STRATOSPHERIC VENUS OBSERVATORY

Cover Page

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EXECUTIVE SUMMARY

The Stratospheric Venus Observatory (SVO) is a mission concept to study Venus's atmosphere at altitudes between the surface and 120 km. The goal of SVO is to explore the four types of interconnected processes that control Venus's climate: circulation, atmospheric chemistry, radiative energy transfer, and cloud microphysics. A number of fundamental advances have been made in these areas since the last Decadal Survey was written, in large part due to observations made by the Venus Express (VEx) and Akatsuki missions and associated modeling efforts. SVO will surpass the spectral and spatial resolutions of Akatsuki/VEx instruments and provide a unique time-domain data set to address the suite of questions raised by those missions.

SVO observes Venus from the Earth's stratosphere. Its 3-m sparse-aperture telescope provides 10-km resolution UV images of Venus's cloud tops and 45-km resolution of Venus's middle and lower cloud decks in the CO₂ windows at 1.74 and 2.3 μm. SVO will observe Venus in key UV bands: 198 nm (nitric oxide emission from ~115 km [1]), 200-230 nm (to assess vertical mixing of SO and SO₂ at the cloud tops [2]), 283 nm (exploits SO₂ as a tracer at the cloud tops), and 365 nm (tracks the unknown UV absorber at the cloud tops). SVO will track trace gases CO, OCS, H₂O, HCl, HF, and SO₂ below the cloud base in near-IR windows at 1.74 and 2.25 - 2.55 μm [3,4] and determine cloud properties (opacity, particle sizes, H₂O/H₂SO₄ ratios and the altitude of the cloud base [5]). Observations of O₂¹Δ emission from 95 km will complement the NO emission maps to provide vertically resolved views of the subsolar to antisolar transition region. Imaging at 5 μm provides cloudtop temperature maps at ~66-68 km altitude to characterize planetary scale waves [6,7] and the time-of-day dependence of gravity waves launched from mountains on Venus [8, 9].

SVO is a timely mission for the upcoming decade. It takes advantage of NASA's new super-pressure balloon capability, which enables 100-day flights of balloon-borne telescopes that fly above 99.3% of the Earth's atmosphere. It leverages recent work on the thermal control of balloon-borne telescopes and stabilization of their focal planes. Unlike a spacecraft in orbit around Venus, SVO is recoverable and can be re-flown every 19 months during Venus inferior conjunctions. SVO corrects some of the observing deficiencies of Venus Express (cloud tracking restricted to the southern hemisphere every 24 hours) and Akatsuki (no spectral capabilities), and SVO's nearly continuous time domain coverage is well-suited to provide data for assimilation into GCMs that have been developed in response to Venus Express and Akatsuki observations (e.g., [10]).

1. MISSION AND INSTRUMENT OVERVIEW

NASA's balloon program regularly flies payloads weighing several tons to altitudes of 33 - 40 km, above 99.3 - 99.7% of the Earth's atmosphere, respectively. The inner Fried para-

meter is at least 4 m at those altitudes [11]: balloon-borne telescopes with 4-m apertures can produce diffraction-limited images, even at UV wavelengths where ground-based adaptive optics perform poorly. Balloon-borne telescopes have nearly complete access to the spectrum from 0.2 - 5 μm , except for a drop-out between 230 - 280 nm and partial obscuration at 4.3 and 4.6 μm due to CO_2 and CO (Fig. 1).

Fig. 1 From [12]: MODTRAN simulations of the telluric transmission between 200 nm to 5 μm from 38 km (red), showing stratospheric access to UV and IR wavelengths.

Telescope: For SVO, we propose a 3-m aperture telescope with separate UV and IR cameras to obtain spectral image cubes of Venus over key wavelength ranges. Because a monolithic 3-m mirror - even aggressively lightweighted - would be prohibitively heavy, SVO uses a Golay3 design: three 1-m mirrors with their centers separated by 2 m. The resulting PSF has a central core that is narrower than that of a monolithic 3-m mirror, surrounded by six lobes that peak at 30% of the height of the central core (Fig. 2). This PSF would not be ideal for imaging exoplanets around stars, but it works well for the relatively low-contrast problem of tracking clouds or mapping trace gas distributions on Venus.

Fig. 2 The top row shows three apertures, consisting of a 1-m mirror, a 3-m mirror and a sparse aperture (3 separate 1-m mirrors). The bottom row shows the Point Spread Functions that each aperture would produce, normalized to the peak of each PSF. The central lobe of the 3 x 1-m aperture is slightly narrower than the 3-m PSF; the six side-lobes peaks are 30% as high as the central peak.

