Atmospheric planetary probes and balloons in the solar system

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Abstract: A primary motivation for *in situ* probe and balloon missions in the solar system is to progressively constrain models of its origin and evolution. Specifically, understanding the origin and evolution of multiple planetary atmospheres within our solar system would provide a basis for comparative studies that lead to a better understanding of the origin and evolution of our
Q1 own solar system as well as extra-solar planetary systems. Hereafter, the authors discuss *in situ* exploration science drivers, mission architectures, and technologies associated with probes at Venus, the giant planets and Titan.

Q2 **Keywords:**

1 INTRODUCTION

Since the beginning of the space age in 1957, the United States, European countries, and the Soviet Union have sent dozens of spacecraft, including probes, to explore the solar system. While some of these spacecraft failed to reach their targets, many others have sent back valuable information. In this article, the authors focus on the *in situ* exploration of solar system planets with significant atmospheres: Venus, the giant planets, and Titan.

While work has been done since the 1960s on robotic 'rovers' and static landers to explore the Moon and
Q3 other worlds in the solar system, such machines have limitations. They tend to be expensive, have limited or no traversing range, and, due to the communications timelag over interplanetary distances, autonomous operation is required. For example, static landers need to be designed for landing hazards, which could provide significant design challenge, thus translating to high mission complexity, risk, and cost.

This article focuses on the exploration of planetary bodies with sizable atmospheres, using entry probes and aerial mobility systems, namely balloons. Besides Earth, solar system planets and moons with sizable atmospheres include Venus, the giant planets Jupiter and Saturn, and one of Saturn's moons, Titan. Various *in situ* missions have visited most of these destinations with descent probes, balloons, landers, and rovers, supported by orbiters or flyby spacecraft. Mars does not have a dense atmosphere; however, balloons and balloon technology were considered and studied for Mars exploration and the associated energy supply. For more information, the reader is referred to articles by Kerzhanovich *et al.* [**1**] and Gurfil and Cory [**2**]. Q4

Probes provide science measurements along their entry trajectories and in some cases down to the surface. Due to their simplicity (and often short lifetime), these missions tend to be less expensive than longer-lived lander or surface-rover missions. Balloons spend most of their lifetime floating at a constant or near-constant altitude and can have varying lifetimes depending upon the environment and the balloon design.

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This section provides a brief overview of relevant past and ongoing missions to explore Venus, the giant planets, and Titan, with probes and balloons. In what follows, material from several white papers submitted to the Decadal Surveys, NASA and ESA study reports (NASA Science Plan for NASA's Science Mission Directorate 2007–2016: http://science.hq.nasa.gov/strategy/Science_Plan_07.pdf; NASA's Flagship Mission to Venus: Final Report of the Venus Science and Technology Definition Team, April 2009, http://vfm.jpl.nasa.gov; Titan Saturn System Mission (TSSM) Flagship reports at: http://opfm.jpl.nasa.gov/library/), and Outer Planet Advisory Group (OPAG, http://www.lpi.usra.edu/opag/opag_pathways.pdf) recommendations, is used.

1.1 Venus exploration

By early 2010, at least 35 probes had been launched towards Venus with 22 achieving their science objectives. Of these, 17 have been Soviet, including the first two spacecraft launched to Venus in 1961. (One of these actually flew past Venus, although by then its radio system had failed.) The first successful mission to Venus, in fact, the first successful planetary mission, was Mariner 2. This American spacecraft flew past Venus in December 1962 at a distance of 21 600 miles (34 762 km) and returned data about its atmosphere.

The Soviet Venera 3 mission, in March 1966, was the first probe to enter the Venus atmosphere and reach the surface. Venera 3 was, in fact, the first spacecraft to impact another planetary body. Through the late 1960s, the Soviets continued to send probes to Venus to obtain data from the inhospitable surface, but none succeeded until Venera 7, which returned the first information from the surface in December 1970. For 23 min, the Venera 7 lander returned data about conditions on the ground before succumbing to the extreme heat and pressure. It was the first time that any probe had returned information from the surface of another planet.

The two Soviet probes, Venera 9 and Venera 10, were launched in 1975, and returned the first photographs from the surface of Venus. These images showed flat rocks spread around the landing area. Two new probes, Venera 11 and Venera 12, landed on the planet in 1978 (although they were unable to return images). In 1982, another pair, Venera 13 and Venera 14, returned the first colour photographs of the surface. Venera 13 set the record of surviving on the surface of Venus for 127 min. Orbiter missions such as Venera 15 and Venera 16 mapped the Venusian surface using high-powered radars. Perhaps the most ambitious Soviet missions to Venus were the highly successful VeGa 1 and 2 missions, launched in 1984. Each of the two carrier spacecraft delivered landers and atmospheric balloons, and flyby carriers to encounter Halley's comet. The superpressure VeGa balloons operated in the atmosphere for 48 h, demonstrating the feasibility of planetary ballooning [**3**] (Fig. 1). This short lifetime was caused by the depletion of the on-board batteries.

NASA has also implemented several ambitious missions to Venus, including the 1978 Pioneer-Venus mission, comprising an orbiter with a powerful radar, and a spacecraft bus with one large and three small atmospheric entry probes. The smaller probes scattered through the atmosphere and collected data as they descended to the surface, and provided evidence that the Venusian atmosphere is relatively clear below about 30 km. All of the Pioneer probes successfully performed descent science, but experienced electrical failures near the surface, the 12.5 km anomaly. Since Pioneer-Venus, NASA has conducted only one mission to Venus, the Magellan orbiter. Launched in 1989, Magellan successfully went into orbit around Venus in August 1990. By the time its mission ended in 1994, Magellan had successfully mapped 98 per cent of the surface of the planet using a synthetic aperture radar that was designed to see through the thick atmosphere. Magellan discovered that at least 85 per cent of the surface of the planet is covered with volcanic flows.

More recently, ESA's ongoing Venus Express (VEX) orbiter has been observing Venus since April 2006. VEX observed new dynamical phenomena, whose understanding requires follow-on exploration missions that acquire additional data in greater detail and wider coverage. Japan's Akatsuki Venus Climate Orbiter (VCO) was successfully launched on 20 May 2010. While VEX is designed to make extensive composition and polar dynamics observations, VCO will study primarily the weather and climate of the planet including possible lightning, thus complementing the results of the VEX mission. VCO also has a solar sail demonstrator on board. To address the highest priority science questions related to the origin, evolution, and the coupling between the subsurface, surface, and the atmosphere of Venus, *in situ* missions are essential. Options include balloons, descent probes, and landers performing descent science.

1.2 Giant planets exploration – Jupiter

Due to distances and corresponding mission cost and complexity, outer solar system missions are less frequently than those travelling to the inner planets. The NASA Pioneer 10 and Pioneer 11 spacecraft, launched in 1972 and 1973, respectively, were the first missions to traverse the asteroid belt and fly past the gas giant planets Jupiter and Saturn. Pioneer 10 flew 130 354 km above the cloudtops of Jupiter on 3 December 1973 and provided the first close-up images of the planet, and studied the radiation belts and magnetic field of Jupiter. Pioneer 11 flew only 43 000 km above the cloudtops in December 1974. During its encounter, Pioneer 11 made the first observation of the immense polar regions and determined the mass of Jupiter's

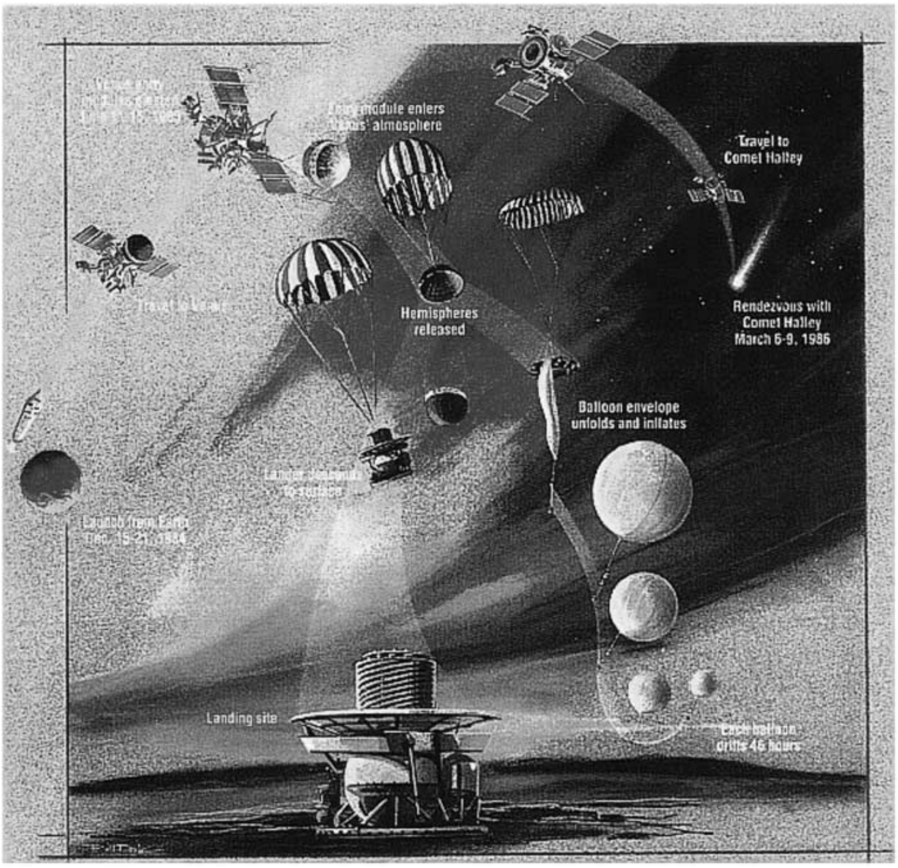


Fig. 1 VeGa balloons at Venus [**3**]

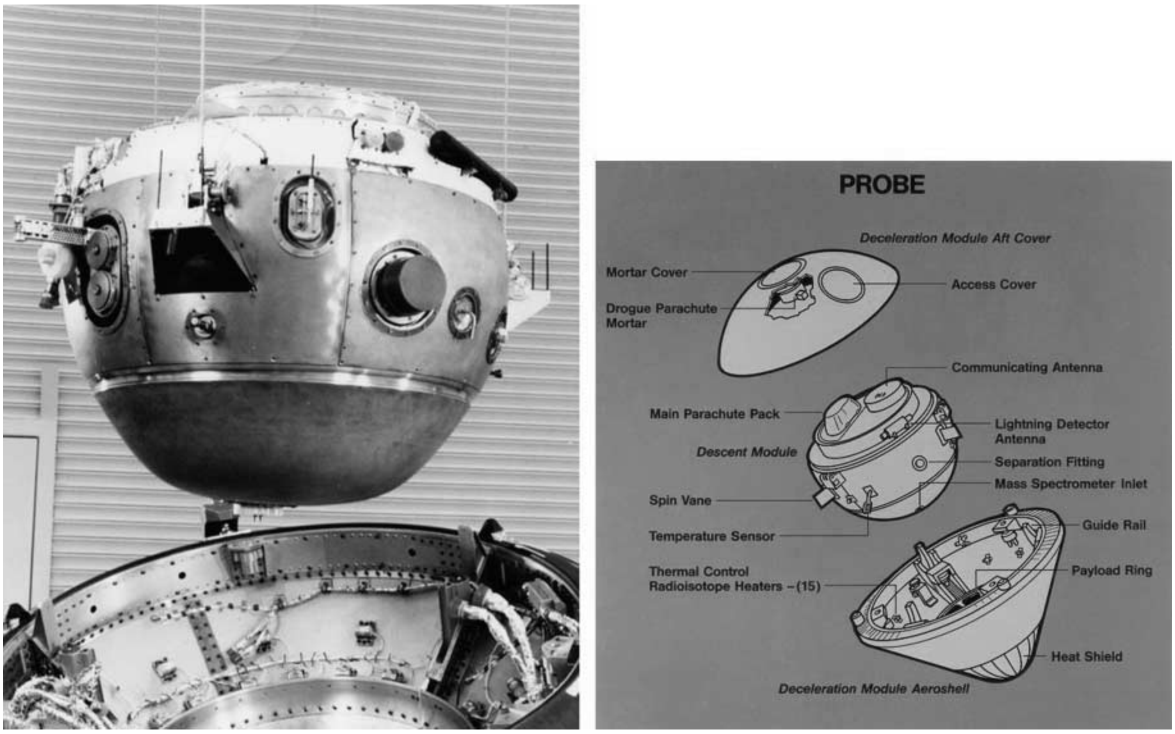
moon, Callisto. In September 1979, Pioneer flew past Saturn and not only returned the first close-up images of Saturn, but also discovered two previously unknown moons and a new ring, studied Saturn's magnetic field and magnetosphere, and made the initial observations of Titan.

