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ORIGINAL ARTICLE

The 2010 European Venus Explorer (EVE) mission proposal

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A full listing of the 220+ members of EVE team is included as Appendix.

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Abstract The European Venus Explorer (EVE) mission described in this paper was proposed in December 2010 to ESA as an 'M-class' mission under the Cosmic Vision programme. It consists of a single balloon platform floating in the middle of the main convective cloud layer of Venus at an altitude of 55 km, where temperatures and pressures are benign (~25°C and ~0.5 bar). The balloon float lifetime would be at least 10 Earth days, long enough to guarantee at least one full circumnavigation of the planet. This offers an ideal platform for the two main science goals of the mission: study of the current climate through detailed characterization of cloud-level atmosphere, and investigation of the formation and evolution of Venus, through careful measurement of noble gas isotopic abundances. These investigations would provide key data for comparative planetology of terrestrial planets in our solar system and beyond.

Keywords Venus · Planetary mission · Cosmic vision · Superpressure balloon · Geochemistry · Dynamics

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1 Introduction

Of all our planetary neighbours, Venus should be the most Earth-like: its size, bulk composition and distance from the Sun are very similar to those of the Earth. Its original atmosphere inventory was probably similar to that of early Earth, with large abundances of carbon dioxide and water. While on Earth a moderate climate evolved, Venus experienced runaway greenhouse warming, which led to its current hostile climate. Where did it all go wrong for Venus? What lessons can we learn about the life story of terrestrial planets in general, including our own Earth?

While ESA's Venus Express mission is answering many questions about Earth's sibling planet, several key questions require in situ investigation, in particular relating to the noble gas isotopic signatures of past history and the complex cloud-level atmosphere. Here, we show that these fundamental questions can be addressed using a fairly small in situ mission based on a single balloon probe, called the European Venus Explorer (EVE).

The EVE mission was proposed in December 2010 to the European Space Agency (ESA) in response to the Cosmic Vision Call for Ideas for missions in the 2020–2025 period for 'M-class' missions, i.e. with a cost cap of €420 m (including launch costs but not including scientific payload, which is funded by the member states). It may be noted that the EVE team had submitted an earlier proposal, also named EVE, to ESA's first Cosmic Vision call in 2007 [7, 8]. This first proposed mission, 'EVE 2007', was a large ESA-Russia joint mission with a lander and orbiter as well as a balloon. In the 'EVE 2010' mission proposal described here, a much more focussed mission, consisting of a single balloon platform with no orbiter, was proposed in order to demonstrate that many important science objectives could be achieved by ESA alone without international partners.

2 Science goals

An overview of outstanding science questions at Venus, with a particular focus on those which require in situ measurements, has been given elsewhere [7–9]. Here we present a brief summary of that discussion before continuing on to describe the proposed mission and payload.

The first core topic for EVE is the formation of terrestrial planets and the origin of their atmospheres. It is generally believed that Venus received similar amounts of volatiles from the proto-planetary nebula as the Earth did. The atmosphere of Venus contains about twice as much carbon and nitrogen than are contained in the atmosphere, hydrosphere and sediments of the Earth [27]. The low quantity of water in the present atmosphere of Venus could result from a combination of crustal hydration and past escape processes. The present value of the D/H ratio on Venus, enhanced over that on Earth by more than a factor of 100, suggests that hydrogen escape has played an important role in removing water from the Venus atmosphere. Recent results from the ASPERA instrument on Venus Express show that oxygen is escaping at a rate about half that of hydrogen [3], suggesting that significant escape of both H and O through non-thermal processes has occurred during Venus history. Although thermal escape is no more effective at the present time, large amounts of these water-forming constituents could have been removed by hydrodynamic escape (the content of one or several terrestrial oceans) during the few first hundred million years [15, 22]. Volatile loss could have also occurred through catastrophic early impacts [39]. These primitive episodes of atmospheric losses, which probably also affected Earth's and Mars atmospheres, are suggested by noble gas elemental and isotopic data, which remain quite incomplete for Venus. The presence of an early massive atmosphere of water vapour on Venus, which further escaped to space, and/or was trapped in the interior in the form of hydrates, is generally considered to have initiated the strong greenhouse effect observed today [30, 32]. This massive H_2O atmosphere may have resulted either (i) from the evaporation of a primordial water ocean, followed by hydrodynamic escape of hydrogen [23], or (ii) from outgassing of the primordial magma ocean, not necessarily followed by the formation of a (transient) water ocean [15].

Major constraints on evolution models are provided by noble gas elemental and isotopic spectra, and light isotopes. Noble gas elemental and partly isotopic abundances in Venus' atmosphere were measured by Pioneer Venus and various Venera missions. These reconnaissance data have widely contributed to our present-day understanding of the accretion and degassing history of Venus, and allowed first order comparisons with Earth and Mars (e.g. [9]). However, the data base is largely incomplete, many data have very large uncertainties and some analyses were plagued by severe experimental problems (see [13], and refs. therein). In particular, abundances of the heaviest elements—xenon and krypton—have large uncertainties spanning at least an order of magnitude and no useful isotope data on these two elements are available. A more complete, more accurate and more reliable noble gas data base than what could be provided more than 30 years ago is therefore urgently needed and is a high-priority goal for future missions to Venus. The isotopic ratios of the light elements, namely H, C, O, N, S, provide exceptional insights into the origin and processing of planetary atmospheres; these have also to be more extensively and accurately measured.

A second core topic for EVE is the strong greenhouse effect which heats its surface temperature to be some 500 K above its effective radiometric temperature, due to gaseous and particulate absorbers. In contrast to Earth and Mars, a significant portion of solar energy is deposited at the cloud tops. Better modelling of the radiative balance today will require measurement of the optical scattering properties of the cloud particles, and their spatial variability, as well as measurement of trace gases in the lower atmosphere. Measurement of solar and thermal fluxes in a range of different cloud conditions, latitudes and solar zenith angles, would significantly enhance our understanding of the greenhouse mechanism and radiative forcing of atmospheric dynamics [11, 36].

The cloud layer which completely surrounds Venus is the third core topic. Particulate matter can be found at all atmospheric levels, from near-surface hazes at only 1–2 km altitude [16] to stratospheric hazes above 100 km in altitude [38]. Most clouds lie between 48 km and 70 km in altitude: this layer includes a region of convective cloud from 50–60 km altitude, as well as stratospheric cloud from 60–70 km. This deep layer of cloud encompasses a diverse range of environments, with pressures and temperatures ranging from 1.5 bar and 100°C at the cloud base to ∼40 mbar and −40°C at the top of the stratospheric cloud; it is expected that the diversity of environmental conditions is reflected in a rich variety of chemical, dynamical and microphysical processes in each of the different cloud layers.

The composition of much of the cloud layer is still unknown. The lower cloud was found by the Pioneer Venus large probe to contain large, non-spherical 'Mode 3' particles [24]. Soviet X-ray measurements found evidence of iron, phosphorus and chlorine in the cloud particles [1], an observation that has been impossible to follow up with subsequent missions. A third mystery found in the cloud layer occurs at 60–70 km altitude in the upper cloud, where most of the solar energy absorbed by Venus is deposited; half of this energy is deposited in an as yet unidentified UV absorber. The intervening main convective cloud layer, stretching from 50–60 km in altitude, is thought to be akin to tropospheric clouds on Earth, but with sulphuric acid taking the place of water as the main condensable species. Measuring the composition of the cloud particles, as well as measuring trace gas abundances in the cloud layer, will be essential in order to unravel the complicated cloud chemistry. A balloon float altitude of 55 km is optimal for the study of the main convective cloud layer. It may also permit identification of the controversial Mode 3 particles (during updrafts) and possibly also the unknown UV absorber (in downdrafts).

The fourth core topic for EVE is the characterization of atmospheric dynamics. Venus rotates very slowly around its axis—one rotation takes 243 Earth days—but its atmosphere at cloud level, spins some 50–60 times faster. The mechanisms responsible for maintaining this zonal super-rotation are not well understood at all. Although Venus Express is providing maps of cloud-top and cloud-base altitude wind fields, in situ measurements of winds to determine momentum transport, and improvements in the understanding of the radiative forcing of dynamics, will be needed. The characteristics of solar thermal tides in the atmosphere and their role in the meridional and vertical momentum transports also need to be determined [28].