Image Quality: Balloon-borne telescopes suffer from thermal gradients and image motion. SVO leverages recent work from NASA's THAI-SPICE and SuperBIT balloon missions: THAI-SPICE investigated passive thermal shielding as a means to drastically reduce thermal

gradients across balloon-borne telescopes. For SVO, each 1-m mirror has an articulated sugar-scoop baffle to act as a sunshield. Several balloon missions (e.g., HySICS, BOPPS, SuperBIT) have demonstrated coarse pointing systems that stabilize a telescope at the few arc-second level. SVO, like THAI-SPICE, uses an orthogonal transfer CCD (OTCCD) camera in UV-visible wavelengths to perform fine stabilization: on-chip tip-tilt corrections at kHz rates to stabilize the focal plane at the 0.02" level (rms). In wavelengths from 0.8 - 5 μm , SVO can either use an HgCdTe array that is bump-bonded to an OTCCD to provide tip-tilt correction or SAPHIRA HgCdTe arrays (from Leonardo S.p.A.) with avalanche read-out electronics. The latter allows very fast frame rates with negligible read noise, but requires co-registration of frames in software and is currently limited to $\lambda = 0.8\text{-}2.5 \mu\text{m}$.

Instrumentation: SVO has two instruments, UVCam and IRCam, operating simultaneously via a dichroic with a pivot at 0.7 μm . UVCam obtains spectral image cubes from 200 - 600 nm ($R = 100$), IRCam from 0.8 to 5 μm ($R = 500$ at 2.25-2.55 μm , plus narrow fixed filters for SO_2 characterization). SVO also has two guide cameras (wide-field and narrow-field), similar to those on the THAI-SPICE mission. The narrow-field guide camera provides 0.02" (rms) pointing error updates at 100 Hz. The 0.02" pointing requirement is driven by the 0.024" diffraction limit of a 3-m aperture at $\lambda = 283 \text{ nm}$. UVCam and IRCam use fixed and tunable filters (e.g., Acousto-Optic Tunable Filters as described in [13]) to identify trace gases (CO , OCS , H_2O , HCl , HF , and SO_2 below the cloud base, and the SO/SO_2 ratio at the cloud tops), constrain the composition of the unknown ultraviolet absorber, detect airglow from NO and O_2 and to identify cloud properties (opacity, particle sizes, $\text{H}_2\text{O}/\text{H}_2\text{SO}_4$ ratios and cloud base altitudes).

Mission Opportunities: SVO observes Venus during the 100-day periods around Venus's inferior conjunctions, when its angular diameter ranges from $\sim 32''$ to $\sim 60''$ and the dayside crescent is 38% of the disk or less. These circumstances let SVO observe several phenomena on Venus's nightside: cloud-tracking in the middle and lower cloud decks (48-55 km altitude), trace gases (0-48 km) and airglow (from NO and O_2). On the dayside, SVO observes the cloud tops (10-km resolution), UV spectra diagnostic of the unknown UV absorber, and the SO/SO_2 ratio.

NASA's 100-day super-pressure balloon flights will launch from McMurdo Bay or Wanaka, NZ, since long flights in the northern hemisphere are precluded from flying over Russia. This means that the inferior conjunctions on 25-OCT-2026 and 06-JAN-2030 are preferred: Venus's southern declination during those events allows a balloon-borne telescope to observe Venus for 16 out of 24 hours each day from Wanaka latitudes or 23 out of 24 hours from McMurdo (Fig. 3). Daytime observing is possible at all wavelengths, but the sky background is significant at UV wavelengths (albeit $\sim 100\times$ less at balloon altitudes than at the surface). Short exposures with co-adds are required to avoid daytime saturation in UV wavelengths. Daytime observations of Venus in IR bands (0.8 to 5 μm) are routinely

conducted from ground-based observatories and will be trivial from the stratosphere.

Fig. 3 Venus's angular diameter (orange) gets as large as 62" during inferior conjunctions every 19 months. Venus's declination varies roughly from +20 to -20 degrees. Southern declinations are preferred, due to NASA's balloon launch sites in the southern hemisphere.

Table 1. Goal II (Understanding Atmospheric Dynamics and Composition) from The VEXAG document *Goals, Objectives and Investigations* (2019).

