MVSE

Magnetospheric Venus Space Explorers: A Proposal for Understanding the Plasma Environment of Induced Magnetospheres by Multi-Point Observations

Roland Albers, Henrik Andrews, Claire Baskevitch, Gabriele Boccacci, Francesca Covella, Luca Cressa, Juan Garrido Moreno, Joshua Hollowood, Eva Krämer, Sunny Laddha, Adel Malatinszky, Nadim Maraqten, Daiana Maria Alessandra Nidelea, Luca Rigon

Science tutor: Elise Wright Knutsen *Engineering tutor:* Christian Gritzner

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Abstract

The dynamics of induced magnetospheres raise several unsolved questions. Among the most pressing are the interaction between the solar wind and induced magnetospheres, and the variation in heating processes. The Magnetospheric Venus Space Explorers (MVSE) mission is a proposal aiming to fill the gap in understanding magnetospheric phenomena by studying the magnetosphere around Venus. MVSE is a multi-spacecraft mission, that complements previous mission to Venus, including the Pioneer Venus Orbiter (PVO) and Venus Express (VEX), and will greatly improve our understanding of induced magnetospheres due to tailored instrumented satellites on prescribed orbits around Venus. It comprises a four-satellite formation that perform magnetic field, electric field, and ion-electron distribution function measurements. The greatest advantage of the MVSE mission over prior missions on Venus is the ability to perform multi-point measurements of Venus' magnetosphere to further understand its dynamics.

Three satellites comprising the MVSE mission are designed for scientific objectives. The aimed mission lifetime is of three years. Two of the scientific satellites orbit in a circular orbit, with a period of 11.47 hours and phase angle of 180°relative to each other. The third scientific satellite has an elliptical orbit with a period of 5.96 hours. After operating as the transfer vehicle, the satellite keeps operating in the circular orbit used as a relay satellite for communications. The instruments onboard the satellites are state-of-the-art instruments for measuring the quantities of interest.

1 Introduction

Plasma is one of the four states of matter, comprising of electrons and ions. The outward expansion of plasma from the Sun's corona results in the creation of the solar wind. Solar system bodies with a dynamo effect, such as the Earth, have an intrinsic magnetosphere, whereas unmagnetised solar system bodies, like Venus and Mars, have an induced magnetosphere. Induced magnetospheres form when the solar wind interacts with the ionosphere of unmagnetised solar system bodies. Venus' magnetosphere has been studied but its dynamics and the details of its relationship with the variable solar wind still raise open questions in the scientific community.

1.1 Scientific Background and Past Missions

Venus completes one full rotation on its axis every 243 Earth days, making Venus almost tidally locked to the Sun. The radius of Venus is 6050 km (0.95R_E) and despite its similar size and position in the solar system, Venus has major differences from Earth. Venus' atmosphere is approximately 100 times denser than Earth's atmosphere and surface temperatures are 715 K (over 400 K hotter than the Earth's surface) [1]. Unlike Earth, where the magnetosphere is formed by its intrinsic magnetic field, Venus has an induced magnetosphere, generated by the interaction of the solar wind with Venus' ionosphere.

Like Venus, Mars also has an induced magnetosphere, but with a distinction; it also has localised regions of magnetised regolith [2]. The Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft has mapped Mars' induced magnetosphere. One key finding from MAVEN was the discovery that Mars' magnetic tail was tangled [3]. Venus has also been the subject of studies by several spacecraft since Mariner 2 first visited in 1962. Missions of note include the 14-year long Pioneer Venus Orbiter (PVO) mission (1978-1992) and more recently the Venus Express (VEX) mission (2006-2014) [4]. These two missions provided many insights into the evolution of planetary atmospheres and their escape processes [5]. PVO and VEX have also provided information on the processes governing induced magnetospheres. Measurements of Venus' bow shock have found the standoff distance bow shock orbit varies between $1.364 - 1.459\,\mathrm{R_V}$ [5], and the larger distance is typically found during the maximum of the solar cycle [5].

1.2 Current and Future Missions

There are currently missions exploring Venus and upcoming missions have been announced to study Earth's closest neighbor. Akatsuki is a current mission launched by The Japanese Aerospace Exploration Agency (JAXA) in 2010, primarily investigating Venus' atmosphere with the goal of understanding the Venusian atmospheric dynamics and cloud physics [**Nakamura˙2007**]. Current missions including Solar Oribter, the Parker Solar Probe, and BepiColombo have performed flybys of Venus. The solar orbiter flyby found that Venus' magnetotail was very active, and found evidence for flux rope structures and reconnection sites [6],[7]. However, due to only having one spacecraft, someone is yet to perform multi-point observations of Venus' induced magnetosphere.
Upcoming missions to Venus include EnVision, planned by the European Space Agency (ESA), as well as DAVINCI+ and VERITAS, which are being planned by The National Aeronautics and Space Administration (NASA). EnVision is dedicated to characterising the interactions between Venus' atmosphere, surface, and interior. DAVINCI+ will measure the composition of Venus' atmosphere and VERITAS has the primary goal of searching for evidence of past or present water in Venus' surface and interior.