Finally, no summary of outstanding Venus questions would be complete without discussing its surface and interior. Surface mapping from orbit is hampered by the opacity of its atmosphere at all almost all optical wavelengths, and in situ geological exploration is technically challenging due to the extreme surface temperatures, so orbital radar remains the most viable technique for Venus geological investigation. Radar mapping from the Magellan orbiter revealed that the Venus surface is one of the youngest in the Solar System and that the planet might be still geologically active [6, 12, 20, 33]. Important issues that remain poorly understood or unsolved are the extent and nature of current volcanism; composition and mineralogy of tesserae and lowlands—two main types of surface on Venus; surface-atmosphere interactions; surface hidden below the young lavas, and inner structure of the planet. Solution of these problems would require either a next-generation radar orbiter and/or in-situ measurements at the surface of the planet, both of which are outside the scope of the proposed EVE 2010 mission. Nevertheless, an aerial platform offers the opportunity to detect and quantify phenomena such as active volcanism, remnant crustal magnetisation and the presence of water in the subsurface, all closely related to the history and evolution of the solid planet.

3 Science payload

The EVE mission is based on a platform floating at (55 ± 2) km altitude, achieved by using a helium superpressure balloon. This altitude is chosen because it is in the heart of the convective cloud layer, which is understood to extend from 51–60 km on the basis of temperature structure measured by radio occultation [35]. Environmental conditions in this altitude range are benign, at (29 ± 20)°C and (0.55 ± 0.16) bar; this temperature range is scientifically interesting because it allows liquid water and sulphuric acid, and is technologically convenient because it requires only minimal thermal design for the gondola instruments. The most severe environmental concern is the concentrated sulphuric acid of the cloud particles; however, careful choice of materials and protective coatings can be used to mitigate this environmental risk. The zonal winds at this float altitude will carry the balloon through a full circumnavigation of the planet in a period of 6–8 Earth days. The minimum mission lifetime proposed is 10 Earth days, which is long enough to allow a full circumnavigation of the planet, including margin, and enough time to return all science data from the circumnavigation, as will be discussed below.

The EVE mission scenario builds on direct heritage from the highly successful Soviet/French Vega balloon mission, launched to Venus in 1984. Each of the two Vega balloons was a helium superpressure balloon, 3.4 m in diameter, with a nominal float altitude of 55 km (as is proposed for the EVE balloon). Each Vega balloon carried a small payload of pressure, temperature, vertical wind velocity, light level, and backscatter sensors; they also carried an ultrastable oscillator in order to permit tracking from Earth using very long baseline interferometry (VLBI). The Vega balloons revealed for the first time the high level of convective activity at this altitude in the cloud deck, with vertical wind speeds of typically 0.5 to 1 m/s but reaching up to 3 m/s.

The Vega balloons showed that it is possible to deploy and operate balloons in the acidic cloud environment of Venus. They also lend confidence to longer-duration ballooning on Venus: the balloons' operational lifetime of 46 hours was ended not by leaking or failure of the balloon envelope, but rather by the depletion of the primary batteries. The EVE mission builds on the success of the Vega balloons by flying the same balloon type in the same environment, with a much more capable payload and a longer duration.

In this section we describe a proposed payload to address the science topics outlined above. The baseline payload mass is 15 kg including 24% margin (Tables 1 and 2); however, we also define an extended payload of 20 kg including margins which could address additional science goals.

3.1 Baseline payload

Planetary formation and evolution goals are addressed with a dedicated Isotopic Noble Gas Mass Spectrometer (INGMS) instrument, which will measure the abundances and isotopic ratios of He, Ne, Ar, Kr, and Xe, with an accuracy better than 1%. Noble gases in the Venus atmosphere have been analyzed by mass spectrometry and gas chromatography on board Pioneer Venus and several Venera probes, but only the Ar isotopic ratios have been accurately measured (≈2%). The $^{20}Ne/^{22}Ne$ ratio is known with 10% accuracy, but the less abundant ^{21}Ne, and the full series of Kr and Xe isotopes, are still not measured. Achieving the 1% accuracy level requires the implementation of a devoted high-performance instrument, which we propose to consist of an ultra clean separation and purification line coupled with a static mass spectrometer. The use of a dynamic mode (GCMS technique) is not well adapted to the measurement of noble gases. In a dynamic mode, huge amounts of gas would have to be processed to reach the required accuracy, particularly for Kr and Xe, present at only ppb levels. The proposed concept is based on successful, well-established techniques used in the laboratory for measuring noble gases, and adapted for the PALOMA/MACE instrument proposed for the NASA MSL mission [37], and draws additionally from the Beagle 2 Gas Analysis Package isotopic static mass spectrometer.

Since noble gases are not reactive, they can be easily separated from all other chemical species, especially volatile contaminants which always come with noble gas samples, using a getter. This avoids some mass interferences and optimizes the pressure in the mass spectrometer. There remains however a problem: Ar, Ne and He are by far (≈4 orders of magnitude) more abundant than Kr and Xe. In the absence of any separation, the partial pressures of Kr and Xe in the ion source would be small (<10–9 mbar) because the Ar partial pressure cannot be larger than ≈10–5 mbar. Cryo-separation is routinely used to overcome this difficulty: in the laboratory using a charcoal trap at liquid nitrogen temperature, and for a space instrument using a thermo-regulated cryotrap. It will allow to separate Venus noble gases into two fractions: [He, Ne, Ar], [Kr, Xe], and to maximize the partial pressure of each fraction in the ion source. Because of the very low abundances of noble gases, in particular heavy ones, the mass spectrometer is operated in static mode. This also permits to getterize and separate the gas fractions from a sample of limited size. Analysis of krypton (six isotopes) or xenon (nine isotopes) will require long integration times (hours) in order to achieve the required measurement accuracy. Several sequences of 1 hour integration time will be performed for each of the analysed fractions in order to reach the 1% accuracy level.

Table 1 Balloon scientific payload

Instruments	Science objectives	Measurement objectives	CP-GCMS
ACP-GCMS	Atmospheric chemistry, including cloud chemistry.	Map important species involved in cloud chemistry. Measure isotopic ratios of H, O, C, N, S; study variation in space and time.	Composition of atmosphere and of cloud particles (ppb detection level). Isotopic ratios of O (16/18), C (12/13), N (14/15), S (32/34). – Concentrations of isotopes: 5–10%. – Isotopic ratios: 1%.
Cloud XRF	Cloud particle composition, microphysics & optical properties.	Identify trace species in cloud particles. Search for surface- or volcano-related mineral particles.	Sensitivities of 1–10 $\mu g/m^3$ for all species with $Z = 14$ to 46, in particular S, P, Cl and Fe. Search for other species including Al, Na, Mg, Si, K.
Isotopic noble gas MS (INGMS)	Evolution of solar system, of Venus and its climate; cloud processes (isotopic fractionation of condensable species).	Measure bulk elemental and isotopic ratios of noble gases.	– Concentrations of major isotopes (^{4}He, ^{20}Ne, ^{36}Ar, ^{40}Ar, ^{84}Kr, ^{130}Xe): 5–10%. – $^{3}He/^{4}He$: 5–10%; other major isotope ratios: 1% ($^{20}Ne/^{22}Ne$; $^{36}Ar/^{38}Ar$; $^{82,83,86}Kr/^{84}Kr$; $^{129,131-136}Xe/^{130}Xe$). – Minor isotope ratios if possible ∼5% ($^{21}Ne/^{22}Ne$; $^{78,80}Kr/^{84}Kr$; $^{124-128}Xe/^{130}Xe$).
TDL spectrometer	Cloud chemistry.	Measure active species involved in cloud formation. Provide backup measurement of oxygen isotopic ratios.	Measure species with the following precision: SO_2: 0.1 ppm; S_8 1 ppb; $H_2SO_4(g)$ 0.01 ppm; $H_2O(g)$ 0.1 ppm, CO 0.1 ppm; H_2S 0.02 ppm; HCl 0.002 ppm; HF 0.1 ppb; OCS: 10 ppb.
Nephelometer	Cloud particle microphysical parameters (size, composition, shape) and number density.	Measure the refractive index, size distribution, and shape of cloud particles, and their number density.	Phase function at six scattering angles, for total flux and two polarization states, at two wavelengths.
Radiometer	Radiative balance; search for lightning.	Correlation of radiative fluxes with cloud structure and with atmospheric dynamics. Correlation of lightning with other atmospheric properties.	Upward and downward radiances in six spectral bands from UV to thermal IR. 2% absolute accuracy for all channels, 5% accuracy for IR channels. High-rate visible avalanche photodiode sampling mode for lightning detection.

