VALENTInE: A Concept for a New Frontiers–Class Long-Duration In Situ Balloon-based Aerobot Mission to Venus

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Abstract

Described here is a concept for a variable-altitude aerobot mission to Venus developed as part of the 2020 NASA Planetary Science Summer School in collaboration with NASA Jet Propulsion Laboratory. The Venus Air and Land Expedition: a Novel Trailblazer for in situ Exploration (VALENTInE) is a long-duration New Frontiers-class mission to Venus in alignment with the goals recommended by the 2013 Planetary Science Decadal Survey. VALENTInE would have five science objectives: (1) determine the driving force of atmospheric superrotation, (2) determine the source of D/H and noble gas inventory, (3) determine the properties that govern how light is reflected within the lower cloud layer, (4) determine whether the tesserae are felsic, and (5) determine whether there is evidence of a recent dynamo preserved in the rock record. The proposed mission concept has a total duration of 15 Earth days and would float at an altitude of 55 km, along with five dips to a lower altitude of 45 km to study Venus’s lower atmosphere. The instrument payload allows for measurements of the atmosphere, surface, and interior of Venus and includes six instruments: an atmospheric weather suite, a mass spectrometer, a multispectral imager, a near-infrared spectrometer, light detection and ranging, and a magnetometer. Principle challenges included a limitation caused by battery lifetime and low technology readiness levels for aerobots that can survive the harsh conditions of Venus’s atmosphere. This preliminary mission was designed to fit within an assumed New Frontiers 5 (based on inflated New Frontiers 4) cost cap.

Unified Astronomy Thesaurus concepts: Venus (1763); High altitude balloons (738); Planetary probes (1252); Planetary atmospheres (1244)

1. Introduction

In situ studies of Venus’s atmosphere provide an opportunity to retrieve in situ data about another terrestrial planet in the solar system that has direct implications for planet formation, atmospheric evolution, and astrobiology. Venus is often referred to as Earth’s sister planet because of the similarities in radius, uncompressed density, bulk composition, and approximate distance from the Sun (Taylor et al. 2018).

However, previous Venus missions have revealed many differences between the current environmental conditions of the two planets. These differences raise questions about the origins and evolution of terrestrial bodies and whether Earth could evolve to a Venus-like state.

Previous missions to Venus have explored surface volcanic features and plains, the possible continental crust, the weak magnetic field, and the atmosphere (e.g., Titov et al. 2002; Svedhem et al. 2009; Nakamura et al. 2018). These missions were typically landers or orbiters and collected data that were limited in spatial and temporal resolution and global extent. Landers were sent to obtain precise mineralogical data at a preselected landing site and could only survive a couple of hours owing to the high surface temperatures. As a result,
in situ data from the surface of Venus are limited. Orbiters avoided the high temperatures and pressures of the surface environment but had to contend with Venus’s thick clouds, which obscure the surface, with the exception of a few spectroscopic windows. Future missions to Venus are necessary to address fundamental questions surrounding the chemical composition and dynamics of the Venusian atmosphere (Lima et al. 2009), its geologic history (Ivanov & Head 2011, 2015; Smrekar et al. 2018), its internal structure (O’Rourke et al. 2018, 2019), and its habitability throughout time (Way et al. 2016; Way & Del Genio 2020).

Recently, the National Aeronautics and Space Administration (NASA) selected two Discovery-class missions to Venus to investigate the divergence in planetary evolution between Earth and Venus. The lander mission, Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging (DAVINCI) will take measurements of Venus’s lower atmosphere as it descends to search for evidence that an ancient ocean once existed. On its descent, DAVINCI will also acquire high-resolution images of Venus’s surface. The estimated time for in situ science is ~59 minutes (Garvin et al. 2020). An accompanying orbiter will acquire a global map in the ultraviolet (UV) and at the 1 μm near-infrared (NIR) band. The second mission is Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS), an orbiter that will investigate the geologic history of Venus using radar and NIR spectroscopy (Freeman et al. 2016). VERITAS will map the surface topography of Venus and generate radar imagery with 250 and 30 m spatial resolution, respectively. The European Space Agency (ESA) also announced its own medium-class (roughly equivalent to a NASA Discovery-class) orbiter mission to Venus called EnVision. EnVision will carry three instruments on it: a synthetic aperture radar, a subsurface radar sounder, and a spectroscopy suite (Ghai et al. 2016). Both VERITAS and EnVision will map the gravitational field of Venus as they orbit, which, when combined with the surface data acquired from radar sensing by both missions, will constrain Venus’s internal structure. Together, these future missions will enhance our knowledge about Venus and its history. However, with the short duration of DAVINCI and the altitude limits of VERITAS and EnVision, there is still a knowledge gap about the structure, chemistry, and dynamics of the lower atmosphere that another mission could address.

An atmospheric balloon can survive for weeks rather than hours in the Venusian climate and can therefore provide observations at multiple locations, resulting in a significant increase in the science return relative to a lander mission. A balloon-based mission would also be able to retrieve in situ data inaccessible to an orbiter owing to its position within and below the thick cloud deck. A variable-altitude balloon provides an opportunity to analyze multiple samples of the atmosphere’s composition and record information about the physical structure, temperature, and pressure at different locations within Venus’s atmosphere. These details are critical for determining how Venus’s atmosphere has evolved and for supplying information to global climate models to better understand how thick atmospheres convect and rotate. For Venus, this is especially important, as it has superrotation, a phenomenon that is not well understood (Read & Lebonnois 2018).

The Venus Air and Land Expedition: a Novel Trailblazer for in situ Exploration (VALENTInE) mission is a variable-altitude aerobot that would passively float in the Venusian atmosphere at altitudes between 45 and 55 km. VALENTInE is designed as a New Frontiers–class NASA mission ($1B cost cap), giving it the advantages of being able to carry a larger scientific payload and support for more intense technical development than Discovery missions. This mission differs from the DAVINCI, VERITAS, and EnVision missions in its structure and mission scope of gathering observations at various latitudes, longitudes, and altitudes, providing the opportunity to construct robust profiles of the Venusian atmosphere. In addition, this mission provides the opportunity to study Venus’s surface and bulk mineralogy in multiple locations and directly compare terrains across Venus’s surface to address their relative ages and potential origins. VALENTInE would provide valuable observations relevant to planetary interiors, magnetic fields, atmospheres, and surfaces and enable cross-disciplinary collaboration and interdisciplinary science.

This paper describes a concept for a variable-altitude aerobot mission to Venus. Section 2 provides scientific background on Venus, and Section 3 outlines the science goals that are the drivers of this mission. The instruments used to address the science goals are detailed in Section 4. Section 5 explains the mission design, and Section 6 describes the aerobot design. Cost is discussed in Section 7.

