Meteors May Masquerade as Lightning in the Atmosphere of Venus

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Abstract

Lightning in the atmosphere of Venus is either ubiquitous, rare, or non-existent, depending on how one interprets diverse observations. Quantifying when and where, or even if lightning occurs would provide novel information about Venus's atmospheric dynamics and chemistry. Lightning is also a potential risk to future missions, which could float in the cloud layers (~50–70 km above the surface) for up to an Earth-year. Over decades, spacecraft and ground-based telescopes have searched for lightning at Venus using many instruments, including magnetometers, radios, and optical cameras. Two optical surveys (from the Akatsuki orbiter and the 61-inch telescope on Mt. Bigelow, Arizona) observed several flashes at 777 nm (the unresolved triplet emission lines of excited atomic oxygen) that have been attributed to lightning. This conclusion is based, in part, on the statistical unlikelihood of so many meteors producing such energetic flashes, based in turn on the presumption that a low fraction ($< 1\%$) of a meteor's optical energy is emitted at 777 nm. We use observations of terrestrial meteors and analogue experiments to show that a much higher conversion factor (~5–10%) should be expected. Therefore, we calculate that smaller, more numerous meteors could have caused the observed flashes. Lightning is likely too rare to pose a hazard to missions that pass through or dwell in the clouds of Venus. Likewise, small meteors burn up at altitudes of ~100 km, roughly twice as high above the surface as the clouds, and also would not pose a hazard.

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Key Points:

- We investigate whether meteor fireballs could have produced the optical flashes that have been detected at Venus and attributed to lightning
- We find that flashes from meteor fireballs are statistically likely to occur at the observed rates and brightness
- There is no affirmative evidence that lightning is a hazard to missions that pass through or dwell within the clouds of Venus

Abstract

Lightning in the atmosphere of Venus is either ubiquitous, rare, or non-existent, depending on how one interprets diverse observations. Quantifying when and where, or even if lightning occurs would provide novel information about Venus's atmospheric dynamics and chemistry. Lightning is also a potential risk to future missions, which could float in the cloud layers (~50–70 km above the surface) for up to an Earth-year. Over decades, spacecraft and ground-based telescopes have searched for lightning at Venus using many instruments, including magnetometers, radios, and optical cameras. Two optical surveys (from the Akatsuki orbiter and the 61-inch telescope on Mt. Bigelow, Arizona) observed several flashes at 777 nm (the unresolved triplet emission lines of excited atomic oxygen) that have been attributed to lightning. This conclusion is based, in part, on the statistical unlikelihood of so many meteors producing such energetic flashes, based in turn on the presumption that a low fraction (< 1%) of a meteor's optical energy is emitted at 777 nm. We use observations of terrestrial meteors and analogue experiments to show that a much higher conversion factor (~5–10%) should be expected. Therefore, we calculate that smaller, more numerous meteors could have caused the observed flashes. Lightning is likely too rare to pose a hazard to missions that pass through or dwell in the clouds of Venus. Likewise, small meteors burn up at altitudes of ~100 km, roughly twice as high above the surface as the clouds, and also would not pose a hazard.

Plain Language Summary

Artists depicting the atmosphere of Venus love to include lightning bolts to emphasize its hellish environment. Even though missions like DAVINCI would most likely be safe from strikes as they descend quickly through the atmosphere, long-lived aerial platform missions supported by large balloons floating in the cloud layer ~50–70 km above the surface might not be so fortunate. Do engineers need to build aerial platforms with the toughness (and thus expense) required to survive a lightning strike? Quantitative estimates of lightning strike frequency are inconsistent based on different forms of evidence. Observations of certain electromagnetic signals, interpreted as lightning in the clouds, suggest a strike rate several times that of Earth's lightning. In comparison, optical flash rates at Venus, as observed at the Mt. Bigelow observatory in Arizona and by the Akatsuki mission currently orbiting Venus, suggest a far lower flash rate. In this study, we argue that these optical flashes were plausibly produced by meteor fireballs ~100 km above the surface, not by lightning in the clouds. If so, then lightning poses no significant threat to balloon missions in the clouds of Venus. Lightning may still exist at the surface, produced by aeolian processes or explosive volcanism.