The NASA Voyager mission took advantage of an exceptionally favourable planetary alignment that occurs once every 180 years. The 1980's alignment of Jupiter, Saturn, Uranus, and Neptune provided the opportunity for successive gravity assists and allowed Voyager 2 to visit these four planets in sequence, a grand tour. The Voyager 1 spacecraft visited the Jupiter and Saturn systems, while flying by the largest Saturnian satellite, Titan. Although neither the Pioneer nor the Voyager spacecraft carried atmospheric entry probes, these missions provided the basis for the present knowledge of the outer solar system, revealing properties, structures, and dynamics of the giant planet clouds and atmospheres, and showed the satellite systems of these gas giants to be extraordinarily diverse and comparable to mini solar systems.

The Galileo mission was sent by NASA to study the Jupiter system. Named after the astronomer and Renaissance pioneer Galileo Galilei, it was launched on 18 October 1989 via the space shuttle Atlantis, and arrived at Jupiter on 7 December 1995 following gravitational assist flybys of Venus and twice by Earth. Galileo conducted the first asteroid flyby, discovered the first asteroid moon, was the first spacecraft to orbit a giant planet, and successfully deployed the first giant planet entry probe targeting Jupiter. On 21 September 2003, after 14 years in space and 8 years of service in the Jovian system, Galileo's mission was terminated by the orbiter's plunge into Jupiter's atmosphere to avoid any chance of an accidental impact on Europa, carrying the possibility of depositing foreign basic organics on Jupiter's ice-crusted moon that scientists suspect may have a life-harbouring salt water ocean beneath its surface.

The Galileo atmospheric entry probe, released from the main spacecraft in July 1995, carried a payload of seven science experiments (Fig. 2), including:

(a) an atmospheric structure instrument to measure temperature, pressure, and acceleration;
(b) a neutral Mass Spectrometer (MS) for measuring composition;
(c) a helium-abundance detector;
(d) a nephelometer for cloud location and cloud-particle observations;
(e) a net-flux radiometer to measure the difference between upward and downward radiant flux at each altitude;



Q5 **Fig. 2** Galileo probe descent module (left) and a diagram (right) of Galileo atmospheric entry probe instruments and subsystems (Credit: NASA/JPL)

(f) a lightning/radio-emission instrument with an energetic-particle detector to measure lightning in the atmosphere and energetic particles in Jupiter's radiation belts;
(g) a Doppler wind experiment to measure Jupiter's deep zonal wind profile [**4**].

Entering Jupiter's atmosphere on a direct ballistic trajectory, the Galileo probe was slowed from an arrival speed of ~47.8 km/s to a subsonic speed in less than 2 min, then deployed a 2.5 m main parachute, and descended through 150 km of the top layers of the atmosphere, collecting 58 min of data on the atmospheric composition, chemistry, structure, and dynamics. The Galileo probe descended into a warm, cloud-free region known as a 5-micron hotspot and therefore did not make the desired water or cloud measurements. However, the probe did find an atmosphere that was enriched in heavy elements, hotter and more turbulent than expected, with winds that increased with depth.

1.3 Titan

The joint NASA–ESA–ASI Cassini–Huygens mission was launched in October 1997 with great success [**5**]. This mission's goal is the study of the Saturn system and particularly its satellite Titan (Fig. 3). Cassini is an orbiter developed by NASA, which entered orbit around Saturn in July 2004. In December 2004, Cassini deployed the Huygens probe (developed by ESA) towards Titan to study its atmosphere. On 14 January 2005, the Huygens probe entered the atmosphere of Titan and landed, 2 h and 32 min later, onto its surface. Huygens is a robotic probe that has landed the furthest away from the Sun (about 10 AU) thus far. It returned an unprecedented set of new data about Titan to Earth through its six instruments that were designed to measure the atmospheric composition and structure (Huygens atmospheric structure instrument), the winds field (Doppler wind experiment), to collect and analyse the composition of atmospheric particles (aerosol collector pyrolyser), to acquire the mass spectrum of the atmospheric and surface components (Gas Chromatograph(GC)/MS) and spectro-image the surface and determine its properties with the descent imager spectral radiometer and the surface science package [**6**]. Because of what Cassini–Huygens has discovered, future exploration of Titan, as described hereafter, would need to involve both remote and *in situ* explorations, the latter using such elements as possibly a balloon, an airplane, and/or a lake lander.

2 SCIENCE DRIVERS FOR *IN SITU* EXPLORATION

2.1 At Venus

Venus, while considered Earth's sister planet, is a world quite different from our own, but with a number of similarities. Of similar size and formed in the same neighbourhood of the solar nebula, Earth and Venus

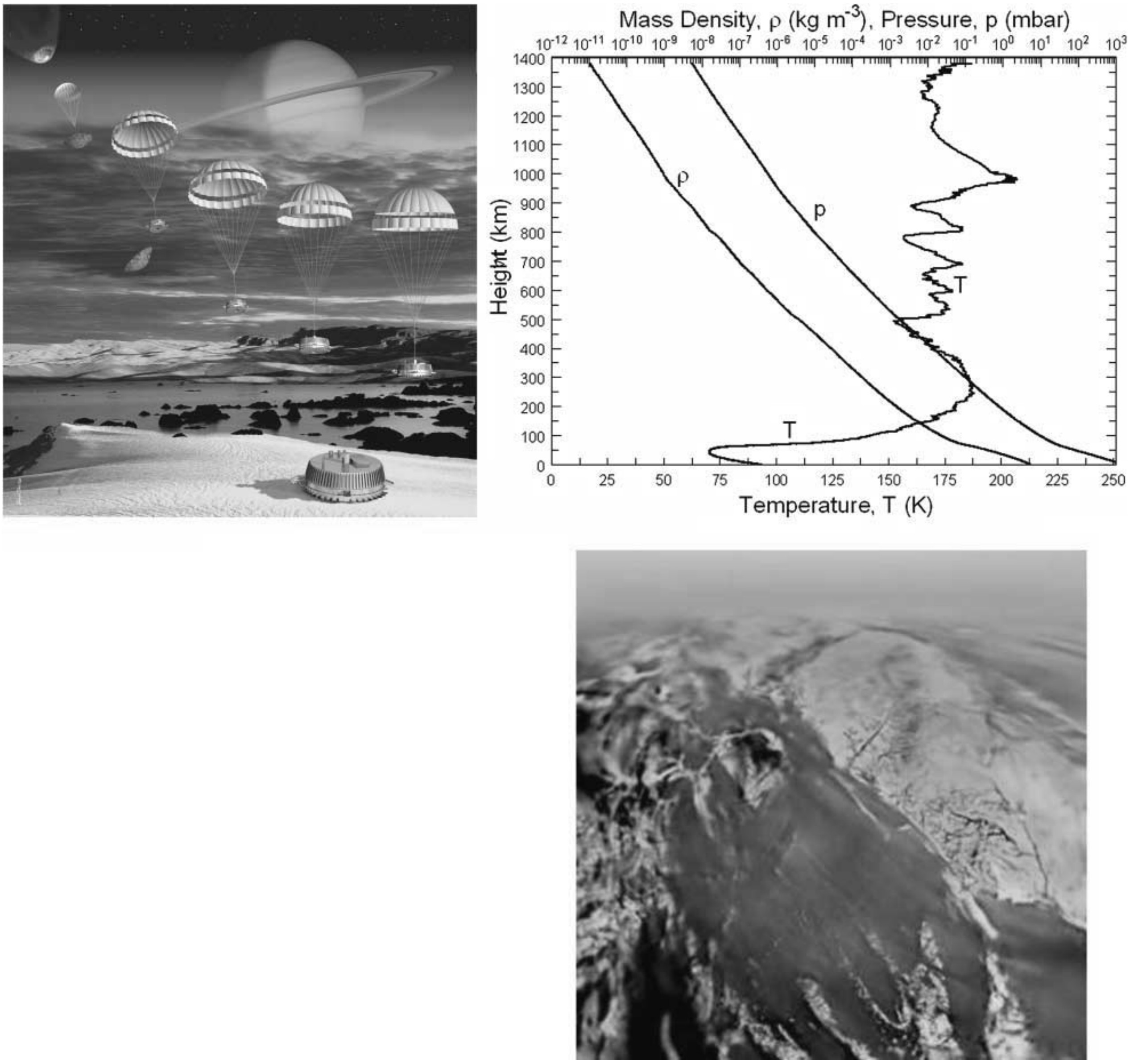


Fig. 3 Huygens probe delivered to Titan by the Cassini spacecraft. Its deployment in Titan's atmosphere (left) and some of the science results: the thermal profile and atmospheric properties
Q5,Q6 by the HASI instrument (upper right) and a panorama of the surface images taken by the DISR instrument (right lower) (Credit: ESA and NASA/JPL/University Arizona)

were most likely constructed from identical planetary building blocks so that in many ways they are nearly twins. The surface of Venus shows familiar geological processes, and its climate, like Earth's, may be driven by interactions between the atmosphere, surface, and interior. In spite of the common heritage, the two planets show significant contrasts. Underneath a supercritical gaseous envelope of 96 bar of CO_2, N_2, H_2O, and sulphur gases, Venus has a burning hot surface ($T \sim 740$ K). Recent research on the evolution of Earth's greenhouse effects has shown that understanding of non-linear feedbacks (such as those on Venus) is crucial if one wants to understand and to be able to predict the influence of natural and anthropogenic climate perturbations on our own planet and elsewhere [**7**, **8**].

The bulk of Venus' atmosphere rotates faster than its surface, with many layers at the equator moving as much as 60 times faster than the surface. The atmosphere is responsible for 0.15 per cent of the angular momentum of the planet. The ways by which angular momentum and heat are transferred in the Earth's atmosphere represent some of the most important areas of current research and are very important for the basic understanding of our own climate. Venus' exaggerated dynamics promise to help elucidate subtle aspects of the Earth's circulation and their feedbacks.

Thus, there is strong motivation of global terrestrial concern for exploring Venus: As the authors discover how climate and geology work on a world similar to our own, a deeper understanding of the processes at work in our own environment is gained. The authors better appreciate today that the Earth's climate system is not sufficiently well understood, and that the threat of accelerating anthropogenic changes to the atmosphere becomes a valid concern for the vulnerability of the world in which live. The study of the links between surface, interior, and climatic processes on Venus has reinforced the idea that Venus could represent the fate of the Earth. The realization that two such similar planets could produce this extreme range of processes and conditions makes Venus an essential target both for improved understanding of the Earth system and for the exploration of Earth-like planets beyond our solar system [**9**]. This argument is also valid in the case of Titan's exploration.

By studying Venus's current and evolving inventory of atmospheric gases, surface mineralogy, and meteorology, a well-defined Venus surface mission could address a number of key questions about the history and evolution of Venus and help define essential factors in the climate system to increase our understanding of how terrestrial planetary environments arise and evolve. The increasing recognition of the exchanges between atmosphere, surface, and the interior and climate evolution as modulated by geology and tectonics [**10–12**] call for an integrated study essential in order to advance our understanding of planetary systems.

In the course of future Venus' exploration, space missions will investigate important differences and analogies between Venus and Earth [**13**]. Key questions to be addressed include the following.

1. *Origin and evolution*: How did Venus originate and evolve, and what are the implications for the characteristic lifetimes and properties of habitable environments on Venus and similar planets in other (extrasolar) planetary systems? Did early Venus have a dynamo, perhaps driven by plate tectonics and/or an early ocean resulting from interior outgassing? If so, what stopped these processes and how was the ocean lost?
2. *Venus as a terrestrial planet*: What are the processes that have shaped Venus? Are some of them still active? Although Earth and Venus are quite similar in size and mass, Venus' surface at this time is clearly hostile to Earth-like carbon–water-based organisms. The far denser Venusian atmosphere (compared to Earth's) is composed mostly of carbon dioxide with abundant sulphur oxides and has a significant deficit of hydrogen, while the interactions with the surface play an important role. An important question concerns the level of activity on Venus today. The search for it ranges from observing active volcanic processes, to tracking the clouds and analysing meteorological data such as winds, pressures, and temperatures. In order to confirm and define internal structure and activity one needs to detect ground movement at one location and survey the planet globally for seismic events. Mineralogical and chemical analyses of Venus' surface, if done with sufficient precision, have the potential to revolutionize our understanding of Venus' geology and provide answers to questions such as when and where did the water disappear from the surface of Venus. The ability to analyse both rocks and soils and to drill to depths within pristine rocks holds the key to past changes in atmospheric conditions, volcanism, and climate.
3. *Climate change and the future of earth*: What does Venus tell us about the fate of Earth's environment? The greenhouse effect on Venus is terribly strong: the abundance of carbon dioxide is such that it absorbs almost all of the thermal radiation, producing an average surface temperature in excess of 455 °C. The state of Venus' climate is what we call 'runaway greenhouse' [**14**], but it has also been applied to the dangerous extreme anthropogenic climate change on Earth [**15**]. The Venus greenhouse is poorly understood because it is coupled to still mysterious atmospheric dynamics and cloud physics. By studying the runaway greenhouse effect on Venus, one could learn something about the fate of Earth's climate and to better understand the atmosphere in general, *in situ* experiments that simultaneously probe dynamics, chemical cycles, energy balance, and isotopic abundances must be performed.

