# Cruise phase science opportunities with the JUICE spacecraft

Derek van Winden Supervisor: Niklas Edberg

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# Contents

# Chapter 1

# Abstract

The Jupiter Icy Moons Explorer of ESA is scheduled to be launched in 2023. During its more than seven-year-long cruise phase there is plenty of time to perform experiments. In this report, we have identified two types of science opportunities during the cruise phase. The first one involves measuring the properties of the solar wind during conjunctions between JUICE and other spacecraft. Several conjunctions between JUICE and spacecraft like the Parker Solar Probe, BepiColombo, Solar Orbiter, MAVEN, and Mars Express have been found. These conjunctions allow for measuring variations of the solar wind along with one of the coordinates of the heliocentric coordinate system (radius distance, latitude, and longitude). There are several periods at which variations along distance (radial alignment) or latitude (radial and longitudinal alignment) can be detected in this way. The other type of experiment that could be performed is the detection of interplanetary dust in the dust clouds that are thought to envelop the orbits of Venus and Mars [1–3]. During the cruise phase, five crossings through the primary population of the Martian dust halo, and two through Venus' dust belt take place. If the instruments on JUICE can detect the dust grains, the density of the belt along the direction of motion could be mapped.

# Chapter 2

# Introduction

In 2023 the Jupiter ICy moons Explorer (JUICE) will be launched. Over the course of at least three years, it will study the planet Jupiter and three of its moons: Europa, Ganymede, and Callisto. Among its objectives are to study Jupiter's magnetosphere and interactions concerning magnetic fields and plasma that occur in the Jovian system. Before it reaches Jupiter in July 2031, the spacecraft will spend more than seven years in cruise phase while on its way to the gas giant[4]. During this period a wide variety of additional experiments can be performed [5]. Among these possibilities, the ones which will be discussed in this report are multiple ways of studying the solar wind, and the detection of interplanetary dust. Other science opportunities that have been put forward, but that will not be discussed further are the measurement of relativistic electrons that escape the Jovian system, testing general relativity during a conjunction, observing the cosmological background radiation, and a possible asteroid flyby. JUICE carries a total of 104kg payload of instruments, including the Juice-Magnetometer (J-MAG), Particle Environment Package (PEP), and the Radio Plasma Wave Instrument (RPWI). For a list with all the instruments on board, and a more elaborate description of them, we refer to [4]. With these instruments, JUICE can do measurements on the magnetic fields, and the plasma of the interplanetary medium. An especially interesting experiment would be to do simultaneous measurements with another spacecraft that carries a similar science package, at moments when they are radially or angularly aligned. Especially the Solar Orbiter (SOLO) and the Parker Solar Probe (PSP), both of which study the sun and the solar wind, and BepiColombo which will be orbiting Mercury in 2025, are suited for such alignments with JUICE. As they all carry similar instruments that can detect electric- and magnetic fields, and the particles of the solar wind (see table 2.1). This report is based on the trajectories that were calculated for the initial launch date of 1 October 2022. But since the launch of the spacecraft was postponed, and moved to August 2023, the trajectories and calculated dates for events in this report will not be applicable for the updated mission but the general conclusions should still hold.

| JUICE | Parker Solar Probe | Solar Orbiter | BepiColombo | MAVEN | Mars Express |
|---|---|---|---|---|---|
| J-Mag | FIELDS | MAG | MERMAG | MAG | |
| PEP | SWEAP and ISIS | EPD and SWA | MPPE | SWEA and SWIA | ASPERA-3 |
| RPWI | | RPW | PWI | LPW | |

Table 2.1: A table containing the comparable instruments aboard each of the spacecraft, relevant for studying the solar wind. For more information about the instruments we refer to [4, 6–10].

## 2.1 The solar wind

The sun is continuously ejecting a varying stream of charged particles. This plasma which consists mainly of protons and electrons is called the solar wind. Regions near the equator emit rapidly varying slow solar wind, while zones closer to the poles eject a more stable and faster solar wind. As the magnetic fields are essentially 'frozen in' into the plasma, the solar wind takes the magnetic field of the sun out into space, explaining the origin of the interplanetary magnetic field (IMF). The solar wind is not constant, however, as the solar activity fluctuates on both long time scales, like the 11-year solar cycle, and on shorter time scales due to the unstable nature of the solar atmosphere. There is also a variation of the solar wind along the latitude of the sun. Short events like coronal mass ejections and solar flares may eject a sudden high-density burst of particles at a high velocity, while corotating interaction regions that are longer lived, act as a source of a quickly moving solar wind. As we move away from the sun, the particle density drops with $\propto 1/r^2$, and while the IMF in radial direction drops with $\propto 1/r^2$ , the fields in the polar and azimuthal direction drop by $\propto 1/r$ [11]. The interplanetary magnetic field and particle densities in the solar wind can be detected using magnetometers and particle detectors respectively. In this way, JUICE can study the evolution of the solar wind while it cruises through the solar system, and if one could link the information obtained by JUICE with that of another probe, even more extensive experiments can be performed. JUICE carries a magnetometer (J-MAG) to measure the interplanetary magnetic field, a PEP that can detect negative ions, electrons, exospheric neutral gas, thermal plasma, and energetic neutral atoms. While the Radio and Plasma Wave Investigation (RPWI) can measure the electric and magnetic fields in the plasma.

| | |
|---|---|
| $v$ | 400 $km/s$ |
| $B$ | 5 $nT$ |
| $n_e$ | 5 $cm^{-1}$ |
| $T_e$ | $5 - 10$ $eV$ |

Table 2.2: Properties of the solar wind. A table containing some typical values for the solar wind at 1 AU. Taken from: [12].

## 2.2 Dust halos

Recently, during its cruise phase on the way to Jupiter, the Juno spacecraft detected interplanetary dust particles (IPD) of sizes ranging from 1 to 100$\mu m$ [1]. These particles collided with the 60$m^2$ solar panels that served as a collecting area, while the 4 on-board star cameras acted as detectors. The highest concentration of dust was found in a Keplerian orbit between the aphelion of the Earth (1.02AU) and the 4 : 1 mean resonance of Jupiter (2.065AU). This dust extended in a torus-like shape with a primary high-concentration region extending to 1.85° on both sides of the ecliptic plane, and a secondary population resulting from the Kozai-Lidov mechanism stretching to 7.4° from the ecliptic plane [1]. Because the dust cloud occupies a region bounded by the earth's aphelion and Jupiters 4 : 1 mean resonance and appears to have a Keplerian orbit, Jorgensen et. al have proposed a possible Martian origin of the dust. On its way to Jupiter, JUICE also crosses the orbit of Venus multiple times, as part of the gravity assist manoeuvre. Like Mars, Venus' orbit also seems to be enveloped by a dust halo [2, 3], which could be studied by JUICE as well. The dust particles in the halos are much bigger than the electrons and protons usually found in the solar wind, but they could still be detected with JUICE's on board instruments. For example, the RPWI might be able to detect the ringing of the E-field caused by dust particles, or by the detection of ions that reside in the vicinity of the dust. Another method would be to use the solar panels of JUICE as a collection area for the IPD in a similar way as in [1]. The solar panels of JUICE have a larger total area (85$m^2$) compared to JUNO, which increases its detection abilities. The disadvantage of this technique is that it is not sensitive to smaller dust particles. Furthermore, it is not clear if the different type of solar panels used on JUICE lend as well as JUNO's for such a detection method, or whether the cameras aboard JUICE can serve as detectors.