Meteorological package	Atmospheric dynamics; atmospheric structure and stability; turbulence.	Balloon phase: temperature, pressure, vertical wind.	Atmospheric pressure to 1% accuracy, temperature to 0.2 K accuracy; Vertical wind to 0.1 m/s accuracy; RMS turbulence levels at 5 min intervals.
		Entry phase: determine upper atmospheric structure.	In entry phase; 1-axis accelerometer.
Electrical and mag. package incl. photodiode and microphone	Electrical and magnetic properties of atmosphere, ionosphere and subsurface.	EM spectrum characterization.	Electrical conductivity and permittivity.
	Subsurface sounding; search for lightning.	EM transient event detection and characterization.	1-D E-field spectrum from 10 Hz–20 kHz, with sensitivity of 20–50 nV/ $Hz^{1/2}$.
		Electric relaxation and conductivity measurement. M-T sounding.	1-D Magnetic field measurements as phase ref. For M-T sounding, with sensitivity of 0.05–0.1 pT/$Hz^{1/2}$.
	Public relations/outreach.	Record sound of thunder if possible.	Triggered EM, acoustic and optical event detection.
Camera	Public relations/outreach.	Obtain image showing balloon and top deck.	Deployment images and 1 monochromatic image per day.
Extended payload			
Attenuated Total Reflection Spectrometer (ATRS)	Cloud composition.	Complementary measurement of cloud particle composition.	Infrared transmission spectra of deposited aerosol material, in range 3–25 μm with $\Delta\upsilon = 10\ cm^{-1}$.
3D fluxgate mag.	History of geodynamo.	Search for remnant crustal magnetism.	3-D B-field measurement, sensitivity of 0.05–0.1 nT.
Microbalances	Cloud microphysics; cloud particle charging.	Measure ratio of condensation nuclei to condensable species; measure dew point; measure charging of individual particles.	Thermal quartz crystal microbalances, mass sensitivity of ~1 ng.

Table 2 Balloon scientific payload parameters

Instrument	Mass (kg)	Power (W)	Volume (cm^3)	Accommodation constraints required mechanical devices	Data rate (bps)	TRL level/ heritage	Potential provider (laboratory, consortium)
ACP-GCMS	3.5	15 W (peak)	20 × 12 × 12 cm	Envelope must be in contact with atmosphere. ACP will use pump to draw atmospheric air through an aerosol collection filter.	25.5	4–5/Huygens, MSL, Rosetta, ExoMars, Phobos	LATMOS, LISA (Fr)/ MPS (Germany)/ Open Univ. (UK)/ U. Berne (CH)/ IKI (Russia)
Cloud XRF	0.3	3 W (peak)	47 mm Ø × 47 mm L	Will point at the filter in ACP.	0.1	5–8/Beagle 2, Bepi Colombo	Leicester University (UK)
Isotopic Noble gas MS	3.5	15 W (peak)	30 × 20 × 12 cm	Inlet placed to minimize contamination by gondola outgassing	4.6	4–5/Beagle 2, Rosetta	Open Univ (UK)/ LATMOS (Fr)/ U. Berne (CH)
TDL spectrometer	1.7	2 W	15 cm L × 5 cm diam.	Sensor module to be open to atmosphere. Electronics module plus sensor module (joined by Harness).	2.4	5–8/Mars 2001, MPL, TDLAS/ Phobos-Grunt	GSMA (France)/ IKI (Russia)/ SWRI (USA)
Nephelometer	1.0	2 W	400 cm^3	Electronics module plus sensor module (semicircular arm, 25 cm diameter).	0.6	4/Venera, Vega, Pioneer Venus	Cornell Univ. (USA)/SRON Netherlands Institute for Space Research (NL)
Radiometer	0.5	1.2 W	10 × 9 × 4 cm	Will include rotating scan mirror, to point up, down, or at calibration target.	1.3	4–8/Mars Climate Sounder, Mars Trace Gas Orbiter	Oxford Univ./ Open Univ. (UK)
Meteorological package	0.5	2 W	10 × 8 × 5 cm	Must be located on outer surface of gondola.	0.9	4–9/Beagle 2, ExoMars, Huygens	FMI (Finland)/ Oxford Univ./ Open Univ. (UK)/ Padova (Italy)

Electrical and mag. package incl. photodiode and microphone	0.9	2.5 W (peak)	11 × 10 × 2 cm	Requires 2x electric field antenna, dimension 80 cm L × 5 mm ø, and 1x search coil, 20 cm L × 1 cm ø.	4.4	4–6/Huygens, Compass-2, ISS	Eötvös U. (Hungary)/ RAL & Oxford U.(UK)/ LATMOS (Fr.)/ Tohoku Univ. (Japan)
Camera	0.2	2 W	77 mm × 82 mm × 75 mm	Camera should view balloon and top deck (120° FOV)	4.0	9/Proba-2, ExoMars, Beagle 2, …	Space-X (Switzerland)/ UCL (UK)
Total	12.5 kg w/o margin; or **15 kg including 20% margin**						
Extended payload							
Attenuated Total Reflection Spectrometer	2	10 W	15 × 15 × 10 cm	External surface of prism in contact with atmosphere. 20 prisms included to allow multiple sample acquisition.	0.2	4–9/VEX, MEX, Phobos-Grunt	IKI (Russia)/INAF & Politec. Milano (Italy)/ Norway/Open Univ. (UK)
Fluxgate magnetometer	0.30	0.5 W	4 × 4 × 4 cm (sensor)	Should be mounted halfway out on one of the E-M booms. Electronics will be shared with EM instrument.	0.3	5–9/FAST, PVO, ST4, DSX, MMS	Dan. Nat. Space Center (Denmark)/Imperial College London (UK)/UCLA (USA)
Microbalances	0.4	0.2 W (mean)	0.1 cm^3 (sensor)	In contact with atmosphere	1.2	4–9/Rosetta, ISS	INAF (Italy)
Total	15.2 kg w/o margin; or **20 kg including 32% margin**						

Where a range of TRL is given (e.g. 4–9) it signifies the TRL of different subcomponents of an instrument are different
All instruments can survive and operate in temperatures of −55 to +125 °C

The instrument may consist of a static mass spectrometer (which may be a Time-of-Flight or a magnetic sector instrument) and supporting equipment to enable chemical adsorption of major species and cryo-separation prior to analysis by the static MS. The function of the getter (e.g. zirconium alloy) is to eliminate background and/or reactive gases from the sample volume. It chemically traps and separates major volatile gases (CO_2, N_2, SO_2, CO, etc.) from minor noble gases. The cryocooler (e.g. Stirling), coupled with a heater, operates from $\approx$100 K up to 330 K. It is devoted to the selective trapping of noble gases. The cooler surface is covered with activated charcoal to increase trapping efficiency. The typical mass range is 1–150 amu. The static MS has a mass resolution of typically 500 at 0.1% of peak height and high sensitivity ($<$100 ppt). This instrument could be provided by a consortium of European laboratories (UK, France, Germany, Switzerland).

The Aerosol Collector/Pyrolyzer and Gas chromatograph mass spectrometer (ACP-GCMS) will measure (i) the molecular (H_2O, CO, CO_2, SO, SO_2, H_2S, etc.), elemental and isotopic (C, H, O, N, S) composition of the Venus atmospheric gases and (ii) the chemical composition of the aerosols that constitute the clouds down to the ppm level with gas chromatography (GC), and ppb level with mass spectrometry (MS). The gas will be directly sampled from the atmosphere. Aerosols will be collected on a filter and introduced into an oven, then vaporized and/or pyrolysed through multi-step heating of the collected material, up to typically 100°C (or more: 600°C in the case of ACP on Huygens). In this way, the nature and relative concentration of the species composing the aerosols will be determined by vaporisation of the condensed species and pyrolysis of the possible refractory nucleus.

The gas from the atmosphere, or that issuing from the ACP, will be analyzed by a GC coupled with an MS. The two subsystems will also have the capacity to work separately. GC is used to separate the different species and to detect them with simple detection devices, either by measurement of the thermal conductivity of the gas or with ionisation detection. The separation is made by carrying the sample into tubes (named columns) specifically treated where the separation occurs by the difference of affinity of the different sample components with the column. Identification of the species, even if no structural information is directly measured (as with MS), is assured by the measurement of the time spent by the different species within the columns. MS is used to provide structural information on the analysed species and sensitive detection of the minor components which cannot be detected by pure GC.

Several European laboratories have been involved in spaceborne GCMS, by providing either full instruments (ROSETTA Ptolemy GC-ion trap-MS and ROSETTA COSAC GC-ToF-MS) or key systems like GC columns or pyrolysis system: ACP for the GCMS on the ESA Huygens Probe, GCMS for the US-led SAM on the Mars Science Laboratory NASA mission.