2.2 At the giant planets

The giant planets offer a window into the past when the solar system was forming. The giant planets are a natural laboratory for studying the atmospheric chemistry, dynamics, and interior of all planets, including the Earth. The well-mixed atmospheres and interiors of the giant planets are believed to harbour the primordial solar nebular material from which all of the Sun's planetary systems formed and subsequently evolved over 4.5 Gy. Additionally, the atmospheres of the giant planets hold clues to the chemical nature of the refractory materials from which the original planetary cores formed. These clues can be derived from measurements of the composition, dynamics, and structure of giant planet atmospheres.

2.2.1 Composition

Conventional models of the formation of giant planets predict that the proportion of the core mass relative to the planetary mass should increase with distance from the sun, with a corresponding increase in heavy elements (ratioed to H) compared to the Sun, going from Jupiter outwards to Neptune. Carbon, in the form of methane, is the only heavy element measured so far on all the giant planets. As predicted, Voyager, Galileo, Cassini, and ground-based remote sensing have shown that the ratio of carbon to hydrogen increases from three times solar at Jupiter to 30 times solar or greater at Neptune.

In addition to carbon, of particular importance to constraining and discriminating between competing theories of giant planet formation are the mixed-atmosphere abundances of the heavy elements (mass > 4He), particularly nitrogen, sulphur, oxygen, heavy noble gases, and their isotopes; and the isotopic ratios of hydrogen, helium, nitrogen, oxygen, and carbon. In addition, helium is especially important for understanding the interior structure, equation of state, and the formation of the giant planets. Abundances of disequilibrium species such as carbon monoxide, phosphine, germane, and arsine can provide insight into convective and other not easily observable dynamical processes occurring in a planet's deep atmosphere.

2.2.2 *Structure and dynamics: transport, clouds, and mixing*

High-speed lateral and vertical winds are known to move constituents, thereby creating the strongly banded appearance of zonal flows modulated by condensation (clouds), and by vertical and lateral compositional gradients. As temperature decreases with increasing distance from the Sun, the expected depths of the cloud layers should also increase. At the warmer temperatures of Jupiter, equilibrium models predict three cloud layers: an upper cloud of ammonia (NH_3); a second, slightly deeper cloud of ammonium hydrosulphide (NH_4SH); and deeper still cloud(s) of water ice and/or water–ammonia mixture. At Jupiter, water is the deepest cloud expected, with a cloud base predicted to be at depths of 5–10 bar with O/H ranging between 1 and 10 times the solar value (references [**16**] and [**17**]). In the colder environs of Saturn, Uranus, and Neptune, clouds are expected to form much deeper with the base of water ice and ammonia–water solution clouds at Saturn at pressures of 10 and 20 bar, respectively, for 10× solar O/H. At Neptune with an expected solar O/H ratio of 30–50 times, the water–ice and ammonia–water solution clouds could be as deep as ~50–100 and 370 bar, respectively [**17**, **18**]. Since atmospheric chemistries and diffusion and condensation processes affect the location and composition of clouds and tend to fractionate constituents above the clouds, the well-mixed state is expected to be well beneath the clouds.

2.2.3 *The need for the* in situ *exploration of the giant planets*

To fully address the science goals of giant planet exploration, a combination of *in situ* entry probe missions and remote sensing studies is needed. Although some important measurements addressing planetary composition, structure, and dynamics can be accomplished with remote sensing alone, other critical information is difficult or impossible to access via remote sensing. This is the case when constituents or processes of interest, at depths of interest, have no spectral signature at wavelengths for which the atmospheric contribution is optically thin. Although the noble gases can be accessed at relatively shallow depths, the bulk abundance of the other heavy elements discussed above may be found only well below their respective cloud bases, a region not accessible to remote sensing. Entry probes circumvent such limitations by performing *in situ* measurements, providing bulk composition data, cloud meteorology, vertical profiles of key constituents that are invaluable for elucidating thermochemical processes such as those that allow NH_3 and H_2S to combine and form NH_4SH clouds, and for tracing vertical dynamics (e.g. the PH_3 profile, where the competing processes of photochemical-sink at altitude and supply-from-depth could give a variety of profiles, depending, for example, on the strength of vertical upwelling). Key science questions to be addressed by giant planet entry probe missions are as follows.

1. What was the timescales over which the giant planets formed, and how did the formation process of the ice giants differ from that of the gas giants?
2. What is the history and distribution of water and other volatiles in the solar system?
3. What are the processes that have and continue to shape the character of the outer planets, and how do they work?
4. What can be learned about exoplanets by observing the giant planets of our solar system?

2.3 Science goals for Titan *in situ* exploration

The Cassini–Huygens mission to Saturn and Titan answered some questions but also raised many more. Ongoing Cassini remote sensing studies of Titan will not be able to address many of the outstanding questions because of inherent limitations in the instrument suite and because both remote and *in situ* elements are required to achieve much of the desired science return. While a spacecraft in orbit around Titan allows for a thorough investigation of Titan's upper atmosphere, there are questions that can only be answered by extending the measurements into Titan's lower atmosphere and down to the surface. Key steps towards the synthesis of prebiotic molecules that may have been present on the early Earth as precursors to life might be occurring high in the atmosphere, the products then descending towards the surface where they might replicate. *In situ* chemical analysis of gases, liquids, and solids, both in the atmosphere and on the surface, would enable the identification of chemical species that are present and how far such putative reactions have advanced. The rich inventory of complex organic molecules that are known or suspected to be present in the lower atmosphere and at the surface gives Titan a strong astrobiological potential (Pilcher, C., for the NAI Executive Council, 'Titan is in the List of Highest Priority Astrobiological Targets in the Solar System', 22 September 2008).

In situ science at Titan comprises several science objectives. In particular,

(a) perform chemical analyses in the atmosphere and the surface;
(b) analyse the regional geology and composition of the surface, in particular any liquid or dune material and in context, the ice content in the surrounding areas by hyper-spectral imaging;
(c) study the forces that shape Titan's diverse landscape at a range of locations.

Particular goals of the science investigations include:

(a) determining the composition and transport of volatiles, haze, and condensates in the atmosphere and at the surface, including hydrocarbons and nitriles, on both regional and global scales, in order to understand the hydrocarbon cycle;
(b) determining the climatological and meteorological variations of temperature, clouds, and winds;
(c) characterizing and assessing the relative importance, both past and present, of Titan's geologic, marine, and geomorphologic processes (e.g. cryovolcanic, aeolian, tectonic, fluvial, hydraulic, impact, and erosion);
(d) determining the chemical pathways leading to the formation of complex organics in Titan's troposphere and their modification and deposition on the surface with particular emphasis on ascertaining the extent of organic chemical that has evolved on Titan;
(e) determining geochemical constraints on bulk composition, the delivery of nitrogen and methane, and exchange of surface materials with the interior;
(f) determining chemical modification of organics on the surface (e.g. hydrolysis via impact melt).

3 TECHNIQUES FOR *IN SITU* EXPLORATION

The techniques employed for *in situ* exploration vary as a function of the target. Each planetary body involves a specific environment and hence the technology investment and the techniques that must be applied are established given the scientific objectives and also the milieu in which the mission will evolve [**19**].

3.1 Extreme environments experienced by planetary *in situ* missions

For the purposes of this article, a mission environment is defined as 'extreme' if one or more of the following criteria are met:

(a) heat flux at atmospheric entry exceed 1 kW/cm^2;
(b) hypervelocity entry speed higher than 20 km/s;
(c) low temperature: lower than $-55\,^\circ$C;
(d) high temperature: exceeding $+125\,^\circ$C;
(e) thermal cycling: between temperature extremes outside of the military standard range of -55 to $+125\,^\circ$C;
(f) high pressures: exceeding 20 bar;
(g) high radiation: with total ionizing dose exceeding 300 krad (Si);

Additional extremes include

(h) deceleration (g-loading) exceeding 100g;
(i) acidic environments;
(j) dusty environments.

A summary of targets of interest and the relevant extreme environments are shown in Table 1 (see also references [**20**] and [**21**]). Targets are organized by extremes in temperature; however, it is evident that missions often encounter multiple extremes simultaneously. In general, high temperature and pressure are coupled and typical for Venus *in situ* and deep entry probe missions to giant planets, such as to Jupiter and Saturn [**22**]. High radiation and low temperature are also coupled for missions to the Jovian system; relevant mission concepts are the Jupiter orbiter and Europa lander missions, which are not discussed here. Low-temperature missions are associated with surface missions to the Moon, Mars, Titan, Triton, and comets. Thermal cycling with fluctuations of 60–100 °C would affect missions where the frequency of the diurnal cycle is relatively short, such as for Mars (similar cycle to Earth) and on the Moon, where the day length is 28 Earth days.

3.2 Atmospheric entry techniques

One of the challenging aspects of planetary probe and balloon operations is inserting them into the atmosphere for *in situ* operations. Probes and balloons enter the planetary atmospheres in 'aeroshells', which typically consist of an ablative thermal protection system (TPS) and supporting structures. These blunt body aeroshells typically have the shape of axisymmetric flattened cones (Fig. 4).

The probe enters the atmosphere at the atmospheric entry interface (e.g. at Venus it is at an altitude of 170–200 km). The aeroshell is initially slowed down by atmospheric drag. The ablative material protects the aeroshell from extensive re-entry heating from energy that has not been dissipated over approximately 1 min.

Table 1 Extreme environments experienced by planetary *in situ* missions

Mission stage		Space	Entry		*In situ*					
Example target	Example mission architecture	Radiation	Heat flux at atmosphere entry	Deceleration	High pressure	Low temperature	High temperature	Thermal cycling	Chemical corrosion	Physical corrosion
High temperature and high pressure										
Venus *in situ*	Aerial mobility, lander, or rover		X	X	X		X		X	X
Saturn	Atmospheric entry probes		X	X			X			
Jupiter	Atmospheric deep entry probes	X	X	X	X		X			
Neptune	Atmospheric deep entry probes		X	X	X		X			
Low temperatures										
Comet nucleus	Sample return		X			X				
Titan *in situ*	Balloon, aerobot, lander, and rover		X			X				
Triton surface	Lander					X				
Low temperatures and high radiation										
Europa surface	Lander and impactor (with orbiter support)	X		X		X				
Thermal cycling										
Mars	Balloon, lander, and rover					X		X		X

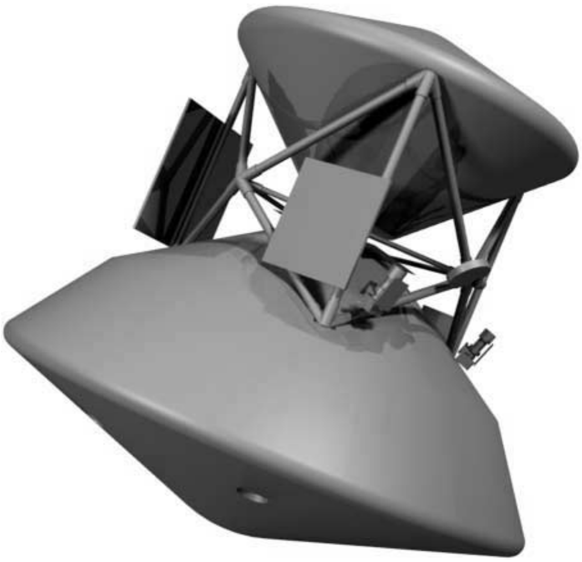


Fig. 4 Future mission to Titan could utilize both aerocapture and aeroentry manoeuvres. This figure shows a double aeroshell where the larger part could deliver the orbiter to orbit on a single pass through the atmosphere, while the smaller aeroshell would deliver the *in situ* element on a direct entry. During the cruise to Titan the aeroshells could be mounted back-to-back, and released from the carrier spacecraft sequentially (Credit: T. Balint)

A drogue parachute opens and slows the aeroshell further to a subsonic velocity in about 2 min. During this time, the telecom system transmits signals through the
Q7 radio frequency (RF) transparent backshell to the carrier, signalling successful completion of the various entry stages. Once subsonic, the backshell and drogue parachute are jettisoned, the main parachute opens, and the front shell drops, initiating the science phase of the *in situ* mission.

To reduce entry heating, the probe's approach velocity is minimized by a suitable trajectory before entry, or by utilizing the atmosphere to provide initial slowdown through aerocapture or aerobraking manoeuvres. From an interplanetary trajectory direct entry has higher entry velocities than entry from orbit. However, orbiting around the planet or moon might be constrained by mission total mass and cost. Entry heating could also be reduced by entering at a shallow angle. In turn, this could limit telecom options between the *in situ* element and Earth by relay through the carrier spacecraft, which is not desirable. Propellant requirements on the orbiter could be reduced by using an aerobraking manoeuvre, where the spacecraft lowers its apoapsis through multiple passes through the upper atmosphere. This can take several months to complete. Finally, the spacecraft can be inserted into orbit in a single pass, called aerocapture. This is further explained in the next subsection. Once in orbit, the spacecraft can release the *in situ* element for atmospheric entry, at relatively lower entry velocities.

