Seismology on Venus with infrasound observations from balloon and orbit

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Title of the white paper: Seismology on Venus with infrasound observations from balloon and orbit

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Contributions to this document by authors at the Jet Propulsion Laboratory, California Institute of Technology, were supported under a contract with the National Aeronautics and Space Administration (80NM0018D0004). Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Seismology on Venus with infrasound observations from balloon and orbit. S. Krishnamoorthy, A. Komjathy, J. A. Cutts, P. Lognonné, R. F. Garcia, M. P. Panning, P. K. Byrne, R. S. Matoza, A. D. Jolly, J. B. Snively, S. Lebonnois, and D. C. Bowman

Abstract: The study of Venus' evolution is inexorably linked with studying its interior properties, which can be investigated by performing seismic studies on the planet. However, seismology on Venus has long eluded planetary scientists due to technological challenges presented by high surface temperature and pressure, which limit lifetimes of surface-based instrumentation. In this white paper, we present two complementary techniques for performing seismology on Venus by measuring the low-frequency acoustic signature (infrasound) produced by seismic activity through coupling between the solid planet and the atmosphere. These techniques may be implemented with technology available today, without the use of high-temperature electronics.

The need for seismology on Venus: Carrying out a seismic investigation at Venus would provide critical insight into the current levels of seismicity of the planet. For example, there are numerous instances in the planet's lowlands where, as seen with Magellan radar data, tectonic structures cross-cut, and thus postdate, the emplacement of local plains material [1]. Although the ages of those plain units are unknown, the well-preserved nature of the cross-cutting structures indicates that they are geologically young. Given that ongoing mantle convection is a plausible means by which these structures could have formed [1], it is possible that tectonic deformation at these or other sites may be active today. The InSight lander recently detected quakes from similar extensional structures in the Cerberus Fossae region on Mars [2].

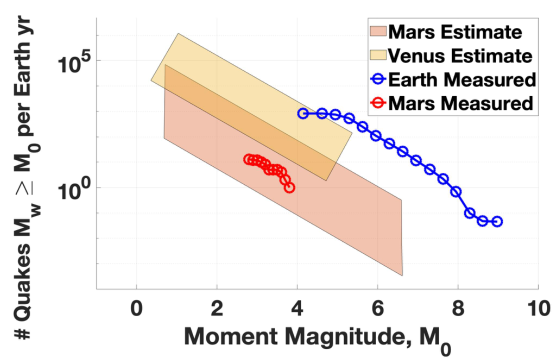

Figure 1: Bounds on rates of Venus seismicity adapted from [5]. The red region represents pre-mission estimates for InSight, while initial results (red circles) suggest seismicity near the middle of this range [6].

Seismicity is also typically associated with volcanic and magmatic activity. Although circumstantial, there is evidence that volcanism may currently be active on Venus, via differences in radar emissivity and thermal signatures [3, 4]. It may be, then, that volcanic and magmatic processes on Venus could lead to seismic and/or acoustic activity detectable by a surface or atmosphere-based geophysical instrument suite. Carrying out a seismic investigation at Venus could provide critical and presently unavailable information regarding the planet's current levels of tectonic and volcanic activity, the spatial and temporal distribution of that activity, possibly the contemporary impact flux there, and even information about the planet's interior itself.

Seismic observations. Beyond observations of evidence for geologically recent tectonic activity on the surface, broad energetic arguments suggest Venus' seismicity should likely be bounded by the observed seismicity on Mars and Earth (**Figure 1**). This implies that there could be several events with moment magnitudes ranging from 4.6 to 5.3 per year, large enough for regional observations (at the lower end) and possibly global observations (at the higher end) of both body and surface wave phases, depending upon attenuation and noise conditions. For a single measurement in the atmosphere or a station on the surface, multiple techniques are available for locating events and determining interior structure (e.g., [7, 8]), but multiple platforms allow for the network approaches routinely used on Earth if adequate time synchronization can be maintained. Data collected by the InSight SEIS instrument on Mars has yielded some surprising results – seismicity on Mars appears to be different from that on the Earth or the Moon, while marsquakes have similar spectral characteristics as moon- or earthquakes [6, 9]. InSight results also report a high degree of scattering of seismic waves as they travel through the Martian crust [10], leading to a disruption of the familiar pattern of seismic waves seen on the Earth. Thus, encountering a seismic regime on Venus that is dissimilar to the Earth is a distinct possibility.