2. Scientific Context

2.1. Comparative Planetology

Venus is called Earth’s sister planet owing to their similarities in bulk composition, size, density, and approximate distance from the Sun. Yet the two planets have evolved into completely different end states, raising many questions about the origins and evolution of terrestrial planets and whether Earth is on a similar path to inhospitable conditions. Moreover, the rapidly growing number of known terrestrial exoplanets means that comparative planetology is no longer strictly limited to the solar system. Venus contains key pieces of information for both planetary and exoplanet science because of its uniqueness within the solar system and its potential commonness outside of it. Studying the atmosphere of Venus is an opportunity to learn about the origins of the terrestrial neighborhood and possible futures for Earth (Taylor et al. 2018) and provide exoplanet science with in situ data of a terrestrial, Earth-sized planet with a thick atmosphere. An atmospheric mission to Venus would provide an additional dimension in comparative planetology studies that complements past and upcoming missions and supplies the planetary science community with entirely new data on an understudied planet.

Venus and Earth appear very different today, though they may have been more similar in the past. Given their similar distances from the Sun, Earth and Venus likely accreted with similar bulk compositions and relative water content. Like Earth, Venus potentially had liquid water oceans on its surface in its past, potentially for much of its history (Way et al. 2016). Perhaps as recently as 500 Ma, Venus entered a runaway greenhouse state (Way & Del Genio 2020) that caused any water oceans at the surface to boil and vaporize. Water vapor then diffused throughout Venus’s atmosphere, and large quantities have subsequently been photolyzed by solar extreme-ultraviolet (EUV) photons at the top of the atmosphere. On Earth, an atmospheric cold trap keeps condensible
water vapor close to the surface in the troposphere, where it is protected from photolysis by the atmosphere above (Wordsworth & Pierrehumbert 2013). The high D/H ratio in the atmosphere of Venus relative to Earth (Donahue et al. 1982) is consistent with the loss of water on the same order of magnitude as an Earth ocean. However, this ratio has not been measured precisely; data suggest that this quantity varies with altitude (Krasnopolsky et al. 2013). Furthermore, the initial D/H ratios of Earth and Venus may not have been identical, which affects the interpretation of the sparse data currently available. The present-day Venus environment may represent a possible future for Earth, as the concentrations and composition of greenhouse gases lead to increased surface temperatures. Knowing what happened to Venus is critical for extrapolating future pathways for Earth.

If Venus ever had plate tectonics, water loss at the surface likely led to its cessation (Lammer et al. 2010). Lack of water at the surface, combined with the lack of plate tectonics, prevented dissolution and burial of CO₂, leading to its buildup in the atmosphere as the gas continued to be exsolved by volcanic activity. Greater buildup of CO₂ further exacerbated the runaway greenhouse state (Walker 1975) and raised the surface temperature until an equilibrium configuration was reached. Comparison between the current and past atmospheres of Venus and Earth provides vital tools with which we can better understand atmospheric evolution. More precise measurements than are currently available will improve our understanding of the dynamic interactions between atmospheric constituents so that existing models may be extrapolated to other bodies, including exoplanets, with greater fidelity (i.e., Kane et al. 2021).

All life on Earth requires liquid water to survive. Clement conditions are nowhere to be found on Venus that coincide with the presence of water—surface temperatures (~462 °C; Titov et al. 2013) far exceed the limits observed for life on Earth (122 °C; Takai et al. 2008). Locations on Venus where the atmospheric temperature becomes more favorable for life, at around 45 km altitude, contain condensable liquids that are dominated by H₂SO₄ droplets. Although some water is present, the water activity of droplets is below the limits of habitability for life on Earth (Hallsworth et al. 2021). Seager et al. (2021) hypothesize about life cycles of potential microbes on Venus; however, the viability of fundamental processes important to life is challenged by the concentrated acid of Venus’s clouds.

Although Venus is not habitable today, its previously high water inventory suggests that the planet may have been habitable in the past. This possibility drives the interest in Venus as an exoplanet analog to explore the inner limits of habitability (Kane et al. 2019, 2021). The locations of the habitable zones (HZs; Kopparapu et al. 2013) around different types of stars are an area of active research in exoplanet science. Venus likely represents a planet that was once in the HZ but has since moved out of it, suggesting that it is possible for planets to move across the inner and outer HZ boundaries as their star–planet systems evolve (e.g., Tuchow & Wright 2021). Thus, Venus represents the best opportunity to directly observe the signatures of a formerly habitable planet. Venus’s atmosphere specifically contains many of these data because of its volume, structural complexity, and chemistry. While the brand new James Webb Space Telescope is now deployed, it will not have the capability to determine that a Venus-sized exoplanet has a Venus-like atmosphere. Future missions such as HabEx and LUVOIR, however, will have the capability to detect tens of Venus-sized exoplanets (Morgan et al. 2019). In many cases, the information received from these exoplanets will include spectra of their atmospheric compositions. Comparing these spectra to Venus’s atmosphere will enable more accurate characterizations of these exoplanets and determination of the general histories of other potentially habitable worlds and planetary systems. These are priority goals named in the most recent Decadal Survey on Astronomy and Astrophysics (National Academies of Sciences, Engineering, and Medicine 2021).

2.2. Characteristics of Venus

2.2.1. Atmospheric Circulation

Venus’s atmospheric temperature and pressure are believed to change as a function of latitude (Seiff et al. 1985). Earth-like pressures and temperatures can be found near the tropopause (~50 km), an altitude that is rarely studied owing to the limited measurement time of lander missions on descent and the opaqueness of the cloud deck to orbiters. Direct measurements of these values are also critical for building robust atmospheric models.

Venus’s atmosphere also exhibits superrotation, which is when the atmosphere of a planet rotates faster than the planet itself. The mechanism for such motion requires transport of momentum into the atmosphere toward the equator balanced by momentum out of the atmosphere; however, this mechanism is yet to be fully understood. The atmosphere superrotates around the planet once every 4–5 days in the cloud-top region (65–70 km) at speeds of about 100 m s⁻¹, decreasing both poleward and toward the surface. Additionally, poleward meridional motion at cloud tops is often observed, commonly interpreted as the upper branch of a Hadley cell. However, observations at lower altitudes (40–60 km) find slower meridional motion and do not clearly show the equatorward motion expected for the lower branch of a Hadley cell. Past in situ missions found vertical motion between −3 and +3 m s⁻¹, possibly originating from vertically propagating waves, convection, or Hadley circulation. Understanding vertical shear in Venus’s atmosphere and overall atmospheric motion with greater spatial resolution will inform us about the provenance of momentum transport, whether primarily up from the surface via gravity waves, top-down from solar tides, or some combination thereof (Sánchez-Lavega et al. 2017). By understanding the transport of momentum in Venus’s atmosphere, we can more clearly understand the mechanics of atmospheric superrotation, which has implications for planetary evolution of tidally locked exoplanets and climate change on Earth.