3.3 Aerocapture

Aerocapture is an orbital insertion manoeuvre, whereby a spacecraft traverses through a planet's atmosphere using aerodynamic drag to precisely decelerate during a single pass and reduce its energy from a hyperbolic trajectory to that of a captured orbit, using very little propellant. Previous high-fidelity systems studies have shown that aerocapture enables almost three times more payload to be delivered to Titan, compared to using a purely propulsive orbit insertion. This would enormously increase the scientific return. Alternatively, a smaller launch vehicle could be used to deliver a given payload, allowing for significant cost reduction (tens of millions of dollars, or Euros, or…).

Aerocapture has been seriously considered for decades. It utilizes high-heritage elements and operating sequences adapted from previous spacecraft and hypersonic entry missions, including a blunt aeroshell, a TPS, a reaction control system, thermal management, aeroshell jettison, and autonomous manoeuvres. Titan is an easy aerocapture target, due to the large atmospheric scale heights and due to a benign heating environment. A future mission would also benefit from the Cassini–Huygens mission provided knowledge of the atmosphere and ephemeris. During the aerocapture phase, the aeroshell (Fig. 4) would experience aerodynamic drag and lift forces, while dissipating energy. A TPS would protect the spacecraft from heating, while all components would be designed to tolerate deceleration loads. Aeroshells for planetary destinations discussed here have high technological maturity and heritage, having been utilized on many previous missions. Therefore, no additional technology development is required for aerocapture at Titan. The only aspect remaining is validation of the autonomous closed-loop guidance and control system in a relevant environment; in particular, addressing the exit flight phase with respect to the target's orbit.

3.4 Aerial mobility techniques

For planets with atmospheres of any substance, balloons could provide a mobile platform alternative to surface rovers. Flying above obstructions and carried by the winds, a balloon could survey and inspect large regions of a planet in great detail for relatively low cost considering the total surface area covered.

The first, and so far only, planetary balloon mission, consisted of the dual identical VeGa balloons to Venus (Fig. 1), was performed by the Russian space agency, the Space Research Institute of the Russian Academy

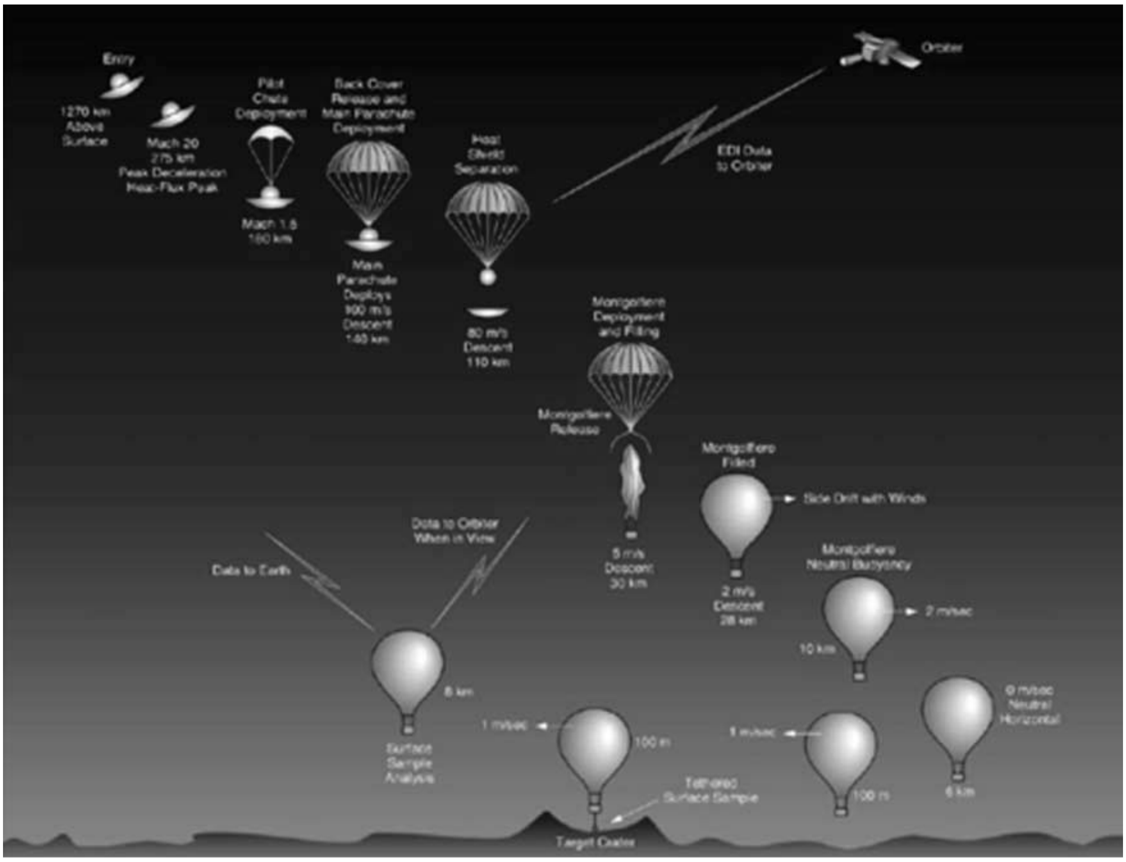


Fig. 5 Conceptual deployment of the montgolfière hot-air balloon in Titan's atmosphere (Lunine, J. *et al.*, 'Titan Planetary Exploration Study,' JPL Final Report, Pasadena, CA, May 2006)

of Sciences (IKI), and in cooperation with the French space agency CNES, in 1985.

In a future mission, after jettisoning the aeroshell, the probe or the balloon would descend under the main parachute. The inflation system would inflate the balloon, and then jettison the helium tanks and the main parachute. The balloon would rise to a float altitude, initiating the science operations phase (similar to the case of a Titan balloon deployment, as shown in Fig. 5). Once operational, this aerobot will be largely on its own and will have to conduct its mission at least semi-autonomously, accepting only general commands over its communication link to Earth (either directly or via a flyby/orbiter relay). The aerobot will have to determine its position in three dimensions: acquire and store science data, perform flight control (potentially by varying its altitude for some of the configurations), and possibly make 'landings' at specific sites to perform close-up surface investigations.

A balloon is conceptually the simplest of all flying machines, consisting of nothing more than a flexible 'envelope' filled with a 'lifting gas' that is lighter than the surrounding atmosphere. As the gas-filled balloon is less dense than its surroundings, it rises, taking along with it a 'gondola attached underneath that carries passengers or payload' (Fig. 5).

The first montgolfière, launched in 1783 by two Parisian brothers, used hot air as the lifting gas. Balloons using the light gas hydrogen (or helium) for buoyancy were also developed at the same time. Although a balloon has no propulsion system, as balloonists became more experienced they learned a degree of directional control through the measure of rising or sinking in altitude to find favourable winds.

Both the 'montgolfière'-type hot-air balloon and the light-gas balloon are still in common use for Earth-based activities. Montgolfière balloons are relatively straightforward, as they do not require high-grade materials ensuring leak tightness for their envelopes nor bottles of e.g. helium. A montgolfière is proposed for Titan future exploration (Fig. 6), using the ambient air for inflation and the multi-mission radioisotope thermoelectric generator (MMRTGs) for the thermal Q8 heat source (TSSM Reports, 2008).

Light-gas balloons are predominant in Earth-based scientific applications, because they are capable of reaching much higher altitudes and staying for much longer periods of time than hot-air balloons. They are generally filled with helium. Although hydrogen has more lifting power, it has the disadvantage of becoming flammable or explosive in an oxygen-rich atmosphere. Modern scientific balloon missions are unmanned.

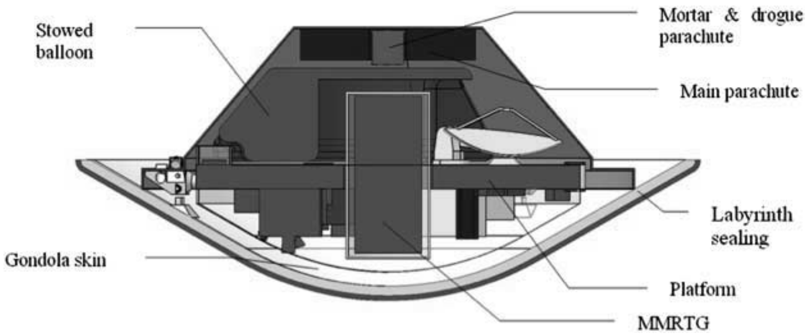


Fig. 6 Titan montgolfière configuration. The hot-air balloon would ride the winds at jetliner altitudes (10 km), and perhaps periodically accessing the surface over its 6 months lifetime. It would be heated by the excess heat of an MMRTG (TSSM ESA Study Assessment Report, 2008)

There are two types of light-gas balloons: 'zero-pressure' and 'superpressure'. Zero-pressure balloons are the traditional form of light-gas balloons. They are partially inflated with the light gas before launch, with the gas pressure the same inside as the air pressure and outside the balloon. As the zero-pressure balloon rises, its gas expands and maintains the zero pressure difference, while the balloon's envelope swells.

At night, the gas in a zero-pressure balloon cools and contracts, causing the balloon to sink. A zero-pressure balloon can only maintain altitude by releasing gas when it rises too high, where the expanding gas can threaten to rupture the envelope, or by releasing ballast when it sinks too low. Loss of gas and ballast limits the endurance of zero-pressure balloons to typically a few days.

A superpressure balloon, in contrast, has a tough and inelastic envelope that is filled with light gas to a pressure somewhat higher than that of the external atmosphere, and then sealed [**23**]. The superpressure balloon cannot change size very much, and so maintains a nearly constant volume. The superpressure balloon maintains an altitude at a constant density in the atmosphere, and flies until gas leakage gradually brings it down.

Superpressure balloons offer flight endurance of months, rather than days. In fact, in typical operation an Earth-based superpressure balloon mission is ended by a command from ground control to open the envelope, rather than by natural leakage of gas.

While the idea of sending a balloon to another planet sounds unusual at first, balloons have a number of advantages for planetary exploration. They can be made light in weight and are potentially less expensive when compared with the complexity of the guidance and navigation control required by a typical lander mission. They can fly over a large portion of ground, and their view from an elevated altitude gives them the ability to examine wide swathes of terrain in far more detail than would be available from an orbiting satellite. For exploratory missions, their relative lack of directional control is not a major obstacle, as there is generally insufficient knowledge available in advance of the mission to require directing them to specific locations. In addition to the configurations discussed above, balloon designs for possible planetary missions have involved a few unusual but interesting concepts.

One concept is the solar or infrared (IR) montgolfière. This is a hot-air balloon where the envelope is made from a material that traps heat from sunlight, or from heat radiated from a planetary surface. Solar montgolfières have several advantages for planetary exploration, as they can be easier to deploy than a light-gas balloon; do not necessarily require a tank of light gas for inflation; and are relatively forgiving of small leaks. A solar montgolfière, conceived for Mars exploration, would sink at night, and would have a guide rope attached to the bottom of the gondola that will curl on the ground and anchor the balloon during the darkness hours. A second concept is a 'reversible fluid' balloon. This type of balloon consists of an envelope connected to a reservoir, with the reservoir containing a fluid that is easily evaporated. The balloon can be made to rise by vaporizing the fluid into gas and can be made to sink by condensing the gas back into fluid.

A third concept targets near-surface exploration of Venus, where the conditions require replacing the flexible balloon material with a thin stainless steel bellow folded as an accordion (Fig. 7). For this concept, the operating lifetime would be limited by the power system and the thermal design of the gondola. With batteries and passive cooling this concept could work up to about 6 h *in situ*, including a 1 h descent to the surface [**24**].

All balloons designed for planetary exploration would carry a small gondola containing the instrument payload. The gondola would also carry power, control, and communications subsystem (Figs 6 and 7). Due to weight and power supply constraints, the communications subsystem would generally be small and using low power. Consequently, to achieve significantly higher data rates, interplanetary communications might be performed through a flyby

Fig. 7 Probe missions to Venus and the giant planets would descend under a parachute while performing descent science measurements (Credit: T. Balint)

or orbiting spacecraft acting as a relay (although Venus balloon concepts have been conceived using direct to Earth communications with significant reduction in data rate and volume). The optimum choices between the telecom trades are driven by science, mission architectures, and programmatics (such as mission cost cap).

4 PLANETARY PROBE TECHNOLOGIES FOR *IN SITU* EXPLORATION

In situ exploration is driven by our quest to answer key science questions about the solar system's formation, evolution, composition, and dynamics. For example, the deep interiors of the giant planets hold clues to the chemical nature of the rocky and icy debris from which they formed. The atmospheres of Venus and Titan provide laboratories for studying atmospheric chemistries and dynamics as well as providing insight into the history and possible future of Earth's atmosphere.

