Aphrodite Mission

Green Team, Summerschool Alpbach 2014

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Abstract

The Aphrodite mission aims to understand why Venus differs from Earth on so many aspects even though they have similar mass, volume and distance to the Sun. Differences are found in geology, lack of magnetic field, slow spin rate and dense, hot atmomsphere. The objectives of the mission is observing the atmospheric effects of volcanic activity, evidence of past activity, variations in the spin rate and how this is correlated with activity in the atmosphere. Aphrodite will achieve these objectives with an orbiter and an in situ balloon. In orbit infrared spectroscopy and ground penetrating radar, in situ acoustic, optical IR and mass spectrometer measurements. Passive surface reflectors will be used to determine the spin rate. The mission duration of three years will allow for detection of periodic variations of Venus' nature and not just current status. Aerobraking is used to reduce fuel requirements, permitting a Kourou Soyuz launch, for a total cost under one billion euros.

1 Introduction

With its similarity in mass and radius, Venus is often called Earth's twin, but there are substantial differences between the two:

- Venus lacks an intrinsic magnetic field
- It rotates more than 240 times more slowly than Earth and in a retrograde sense
- Earth has active volcanoes related to plate tectonics, Venus has only hot spot volcanism
- Venus has no water oceans but a hot, dense atmosphere

The Aphrodite Mission proposes an investigation of the differences in spin rate and assess the level of tectonic and volcanic activity at Venus.

2 Scientific Objectives

2.1 Tectonic & Volcanic Activity

2.1.1 Evidence for Past Activity

There are two competing theories for explaining volcanic and tectonic activity on Venus: episodic catastrophic resurfacing, which predicts planetary-scale lava flows hundreds of metres thick, and equilibrium resurfacing which predicts local interleaved volcanic flows 30 m thick. Determining flow thicknesses will distinguish between these two predictions and so resolve its resurfacing history. Observations of faults, wrinkle ridges and other features in the third dimension will also help determine the nature of past tectonic activity on Venus

2.1.2 Current Activity and Evolution

Geologically recently active hot spots were identified in the southern hemisphere of Venus from VIRTIS images on ESA's Venus Express [1], which measured variations in thermal emissivity of the surface. Possible volcanic activity during the Venus Express mission was also inferred at the Ganiki Chasma rift zone from near-infrared night-time observations with the Venus Monitoring Camera [2]. Global IR monitoring is essential to determine the current rate of volcanic activity at Venus.

Chemical and isotopic measurements of the atmosphere above, through and below the cloud layer which could constrain the present-day input of volcanic gases into the Venus atmosphere. A global decrease in SO_2 on decadal scales was observed in the atmosphere above the clouds by the Pioneer Venus Orbiter [3], perhaps resulting from the exponential decay of volcanic SO_2 prior to the arrival of the spacecraft. Improved measurements of H_2O [4] and SO_2 [3], as well as the isotopic ratios of D/H [5], $^{16}O/^{18}O$ [6] and $^{32}S/^{34}S$, will reveal the sources, reservoirs and sinks of these important volcanic gases.

The lowest cloud layer, at about 45 km above the surface, may consist of volcanic ash [7]. Measurement of this ash layer might demonstrate that explosive eruptions occur on Venus, implying that its lack of oceans may not be an intrinsic feature. In order to study the nature of this layer, the particle sizes of volcanic ash / dust will be looked for. This will help to distinguish between H_2SO_4 aerosols [8] measured chemically.

The Earth's interior is known to be seismically coupled with the atmosphere [9]. Acoustic waves generated by Rayleigh surface waves have been observed in earthquakes [10]. On Venus quakes with the same magnitude will have infrasound waves with amplitudes 600 times larger than recorded on Earth at the same height. This is due to the different atmospheric pressure and density conditions of the planets. Wave disturbances in the atmosphere can be triggered by convection or horizontal flow passing an obstacle, but also by volcanic eruptions. On Venus gravity waves manifest themselves as regular cloud structures or quasi-periodic disturbances on the atmospheric temperature profiles [11].

2.2 Spin Rate & Direction

2.2.1 Spin variability

Deviations of reference points on Venus as measured by Venus Express compared to the Magellan predicted locations show a change in rotational period of 6.5 minutes after 16 years [12]. Furthermore Magellan determined three different spin rates within three years [13]. The cause for this change is still largely unknown. It appears as if a periodic function can be fitted to these datapoints. The mission will try to confirm this periodicity, and if achieved, confirm its period and amplitude, and look for what might cause this.