Challenges in Surface Seismology. Seismology on Venus requires long-duration monitoring of seismic activity. No lander has survived the challenging Venus surface environment of approximately 460°C temperature and 90 bar atmosphere pressure on the surface for more than two hours. High-temperature electronics that allow for a few days to weeks of lifetime in these conditions are currently under development. Seismic monitoring also requires the collection, storage, and processing of a large amount of data in a quiet environment. The SEIS instrument, which is capable of detecting extremely weak accelerations (~$nm/s^2/Hz^{0.5}$) [11] has predominantly detected events during Martian night-time, when atmospheric disturbances are minimal [10]. Thus, substantial systems engineering challenges exist for surface-based seismology on Venus, including the development of long-duration, extreme-environment counterparts for auxiliary technology needs such as memory, power, processors, and communication systems. On the other hand, Venus' thick atmosphere allows for 60 times better coupling with the solid planet than on Earth, implying that any ground motion signatures are replicated faithfully in the atmosphere. At 60 km altitude, the temperature and pressure are remarkably Earth-like, and high-temperature electronic systems are not required to guarantee long mission lifetimes. For example, instrumentation on board the Soviet VeGa balloon [12] survived for at least two days at 54 km altitude before the batteries were exhausted. In addition, balloons float with the prevailing wind, minimizing wind velocity relative to the inlet and associated acoustic noise. Multi-year lifetimes have already been demonstrated for several orbiters at Venus. Thus, the search for atmospheric signatures of seismic activity generated by strong ground-atmosphere coupling on Venus using remote platforms is an attractive option for performing exploratory seismology on Venus. Highly advanced surface-based seismometers compatible with extreme environments may then be deployed in subsequent missions for targeted investigations in regions of interest flagged by the remote platforms.

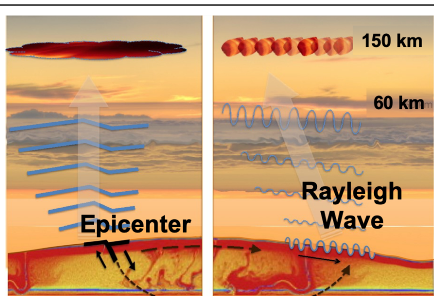

Figure 2: Infrasound originates both from epicentral ground motion and from propagating surface waves after a quake (from [14]).

Infrasound production from quakes: Observations on Earth have revealed that seismic activity produces a host of acoustic and gravity waves in the atmosphere. Near the epicenter, the ground acts as a large baffle moving coherently over horizontal distances comparable to the size of fault displacement. The amplitude and spectrum of the resulting atmospheric waves strongly depend on the quake magnitude – the larger the quake, the greater the energy emitted at low frequencies. Ground displacements above the seismic source also adopt the symmetry properties of the fault, replicating upward and downward motion controlled by the source mechanism, as observed in the ionosphere using GPS receivers for several earthquakes (e.g, [13]). Ground displacements from weak quakes produce infrasonic waves in the 0.005–10 Hz range that propagate almost vertically due to the large propagation velocity contrast between atmospheric acoustic waves (~340 m/s on Earth and ~220–250 m/s on Mars and Venus) and the seismic waves (~3 km/s for the Earth's crust). For large quake magnitudes, frequencies below 5 mHz are excited, thus generating atmospheric gravity waves. These waves also propagate upward, but with a group vector inclined at angles less than 45° relative to the horizontal direction. In addition to the near-field ground displacements above the seismic source, the ground displacements induced by seismic body and surface waves also produce upwardly propagating acoustic waves, which retain the frequency content and dispersion of their seismic counterpart. If Venus' crust shows similar scattering behavior as that observed for Mars by InSight, the amplitude and frequency content of seismic waves may undergo significant alteration and scrambling as they traverse the planet. However, epicentral ground motion that couples with the atmosphere would be able to avoid such scattering and be preserved in relatively pristine form in the acoustic wave originating directly above the epicenter.