In situ exploration of atmospheres of the giant planets [**19**], Venus [**25**], and Titan (http://opfm.jpl.nasa.gov/library/) could be achieved with entry probes, landers, and aerial platforms. Unlike orbiter missions, atmospheric entry probes must be delivered to their *in situ* targets and designed to operate from carrier release through planetary approach, atmospheric entry, deployment, descent, and *in situ* science phase. These planetary environments impose extreme conditions on the systems, including entry heating and g-loading, temperature extremes, thermal cycling, high pressures, and chemical or physical corrosion [**20**, **21**].

To ensure safe entry and survival into the deep atmospheres of Venus, the giant planets, and Titan, a number of key technologies must be addressed [**26**, **27**]. Entry systems, including TPSs, protect the payload during atmospheric entry against heat flux and g-loading, which increases with entry velocity (driven by the gravity of the planet) and atmospheric density. At the giant planets, the atmospheres could significantly attenuate telecom signals, greatly affecting the architecture of deep probe mission concepts, impacting communication system, antenna, and power system designs. Atmospheric probes and platforms must provide structural and thermal integrity to isolate critical components from the severe environmental conditions, and yet provide inlets, pass-throughs, and windows, for sample acquisition systems, direct contact sensors, and remote sensing such as imagers. To increase the payload mass fraction for a given entry mass, advances are needed in the technologies of strong and lightweight materials for the pressure vessel. Furthermore, for these short-lived probe missions improved passive thermal control technologies are needed to maintain the probe's interior at moderate temperatures during probe descent and *in situ* operations, for up to several hours.

Based on these considerations, this section provides a brief overview of key technologies required to enable *in situ* exploration of planetary targets with sizable atmospheres, namely the giant planets, Venus and Titan.

4.1 Entry and descent technologies

Hypervelocity atmospheric entries at Venus and the giant planets produce extreme heating (measured as heat flux in kW/cm^2) through both convective and radiative processes, and require TPSs that allow only a small fraction of the entry heating to penetrate conductively, and to reject the majority of the heat through re-radiation and ablation. Robust materials such as highly dense carbon-phenolic (C-P) are required to mitigate the high convective and radiative heating, and long heat pulse effects of entry (Fig. 8).

Three parameters are key in the entry system design: peak heat flux, total heatload (which is a function of duration), and peak pressure. Since TPS is a single-point failure system, the challenge for entry systems is to provide, with the lowest TPS mass fraction possible, thermal protection without risk of catastrophic failure, while ensuring structural integrity. Heritage C-P TPS has been demonstrated for missions ranging from 5 to 30 kW/cm^2, requiring mass fractions ranging from 12 per cent for Venus missions to as high as 50–70 per

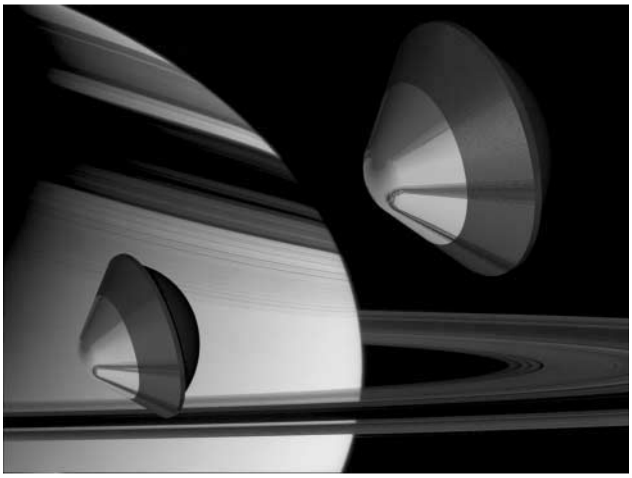


Fig. 8 Saturn probes would encounter extremely high heat fluxes during atmospheric entry. The payload would be protected by a highly dense carbon-phenolic TPS, based on Galileo heritage (Credit: T. Balint)

cent for missions to Saturn, Titan, and Jupiter, where the heat fluxes are significantly higher.

The highest-velocity entry, at Jupiter, requires the use of ablative dense C-P TPS, used previously on the Galileo entry probe mission. Probe entries to other giant planets face heating rates that are about ten times lower, but still require C-P. Due to a relatively high gravity field and dense CO_2 atmosphere, Venus presents a more challenging target for entries than Mars, Titan, or Earth entries. Specifically, entry probes at Venus with steep entry flight path angles (EFPA) would also encounter very high heat fluxes, requiring highly dense C-P ablative TPSs. However, Venus entry mission with shallow EFPA will experience much lower peak heat flux and pressure, potentially allowing the use of lighter ablative materials and thereby increasing payload mass fraction for the same delivered mass. Due to the slow rotation of Venus, the planetary entry is not limited by the approach trajectory option, resulting in equally feasible prograde and retrograde entries with the same TPS design.

Q9 Following completion of the Galileo Jupiter probe mission in 1995, development and testing capabilities for high-density ablators at the performance level, as required for giant planet probes, is currently available only at certain few facilities and is not manufactured routinely. As there are currently no proven alternatives to the 'heritage' carbon–phenolic (HCP) used on Galileo, future Venus and giant planet entry probe missions must either rely on this material or develop and test an alternative to HCP base resin. Development of new TPS materials is considered a long-lead item and will require extensive technology maturation and ground testing. Therefore, investment in re-establishing the HCP capability and development of an alternate to HCP would be desirable.

4.2 Power technologies

Advanced power system technologies are required to enable and enhance the capabilities of many solar system entry probe missions. Most future planetary missions will require power systems with mass and volume efficiency, long-life capability, and the ability to operate in extreme environments such as low and high temperatures. Advanced power system technologies for typical future *in situ* missions may require power generation (e.g. radioisotope power systems (RPSs), solar arrays) and power storage (e.g. batteries) systems and power electronics [**26**]. Since probe missions are mostly relatively short lived, with *in situ* operating lifetimes measured in hours, the relevant power technologies are limited to batteries. The lifetime of aerial mobility platforms, such as balloons to explore Venus and Titan, was proposed for 30 days and up to 2 years, respectively. These long-lived missions can be enhanced or enabled by RPSs.

4.2.1 Power storage systems

The energy storage systems that are presently being used in space science missions include both primary (non-rechargeable) and secondary (rechargeable) batteries. In addition, thermal batteries are used during short atmospheric entry operations, for example to power pyro-cutters, and parachute deployment systems.

To reach the deep atmospheres of the giant planets, the probes' descent times need to be increased from the approximately 1 h descent of the Galileo, Pioneer-Venus probes to ∼2.5 h of the Huygens probe. The descent time and corresponding pressure elevation at the end of the descent are limited by telecom constraints of the missions, namely the trades between the probe-to-carrier range and the corresponding telecom window for communicating the data. Over the increased descent time, advanced primary batteries with higher storage capacity could provide lower mass and volume, thus minimizing the overall system mass. For future planetary entry probes, short-lived landers, and aerobot missions, advanced primary batteries with high specific energy (>500 Wh/kg) and long storage-life capability (>15 years) could provide clear benefits to the missions. Specifically, investment is needed in low-mass, high-energy-density battery technologies, and low-powered logic and power conditioning electronics, which would enable long descent times into the atmosphere without unacceptable increases in battery mass. Technology development could also increase
UHF transmitter efficiencies from the current ∼30 Q10
per cent to levels approaching ∼50 per cent, further reducing internal thermal loading and providing more efficient use of limited energy resources.

On short-lived planetary probes primary batteries are placed inside a pressure vessel, where the temperature-controlled environment does not necessitate high-temperature batteries over the few hours of operation.

4.2.2 Power generation systems

Venus superpressure balloons could operate for 30 days or more at cloud level (~55 km altitude), where the temperature and pressure conditions are Earth like. That is, the temperature is ~30 °C and the pressure is ~0.5 atm. Increased lifetime linearly scales power requirements, and with it battery mass and volume. Therefore, longer missions could be enabled by the use of an advanced Stirling radioisotope generator (ASRG), resulting in over ten times higher science data return than that from a battery-powered configuration. ASRGs use dynamic power conversion, and are about four times more efficient than RPSs using static conversion. Consequently, for a similar power output ASRGs require about four times less plutonium than static conversion-based systems. In turn, this lowers the excess heat generated by the power source, and simplifies the thermal system design (e.g. the size of the heat rejection system during the cruise phase, when the RPS is housed inside the aeroshell). RPSs currently under development (ASRG and MMRTG for multi-mission radioisotope thermoelectric generator) are designed to operate in space and in atmospheres at Mars surface conditions. Therefore, future long-lived Venus surface missions with require development of
Q11 a custom-designed Venus surface-specific RPS. This system would likely use a Stirling convertor, and the power system would be coupled with an active refrigeration system to maintain a quasi-steady-state environment for the payload inside the thermally insulated pressure vessel.

While a Venus balloon would benefit from an ASRG, a Titan balloon would not. Instead, a montgolfière-type Titan balloon (Fig. 6) would be enabled by a static conversion-based MMRTG (TSSM 2008 report). For a hot-air balloon, the four times more plutonium would generate four times more excess heat than the ASRG, which could be utilized to heat the balloon during its 2-year lifetime, while the larger Titan balloon could accommodate the heavier MMRTG design. Of course this configuration would require a more capable thermal design to remove the waste heat during the cruise phase, when the MMRTG is housed inside the aeroshell.

For more information on ASRG and MMRTG, the reader is referred to the following references:

e.g. for the MMRTG:

Q12 DoE (2008). 'Space Radioisotope Power Systems, Multi-Mission Radioisotope Thermoelectric Generator', website: http://www.ne.doe.gov/pdfFiles/MMRTG_Jan2008.pdf

and for the ASRG:

NASA (2010). 'DISCOVERY 2010, ADVANCED STIRLING RADIOISOTOPE GENERATOR (ASRG), INFORMATION SUMMARY', Discovery 2010 Program Library, web site: http://discovery.larc.nasa.gov/dpl.html Q12

Cloud-level Venus balloon designs (Fig. 9) could also consider a hybrid system of solar panels and secondary batteries. However, the mission impact of such a design should be traded against a primary battery-powered system. Since the specific energy of secondary batteries is lower than that of primary batteries, the overall mass and volume impact of the batteries and solar panels may not provide sufficient benefits on short-lived missions. Therefore, this configuration is not discussed further.

4.2.3 Power electronics technologies

While currently no significant efforts are underway at NASA to develop high-efficiency power electronics (e.g. advanced power conversion, management, distribution technologies, or advanced packaging concepts for high-power devices) for future solar system exploration missions, these technologies could support a more efficient use of the limited power resources on planetary probes and would mitigate potential thermal issues. The development of highly efficient power electronics is then recommended.

Fig. 9 Artist's concept of a superpressure Venus balloon, performing 30-day science investigations while circumnavigating the planet several times at a float altitude of ~55 km (Credit: T. Balint)

4.3 Telecommunications technologies

Deep space communications between Earth and the outer planets and Titan pose notable challenges for retrieving science data sets. For *in situ* missions, communications can be particularly challenging due to constraints on power and mass, and the great distances involved. Additionally, the presence of water and ammonia in the atmospheres of the outer planets can significantly attenuate microwave signals and greatly affect the architecture of deep probe communication systems. Even for *in situ* Venus missions the resource bounds on telecom system mass, battery power, and antenna design, combined with the required UHF-band, would significantly limit direct to Earth telecom data rates, compared to that using telecom relay through an orbiter or a flyby carrier.

4.3.1 Antennas

Many of these challenges can be addressed by focusing on key technologies, including improvements in antenna design (including UHF for giant planet descent probes), and development of high-power, high-efficiency transmitters and power amplifiers. Because descent probes are inherently unstable along their vertical rotational axis, probe communication architectures would benefit significantly from the development of electrically steerable UHF antenna technologies. Additional technology developments, to improve communication link margins, could target hardware on the orbiter or carrier flyby spacecraft, hardware on the probe or balloon, hardware on Earth, or software at any of these segments.

For the orbiter or flyby carrier:

Mature and advanced higher-power transmitters, building on the successful 200 W flight engineering model Ka-band travelling wave tube amplifier. The
Q10 Kepler and LRO missions are now flying lower-power versions of this design.

Q13 High-gain, *lightweight*, deployable Ka-band antenna technologies, and 5 m or larger for long distance, direct to Earth links.

Next-generation transponder that supports: 10 Mbps uplink; 100 Mbps downlink; integrated proximity and direct-to-Earth (DTE) communications in a single transponder (currently two separate devices must be used); integrated radio science capability to support advanced atmospheric and gravity experiments with few-μmicron/sec two-way Doppler capabilities.

Alternate architectures would include optical (laser) communications flight transceivers to support very high mission data return to Earth (up to two orders of magnitude enhancement) in trunk-line-mode from orbiters, DTE-mode from planetary surface, and access-link from surface to orbiters, in conjunction with RF telecom for the lower spacecraft data rates.