An X-ray fluorescence spectrometer (XRF) will be used to measure elemental abundances of aerosols deposited on the aerosol collector filter of the ACP. A primary aim of the instrument will be to repeat the measurements of Fe, S, P, and Cl in cloud particles made by the X-ray radiometer instruments on the

Vega descent probes [1, 34]. It will use ^{55}Fe and ^{109}Cd sources in combination to measure X-ray fluorescence from a broad range of elements—in principle from ~1–25 keV corresponding to K-shell fluorescence from elements Z = 11 to Z = 47 in the periodic table. It will employ modern commonly available, large area (up to 100 mm^2) solid state detectors (e.g. silicon drift detector) with a resolution of ~140 eV at 5.9 keV which have a vastly improved resolution compared to the ~1,500 eV resolution of the gas proportional counters used in the Vega/Venera instruments. The XRF spectrometer would also be able to detect rock-forming elements including Al, Na, Mg, Si, and K if present at this level due to lofted surface dust or volcanic aerosol.

The proposed X-ray spectrometer would be a development of that flown on the Beagle 2 Mars lander, which was developed to TRL 8 (Fig. 1). The characterisation of aerosols with a portable XRF is in widespread use both for industrial environment monitoring and for atmospheric aerosol characterisation on Earth, so this can be considered an 'off-the-shelf' technique. The XRF spectrometer weighs only 300 g including its sources and electronics, and would be integrated into the aerosol collection system used for the ACP-GCMS instrument. Detection limits of Fe, S, P and Cl are estimated to be of the order of 1 μg/cm^2 for sample deposited on the filter. Depending on the filter design and pump rate, this corresponds to an airborne detection limit of order 5 μg/m^3 for atmospheric loading, which is two orders of magnitude more sensitive than the Vega XRF results.

The XRF will thus be able to measure the atmosphere and aerosol composition at much improved accuracies and detection limits to both confirm previous measurements and investigate undetected constituents. For example, the measurement of Cl by Vega may indicate the presence of $AlCl_3$ in the middle cloud layer at 53–58 km [26]. The poor sensitivity of the Vega XRF instrument at ~1.5 keV (Al K shell) would have prevented a reliable measurement. An improved XRF will be able to confirm or deny its presence at a much improved sensitivity. It will also seek to replicate the tentative measurement of mercury

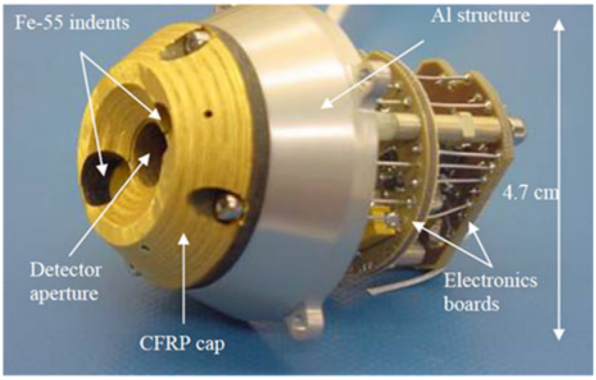

Fig. 1 Beagle 2 XRF spectrometer. Like the proposed EVE XRF, this instrument includes two ^{55}Fe and ^{109}Cd sources

halides by Venera at ~10 keV (L shell) and ~2 keV (M shell) and investigate the presence of other heavier elements that have been theorised to be present such as As and Se [5].

A tunable diode laser spectrometer (TDL) is proposed in order to measure the abundances of gaseous species in the atmosphere, in particular of the crucial H_2SO_4, SO_2 and H_2O species which are so important in cloud formation. Although the GCMS instrument will measure these species as well, quantitative measurements can be difficult due to adsorption of these species onto the internal walls of the instrument, and due to changes in the molecules when they pass through the ionisation source of the MS instrument. The TDL spectrometer offers a robust method for frequent measurements of these crucial gaseous abundances while using less power than an MS instrument. The frequent measurement capability allows correlation of compositional changes with vertical winds—revealing vertical turbulent eddy fluxes—or with cloud boundaries, shedding light on the chemical cycles at work in the clouds.

Tunable diode laser spectrometers are transmission spectrometers, scanning over a narrow spectral range using tunable diode lasers. The laser and detector are kept away from the harsh environment by using optical fibres to transport light signals to and from the optical cell. Multiple laser diodes can be used to examine different spectral ranges; an optical switch is used to switch different laser diodes in and out of the signal path. A short multi-pass cell allows an absorption path length of many metres in a package only 20 cm long. Fibre optic couplings allow easy switching between different TDL diodes but also allow the electronics to be remote from the pass cell. Heated mirrors will be used to evaporate deposited volatile substances. Lasers could include a combination of antimony lasers. Depending on the available mass, two additional channels with quantum cascade lasers (mid-infrared, QCL) to measure SO_2 with a much better precision and access HDO could be added (QCL option).

The TDL instrument could be provided by teams in France or in the U.S., all of whom have extensive experience and would build on extensive heritage from missions including Vega, Mars Polar Lander and Phobos Grunt, as well as Earth atmospheric deployments. The performance figures in Table 3 were provided by the French team at GSMA (France), who base their design on performance figures from a full TDL spectrometer instrument flown on the Phobos Grunt mission.

A nephelometer will be used to characterize the cloud and aerosol particles. As discussed in Section 2, there are many mysteries left surrounding these particles. Firstly, the 'Mode 3 controversy': Is there a distinct population of large, non-spherical particles in the lower cloud deck? Secondly, what is the nature of cloud processes in the 50–60 km convective region? Thirdly, what is the nature of the UV absorber?

The Planetary Polarization Nephelometer (PPN) will measure the intensity and degree of (linear) polarization of light that has been scattered by cloud and aerosol particles at six scattering angles and two wavelengths. In particular the polarization phase function is very sensitive to the microphysical properties (size, shape and composition) of the scattering particles [18, 19]. An added

Table 3 Expected performance of a TDL system

Multipass = 36 m (20 cm base length)					
$P = 500$ mbar		$T = 300$ K		Detection limit = 5e-6	
Species	Estimated abundance	Required precision	Wavelength (micron)	Absorption depth	Estimated sensitivity (1 σ)
SO_2	1.0E-04	1.0E-07	2.46	4.0E-04	1 ppm[a]
OCS	4.0E-06	1.0E-08	2.43	1.0E-02	2 ppb
H_2O	3.0E-05	1.0E-07	1.85	2.0E-01	0.8 ppb
$H_2^{18}O$	6.0E-07	1.0E-04	1.85	5.0E-04	6 ppb
CO	4.0E-05	1.0E-07	2.32	5.0E-02	3 ppb
H_2S	3.0E-06	1.0E-08	2.60	3.0E-03	5 ppb
$H_2^{34}S$	1.0E-07		2.60	2.0E-04	3 ppb
HCL	5.0E-07	1.0E-09	1.74	2.5E-03	1 ppb
$H^{37}Cl$	1.0E-07		1.74	1.0E-03	0.5 ppb
HF	2.0E-09	1.0E-10	2.45	1.8E-03	10 ppt
CO_2	9.0E-01		2.17	3.0E-02	150 ppm
$^{13}CO_2$	1.0E-02		2.14	3.0E-02	1.5 ppm
H_2O[b]	3.0E-05			1.5E-01	1 ppb
HDO[b]	6.0E-07			1.5E-03	2 ppb

[a] 1 ppb using QCL
[b] Requires using QCL

advantage of nephelometry is that it is a relative measurement that can be obtained very accurately with few instrumental effects.

Combining intensity and polarization phase functions gives unique access to cloud and aerosol microphysical properties that cannot be obtained from traditional nephelometers that measure only intensities. For example, the simple backscatter nephelometers which have been deployed on several previous Venus descent probes yield only the product of particle number density and size. Nephelometers that measure intensity phase functions (thus at several scattering angles) can separate particle number density from size, but in order to do so, one has to assume the particle shape and index of refraction. Measuring intensity and polarization phase functions at two well-separated wavelengths, as the EVE nephelometer would do, dramatically enhances particle characterisation capabilities in particular for the refractive index (real and imaginary parts) and for detection of non-spherical, non-liquid particles.