Crucially, none of these three missions have the objective of investigating Venus' magnetosphere. Understanding the plasma environment of induced magnetospheres through multi-point observations provides a reference for future studies of comets and other bodies lacking a magnetic field. In addition, the intrinsic field of the Earth can weaken during magnet field reversals, which occur approximately every 450,000 years [8]. Venus can then serve as a laboratory for fundamental plasma processes, and could help understand what happens around planets with a diminishing intrinsic field during magnetic polarity reversals.

1.3 Scientific Return

One of the major discoveries of the PVO mission is that the nightside ionosphere becomes filamentary at high altitudes, forming comet-like tail rays [9]. However, PVO could not establish how far tail rays extend into the wake of Venus, nor constrain how they form. Owing to its different orbit from that of PVO, VEX made unique measurements in the polar and terminator regions, and probed the near-Venus tail for the first time [10]. The near-tail hosts dynamic processes that lead to plasma energisation, which itself leads to the loss of ionospheric ions to space and so, the slow erosion of the Venusian atmosphere over time [11].

The PVO and VEX missions had low energy and angular resolutions, as well as low temporal resolutions for their plasma instruments where the distribution functions were probed on a scale of minutes [12]. Also, since VEX did not have a electromagnetic cleanliness (EMC) program on board, its magnetic field measurements were very limited [13],[14]. A multi-point mission, with a higher-resolution instrument array, optimised to study Venus' magnetosphere therefore enhances the understanding of dynamic processes in Venus' induced magnetosphere. The knowledge gained from such measurements helps in our understanding of planetary evolution and illuminates the differences in magnetospheric impact from intrinsic to induced. In addition, the results give insight into mangnetotails behind other objects in the solar system such as comets.

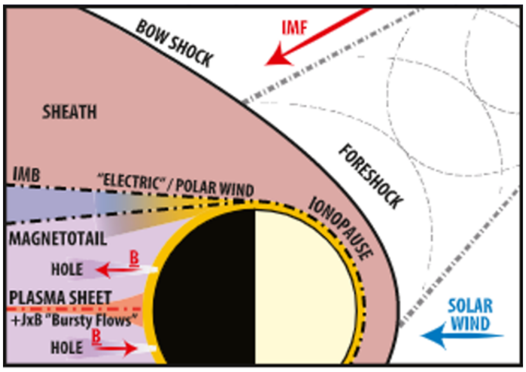

Figure 1: Conceptual sketch of the Venusian magnetotail based on VEX observations. [9]

1.4 Proposed Mission

The Magnetospheric Venus Space Explorers (MVSE) mission complements the upcoming missions designed by NASA and ESA and will provide a greater holistic view of Venus, from its interior up to its magnetosphere. MVSE aims to measure the dynamics of the magnetosphere due to the variable solar wind, both downstream of the bow shock and in the magnetotail. Such measurements help understand sectorial boundary crossings, how reconnections function, and the dynamics of ion heating and acceleration through wave-particle interactions [11]. In addition, MVSE probes how magnetospheric dynamics respond to high energy solar eruptive events, such as interplanetary coronal mass ejections (ICMEs) and solar flares. To provide the measurements required to resolve these topics sufficiently, this novel mission includes four spacecraft, one in an elliptical orbit with a pericythe of 1.17 Rv and an apocythe of 4 R_V, and three science spacecraft in a circular orbit, with $r = 4R_V$ around Venus, and a fourth transport/communications module in the same circular orbit.

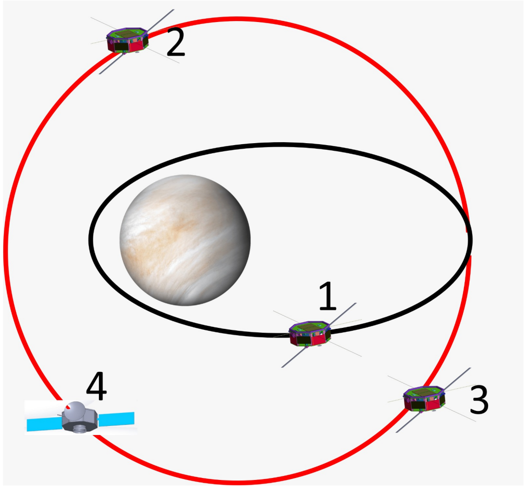

Figure 2: Sketch of the chosen regions in which the MSVE-spacecrafts shall be situated around Venus. 1,2 and 3 are the scientific s/c, 4 is the transfer vehicle; this one will also be situated in the same orbit of s/c 2 and 3.

