aimed mainly to study the magnetic disconnection and reconnection around the Earth; specifically, the goal was to cross the regions in which these two phenomena occur. Indeed, the magnetic reconnection is a process where the Sun's and Earth's magnetic fields explosively transfer energy from one to the other and that is of fundamental importance for the all universe.

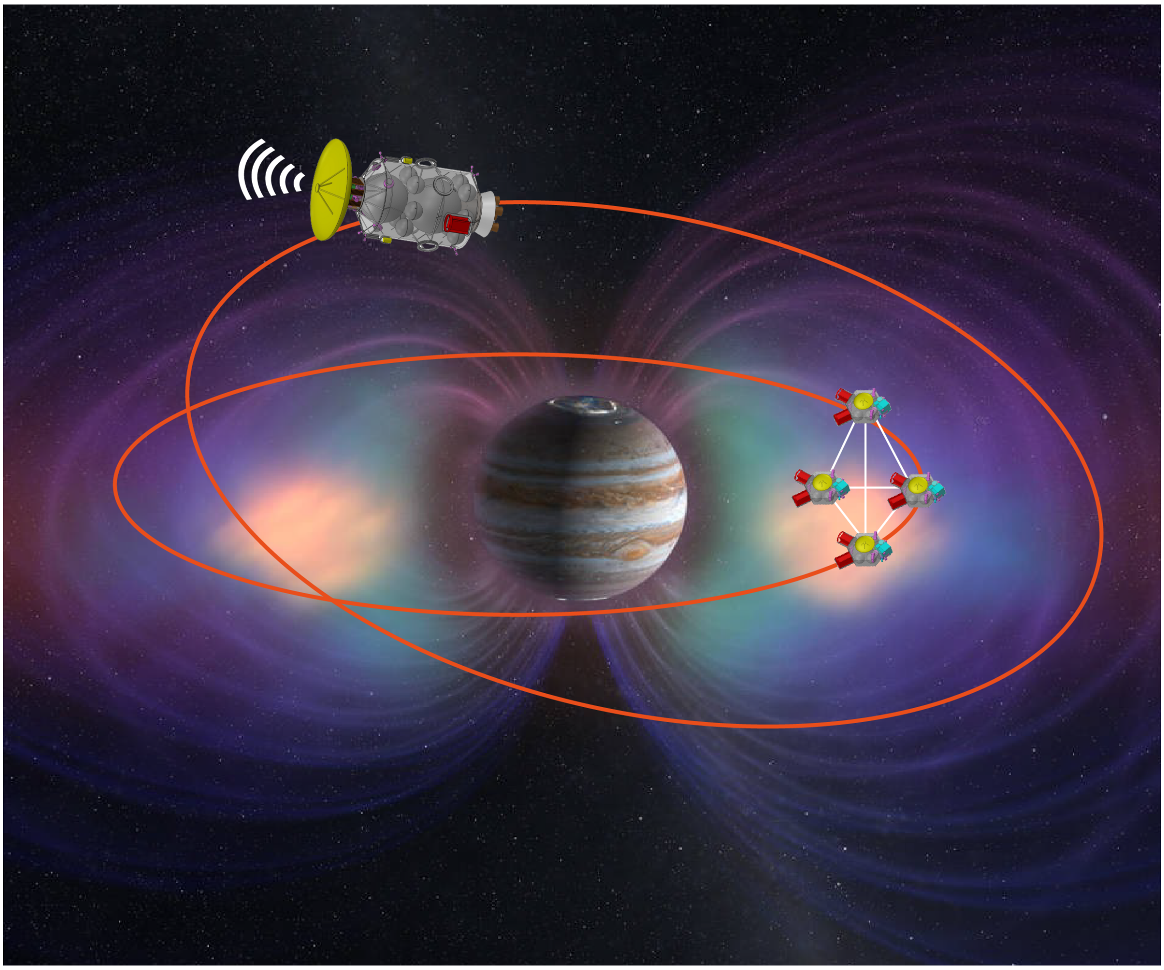
Cluster II is a mission founded in collaboration by ESA and NASA launched in 2000; this mission's aims were to map the terrestrial magnetosphere and to study its interaction with the plasma of the solar wind.
This mission boasts an innovative concept in the construction of a formation flying, employing four satellites to perform a 3D mapping of the Earth magnetosphere.

Why JOLLY?

