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WHY WE NEED TO GO TO VENUS: THE FUTURE OF EUROPEAN VENUS EXPLORATION

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ABSTRACT

Venus is the most Earthlike planet we know besides our own, in terms of its size and distance from its parent star. It was probably formed from the same materials as the Earth and Mars, at a similar time - why then has it become so different?

To address this key question, a team of 170+ scientists from around the world formulated the European Venus Explorer (EVE) mission proposal to the European Space Agency's Cosmic Vision Programme in 2007. Although it was not chosen in the 2007 selection round for programmatic reasons, it was rated a high priority for the future European Space Science so we take this opportunity to reiterate the science goals which motivated the EVE mission, and to discuss the status of technological and programmatic developments required to address these goals.

INTRODUCTION

Spacecraft exploration of Venus started with the Mariner 2 flyby of Venus in 1962, a mere 5 years after Sputnik 1. The ‘golden era’ of Venus exploration came arguably with the USSR’s Venera & Vega spacecraft programme (1967-1985), which saw no less than 16 spacecraft successfully reach Venus, including orbiters, landers and flyby missions. The last of these missions were Vega 1 & 2, which demonstrated successful deployment of balloons in the cloud layer of Venus. As to NASA’s programme, 1978 saw the launch of the Pioneer Venus missions, which included an orbiter as well as four descent probes and form the basis of much of our knowledge of Venus’ environment. This first phase of Venus exploration was followed in 1989 by NASA’s Magellan mission, a dedicated radar mapper, which returned global topographic maps on which our understanding of Venus’s geology is based.

After the Magellan mission, though, there have been no new Venus missions until ESA’s Venus Express orbiter was launched in 2003.

Most of the Venus Express experiments are currently operating successfully, returning a wealth of remote sounding data addressing many aspects of Venus science. However, mainly because of the thick Venus atmosphere, there are many questions which cannot be addressed by remote sensing measurements alone, in particular those related to the isotopic ratios of noble gases and cloud chemistry cycles, issues which are the keys to understanding current climate and evolution of Venus in particular and, in general, of other terrestrial planets.

To address these issues, we formulated the European Venus Explorer (EVE) mission, which would include a balloon, a descent probe and an orbiter. The central goal of the mission is ***to understand the evolution of Venus and its climate, with relevance to terrestrial planets everywhere*** (including in other solar systems). Starting from this goal, we derived the following measurement objectives:

1) To derive a unified model of the formation and evolution of terrestrial planets, by studying the record preserved in the atmospheric elemental and isotopic composition, together with data on escape processes.
2) To study the stability of the current climate on Venus, by quantifying the exchange of atmospheric constituents with the surface and interior of the planet, and at the interface with space.
3) To study the complex chemical and radiative processes in the lower atmosphere and, in particular, in the cloud layer by in situ measurements of gas and aerosol composition and radiative fluxes.
4) To re-construct the geological history of Venus, by mapping the subsurface structures by low frequency radar and to characterize the chemical composition of tesserae terrains.
5) To study the atmospheric dynamics, including the enigmatic super-rotation, using in situ probes and balloon trajectory tracking completed by remote sensing wind measurements.
6) To study electrical processes in the atmosphere through the search for lightning signatures by balloon and orbiter, and their potential impact on atmospheric electric and chemical properties

The detailed scientific case and instrument payload are described in detail in Chassefière et al. 2008a and Chassefière et al. 2008b.

We will not repeat this discussion in the present paper; instead, we will just re-emphasize that an in situ Venus mission such as EVE directly addresses many of the objectives of solar system exploration criteria as expressed in ESA’s *Cosmic Vision*:

- What are the conditions for planet formation and emergence of life?

1. Measurements of the noble gases and their isotopes will help to construct a unified scenario of the origin and evolution of terrestrial planets, helping to interpret observations of Earth-type extra-solar planets.
2. Study of escape processes and surface-atmosphere interactions will shed light on the

fate of oxygen on Venus, with relevance to all terrestrial planets, in particular those without a magnetic field.

3. Investigation of the current and past climate on Venus and its sensitivity to the internal and external factors will reveal if the planet once offered suitable conditions for the emergence of life, when and why they became unfavourable for life, and whether life could survive somewhere in the Venus atmosphere. These studies will also help to determine the size of the habitability zone in the Solar System.

4. The cloud layers on Venus in particular represent a potential habitat due to their benign temperatures and liquid water (albeit with high acidity). The cloud particles will be examined for the presence of pre-biotic or biotic constituents.