2.2.2 Atmospheric influence

Due to the high density of Venus' atmosphere, it may exert substantial tidal and frictional forces on the planets body, giving a torque to its rotation. By measuring temperature, wind speeds and pressure of the atmosphere and accurately determining the planet's spin rate over time, we hope to find a correlation between global circulation models, and Venus' spin rate and variability, thereby maybe finding a correlation between processes in the atmosphere and the interior of the planet if there indeed is one.

Furthermore, Venus might be used as the only „laboratory planet" in the Solar System where we can study the correlation between geological processes and atmosphere. This may provide us with an indicator of geological activity on other „exo-Earths" in the case of the exoplanets where we can only measure the atmosphere.

3 Scientific Requirements

Scientific Requirement		**sensitivity**
Surface topography & Subsurface features	Vertical resolution: 10m Penetration depth: > 100m	
Thermal signature	Smallest volcano: 2km	0.1K
Physical parameters	Wavelength (gravity wave): 2-20km Wavelength (acoustic wave): 4.3 µm	
Chemical composition	Aerosols: range: 0.1 - 10 µm	
	Gas & Isotope species:	0.1 µm
	H_2O = 30ppm (1-4ppm in the clouds)	
	SO_2 =150ppm	< 5%
	D/H = 0.016±0.002	< 10%
	$^{16}O/^{18}O$ = 500 ± 80	< 1%
	$^{32}S/^{34}S$ = n.n.	< 0.1%
		<0.2%

Spin rate determination & variability over mission	Spin rate Acceleration range: $0.01 m/s^2$	Venus day + -10sec $< 10^{-5} m/s^2$
Atmospheric conditions	Pressure range: 0.1-100bar	0.1 bar
	Temperature range: 150-750K	1K
	Wind Speed range: 0-800km/h	1km/h

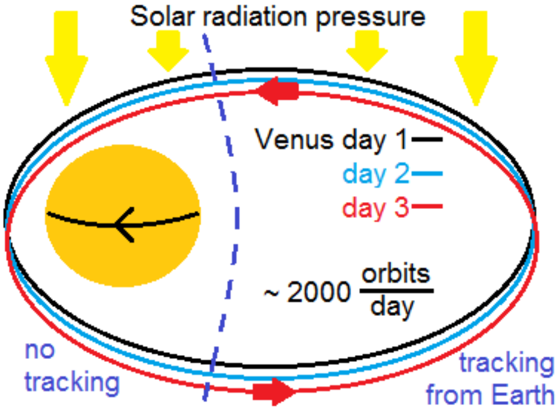
4 Payload

Instrument	**Scientific Requirement**	**Accuracy**	
Hephaestos Orbiter			
Spectral Imager	Measurement of temperature on surface and the imprint of acoustic and gravity waves in the atmosphere.	spectral	3 nm (VIS) 15 nm (IR)
		spacial	1 mrad
Submillimeter Sounder	Measurement of various chemical species (e.g. H2O, SO2, H2SO4), wind speed and temperature.	H_2O, SO_2	<1 ppb
		Wind speed	18 km/h
		temperature	1-2 K
Ground Penetrating Radar	Observation of surface and subsurface topography as indicators of past volcanic and tectonic activity. Penetration depth: up to 1 km	horizontal	0.3-3 km x 3-7km
		vertical	7.5-15m
Spin Rate Measurement Package: Accelerometer	Measuring of non-gravitational perturbation for exact orbit determination. *see text below for detailed explanation	< 3 E-9 m/s^2	
Adonis Balloon			
Neutral Mass Spectrometer	Measurement of chemical and isotopic composition of the atmosphere to link it to volcanic processes and evolution of the atmosphere.	H_2O	< 5%
		SO_2	< 10%
		D/H	< 1%
		$^{16}O/^{18}O$	< 0.1%
		$^{32}S/^{34}S$	< 0.2%
Atmospheric Science Suite	Measurement of pressure, temperature and wind speed in the atmosphere.	pressure	0.1 mb up to 0.1 bar 25 mb up to 92 bar
		temperature	1 K
		Wind speed	0.18 km/h
Nephelometer	Sample gas from the atmosphere, illuminate with laser and measure light scattering to determine size and composition of aerosols.	Particle size	0.1 µm
Spin Rate Measurement Package: Agaelis	Reflect X-Band signal for position determination.		
Microflown Infrasound	Measurement of infrasound signal of acoustic and	Frequency	0.01 Hz