A sketch of the Planetary Polarization Nephelometer is shown in Fig. 2. Optical elements are arranged around an arc-like structure which is open to the atmosphere. From one end of the arc, lasers illuminate the particles with light that is modulated in its state of polarization. The intensity and polarization phase functions of the scattered laser light are sampled through apertures along the arc's inside rim. The polarization modulation of the incident light results in the DC component of the scattered intensity being proportional to the intensity phase function, while the AC component is proportional to the degree of polarization. The PPN has no moving parts, and by using fibers, all the sensitive components can be housed within the probe's body. Only passive optics will be exposed to the environment. Simpler nephelometers (with less

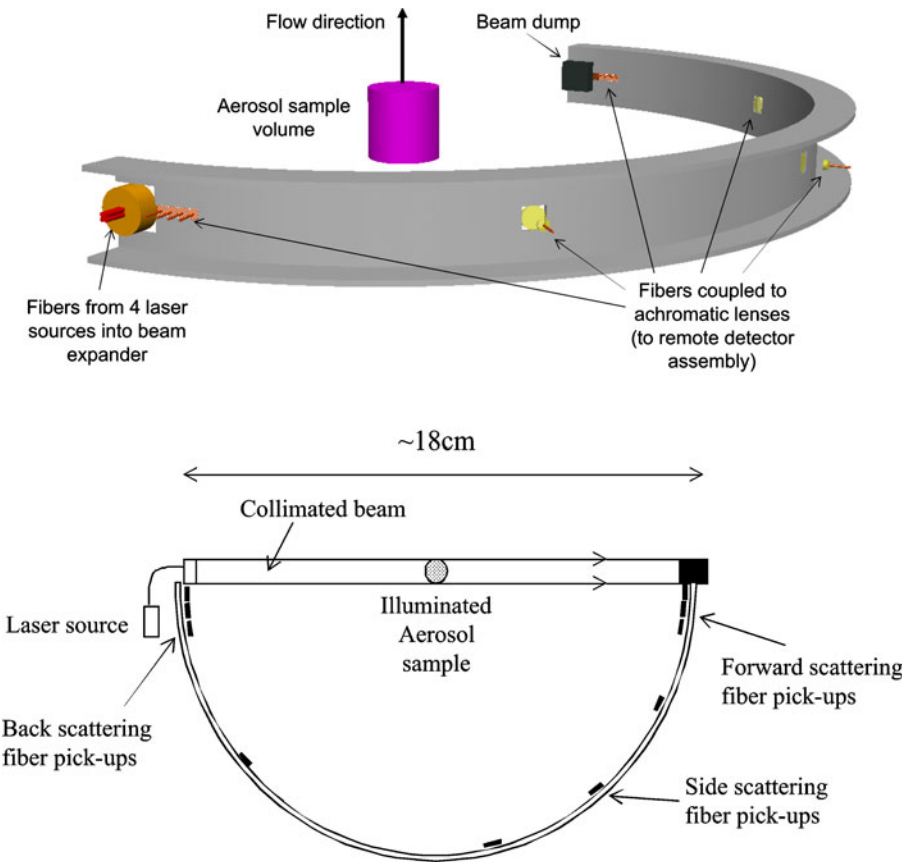

Fig. 2 Two views of the planetary polarization nephelometer—aerosols near the centre of the arc are illuminated by laser from the left, and scattered light is sampled by lenses/fibres arranged around the arc to the right (from [2])

scattering angles and/or without polarization) simply cannot yield a complete, unambiguous, characterisation of Venus' aerosol and cloud particles.

A radiometer will be used to examine the radiative balance in the clouds of Venus; and to to study the interdependence between radiative fluxes and dynamics, cloud microphysics and chemistry. This instrument will measure radiative fluxes in 8 spectral channels from the UV to the infrared. The currently envisaged channels are shown in Table 4.

The UV and visible channels permit measurement of the integrated solar flux at the balloons altitude, to see how much this varies due to changes in the upper cloud. The instrument includes a scan mirror which will allow pointing upwards, downwards and at a calibration target (particularly important for the infrared channels). Measurement of flux at intermediate zenith angles will also be performed, although only infrequently because of the restricted data rate. Multiple channels in the UV allow characterisation of the UV absorber;

Table 4 Channels for radiometer

Wavelength [μm]	Width [μm]	Detector	Purpose
0.35	0.065	Si photodiode	UV absorber; UV-A dose
0.30	0.035	Si photodiode	SO2 absorption; UV-B dose
0.23	0.012	Si photodiode	UV-C dose
0.2–0.8	No filter	Si photodiode	Solar broadband flux
1.0	0.04	Thermopile	IR window (flux from surface)
1.73	0.08	Thermopile	IR window (flux from 10–25 km)
2.32	0.04	Thermopile	IR window (flux from 30–40 km)
1–50	No filter	Thermopile	Thermal broadband flux

measurement of column-integrated SO_2; and astrobiologically significant UV-C dose. Infrared channels are centred on the important 1.0, 1.7 and 2.3 μm spectral window regions, as well as a broad long-wave channel. The spectral window channels will be used to characterise the cloud below: Is the balloon above a region of thick cloud or thin cloud?

By combining the radiometric data with composition measurements from the nephelometer and GCMS, we can validate countless IR studies. For example, are changes in the 1.7/2.3 μm ratio primarily associated with cloud particle size variations or with cloud particle composition variations [4]? The correlation between fluxes and dynamics are also crucial: Are regions with thick cloud (low fluxes) associated with updrafts, as expected from convective clouds on Earth? Quantifying this relationship will allow estimates of vertical convective transport within the cloud layer for the Venus Express/VIRTIS dataset.

We include in this instrument also a radiation sensitive transistor (RadFET), which records the cumulative ionising radiation dose. Multiple channels, to probe different energies, are possible in a sensor of <100 g. This, combined with the U.V. radiation channels described above, serves the astrobiological goal of characterising the habitability of the current-day Venus cloud environment.

A meteorological payload, including pressure, temperature and vertical wind measurements, is vital to provide context measurements for all of the other scientific measurements.

Capacitive 'Barocap' sensors will be used to measure absolute pressure. Originally developed for balloon-based meteorology on Earth, these also have space heritage having been included in the payload of a number of Mars missions. The pressure sensor serves as an altimeter. At the 55 km float altitude of Venus, the altitude of a constant pressure surface is expected to vary by less than ±500 m (S. Lebonnois, private communication based on results from Paris Venus GCM, 2010). The measurement precision of VLBI tracking from Earth is expected to be ∼50 m, so it will be possible to search for such variations in the geopotential height, which would be very revealing as to global atmospheric dynamics.

Platinum resistance thermometers, similar to those used on Huygens HASI will be used to measure air temperature to an accuracy of 0.1 K. Measurement of temperatures in updrafts and downdrafts will help elucidate convective processes in the clouds; a direct cross-correlation of temperature with vertical wind will yield the vertical eddy flux of heat.

This requires that the vertical wind be measured. Our preferred anemometer is a compact (50 mm Ø × 18 mm L), low mass (50 g), low power (12 mA) design which can be used ‘off the shelf’ with minimal modification: the FT702 ultrasonic anemometer from FT technologies in the UK. The 0.1 m/s uncertainty in wind speed achievable using this instrument is more than sufficient for eddy flux covariance methods. We note that the absolute vertical wind speed can be determined by combining the balloon’s vertical airspeed (measured) with its rate of change of pressure, in a procedure demonstrated for the Vega balloons [29].

Finally, the meteorological science team will also analyse accelerometer data from the entry phase to determine upper atmosphere structure, as has been carried out on most entry probe missions. The science team will assist the engineering team in specifying the requirements for a 1-D accelerometer for use during the entry phase; use of accelerometry during the float phase to characterise atmospheric turbulence shall be considered in the definition phase.

Another important instrument in the core payload is an electrical/magnetic instrument suite. The core instrument of the EVE EM suite is a combined electromagnetic wave analyser and permittivity sensor. The electromagnetic wave analyser is based on a Hungarian instrument with extensive flight heritage on Compass-2, Chibis and Relec satellites and the ISS [14]. This instrument measures the horizontal electric field from 0–20 kHz by measuring the potential between two electrodes deployed on 1 m booms on opposite sides of the gondola. Physical displacement of ~1 m from the gondola is required as well as a horizontal displacement of >2 m between the two electrodes for the electromagnetic wave analyser. This can be achieved using two single segment carbon-fibre booms deployed from the sides of the gondola. The booms are based on the design proposed for the Atmospheric Relaxation and Electric field Sensor (ARES) and meteorological instrumentation on ExoMars, and each weighs 250 g, including actuator and hinge assembly. The electrodes would be of a design similar to that used for ARES i.e. electroformed aluminium wrapped in a cylindrical shape at the end of each boom (10 cm long × 10 cm circumference). Multi-mode electronics would permit the electrodes to be used (i) for EM background characterization, (ii) for rapid transient detection and characterization with a triggered mode, and (iii) as relaxation probes to measure the atmospheric electrical conductivity. The possibility to implement the measurements of the complex permittivity and of the DC high impedance current to sense impacts of charged particles will depend on the mass and power budget (requiring more complex boom, structure, additional electronics, and EMC requirements), and would be studied during Phase A.

Measurement of the vertical atmospheric electric field may be achieved by adding a third electrode; a trade-off between accommodation solutions could be carried out in Phase A study.

This instrument also provides the possibility of magneto-telluric sounding, which could constrain subsurface conductivity profiles and mantle water content [17]. This would require either measurement of the vertical component field using a third electrode or by measurement of a perpendicular horizontal component of the magnetic field. A search coil is included in the payload, mounted on one of the EM booms, to conduct this measurement. A search coil is the preferred magnetometer for this purpose because it would provide the required sensitivity at low frequencies (8–12 Hz) at which the Schumann resonances may be found.