For the probe or balloon:

UHF antenna designs and relay systems with increased efficiencies for relay and proximity communication UHF transmitters.

For the ground segment:

Deep space network antenna arraying: Ka- and X-band downlink arraying equivalent to a 70 m (or larger) aperture. X-band and potentially Ka-band uplink arraying for commanding at large distances.

For the coding and software:

Implement advances in data compression to more efficiently transmit science data to Earth.

Baseline more effective error-correcting coding enhancements, including low-density parity check codes (LDPC) for high-rate bandwidth-efficient coding on the downlink. Current codes will be inadequate due to decoder complexity and/or performance limitations. LPDC decoders can be easily built at >100 Mbps and parallelized decoders can reach the Gbps range. For uplink, forward link coding can result in a >5 dB (three times) improvement. The error-correcting version of these codes can be used effectively to fill gaps in the data stream.

Data compression: the link can be used more efficiently by sending the information to Earth in the most efficient representations possible.

4.3.2 DTE communications

As an efficient backup for critical mission operations and experiments, a low data-rate link can be achieved with the nominal transmission from a Titan montgolfière and received by large Earth-based radio telescopes [**28**, **29**] (Fig. 6). The most attractive option of DTE communications would involve the square kilometre array (SKA) as the Earth-based facility operating at S-band (2.3 GHz) frequencies. This facility is expected to be fully operational by 2020. Preliminary assessment estimates [**30**] indicate that SKA will be able to receive data streams through a low-gain antenna at Titan at the rate of 30–100 bps. Venus probes and balloon missions could also use S-band DTE when in view of Earth; however, this data rate would be significantly lower then communicating the data through an orbiter or a flyby carrier spacecraft. DTE from giant planet probes could introduce significant challenges due to mission architecture, mass, and resource constraints. For example, typical Saturn probe architectures would result in an entry location of the probe not visible from Earth. Moving the entry location to Earth view could extend the flight time by several years. The atmospheric conditions would limit the telecom to UHF-band, which would not be as efficient from giant planet distances as X- or Ka-band. Furthermore, small probes limit the antenna and battery sizes, and constrain the telecom system to a low-power configuration. Consequently, giant planet probe missions will likely utilize relay telecom architectures.

4.4 Planetary protection

Under United Nations treaty, it is a requirement that missions to future planetary destinations of astrobiological interest such as Europa, Titan, and Enceladus must not cause harmful contamination until the biological exploration of the body is completed. Planetary protection regulations specified in international agreements are imposed on robotic space missions to prevent biological contamination of future exploration sites ('forward contamination') and, in sample return missions, to protect the Earth from possible extraterrestrial contaminants ('back contamination'). Further, exploration activities themselves must not compromise the integrity of life-detection experiments. Therefore, measures must be taken to ensure that samples collected by onboard instruments on landed spacecraft do not experience contamination by the spacecraft itself or other materials brought from Earth. Also, the spacecraft must not do anything to the target body that would compromise future sampling or experiments.

Planetary protection needs can be categorized broadly as those technologies needed to meet forward protection requirements and those involved in returned sample handling. The forward contamination issues are of most pressing concern to entry probe missions to Titan. Currently, the Mars exploration programme is developing new planetary protection technologies and approaches to address forward contamination protection requirements for future missions. Planetary protection in the surface and atmosphere of Titan is considerably simplified by the environment which is totally inhospitable to terrestrial-type life. Further, the chances of an atmospheric or surface vehicle being introduced into the interior where a water–ammonia ocean might exist are sufficiently small that Titan remains a Category II object. One needs only to ensure, in sampling organics in the environment, that onboard instrumentation does not inadvertently measure terrestrial organic molecules carried to Titan. This problem has already been dealt with for Rosetta, and so is not a new issue for planetary protection.

In situ missions to the giant planets and to Venus are not impacted by planetary protection regulation, thus greatly simplifying the mission and system designs and relieving mission cost and risk impacts.

4.5 Extreme environment technologies

In situ exploration missions to the giant planets, Venus and Titan experience a wide range of extreme environments (Figs 10 and 11), and mitigating them would require significant technology development. Deep probe missions to the giant planets and to the surface of Venus experience similar high-temperature and high-pressure conditions during their short 1 to 2 h descents, while Titan probes and balloons operate under extremely cold conditions. These missions could also encounter chemical or physical corrosion, and longer balloon missions, circumnavigating the planets would face thermal cycling. Before starting the *in situ* operations phase, these missions have to perform a successful atmospheric entry, descent and for some architectures inflation (for balloons)

Fig. 10 Left: Venus lander concept from the Venus flagship mission study. The lander would use a rotating pressure vessel with a permanently mounted sample acquisition system and panoramic camera. Right: Venus mobile explorer concept, showing the inflated metallic bellows ascending to a float altitude of ~5 km, leaving the empty helium tank at the landing site (Credit: T. Balint)

Fig. 11 Artistic impression of the montgolfière concept over Titan's landscape, valleys, lakes, or hills eroded by atmospheric deposits (Credit: T. Balint)

or landing (for landers). During entry, the spacecraft would experience extremely high heat fluxes and high g-loads.

Atmospheric entry and power technologies were discussed in sections 5.2 and 5.3, while the telecom challenges were outlined in section 5.4. Other critical technologies include pressure and temperature mitigation and instrument technologies.

4.5.1 Pressure

Venus probes and giant-planet deep probes (to pressures of 50–100 atm) require suitable structures (including pressure vessels, external sensors, ports, inlets, and seals) that can provide structural integrity and pressure and thermal management to protect instruments from the encountered extreme pressure and temperature conditions (Fig. 7). While the current state of the art uses titanium, emerging pressure vessel materials must also avoid yielding by buckling or creep at a temperature up to 500 °C, while tolerating a pressure range of 100–150 atm over the anticipated lifetime of the mission. Other factors include gas permeability, thermal conductivity, chemical compatibility with the atmospheric environment, fracture toughness, heat capacity, and the thermal expansion coefficient. A very important consideration in the selection of materials is its manufacturability into a spherical pressure-vessel shell that includes windows and feed-throughs. Almost-monolithic shells can be fabricated from titanium or beryllium, which has been the traditional manufacturing process for spacecraft landing on Venus' surface (Fig. 10). Composite wrapped shells are commonly seen in pressure cylinders and the technology is well developed. These new strong and lightweight materials are desirable, since any mass savings could translate to a heavier payload.

4.5.2 Temperature

Thermal control technologies are necessary to maintain the probe interior at moderate temperatures for mission durations of up to several hours on Venus and the gas giants, and for months at Titan. This will require the development of advanced passive thermal control technologies, such as thermal energy storage (using phase change materials (PCM)) and multi-layer thermal insulations (MLI), which would provide better performance than the current state of the art materials. On short-lived Venus surface missions and gas giant descent probes, passive thermal control is suitable. With its very low thermal conductivity, aerogel provides good insulation without convection; however, it has a low tolerance to atmospheric entry g-loads, and thus is difficult to implement for these *in situ* missions. Possible next-generation MLI materials include a cocoon of high-temperature multi-insulation, manufactured by stacking and sewing together crinkled reflective metal–alloy foils, separated by ceramic fabric and/or insulated with xenon gas. Although MLI only provides significant performance improvements when used in a high vacuum, in the more external part of a pressure vessel, metallic, ceramic, or PBO (poly-p-phenylenebenzobisoxazole) materials could be used. For PCM materials, the need for low volumetric change limits the transformations to solid–liquid and solid–solid transitions. Also, a higher-density PCM may be more appropriate, requiring smaller volume and less container or filler mass. Extreme environmental conditions are often coupled. High-temperature (above 400–460 °C) and high-pressure environments can be coupled and representative of short-lived deep probe missions to the giant planets and to Venus (Fig. 7). For these, the subsystems and components can be placed inside the pressure vessel with passive thermal control, using Pioneer Venus probe heritage. Therefore, these missions will not require high-temperature electronics or subsystem components. On the other end of the temperature range experienced by planetary missions to Titan (e.g. probes, lander, and montgolfière; Figs 11 and 12) could use electric heaters or radioisotope heater units, combined with suitable insulation.

4.5.3 Balloon materials

Materials research plays an important role in developing technologies for aerial mobility. Balloons are envisioned for the exploration of Venus and Titan (Figs 6 and 9), but the balloon must survive the environment. Balloon missions must address material issues, including temperature (high or low) and corrosion. Balloons operating at Venus' cloud levels are at relatively high technical readiness levels, but the technology required to implement a lower-altitude (<50 km) Venus balloon (Fig. 9) is not mature and faces four main challenges, which are related to materials,

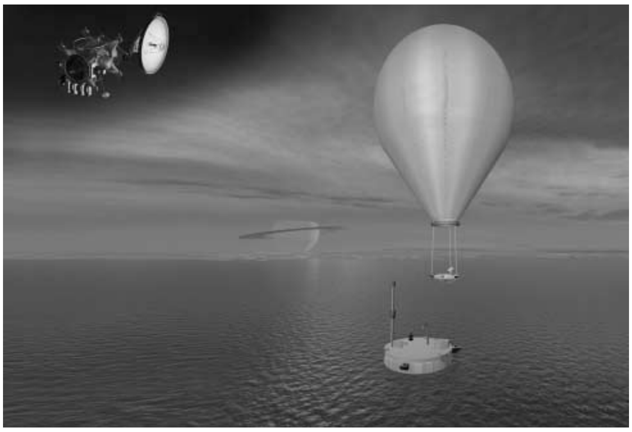


Fig. 12 TSSM scheduled to be launched towards Titan and Enceladus in 2025, comprises a Titan-dedicated orbiter, a montgolfière, and a lander (Credit: C. Waste)

high temperatures (requiring thermal management), power, and mass limitations. Titan balloons will also need to respond to the cold environment and long interplanetary transfer durations by using suitable materials (Fig. 11).

4.5.4 Instruments and subsystems

For giant planets, Venus and Titan probe and balloon missions (Figs 7 and 12) the subsystems and instruments are well protected against pressure, temperature, and corrosion. However, miniaturization of these components would reduce accommodation mass, volume, and power, consequently providing a beneficial easing of requirements that ripple through the design.

4.6 Aerial mobility

4.6.1 Aerial mobility in Venus

In 1985, the USSR's twin superpressure VeGa balloons (Fig. 1), each carrying a 6.9 kg payload, were suspended 12 m below a fluoropolymer-coated Teflon fabric balloon and floated in the most active layer of the Venus three-tiered cloud system at ∼54 km altitude. This mission successfully pioneered the use of aerial platforms to explore planets.

There is renewed interest in balloons for Venus, and mission concepts have been proposed in the US, Europe, and Japan (Figs 7 and 9). High-altitude balloons flying at ∼55 km would experience Earth-like temperatures and pressures (∼30 °C and ∼0.5 bar). Therefore, the balloon material is not affected by extreme pressure and temperature conditions, although the balloon material still must tolerate the sulphuric acid droplets in the clouds. For balloons operating at lower altitudes, finding a single balloon material that can withstand the high temperatures and pressures is challenging. In addition to materials issues, mid-altitude balloons will require low mass, pressure, and thermal management systems, or high-temperature electronics and telecom systems that could operate in these extreme environments. High-altitude balloons could be designed to cycle between altitudes using a buoyant fluid that changes phase from a liquid to a gas depending on the balloon's altitude and ambient temperature. Large altitude excursions between 60 km and the surface at Venus are not possible due to the lack of a single balloon material that could tolerate the environment throughout the altitude cycles. Cycling balloons are considered for altitude excursions of ±5 km from a mean float altitude of ∼50–55 km. This type of balloon platform was included in the Venus flagship mission study ([**31**], Fig. 9). One-way Doppler and very long baseline interferometry tracking of the VeGa balloons was done by a global network of stations and provided cloud-level wind speeds. Doppler tracking of future Venus balloons, together with well-calibrated onboard pressure sensors, accelerometers, and/or inertial momentum units and gyros, can yield knowledge of all three components of the balloon's velocity. These measurements could yield an order of magnitude higher accuracy than achieved by the VeGa balloons (Fig. 1). These accuracies could be better than 10 cm/s on time scales of a minute in the vertical and an hour in the horizontal directions, using new, highly miniaturized instrument technologies. For near-surface aerial mobility, superpressure balloons made from typical balloon materials and adhesives would not work, due to the very high surface temperatures (∼460 °C). If large altitude traverses are not required, then a metal balloon made of thin sheets of stainless steel or other suitable alloy would suffice at and near the surface. Passive thermal control could enable such a mission to operate near the surface for up to ∼3–5 h following the initial 1 h descent. This architecture is discussed in the Venus Mobile Explorer study [**24**].