Detector	gravity waves.		
Context Camera	Provide visual context to other measurements.	Resolution	1 Mpixel

By tracking the orbit in the communication phase and from our knowledge of Venus' gravitational field from Magellan we can predict the satellites orbit. If Venus has rotated by a different amount than predicted the gravity anomalities will have shifted and this will lead to a slight *systematic* orbit shift which can be detected by the next tracking period.

Each shift will be very small, but over the duration off the mission we will measure almost 10000 orbits over the course of 4.5 Venus sidereal days, and all systematic shifts due to variation in the rotation period should accumulate into a measurable amount. The shifts due to the J-term will need to be taken into consideration. With the accelerometer non-gravitational effects on the orbit can be measured and thus subtracted from the measurement such that only the gravitational effects on the orbit remains before the analysis process begins.



5 Mission Profile

- Launch from Kourou with Soyuz-Fregat on 7/12/32.
- The launch window between 28/11/32-17/12/32 was chosen to optimally perform the scientific measurements using the balloon in the Northern hemisphere of Venus.

5.1 Transfer and Approach to Venus

By use of a Hohmann transfer, a fuel efficient transfer using a Δv of 2.7 m/s, the vehicle enters the Venus sphere of influence in a hyperbolic trajectory (expected 3/7/33).

Aerobreaking is used to decrease the apoapse of orbit about Venus (figure 2), requiring significantly less propellant than chemical manoeuvres. A burn puts the spacecraft into an elliptic orbit and due to atmospheric drag at periapse the orbital period will be steadily reduced. To reach the final orbit (periapse: 297 km / apoapse: 6084 km / orbital period: 2.7 h), another burn occurs at apoapse to raise the periapse above the atmosphere, followed by a final burn to lower the periapse (expected 18/9/33).

5.2 Balloon Release and Operations

After intensive measurements to determine the suitable conditions, the balloon gets released near the apoapse of the orbit and implementing a Δv of 36m/s to get to the desired periapse altitude. This procedure is performed after the aerobraking, yielding to higher fuel demand but actually reducing the mission risk significally.

Once in the atmosphere, the balloon descent system will be slowed down slightly due to the atmospheric drag – it is then stabilised and decelerated by the opening of a drogue chute at about 65 km altitude. Afterwards, the thermally protective shell separates and the balloon is deployed by a parachute (figure 1 [14]). The three passive reflectors separate and fall to the surface at approximately 120 degree intervals around the equator. Due to the wind conditions the balloon gradually spirals towards the North pole. Balloon-satellite communications are possible at all orbital altitudes within line of sight. Scientific measurements are performed during the 25 days of operation prior to gondola disconnect.

There will be data generation during which the orbiter is pointing towards the balloon. Data is stored onboard of the satellite during the orbit stages where the distance range does not allow fast data downlink to Earth. During the other 8 hours of the day the system will not generate data and out of these 8 hours, 6 hours will be scheduled for communication with Earth and transfer of the stored data.

There will be data generation 16 hours a day during which the orbiter points towards the balloon. Data is stored on-board of the satellite during the orbit stages where the distance range does not allow fast data downlink to Earth. During the other 8 hours of the day the system will not generate data. Out of these 8 hours, 6 hours will be scheduled for communication with Earth and transfer of the stored data.

5.3 Main Operations of Orbiter

The final orbit selected was determined by balancing instrument requirements. For spin rate measurements, calculations are simplified by a circular quasi-polar orbit and are ideally taken below an altitude of 500 km, corresponding to 12 mins per orbit. Spectral imaging measurements require a periapse altitude in the range of 155-320 km [15], and a wide field of view, given by an elliptical orbit. They have an ideal apoapsis of 12000 km, with minimum allowable apoapsis altitude of 6000 km. A mission lifespan of 3 years is expected with this orbit.

This mission requires 500N of thrust. The European Apogee Motor [16] has been selected which uses bipropellant MMH and MON, fuel requirements are shown in table 1.