Venus’s topography may also cause changes in the atmosphere that VALENTInE would be able to trace by virtue of its passive navigation. Topographic highs appear to cause stationary gravity waves in Venus’s atmosphere, a pattern that has been observed in Soviet Vega balloons (Young et al. 1987) and from Venus Express data (Peralta et al. 2017). The JAXA mission to Venus Akatsuki detected an ultraviolet-bright stationary wave centered downwind from the Aphrodite Terra highland region (Fukuhara et al. 2017). Though the anomaly was detected in the upper atmosphere, it is likely the result of near-surface atmospheric winds flowing over elevated topographic features. These waves also appear sensitive to latitude,
The bulk of Venus’s atmosphere by mass is contained in the region below 45 km, but studying this layer is challenging. Thick clouds of photochemically derived H$_2$SO$_4$ and water vapor (Sill 1972; Young 1975; Pollack et al. 1978) form around 50 km in altitude and are opaque in visible wavelengths, making Earth-based observations of Venus’s surface difficult (Figure 1). The clouds themselves show inherent variation both spatially and temporally (Arney et al. 2014). For example, clouds at different altitudes differ in composition and particle size distribution (Krasnopolsky & Parshev 1981; Satoh et al. 2015), parameters that fundamentally change how light is reflected and emitted (Arney et al. 2014; Crisp 1997). Data from different experiments by spacecraft in the past are contradictory to one another. For example, to study the physical properties of the cloud particles, the payload of the Vega missions included a mass spectrometer, an X-ray spectrometer, particle size spectrometers, and a nephelometer, which all showed different results regarding particle size and composition (Krasnopolsky 1989). Likewise, data from the Pioneer Venus cloud particle size spectrometer detected large ($D \sim 7 \mu$m) particles in the lower clouds of Venus (called mode 3 particles because they form a third peak in plots of size distribution), which implies that the composition of Venus’s clouds is not dominated by sulfuric acid, contrary to previous belief (Knollenberg & Hunten 1980). A discussion of the existence of these mode 3 particles is given in Toon et al. (1984), who conclude either that there are large mode 3 particles in the atmosphere or that there was an instrumental error while obtaining the data and the observed mode 3 particles are simply the tail of the mode 2 particles of sulfuric acid. Therefore, there is strong motivation to constrain the values of cloud opacity, particle size, and composition with direct measurements to better describe the complex and interconnected chemical cycles in Venus’s atmosphere. Additionally, any inferences derived from Venus’s atmosphere are directly applicable to refining the data from exoplanets, as bulk atmospheric data are deeply informative observables of a planet’s possible states.

Venus’s atmosphere is primarily composed of CO$_2$ (96.5%), with a small amount of N (3.5%) and trace amounts of SO$_2$, H$_2$O, CO, COS, and HCl (Svedhem et al. 2007). Atmospheric windows exist through which observations of the lower atmosphere are possible at 1.00, 1.10, 1.18, 1.27, 1.31, 1.74, and 2.3 $\mu$m (Allen & Crawford 1984; Allen 1987; Carlson et al. 1991; Crisp et al. 1991). The cloud layer between 48 and 57 km in altitude is made up of mode 2 and mode 3 particles that have a mean radius of 3.85 $\mu$m (Arney et al. 2014). Larger particles are observed at low latitudes (Satoh et al. 2015), which may be a function of excess H$_2$SO$_4$ condensation onto preexisting condensation nuclei (Imamura & Hashimoto 2001). Mode 3 particles account for most of the mass of the clouds and their opacity (Crisp 1986) and may have a crystalline component (Knollenberg & Hunten 1980). The light scattering caused by these particles in the 1.0–2.3 $\mu$m NIR range can cause a false inferred decrease in the abundance of various atmospheric species, especially at longer wavelengths (Marcq et al. 2006; Arney et al. 2014). The failure to correct for these factors may lead to inaccurate interpretations of data. Thus, knowing more about the cloud particles themselves, how they vary spatially, and how they correlate with chemical species in the cloud layer are fundamental measurements to generate a deeper understanding of Venus’s atmosphere via improved modeling.

The isotopic ratios of hydrogen, oxygen, and select noble gases (He, Ne, and Ar) hold clues to Venus’s past habitability. The accepted explanation for Venus’s present state is the runaway greenhouse (Ingersoll 1969; Walker 1975), in which the incoming insolation from a younger, more energetic Sun caused the oceans to evaporate, increasing the water vapor in the atmosphere. The D/H ratio measured by Pioneer Venus is high relative to Earth’s value, suggesting that significant (≈99%) amounts of hydrogen from evaporated oceans have been lost to space (Donahue et al. 1982). The increased moisture in the atmosphere accelerated hydrogen escape. Alternatively, volcanism may have been the main driver in the onset of the greenhouse state (Way & Del Genio 2020) rather than insolation. Each of these scenarios would have caused different escape rates for various molecules; therefore, information about the timescale of water loss is recorded in atmospheric isotope ratios. For example, measuring the
radiogenic $^4$He places constraints on how long Venus has been in its current state. Measuring the $^{36}\text{Ar}^{38}\text{Ar}$ and $^{20}\text{Ne}^{22}\text{Ne}$ values and comparing them to stellar abundances puts constraints on the speed of hydrogen escape in Venus’s early history (Zahnle et al. 1990; Ozima & Zahnle 1993; Gillmann et al. 2009). Finally, studying oxygen yields clues about both hydrogen escape and the atmosphere’s interchange with the surface. Measuring a strong mass fractionated $^{16}\text{O}^{18}\text{O}$ value implies that oxygen did escape rapidly along with hydrogen. Measuring a weak mass fractionated $^{16}\text{O}^{18}\text{O}$ value implies that oxygen did not escape in large quantities, and instead was sunk into Venus’s mantle (Gillmann et al. 2009; Hamano et al. 2013).

2.2.3. Surface Geomorphology

Most of Venus’s surface has been shaped by volcanic activity. There are hundreds of large volcanoes on Venus, though there is little evidence of lava flow coming from these calderas. Despite this, the concentration of sulfur dioxide in the atmosphere suggests that volcanic activity is ongoing. Venus has a low crater count with limited overlap of craters, which implies that the surface is young on average. Volcanism on Venus would also output large amounts of both water vapor and $\text{H}_2\text{SO}_4$, both important molecules in Venus’s atmosphere. Studying the surface at the same time as the atmosphere is the ideal way to assess how the two interact.

The average age of Venus’s surface is ~750 million years, as estimated from crater counts (Schaber et al. 1992). The regions on Venus’s surface that are locally older than their stratigraphic neighbors are called the tesserae and may provide insight into surface conditions up to 1.75 Ga. The surface of Venus contains ~8% tesserae, which are radar-bright regions of high topography and tectonic deformation (Ivanov & Head 2021). The largest tessera region is Aphrodite Terra, which is half the size of Africa (Figure 2). The topography of the tesserae exhibits ridges and troughs, resembling mountain building and faulting. The composition of the tesserae is likely different from that of the basaltic plains. Understanding the composition of the tesserae will inform us of its age and can place a constraint on planetary formation models.