Unlike the previous plasma missions, which all performed single-point, static measurements of Venus' dynamic plasma environment, the MVSE mission is the first to provide simultaneous multi-point observations of Venus' magnetosphere. The optimal constellation for those observations can be obtained by collecting simultaneous measurements with one satellite situated upstream of the bow shock, monitoring and measuring the incoming solar winds, one satellite inside the so-called stagnation region, a barely explored region situated in between the bow shock boundaries and Venus' outer ionosphere [15], and the last one in the outer magnetotail. Since the effects of the inter-planetary magnetic field (IMF) on Venus' near plasma environment last for only a few hours [16], it is essential to have measuring probes in the regions of interest within these time spans. By putting two satellites in an approximate 180°-phase difference between each other onto an outer circular orbit (covering the upstream point and the outer magnetotail) and the third one in a closer elliptical orbit (with approximately half the period of the circular orbit, passing through the stagnation region close to Venus), the previously mentioned requirements can be fulfilled. The two-hour span allows valid measurements without having a perfect alignment of the three satellites. A representation of this configuration is shown in Fig.2.

2 Science

2.1 Science Questions and Objectives

The goal of the MVSE mission is to answer the following question: **How does the sun drive the dynamics of an induced magnetosphere?**

In order to answer this question it is necessary to make the following observations:

- SO 1 Observe the reactions of an induced magnetosphere (MS) to the variations of the solar wind (SW) conditions
  - SO 1.1 Change of magnetosphere structure
  - SO 1.2 Variation of heating process
- SO 2 Observe the reactions of an induced magnetosphere to solar eruptive events such as interplanetary Coronal Mass Ejections (ICMEs), Corotating Interaction Region (CIR), and Solar Flares

2.2 Scientific measurement and instrument requirements

The above stated science objectives result in measurement requirements for observation, location and timing. The scientific measurement requirements and instrument performances which follow from the objectives are listed in this section.

- SR 1 Measure the 3D magnetic field with an accuracy of 0.1 nT for each component and frequencies going from DC to 2 kHz in order to resolve electromagnetic plasma waves. The instrument has to be able to determine values in a range of ±600 nT.
- SR 2 Measure at least two electric field components in a range of $\pm 100\,\mathrm{mV\,m^{-1}}$ at once with a high enough frequency to resolve plasma oscillations. A resolution of $0.1\,\mathrm{mV\,m^{-1}}$ per component is needed for such measurements.
- SR 3 Measure ion and electron distribution with a 4s - time resolution to resolve plasma waves affecting the plasma moments. The distribution requires a 360°- field of view and a resolution of $11.25° \times 22.5° \times 0.2$ (res. azimuth × res. polar × $\Delta E/E$).
- SR 4 Measure the ion composition to resolve the most common pickup ions from Venus' atmosphere. This requires a mass spectrometer capable of resolving the masses of H, He, O and C ions.

SR 5 Location of the spacecraft: as already mentioned in section 1.4, the s/c have to be assigned onto specific locations: One s/c at a distance larger than $1.7R_V$ observing the solar wind (P1), one s/c observing the dayside downstream of the bow shock at a distance larger than $1.3R_V$ from Venus (P2), and the last s/c observing the magnetotail in the region between $3R_V$ and $5R_V$ behind the planet.

SR 6 All s/c need to fullfill SR 5 for long enough in order to measure the reactions to solar wind changes in the magnetotail. This ideal constellation should appear at least for one hour continuously and at least once every 24 hours.

SR 7 The mission has to last long enough in order to observe enough ICME events while having an appropriate alignment of all three s/c. Hence, the mission shall observe at least 10 CME events; in order to ensure this requirement, the mission shall last at least for three years.

3 Payload

To meet the science objectives and derived requirements, the payload consists of the following instruments:

- **Fluxgate magnetometer (FGM)**: needed to measure the magnetic field in a range of $\pm 2\,\mathrm{mT}$, with a resolution of $2\,\mathrm{pT}$, and a time resolution of $128\,\mathrm{Hz}$;
- **Search coil magnetometer (SCM)**: measures the magnetic field with a range of $\pm 5\,\mathrm{nT}$, resolution of $0.15\,\mathrm{pT}$, and a time resolution up to $6\,\mathrm{kHz}$;
- **Spin-Plane Double Probe (SDP)**: measures the electric field in a range of $\pm 500\,\mathrm{mV\,m^{-1}}$, with a resolution of $0.05\,\mathrm{mV\,m^{-1}}$, and a time resolution of $32\,\mathrm{kHz}$;
- **Electrostatic Analyzer (ESA)**: measures the ion and electron distributions with a time resolution of $0.25\,\mathrm{Hz}$. The ion distribution is measured between $1.6\,\mathrm{eV}$ and $50\,\mathrm{keV}$, with a polar and azimuthal resolution of $11.25°$, and energy resolution $\Delta E/E = 17\,\%$. The electron distribution is measured between $2\,\mathrm{eV}$ and $32\,\mathrm{keV}$, with a polar resolution of $22.5°$, azimuthal resolution of $11.25°$, and energy resolution $\Delta E/E = 18\,\%$;
- **Mass Spectrum Analyzer (MSA)**: measures the ion composition in the range $1\,\mathrm{eV/q}$ - $38\,\mathrm{keV/q}$, with a mass resolution $(\Delta m/m) = 40$, and a time resolution of $0.125\,\mathrm{Hz}$.
- **Active Spacecraft Potential Control (ASPOC)**: this instrument is supposed to control the spacecraft's potential with respect to the ambient plasma, by cancelling out eventual electric fields generated through photoionization of the spacecraft.

Details about mass, power, data rate, and the heritage of the single instruments can be found in Table 1. The data rates are too high to be downlinked and so, only averaged data is downlinked for the regions of interest and only certain events are downlinked with the full time resolution.

4 Spacecraft Design

4.1 Spacecraft Architecture

The selected spacecraft formation involves two different types of spacecraft. Three science spacecraft perform in-situ plasma measurements. A transfer vehicle provides the orbit transfer and also acts as intermediate communication relay with the ground segment. The octagonal science spacecraft are spin-stabilised. The configuration trade-off has converged on this solution over the three-axis-stabilised configuration according to the following reasons:

- To provide complete 360° azimuthal coverage to any instrument pointed radially outwards.
- To Enable deployment of long-distance wire booms.

The planned layout has been preserved for continuity in spacecraft staggering for the launch configuration. Three-axis-stabilisation is required to enable precise pointing of the high-gain antenna with the ground communications segment.

4.2 Structure and Mechanisms

4.2.1 Science Spacecraft

The load bearing structure of the science spacecraft consists of an octagonal truss structure with aluminium honeycomb panels for instrument and solar panel mounting. Most of the load of the structure will go through the axis of rotation due to the stacking of the spacecraft during launch. The payload bay is located under the top face of the spacecraft. Solar panels cover the side panels of the spacecraft.

4.2.2 Transfer Vehicle / Relay

The structure of the transfer vehicle is of the same identical octagonal shape as the science spacecraft. Instead of a payload bay, the truss structure contains the propellant tanks needed for the main engine, along with the communications infrastructure to use for the relay high gain antenna.

Instrument	m(kg)	P(W)	datarate (kb/s)	heritage
FGM	2.5	5.7	13	BepiColombo [17]
SCM	0.42	0.13	400	MMS [18]
SDP	4.3	0.4	400	MMS [19]
ESA	1.6	2.5	12.3	THEMIS [20]
MSA	4.46	9.1	20	BepiColombo
ASPOC	1.9	2.7	0.1	Cluster [21]
Total [22]	28	21.7	≈ 830	

Table 1: The mass, power and estimates for the data rates for the planned instruments on all three science spacecraft. The estimated data rate is when the space craft is in burst mode.