Acoustic waves arrive first in the atmosphere above the source area. The dissipation of these waves in the upper atmosphere creates a local temperature fluctuation. Further from the source, gravity waves generated at the epicenter reach the upper atmosphere. Finally, seismic waves propagate around the planet and generate upward-propagating acoustic waves [14, 15] (**Figure 2**).

All the above phenomena have been observed on Earth for shallow quakes of large magnitudes (Mw>7) and have been modeled for Venus [16]. The conversion coefficient between seismic and atmospheric waves is inversely proportional to the impedance contrast at the solid–fluid interface. Thus, dense atmospheres result in more efficient coupling with the solid planet. On Venus, the maximum quake magnitude for observation is thus expected to be lower than the Earth, and the observation of a single surface wave waveform could help characterize the crust and upper mantle structure [15]. In addition, the acoustic waves generated by seismic waves propagate horizontally at the speed of seismic waves, allowing for the unambiguous separation of these perturbations from atmospheric effects. During their upward propagation, both acoustic and gravity waves are attenuated by the atmosphere and amplified due to the atmospheric density decrease through conservation of kinetic energy. On Earth, the attenuation acts mainly as a low-pass filter, removing higher frequencies without inducing dispersion. However, in atmospheres composed mainly of CO_2, the wave attenuation is mainly due to the vibrational relaxation of CO_2 molecules. Thus, atmospheric propagation may induce additional dispersion terms to the acoustic waveforms that would have to be corrected in order to recover the wave dispersion at the surface.

Infrasound production from volcanic activity: Volcanoes produce a rich variety of seismic and seismo-acoustic signals associated with subsurface magma storage, transport, and eruption into the atmosphere. Volcanic seismicity occurs from mantle depths to the surface, and elucidates magmatic and faulting processes occurring within and around volcanoes [17]. Infrasound is produced by shallow subsurface and subaerial processes, including explosive eruptions, shallow degassing, surface flow, and mass wasting [18]. Seismo-acoustic wave conversion and coupling commonly occur. Volcanism is highly variable in eruption style, with a spectrum of processes ranging from effusive to explosive behavior (each with their own seismo-acoustic signature) possible for a single volcano and even within a single eruptive episode. Explosive eruptions can vary from short-duration strombolian or vulcanian eruptions producing impulsive acoustic transients, to sustained eruptions producing volcanic jet-noise and seismic tremor signals lasting from minutes to days in duration. Volcanism generates seismicity by an array of fluid and solid processes. Volcanic seismicity includes individual volcano-tectonic (VT) earthquakes, long-period (LP) (0.5–5 Hz) events, and various types of volcanic tremor, including *eruption tremor* (a sustained broadband ~0.1–20 Hz seismic signal). Infrasound technology has become indispensable for capturing local and remote explosive volcanism and for understanding the dynamics of shallow volcanic degassing and eruption columns for the Earth's volcanoes. Shallow and subaerial volcanic processes radiate sound directly into the atmosphere; sampling this sound complements seismic data, which record subsurface sources. Infrasound from major explosive eruptions can propagate for thousands of kilometers in atmospheric waveguides.

On Earth, a typical VEI 4 (VEI: Volcanic Explosivity Index [19]) eruption may produce precursory and co-eruptive seismicity recordable at local distances (<50 km), co-eruptive seismicity recordable to regional or even global distances, and infrasound signals recordable for several thousand kilometers from the source, depending upon stratospheric wind direction and site noise conditions [20, 21]. In the far-field, acoustic and gravity waves (AGWs) generated by volcanic and seismic activity may be detected well into the mesosphere and thermosphere. The atmospheric amplification of acoustic waves enables them to evolve nonlinearly into shocks, which are later dispersed and scattered throughout the atmosphere [22, 23]. Mesospheric airglow fluctuations at acoustic periodicities were reported by [24] for the hydroxyl (OH) layer (87 km) above Mount Etna, Sicily in 2011. Spaceborne measurements of OH airglow revealed concentric gravity waves emanating from the VEI 4 April 2015 eruption of Calbuco, Chile [25].