2.2.4. Magnetic Field

Venus’s high surface and interior temperatures were thought to have precluded its ability to sustain and record a core dynamo (Breuer et al. 2010). Recent modeling has demonstrated that Venus was capable of producing and sustaining an Earth-strength surface magnetic field for 2–3 Ga (O’Rourke et al. 2018). Modeling of magnetic minerals on the Venus surface demonstrates that remnant magnetization is possible and perhaps has yet to be detected. Several spacecraft measurements have placed upper limits on the strength and location of crustal magnetization (Burba 1990; Phillips & Russell 1987). However, latitudes south of 50° S remain viable for detection of surface remnant fields from an orbiter. In situ spacecraft are able to detect magnetic fields with coherency at their approximate operating latitude, making detection of crustal magnetic fields on Venus more feasible by balloon and lander missions than by orbiter missions (O’Rourke et al. 2019). Depending on the thickness of the magnetized crust, a magnetic anomaly measured at an altitude of 50 km could be up to 200 nT. The intensity of a dipole field is directly correlated to the cube of the distance between the source and...
the observer, making observations of small-scale magnetization from 50 km ~27 times more sensitive than from an orbiter (O’Rourke et al. 2019).

2.3. Previous Missions to Venus

The first successful mission to Venus was Mariner 2, which indicated that the surface of Venus was hot based on radio brightness measurements (Barath et al. 1964). In 1967, the Venera 4 mission was the first atmospheric probe mission to measure the atmosphere of a planet other than Earth (Reese & Swan 1968). Venera 5 and Venera 6 were atmospheric probes but were short-lived, each recording data for less than an hour before their batteries died (Avduevsky et al. 1970). In 1972 the Venera 7 mission was the first successful landing mission on the Venuvian surface, and from 1972 to 1985 a total of five Venera landers and two Vega landers measured the surface geochemistry of Venus by X-ray fluorescence (XRF) and gamma-ray spectroscopy (GRS) (Grimm & Hess 1997; Treiman 2007). Geochemical analyses from these missions showed that surface measurements from the landing sites have similar potassium, thorium, and uranium to terrestrial mafic rocks (e.g., Barsukov 1992). Treiman (2007) then demonstrated that Venuvian surface analyses are similar to both tholeiitic and highly alkaline basaltic rocks on Earth. However, Verena and Vega geochemical analyses are imprecise and measured few elements, and they could not measure sodium (Gilmore et al. 2017). The Venera 15 and Venera 16 missions produced synthetic aperture radar images of 25% of the Venuvian surface with a resolution of 1–2 km (Kotelnikov et al. 1985). This mission was the first to recognize structures such as ridge belts, tesserae, and coronae. The Pioneer Venus Orbiter studied the atmosphere for 14 yr, with four probes and an orbiter (Donahue 1979). During this mission, it acquired data that led to the discovery of the high deuterium-to-hydrogen ratio D/H, which is 150 times larger than that in Earth’s oceans (Donahue et al. 1982). The large D/H ratio implies that Venus may have lost a significant amount of water (e.g., Donahue & Russell 1997). In addition to atmospheric measurements, the orbiter in the Pioneer Venus mission used radar to map the topography, gravity, and roughness characteristics (Masursky et al. 1980). Two balloon missions to Venus in 1984, Vega 1 and Vega 2, demonstrated the potential for aerobot missions. These meteorological balloons were limited to 54 km, the most active layer of the Venuvian cloud system, and relatively short-lived (~47 hr). Nonetheless, atmospheric measurements spanning ~1/3 of the way around Venus and temperature measurements were achieved. In situ atmospheric observations provided by balloon missions have the potential to enable multiple science investigations, allowing for a broad range of science objectives outlined by the Decadal Survey to be met.

3. Science Objectives and Mission Requirements

3.1. Goals and Science Objectives

The VALENTiNe mission seeks to address two priority questions outlined in the most recent Planetary Science Decadal Survey (National Research Council 2011). The first is, “How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved to influence the Venuvian atmosphere?” The second is, “What governed the accretion, chemistry, and internal differentiation of Venus and the evolution of its atmosphere?” To address these questions, VALENTiNe would have five main science objectives:

1. Determine whether the driving force of the superrotation of Venus’s atmosphere is caused by horizontal or vertical momentum transport. Superrotation of the dense Venus atmosphere has played a major role in Venus’s climate evolution. Superrotation on Venus requires transport of momentum toward the equator; however, the cause is unclear. If vertical angular momentum transport is the driving force, then the regional average of wind shear in the vertical direction would be larger than the wind shear with latitude variation. If horizontal momentum transport is the driving force, the opposite would be true.

2. Determine whether the atmospheric composition (i.e., D/H) and noble gas inventory of the Venuvian atmosphere are a product of outgassing from the initial protoplanetary source, or if there are significant contributions from exogenic sources. The D/H ratio of Venus’s atmosphere tells us how much water Venus has lost and therefore how similar the original water content on Venus and Earth was. Noble gases are chemically inert and volatile and can thus tell us about several processes in the evolution of planetary bodies such as outgassing, atmospheric loss and acquisition, accretionary history, and whether Venus came from the same part of the protoplanetary nebula as Earth and Mars (Kane et al. 2019). The large uncertainty in previous noble gas measurements leads to many possible conclusions of the source of Venus’s atmosphere. Measurements of D/H ratio and noble gas abundances will resolve outstanding questions regarding the provenance of atmospheric constituents.

3. Determine the properties that govern how light is reflected within the lower cloud layer to resolve discrepancies in atmospheric models that are a direct result of uncertainties in the composition of Venus’s clouds, and to verify that mode 3 particles exist. Opacity is a fundamental property of Venus’s atmosphere and is controlled by the thick clouds within it. Clouds at different altitudes in Venus’s atmosphere differ in composition and particle size distribution (Krasnopolsky & Parshev 1981; Satoh et al. 2015), parameters that fundamentally change how light is reflected and emitted (Crisp 1997; Arney et al. 2014). Wavelength of the light can also change the incident flux (Arney et al. 2014). Many atmospheric models rely on subtracting the effects of atmospheric attenuation by the thick clouds to accurately interpret observable data. Failing to do so vastly changes the results of long-term atmospheric models. Resolving the uncertainties in the physical properties of mode 3 particles will resolve these large discrepancies in the modeling of Venus’s atmosphere.