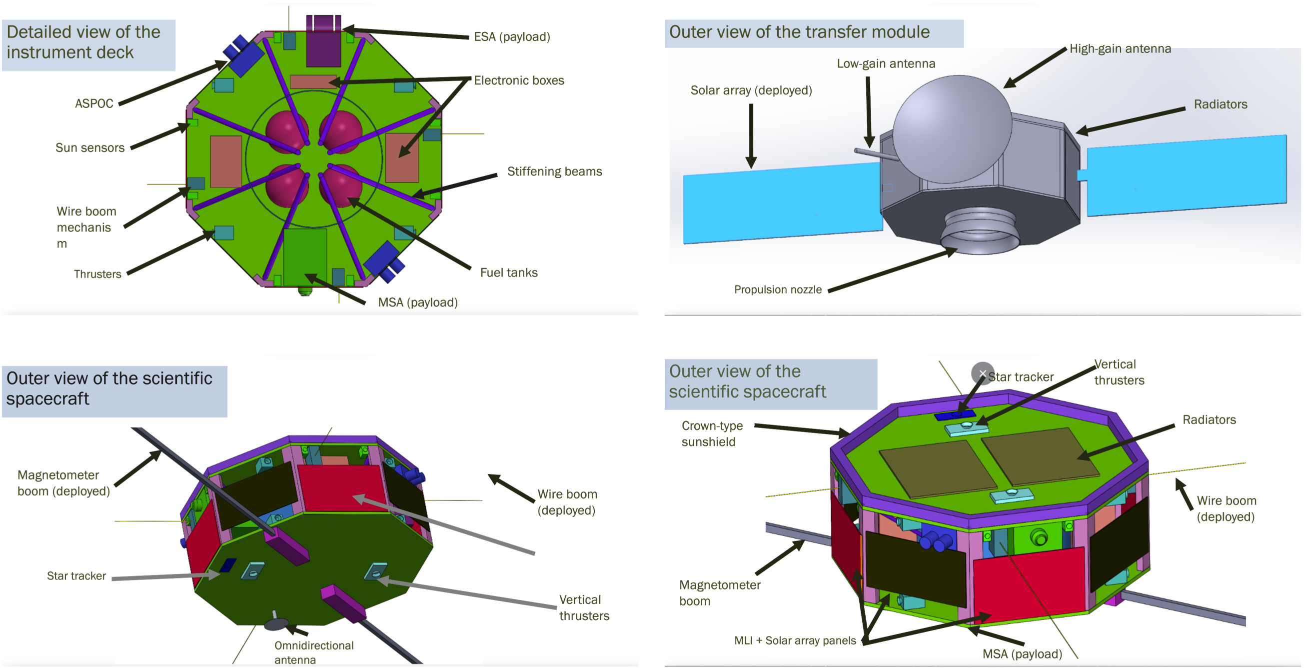

Figure 3: Spacecraft configurations when deployed in desired orbit.

	Mass (kg)	Margin
Payload	29.48	5%
Structure and Mechanisms	44.88	20%
Thermal Control	24	20%
Power	22.66	10%
Comms	5.50	20%
On-board Computer	2.64	10%
AOCS	9.60	20%
Propulsion	n/a	n/a
Total	166.52kg	20%

(a) Mass budget - science spacecraft

	Mass (kg)	Margin
Payload	n/a	n/a
Structure and Mechanisms	48	20%
Thermal Control	20	10%
Power	19.6	10%
Comms	36	20%
On-board Computer	2.6	10%
AOCS	9.9	10%
Propulsion	63.8	10%
Total	242.6kg	20%

(b) Dry mass budget - transfer vehicle

4.3 Spacecraft Separation Mechanism

The three science spacecraft and the transfer vehicle are connected via standard adaptors until separation at Venus. The transfer vehicle is connected to the Ariane 62 launcher via a standard launch adaptor of the same diameter.

4.4 Thermal

During the MVSE mission, the spacecraft are subject to contrasting temperature environments, from the cold environment experienced during transfer orbit, to the hot environment of daytime Venusian orbit.The worst case temperature range is estimated to be: 120 K to 595 K. The temperature of the surface of the spacecraft oscillates in this range, never reaching the maximum and minimum temperatures. To sustain this, a combination of passive and active thermal control has been designed:

- Passive control: A radiator with surface area 0.5 m^2, optical solar reflectors, and multi-layer insulation (MLI) behind the solar panels provide sufficient insulation.
- Active control: Active heaters, used to maintain the internal temperature constraints, compensate for the cooling driven by the insulators.

4.5 Radiation

The radiative environment in the orbit is dominated by two main types of radiation:

- Solar rays: Their energy ranges around 10MeV. They are time localized, do not last long, but present a maxima during each solar cycle. These are the main source of radiation.
- Galactic cosmic rays: Their energy ranges from 10MeV to 1GeV, and they are mainly present at solar minimum. Since magnetic fields shield against them, their effect will not be predominant.

The MLI layer will serve also as radiation protection from solar rays, in the places of the satellite where there are no solar panels.

4.6 Propulsion and AOCS

The Δv is provided by a bipropellant (MMH/NTO) system that provides an ISP of $\sim$ 320 s. The fuel mass of $\sim$ 930 kg (incl. 15% margin), which is required for all orbit manoeuvers of the transfer vehicle, is stored in 4 spherical tanks. The estimated total dry mass of the propulsion system is 70 kg (incl. 20% margin).

The Attitude and Orbit Control Subsystem (AOCS) of the 3-axis stabilized transfer vehicle is driven by the pointing requirements mainly derived from telemetry and communication. The technical solution encompasses 3 star trackers, 12 sun sensors, and 2 Intertial Measurement Units (IMUs) for attitude determination. These are accompanied by 12 thrusters and 4 reaction wheels as actuators. The spin-stabilized science spacecraft require precise altitude determination to fulfill the science requirements and thus carry 2 star trackers, 3 sun sensors and 2 IMUs. 12 thrusters and nutation-damping components allow for correction manoeuvers and stabilization.