Manoeuvre	***Delta-v (m/s)***	***W/ margin (m/s)***	***Fuel (kg)***
Hohmann transfer	-	-	5.2
Aerobreaking entry	*1000*	*1050*	308.3
Aerobreaking exit	*50*	*52.5*	17.8
Perigee lowering	*6*	*6.3*	2.3
Maintenance (/yr)	*10*	*20*	2
Total	***1066***	***1128.8***	**335.6**

Table 1 … of fuel and delta-v requirements for manoeuvres

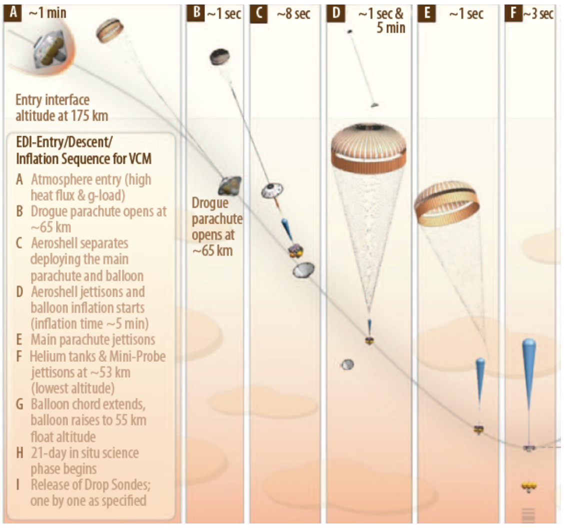


Figure 1 … balloon launch

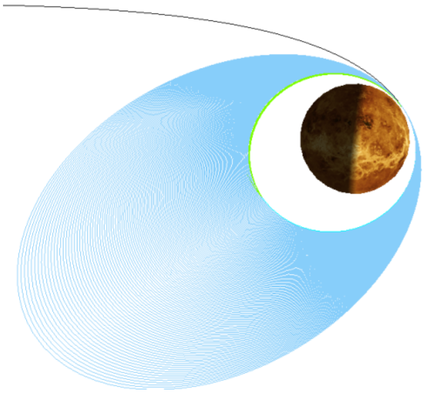


Figure 2 … STK image of transfe
and aerobreaking manoeuvres

5.4 Costs Analysis

	Cost (M€)
1) Ground Segment & Operations	85
2) Management & Facilities	75
3) Spacecraft Development	165
4) Payload development	100
5) Balloon & Entry System	350
Total	775
Total including contingency (15%)	981
Launcher	75
Total including launcher	966

5.5 Risk Analysis

The main risks of the mission proposed in this paper are the balloon separation and insertion into the Venus atmosphere. A failure of the balloon mission could implicate reduction in science return. In order to mitigate this risk, the balloon will be released in the parking orbit after the aerobraking and performing additional measurements of the atmosphere. The balloon thruster will provide the necessary Δv to enter the atmosphere of Venus from the apoapse to achieve the appropriate periapse altitude. The balloon scenario continues to present risks once it is ready to take measurements. The development of the material used in Aglaea is currently under investigation. Nevertheless it does not have high severity concerning the mission success. Finally, the instruments with low TRL (the Nephelometer and the Submilimiter Sounder) have a higher risk. However, the impact on the science return is not severe.

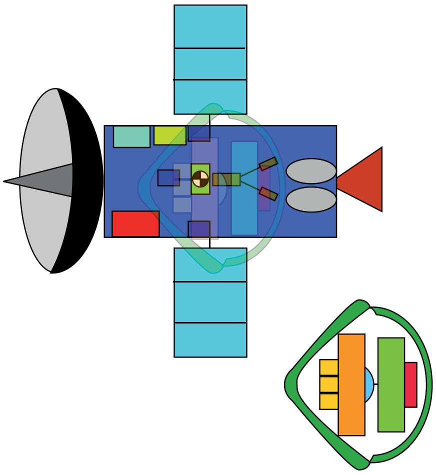
5.6 Planetary protection

Aphrodite is classified as a category I according to the Planetary Protection Recommendations of COSPAR, thus representing no degree of concern or special requirements.