4. Determine how similar the original water content on Venus and Earth was, and how they vary spatially with latitude and longitude. Water is a fundamental component of life, and understanding the origin and evolution of water on Venus will provide further constraints on the formation of life on Earth and other planets, and potentially others (e.g., Donahue & Russell 1997). Nuclei in the protoplanetary nebula, from which Venus, Earth, and Mars were formed, had at least 1% of the initial water content in the inner solar system (e.g., Masursky et al. 1980, 1982). The VALENTiNe mission will determine whether the amount of water on Venus has been similar to that on Earth and Mars, and how the abundance of water varies with latitude and longitude. If the original water content on Venus was similar to that on Earth, then Venus may have supported liquid water oceans in the past, and therefore may have had the potential to support life. If the water content on Venus is significantly different from that on Earth, then the role of outgassing and accretionary processes will be better understood.

5. Determine the potential for habitability of Venus’s surface. Venus is the second planet from the Sun and is negatively habitable due to the extreme temperatures and pressures at the surface. However, if Venus is negatively habitable, then the conditions that make Earth and Mars habitable must be fundamentally different. Understanding the conditions on Venus will provide further constraints on the formation of life on Earth and other planets, and potentially others (e.g., Donahue & Russell 1997). To address these questions, VALENTiNe will use synthetic aperture radar images to map the topography of Venus and gravity and roughness characteristics of the surface to better understand how Venus’s surface has evolved. The VALENTiNe mission will study the surface geochemistry of Venus by X-ray fluorescence (XRF) and gamma-ray spectroscopy (GRS) (Grimm & Hess 1997; Treiman 2007). Geochemical analyses from these missions showed that surface measurements from the landing sites have similar potassium, thorium, and uranium to terrestrial mafic rocks (e.g., Barsukov 1992). Treiman (2007) then demonstrated that Venuvian surface analyses are similar to both tholeiitic and highly alkaline basaltic rocks on Earth. However, Verena and Vega geochemical analyses are imprecise and measured few elements, and they could not measure sodium (Gilmore et al. 2017). The Venera 15 and Venera 16 missions produced synthetic aperture radar images of 25% of the Venuvian surface with a resolution of 1–2 km (Kotelnikov et al. 1985). This mission was the first to recognize structures such as ridge belts, tesserae, and coronae. The Pioneer Venus Orbiter studied the atmosphere for 14 yr, with four probes and an orbiter (Donahue 1979). During this mission, it acquired data that led to the discovery of the high deuterium-to-hydrogen ratio D/H, which is 150 times larger than that in Earth’s oceans (Donahue et al. 1982). The large D/H ratio implies that Venus may have lost a significant amount of water (e.g., Donahue & Russell 1997). In addition to atmospheric measurements, the orbiter in the Pioneer Venus mission used radar to map the topography, gravity, and roughness characteristics (Masursky et al. 1980). Two balloon missions to Venus in 1984, Vega 1 and Vega 2, demonstrated the potential for aerobot missions. These meteorological balloons were limited to 54 km, the most active layer of the Venuvian cloud system, and relatively short-lived (~47 hr). Nonetheless, atmospheric measurements spanning ~1/3 of the way around Venus and temperature measurements were achieved. In situ atmospheric observations provided by balloon missions have the potential to enable multiple science investigations, allowing for a broad range of science objectives outlined by the Decadal Survey to be met.
4. Determine whether the tessera region (particularly Aphrodite Terra) is felsic and relatively older than surrounding regions known to be basaltic in composition. Knowledge of the composition and relative age of the tesserae places a strong constraint on models of planetary formation. Venustian mantle plumes produce coronae that represent different plume–lithosphere interactions and/or evolution stages (Kane et al. 2019) that may be identified by IR spectral signatures. Aphrodite Terra has multiple volcanic features confirmed by Magellan data (Phillips et al. 1987) such as lava channels, coronae, and shield volcanoes, which all have different topography detectable by light detection and ranging (LIDAR). The LIDAR measurements will complement the global digital elevation model made by the upcoming VERITAS mission, which will use radar to map topography on Venus.

5. Determine whether there is any evidence of a recent dynamo preserved in the rock record on Venus. Venus’s presence or lack of a current core dynamo is crucial to distinguish between models of how terrestrial planets cool, how likely they are to host dynamos, and what mechanisms might be involved in Earth’s long-lasting dynamo (Phillips et al. 1987; Nakamura et al. 2018). If there is visible magnetization, then Venus’s dynamo only shut down recently. If there is not detectable magnetization, Venus may not have had a recent dynamo, with significant implications for how its cooling history diverged from Earth. However, due to limitations in spatial coverage and measurement precision, a nondetection does not definitively prove that a recent dynamo did not exist.

The concept mission’s science traceability matrix (STM) describes the measurements, instruments, and mission performance requirements necessary to address the science objectives described in this section. Figure 3 presents an abridged version of the STM for the VALENTInE mission concept.

In addition to addressing two priority questions from the Planetary Science Decadal Survey, the VALENTInE mission is relevant to the goals outlined in the 2021 Astrophysics Decadal Survey (National Academies of Sciences, Engineering, and Medicine 2021). In particular, this mission would address the following questions: “What are the properties of individual
planets, and which processes lead to planetary diversity?” and “How do habitable environments arise and evolve within the context of their planetary systems?”

3.2. Mission Requirements

To meet the science requirements, this mission uses an aerobot designed as a gondola (instruments/avionics/power) suspended from a large, helium-pumped weather balloon. This vehicle would allow the mission to retrieve in situ atmospheric data along with remote sensing of the surface. The requirements for this mission focus on the necessary lifetime of the electronics and materials for the instrument suites and the vehicle. This is due to Venus’s harsh atmosphere, which constrains the altitude the balloon can reside in and the duration that instruments can operate. Due to these restrictions, the total lifetime of the mission is 15 days. During these 15 days, the aerobot would perform five dip maneuvers, lowering the altitude of the aerobot to 45 km for 3 hr (Section 5.2). The aerobot would carry a suite of six instruments weighing 669 kg and requires 28.8 kWh of power for the duration of the 15-day prime mission. The six instruments aboard must be able to withstand the Venusian atmosphere for a 15-day life cycle. This requires electronic hardening of any external components within the temperature range of −10 °C to 143 °C. The launch date for the mission is assumed to be no later than 2029 April 10, using an intermediate-to-high-performance-class Expendable Launch Vehicle (ELV) that will deliver the spacecraft to an interplanetary transfer orbit targeted at Venus. The spacecraft will aim for the aerobot’s entry, descent, and inflation (EDI; shown in Figure 4) to be over the Aphrodite Terra region (Figure 2). During the 15-day mission, the aerobot will have periodic contact with an orbiter using an S-band (2 GHz) signal, and the orbiter will communicate back to a ground-based DSN antenna. The following section provides detailed descriptions of the instrument suite and the engineering design of the aerobot.