4.6.2 Titan aerial mobility

Recent Titan flagship mission studies have recommended *in situ* exploration involving aerial mobility, to complement a Titan orbiter and a lake lander (Fig. 12). For example, the TSSM study baselined a 10.5 m diameter hot-air (montgolfière) balloon carrying a 144 kg payload mass at an altitude of 10 km for a minimum of 6 (Earth) months (Figs 11 and 12). Buoyancy for the Titan balloon would be generated by heating the ambient atmosphere inside the balloon with the excess heat from a MMRTG-type RPS that would also provide electrical power to the gondola (Fig. 6). The montgolfière balloon would circumnavigate Titan at least once during its 6-month primary mission, imaging the surface and acquiring atmospheric composition and weather data along the way (Fig. 11).

Hot-air balloons are ubiquitous on Earth. However, their adaptation for the Titan environment requires advanced development and risk reduction efforts in key areas. Balloon thermodynamics and ambient gas heating are the most important design issues in terms of demonstrating that a Titan montgolfière would generate sufficient buoyancy under all expected conditions, while using a constant thermal power source of 1700 W. Adequate thermal margins must be present to accommodate atmospheric turbulence and other transient conditions that might be encountered in Titan's atmosphere. The other important aspect of the montgolfière that must be further developed and validated is its aerial deployment and inflation system, which enables the vehicle to transfer from atmospheric entry to its stable float altitude of ~10 km. Fortunately, there are designs that can make several hours available for this transition.

Although the TSSM balloon was designed to fly at a constant altitude, more capable options for a Titan montgolfiere balloon can include altitude control through the use of a vent valve at the top of the balloon, the addition of electric motor-driven propellers to provide some lateral manoeuvring capability, autonomous flight control systems to provide go-to targeting of surface exploration sites, and surface sample acquisition capability.

Light-gas (helium or hydrogen) balloons or blimps are a possible alternative for Titan but they are typically associated with much shorter mission life times and hence may not achieve the desired science requirements. They have the advantage of a superior lift mass-to-volume ratio, but could be affected by potential pinhole formation over time and gas diffusion as the balloon material flexes in the cryogenic environment.

Airplanes, helicopters, and other heavier-than-air vehicles have also been considered for Titan (as in
Q14 Venus), such as the AVIATR (aerial vehicle for *in situ* and airborne Titan reconnaissance) concept [**32**] (Fig. 13), which would offer the opportunity to control the vehicle and to orient it towards different locations. Since the solar flux at Titan is very low, the Titan airplane would likely use an RPS power source. By comparison, at Venus the solar flux is twice as high as at Earth, and therefore, a Venus airplane could use solar panels, as shown in the figure. Furthermore, the Venus airplane is limited to operations on the Sun-lit side of Venus (which may complicate communications and could necessitate an orbiter) and the airplane is limited to operations above ~50 km altitude to avoid the extremely high-pressure and -temperature conditions closer to the surface. Finally, the solar panels would have to be tolerant to sulphuric acid droplets of the clouds. However, interestingly, these concepts are limited in performance, compared to balloons because of the need for significant amounts of power to generate lift. Concepts for such vehicles are in their infancy and will require substantial technological advances to yield a feasible solution.

Technologies required to realize the full potential of aerial mobility at Titan include autonomous navigation, cryogenic actuators, and motors (for self-propelled options), DTE or proximity telecommunications to an orbiter, and autonomous science capabilities for data analysis and opportunistic observations.

4.7 Other and cross-cutting technologies

4.7.1 Development of small probe networks, miniaturization

In situ studies of planetary atmospheres would benefit from multi-probe missions, requiring the development of technologies to support missions comprising a network of small, low-power, light-weight, scientifically focused spatially and possibly temporally separated probes. Key technologies for multiple probe explorations include miniaturized and low-power, integrated sensors, data storage, transmitters, and avionics, thermal and power management, on-board

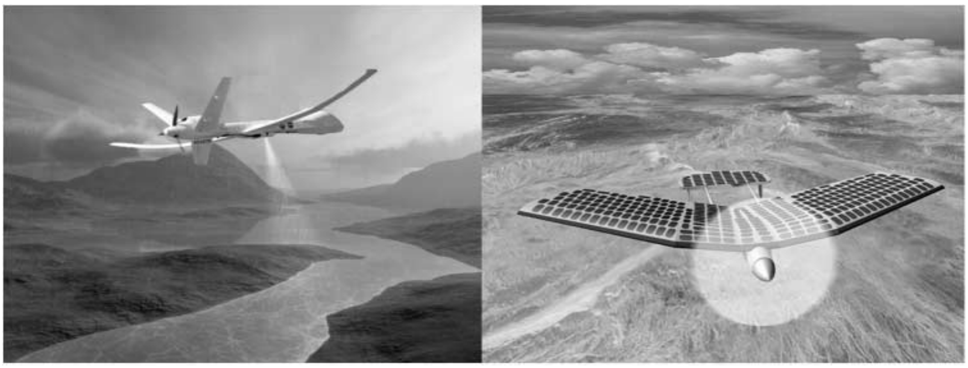


Fig. 13 Airplane concepts for Titan (left, AVIATR, reference [**32**]) and Venus (right, reference [**33**]). Both concepts can be used in the highly dense atmospheres of Titan and Venus.

processing, spacecraft autonomy, and advanced primary batteries. Since the pressure and temperature conditions between giant planet deep entry probes and Venus probes are similar (i.e. 90–100 bar and 400–460 °C), technologies developed for one destination could feed forward to support the developments for other probe missions (Fig. 7).

4.7.2 In situ *autonomous operations*

The scientific diversity of Titan and Venus and the limitations of orbital surveys, due to the cloud cover of these bodies and limits of remote sensing compared to contact measurements, lead to the desire for *in situ* platforms with some degree of mobility (Fig. 12). Such platforms will be faced with significant challenges, including communications latencies with Earth (which increase with distance), communications blackouts driven by occultation, the absence of magnetic fields, low surface illumination conditions, and other factors. Furthermore, *in situ* systems that are airborne will not be able to stop and wait for commands from Earth if a fault condition is detected. As a result, short-lived probe and aerial platforms will have to operate at levels of autonomy that will build on, but go beyond, the capabilities of heritage missions, including the Mars exploration rovers, and the Pioneer-Venus, Huygens, and Galileo probes. Key autonomous capabilities include:

(a) aerobot autonomous monitoring, saving, and control to ensure that all onboard systems are being monitored and co-ordinated, that scarce power, communications, and processing resources are allocated adequately, and that the vehicle is kept safe at all times;
(b) aerobot global localization to associate scientific observations obtained by aerobots with specific co-ordinates on the surface to significantly realize the science potential of an *in situ* mission;
(c) vehicle navigation planning and control of lighter-than-air vehicle architectures being considered for Titan include passive balloons, unpropelled montgolfière with vertical actuation, and propelled montgolfière with both vertical and horizontal actuation;
(d) science autonomy arising from communications latency with Earth it is necessary to allow the identification of situations of high potential scientific interest or hazard and initiate appropriate action. An assessment and additional instructions from Earth will follow once communications between the Earth and vehicle have been achieved;
(e) mission operations that address the challenge of operating airborne vehicles on Venus and Titan.

5 POTENTIAL FUTURE PLANETARY PROBE MISSIONS

5.1 Venus mission concepts

The study of Venus is essential to understanding the evolution of all the terrestrial planets including the Earth [**7**]. Addressing the question of the evolutionary divergence of Venus and Earth is key to determining when and if planets will develop and maintain habitable zones [**34**]. The science goals for future exploration of Venus were given in the previous sections (particularly in section 3.1).

A variety of mission element options are available for the continued *in situ* exploration of the Venus atmosphere, surface, and interior (Fig. 7), including aerial mobility platforms (e.g. balloons at various altitudes; Fig. 9), descent probes, short- or long-lived landers (Fig. 10), rovers supported by orbiters or flyby carrier spacecraft. The mission elements then could be assembled in mission architectures, from single elements to multi-element configurations, driven by science and mission cost caps. The scope of these missions largely depends on the scale of the individual mission, and can be defined as large, Flagship-class or medium-class (New Frontiers) missions with a smaller set of science objectives, and small-class (Discovery) missions designed to achieve a very specific set of science objectives. Examples for mission architectures under these categories are provided next.

5.1.1 Venus flagship class mission concept

A flagship mission to Venus consisting of several platforms working in synergy could provide a much deeper understanding of how atmospheric greenhouses work, how volcanic and tectonic processes operate on a planet without plate tectonics, and the fate of oceans on terrestrial planets, and represents a first opportunity to fly a large mission with the explicit intention of better understanding the context of the Earth in the solar system.

A Venus flagship mission, comprising a highly capable orbiter, two cloud-level balloons (Fig. 9), and two short-lived landers targeting different terrains, would be optimized to achieve the largest number of high-priority scientific goals, set by the NRC Decadal Survey (2003) and the Venus Exploration Analysis Group (VEXAG 2009 Decadal Survey white papers at: http://www.lpi.usra.edu/vexag/) [**31**]. Q10
The orbiter on a highly elliptic orbit would provide telecommunication-relay support for a month-long balloon campaign and for the two landers with 5 h lifetimes. Over 30 days the balloons would circumnavigate the planet up to ten times following a path that spirals up from the mid-latitude entry location and goes to higher latitudes, towards the polar vortex, continually sampling gases and cloud aerosols, and

measuring the solar and thermal radiation scattered within the clouds. The landers would perform descent science, obtaining atmospheric measurements in complementary vertical slices and taking images of the surface on the way down. While on the surface, the landers would perform very accurate analyses of the elemental and mineralogical content of rocks and soils on and beneath the surrounding surface. Panoramic images of the landing sites at an order of magnitude higher resolution than achieved with previous landers (i.e. Venera) would provide the geologic context for the landing and sampling sites. After completion of the *in situ* science segment of the mission, the orbiter would aerobrake into a 230 km circular orbit for a 2-year mapping mission. Extremely high-resolution (up to two orders of magnitude greater than was achieved with Magellan) radar and altimetry mapping would allow for a thorough investigation of the surface, opening new avenues to studies of comparative geology. The mission would require two Atlas V 551 launches in the 2020–2025 timeframe: one for the orbiter and the other for a flyby carrier to deliver the two entry systems, each accommodating a balloon and a lander.

5.1.2 Venus mobile explorer concept

In support of the National Research Council's 2010 Planetary Decadal Survey Inner Planets Panel, a study was performed at the NASA Goddard Space Flight Center for a near-surface aerial mobility mission concept [**24**]. Because of the extreme environmental conditions at the surface, the study considered a thin-walled stainless-steel metallic bellows system that would permit loitering at an altitude of 5 km to allow a range of about 8–16 km between the initial and secondary landing sites. The Venus mobile explorer (VME) would carry a nominal science payload to make *in situ* measurements of noble and trace gases in the atmosphere, conduct elemental chemistry and mineralogy assessments at two surface landing sites, image the surface on descent and along the transect connecting the two surface locations, measure physical attributes of the atmosphere, and detect potential magnetic signatures of the surface (Fig. 10). The bellows system, helium tank, the gondola, and supporting structures would fit inside a 3.5 m diameter aeroshell. The thermal design of the gondola would be based on heat pipes and lithium nitrate trihydrate PCM, which would allow the gondola electronics and instruments to survive 5 h near the Venus surface. The power system was designed with primary batteries. Based on the study guidelines, the VME would be launched on an Atlas V 551 in either 2021 or 2023, on a Type II re-counter trajectory to Venus. After release from the carrier, the VME would enter the atmosphere, descend on a parachute briefly, and then free-fall to the surface. Science would be conducted on descent, at the surface landing sites, and during aerial traverse between the landing sites using the metal bellows (filled with helium). The science data from VME are sent to the carrier spacecraft, and after completion of the *in situ* mission sent from the carrier to Earth.

5.1.3 Venus balloon and drop sondes concept

The global super-rotating wind structure and the sulphur-based chemistry in Venus's atmosphere and its role in producing and maintaining clouds, radiative balance, and climate are not well understood. The high-speed winds of Venus's middle atmosphere, which whip around the planet at speeds up to 60 times the planet's rotation rate, are an enigma. Possible mechanisms to accelerate the atmosphere on a global scale to explain the super-rotation include momentum transport by solar thermal tides and eddy circulation. To understand atmospheric tides and the eddy motions, the zonal and meridionally averaged winds and their spatial variability at a given level and latitude must be known [**35**]. However, both zonal and meridional winds have been difficult to measure from orbit with conventional cloud-tracking techniques because cloud tracking provides winds on day and night sides at different levels, and the clouds themselves may vary in altitude longitudinally. By circumnavigating Venus at a known altitude and latitude, a Venus balloon could provide the requisite data to determine the mean tidal effect and estimates of the local eddy components. Additionally, such a balloon could measure numerous other dynamical phenomena that may contribute to super-rotation as well as to the meridional circulation, including the characterization of planetary waves and Hadley cells.