Volcanic landforms abound on Venus; the planet possesses thousands of shield volcanoes, as well as shield fields and domes [26], and a range of volcanotectonic landforms including calderas and distinctive corona structures [27]. Alkaline and tholeiitic basaltic compositions, respectively, were found at landing sites of the Soviet Venera 13 and 14 missions [28], suggesting that much of the surface of Venus is predominantly basaltic. The Magellan mission [29] provided abundant evidence for intrusive and extrusive activity on the planet [30], and revealed a dearth of impact craters less than 25 km in diameter [31]. Indeed, crater statistics derived from global Magellan data yield an average model age for the surface of 700–800 Myr [32], with global-scale volcanic resurfacing likely the dominant reason for such apparent youthfulness [31]. Volcanism has probably operated on Venus for billions of years [33], and active lava flows may have been present there as recently as 100,000 years ago [3]. There is also indirect evidence of present-day explosive volcanism on Venus through observations of episodic sulfur dioxide increases [34] and weathering rates of olivine [35]. Transient and resonant infrasonic signatures through direct acoustic as well as seismo-acoustic coupling, as seen on Earth, can be anticipated on Venus above volcanic sources. Multiple observable airglow layers exist on Venus from 90–120 km altitude [36]; thus, it is also fruitful to build a theoretical basis for diagnosing AGW dynamics from optically sensed measurements, complementing in-situ strategies.

An overview of Venus' atmosphere: Venus is covered by a thick global cloud layer, between altitudes of 48 to 70 km. This cloud layer is divided into three regions, characterized by variations in the distribution of cloud particles [37]. The upper cloud (~60 to 70 km) absorbs most of the UV flux coming from the Sun. A planet-wide deep convective layer is localized in the middle cloud (~50 to 60 km) and lower cloud layers (~45 to 50 km). The energy absorbed below the clouds cannot escape past the cloud base through radiative processes, due to cloud and CO_2 optical thickness. This results in the destabilization of the lower and middle cloud layers, with strong convection that transports energy from the cloud base to ~60 km [38]. Vertical winds in the range of a few m/s were measured by the VeGa balloons near 54 km altitude [39].

Venus does not have significant obliquity, which means that the equatorial region is more heated than higher latitudes. The energy is redistributed in the clouds, where most of the solar heating is absorbed, through Hadley-type circulation cells; ascending motions are present at equator and descending branches above the poles, since the Coriolis force is two orders of magnitude lower than on Earth. At 60–70° latitude, in the upper cloud, this circulation and cloud distribution pattern induces a cold region encircling each pole, called the cold collar, which is almost 40 K lower than the equatorial region [40]. Above 50° latitude, the zonal wind field observed within the clouds indicates the presence of a polar vortex. The zonal wind vertical gradient in the cloud for latitudes lower than 50° is large, increasing to more than 100 m/s at the cloud top [41]. The trajectory of a balloon within the cloud layers may be investigated with general circulation models (GCMs). According to the IPSL Venus GCM, for example, a balloon launched in the equatorial region may have large latitudinal variations, up to 60° of latitude, over a timescale of tens of Earth days [42].

Infrasound measurement from balloons on Venus: Balloons offer a unique vantage point for studying seismicity on Venus. Balloons can float in the relatively benign temperature of the mid- and upper atmosphere of Venus for much longer durations than landers on the surface, and can be used for a variety of scientific investigations. Multiple balloons with several investigations on board may also be deployed from the same aeroshell before rapidly separating in prevailing winds to form a regional or global network of sensors. Balloon deployment on Venus has already been demonstrated by the VeGa balloons [39]. A recent NASA-sponsored study [43] established that variable-altitude balloons with lifetimes of close to 100 days were achievable with current technology and provided the largest science return for deployment and operational complexity.

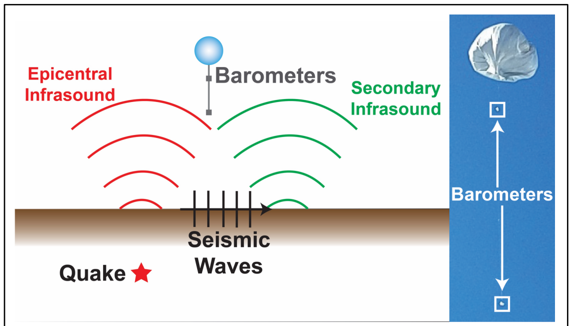

Figure 3. (Left) A schematic showing the detection of seismic activity from balloon-borne infrasound barometers on a tether. (Right) Picture of a stratospheric balloon on Earth with two barometers on a tether.