Objective	Investigation
A. What processes drive the global atmospheric dynamics of Venus?	DD. Deep Dynamics (1). Characterize the dynamics of the lower atmosphere (below about 75km) of Venus, including: retrograde zonal super-rotation, meridional circulation, radiative balances, mountain waves, and transfer of angular momentum.
	UD. Upper Dynamics (1). In the upper atmosphere and thermosphere of Venus, characterize global dynamics and interactions between space weather and the ionosphere and magnetosphere.
	MP. Mesoscale Processes (2). Determine the role of mesoscale dynamics in redistributing energy and momentum throughout the atmosphere of Venus.
B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?	RB. Radiative Balance (1). Characterize atmospheric radiative balance and how radiative transport drives atmospheric dynamics on Venus.
	IN. Interactions (1). Characterize the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere.
	AE. Aerosols (2). Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components.
	UA. Unknown Absorber (2). Characterize the unknown short-wavelength absorber in the upper atmosphere of Venus and its influence on local and global processes.
	OG. Outgassing (3). Determine the products of volcanic outgassing on Venus and their effects on atmospheric composition.

2. SCIENCE JUSTIFICATION AND RELEVANCE TO KEY QUESTIONS

SVO will monitor and measure most of the processes that have been identified in VEXAG *Goal II: Understand atmospheric dynamics and composition on Venus* in the most recent VEXAG (Venus Exploration Analysis Group) GOI document (Goals, Objectives and Investigations) [14]. Table 1 lists eight key investigations (*Deep Dynamics, etc.*), and SVO addresses all of them with the possible exceptions of *UD* and *OG*. We now list SVO's investigations, broken down into four categories (Dynamics, Atmospheric Chemistry, Radiative Balance and Cloud Microphysics) and referenced to the VEXAG investigations in Table 1.

Dynamics: SVO will track atmospheric motion from the surface to 120 km with four types of observations: **monitoring trace gas distributions** from the surface to the cloud base (observing H₂O, CO, OCS, HCl, HF, and SO₂ at 1.71-1.74 μ m and 2.25-2.5 μ m with expected spatial resolutions of ~50-100 km and velocity resolutions of 7-15 m/s); **tracking clouds on Venus's nightside** in the lower and middle cloud decks (observing cloud silhouettes at 1.74 and 2.3 μ m, 48-55 km altitude, with spatial resolutions of ~42-51 km and velocity resolution of 1 m/s); **tracking dayside clouds** at or near the cloud tops (at 200-230 nm to assess vertical mixing, at 283 nm to track SO₂, at 365 nm to track the unknown absorber - all with a spatial resolution of 10 km and velocity resolution of 0.25 m/s, plus imaging at 5 μ m to generate **cloudtop thermal maps** at ~66-68 km altitude with ~112 km spatial

resolution); and **monitoring airglow** from $O_2^1\Delta$ and NO (at altitudes of 95 and 115 km with expected spatial resolution of 29 km and velocity resolutions of 3-5 m/s).

Significance: (1) GCM models suggest that Venus has Hadley cell-like circulation (e.g. [15]), but complete Hadley cells have never been observed. Cloud-tracking studies at 70 km show that meridional motion at the cloudtops is poleward, as expected for the top of equatorial-high latitude Hadley cells. The return branch beneath the clouds has never been observed. SVO will provide long stares at advecting trace gas distributions to obtain rough wind maps between 0-48 km. SVO also obtains nightside cloud opacities to deduce “wet” or “dry” regions and to constrain areas of upwelling and downwelling. (2) Recent explanations for Venus’s super-rotating atmosphere [Horinouchi et al., 2020] predict patterns of mean meridional and mean zonal cloud motion. SVO will resolve horizontal motion in the lower/middle cloud decks and at the cloud tops and help confirm these predictions. (3) circulation models can now simulate mountain waves [9] and planetary scale waves, both of which are observables at the cloud tops for SVO’s 5 μm filter and represent an important synergy between observations and modeling efforts. (4) Altitudes from ~ 90 -120 km represent a transition region, where subsolar-to- antisolar (SS_AS) winds dominate the background retrograde zonal flow. Observations of NO and O_2 emission will track the convergent flow at two levels in the transition region and help assess the transfer of angular momentum through that region. *These combined observations address the VEXAG investigations DD, MP and UA.*

Atmospheric Chemistry: SVO will map trace gas distributions through spectral windows in Venus’s CO_2 atmosphere (Fig. 4). [17] used CO from Venus Express/VIRTIS spectra as a dynamical tracer below the cloud base, but with significant spatial binning to improve their SNR. SVO is further from Venus than Venus Express was, but its larger aperture and much longer integration times produce maps with SNRs better than VIRTIS by an order of magnitude and spatial resolutions of ~ 45 km, similar to VIRTIS. SVO will retrieve **SO and SO_2** at the cloud tops from 200-230 nm spectra; **multi-level H_2O distributions** from three spectral windows (1.18, 1.74 & 2.4 μm) to track advection below the cloud base; **SO_2 and CO below the cloud base** (2.3, 2.53 μm); and **ratios of OCS and CO** from 2-11 bar.