# Chapter 3

# Science opportunities

In figure 3.1 the trajectories of all the objects mentioned in this report are shown. It can be seen in the right frame that the trajectory of JUICE lies in the ecliptic plane and that the spacecraft initially moves closer to the sun until it has a Venus flyby, which serves as a gravity assist manoeuvre to launch it towards Jupiter. Another notable feature, visible in the right frame is that the Parker solar probe has a highly eccentric orbit, with a perihelion very close to the sun. The other solar probe, SOLO, starts at a low inclination, but after a few orbits, it reaches high inclinations of about 28.7 degrees from the ecliptic plane. BepiColombo gradually moves closer to Mercury and will have multiple flybys around the planet, until it is finally in orbit at the end of 2025.

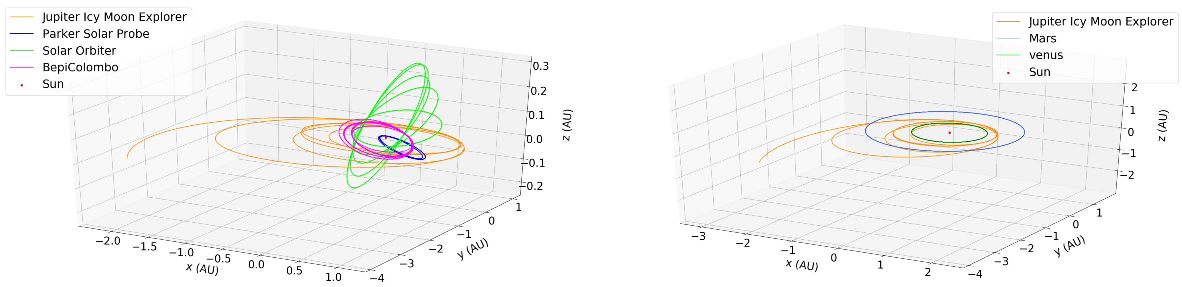


Figure 3.1: Left: The trajectories of JUICE and the other spacecraft. Right: The orbits of JUICE, Venus, and Mars.

The spherical coordinates of JUICE during its journey are plotted in figure 3.2. The absolute latitude never exceeds 1°, and its latitude changes during the first six years, but as soon as it gets its final gravitational assist of the Earth in 2029 it will head for Jupiter with a lower angular velocity. In figure 3.3, it is visible that JUICE's aphelion increases after its first flyby with Venus in September 2025 and during the Earth flybys at the end of 2026 and the beginning of 2029.

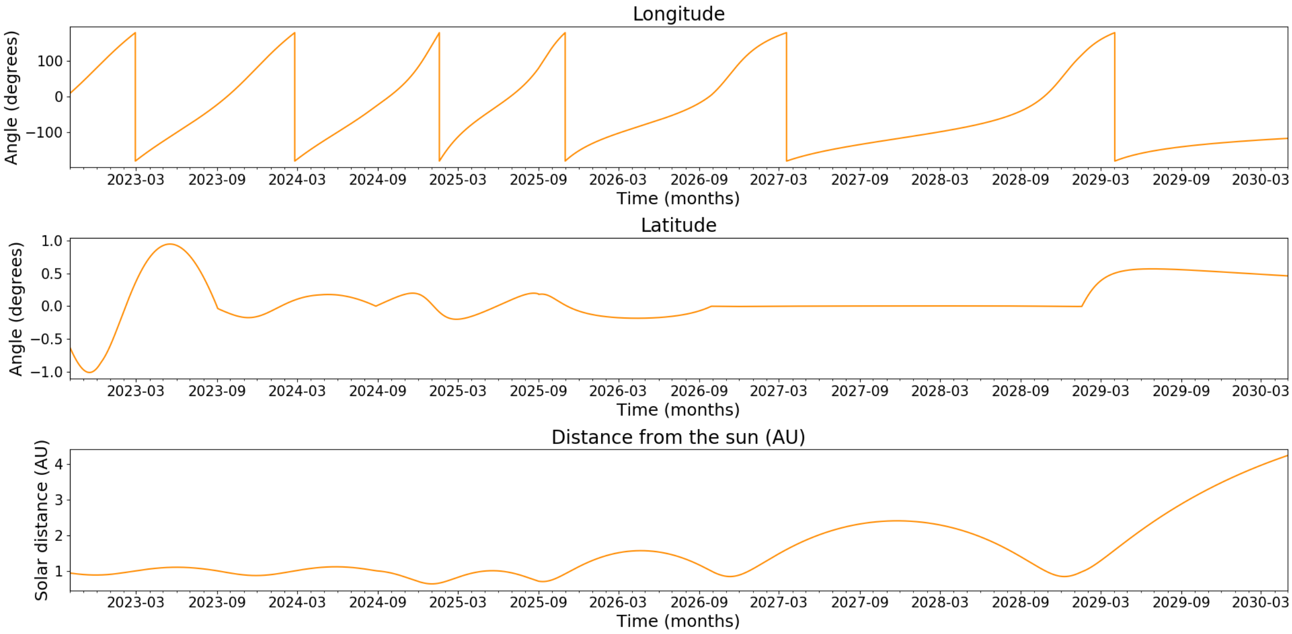


Figure 3.2: Coordinates of the Jupiter Icy Moons Explorer.

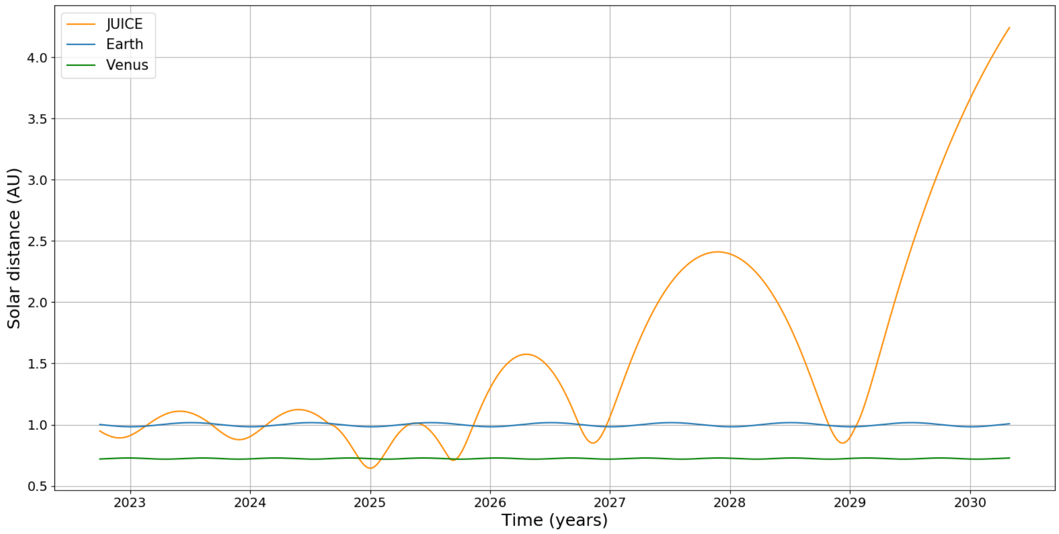


Figure 3.3: Solar distances of JUICE, Venus, and the Earth. The flybys are visible as crossing points.

## 3.1 Alignment between spacecraft

A class of experiments that JUICE can perform during the cruise phase is when it is aligned with other spacecraft. These conjunctions would allow us to study the solar wind, and its variation in the radial direction away from the sun (in case of radial alignment), or across longitude (when the probes are both radially and longitudinally aligned).

### 3.1.1 Radial alignment

In figure 3.4 the periods of radial alignment between JUICE and the other probes can be seen. The first thing that stands out, is that BepiColombo has many short alignments with JUICE that occur almost periodically. In this case, the later conjunctions when JUICE has moved past the orbit of Mars ($\sim 1.5$ AU) are the most interesting. The reason for this is that there are simply no spacecraft probing the interplanetary medium between Mars and Jupiter. The conjunctions with the longest periods occur between JUICE and the Parker Solar Probe and last for a month or more. But these occur when JUICE is around 1AU, so they are less important. The beginning of the last alignment between JUICE and SOLO at the end of November 2026, could be used to compare the measurements and to calibrate the instruments of JUICE, since during this time the spacecraft are not only radially aligned, but also about the same distance from the sun. Finally, there are also periods when JUICE is aligned with two other spacecraft at the same time. The periods and spacecraft involved in these conjunctions are denoted in table 3.1. At all these alignments JUICE is at 1AU from the sun.