- How does the Solar System work?

1. The measurements of the atmospheric, cloud and surface composition by EVE will clarify the details of photochemical and thermochemical cycles in the Venus atmosphere and the buffering role of the surface on the atmospheric composition.

2. The atmospheric dynamics investigations will result in a better understanding of the general circulation for a slowly rotating planet.

3. The investigation of the atmosphere and clouds will reveal the details of the greenhouse effect and its role in the environmental and geological history of Venus and potentially that of the other terrestrial planets. Of particular interest is the question about whether Earth would evolve toward a massive Venus-type greenhouse dominated atmosphere, due to future increase of solar flux and anthropogenic influence.

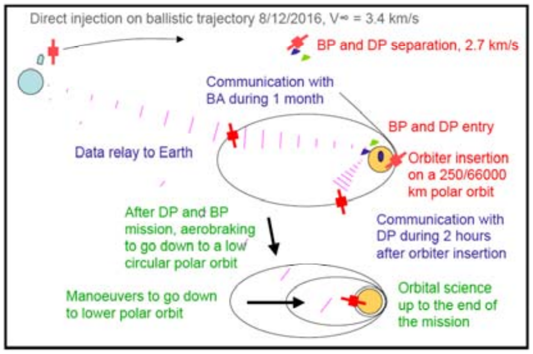
4. Investigation of the electric/ electromagnetic dynamics and lightning will contribute to a better understanding of the atmospheric processes, which are different from the Earth-like systems.

5. The EVE observations of escape processes and electromagnetic fields will significantly contribute to our understanding of the solar wind interaction with a non-magnetic planet.

6. The ionospheric and subsurface radar investigations coupled to the measurements will shed light on why the average age of the surface of Venus is about 700 Myr, i.e not so very different from the Earth. This may also resolve controversy about the current tectonic state of this dry, Earth-like planet.

EVE MISSION DESIGN

EVE is an "M-class" mission—roughly equivalent to NASA's "Discovery class" missions—which means that the total cost to ESA is estimated to be 300 M€. This figure does not include the cost of scientific instruments, which would be funded by individual nations, nor does it include sizable international contributions to the mission, in particular from Russia. This relatively low cost for such an ambitious mission architecture is made possible by taking advantage of the extensive heritage from the Russian Venera and Vega entry probes, and in particular from the French– Russian collaboration on Vega balloons.



EVE Baseline Mission scenario

EVE consists of one balloon platform floating at an altitude of 50–60 km, one descent probe provided by Russia, and an orbiter with a polar orbit which will relay data from the balloon and descent probe, and perform science observations. Several kinds of balloon have been proposed for planetary exploration [Blamont et al., 1997]. The balloon type preferred for EVE scientific goals is one which allows repeated vertical excursions through the cloud deck. A suitable flight profile will be obtained by filling the balloon envelope with a phase change fluid such as water, resulting in a flight profile which oscillates in altitude [diCicco et al., 1995; Nock et al., 1995]. However, most of the science goals can also be achieved using a helium superpressure balloon, as previously used for the Vega balloon missions, which would maintain a near-constant altitude for the duration of the mission. The nominal balloon lifetime is 7 days—enough for one full circumnavigation of the planet. The descent of the probe through the atmosphere takes 60 min, followed by 30 min of operations at the surface. The nominal orbiter life time is 2 years.

The EVE spacecraft is launched via Geostationary Transfer Orbit (GTO) by a Soyuz Fregat 2–1b from Kourou. The spacecraft delivers the balloon and descent probes to Venus from transfer orbit, and then is itself inserted into orbit around Venus. The orbiter performs data relay from the descent probe and balloon, while also performing context science observations. After the end of balloon operations, the orbit is lowered using aerobraking, to optimise further science investigations. The balloon and the descent probe are both tracked by Earth-based very long base interferometry (VLBI) to derive winds in the lower atmosphere.

The EVE balloon carries comprehensive chemistry and isotopic analysers, focussing on cloud-level processes. The key instrument is a state of the art gas chromatograph/ mass spectrometer (GCMS) system to analyse cloud and gas composition. Other instruments provide optical investigations of aerosol composition, microphysical properties, and radiative balance. In particular, the balloon provides a stable platform for the long integration times (~hours) required for isotopic mass spectrometry. The feasibility of deploying and operating balloons on Venus was demonstrated in 1984 by the Vega balloons—but those balloons carried only a very small payload of pressure, temperature, light flux, and backscatter sensors, and operated for only 48 h compared to the 7 day minimum lifetime specified for the EVE balloon.