6 Orbiter and Balloon Design

6.1 Orbiter (Hephaistos)

6.1.1 Thermal control system



The thermal control system is designed to withstand the worst hot and cold case scenarios. The worst hot case is when the spacecraft is at the closest point with both Venus and the Sun and it is irradiated from opposite sides. All the exceeding heat needs to be evacuated, e.g. batteries can operate at < 25°C and the hydrazine tank and lines at < 50°C. The worst cold case is when the spacecraft is just after the launch from the Earth. While the spacecraft is in orbit around Venus, the coldest case is when it is in eclipse. The orbiter components and structure need to be heated. To satisfy the range of temperatures required, the thermal control system is both active and passive. A dedicated active thermal control system is needed to maintain the operating temperature (60 K) of the Spectral Imager.

6.1.2 Power system

The total power per orbit required for operating the instruments and the sub-systems is 711 W. The solar array consists of two identical deployable wings. The chosen solar cell technology is the improved-triple junction (ITJ) GaAs. The maximum power produced is 3.5 kW with the use of 6 m^2 of solar panel. That size was chosen in order to perform the mission even if the deploying system one of the two wings fails.

Moreover, that area facilitates the aerobreaking. Li-ion batteries with specific energy density of 70-110 Wh/kg are used to store the energy.

6.1.3 Attitude and Orbit Control System

The S/C is 3-axis-stabilized (heritage from Venus Express) . Three Star trackers, sun sensors and inertial measurement units provide attitude determination. Four reaction wheels offer a periapse rate of change of 1,8°/s. The S/C is also equipped with 4 hydrazine redundant thrusters. A Bi-propellant European Apogee Motor provides 500N of propulsion force.

6.1.4 OnBoard Data Handling and Communications

The OnBoard Data Handling system is equipped with a rad-hard ASIC including both SPARC V8 processor and all of its I/O support. The data processing system also includes a 2TBytes solid-state storage unit that provides data buffering during the times when the downlink to Earth is not operational or the available bandwidth is not satisfactory. The total data rate storage per orbit 756 Mb translates to 4480 Mb daily data storage capacity. The average transmission rate per hour 840 Mb, which is equivalent to 5040 Mb daily data transmission. The balloon data rate contribution to the satellite data storage is 8.05 kbps (during operational time) or 805.2bits per orbit with 10% working time for each instrument included in the balloon system. It allows 4 Mbytes of data storage for buffering data until transmission with the orbiter.

6.2 Balloon (Adonis)

The orbiter is coupled with a change-phase (CP) balloon, arranged with a two envelopes system. The primary envelope has a radius of 5 m and it is filled with gaseous He. The secondary envelope, placed inside the primary one, has a radius of 1.5 m and is filled with H_2O vapour. An external tank of liquid water is connected with the smaller envelope. A valve regulates the pressure and the inflow of the evaporated liquid water through the small balloon and vice versa. The selected balloon material is Teflon coated with Kapton. The CP technology allows an average altitude of 40 km with oscillation amplitude of ~16 km. This process permits to have *in situ* measurements at a wide range of altitudes and, at the same time, to cool down the payload when the balloon reaches higher elevations, where the temperature drops at around 250 K (56 km). Test performed in Earth and models confirmed the feasibility of this investigation approach in the Venus environments.

Three operational modes are studied. Nominal mode, when the planned measurements received by the orbiter take place; Com mode, when the raw data are sent back to the orbiter; Safe mode, when the altitude is around 30 km and the risk of thermal damage on the electronic components rises; therefore all instruments are powered off and the He replenishment is activated (for fast ascension)

6.2.1 Thermal system

On the balloon the thermal control system is only passive. During the science operations the temperature will change due to the day/night and the altitude cycling. The temperature range is 250-350 K. The balloon is designed so that the buoyancy effect brings the payload up to higher altitudes, allowing the instruments to be cooled down. The gondola is equipped with a passive heat rejection for the electronics.

6.2.2 Power

The total energy required for the 25 day mission is 5700 W/h with maximum power output of 72 W. The power source chosen is a $Li\text{-}SOCl_2$ battery of 90 A/h. It must be designed to operate throughout the balloon mission, without recharging. The DOD at the end of the nominal mission is 91%.

6.3 Passive Reflector (Aglaea)

Three octahedral corner reflectors are placed on three different surface points close to the equator and longitudinally displaced by an angle of 120°. The preliminary material chosen is TiO_2, which has high melting point (1855°C) and relative permittivity (80-170). Technology development is still underway, evenmore investigation of effective material. Each passive reflector has a mass of 5 kg. The orbiter will detect their positions emitting and receiving the reflected signal with an X-band antenna. The data will permit to measure the exact fixed position of each probe and to elaborate a model of the spin rate changing of the planet.