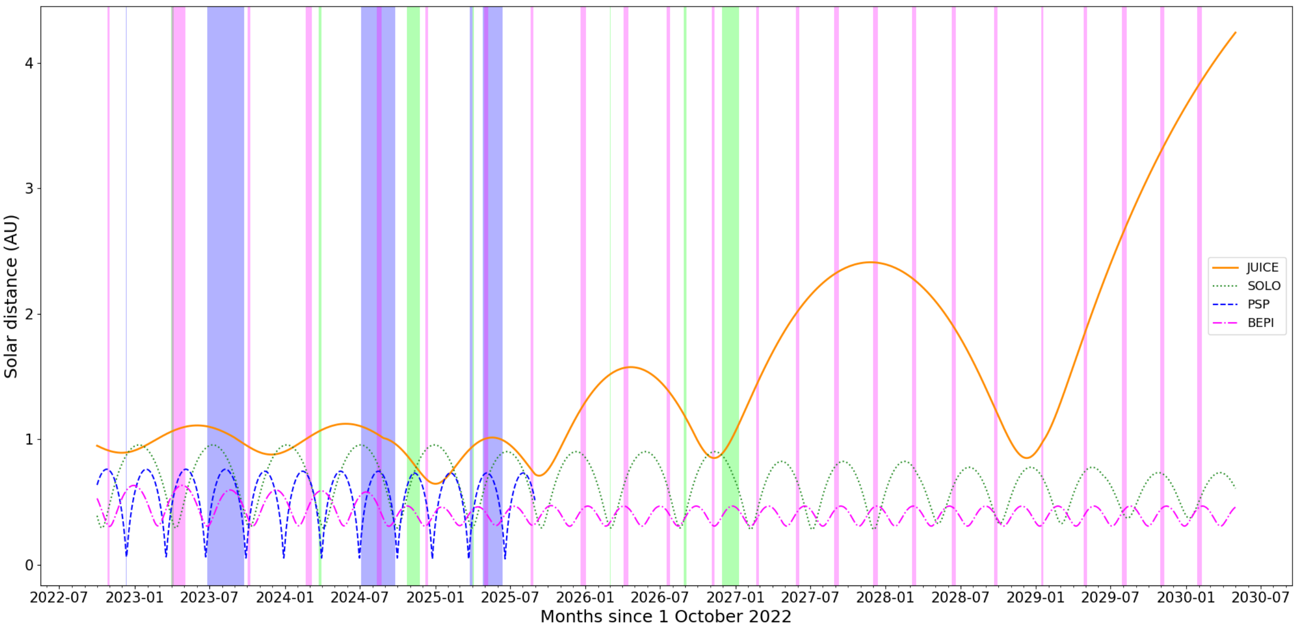


Figure 3.4: Radial alignment between JUICE and the other spacecraft within an angular separation of 15 degrees. The periods of alignment are marked in the colour of the respective spacecraft that is in conjunction with JUICE at that moment.

| Period | Probes |
|---|---|
| Beginning April 2023 | BEPI-SOLO |
| Mid August 2024 | BEPI-PSP |
| Beginning April 2025 | PSP-SOLO |
| Beginning May 2025 | BEPI-PSP |

Table 3.1: Triple conjunctions between JUICE and two other probes.

### 3.1.2 Latitude variation solar wind

Another experiment is to study the solar wind when JUICE and a solar probe are located at the same distance from the sun, while also being aligned in longitude, but not in latitude. Such that the only significant motion between the spacecraft is along the latitude. This is especially fascinating when there is a prolonged period in which the latitude difference between the probes increases rapidly so that changes in the solar wind across latitude can be measured. The Solar Orbiter is especially suited for this, as during its trajectory around the sun it reaches high latitudes, as can be seen in figure 3.1.

In figure 3.5, graphs containing the spherical coordinates of both JUICE and Solar Orbiter can be seen. There are multiple periods in which JUICE and SolO are aligned, but the early alignments are not of interest since the angular separation in longitude between Solar Orbiter is rather small. More interesting are the latter two periods of overlap, which are also the longest. In the second-last alignment, the maximum latitude that is reached is 12.4 degrees and in the last one separation of more than twice as much: 25.3 degrees, is achieved. Unfortunately, the longitude separations associated with these intervals are quite wide, going as far as 45°. At such large separations between the spacecraft, the longitudinal variation in the solar wind might have a significant effect on the measured values.

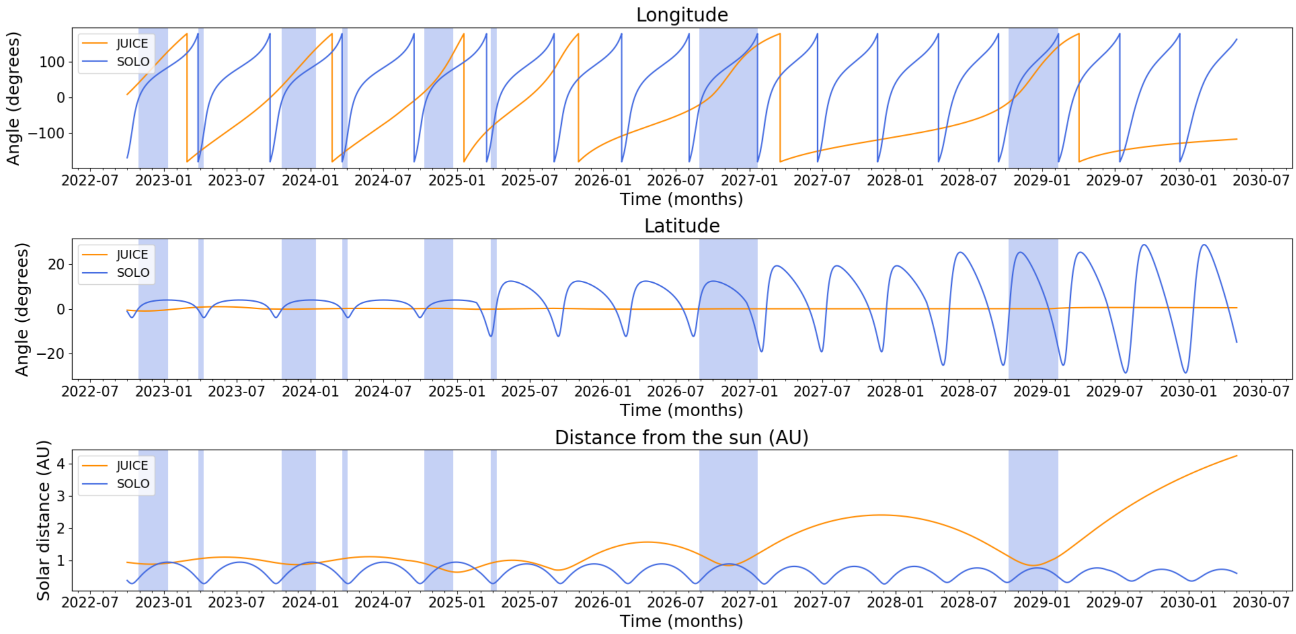


Figure 3.5: Longitudinal alignment between JUICE and Solar Orbiter within 45 degrees and at a maximal spacecraft separation of 0.83 AU. Areas of overlap have been coloured light blue. Note that these marked periods offer a window of opportunity to study the solar winds latitudinal variation.