The orbiter carries a range of instruments to complement the in situ measurements of the probes, especially:
a) A low-frequency radar for subsurface sounding and a sub-millimetre instrument to directly measure atmospheric winds will be used at Venus for the first time, and
b) A thermal infrared (IR) spectrometer will recover the science goals of the nonoperational PFS instrument on Venus Express.

The Russian descent probe carries instruments similar to the balloon payload, including a GCMS, but will focus on the vertical profiles of isotopic and molecular abundances, aerosol properties, radiative fluxes and convective stability. A particular scientific objective is the characterization of near-surface chemistry. The probe will return images during descent and from the surface, and measure surface composition after landing e.g. by gamma-ray spectroscopy. The planned landing site is in the highland tesserae regions, which are understood to be the oldest terrain on Venus, and have not yet been visited by any spacecraft.

The Japanese space agency (JAXA) has been developing a small, water vapour-inflated balloon which would be deployed at 35 km altitude and would communicate directly with Earth. This balloon would carry a few meteorological sensors and a radio beacon for trajectory determination, with a goal of determining the circulation at this altitude, which is important for understanding the atmospheric super-rotation. The JAXA balloon is an optional element of the EVE mission.

The entry mass of the balloon and descent probes is 170 kg each, and the orbiter dry mass is 690 kg before adding system margins; once 1800 kg of fuel have been added as well as various system margins, the total launch mass is roughly 3,000 kg, consistent with a Soyuz-Fregat 2–1b launch capability via GTO.

The mass of the science payload, including a 20% margin, is 52 kg for the orbiter, 12 kg for the balloon and 24 kg for the descent probe.

KEY MEASUREMENTS

Out of the large set of science objectives, it is useful to identify the key measurement objectives, which represent the minimum science return to be guaranteed by this mission. These are:

a) In situ measurement from the balloon of noble gas abundances and stable isotope ratios from the balloon, to study the record of the evolution of Venus.

b) In situ balloon-borne measurement of cloud particle and gas composition, and their spatial variation, to understand the complex cloud-level chemistry.

c) In situ measurements of environmental parameters and winds (from tracking of the balloon) for one rotation around the planet (7 days), to understand atmospheric dynamics and radiative balance in this crucial region.

These key measurement goals all require in situ atmospheric measurements. However, they also require use of an orbiter for three reasons: (1) to ensure sufficient data relay; (2) to provide context for the in situ measurements; and (3) to enable tracking and communications when the balloon is not visible from the Earth. The orbiter significantly increases the science return of the mission, with important new remote sensing observations including subsurface radar sounding and direct Doppler wind measurement, with very little programmatic or technological risk.

Finally, a full treatment of the question of Venus' evolution must include an investigation of Venus' geological history. In the EVE mission, this is addressed in two principal ways: firstly by the Russian descent probe, which would measure directly the mineralogy and geomorphology of the unexplored highland "tessera" regions, and secondly by the orbiter's next-generation multi-wavelength radar, which would provide a much-needed update to the Magellan radar maps. The provision of the descent probe by Russia takes advantage of the immense flight heritage of the Venera program which included no fewer than 12 descent probes, and avoids the need in Europe to fund the extensive technology development which would be required to create a European descent/surface probe. Even if the descent probe fails, though, the geological evolution of Venus will be addressed through the orbiter's radar mapper and, possibly, by using balloon-deployed descent probes (described below).

KEY TECHNOLOGIES

The EVE mission was designed to take advantage of existing heritage from all the international partners in the consortium: ESA was to provide the orbiter building on experience from spacecraft including Venus Express and Bepi Colombo. The balloon would take advantage of the heritage of the French/Russian Vega balloons; Russia was to design the entry system and the descent probe, based on its extensive heritage of Venera & Vega landers; Japan was optionally to provide a low-altitude balloon based on its existing technology development programme [Izutsu et al., 2004]. The possibility of using NASA/JPL developed Venus balloon technology through international collaboration, under NASA's Mission of Opportunity (MoO) program, is also being considered.

The key technologies required for the various mission elements are now explored in more detail.

Orbiter

The insertion orbit is a polar elliptical orbit (250x66000 km) similar to the Venus-Express orbit. After a period of 1 Venus sol (≈250 Earth days), the apoapsis will be lowered by aerobraking to reach an orbit of 250x11000 km.