The airborne measurement of seismic activity using its infrasound signature is a relatively new area of research, but rapid progress has been made with artificial seismic sources such as seismic hammers and subsurface chemical explosions. Experiments using weak artificial seismic sources and Earth's atmosphere as a Venus analog have shown that seismic activity is detectable in the air from infrasonic signatures [44]. Moreover, the frequency content of ground motion is imprinted into its atmospheric signature, meaning that the measurement of pressure in the air may be equivalent to measuring ground motion to within a multiplicative factor in the infrasound frequency regime [45]. Quakes may also be localized on the ground by deploying multiple barometers on a tether and measuring the time of flight of the signal between the barometers. Time-of-flight measurements can also be used to distinguish direct infrasound arrivals from the quake's epicenter from infrasound generated by traveling seismic waves as they pass under the balloon (**Figure 3**). Lastly, since the balloon drifts with the prevailing wind, the wind-relative velocity of the infrasound sensor is reduced greatly and background wind noise is minimized compared with ground-based stations [44, 46]. With reliable motion tracking using Earth-based and orbital tracking assets and stable inertial measurement units (IMUs) on board the balloons, pressure variations induced by altitude change in a convective atmosphere can be removed.

The detection limit of this technique is currently undetermined. Preliminary computations with one-dimensional geometric attenuation profiles suggest that infrasound from quakes with surface magnitudes as low as 3.0 may be detected over 100 km away from the epicenter of a quake on Venus, if pressure fluctuations as low as 10^{-3} Pa can be accurately measured. Further refinement of detection limits is being pursued through a coordinated campaign of data collection in Earth's atmosphere over regions of high seismic activity, and mapping the results to Venus. Once detected, the infrasound signature may be used to study several outstanding questions about Venus seismicity. On Earth, floating hydrophones in the ocean have already demonstrated the mapping of sub-ocean mantle plumes through tomography using earthquake P-waves [47]. Determining quake magnitude and location can yield bounds on current levels of seismic activity and crustal motion. The direction of first motion inferred from the waveform, when compared with existing radar images of the surface from Magellan or any future spacecraft, can help understand the types of faulting mechanisms present on Venus, in turn informing models of Venus' interior. If large quakes with multiple detectable seismic phases occur, the time difference of arrival between these phases can place bounds on estimates of crustal rigidity and density. In particular, the dispersion of low-frequency seismic modes such as Rayleigh waves from large quakes can help in studying the crustal structure of Venus.

Two major challenges that need to be addressed with this technique are the differentiation of seismic events from other atmospheric or geophysical sources, and autonomous identification of scientifically relevant events from background sources to reduce the volume of data for transmission. Both these challenges can be effectively addressed by collecting and analyzing large datasets on Earth. Infrasound signals in these datasets may be attributed to their originating events using other independent streams of "ground truth" available on Earth, then identifying unique features in the infrasound signal to enable autonomous event identification and discrimination.

Infrasound measurement from orbit using infrared emissions: High-altitude atmospheric and ionospheric disturbances associated with acoustic waves generated by Rayleigh surface waves have been routinely observed on Earth in the far field of very large (M_w >7) quakes [16, 48, 49], but also in the near field of smaller quakes (M_w ~ 6 [50]). Observations of Rayleigh waves allow for the determination of the phase and group velocity of surface waves, with a resolution enabling the measurement of lateral variations in the surface wave velocity [48] or of surface wave scattering associated with 3D structure [49].