### 3.1.3 Alignment with Mars orbiters

JUICE does not only have alignments with probes within the Earth's orbit but also with satellites orbiting Mars. ESA's Mars Express and NASA's MAVEN have already been orbiting the red planet since 2003 and 2014 respectively. As can be seen in table 2.1, MAVEN has the most instruments on board that could be of use during a conjunction. In this case, it would be interesting to see how the solar wind evolves further away from the sun, and for that MAVEN has comparable instruments to JUICE while Mars Express only has the ASPERA-3 (Analyzer of Space Plasmas and Energetic Atoms). The periods during which JUICE is aligned with Mars (and therefore also with the two satellites) are marked in figure 3.6. In total there are five conjunctions of which the first 3 occur when JUICE is around or below 1AU, while the last two happen beyond 2AU when JUICE is outside of the Martian orbit. This, and the fact that they are the longest intervals of alignment, are what makes the latter two periods the most suitable for an experiment.

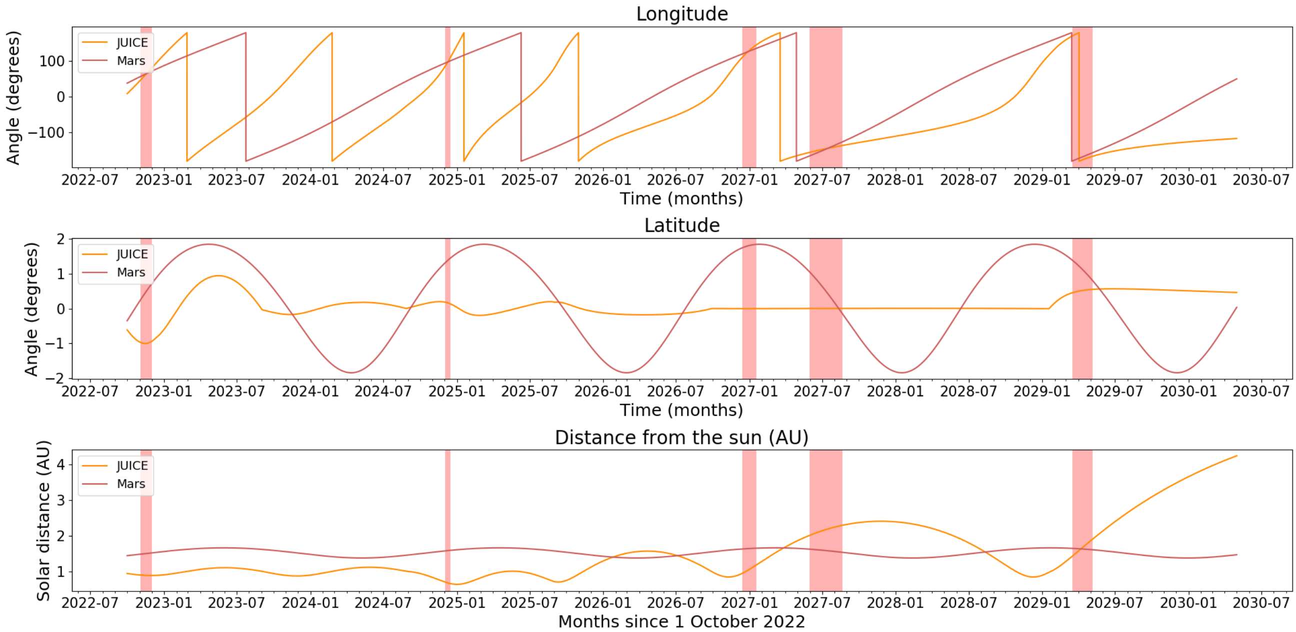


Figure 3.6: Radial alignment of JUICE with Mars. The red strips indicate periods when JUICE and Mars are radially aligned within within 10 degrees.

## 3.2 Dust detection

As mentioned in the introduction, one of the science opportunities for JUICE during the cruise phase is to detect and map the density of interplanetary dust in the solar system. In contrast to JUICE, JUNO didn't cross the orbit of Venus, as it only used the Earth for its gravitational assist. Therefore it would be interesting to exploit the opportunity that JUICE offers us to study the dust halo surrounding the orbit of Venus. In figure 3.7, a trajectory plot for each date at which JUICE crosses the orbit of Venus is shown. These crossings occur between 28 November 2024 and 19 September 2025. The dust halo near the orbit of Venus has been measured to be roughly extending up to 1.7° from Venus' orbital plane [2]. Because Venus itself has an inclination of about 3.394° with respect to the ecliptic plane[13], JUICE will not always pass through the dust cloud when it crosses the orbit of Venus. In figure 3.8 it can be seen that JUICE passes through the dust cloud in November 2024, and again when it has a Venus flyby in August 2025. But during the two other crossings, the latitude of JUICE is too low for it to pass through the dust halo.

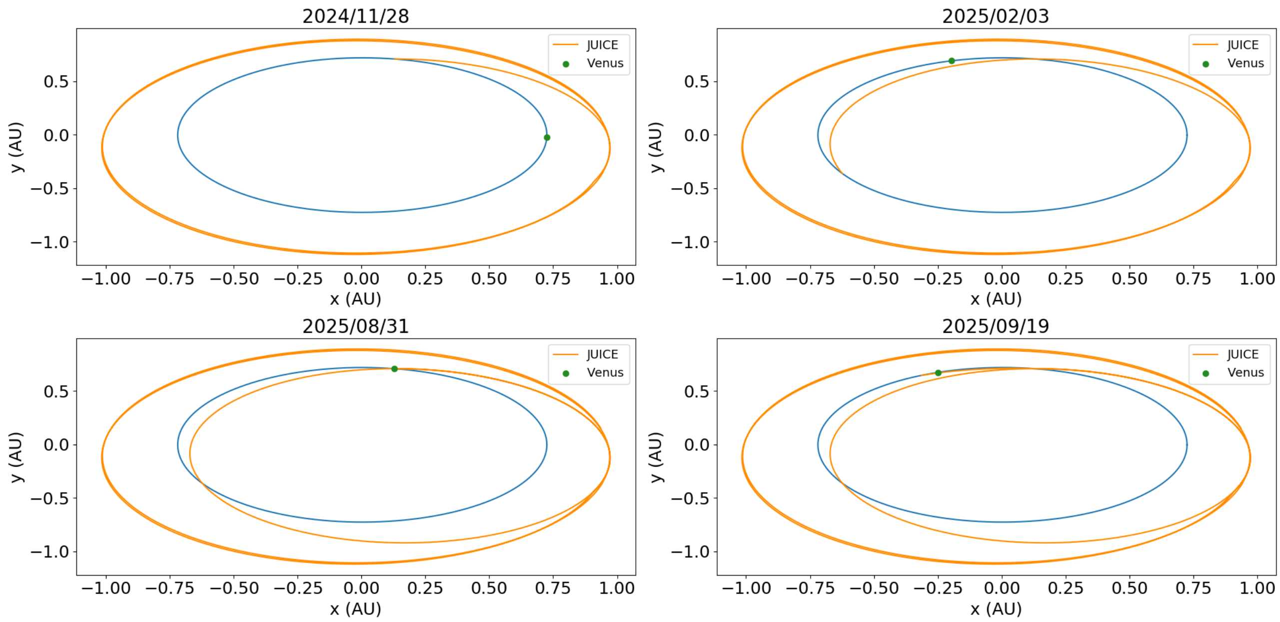


Figure 3.7: Crossing points of JUICE with the orbit of Venus and their respective dates. After launch, the spacecraft crosses through the orbit of Venus 4 times (as seen from the ecliptic plane). The Venus flyby, serving as a gravitational assist manoeuvre, can be seen in the bottom left panel.