1 Introduction

Venus is a natural laboratory for studying the atmosphere of a non-Earth-like planet. While Venus is unique among terrestrial planets in our Solar System, it is an analogue to a common class of exoplanets (e.g., Kane et al., 2019; Way et al., 2023). For example, Venus's present-day atmosphere is far more massive than the atmospheres of Earth and Mars (e.g., Taylor et al., 2018)—dominated by carbon dioxide and perpetually shrouded in clouds rich in droplets of sulfuric acid at altitudes from ~47–70 km (e.g., Titov et al., 2018). Exoplanets born near their parent stars may outgas thick, CO_2-dominated atmospheres shortly after they accrete (e.g., Hamano et al., 2013; Gillmann et al., 2022; Miyazaki & Korenaga, 2022) or, later, if they experience a runaway greenhouse (e.g., Krissansen-Totton et al., 2021; Way et al., 2022).

Venus's clouds are super-rotating, moving westward much faster than the solid body (e.g., Read & Lebonnois, 2018). This attribute can be exploited for exploration: a surface station would take ~243 Earth-days to experience a sidereal day, but an aerial platform in the clouds could circumnavigate Venus at the equator every ~5–7 Earth-days (e.g., Cutts et al., 2022; O'Rourke et al., 2023). Likewise, many terrestrial exoplanets may have superrotating atmospheres (e.g., Imamura et al., 2020; Lee et al., 2020). As the number of observed exoplanets grow, so does the complexity of work to understand their evolution and current environments, and the need to study Venus. Lightning is an important aspect of terrestrial atmospheres, in part for its ability to instigate non-equilibrium chemistry (e.g., nitrogen fixation) relevant to biology and life detection (e.g., Ardaseva et al., 2017). Venus offers a natural laboratory for studying lightning on a major class of exoplanets.

On Earth, lightning flashes occur hundreds of times each second across the globe (e.g., Desch et al., 2002), illuminating areas where the atmosphere is dynamically active. Lightning flashes occur after a significant charge separation has been built up in the atmosphere (e.g., Yair, 2012; Aplin, 2006; Dwyer & Uman, 2014). Once released, lightning dissipates an enormous amount of energy, a fraction of which flashes as optical energy. In Earth's atmosphere, lightning strikes are most often facilitated via the interactions between liquid water and water ice particles, where the polarity of the molecules contributes to the buildup of this charge difference. Volcanic plumes (e.g., Nicoll et al., 2019; Mather & Harrison, 2006) and dust storms (e.g., Aplin, 2006) can also produce lightning by triboelectric charging, in which ash and dust particles are the medium of charge buildup.

On Venus, lightning could arise from mechanisms analogous to those seen on Earth. Sulfuric acid molecules in the clouds may have sufficient polarity to produce charge separation if both solid and liquid phases exist, though this is debated (e.g., McGouldrick et al., 2011). The frequency of volcanic events on Venus today is uncertain. However, Venus and Earth could have similar rates of volcanic activity overall (e.g., Byrne & Krishnamoorthy, 2021). Radar images from Magellan revealed ~10^5 volcanoes on the surface larger than 5 km in diameter (Hahn & Byrne, 2023). Magellan may also have observed active volcanism (e.g., Herrick & Hensley, 2023). At least some volcanic eruptions were explosive in the past (e.g., Ganesh, 2022; Ganesh et al., 2022; Ganesh et al., 2021; Airey et al., 2015). Lightning produced by either volcanic or atmospheric processes would provide a probe into Venus's current and past evolution. Lightning strikes could also excite global Schumann resonances at frequencies of tens of Hz, enabling electromagnetic sounding of Venus's lithosphere from an aerial platform (e.g., Grimm et al., 2012). Finally, lightning on Venus would create unique chemical environments in the atmosphere (e.g., Krasnopolsky, 2006; Delitsky & Banes, 2015). Almost anyone studying Venus, especially those planning future missions, should feel motivated to find lightning, if it exists.