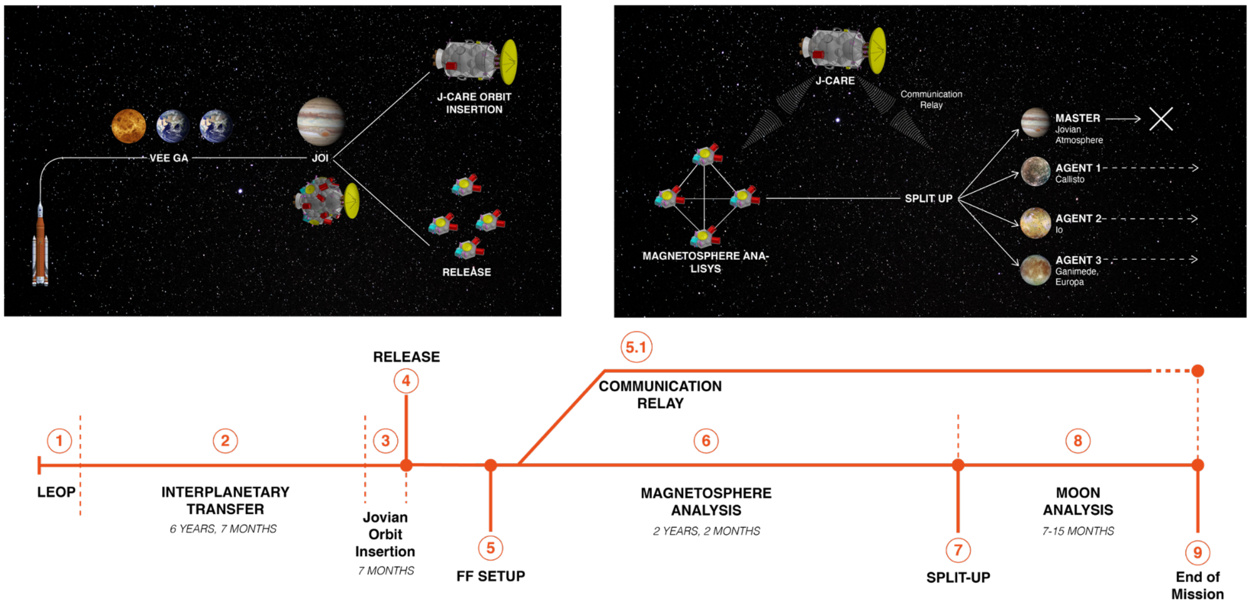
An understanding of the origin and evolution of Jupiter, as the archetype of giant planets, can provide the knowledge needed to help us understand the origin of our Solar System and planetary systems around other stars.

JOLLY primary goal is to retrieve scientific data granting the possibility to improve the knowledge regarding the origin and evolution of Jupiter. Employing four spacecraft as a formation flying in a tetrahedron shape, placed in an highly elliptical orbit, JOLLY will observe the Jovian magnetosphere, atmospheric dynamics and composition, and the coupling between the interior, atmosphere and magnetosphere with the Galilean Moons.

To satisfy the high level requirements of the mission, at least four spacecraft to perform a 3D mapping of the magnetosphere are needed. Therefore, to avoid a multiple launch strategy, a cargo spacecraft is employed to bring the Master and Agents into the Jovian System, and it is exploited as a relay in order to simplify the communication with the ground station.



Mission overview



To understand the evolution in time of JOLLY mission, a sketch about the ConOps is shown in figure above. Moreover, the various phases are explained hereafter in their details and for each of them the corresponding modes are specified:

1. *LEOP*: from the launch countdown until the insertion in the interplanetary orbit

2. *Interplanetary Transfer*: the system will travel on an interplanetary trajectory up to the Jovian system, performing GAs (e.g. with Venus and Earth);

3. *JOI (Jovian Orbit Insertion)*: deceleration manoeuvre which will insert the system (J-CARE and M&As) into an orbit around the arrival planet;

4. *Release*: manoeuvre that will place the spacecrafts into their operational orbit as a Formation Flying;

5. *Formation Flying Set-Up - Communication Relay*: manoeuvre to set the M&As into the tetrahedron shape formation flying; J-CARE will be placed on a high elliptical orbit outside the Jovian magnetosphere to enhance telecommunications;

6. *Magnetosphere Analysis*: the Formation will perform a 3D Mapping of the Jovian magnetosphere;

7. *Formation Split-Up*: manoeuvre that will drive M&As from their initial formation flying configuration to a distributed segment where to each S/C a different role will be assigned;

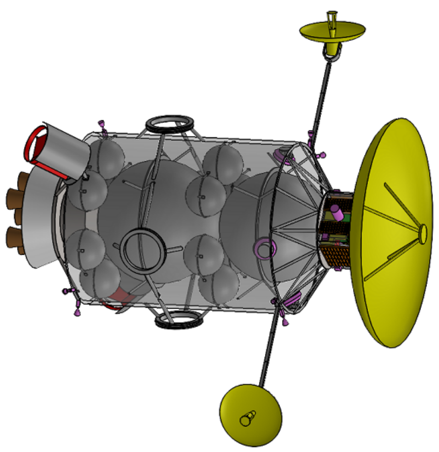
8. *Moon and Atmosphere Analysis*: once split, M&As will perform their singular scientific tasks around their target;

9. *End of Mission*: end phase of the mission, the S/Cs will be decommissioned, taking into consideration Planetary protection constraints.