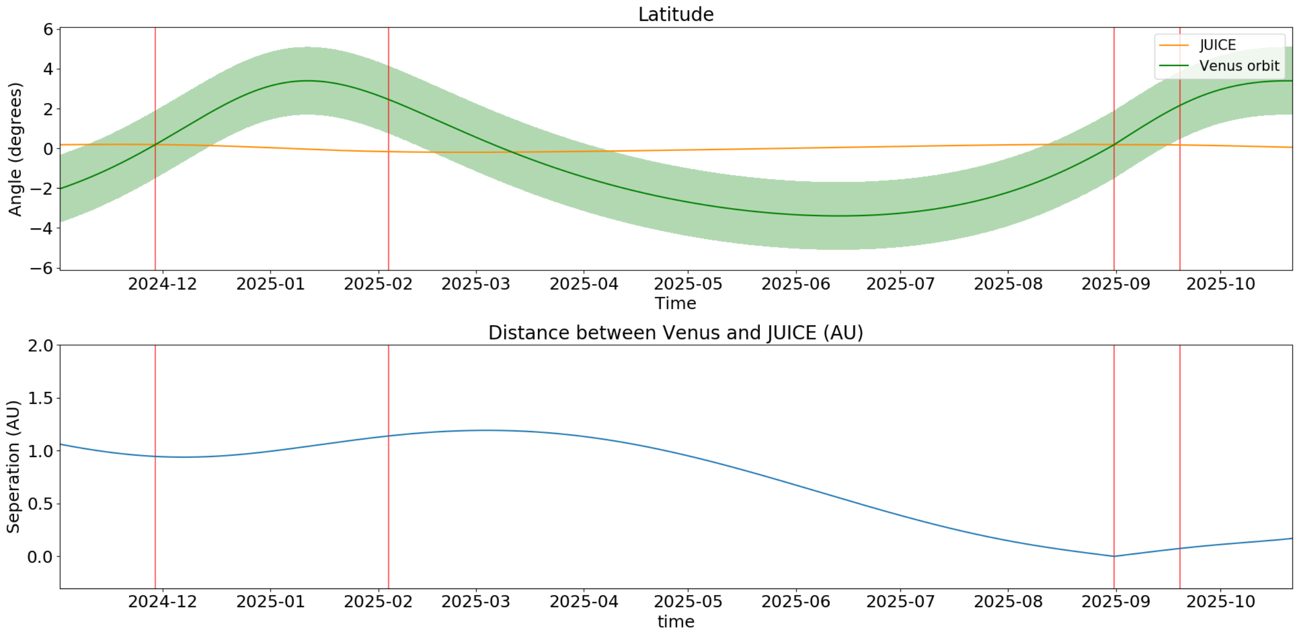


Figure 3.8: **Upper figure:** The latitude of JUICE and the Venus dust halo. The latitudes for the orbit of Venus are taken at the same longitudes as JUICE. The green region around the line of the Venus orbit indicates the extent of the dust halo. The red lines mark the moments at which JUICE crosses the orbit of Venus. **Bottom figure:** The distance between JUICE and Venus. The second-last crossing marks JUICE's Venus flyby.

Similar to Venus, the region surrounding the orbit of Mars also possesses a dust belt. The primary population of the Martian dust there is thought to lie within ±1.85° from the ecliptic plane [1]. In figure 3.9 it can be seen that the crossings occur between 19 February 2026 and 8 April 2029. A glance at figure 3.2 shows that JUICE moves through the central region every time it passes through the dust cloud as its latitude always remains within 0.5 degrees with respect to the ecliptic plane.

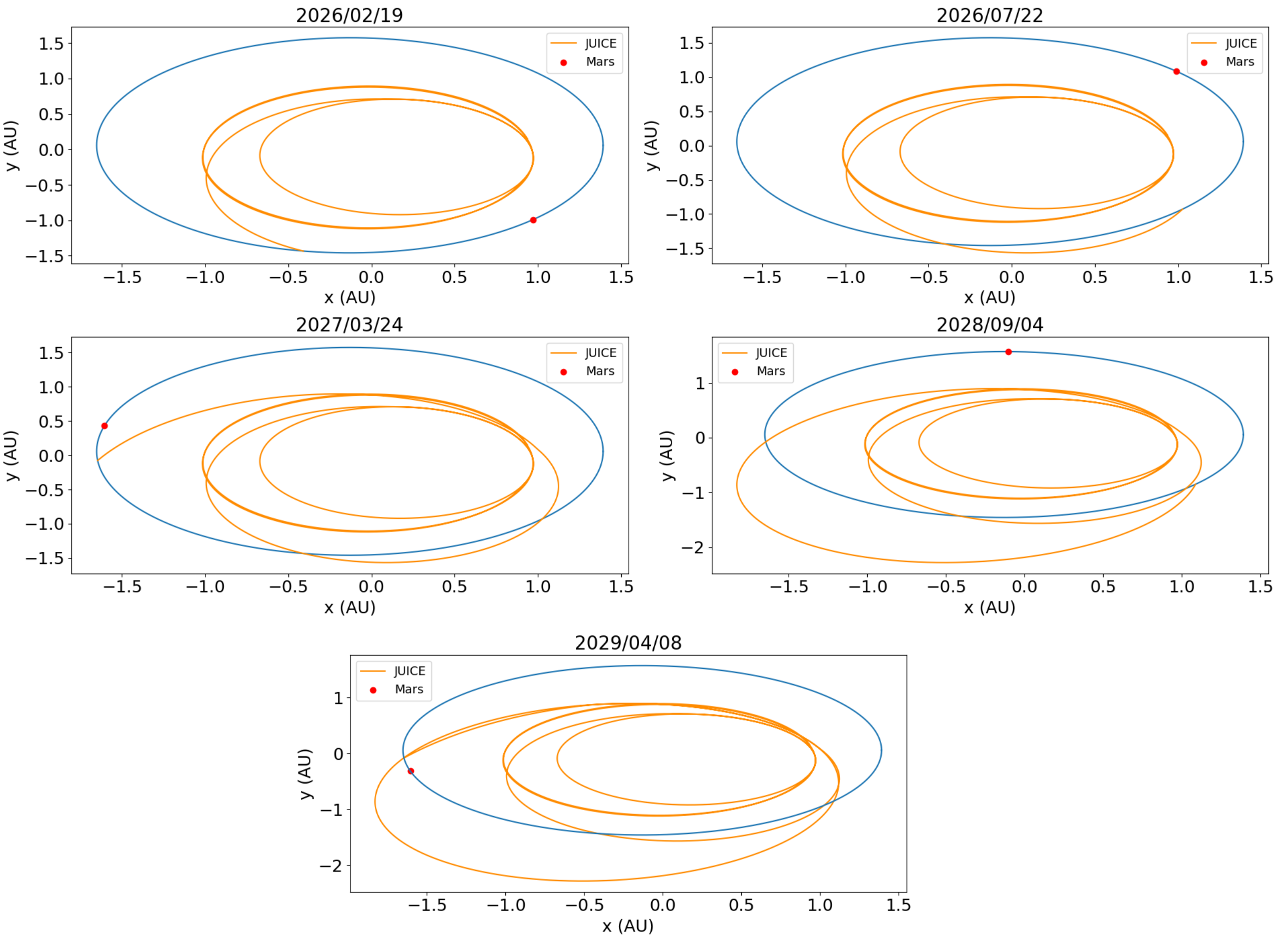


Figure 3.9: Crossing points of JUICE with the orbit of Mars at the respective dates. After launch, the spacecraft crosses through the orbit of Mars 5 times. Two times while moving inwards and three times while oriented outwards, with respect to the Martian orbit.