A mission consisting of both *in situ* platforms (balloons and drop sondes; Fig. 7) and a planetary orbiter to explore Venus's surface and atmosphere below the cloud tops would provide *in situ* sampling of winds, temperatures, pressures, aerosols, and trace species over a large range of precisely known altitudes, latitudes, longitudes, and times of day. These datasets would be supplemented by high-spatial measurements of chemicals and aerosols obtained remotely from orbit that extend the localized *in situ* measurements globally and over time. The orbiter and *in situ* platforms would provide surface imagery as well as topographic mapping from an orbiter-borne radar system. The orbiter would also serve as a communications relay to transmit data from the balloon and track it when it flies on the backside of the planet, hidden from Earth.

The *in situ* vehicles would consist of a single 7 m diameter super-pressure balloon, floating at 55 km altitude, carrying a 100 kg instrumented gondola, and up to two drop sondes. The balloon would drift with the 65 m/s zonal winds to circle Venus in about 6 days. Over a month, the balloon circumnavigates the planet about five to ten times, drifting poleward from temperate to polar latitudes in the gentle (1–5 m/s) meridional winds of Venus [**36**]. Science instrumentation would measure

(a) reactive trace gases as well as stable and noble gas isotopes via a GC/MS or a combination Mass Spectrometer/Tunable Laser Spectrometer (MS/TLS) instrument;
(b) aerosol size and column density via a two-channel nephelometer;
(c) pressures and temperatures with suitable sensors;
(d) the rate and strength of nearby lightning, via an electromagnetic lightning detector.

In addition, Doppler/radio tracking of the vehicle by the orbiter as well as by an interferometric array of Earth-based radio telescopes yields the balloon's velocity in all three dimensions with high accuracy, providing invaluable data on atmospheric circulation.

Two drop sondes, each deployed over targeted surface features from their stowed position on the outside of the gondola, would measure the vertical profiles of key trace gases via chemical microsensors (e.g. reference [**37**]) and the pressure/temperature structure. The drop sondes could be tracked by both the orbiter and the balloon to obtain deep-atmosphere wind measurements. In addition, a camera would take about a dozen single-filter images of the targeted surface feature as it descends through the last 5 km of altitude, acquiring detailed high-resolution (better than 1 m) topographic, surface albedo, and texture information.

A topographic radar on the orbiter could map the surface at 1 km/pixel spatial resolution near periapsis, with a vertical resolution of about 1 m, and over the course of a 1-year mapping mission will ensure nearly complete, high-resolution coverage of the periapsis-centred hemisphere. A high-inclination orbit would not only ensure high-resolution radar mapping over a large latitude range, but would also provide a good vantage point near apoapsis to monitor the evolution of the hemispheric vortex with the near-IR spectral-mapper, thus enabling long-term observations of dynamic instabilities recently observed by
Q10 VIRTIS on VEX [**38**].

This mission could likely fit under a medium-class (New Frontiers) cost cap. However, this architecture could be descoped to a small-class (Discovery) mission. For this mission architecture, the orbiter would be replaced by a flyby carrier spacecraft, the *in situ* element would be limited to the superpressure balloon only (without the drop sondes), the number of science instruments would be reduced to fulfil only a subset of the science objective discussed above. The gondola could be powered by either primary batteries or with an ASRG. The ASRG option would increase the science data return about ten fold, but it would increase mission cost and introduce constraints to the mission architecture driven by the g-load tolerance limit and waste heat mitigation of the ASRG [**23**].

Another Venus *in situ* mission concept, called the European Venus Explorer has been proposed under ESA's cosmic vision programme by a European-led international team. This M-class mission concept would consist of a cloud-level balloon, a short-lived lander and an orbiter, with potential added elements of drop sondes and a contributed mid-altitude balloon [**39**].

5.1.4 Venus descent probe/lander concept

The goals of a medium-class mission to Venus are to allow for a comparative study of Venus, Mars, and Earth, in order to better understand the history of Venus, and to facilitate modelling and reasonable extrapolation of the data leading to an improved knowledge the future evolution of all the terrestrial planets. Specific scientific questions that can be addressed include the formation of the terrestrial planets, the history of Venus, whether Venus once had an ocean, surface–atmosphere interactions (weathering), the possible location and composition of volcanoes, and the chemical evolution of the atmosphere. There are a number of key scientific objectives that a single-lander Venus mission (Fig. 10) can address a defined in the Venus *in situ* explorer proposal described in the recent decadal surveys [**8**], and this proposal includes measurements of:

(a) noble gases and their isotopes to constrain the Venusian history;
(b) trace gas profiles and sulphur compounds for chemical cycles and surface–atmosphere interactions;
(c) meteorology on the surface;
(d) surface and subsurface composition;
(e) the coupling of radiation, dynamics, and chemistry between the surface and the atmosphere.

To make this kind of measurements it is essential for a Venusian probe to have a successful landing and to survive on the surface for several hours so as to be able to use its instruments for descent science and for photographing and sampling the surface and the subsurface near the landing site. Such a lander would carry a science payload that includes cameras, spectrometers, neutral mass spectrometer, meteorology package, and instruments to determine the mineralogy and surface texture and could fit under the medium-class (New Frontiers) cost cap, while providing significant science capabilities [**8**].

5.2 Giant planets probes concepts – to Saturn, Jupiter–Neptune

To date, Jupiter is the only giant planet to have been studied *in situ*. To help discriminate among competing

theories of the formation and evolution of the gas giant planets and their atmospheres, it is essential that the Galileo probe studies of Jupiter be complemented by similar studies at Saturn. For a complete understanding of the formation of the entire family of giant planets, including both ice giants and gas giants, probe missions to the ice giants, Uranus, and Neptune are also essential. Both observationally (e.g. measured carbon abundances) and theoretically (e.g. atmospheres forming from some combination of accreting nebula
Q10 gas, degassing of core material, and influx of SCIPs), there are several reasons to expect the atmospheric composition of the ice giants will be greatly different from those of Jupiter or Saturn.

5.2.1 Gas-giant probe mission concepts

A single or multi-probe return-mission to Jupiter should be considered soon after water and ammonia data from NASA's Juno have been received and analysed. In addition to measurements of Jupiter's deep atmosphere provided by the Galileo probe, and the anticipated measurements of water abundance from Juno microwave measurements, an entry probe mission to Jupiter is still needed since measurements of deep atmospheric composition, clouds, and dynamics at spatially separated locations are essential for unambiguous understanding of the formation of Jupiter and the origin of its atmosphere. Results from Juno will help to select the optimum number, location, and depth of *in situ* probe explorations. Several mission options are available for Saturn *in situ* exploration, including deep (20–100 bar) entry probes alone, and shallow (<20 bar) probes, possibly complemented by Juno-type remote sensing with microwave radiometers from a flyby carrier or orbiter for determination of water vapour [**18**, **40**]. A dual-probe mission – one equatorial and one mid-latitude – to sample spatially separated environments is especially desirable (Fig. 8). The key measurement of giant planet probes is composition of the well-mixed atmosphere below the cloud layers, including the heavy elements O, C, N, and S, the noble gases He, Ne, Ar, Kr, Xe, and their isotopes, isotope ratios $^{14}N/^{15}N$, $^{12}C/^{13}C$, and D/H, and disequilibrium species such as CO, PH_3, AsH_3, GeH_4 as tracers of internal processes. He sedimentation is thought to be a major energy source at Saturn and a measurement of the He abundance in Saturn's atmosphere would put the theory for the cooling of all giant planets on firmer footing [**41**]. Other than oxygen (in the form of water), all these species can be accessed and measured by entry probes at depths of several bars for Jupiter, and less than 10 bars for Saturn. Retrieval of oxygen abundances will require either deep probes or microwave radiometry. This is not a serious drawback, as even at Jupiter (for different reasons) no reliable measurement of O was obtained from Galileo. Complementary data on the deep winds, atmospheric pressure versus temperature structure, and cloud location, composition and structure, and measurements of net radiative flux as a function of depth and wavelength are highly desirable.

5.2.2 Ice-giant probe missions

Probe missions to the ice giants Uranus and Neptune are also essential to provide a complete understanding of the origin and evolution (both chemical and dynamical) formation of the solar system, since the location of well-mixed water and ammonia is expected to be at depths of kilobars to (possibly) hundreds of kilobars at Uranus and Neptune, probe missions into these truly extreme environments are not currently feasible, and orbiter-based microwave radiometry to obtain abundances of oxygen is not expected to be particularly useful [**42–45**]. Shallow probes, a far less challenging engineering problem, will retrieve abundances of most heavy elements other than oxygen and nitrogen, and can make atmospheric structure and dynamics measurements below the levels significantly influenced by sunlight. Ice giant shallow probes can measure noble gas and methane abundances, thereby helping to unravel important atmospheric chemistries and processes that are currently not well understood. In turn, this will help constrain the bulk abundances of oxygen, nitrogen, and sulphur.

5.3 Titan mission concepts – balloons, probes

The forces that shape Titan's landscape, including dunes, cryovolcanoes, and rivers, and interior including a possible subsurface ocean, are not well understood (Fig. 11). To understand the diversity of environments, including the rich-in-organics atmosphere, requires detailed investigations relying on very high-spatial-resolution remote sensing at a variety of locations. A demanding requirement anywhere else, high-spatial-resolution remote sensing is uniquely possible at Titan using *in situ* aerial mobility platforms such as a hot-air balloon (montgolfière), or an airplane (Figs 12 and 13). All the recent future-exploration concepts for Titan (Titan Explorer, TandEM, and TSSM) have included a balloon [**28**, **29**, **46**]; TSSM final report; TSSM *in situ* elements ESA assessment study report; TSSM NASA/ESA Joint Summary Report: http://opfm.jpl.nasa.gov/library/).

Titan's thick cold atmosphere and low gravity make the deployment of *in situ* elements under parachute (as demonstrated by the Cassini–Huygens probe) and balloons vastly easier than for any other solar system body. A montgolfière with an adapted payload floating across the Titan landscape for periods up to Earth months or even years offers the mobility required to explore the diversity of Titan in a way that cannot be achieved with any other platform. Titan *in situ* elements could enable powerful techniques such as subsurface sounding and potentially seismic measurements, to examine and better understand Titan's crustal structure. Due to Titan's cold and dense atmosphere ($5\,kg/m^3$ at the surface compared to $1\,kg/m^3$ on Earth), and the effect of differential molecular mass between the buoyant gas and the ambient air, Titan is the best place in the solar system for scientific ballooning. The low value of solar radiation (10^{-2} of radiation at Earth) creates, in all practicality, no diurnal variation of the external energy source and opens the possibility of long duration flights – less stress on balloon materials and cyclic impact on buoyancy. Because of the scale height of Titan's atmosphere, inflation during descent occurs over a long period; for example, it can be initiated at a vertical velocity of 5 m/s around 30 km of altitude (20 mbar pressure) and completed over a number of hours (compared to 30 m/s initial velocity). While other elements identified in Titan mission architectures (notably landers/surface elements) appear to have significant flight heritage, a balloon has not been flown at Titan.

The 2008 TSSM NASA and ESA studies confirmed the feasibility of implementing a montgolfière balloon at Titan and identified several risks that should be addressed to demonstrate flight readiness, including balloon deployment and inflation upon arrival at Titan, balloon packaging inside the aeroshell with RPS thermal management, and interface complexity between balloon, RPS, and aeroshell (Figs 5 and 6).

Although to date, balloons have only been deployed in Venus' atmosphere, balloons offer the only possibility today of conducting a long-duration voyage in terrestrial-like atmospheres in the solar system. As envisioned in mission studies, a montgolfière is capable of circumnavigating Titan every 3–6 months. Carried by 1–3 m/s winds, a Titan montgolfière could explore the Titan environment with a host of highly capable instruments including high-resolution cameras, chemical analysers and subsurface-probing radar (Fig. 11). There are no obvious life-limiting factors, and so its flight could continue for many months, perhaps even years and could provide global coverage from a nominal altitude of about 10 km. Furthermore, the capability of performing surface sampling from the balloon has been investigated and development of this capability would further increase the science value of such a mobile platform. A combination of orbiting and *in situ* elements would provide a comprehensive and, for Titan (indeed, for the outer solar system!), unprecedented opportunity for synergistic investigations. The balloon platform alone, with a carefully selected instrumentation suite, is a powerful pathway to understanding this profoundly complex body. The montgolfière is Titan's 'Rover', albeit with the advantage of an extended range.

6 SUMMARY

To a large degree, space exploration of the solar system has been dominated by remote observations using planetary flyby and orbiting mission architectures. The technologies for these missions are mature and well understood. Pursuing with extensive *in situ* exploration in the atmosphere and on the surface of planetary objects is the next critical step for achieving a breakthrough in scientific knowledge. Balloons, landing probes, and airplane concepts are viable elements that have been or are being proposed for *in situ* exploration of Venus, Titan, Jupiter, Saturn, and Neptune. These elements require technology advancements to assure mission success in the extreme environments and more challenging science operational scenarios they face. Clearly, the future provides great opportunities for technological developments and challenging first-of-a-kind mission implementations.

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