Title of the white paper: Venus Orbital Mission Concept: Kythiran Eolian dYnamics from the Surface to the Thermosphere from an Orbital NEtwork (KEYSTONE)

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Venus Orbital Mission Concept: Kythiran Eolian dYnamics from the Surface to the Thermosphere from an Orbital NETwork (KEYSTONE). K. McGouldrick, et al.

We propose a two-component planetary mission concept to answer long-standing questions surrounding the nature of the atmospheric circulation of Venus, specifically the origin and maintenance of the tropospheric Retrograde Zonal Super-rotation (RZS) and the transition to (and from) the ionospheric Subsolar to Antisolar (SSAS) flow. The primary objective of this mission concept is to obtain measurements of meteorological parameters and solar forcings with sufficient spatiotemporal coverage and resolution to permit the elucidation of the atmosphere through the application of global general circulation models and mesoscale dynamical models. While this White Paper focuses on a specific mission concept to Venus, the general concept of is applicable also to the atmospheres of Mars and Titan (and is already being applied at Earth). The general concept would advance the goals of not only NASA's Planetary Science Division, but also Earth Science, Heliophysics, and Astrophysics.

KEYSTONE is designed to answer numerous Essential or Important Science Investigations, as outlined in the most recent Venus Exploration and Analysis Group (VEXAG) Goals, Objectives, and Investigations (GOI) document [33]. Altogether, these questions encompass a majority of Goal II (Understand the Dynamics and Composition), and key atmospheric contributions to Goal I (Understand Venus' Early history and potential habitability) and Goal III (Understand the geological history and present-day couplings between the surface and atmosphere). Namely:

- What processes drive the atmospheric dynamics of Venus?
 - What determines the origin and the maintenance of the tropospheric RZS?
 - What determines the characteristics of the transition from RZS to SSAS flow in the lower ionosphere, and back to RZS in the upper ionosphere?
 - What is the magnitude of the contribution from wave propagation and convection on both the global and mesoscale dynamics of the Venus atmosphere?
- What processes determine the baseline and variations in the atmospheric composition and global and local radiative balance?
 - What is the magnitude of the contribution by the unknown absorber to observed spatiotemporal variations in circulation?
 - How do [aerosol properties and size distribution and compositions of key chemical and radiative species] vary spatiotemporally and what effect does this have on the global and mesoscale circulation?
- How do the surface and atmosphere of Venus interact?
 - What is the flux of atmosphere across the surface from possible volcanic activity, and chemical weathering processes?
- How do planetary systems evolve in general?
 - What is the effect of planetary size and a minimal or non-existent intrinsic planetary magnetic field on the loss of volatiles from an earth-sized planet?

The primary science goals of KEYSTONE would be to characterize the four-dimensional spatiotemporal variability of key constituents of the Venus atmosphere on a wide range of both spatial resolutions and temporal cadences. In doing so, it would emulate the elucidation of global and local processes in the Earth’s atmosphere; namely, the production and launch of Geostationary Operational Environmental Satellites (GOES), and the Earth Observing System (EOS). The former provides key global and mesoscale dynamical information through the tracking of contrasts at 16 (in the most current version) distinct narrow wavelength bands [39]. The latter measures variability in key radiative and chemical components of the Earth atmosphere in an effort to better constrain the roles of radiation, clouds, water vapor, and precipitation; the oceans; greenhouse gases; land-surface hydrology and ecosystem processes; glaciers, sea ice, and ice sheets; ozone and stratospheric chemistry; and natural and anthropogenic aerosols.

Venus Science Background: The tropospheric global super-rotation of the atmosphere of Venus was first observationally confirmed about 50 years ago from the comparison of Earth-based radar measurements of the -243.025d rotational period of the solid body (where the negative sign indicates retrograde direction) [11]; and the identification of a four-day – similarly retrograde – period of rotation measured from the tracking of contrasts that occur in the near-ultraviolet in the upper troposphere of Venus [3]. The persistence of this atmospheric super-rotation down to the surface and its global nature was confirmed by the Doppler tracking of the Pioneer Venus descent probes [5], and the measurement through feature tracking of near infrared emission contrasts on the night side of Venus [1, 7]. After more than a half century of effort, a consistent theoretical explanation remains elusive.