# Chapter 4

# Conclusion

In this report, multiple science opportunities have been discussed, and their feasibility in terms of orbits was assessed. For an overview of these opportunities look at figure 4.1. Alignments between JUICE and other spacecraft occur during multiple periods, and with all the probes: PSP, BEPI, SOLO, and also with the MAVEN and Mars Express orbiters. The most suitable periods for an experiment are the ones with BEPI when JUICE is beyond the Earth's orbit, the last two involving SolO, and also the final two with the Mars orbiters. An opportunity for an experiment with both longitudinal and radial alignment between JUICE and SOLO has also been found, although the separation in longitude is rather large and it is not sure if the variation in the solar wind along this direction is too large to consider it a useful alignment. It has also been shown that JUICE crosses the dust halos of Mars and Venus five and two times respectively during the cruise phase. Therefore one would expect JUICE to be able to detect the interplanetary dust in these regions, in case the instruments on the spacecraft are suited for such measurements. Finally, this report was based on the outdated trajectories of the canceled launch in 2022. When the updated trajectories calculated by ESA become available, a new analysis has to be done to see if the science opportunities that have been discussed are still possible, how they are affected by the change, and to find out if it also offers opportunities for different new experiments.

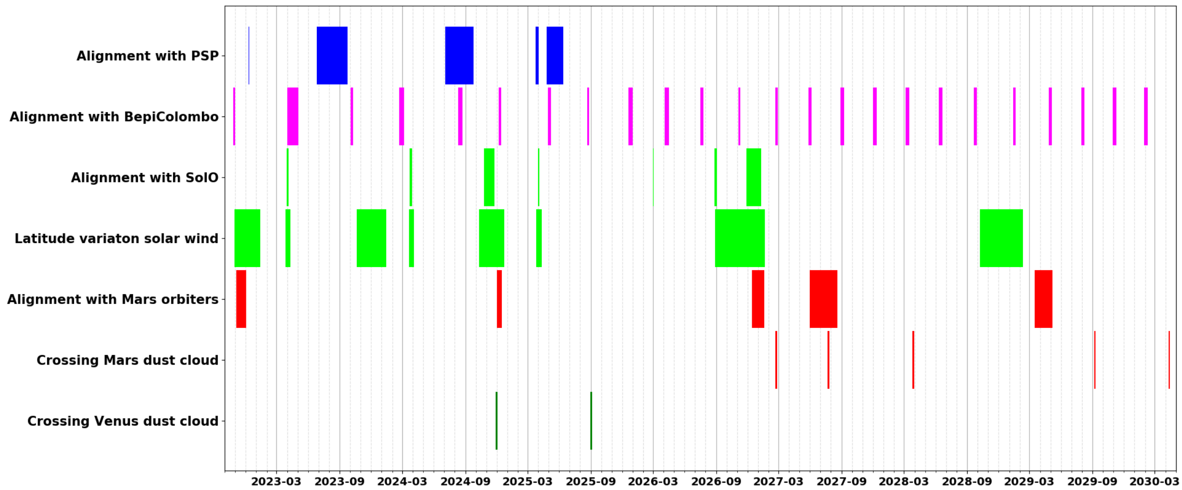


Figure 4.1: JUICE science opportunities calendar. This chart offers an overview during which periods all the science opportunities mentioned in this report occur.

# Chapter 5

# Appendix

## 5.1 Other graphs

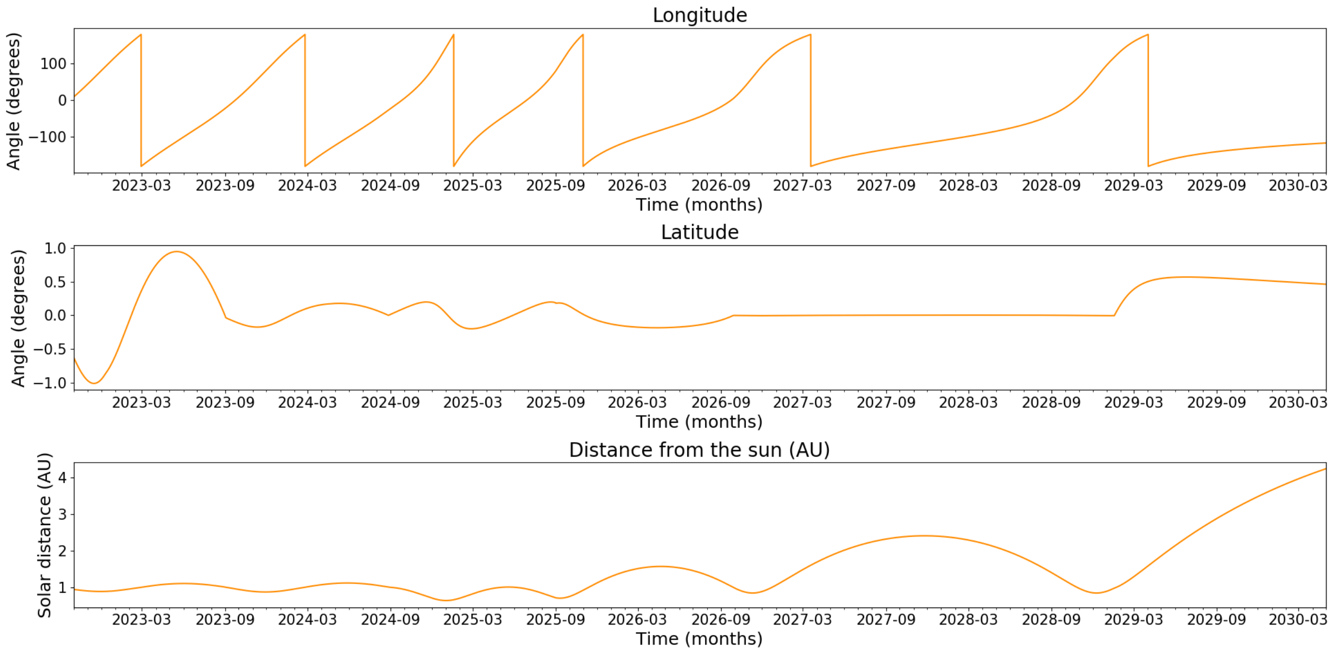


Figure 5.1: Coordinates of the Jupiter Icy Moons Explorer.

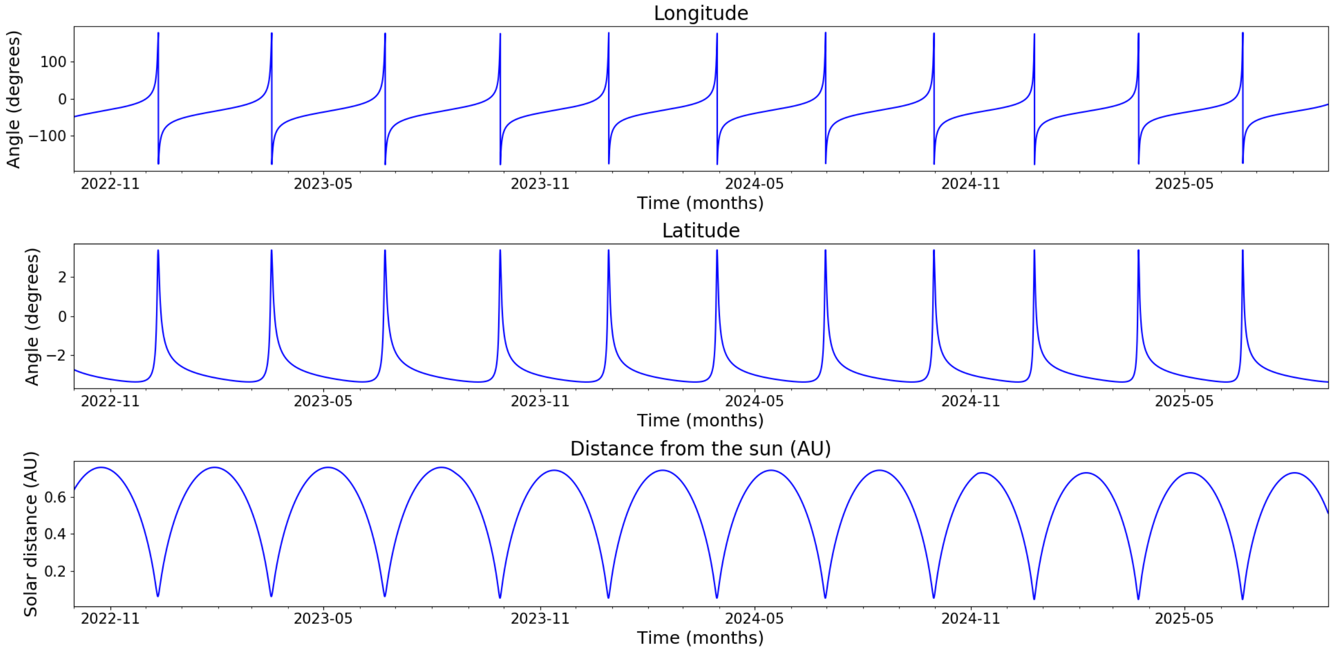


Figure 5.2: Coordinates of the Parker Solar Probe.