The search for the electro-magnetic wave signatures of lightning will be enhanced by the addition of acoustic and optical channels to the E-M instrument. A simple avalanche photodiode (nightside) and photodiode (dayside), contributed by the Japanese team responsible for the Lightning and Airglow Camera on Venus Climate Orbiter, will search for optical transients of lightning at the oxygen excitation line at 777.3 nm. A microphone is included in order to search for thunder and/or precipitation. This investigation will have significant outreach value as well as its scientific value. The microphone and optical channels will be analysed by the EM electronics, which are already designed to search for transients in E-field signals at up to 20 kHz.

The final instrument in the core payload is a camera. The data rate is very limiting—only 5–50 kbytes per day would be available to a camera system—so the camera would be limited to sending back one compressed image per day. The cloudscape around the balloon is expected to be quite homogenous: there is expected to be around a 30% difference between light level between the sunward and anti-sunward directions, so there is a possibility of seeing some cloud shapes, but the lighting would be very diffuse. To create an image suitable for P.R. purposes, we suggest a camera looking up at the balloon, perhaps with a wide viewing angle to show also the gondola's upper deck.

We suggest the use of a micro-camera such as the X-CAM from the Space-X Institute in Switzerland as flown on ESA-s Proba-2 spacecraft, due to its combination of a wide field of view (100°), low mass (221 g for camera head), and flight heritage (TRL 9). The detector is a 2,652 × 1,768 pixel colour CCD, but in nominal mode we would return one binned and compressed 663 × 442 pixel image per day.

3.2 Extended payload

The following instruments should be included if a slightly larger payload mass of 20 kg can be accommodated.

An Attenuated Total Reflection (ATR) spectrometer would provide additional cloud characterisation capabilities. ATR Spectroscopy works by sending a light beam through a prism such that it is totally internally reflected from the prism's surfaces. The spectrum is attenuated by absorption from material deposited on the external surface of the prism: this is effectively an exquisitely sensitive method of performing absorptance spectroscopy of very thin layers of liquid, and is therefore ideally suited for characterising the cloud droplets of Venus. The extended version of the EVE payload includes a 2 kg ATR spectrometer. The spectrometer would include 20 separate prisms; this allows replacement of prisms after each measurement, in order to permit measurement of the spatial variability of cloud composition without cross-sample contamination.

The spectrometer would be of the Fourier type, with a spectral range of 2.5–25 μm and a spectral resolution of about 5 cm^{-1}. The specifications given here were provided by a Russian/Italian team building on their experience from Venera 15/16, PFS-MEX, PFS-VEX, and Phobos-Grunt (Fig. 3); a miniaturised ATR instrument is also under development by a Norwegian/UK consortium.

The extended payload mass would also be used to add a 3-D fluxgate magnetometer to the E-M suite. With a goal of searching for remnant crustal magnetism, this sensor would measure 3 components of the DC magnetic field in the range 0 to 1,000 nT, with an uncertainty of ±0.1 nT. The magnetometer would be accommodated on one of the E-M instrument's booms. This instrument could be provided by several European or US teams.

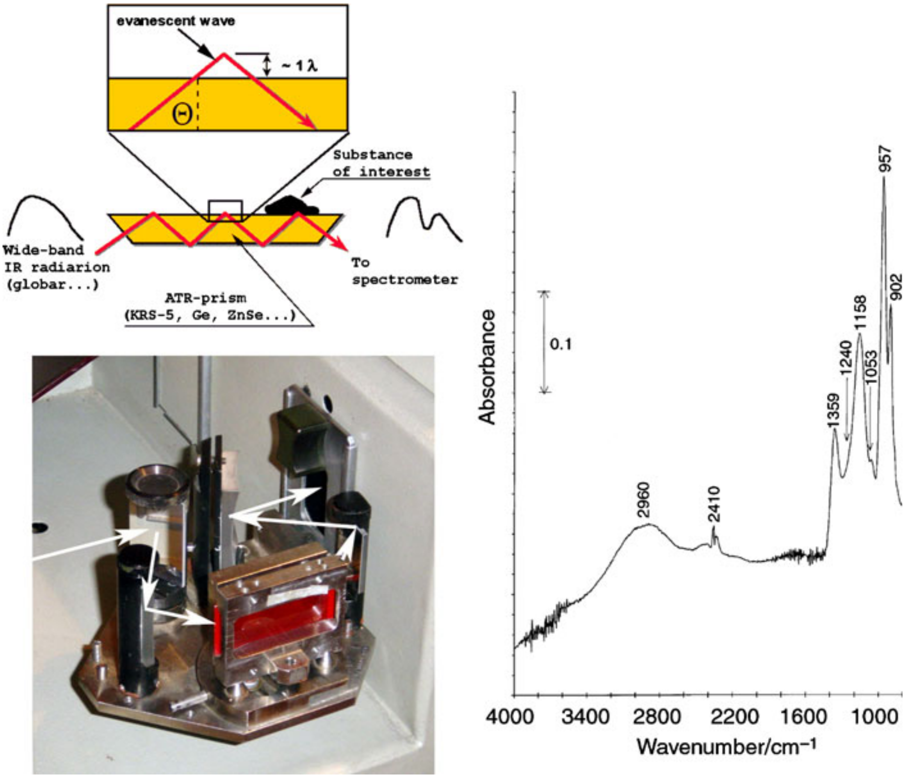

Fig. 3 ATR spectrometer in development: (*upper left*) schematic, (*lower left*) current prototype, (*right*) measured ATR spectrum of sulphuric acid [21]

The final instrument included in the 'extended' EVE payload is a microbalance suite, to perform thermal gravimetry measurements. Thermogravimetric analysis (TGA) is a widely used technique to investigate deposition/sublimation and absorption/desorption processes of volatile compounds in different environments: outgassing contamination in space, dehydration and organic decomposition in minerals, as well as to measure moisture content in foods or to develop temperature profiles for firing ceramics. At the heart of TGA is a measurement of changes in the mass of a sample to a precision of a few nanograms or picograms, as a function of temperature and time. A quartz crystal microbalance is used as the sensitive element, typically of <1 cm^2 in area; a heating element and thermistor are built into the microbalance to minimise the thermal inertia and thus the cycle times of the system. Peltier coolers would be included to permit cooling as well as heating of the microbalance.

For EVE, the microbalance would be used in two modes: condensation and electrostatic. In condensation mode the microbalance would be used much as a chilled mirror hygrometer is on Earth: it would be cooled until condensation formed, providing a measurement of the dew point and thus of the local relative humidity. The microbalance would then be heated up to above ambient temperature to see if any non-volatile residue is left on the microbalance; this would finally permit investigation of suggestions from Pioneer Venus radio occultation data which suggested that lower cloud particles showed properties consistent with "a solid dielectric core with a concentric sulphuric acid coating" [10]. The combination of this measurement with those from the polarising nephelometer and the GCMS instruments will provide a complementary set of measurements to conclusively define the composition and structure of the cloud particles.

Further information as to the electrical properties of the particles can be obtained by applying a series of electrostatic charges—both positive and negative—to the microbalance assembly to see how deposition rates are affected. This would show whether cloud particles have any electric charge, which is vital for understanding the atmospheric electrical circuit and the generation of lightning.

The mass of 400 g quoted for this instrument includes 3× sensor heads and independent electronics. We note the opportunity for significant mass savings if the microbalance sensor heads, weighing only 25 g each, could be integrated into another instrument such as the meteorology suite, using combined electronics. This possibility would be examined in the assessment phase.