On the other hand, the SSAS circulation was hypothesized [9] before it was observationally confirmed through numerous Pioneer Venus measurements [2]. The transition from the tropospheric RZS to the ionospheric SSAS lies above the region of the atmosphere sampled by in situ direct wind measurements, and is currently underconstrained. Furthermore, measurements of light element airglows (*e.g.*, H, He) indicate that an increasing contribution from the RSZ relative to the SSAS component with altitudes above about 150 km [15].

The near-UV contrasts that permitted the initial assessment of the motion of the upper troposphere originate from absorption due to SO_2 and an unknown substance, both of which are intermingled with the upper clouds of Venus. These spatiotemporally varying compositions are tracked to estimate wind speeds to significant precision [37], but their existence reveals that significant solar heating must also occur at these levels. Indeed, at least half of the solar radiation incident at Venus that is not reflected by the clouds is absorbed at altitudes above 60 km [6]. Certainly this massive deposition and redistribution of energy must play a key role in determining the nature of the atmospheric circulation of Venus, but the observed variability of absorptivity in this wavelength region spatially and on both long and short time scales, as well as difficulties in determining the source of this variability as deriving from changes in the absorbers or clouds, leaves much uncertainty regarding the relative magnitude of these effects.

The aerosols in particular exhibit significant variability which, because of the low vapor pressure of sulfuric acid and the photochemical origin of the cloud mass, was initially unexpected. However, the observations of variable night side emission in near infrared spectral

windows revealed a great deal of spatiotemporal variability in the clouds [4], in response to variations in mesoscale dynamics [28, 27]. Significant variations in the cloud particle size distributions were identified by multiple in situ probes [24, 17], as well as via remote sensing [4]. Variations in the upper clouds and hazes are also seen both in observations [41] and cloud models [14, 34, 26]. Further complicating the picture is the coupled nature of the clouds, absorbers, and governing chemistry. Namely, the sulfuric acid is generated via SO_2 (a greenhouse gas and absorber of incident sunlight) and H_2O (a major greenhouse gas), to form highly reflective clouds that are responsible for the very low ($\sim 225\text{K}$) equilibrium emission temperature that results largely from the high albedo that reflects more than 70% of incident sunlight. The variability of the clouds and the timescales of their formation from these constituents has implications for the local radiative balance of Venus on a variety of timescales. Long-term high cadence monitoring of these variations is required in order to assemble the complete picture from all of these disparate building blocks.

The constituency of the deep atmosphere plays a key role in the exchange of volatiles with the surface and perhaps subsurface of Venus. Volcanism, if it is ongoing, will continually release CO_2 , SO_2 , CO , H_2O , and other constituents into the atmosphere. The relatively slow wind speeds near the surface mean that these outgassings will initially be localized, though they will eventually disperse throughout the atmosphere, possibly even making their presence known at altitude. Chemical weathering of the surface is expected to occur very quickly in the atmosphere of Venus, due in part to the high temperatures; hence, any recent volcanism will exhibit a surface signature for only a short time [12]. VIRTIS on Venus Express may have detected some regions of less-weathered surface material [40]. However, VIRTIS-M-IR survived only for about 2.5 years, and its ability to repeatedly observe specific night side locations was extremely limited due to the nature of the Venus Express orbit, and small field of view of the instrument. Frequently repeated observations of surface regions that are expected to exhibit activity – and carried out over longer periods of time – are necessary to understand the probability and nature of geologic activity existing on Venus today.

Among the near infrared spectral windows that permit detection of photons from the deep atmosphere on the night side of Venus are those near $1.0\mu\text{m}$, which exhibit weighting functions that peak near the surface of Venus ($0.9\mu\text{m}$, $1.02\mu\text{m}$, $1.10\mu\text{m}$, $1.18\mu\text{m}$), hence allowing for the assessment of surface emissivity properties, including the ability to distinguish between water-bearing granites and non-water-bearing basalts [16]. However, previous attempts at such measurements have met with difficulty for several reasons. First, the thick atmosphere itself “blurs” the surface via Rayleigh scattering so that a typical footprint minimum size is only about 50km [18], though this improves substantially when observing from aerial platforms beneath the clouds [23]. More significantly, the overlying clouds, while contributing less to variations here than in the windows near $2.0\mu\text{m}$, still contribute to the observed flux, and their variability complicates the retrieval of the surface properties. VIRTIS in particular was subject to this concern, as the repeatability of observations was few in number, hence the odds of a specific region being overlain by thick cloud cover for all observations was non-negligible [29]. Ensuring a high repeatability of observations not only maximizes the likelihood of identifying changes in the surface properties at these wavelengths, but also increases the likelihood of catching particularly clear regions of the cloud coverage; hence the influence of the overlying clouds is reduced, potentially permitting the application of a consistent model of the overlying atmosphere for all of the observational data. This

is reminiscent of the algorithmic techniques used to understand changes in human activity tracked by nocturnal lighting that was used by the "Earth at Night" project [32].