Significance: (1) SO and SO_2 have different (but short) photolysis lifetimes at the cloud tops. The SO/ SO_2 ratio is therefore diagnostic of vertical mixing just below the cloud tops and constrains convective activity, especially given SVO’s spatial resolution of 10 km, commensurate with the size of convection cells [18]. (2) H_2O and SO_2 distributions below the cloud base - combined with dynamics inferred from cloud tracking and cloud opacities - will constrain competing models of cloud formation [19, 20]. (3) CO is thought to be a dynamical tracer of Hadley cell circulation [21]: SVO tracking of CO will help identify the lower return branch of the Hadley cell. (4) Descending CO is thought to be converted to OCS [22, 23]: SVO will provide high SNR maps of both species, characterizing their chemical and spatial relationship. (5) H_2O can serve as a dynamical tracer at three different levels from

the surface to the cloud base (Fig. 4). *These combined observations address the VEXAG investigations IN and AE.*

Fig. 4 Jacobians showing where (in altitude or pressure) and at what wavelengths we have spectral sensitivities to trace gases H₂O, CO and SO₂ - similar plots exist for OCS, HF and HCl [Tsang et al. 2007].

Radiative Balance & Cloud Microphysics: SVO maps Venus's radiative sources and sinks in several ways. **5 μm images** map Venus's temperature at altitudes near 66 km. Maps of the cloud tops at 365 nm (at 10-km resolution) show where the **unknown UV absorber** actually does its absorbing, while mapping motions of convection cells at the same time. SVO maps **cloud optical depths** in the lower and middle cloud decks, plus the altitude of the upper cloud deck (via images at 1.65 and 2.02 μm, which measure overlaying CO₂ columns). These cloud optical depths, combined with abundance maps of **Venus's greenhouse gases** (H₂O, SO₂ & CO) let us model vertical heat transfer via radiative transfer codes. Combined IR images at 1.74 and 2.3 μm are diagnostic of **cloud particle sizes**.

Significance: (1) SVO observes cloud opacities and greenhouse gas distributions at 45-km resolution, both of which serve as inputs to GCMs. SVO also provides simultaneous comparisons to GCM outputs in the form of observed cloud motions with 1 m/s resolution. (2) At the cloud tops, SVO provides simultaneous GCM inputs (maps of the unknown UV absorber, absorbing roughly 50% of incident sunlight) and comparisons to GCM outputs (cloud motions at the cloud tops, at 10-km resolution). (3) SVO's 5 μm images allow further synergies with GCMS: they show stationary features due to orographically launched mountain waves and, with Fourier analysis, the presence of planetary scale waves. *These combined observations address the VEXAG investigations RB, AE and UA.*

3. SUPPORT FOR BALLOON MISSIONS AND NEW TECHNOLOGIES

We encourage the Planetary Science and Astrobiology Decadal Survey to advocate for SVO in two specific areas. First, NASA's Planetary Science Division is unique among the four divisions of SMD in having *no funding avenues to support balloon-borne research*. Astrophysics' APRA program supports the majority of NASA's (non-planetary) balloon payloads. Furthermore, the new Astrophysics Pioneers program supports small satellites and *major balloon payloads* at the \$20M level, about 5-10 times higher than typical APRA awards. The need for balloon platforms to address planetary science goals has been recognized for years: the current Decadal Survey (*Visions and Voyages*) [24] includes text in support of planetary balloon missions, and [25] identified roughly 20% of the key science questions in *Visions and Voyages* as candidates for balloon-borne investigations. We

encourage the Decadal Survey to advocate for changes to NASA/PSD AOs, specifically, to allow balloon missions to compete in research programs (like SIMPLEx) and to consider the creation of a *Planetary* Pioneers program. Second, there are promising technological areas that need development. SVO uses four in particular: narrow-band UV filters between 200-230 nm, phased mirror segments in a sparse aperture telescope, tunable filters with narrow bandpasses in UV and solid-state motion-compensation arrays. NASA's Earth Science Division Technology Office (<https://esto.nasa.gov>) has a strong suite of coordinated research programs to advance technologies. It is our perception that the PSD analog (PESTO) is much more limited than ESTO. We encourage the Decadal Survey to suggest that NASA's Planetary Science Division emulate the ESTO programs in range (spanning broad, low-TRL projects to satellites) and scope (funding levels).

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