Spacecraft

Configuration & Structure

JOLLY comprises of five spacecrafts, J-CARE and four identical scientific satellites (i.e. master and three agents).
J-CARE features a quite compact design relative to its mission, its height is up to 6.5 m and it is 2.6 m wide. It has a main cylindrical structure with the same width but it is only 3.3 m high and it is made of Albemet.



M&As are the sole responsible of the scientific throughput of JOLLY mission. They are quite smaller than J-CARE, featuring a quasi hexagonal structure measuring up to 2.9 m in their biggest dimension. They are built around a main structural cylinder, 0.57 m high and with a diameter of 0.63 m. Externally it is covered by sandwich panels made of Aluminum and Aluminum honeycomb.

Propulsion

All the 5 vehicles employ thermochemical propulsion based on liquid propellant.
In the specific, J-CARE exploits a highly impulsive bi-propellant architecture propelled by hydrazine and nitrogen tetraoxide, for both the primary and the secondary systems. In addition, a common feeding system accounting for two tanks (one for the oxidizer and one for the fuel) is present; a pressure-fed and pressure-regulated scheme is present.
As far as concerns, M&As a mono-propellant solution exploiting hydrazine as fuel is adopted. All the vehicles feature the same system, where the propellant is stored in three spherical tanks along with an inert gas for pressurization purposes.

Attitude Determination and Control

For both J-CARE and M&As, a 3 axis control architecture is designed, adopting reaction wheels and thrusters as actuators while star trackers, sun sensors and inertia measurements are the selected sensors to perform attitude determination. Several redundancies are employed due to the long duration of the mission.

On-Board Data Handling

Command and data handling includes two RAD750 flight processor for both J-CARE and the M&As. It's capable to handle 266MIPS more than enough for payload requirements. The mass storage is hadled by the Airbus Nemo-2 with 4Tb of storage.

Telemetry Tracking Telecommand

J-CARE is employed to act as a relay for M&As throughout the whole mission: even if the complexity increases, this strategy grants higher autonomy and performances inside the Jovian system.
During the interplanetary transfer, communications are done in X band, mainly through J-CARE HGA. For first contact and GAs, LGAs are employed since the main HGA is not Earth-pointing.
In the Jovian system, the relay between J-CARE and M&As is put in place: HGAs handle those communications in Ka band. In addition, while M&As are in formation flight,

an inter-satellite link is established between Master and Agents using a MGA. J-CARE still operates in the same way as for the interplanetary cruise.

Electric Power

Both J-CARE and M&As will employ RTGs as power generating method. NASA ASRGs have been chosen thanks to the higher efficiency, which is able to reduce both S/S mass budget and heat waste. Each vehicle will host 2 units. Batteries will be employed to manage power peaks and have been oversized in order to guarantee at least some degree of operational capability even in case of 1 ASRG unit failure.

Guidance Navigation and Control

The Navigation hardware includes the Deep Space Transponders employed in J-CARE and M&As, mission tracking is performed through ESTRACK DSN for navigation purposes, and the stochastic filters are used for state estimations, following the TCMs. The absolute and relative control accuracy for M&As with Earth and J-CARE respectively, is predicted to be <20 km and <10 km respectively. The station keeping and cruise phase of J-CARE is performed through impulsive control. The formation maintenance of M&As at 600km of relative distance is achieved through $\mathbf{e}/\mathbf{i}$ vector separation using ROEs and Model Predictive Controller with a predicted accuracy of <6 km.

Thermal Control

JOLLY needs a thermal control to guarantee the survivability of the structures and of all the instruments onboard. After a multi-node analysis, some medium/high TRL solutions were found to protect the most sensitive parts of J-CARE and M&As. Passive thermal solution like multi-layer-insulations, heat pipes, coatings and aerogel insulation were adopted, but due to its different environments during the mission also some active louvres were considered.

Payloads

In the picture below, the JOLLY payloads are presented in their position on the M&As.