4. Instruments

The VALENTInE mission aerobot payload would consist of six instruments for addressing the science objectives outlined in the STM and Section 3.1 (Table 1). The Atmospheric Structure Instrument (ASI) is based on the ASI on Pathfinder (Seiff et al. 1997). It would consist of a thermometer, accelerometer, and barometer. The instrument would continuously operate at all longitudes, latitudes, and altitudes but would be duty cycled to 12%. The mass spectrometer is based on the STROFIO mass spectrometer on ESA’s BepiColombo (Gurnee et al. 2012). It would conduct measurements during the five atmospheric dips between 45 and 55 km altitude and over a range of latitudes and longitudes. The infrared spectrometer is based on NASA’s Moon Mineralogy Mapper (M3) on Chandrayaan-1 (Pieters et al. 2009). The IR spectrometer would operate below the Venus cloud deck at the bottom of dips (altitude 45 km) and over a range of latitudes and longitudes including Aphrodite.
Terra. The IR spectrometer would get four acquisitions per image set, for a total of 36 per dip on both the dayside and nightside. On the nightside, only the upper half (thermal glow) band will be acquired. The high-resolution multispectral imager is based on Pancam on NASA’s twin Mars Exploration Rover missions (Bell et al. 2003). The multispectral imager would be used to measure the density of mode 3 particles in the lower atmosphere. The multispectral imager would acquire nine images using four bands per dip while on the dayside. While on the nightside, the multispectral imager will not image. The LIDAR instrument is based on LIDAR on Hayabusa2 (Mizuno et al. 2017). It would operate at the bottom of the cloud deck during the dips and over a range of latitudes and longitudes. The magnetometer is based on NASA’s InSight Auxiliary Payload Sensor Suite (Banfield et al. 2018). It would continuously operate at all latitudes, longitudes, and altitudes but would be duty cycled to 12%.

5. Mission Design

5.1. Launch and Cruise

Initial mission design for VALENTInE, including launch window and trajectory calculations, was carried out using the NASA Ames Research Center Trajectory Browser. The spacecraft trajectory was chosen to optimize the characteristic energy ($C_3$) of a Hohmann transfer from Earth to Venus by the anticipated launch readiness date of the New Frontiers 5 (NF5) announcement of opportunity (AO). The proposed launch window for VALENTInE opens 2029 May 8 and lasts 2 weeks. The trajectory injection energy $C_3$ is 6.5 km$^2$ s$^{-2}$, with a cruise duration of 448 days.

5.2. EDI and Nominal Mission

Venus rendezvous occurs on 2030 July 30, and a separation/dive maneuver 4 days prior separates the orbiter from the entry vehicle. The orbiter performs a capture burn 1 hr prior to the EDI maneuver of the aerobot via aerocapture by Venus’s atmosphere. The approximate point of EDI is N 0°, E 253° at 00:00 local time. Following the capture burn, the orbiter assumes a 300 × 35,000 km elliptical orbit; periapse is situated over the Venus subsolar point (Figure 5).

During the nominal 15-Earth-day mission lifetime, the aerobot will float in Venus’s atmosphere, drifting approximately ±10° from the EDI point in latitude owing to wind. The aerobot will revolve around Venus once every 4–8 days, allowing for a range of latitudes and longitudes to be surveyed. During the time that the aerobot will be on the nightside of Venus, some instruments will not be used. There will be five dips from 55 to 45 km altitude, at which point measurements of the lower cloud deck and the surface can be made. These dips will take 18 hr total, with each including 3 hr of time at 45 km altitude.

Science objective 4 relies on daytime observations of Aphrodite Terra. With Venus’s slow rotation, this constrains the possible launch windows for which the relevant longitudes will be sunlit during the nominal mission. The selected launch window results in local times for the Aphrodite Terra region spanning 07:00 to 16:00 over the 15-day flight at Venus. During this time, the aerobot will drift along with atmospheric winds, circumnavigating Venus 2–4 times at low latitudes. Aphrodite Terra spans a wide longitude range at these latitudes —about 25% of Venus’s circumference at the equator. The frequency of planned dips ensures that some portion of at least one dip will cover the Aphrodite Terra region, and key measurements will be obtained.

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Table 1

A Description of the VALENTInE Instrument Suite with Current Best Estimate (CBE) Values

| Instrument                          | Atmospheric Structure Instrument | Mass Spectrometer       | High-resolution Multispectral Imager | IR Spectrometer | LIDAR | Magnetometer |
|-------------------------------------|----------------------------------|--------------------------|-------------------------------------|----------------|-------|--------------|
| Heritage                            | ASI on Pathfinder                | STROFIO on BepiColumbo   | Pancam on MER                       | M$^3$ on       | LIDAR | SEIS on InSight |
| CBE mass (kg)                       | 2.04                             | 3.25                     | 0.8                                 | 8.2            | 3.7   | 1            |
| CBE power (W)                       | ...                              | 7.93                     | 3.5                                 | 20             | 17    | ...          |
| Peak                                | ...                              | ...                      | ...                                 | ...            | ...   | ...          |
| Average                             | 3.2                              | ...                      | ...                                 | ...            | 1     | ...          |
| Standby                             | ...                              | 4                        | 1.8                                 | 6.6            | 5     | ...          |
| CBE data rate                       | 9.6 kbps                         | 500 bps                  | 16.8 Mbits/band                     | 2.63 Mbits/acq | 2 kbps | 500 bps      |
| Viewing direction                   | starboard (AO)                   | port                     | nadir                               | nadir          | nadir | zenith       |
| CBE dimensions (m)                  | 1.1 × 0.5 (cylinder)             | 0.0087 m$^3$             | 0.27 × 0.12 × 0.11                  | 0.5 × 0.5 × 0.5 | 0.24 × 0.228 × 0.25 | 0.1 × 0.1 × 0.05 |

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Figure 5. Schematic of mission orbital configuration and rendezvous maneuvers at Venus. Each hash mark in the aerobot’s path represents the distance traveled during a single orbital period of the orbiter, which assumes a 300 × 35,000 km retrograde relay orbit around Venus to match the motion of the aerobot. Aphrodite Terra (red swath) is located on the morning limb of Venus at arrival.

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21 https://trajbrowser.arc.nasa.gov/
The location intended for the point of EDI was selected to maintain line of sight with Earth for tracking purposes during this important mission phase. However, for the present mission design, this entry point is on the nightside of Venus. For further refinements to this mission concept, an entry point for EDI on the dayside, centered on Aphrodite Terra, is recommended. Critical observations of this region will be obtained during the initial dip, improving the likelihood of mission success by returning these measurements early in the mission.

5.3. Orbiter Propulsion

The propulsion system consists of two types of engines to accommodate trajectory control maneuvers, divert maneuvers, Venus-orbit insertion maneuver, orbital station keeping, and critical events during the duration of the mission. Overall, the propulsion system will have a dry mass of 142.7 kg, a propellant mass of 786.7 kg, and a wet mass of 929.4 kg.