3.3 Sampling strategy

The sampling strategy is chosen to maximise the science return within the constraints of data and power budgets. Table 5 below shows the trade-off of science return for different average data rates. It is currently envisaged that the same data production rates will apply on both the dayside and nightside of

Table 5 Trade-off of science achievable for different average data production rates (shown in top row of table)

	Science achieved	5 bps	50 bps	200 bps
Evolution	noble gas abundance & isotopic MS	YES (measurement only 1-2 times)	YES (repeated measurements possible)	YES (repeated measurements possible)
Cloud composition	basic gas composition measured	OK (GC and MS only, 6hr intervals)	Good (GC and MS at hourly intervals)	Very Good (Full GCMS at hourly intervals)
	detailed gas composition	No - GCMS not possible	OK - Full GCMS possible at daily intervals	Very Good (Full GCMS at hourly intervals)
	TDL meas't of gas composition	OK - some species at daily intervals	Good (most species at hourly intervals)	Good (most species at 15 min intervals)
	ACP / Pyrolysis for aerosol study	limited (Pyrolysis at 6-12 hr intervals)	Good (Pyrolysis at hourly intervals)	Very Good (Pyrolysis with GCMS possible)
	nephelometer	YES (5 min intervals)	YES (5 min intervals)	YES (5 min intervals)
	correlation with up/downdrafts	limited, using partial TDL & nephelometer	YES using all except GCMS	YES, using all instruments incl. GCMS
	ATR spectrometer	*YES*	*YES*	*YES*
Surface	M-T subsurface sounding	limited	Adequate. M-T sounding every 15 minutes	Good. improved spectral resolution
	Remanent crustal magnetism	*YES*	*YES*	*YES*
Dyamics	mean zonal wind measurement	YES	YES	YES
	tides, Rossby waves, 4-day waves		depends on whether balloon can be tracked on far side of planet - also, answer from an 8-day mission will not be definitive	
	mean meridional wind		depends on whether balloon can be tracked on far side of planet - also, answer from an 8-day mission will not be definitive	
	Turbulence characterisation to 1Hz	Yes on visible side from VLBI	Yes from VLBI & accelerometers	Yes from VLBI & accelerometers
Radiative balance	sensitivity to local cloud	YES - limited range of azimuthal angles	YES	YES
	detection of UV absorber	YES	YES	YES
E-M environment	EM background, conductivity, permittivity	YES - 5 events and 12 bckgrds per day	YES - 12 events and 24 bckgrds per day	YES - 100 events and 300 bckgrds per day
	lightning - optical, elec and acoustic	limited number of events	YES	YES - higher bandwidth, frequency range
Exobiology	Detailed characterisation of cloud droplets	NO (only basic characterisation of cloud)	OK (detailed GCMS cloud study possible)	Good (detailed GCMS runs & variability)
Outreach	images of balloon	NO	1 image per day + descent/inflation images?	2 images per day + descent/inflation images?
	lightning - optical, elec and acoustic	limited number of events	YES	YES - higher bandwidth, frequency range
	POWER CONSUMPTION	**5 W**	**12.5 W**	**15 W**

The power consumption shown in the bottom row is that required by the science payload only and does not include requirement for central electronics or communications system the planet, and both when the probe is visible from Earth and when it is not visible.

The average power required by the science payload for these different measurement scenarios is shown in Table 5; it can be seen that the high data return options require significantly more power.

The table shows that most of the science goals can be satisfactorily achieved with a mean science data production rate of 50 bits per second; when considering that direct-to-Earth communications are not possible when the balloon is on the far side of Venus, this requires a communications link capable of returning 100 bits per second during periods of visibility.

Science return would be greatly enhanced if a higher data rate were available during the initial 2 h of the mission, to permit a full set of results from all instruments to be returned. This initial dataset of 4 Mbits would include an isotopic MS measurement and full GCMS runs of atmospheric and aerosol samples. This high initial data return can be achieved by using the flyby craft as a data relay in this period, as will be shown in the mission scenario presented below.

4 Mission description

4.1 General mission architecture

The nominal mission includes a single spacecraft carrying an Entry Probe (EP) which contains the balloon system and gondola. The EP is composed of two elements: (i) the Entry System consisting of an aeroshell attached to a carrying internal structure, (ii) the Descent Module containing the balloon probe (BP) and its deployment system.

The baseline scenario is as follows:

- A single spacecraft carrying the EP is launched on a Soyuz/Fregat2–1b launcher from Kourou in the April 2023 launch window, which is optimal for propellant consumption. An alternative launch opportunity exists in 2021. The sizing of the spacecraft and payload is compatible with both options.
- Following launch, the carrier bus is injected directly onto a ballistic Earth-Venus trajectory. The transfer from Earth to Venus takes about 6 months.
- The EP is separated from the carrier a few days before arrival at Venus on an entry trajectory.
- After the release of the EP, the carrier is diverted onto a Venus flyby trajectory.
- The EP trajectory is such that the entry takes place on the nightside (for a safer balloon deployment), visible from Earth (to secure the mission), and in the target latitude range at the beginning of its mission (10 to 25°, N or S).

- The entry phase begins when the EP is at an altitude of ~450 km. It is followed by the deployment of the balloon at an altitude of ~55 km (see Section 4.2 for more details).
- During the descent and inflation phase and for about 2 h after the balloon reaches its final float altitude, the carrier bus is used as a data relay for the balloon probe in order to provide sufficient bandwidth (600 bits/sec) to ensure return of all data from this critical period of the mission. The distance between the carrier and the balloon reaches ~50,000 km after 2 hours (see Fig. 4a).
- For the remainder of the balloon's float phase, data are returned using a direct-to-Earth communications link, permitting a downlink rate of 100 bits per second (when the balloon is visible from Earth). The distance between the balloon and Earth is less than 130 million km (0.8 A.U.) for all the balloon mission life-time.

The Balloon communication, power, and science scheduling must accommodate the following visibility constraints (summarised in Fig. 4b):

– Direct contact between Earth and the balloon is possible during the first 4 days.
– Earth becomes visible from the balloon again after ~7 days.
– The balloon is visible from the carrier during the whole of the period where it is not visible from Earth.
– Moreover, the balloon is in sunlight from day 1.5 to 5.5 and after day 9.

The above scenario was calculated for a conservatively high estimate of 8 days for the circumnavigation period, but there is ample flexibility to deal with uncertainty in wind speeds.

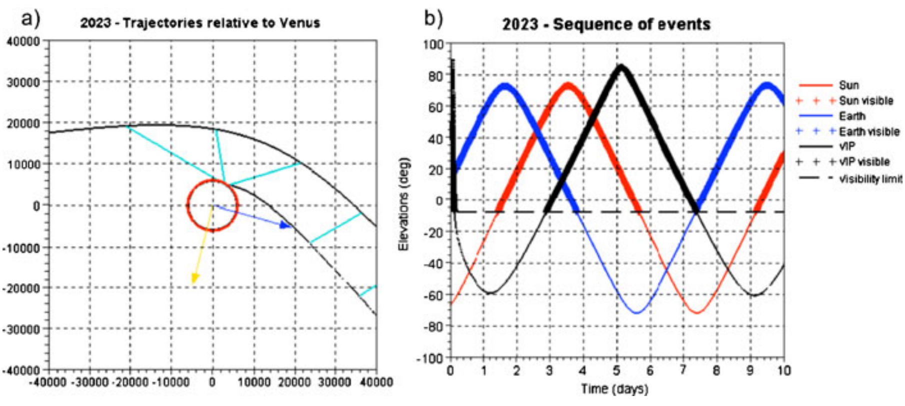

Fig. 4 **a** Trajectories of entry probe and flyby vehicle; pale blue lines show probe-VIP line of sight); and **b** visibility of Sun, Earth, and flyby vehicle from balloon

4.2 Atmospheric Entry, Descent, and Balloon Inflation (EDI)

The entry sequence starts at an altitude of about 450 km at a maximum velocity of 10.8 km/s to 11.2 km/s (worst case, for 2023 launch) and an entry flight path angle of about $-21° \pm 2°$. The front shield of the probe has an aerodynamic shape to reduce the velocity of the probe and protect the inside equipment from the thermal flux induced by the atmosphere. The peak of deceleration and thermal fluxes (both radiative and conductive) occurs between 100 km and 80 km of altitude. The maximal heat flux is ~26 MW/m^2, shared in two almost equivalent convective and radiative contributions. These values are obtained using a ballistic coefficient $\beta = \sim 140$ kg/m^2, derived from a preliminary design iteration.

At an altitude just below 70 km,when the vertical velocity has fallen below 130 m/s, a parachute is opened in order to slow down the entry probe. The front shield is released as soon as possible after the opening of the parachute, above 65 km altitude, to avoid an excessive heating of the gondola due to the rapid increase of the temperature of the backside of the shield. When the vertical velocity has fallen to ~10 m/s, at an altitude near 57 km, the balloon is deployed. The inflation of the balloon with helium gas then takes about 5 minutes, by which time the balloon has reached an altitude of 54 km. The parachute is now cut away and the balloon sinks down to reach its lowest altitude of 50 km. The helium tank is then jettisoned and the balloon ascends to its constant float level of 55 km. The procedure is based on that demonstrated at Venus by the successful deployment of the two Soviet Vega balloons in 1984 [31].

4.3 Gondola design

The gondola accommodates all the scientific instruments, and is responsible for providing them with electrical energy, data management and transmission to the Earth, and for keeping them in a suitable thermal and mechanical environment.