6.4 Communication

6.4.1 Ground Segment and Operations

In order to execute command and telemetry functions, the mission will make use of the ESTRACK, network. It will provide global coverage for our mission, having stations with Deep Space Antennas (DSA) in New Norcia, Cebreros and Malargüe. These DSA stations provide 35 m diameter High Gain Antennas (HGA) for the reception/ transmission of signals in the X-Band. The mission control centre will be located at the European Space Operations Centre.

6.4.2 Telecommunications from Ground to Orbiter

Aphrodite mission will use an X-Band frequencies of 7.166 GHz in the uplink and 8.42 GHz in the downlink with the use of a 2m HGA with a power of 65 W. In addition to the HGA, a Low Gain Antenna (LGA1) will be included to ensure communication and control in case of HGA pointing errors or emergency situations. The current design allows minimum downlink data rates of 76 kbps (at 1.74 AU) up to a maximum of 3.6 Mbps (at 0.25 AU).

6.4.3 Telecommunications from Orbiter to Balloon

For the communication with the balloon, the same HGA as for the Earth communication will be used. As counterpart on the balloon, an X-Band Low Gain Helical Antenna (LGA2) will be installed. At the largest allowable distance of 6 000 km and with a transmitter power of 1 W, the minimum balloon–orbiter data rate transmission is 4.804 Mbps with a 4.8 dB gain for a 70˚ coverage.

7 Conclusion

The Aphrodite mission improves our current understanding of the past and current tectonics and volcanic activity and its link to the atmosphere of Venus. The mission supports a comprehensive study effectively combining different measurements, including ground penetrating radar, submillimeter sounder and complementary instruments to study the composition and variation of the atmosphere by orbiter and balloon. We are proposing an innovative combination of follow-up studies in higher resolution in compare to previous missions and a new approach to the change of the spin rate of Venus. We believe that this mission provides new undertsanding of the formation and geological evolution of the planet.

Hephaestos Power Budget			
	Power* (W)	**Duty Cycle**	**Power / orbit**
Payload			
GPR operational	34	10%	9
GPR heater + stdby	12	90%	29
Spectral Imager	43	50%	58
Submm sounder	25	50%	34
Accelerometer	18	100%	49
Probe Detection Package	240	1%	6
AOCS	72	75%	233
OBDH	18	100%	49
Comms	180	30%	146
Power dist. + thermal ctl.	36	100%	97
Total			**711**

Hephaestos Mass Budget		
	Weight * (kg)	**TRL**
Payload		
Spectral Imager	32	6
GPR	21	8
Submm sounder	8	6
Accelerometer	18	8
Probe Detection Package	4	4
AOCS	34	
Comms	24	
OBDH	2	
Structure + thermal	504	
Engine	55	
Power system	64	
Total	**766**	

Adonis Power Budget					
		Science Ops (22h/day)	per day	Telecom Mode (2h/day)	per day
	Power *(W)	duty cycle	W-hr	duty cycle	W-hr
Payload					
Neutral Mass Spectrometer	33	10%	73	0%	0
Nephelometer	2	10%	3	0%	0
Atmoshpere Science P.	4	10%	8	0%	0
Camera	1	10%	1	0%	0
Microflown	1	10%	1	0%	0
Inflation	24	0%	0	0%	0
OBDH	5	100%	106	100%	10
Telecom	12	0%	0	100%	24
		total (per day)	**192**	total (per day)	**34**
Total for 25 day nominal mission (incl. inflation) : **5700 Whr**					

Aphrodite Mass Budget	
	Weight (kg)
Adonis	
Payload	34
Systems	142
Total dry mass	176
Hephaestos	
Payload	83
Systems	683
Adonis Entry System	107
Total dry mass - Aphrodite	1049
Fuel	526
Total	**1575**

* including margin

Adonis Mass Budget		
	Total (kg)	**TRL**
Payload		
Atmosphere Package	2	8
Nephelometer	1	4
Neutral mass spectrometer	11	6
Camera	1	8
Microflown	1	8
Probes (3 pieces)	18	2
OBDH	2	
Power system	30	
Gondola + balloon	91	
Comms	5	
Thermal	2	
Gas replenishment	12	
Total	**176**	

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