4.7 Power

Onboard secondary batteries were baselined for an eclipse time of 4 hours at peak power, which is a worst case estimate, given an elliptical orbit of 6 hours. Using lithium sulfur cells with a specific power of 152Wh/kg results in a battery mass of 5.5kg. Depth of discharge and life cycles were not considered but are covered in the overerstimation of the eclipse time. Following the same logic for the transfer vehicle, its required battery mass is 12kg.

Since the science spacecraft is continuously rotating, the simplest configuration for the solar panels is to mount them directly on the sides of the octagonal structure. However, only half of the spacecraft is facing the sun at any point, which needs to be kept in mind for solar panel sizing. Taking into account the solar constant at Venus (2652W/m2), a solar panel efficiency of 30%, and a degradation of 10% per year, the science spacecraft requires a solar panel area of 0.89m2 for a end of life performance of 8 years. Taking into account that the batteries need re-charging during time out of the eclipse, the final solar panel size is 1.34m2 required for power generation. Equipping each side of the octagon with 50% of the required solar panel area, ensures more than enough power production for any viewing angle with contingency. In total, this means there are 5.4m2 of solar panels on the spacecraft with a total mass 15.1kg. For the transfer vehicle, since it won't be rotating during times of maximum power needs e.g. data bursts to Earth, the solar panels can be mounted in a wing configuration at the sides. Although the solar constant at Earth (1375W/m2) is much less than at Venus, the end of life (EOL) performance at Venus still drives the solar panel size of 2.07m2 and a mass of 5.8kg due to degradation.

4.8 Telecommunication / Link Budget

The telecommunication concept comprises a bi-directional communication of all science spacecraft with the transfer stage. Main purpose is to transmit the scientific data to the transfer stage (”inter-spacecraft communication”). The transfer stage communication concept is also bi-directional. The transfer stage will send all the scientific data which is stored in a data storage to the ground stations on Earth and may receive commands from ground ("Interplanetary communication").

4.8.1 Interplanetary Communication

The communications relay is equipped with a 2m diameter high gain antenna which has an effective isotropic radiated power of 65dB using 200W transmitter power. Using the deep space network, a downlink rate of 13.34Gb/h is assessed sufficient to download two days of science data in just over an hour. If some instruments require higher data volumes due to burst modes, some data compression and filtering might be needed.

4.9 Operational Modes

The transfer vehicle has the following operational modes: Manoeuver mode ⟶ Coasting mode ⟶ Deployment mode ⟶ Relay mode. In manoeuver mode, the transfer vehicle's rotational axis is aligned with the required thrust vector to enable orbital manoeuvers. The solar panels are orientated to facilitate a minimum power production (on board computer only - no comms). After the manoeuvers, the coasting mode is activated which puts the spacecraft in a slow spin to reduce thermal gradients. This affects power generation. However, power needs are minimal (no comms). During deployment mode, the transfer vehicle orientates its spin axis perpendicular to the ecliptic and initiates a small spin (5 RPM) for a spin stabilised release of a science spacecraft. Whenever Earth communication is necessary (e.g. during transfer or after science spacecraft deployment), the transfer vehicle needs to be 3-axis stabilised with the articulated high gain antenna orientated towards Earth for data dumps or correction commands of the stack during transfer. In this mode it is critical that the solar panels are positioned for maximum power generation.
The science spacecraft have the following operational modes: Standby mode (Launch) → Commissioning mode (Deployment) → Science Mode → Transmit mode → Safety mode. In standby mode all instruments are powered down and the spacecraft is supplied with power from the transfer vehicle. Commissioning mode is activated when the spacecraft is released from the stack and consists of detumbling (if needed), spin up, boom deployment, and a functional health check of the entire spacecraft. Science mode is activated during the relevant parts of the orbits (dayside, bowshock, magnetotail). The spacecraft uses the most power during this time and records measurements to its local data storage. Transmit mode is activated after the science relevant sections of the orbit to transmit the data to the transfer relay. Transmission needs to occur separately since the sensitive magnetic and electric field measurements would be affected by the antenna signal. The interspacecraft comms system is sized to allow full upload of data generated during one orbit.

5 Mission Analysis

5.1 Launcher selection

Arianespace provides two models of the Ariane 6 rocket: 62 and 64. To perform a selection, it is necessary to consider the launch costs (higher for 64) and maximum payload mass they can bring on-orbit. The spacecraft stack plus adapters have a total (wet) mass of 1672 kg, that is lower than the maximum payload mass of 62: 1800 kg. Hence, the more cost-effective Ariane 62 configuration was selected.