The existence of lightning in the atmosphere of Venus has been heavily debated for decades based on interpretations of different types of evidence. Numerous attempts to collect concrete evidence of lightning have been made, with varying results (e.g., Lorenz, 2018; Lorenz et al., 2019 and references therein). Most of the claimed detections rely on observations of radio, magnetic, and acoustic signals. The Venera 11–14 landers observed near-continuous signals at ~10–80 kHz during their descents, which resembled electrical activity (sferics) associated with lightning on Earth (Ksanfomality, 1980). The Pioneer Venus Orbiter detected electric fields thought to be associated with lightning flashes (e.g., Taylor et al., 1979). The Venus Express magnetometer detected magnetic bursts near periapsis that were interpreted as whistler-mode waves—circularly polarized electromagnetic waves with frequencies up to several hundred Hz at Venus, which follow local magnetic field lines—produced by lightning below the ionosphere (e.g., Russell et al. 2006). Most recently, Hart et al. (2022) claimed that Venus has a flash rate several times higher than for lightning on Earth. However, there have also been non-detections of lightning that are in tension with these predictions, including with the radios of Cassini (Gurnett et al., 2001) and the Parker Solar Probe (Pulupa et al., 2021). All claimed detections have been controversial, with spacecraft and plasma noise proposed as candidates to create some of the signals (e.g., Lorenz, 2018).

A second approach to detect lightning at Venus is searching for optically bright flashes, similar to what we associate with lightning here on Earth. Laboratory experiments simulating lightning discharge conducted in a carbon dioxide-dominated atmosphere show a distinctive peak at the excited atomic oxygen triplet near 777 nm (e.g., Borucki et al., 1985, 1996; Qu et al., 2023). Because of the increased abundance of oxygen (in carbon dioxide) at Venus, emission from the OI triplet should be relatively strong compared to at Earth (e.g., Borucki et al., 1985). Numerous searches for lightning have been conducted via optical flash detection at this wavelength, including with the Venera 9/10 Orbiter Spectrometer (Krasnopolsky, 1979), the Pioneer Venus Star Tracker (Borucki et al., 1991), and Venus Express Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) (Moinelo et al., 2016), none of which returned clear detections. Other endeavors, such as the observations made by the Mt. Bigelow 61-in. telescope (Hansell et al., 1995) and the Akatsuki Lightning and Airglow Camera (LAC) (Takahashi et al., 2021; Lorenz et al., 2022), were more successful, with several distinct light flashes recorded (see Section 2.1 below). Theory and simulations predict that the clouds would only absorb ~60% of the optical energy from lightning near the cloud base, although the photons would be scattered horizontally to a width of ~200–300 km (e.g., Williams et al., 1982; Williams & Thomason, 1983). In contrast, only ~0.01% of the visible photons from near-surface lightning could escape to space. Ultimately, orbiting spacecraft or ground-based telescopes could detect lightning that occurs as low as the lower cloud deck.

However, these optical flashes may have alternative sources beyond lightning. On Earth, satellites that observe lightning also observe meteor fireballs. As bolides ablate in the atmosphere, some of their kinetic energy is released as optical energy, which can be observed at visible wavelengths. Observations of small meteors reveal that they, like lightning, emit a distinctive peak around 777 nm (e.g., Madiedo et al., 2023). While slower meteors generate a Planck continuum, the OI emission line is especially strong for faster meteors (e.g., Vojáček et al., 2022). At Venus, we might expect even stronger OI emission.

In this study, we investigate the rate of fireballs from cm-sized meteors ablating in the upper atmosphere of Venus as alternative explanations for observed optical flashes. First, we calculate the global rate of optical flashes inferred from the Mt. Bigelow and Akatsuki detections (Section 2.1). Then, we adapt a power law for impactors at Earth (e.g., Brown et al. 2002) to calculate the flux of small impactors at Venus. We derive a power law for the number of impactors with a certain amount of optical energy in the OI emission line (Section 2.2). Next, we compare those to the rate of observed flashes from Akatsuki and Mt. Bigelow (Section 3). While these optical flashes are likely to come from the cloud layers (if produced by lightning) or even higher in the atmosphere (if produced by ablating meteors or transient luminous events like sprites, elves, and haloes), we also discuss the prospects for lightning elsewhere on Venus, such as volcanic or aeolian lightning near the surface (Section 4.1). Finally, we assess whether cloud-based lightning would threaten future probes or aerial platforms (Section 4.2).