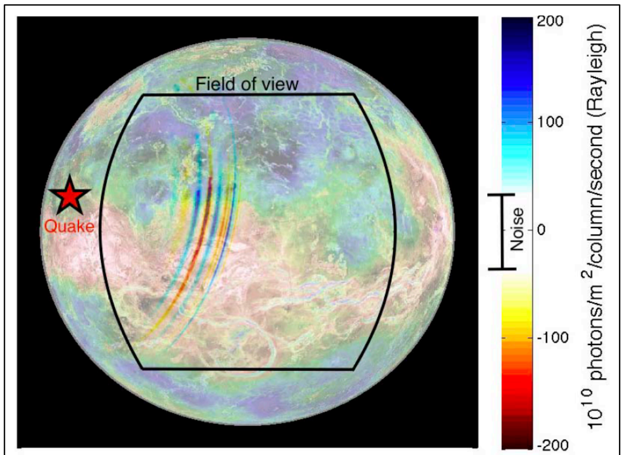

Figure 4: Modeled airglow fluctuations due to 20-sec seismic waves generated by a M_w 5.8 quake. The star is the quake location and the colors indicate airglow fluctuations above the conservative ±30 Rayleigh detection noise estimate using 0.3° planetary resolution.

On Venus, partial ionization and excitation of CO_2 and O_2 molecules in the atmosphere on the day and night side, respectively, leads to thermal emissions in the 4.28 µm and 1.27 µm "airglow" near-infrared optical bands, respectively. An orbiter equipped with the ability to image at these wavelengths may be inserted into a high-altitude, low-inclination orbit around Venus, such that it is able to image the entire planetary disk and track perturbations by upwardly propagating infrasound waves generated by seismic activity. The travelling wavefront imprints itself in the thermal emissions and can be inverted for quake location and phase and group velocities of the surface waves (**Figure 4**). This is the basis of the Venus Airglow Measurements and Orbiter for Seismicity (VAMOS), a concept that was envisaged as part of a NASA-funded study in 2017 [51, 52]. This study analyzed performance limits for such an orbiter, including on-board data processing and automated identification of seismic events, and determined that quakes as low as M_w 5.3 may be detected from orbit [16]. Rayleigh waves generated by quakes as low as M_w 5.5 on the dayside could be used to probe the mean thickness of Venus' crust. Although the balloon-based measurement technique is expected to be more sensitive to weaker quakes that occur in near the balloon (<100 km), the orbiter-based approach has the advantage of a global view of the planetary disk. The orbiter platform can operate in coordination with the balloon platform, serving as a communication relay and a balloon tracking station, and providing global context to local balloon measurements. Thus, the orbiter and balloon techniques are complementary.

Synergistic investigations using infrasound: Infrasound-originating geophysical events on Venus are likely a subset of those often detected on Earth. Possible non-seismic infrasound sources on Venus include bolides, wind–mountain interactions, atmospheric turbulence, convective storms, vortices, and electrostatic discharges. Bolide airbursts in the Venus atmosphere can be detected using infrasound, providing an initial sampling of the population of impacting objects that enter Venus' atmosphere. Wind blowing over mountains creates very-low-frequency infrasound waves that propagate on a global scale on Earth [53]. If detected on Venus, these waves may constrain the magnitude of surface winds. Convective storms radiate powerful infrasound [54]; infrasound sensors on Venus may thus be able to characterize the level of storm activity and investigate individual storms. Infrasonic thunder has been observed by sensors on Earth [55, 56]. Other infrasound-producing electrostatic phenomena such as sprites [57] and cloud charge contraction [58] have also been measured. Acoustic waves record an imprint of the atmospheric conditions through which they pass. Temperature gradients and wind currents cause the waves to refract, and atmospheric composition determines how they attenuate with distance; well-constrained infrasound measurements can determine regional wind patterns. Thus, infrasound can be used to study regions and processes in the atmosphere that are difficult to measure otherwise.

A roadmap for Venus seismology: Although measurements of ground motion using surface landers is the most direct way to perform seismology, on Venus, technology that enables such an investigation is still several years to decades away. In this white paper, we report on two alternative and mutually compatible methods to perform exploratory seismology from a distance. Each of the two techniques discussed here have seen rapid development in the last decade and can be performed with technology available today, in conjunction with other Venus balloon- and orbiter-based investigations (e.g, Venus atmospheric physics and chemistry). These techniques can determine the level of seismic and volcanic activity on Venus, identify locations of heightened activity for further investigation, and may reveal the propagation characteristics of the Venusian lithosphere. These investigations may also be viewed as pathfinder missions to explore Venus' seismic and volcanic character, and pave the way for more advanced, long-lived seismometers deployed on the surface as part of highly targeted investigations to map the deep interior of Venus.

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