The search for evidence of past surface water is of vital importance for the study and understanding of Venus climate history. The isotopic measurements of Deuterium and Hydrogen in the upper atmosphere [*e.g.*, 10] indicated that Venus had lost large amounts of water over its history. Mars also demonstrates evidence for having experienced significant atmospheric loss over its history, the story of which is now being uncovered by MAVEN now in orbit around Mars [22]. That mission was tasked with answering the question, "Was the martian water more likely to have been lost to space, or locked into surface and subsurface reservoirs?" It tackled this problem by measuring the current loss of atmosphere to space, as functions of ongoing solar forcings from fluxes of both photons and particles. MAVEN found that during average solar conditions, the solar wind strips the martian atmosphere to a rate of about 100 g s^{-1} [21]. Similar questions remain for Venus. How quickly (and when) did Venus lose its water? How efficient is the ongoing process of atmospheric loss? Being able to quantify the processes of atmospheric loss from a dense atmosphere (such as that of Venus), in a similar manner to which has been done to for a thin atmosphere (such as that of Mars), and comparison with processes working on a thick magnetically shielded atmosphere (like that of Earth), would provide added clarity to the history of climate evolution of Venus, Mars, and terrestrial planets in general (including exoplanets).

The KEYSTONE concept: An interplanetary mission – under current budget constraints – has not the luxury of resources to launch and operate the several dozen satellites required to exactly mirror the work that has been done by GOES and EOS to understand the atmosphere of Earth and effect it at other planets. However, the KEYSTONE concept allows us to perform similar work in a more efficient manner, using a single satellite. This is accomplished by following the example of the Japan Aerospace eXploration Agency’s Akatsuki (Venus Climate Orbiter) mission [30]. Utilizing the total of about a dozen filters, and observing either reflected sunlight or infrared planetary emission, Akatsuki’s cameras are nominally sensitive to a wide range of relatively isolated altitudes, permitting an assessment of vertical wind structure through the quantification of motion vectors at each observed wavelength, hence altitude. Complementing these observations is an ultrastable oscillator that is utilized to perform high-precision measurements of the vertical atmospheric structure during each Earth-viewed occultation of the Akatsuki spacecraft by Venus. Ultimately, Akatsuki has had a harder time than anticipated of achieving its science goals due in part to a failure to achieve the nominal orbit for which it was designed – which affected the spatiotemporal resolution and coverage capable by the spacecraft, including the frequency of atmospheric profiling via occultation – and the loss of both near-infrared cameras very early in the scientific mission to an electronics fault. However, the successes of Akatsuki [13, 38, 36, 25, 20] demonstrate the validity of the technique. KEYSTONE also would leverage the lessons learned from VIRTIS-M on Venus Express, a medium spectral resolution mapping spectrometer that was capable of generating spectral cubes in two channels having wavelength ranges $0.3 - 1.0 \text{ }\mu\text{m}$, and $1.0 - 5.0 \text{ }\mu\text{m}$; but with a spatial FOV of only about $4 \times 10^{-3} \text{ sr}$. This narrow FOV, coupled with an orbit that permitted only up to about 6 h per orbit of continuous observation in mapping mode, meant that this advantage in constituent characterization and isolation

could not as effectively be parlayed into detailed global dynamical assessments.

KEYSTONE would apply the lessons learned from each of these atmosphere-focused missions to achieve what they could not, by flying several hyperspectral imagers covering the full range of wavelengths from the near UV to the thermal infrared that are useful for assessing the global nature of the atmospheric circulation of the Venus atmosphere [35]. Hence, tropospheric dynamics and composition can be assessed.