2 Methods

To begin unravelling the mystery of lightning at Venus, we predict the rate of optical flashes produced by meteor fireballs. We compare those rates to those inferred from the Akatsuki (Takahashi et al., 2021; Lorenz et al., 2022) and Mt. Bigelow (Hansell et al., 1995) surveys. If the observed flashes occur at a rate consistent with that predicted for meteor fireballs, then one could conclude that meteor fireballs are a plausible explanation for all the flashes. However, if the observed flashes are much more frequent, then some of them probably originated from lightning.

2.1 Searches for optical flashes at Venus

Table 1 summarizes five searches for optical flashes at Venus, following Table 1 in Lorenz et al. (2019). Here, our first goal is to use these observations to place statistical constraints on the global, yearly rate of optical flashes at Venus.

Two surveys yielded the most believable detections of optical flashes at Venus. The Akatsuki mission entered orbit at Venus in December 2015 (e.g., Nakamura et al., 2016) and initiated a search for optical transients with its Lightning and Airglow Camera (LAC) in 2016 (e.g., Takahashi et al., 2018). LAC uses a filter centered at 780.6 nm with a bandwidth (full width at half maximum) of 9.0 nm, which is sufficient to capture the emission from the OI triplet at 777 nm. The sampling rate is 31.25 kHz with a spatial resolution of ~175 km at a distance of ~5000 km (Takahashi et al., 2018). LAC is only operated during the spacecraft's orbit when Venus blocks sunlight from directly hitting its sensor. In its first years of operation, the LAC team confirmed that the triggering system functioned correctly and detected several cosmic rays (Takahashi et al., 2018). After three years, LAC operated for a total of 16.8 hours, covering an area-time product of $\sim 82 \times 10^6$ km^2-hr, without any detections of a flash attributable to lightning or meteors (Lorenz et al. 2019). By late 2020, LAC accumulated an area-time product of $>100 \times 10^6$ km^2-hr and detected a single optical flash that lasted ~100 ms with a total optical energy near 777 nm of $E_{OI} \sim 1.1 \times 10^7$ J (Takahashi et al., 2021), which is several times brighter than the detection limit of $E_{OI} \sim 5 \times 10^5$ J to 2×10^6 J (Takahashi et al., 2018). As of late 2022, LAC reached an area-time product of at least $\sim 200 \times 10^6$ km^2-hr without any additional detections of lightning-like flashes, as shown in Table 1 (Lorenz et al., 2022).

In the early 1990s, a ground-based telescope observed several candidate flashes at Venus. That search used a 1.5-m telescope on Mt. Bigelow, Arizona to image the night side of Venus with a sampling rate of 18.8 Hz over several nights. The instrument used a narrowband filter centered at 777.4 nm, with a bandwidth of 0.7 nm (Hansell et al., 1995). Overall, this survey detected seven flashes, each in a single frame of the imaging sequence collected in ~53 ms. Takahashi et al. (2018) argued that using only one frame per flash admits the possibility that cosmic rays or unknown electrical noise could have produced some flashes. Table 2 of Hansell et al. (1995) reports the "associated optical energy" for each flash, which equals 2.5 times the optical energy measured near 777 nm. This factor of 2.5 (=1/0.4) was inserted based on the assumption that Venusian lightning would emit ~40% of its total optical energy near 777 nm (e.g., Borucki et al., 1981). Therefore, associated optical energies of $\sim 0.1–2.1 \times 10^9$ J are equivalent to $E_{OI} \sim 4–84 \times 10^7$ J near 777 nm. Hansell et al. (1995) inferred a detection limit of

E_{OI} ~0.6–2.5 × 10^6 J for 50–95% detections. Overall, the area-time product from this ground-based survey reached at least ~800 × 10^6 km^2-hr (Hansell et al., 1995), counting additional nights of non-detections by that group that were not published (Lorenz et al., 2019). Other groups may have conducted similar searches using ground-based telescopes with no detections (Yair et al., 2012), but those efforts have not been published or included in Table 1.