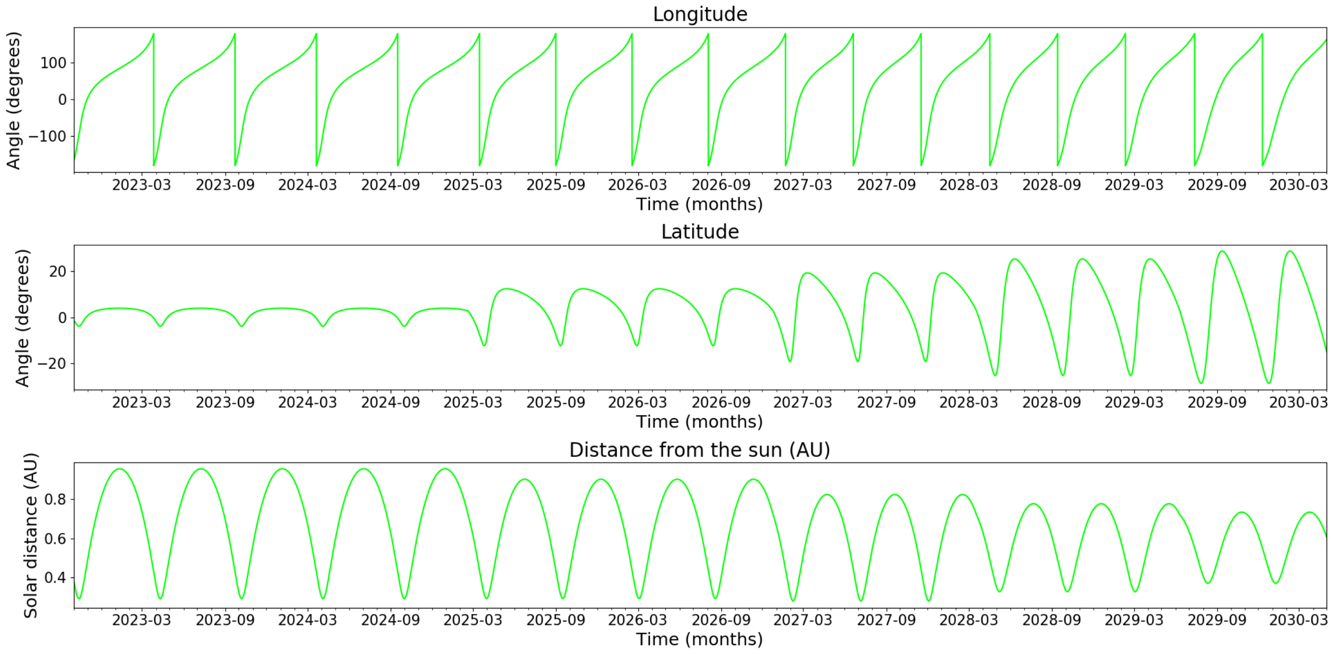


Figure 5.3: Coordinates of Solar Orbiter.

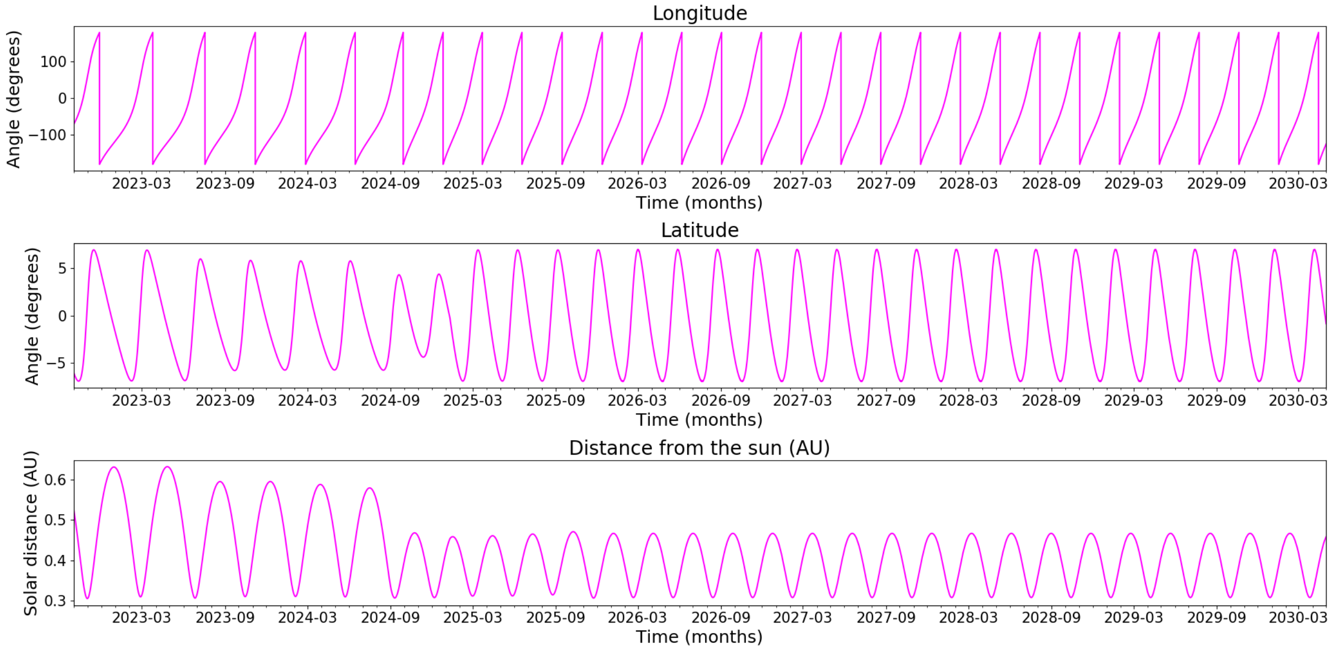


Figure 5.4: Coordinates of BepiColombo.