The two main critical issues of the EVE orbiter are the thermal control design and the aerobraking phase. Passive thermal control techniques were applied on Venus Express. However flying a low altitude orbit around Venus will be more demanding because of the more intense and continuous Venus albedo effect. Considering potential re-use of technological solutions developed for BepiColombo, no show-stopper is anticipated, pending a more detailed thermal control study.

Aerobraking technique was used for the first time by NASA with the Magellan spacecraft in orbit around Venus, and then three times with

Mars orbiters. Although Mars Express and Venus Express were designed to support soft aerobraking, Europe has no operational experience of aerobraking and specific studies, pre-development and qualification programs need to be carried out for its actual implementation. Furthermore it might well be that in future extensions of the Venus Express mission, ESA and scientists decide to lower the orbit pericenter altitude not only to experiment aerobraking, but also to enhance the atmospheric science return of the mission. In addition, several risk mitigation options have been identified by ASTRIUM. Overall EVE's aerobraking strategy is a low-risk opportunity for Europe to acquire the know-how of a maturing technology suitable for more efficient future missions to Venus and Mars.

The scientific payload proposed for the orbiter is mature, with the exception of the Canadian lidar, which requires additional studies and must be considered at the present stage as an option, and the neutral and ion mass spectrometers, which will benefit of developments made for the BepiColombo mission.

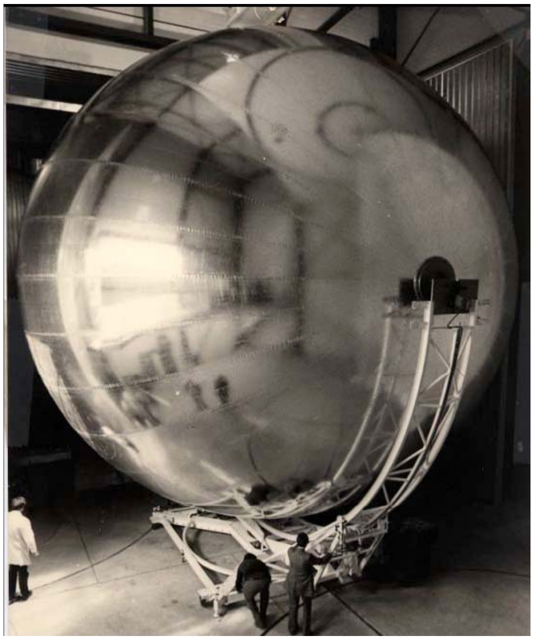
Entry/descent system

The entry/descent system would be provided by Russia and funded by Roscosmos. A Venus exploration mission by means of a descent probe is included in Russian Federal Space Programme with a launch after 2015. The launch, the descent probe and other elements of this national mission could still become a part of joint EVE mission.

The concept of descent probe is proposed by Lavochkin Association, which has a comprehensive experience in design and manufacturing of Venus landers and descent vehicles, including Venera 4-16 and Vega probes. Although the EVE descent probe is much smaller with respect to the previous vehicles delivered to Venus by heavy launchers, key technologies, such as thermal protection, will be assimilated from earlier designs.

Russia would be responsible for the integration of the descent probe payload, while European expertise would be widely used in scientific instruments. The payload exploits heritage from the Russian Vega and Phobos Sample Return missions, as well as ESA's Huygens, ExoMars and BepiColombo missions (TRL for all payload is above 4). Currently, the γ-ray spectroscopy is planned as the primary method of chemical analysis on the surface. Development of an enabling technology to deliver the soil sample into the protected volume would allow substantial mass saving and the study of the soil by a variety of methods (to be validated in 2010).

Identical entry vehicles (3-stage parachute system, front-heat shield) would be used both for the descent probe and the balloon, in order to minimise the development costs. As currently envisaged, these would be studied in an assessment phase by the Lavochkin Association.



CNES Venera supe pressure balloon (1970-80)

Balloon (Envelope and deployment)

The EVE balloon development would be led by CNES, building on its heritage from the successful deployment on Venus of two balloons during the Vega programme. The balloon and its inflation system would be developed by CNES in 4 identified phases:

1) Demonstration of feasibility: development of the balloon fabrication technique, production of

prototypes of balloon systems, engineering for the flight physics analysis.
2) Demonstration of deployment sequence: development of the full scale balloon systems, engineering of interface with the gondola in particular with respect to balloon flight control, engineering of interface with entry/descent system, deployment tests.
3) Validation and qualification testing: overall balloon system test including entry/ descent final phase simulation, and entry/descent system and gondola qualification models.
4) Procurement of flight models: delivery of the balloon system flight models.