5.2 Transfer Vehicle Propellant

The transfer vehicle, as already stated before, carries all the propellant necessary for the manouvers. The fuel used is MMH, while the oxydizer is N_2O_4. Their combination is a hypergolic mixture, thus providing a high I_{sp} of 336 s.

5.3 Mission Phases

The mission consists of three spacecraft that perform science and a transfer vehicle, used for the most transfer, and then employed for communications.

The trajectory can be broken down in five phases:

1. Escape and interplanetary transfer. The first part of the transfer is accomplished by the launcher (Ariane62). The launcher inserts the spacecraft into an elliptical interplanetary trajectory to Venus (Hohmann-type manouver). An optimisation study was performed to select a launch window minimizing the total delta-v for the Lambert problem. Results show that the optimal launch date is 6/12/32 with $C_3 = 10.09 m^2/s^2$.

2. Minor deep space correction manoeuver. 15 days after launch a small correction manoeuver of 0.17 m/s is necessary to place the spacecraft at the desired pericenter distance from Venus.

3. Orbit Insertion. After 157 days from the launch day a capture manoeuver is performed at a pericenter height of $900km$ from Venus' surface. The spacecraft is inserted into an elliptical orbit with a periapsis of $r_p = 6952km$ and an apoapsis of $r_a = 24052km$, as seen in 5. The Δv necessary for the manoeuvre is $1.53km/s$.

4. Circularization Just before performing this manouver one satellite is detached, then at the apoapsis of the elliptical orbit an impulsive manouver is performed to place the two spacectafts and the TV into a circular orbit, with $R = r_a$, as shown in 5. The cost for the manoeuvre is $1.2km/s$.

5. Minor Phasing manouvers. In the circular orbit a small manouver is performed to lower the semi-major axis, just after the second satellite is detached. The third satellite and the TV are placed into a slight elliptical orbit, whose period is shorter and is a multiple of

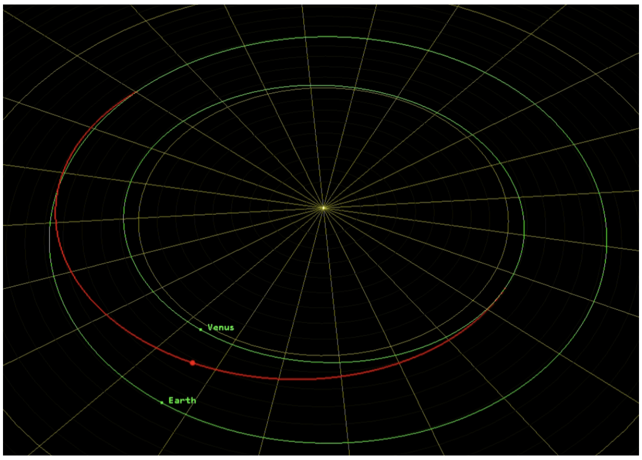

Figure 4: Trajectory from Earth to Venus (red).

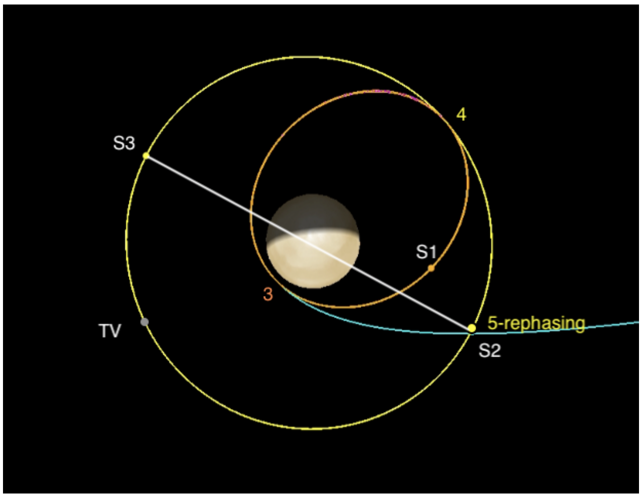

Figure 5: Trajectory of the spacecraft around Venus. Interplanetary phase (blue), with injection at the periapsis of the elliptical orbit (orange) around Venus, with one spacecraft, and circular orbit (yellow) followed by two spacecraft and by the transfer vehicle (TV).

the period of the circular orbit. After a few revolutions a phase displacement of π is achieved and the same impulsive manouver is performed to increase the specific energy of the orbit and insert the third spacecraft in the circular orbit. The same is performed for the TV, but in this case the phase angle is smaller and there is not a strict constrain on that.

A final remark is that once the satellites are placed in their orbit some maintenance must be performed in order to fight perturbations. Around Venus the main perturbative action is due to the solar radiation pressure. An estimate of $20 m/s$ was considered every year for such maintenance.