The attitude control system (ACS) was designed to fulfill the communication requirements between the aerobot, orbiter, and Earth. The ACS hardware is only required on board the orbiter and consists of an internal measurement unit (IMU), startracker, and reaction wheel assemblies (RWAs). Between the time periods of communicating with the aerobot and Earth, there will be a day slew that will rotate 0°.5 three times per day. Overall these maneuvers will require 1.3 kg of fuel considering a 30% margin.

6. Aerobot Design

The choice to use a variable-altitude balloon for the VALENTInE mission imposes certain engineering requirements owing to the need to maintain neutral buoyancy at different altitudes. Presented here is the mechanical design of the aerobot, the general requirements for transmitting data back to Earth, and the balance between the propulsion, power, and thermal systems required to sustain the 15-day mission. Over the course of the mission, the aerobot is designed to conduct five 18 hr dip maneuvers between 55 and 45 km (shown in Figure 6); the mission is limited to five dips owing to power and mass constraints (discussed in Sections 6.3 and 6.5); the dips’ dwell phases are limited to 3 hr owing to thermal limits (Section 6.2). These dip maneuvers are used to obtain in situ vertical profiles of atmospheric composition and dynamics within and below the cloud layer and geological and magnetic mapping of the surface when dwelling below the cloud layer.

6.1. Mechanical and Configuration

The VALENTInE in situ aerobot (shown to scale in Figure 4) consists of a variable-altitude, helium-pumped balloon that supports a gondola. The variable-altitude balloon consists of two balloons: (1) an exterior, zero-pressure balloon made of metalized Teflon (acid and solar heating resistance) and Mylar (gas retention) that is 8.8 m in diameter; and (2) an interior, superpressure balloon made of Vectran (for high strength) and Mylar (gas retention) that is 4.4 m in diameter. The interior balloon inflates with helium from the carbon composite storage tanks (material chosen for gas/tank mass ratio) to increase buoyancy to ascend, and it likewise deflates to descend.

The gondola (Figure 7) is suspended from the balloon by a 20 m tether; measures 1.5 m wide, 1.5 m long, and 1.6 m tall; and is constructed from aluminum struts and face sheets. There is a Teflon coating for acid resistance and a thermal insulation layer (Section 6.2) encapsulating the instruments. There is a window on bottom for nadir viewing instruments and ports for the mass spectrometer and barometer. Within the gondola are the helium tanks used for inflation, thermal phase-change material (PCM), and the mechanically/thermally isolated bus containing batteries, avionics, electronics, mass spectrometer, LIDAR, high-resolution multispectral imager, ASI, IR spectrometer, and inflation system. Connected to the exterior of the gondola are 0.285 m LGA (top), magnetometer and thermometer booms (bottom corners), and the parachute and balloon deployment system (top; see Figure 4).
6.2. Thermal

In order to meet mission requirements, the bus (see Section 6.1) must remain between $-10^\circ C$ and $50^\circ C$ for the duration of the mission. To meet these temperature requirements, three worst-case scenario environments were assessed: worst-case cold steady state, worst-case hot steady state, and worst-case hot transient. The worst-case cold steady state scenario occurs at the highest altitude, 55 km, and assumes an atmospheric temperature of $27^\circ C$. In this scenario, no additional heat is required to maintain the desired bus temperature. The worst-case hot steady state scenario is also at 55 km, when science and telecom power are at a maximum. In this scenario, the surface area and mass of the bus are sufficient to remain at the desired bus temperature without adding a radiator.

The worst-case hot transient environment occurs when the aerobot descends for 9 hr, dwelling at 45 km for 3 hr, and then ascending to 55 km for 6 hr. Venus atmospheric temperatures range from $27^\circ C$ to $110^\circ C$ over this altitude range. In the worst-case transient hot scenario, 27.7 W of heat is required to maintain the desired bus temperature, and this will require the use of PCM, white exterior paint, thermal insulation, and mechanical/thermal isolation. The gondola exterior will be covered in white paint for protection against solar heat. The bus will be mechanically and thermally isolated from the gondola using low conductivity material such as Ti or composites. The bus will also be surrounded by multilayer insulation (MLI). The worst-case hot transient scenario requires extra thermal protection in the form of PCM. The PCM will endothermically change phases when the bus is exposed to high temperatures, absorbing heat and allowing the bus to remain at the desired temperature range. We will use lithium nitrate hydrate, which has a technology readiness level (TRL) of 7 and assumes a heat of fusion of 200 kJ kg$^{-1}$. The total mass of PCM’s required for this mission is 57 kg.

6.3. Power

Due to the thick cloud cover on Venus impacting the ability for solar power and the relatively short mission duration of 15 days, negating the requirement for a Radioisotope Thermoelectric Generator (RTG), the optimal power source for the VALENTInE gondola was decided to be two Saft LSH 20 HTS 3.6 V lithium-thionyl chloride (Li-SOCl$_2$) primary batteries in series (Figure 8). The Command and Data Handling System will control the power subsystem by two Remote Engineering Units (REU A and REU B). The power subsystem would be used in six different power modes: ballistic coast, EDI, dayside science, nightside science, science/telecom, and ascend/descend. Each power mode requires a specified amount of power shown in Figures 8 and 9. The high power density of the batteries (13.0 Ah nominal capacity) permits power requirements to be met for the mass allocation (78 kg) and mission duration. The battery power density also permits 43% systems contingency power for all stages except the EDI stage. The ballistic coast stage would run for 96 hr. The EDI stage would run for 1 hr. The dayside science stage would run for 107 hr. The nightside science stage would run for 143 hr. The science/telecom stage would run for 36 hr. The dayside science hours
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6.4. Communications

Communication between the aerobot and Earth is achieved through the use of an orbiter relay. An overview of this system is provided in Figure 10. The relay uses a 3 m high-gain antenna (HGA) with S/X-band capability. S band is used for all telemetry, tracking, and navigation between the low-gain antenna (LGA) on the aerobot, which is S band only, and the HGA on the orbiter relay. Direct-from-Earth (DFE) and direct-to-Earth (DTE) communications from the orbiter use X band.

The driving requirements of the telecommunications subsystem are a 75 kbps return data rate and a 2 kbps forward data rate. The total available data storage on the aerobot will consist of 64 Gbit using a JPL sphinx card. The instrument suite will collect 1.75 Gbit of data every 3 days, and the aerobot hardware will continuously store data at a rate of 1 kbps. 2.5 Gbit of data will be uplinked to the orbiter at an S-band frequency for 4 hr per day during the 4-day period near apoapsis when the aerobot is in sight of the orbiter. If a safing event occurs, the sphinx card will collect housekeeping data and store the last 2000 commands on a circular buffer, which will later be transmitted to the orbiter on command. The orbiter will also be used to track the aerobot’s location, status, and health as needed during this period. The aerobot LGA has “safemode” S-band DTE capability; during the 4-day periapsis period in which the aerobot is out of sight from the orbiter, this capability will be used for aerobot location and health checks as needed. All DTE/DFE links have > 3 dB link margin, and all relay links have > 6 dB link margin.