Gondola

The gondola would be under the responsibility of ESA. Enabling technologies for the gondola are listed in the Venus Entry Probe ESA technology Reference Study. The identified enabling technologies are: (i) in situ atmospheric instruments, (ii) thin film solar cells, (iii) primary batteries and (iv) miniaturized DPU (Data Processing Unit).

The instruments proposed for the balloon are all at a TRL level of 4 (i.e. using Huygens, Rosetta, Beagle 2 and ExoMars heritages) except for the nephelometer, to be provided by the USA under NASA's MoO program. The model payload is therefore considered robust and mature. The necessary, assessment studies are expected to confirm that the other enabling technologies have a TRL in the range from 3 to 5.

Communications & localisation

The communications strategy for EVE does not require the development of any new technologies. Four types of communications will be established :

- Bidirectional communications in UHF band between the descent probe and orbiter through the Venus atmosphere.
- Bidirectional communications in UHF band between the balloon probe and the orbiter.
- Bidirectional communications at X and Ka band between orbiter and the Earth.
- S-band transmission from balloon probe to Earth – this will be used for VLBI and Doppler tracking of the balloon.

We wish to highlight particularly the probe localisation abilities, being co-ordinated by the Joint Institute for Very Long Baseline Interferometry in Europe (JIVE). Using a small S-band transmitter on the balloon, positioning accuracy in SSBC and Venus-centric frame would be better than 100 m on a time scale of 10-20 s, with radial velocity accuracy better than 1 cm/s on time scale 1s. These measurements of the position and velocity of the balloon will reveal the atmospheric dynamics in the cloud layer.

We note also that the direct-to-Earth communications link of the balloon is a robust link which can be used for scientific data return in the event of failure of the data relay via the orbiter. Using only radio telescopes already existing in 2008, a maximum average data return of 10 bits per second could be achieved from the balloon probe (once coding efficiency and probe visiblities have been taken into account). This is enough to return the key measurements as decribed above.

Optional microprobes

Before the Russian descent probe was incorporated into the EVE mission, two studies were performed on the feasibility of balloon-deployed descent probes to address lower atmosphere and/or surface study. The first study proposed small (100 g) 'micro-probes' equipped with pressure, temperature, light flux and contact chemistry sensors [Wells et al., 2004]. Such probes would be tracked using a phased antenna array mounted on the balloon platform in order to return information about winds, and their sensor payloads would return information about the vertical structure and chemistry of the deep atmosphere. Up to 20 such probes could be carried, thanks to their low mass, in order to return atmospheric profiles at several locations around the planet.

In a second study, a camera was added to the microprobe payload, in order to address surface science goals (specifically, to obtain descent imagery and constrain surface mineralogy). The high data rates required by a camera dramatically increase the power requirements, but the total probe mass with robust margins remains below 2 kg.

These two probe studies show that, even without a dedicated descent probe, some surface geology and deep atmosphere science objectives can be addressed using balloon-deployed probes.

Conclusion

The heritage of Venus-Express and BepiColombo for the orbiter, of the Soviet-French Vega mission for the balloon,of the numerous Venera landers and Huygens for the descent probe, and the performance of the currently existing VLBI network, make EVE a realistic mission. Following Huygens, Rosetta and ExoMars, in situ instrumentation for planetary exploration will be very mature, with unprecedented instrumental performance.

CURRENT STATUS AND OUTLOOK

The EVE mission proposal was not selected in 2007. However, it is included in ESA's "Cosmic Vision technology plan" (ESA/SPC document dated 21 May 2008) because it was judged "a high priority for the future European Space Science". Technology development activities towards this goal to be undertaken in Europe include:

a) Balloon studies: envelope material and & inflation / deployment studies are proposed by CNES with national funding.
b) Heat shield material development, to be funded by ESA (this is proposed specifically for Marco Polo but is also of relevance to Venus entry probes)
c) Payload development activities funded nationally, including MEMS-based gas sensors (U.K. and France), nephelometer (the Netherlands), and electro-magnetic field sensors (Hungary).

The EVE mission consortium has revealed strong scientific interest in an in situ Venus mission, both from ESA countries and from our international partners. Furthermore, it has shown that most of the technologies needed for this ambitious and challenging mission already exist in Europe and/or in Russia. Together with our international partners, we hope to ensure that an in situ Venus mission can be put together before the expertise which has gathered around the Venus Express mission and the EVE proposal become dissipated.

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