Three other attempts to observe optical flashes at Venus were less successful. The Pioneer Venus Star Tracker (Borucki et al., 1991) and Venus Express VIRTIS (Moinelo et al., 2016) accumulated area-time products of ~10^5 and 14 × 10^6 km^2-hr, respectively, with no detections. The Venera 9/10 Orbiter Spectrometer recorded a burst of light lasting ~70 s, almost immediately after it began observations (Krasnopolsky, 1979; 1983). Some authors attribute this observation to lightning (e.g., Hart et al., 2022), while others argue that instrument anomalies or even spacecraft debris are a more likely explanation (e.g., Lorenz, 2018; Lorenz et al., 2019). The total area-time product associated with Venera 9/10 was relatively tiny, only ~2.5 × 10^3 km^2-hr (Lorenz et al., 2019). Ultimately, we might not be surprised that the two surveys with by far the largest coverage are the ones that yielded the most reliable detections.

Table 1. Two surveys produced relatively reliable detections of optical flashes in the atmosphere of Venus. Three other surveys, which had much lower coverage, did not return any uncontested detections.

Search	Coverage (10^6 km^2-hr)	Number of lightning-esque flashes	Equivalent global, yearly rate (95% confidence intervals)	Detection threshold (J)	Energy of the dimmest flash near 777 nm (J)
Mt. Bigelow	800	7	35423 (17476, 66808)	2.5 × 10^6 (95%) 0.6 × 10^6 (50%)	2.8 × 10^7
Akatsuki	200	1	20241 (4902, 112770)	0.5–2 × 10^6	1.1 × 10^7
Venera 9/10 Orbiter Spectrometer	0.0025	0	0 (< 5 × 10^9)	3 × 10^7	-
Venus Express VIRTIS	14	0	0 (< 9 × 10^5)	Unknown	-
Pioneer Venus Star Tracker	0.1	0	0 (< 10^8)	2 × 10^8	-

To compare with the power laws derived in the next subsection, we need to translate these observations into statistical constraints on the global rate of flashes at Venus. Say that a survey observes a given area (A_S) for a given time (T_S). Its area-time product is A_ST_S. If N is the total number of bright flashes (i.e., with optical energies above a certain detection limit) across Venus during one Earth-year, then the expected number of flashes observed by that survey is

$$\lambda_S = N\left(\frac{A_S}{A_V}\right)\left(\frac{T_S}{T_Y}\right), \tag{1}$$

where $A_V = 4.6 \times 10^8$ km^2 is the surface area of Venus and $T_Y = 8.8 \times 10^3$ hr is the duration of an Earth-year. We assume that Poisson statistics govern optical flashes (from lightning or meteors), meaning that the probability of observing an integer number of flashes (k) during a survey is

$$P(k \mid \lambda_S) = \frac{\lambda_S^k e^{-\lambda_S}}{k!}. \tag{2}$$

Here, we know that $k = 1$ and 7 for the Akatsuki and Mt. Bigelow surveys, respectively. We want to calculate the probability density function for λ_S and thus N according to both surveys. By Bayes' theorem, $P(\lambda_S \mid k) \propto P(k \mid \lambda_S)$. We then convert λ_S to N using Eq. 1 and renormalize the probability density function so it integrates to 1 from N equals zero to infinity.

Figure 1 shows our statistical constraints on the global, yearly rate of optical flashes at Venus. For surveys with $k = 0$, we can say that $\lambda_S \leq 3$ with 95% confidence. The upper limits on λ_S are thus ~9×10^5, ~10^8, and ~5×10^9, respectively, from the non-detections by Venus Express VIRTIS, the Pioneer Venus Star Tracker, and the Venera 9/10 Orbiter Spectrometer (assuming Venera 9/10 saw only spacecraft debris or an instrument anomaly). For surveys with more reliable detections of optical flashes ($k \geq 1$), the most likely value of λ_S is simply k. Using Eq. 1, the most likely values of N are 20241 and 35423 for Akatsuki and Mt. Bigelow, respectively. With Eq. 2, we calculated the 95% ("two-sigma") confidence intervals associated with each survey: (4902, 112770) for Akatsuki and (17476, 66808) for Mt. Bigelow. The 68.3% ("one-sigma") confidence intervals are (14325, 66808) and (14325, 54509), respectively. These surveys are both consistent with a global flash rate of $N \sim 10^4$–10^5 per Earth-year. However, we report these estimates separately because each survey may have a different (albeit similar) detection limit.