6 Project Envelope

To reduce development time and cost, the design of the spacecraft builds on the BepiColombo mission, more precisely on the Magnetospheric Mutliscale (MMS) and Mercury Magnetospheric Orbiter (MMO) spacecrafts. The transfer stage is optimized in parallel to satisfy the specific requirements, and the instrument payload combines state-of-the-art technology, requiring only minimal customization. Thus, the development phase can be planned to finish in time for the next ideal launch window in 10 years.

6.1 Schedule

The mission development phase is nine years before launch in 2032, when the optimal orbit window opens. This time allows for further development of the orbits, engineering requirements, manufacturing, and maturing of instruments to be well suited to the Venus environment. After launch, there's half a year until deployment around Venus, and the mission can begin once the constellation is in place. MVSE obtains valuable data over three years and extensions can be made based on satellite degradation.

6.2 Risk

A key risk to the mission is the failure of the separation mechanisms that hold the science spacecraft stack. A separation failure during the first deployment would mean the end of the mission. To prevent this, proven separation concepts and hardware should be used to keep the likelihood as remote as possible. If a science satellite fails after deployment, the mission can continue with a reduced science performance. Should the communications link from the transfer satellite to Earth fail it would also mean the end of the mission. To mitigate this, redundancy in the electronics, AOCS etc. is included.

6.3 Further Development

The mission study presents one feasible orbit configuration to fulfill the science case, based on expert input. The exact orbit configuration and relevant manoeuvers can be further optimised and discussed in collaboration with scientists. One possible orbital configuration to explore would be two elliptical orbits at 90 degrees to each other, which could still satisfy the upstream, bowshock, and magnetotail measurements.

6.4 Cost and Descoping Options

Table 5 shows a subsystem-level cost breakdown for the MVSE mission. In accordance with this breakdown, which is only a rough estimate (”expert guess”) of what the values could be, the three-year mission plan costs approximately 1 billion euros (FY2022). A five-year extension in the lifetime could be possible, allowing the induced magnetosphere to be monitored through half a solar cycle. In terms of running mission costs, an estimate of 10 million euros per year would add 50 million euros to the final budget. Thus, the MVSE mission classifies as an L-class, which is standard for inter-planetary missions. Some de-scoping options are also available in case the cost reduction becomes a critical requirement for the implementation of the mission.

With the reduction by one science spacecraft, the main de-scoping option affects the mission on a top level. The main science objectives can still be satisfied formally with one science spacecraft in circular orbit and one in the elliptical. However, the compromise in the scientific gain has to be considered. Moreover, the lack of a conceptual redundancy also poses a risk for the full achievement of the science goals. In such a case, the consequences can be mitigated by extending the mission duration to increase the collected data. Alternative descoping options on a smaller level are the exemption of scientific instruments, specifically the ASPOC and the mass spectrometer. However, this would disable measurements on the lowest electron energy scales and diminish the knowledge of magnetosphere-ionosphere interaction.

6.5 End of mission

The spacecraft will be moved in a stable end-of-life orbit after the mission ends.

Cost breakdown (M€)	
Industrial costs	510
Internal costs ESA (25%)	128
Mission Operations	120
Subtotal	**758**
20% contingency	152
Launcher (Ariane 62)	90
Total	**1000**

Table 5: Cost breakdown evaluation (FY2022)

6.6 Outreach

MVSE is a public mission, therefore a public campaign is in place to provide information about the current mission status. Scientific results will be prepared in such a way that is suitable for the general public. Furthermore, there’s a focus on encouraging women in science to support this mission to increase the overall interest of females in science which are still underrepresented in most Science, Technology, Engineering, and Mathematics (STEM) topics. The design of our mission logo is based on the female gender symbol, which is also a homage to Roman goddess Venus, and we hope this encourages women to to take an interest in MVSE.

7 Conclusion

A constellation of three spin-stabilised scientific spacecraft plus one transfer stage is proposed. The latter acts as communication relay after delivering the scientific spacecraft into their target orbits. In order to collect in-situ solar wind measurements up- and downstream of the bow shock as well as in the magnetotail, two orbits are chosen. One spacecraft is in an elliptical orbit while the other two spacecraft are in a circular orbit with the same apocythe. This constellation is proposed to answer pressing questions regarding the character of Venus’ induced magnetospheres. MVSE provides a large volume of high resolution data to fill knowledge gaps surrounding the dynamics in induced magnetospheres. MVSE builds up upon previous NASA and ESA missions, while complementing the upcoming missions. It increases our understanding of the magnetospheres of comets and Earth’s plasma environment when the magnetic field is weakened.

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