A block diagram of the aerobot telecom subsystem is shown in Figure 11. The subsystem is fully redundant and uses two lightweight (3 kg) S-band universal Space Transponders for uplink and downlink to and from the command and data handling subsystem; two S-band, 50 W traveling wave tube amplifiers; and two diplexers that allow for uplink to and downlink from the LGA via a coaxial transfer switch. The only part of the system exposed to the Venusian atmosphere is the LGA, which is hardened to withstand Venus atmospheric conditions.

6.5. Mass Limitations

The difficult Venus conditions and balloon-based platform impose strict mass limitations on the VALENTInE configuration. Lack of solar panels on the aerobot (Section 6.3) requires that the entire 15-day prime mission be supported by power from batteries. The stored energy density of these batteries is the primary determinant of the duration of the prime mission, as they constitute a significant fraction of the total gondola mass.

Thermal protection for the batteries, scientific instruments, and flight electronics also composes a significant fraction of the gondola mass. Dip profiles will maintain the aerobot at an altitude with ambient temperatures of about 110 °C. The gondola is designed to slow the influx of heat during these dips to the hotter altitudes; as an additional protective measure, an expendable mass of 57 kg of PCM (Section 6.2) will absorb heat and prevent temperature changes above their melting temperature. The additional mass displaces other possible components, such as further batteries, and increases power needs for compressing helium as needed to adjust the aerobot buoyancy to change altitude.

Storage of compressed helium during the cruise phase also requires a large amount of mass. The VALENTInE configuration described in Section 6.1 requires the use of hypothetical, low-density materials with a strength comparable to steel. This selection was motivated by the need to close the design within a strict time limit. After completing a detailed study including these low-density materials, it was later determined that most of the storage tanks could be jettisoned after the initial EDI phase. This strategy permits a drastic reduction in the mass required to store the compressed helium during dips—much of VALENTInE’s helium storage is needed to maintain a small size for the aerobot between integration with the launch vehicle and initial inflation. Once the helium required to maintain neutral buoyancy at 45 km altitude has been released from the tanks, any and all empty tanks can be jettisoned.

7. Cost

This mission was planned against an estimated NF5 cost cap of $1B, arrived at by adjusting the NF4 cost cap upward, as the NF5 call had not yet been released. The NF5 cost cap is now known to be $900M USD, which is less than the original estimate. The total cost of the VALENTInE mission was estimated to be $706.8M USD in FY22 with a ~40% reserve of $292.2M USD, for a total budget of $999M. The reserves are further split into 30% unencumbered reserves and 10% reserves...
for development and testing, which would be allocated to the highest risk portion of the mission identified by the project manager. Despite cost uncertainties associated with instrument payload and technology development, the VALENTInE final architecture should be able to fit within the estimated NF5 cost cap owing to the planned reserves.

To estimate the total cost of development and production of the spacecraft, the JPL Institutional Cost Model (ICM) was applied. The ICM is based on previously flown missions and uses Cost Estimating Relationships or “wraps” to calculate NASA Work Breakdown Structure (WBS) elements (Table 2). WBS 1, 2, and 3 were estimated based on the scope and class of the mission. WBS 4 was estimated based on the science objectives. WBS 5 was estimated using the NASA Instrument Cost Model (Mrozinski 2018). WBS 7 and WBS 9 were estimated from analogous missions. The launch costs for the NF4 are provided by NASA, so WBS 8 is not part of the budget or counted toward the cost cap. The mission described

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**Figure 9.** Bar chart and table of expected power requirements during each phase.

| Power Subsystem   | Ballistic Coast | Entry and Inflation | Day Side Science | Night Side Science | Science + Telecomm | Ascend/Descend |
|-------------------|-----------------|---------------------|------------------|--------------------|--------------------|----------------|
| Thermal           | 20              | 0                   | 0                | 0                  | 0                  | 0              |
| Telecom           | 10              | 128                 | 10               | 10                 | 123                | 0              |
| Other elements    | 0               | 72                  | 0                | 0                  | 0                  | 26             |
| Instruments       | 0               | 0                   | 3                | 2                  | 1                  | 7              |
| C&DH              | 5               | 5                   | 5                | 5                  | 5                  | 5              |
| Total             | 44              | 214                 | 27               | 26                 | 138                | 47             |

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**Figure 10.** Overview of the aerobot–orbiter–ground communications subsystems.
here fits within the predicted $1B cost cap if the flyby carrier stage, responsible for powering the spacecraft during cruise and for relaying in situ measurements back to Earth, can be contributed by another space agency. The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

8. Conclusion

Few previous missions to Venus have incorporated an aerobot design that enables diverse atmospheric and surface observations. The Soviet Union’s Vega balloons were the first and only balloon-based aerial systems to achieve successful observations of the Venusian atmosphere. In this work we present a mission concept for VALENTInE, the first long-duration suborbital exploration of Venus. VALENTInE uses a novel dipping technique to address open main science questions in the planetary science community. First, VALENTInE will address how the myriad of chemical and physical processes that shaped the solar system operated, interacted, and evolved to influence the Venusian atmosphere. This is achieved by investigating superrotation and lower atmospheric composition. Second, VALENTInE addresses what governed the accretion, chemistry, and internal differentiation of Venus and the evolution of its atmosphere. This is achieved by investigating the following:

1. The physical structure of the atmosphere, including temperature and pressure profiles, wind speed, and direction.
2. The abundances of key molecules in the atmosphere, including H, He, O₂, Ne, and Ar.
3. The details of the physical components of the atmosphere, including the range of particle sizes and their properties.
4. The varied range of surface morphologies present on Venus and their bulk compositional properties.
5. The height of the surface features and how they correlate with changes in the atmosphere.
6. The possible remanent crustal magnetization preserved in Venus’s rocks.

Due to the equal importance of each science goal in our objectives list, the baseline mission is the same as the threshold mission. The VALENTInE mission would obtain essential data needed to refine atmospheric and geophysical models of Venus, constrain the time line of major events in Venus’s history, and test predictions regarding the cause of Venus’s present greenhouse state. Thus, fundamental questions surrounding the chemical composition and dynamics of the Venusian atmosphere, its geologic history, its internal structure, and its habitability throughout time may be more thoroughly investigated. All of this knowledge could then be applied not only to interpreting the history of Earth and outlining its potential futures but also to the characterization of exoplanets. Venus may sometimes feel like a forgotten world, but it would not be if it received a VALENTInE.

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