In addition to this, however, KEYSTONE – especially if the short wavelength capabilities are pushed to the mid UV – can characterize a wide range of airglow and auroral variations on both the day side and night side of Venus. By themselves, after applying assumptions with regard to the altitudes at which these emissions occur, observations of the mean emission and local spatiotemporal variability in emission can be used to assess the transition region of RZS to SSAS flow in the lower ionosphere [15]. Coupled with in situ measurements by a MAVEN-like spacecraft in an orbit that can sample the Venus plasma environment and characterize the shape of the magnetotail and variations thereof, these observations can characterize not only the dynamical processes in the ionosphere and lower thermosphere, but can also quantify the processes of atmospheric loss from a dense atmosphere, in response to a host of solar forcings, just as MAVEN has been doing for interactions with a thin atmosphere, as is the case at Mars. Hence providing a complete picture of the atmospheric dynamics of Venus from the surface to the thermosphere, considering drivers both above and below, and characterization of its atmospheric loss rate. The scientific utility of a specifically MAVEN-like spacecraft at Venus is covered in a separate White paper led by Emilie Royer, and the observational requirements to improve the theoretical assessment of venusian dynamics is covered in a separate White Paper led by Amanda Brecht, so we do not discuss either of those elements further here.

The KEYSTONE concept can be successful, even if the two components are separated into two missions. While the complete picture of Venus atmospheric dynamics and composition is only assembled with data from both components, each individually provides its own partially separable puzzle piece. That is, the Akatsuki-like component can by itself thoroughly characterize the tropospheric processes, while the MAVEN-like component can thoroughly characterize the ionospheric processes. Simultaneous observation, however, would magnify the science return from both spacecraft. Hence, instead of a single New Frontiers

Figure 1: Schematic of orbital configurations of the two KEYSTONE satellites, in comparison with Venus Express and Pioneer Venus, and schematically drawn Venus magnetotail and bowshock. Note that the Inner orbit is nearly polar inclined, and will precess through a range of Solar-Venus angles as Venus orbits the Sun.

class mission, the science objectives could be achieved by means of two complementary Discovery class missions, or two complementary missions built and launched by collaborating space agencies – presuming there will be some overlap in operation between the two. The Akatsuki-like component of KEYSTONE is anticipated to be placed into a “Distant Retrograde Orbit” which is known to exhibit stability to planetary perturbations for millions of years [19]. Because less fuel would be required for orbital maintenance, the limiting factor of the mission longevity would be the instrument and cooler performance. While the cooler on VIRTIS failed after just 2.5 years, survivability of single-step Stirling coolers for over 10^5 h has been demonstrated by Sugimoto Heavy Industries, which has flown such devices onboard recent JAXA missions in Low Earth Orbit (SUZAKU), to the Moon (KAGUYA), and to Venus (AKATSUKI) [31].

A cross-planetary and interdisciplinary concept: A spacecraft in a high circular orbit maintains visible overflight of individual surface locations of approximately 24 h per day (even considering the refraction of the surface-emitted beam that will restrict communication near the surface craft’s horizon). Furthermore, being synchronous with the angular velocity of the middle clouds of Venus, KEYSTONE would be roughly synchronous with the typical flight paths of several in situ aircraft that are being considered for Venus [8]. If the aircraft can be located to the same hemisphere as KEYSTONE, then continuous relay may be set up between the aircraft and the Earth through KEYSTONE, in addition to the contextual information that KEYSTONE can provide to the in situ vehicles.

Although this White Paper is driven by a particularly Venus-focused mission concept, the scientific basis for this concept is adaptable to the study of any planet capable of sustaining a substantial atmosphere (*e.g.*, Mars, Titan). Global, long-term, and high-cadence monitoring is necessary to elucidate the coupled drivers of any planetary atmosphere, because the processes that drive them are so highly coupled and variable. The generalized KEYSTONE concept would enable the exploration of planetary atmospheres within our Solar System using techniques developed by NASA’s Earth Science Division; solar monitoring from vantage points throughout the Solar System, supporting the goals of NASA’s Heliophysics Division; and with applications to Earth-like planets soon to be characterized through the efforts of NASA’s Astrophysics Science Division. Spacecraft placed at relatively synchronous orbits – capable of global monitoring of atmospheric conditions – coupled with lower-orbit spacecraft – capable of in situ sampling of heliosphere/atmosphere interactions – could revolutionize the field of comparative planetology, opening the door to an new era of comparative planetary atmospheric science in which we are able to truly investigate all terrestrial planets as “Earth-like” worlds.

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