The structure, shown in Fig. 5a, is based on an octagonal tube made of carbon and covered with a protection layer to withstand the concentrated sulphuric acid of the Venus clouds. This octagonal structure is aligned with the cylindrical central tube of the carrier, providing a relatively simple interface to the carrier and the entry vehicle back shell, and supporting the huge deceleration during the Venus entry phase by directly leaning on the entry vehicle front shield. The gas tank and the balloon container, which are located inside the octagonal tube, are linked together and fixed to the gondola by 4 pyro-bolts, but this assembly presses directly on the front shield during the entry phase (Fig. 5b).

The scientific instruments are accommodated on the external faces of the tube and have direct access to Venus environment: ambient air can easily flow around the gondola, which facilitates the measurements. The outer faces of the tube provide enough space to accommodate the solar cells and the antennas for the communication with Earth. The inner faces are used to house

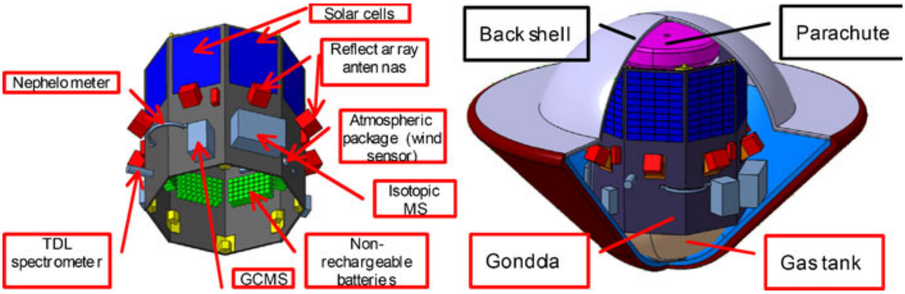

Fig. 5 **a** Gondola design and **b** gondola within entry probe (Figs. 24 and 25 from EVE proposal)

small equipment and electronics which do not need to have visibility on the environment such as non-rechargeable batteries or scientific payload electronics.

4.4 Power subsystem

The scientific payload's average power consumption is 13 W, with a peak requirement of 40 W. Total power consumption also depends on the mission's phase, since data is only transmitted on the Earth side.

Given the sequence of events of the balloon's orbiting life (Fig. 4b), the use of secondary batteries is not necessary: the lower energy storage density achievable by rechargeable batteries and the mass overhead of the conditioning unit would lead to a heavy power system. Furthermore, the only opportunity to recharge them happens early in the sequence, and the secondary batteries would not be sufficiently discharged at that time. Only primary batteries and solar cells are thus included in the mission.

Solar cells are sized with regard to the maximal expected consumption on the dayside, to minimize battery capacity requirements. With the mission's duration of 240 h, 120 h of which are on the sun's side and 154 h of which on Earth visibility (see Fig. 4b), the overall battery requirements are of 8,600 Wh. The 272 battery cells are accommodated in eight packs around the central tube.

It is emphasized that only triple junction GaAs cells are built today, and that they cannot work under the IR-poor radiation spectrum in Venusian clouds. GalnP cells, called "component cells" and used for the calibration of simulators, are well adapted to EVE requirements. They can be considered at TRL 4 because they are built according to space standards, and their qualification for EVE should not be problematic.

4.5 Telecommunication strategy

Several different types of communications links will be established:

- Carrier-Earth X-band link.
- Direct-to-Earth data delivery from the Balloon during the float phase (X-band, see below).

- Carrier-Balloon X-band link during EDI, and in the first two hours of float phase of balloon mission.
- Carrier-Balloon Doppler ranging at $T_0 + 4–8$ days.

Due to the lack of an orbiting relay station, most of the science data will be returned using a Direct-to-Earth (DtE) link from the balloon. The EVE baseline design uses adaptive phased arrays (APhA) of receivers /transmitters onboard the gondola. Either S-band (~2 GHz) or X-band (~8 GHz) operational frequency can be implemented, however the X-band is preferable because of the smaller susceptibility of the radio link to the interplanetary plasma scintillations, a better accuracy of the Doppler velocity, radial distance and lateral coordinates determination, and smaller size of the onboard assembly. Absorption of X-band signals above the balloon's altitude is negligible [25].

Four transmitting X-band array antennas, each being composed of a minimum of nine radiating elements, are placed on four gondola faces. A gain of between 12 and 15 dBi is achievable in a 30° beamwidth for an array of only $10 \times 10 \times 10$ cm^3 in size and 200 g in weight (for one array). An identical set of arrays is used to receive pilot signals broadcast from Earth using ESA ESTRAC 35-m or NASA DSN 34/70-m antennas. During operations, the APhA is electronically pointed at and phase locked to the pilot signal transmitted from Earth. The global distribution of the ESTRAC and DSN stations ensure 24-hour-per-day operational coverage in a two-way link mode during the entire mission lifetime. Use of additional Earth-based radio astronomical antennas in a phased-up mode for downlink signal reception together with the tracking stations could further improve the reception signal-to-noise ratio and robustness of the telemetry data decoding. As a safe/back-up mode, an optional omni-directional and unlocked transmitter can provide 2–10 bps DtE data rate depending on a size of the ground-based receiving antenna. Use of multiple phased-up reception antennas can also improve the downlink capacity in the un-locked omni-directional mode by a factor of 3 to 10.

The on-board APhA implementation will require 5 kg of mass and 25 W power consumption to ensure the required data rate of 100–200 bits per second when using the 35/70 m ESA/NASA tracking antennas and is based on a technology with TRL 8–9.

4.6 Balloon state vector determination

Determination of the balloon's state-vector (position and velocity) in the Venus-centric frame is necessary for many experiments carried out by the mission and characterisation of the wind field dynamics on the scales from local (~1 km) to global (>1,000 km) dimensions. When the balloon is visible from Earth, its position will be determined by using the radial Doppler, radial range and lateral coordinate measurement using two-way and multi-way radio links with ground-based tracking stations. These would include the European and global arrays of the Very Long Baseline Interferometry (VLBI) networks, as a part of the Planetary Radio Interferometry and Doppler Experiment (PRIDE) using primarily the European VLBI Network (EVN). At present, PRIDE can be characterised by TRL 8 to 9.

In a multi-way link mode in which one ground station transmits and several radio telescopes receive the returned signal in a phase-referencing mode, the lateral coordinates of the balloon in the Solar System Barycenter frame (SSBC) can be determined with an accuracy of 10 m (1σ RMS) at a distance of $\sim$1 AU and transmitting power of $\sim$1 W in the signal carrier line and widely separated (by 1–100 MHz) ranging tones with a power of 10% of the carrier line. The achievable accuracy of the Doppler velocity tracking will be at a level of 2–5 mm/s, radial distance measurement accuracy at a level of 1–3 m and lateral coordinates measurement accuracy at the level of 10–30 m at a sampling interval of $\sim$1–10 s in the SSBC or Venus-centric coordinate frame. These estimates assume the Earth-locked Phased array as described above. However, an omni-directional 5 W transmitting beacon could also be used to achieve somewhat lower but still usable Doppler velocity, radial ranging and VLBI measurement accuracy.

When the balloon is not visible from the Earth, it will be tracked from the carrier spacecraft. The carrier's trajectory has been chosen so that it is visible from the balloon probe during the whole of the latter's transit across the backside of Venus ($t \sim t_0 + 3$ to 7 days). The carrier-probe distance is large—1 to 2 million km. The carrier should be equipped with a medium-gain antenna to enable reception of a carrier signal from the gondola for Doppler and ranging measurements. This enables determination of at least the balloon probe's east-west position on the far side of Venus.

A small radar altimeter (only 250 g in mass) could be included on the gondola to help constrain the north-south position of the probe (making reference to topographic maps of surface altitude). The mass and power budgets have included this option, although the efficacy of this technique requires further study.

5 Discussion

Balloon missions will be an essential part of future Venus exploration, as they are ideally suited for exploring the uniquely benign pressure-temperature regime of the Venus cloud layer. In the current EVE proposal we have shown a mission which is achievable in Europe with no major technology development and is viable within the cost constraints of an M-class mission. The EVE team will therefore continue to develop this mission concept to be proposed again at the next opportunity.

A promising avenue for increasing the science return from the mission without increasing the cost to ESA might be found by collaborating with international partners. With the previous EVE proposal, submitted in 2007, we explored a very close collaboration with Russia involving a lander, orbiter and balloon all delivered to Venus using one launch. A programmatically simpler solution to explore might be to have an EVE-like stand-alone balloon probe launched by one partner (e.g. ESA), with a Venus orbiter independently launched by another agency. This orbiter could provide data relay and remote sensing context for one or more in situ platforms in addition to carrying out its own science mission (whether surface- or atmosphere-oriented). Such a collaborative mission would be programmatically attractive in that either mission element would be scientifically valuable as a stand-alone mission, but the joint operation at Venus of an orbiter and balloon would be significantly more valuable than the sum of its parts.

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