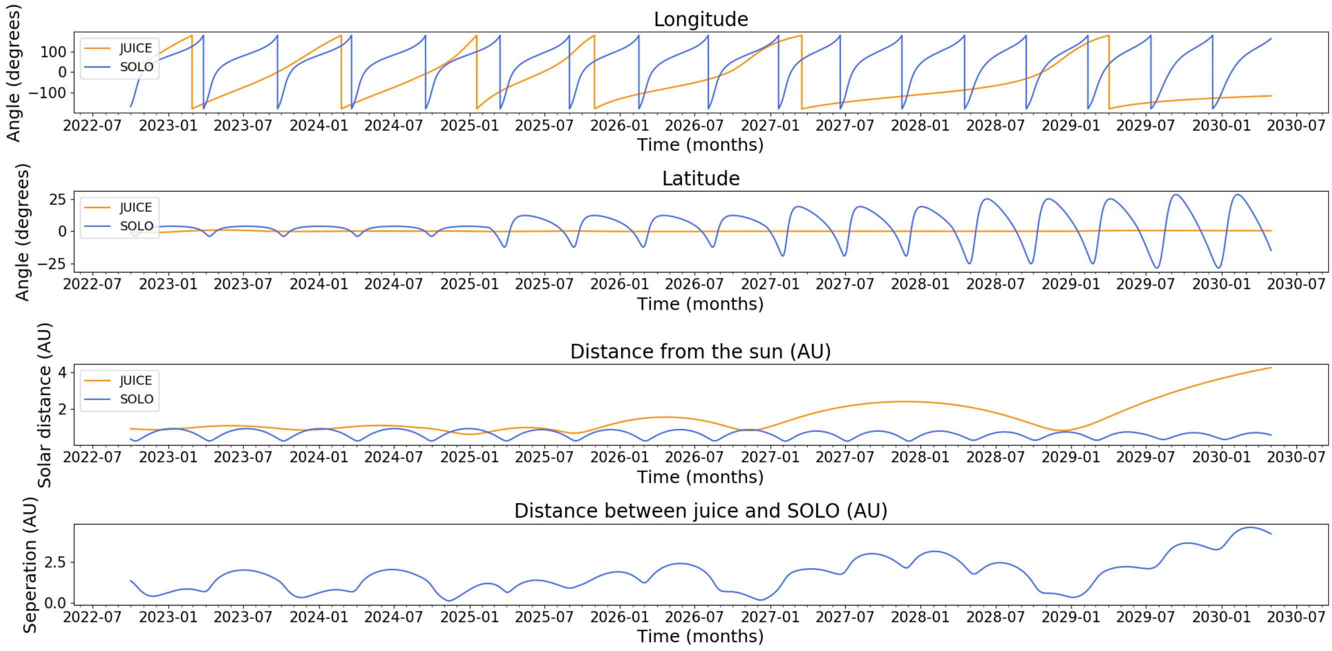


Figure 5.5: Juice and SOLO.

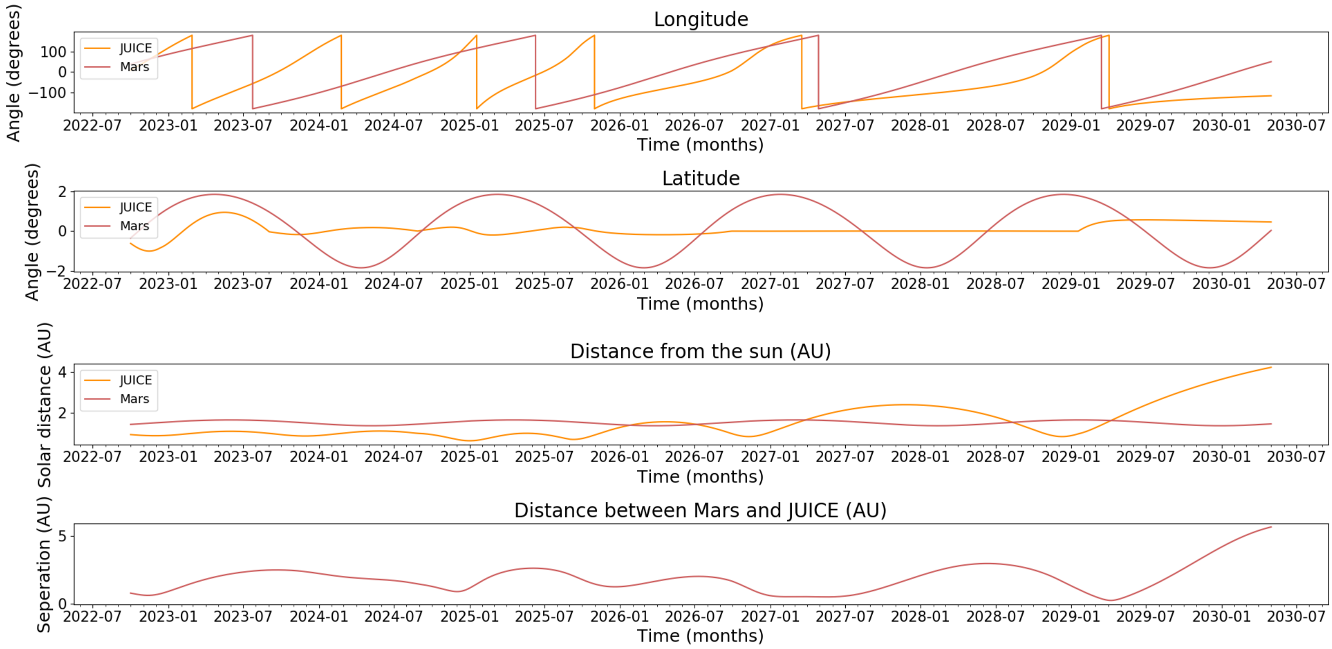


Figure 5.6: Juice and Mars.

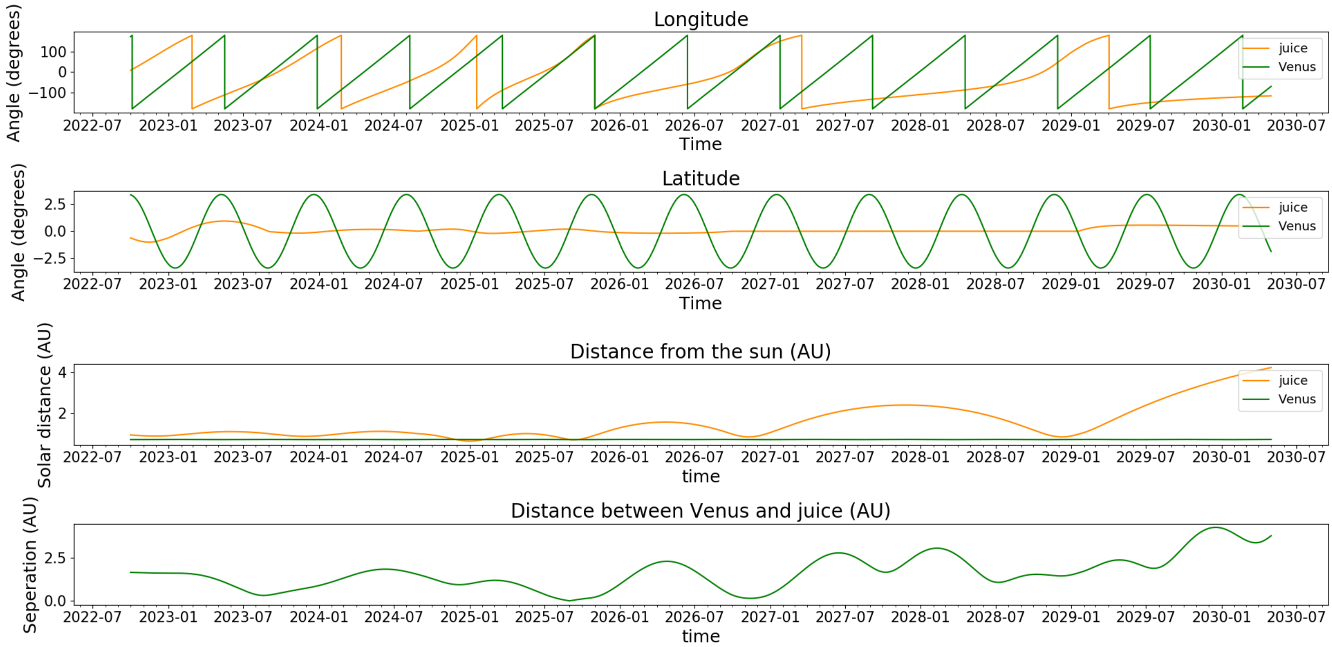


Figure 5.7: Juice and Venus.

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