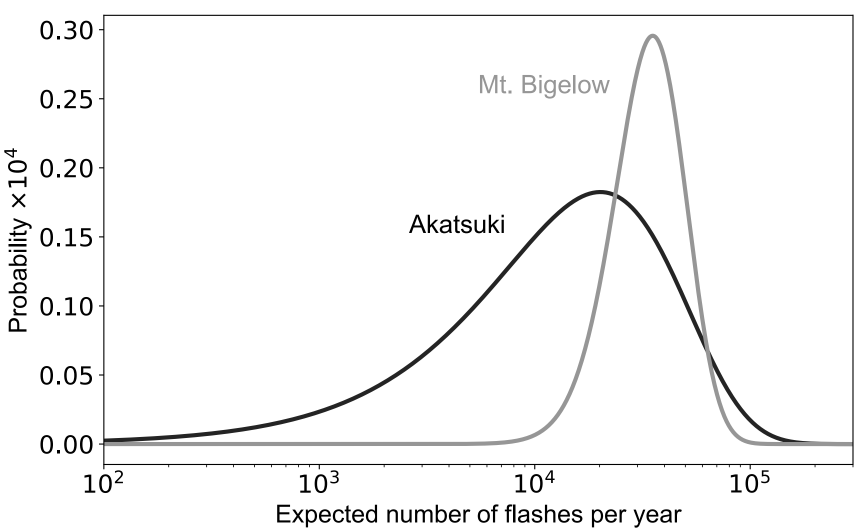

Figure 1. Probability density functions for the global, yearly rate of bright flashes at Venus (i.e., the expected number across the entire planet in one Earth-year with optical energies above the

detection limit of each instrument), estimated from the coverage and detections in surveys from Akatsuki and Mt. Bigelow.

2.2 Impactor production functions and luminous efficiency

To quantify the number of bolides that enter Venus's atmosphere in one Earth-year, we turned to existing studies of meteors at Earth (**Figure 2**). Le Feuvre & Wieczorek (2011) developed a 10^{th}-order power law to describe impactor flux at Venus over a wide range of bolide diameters (Figure 2a). However, our study requires only a log-linear power law, for simplicity, to describe the flux of small impactors at Venus. We thus start with power laws developed by Brown et al. (2002), which were the basis for the low-mass end of the expression derived in Le Feuvre & Wieczorek (2011). Based on the observations described in Section 2.1, we are interested in meteors that could produce flashes with optical energies ~10^7 J. As discussed below, the kinetic energy of those meteors should be at least an order of magnitude higher (~10^8 J). Depending on the impact velocity, the masses of meteors potentially relevant to the detected optical flashes are thus roughly ~0.1–1 kg.

We start with an established relationship between the frequency and kinetic energy of small bolides that collide with Earth (Brown et al., 2002):

$$\log_{10} N_E = 11.93 - 0.90 \log_{10} E_K \,, \tag{3}$$

where N_E is the cumulative number of bolides that strike Earth in one Earth-year with a kinetic energy of at least E_K (in Joules). This equation is the same as Eq. 2 by Brown et al. (2002), who expressed E_K in units of kiloton-TNT equivalent.

Next, we write the equivalent equation for Venus. On average, bolides strike Venus with faster velocities and thus higher kinetic energies. Le Feuvre & Wieczorek (2011) found that the average impact velocity at Venus is 25.0 km/s, whereas the average velocity for Earth is 20.3 km/s (Brown et al., 2002). From Table 3 in Le Feuvre & Wieczorek (2011), the impact rate at Venus per unit area is higher by a factor of 1.75/1.58 = 1.11 than the impact rate at Earth. However, Venus also has less surface area than Earth, by a factor of $(6052/6371)^2 = 0.902$. Overall, we can combine these factors to write the power law for the bolide flux at Venus:

$$\log_{10} N = 12.09 - 0.90 \log_{10} E_K \,, \tag{4}$$

where N is now the cumulative number of bolides that strike Venus in one Earth-year with kinetic energies of at least E_K (in Joules).

When a meteor ablates in a planet's atmosphere, only a fraction of the total kinetic energy is converted to optical energy. We can relate kinetic and optical energy with $E_O = \tau\, E_K$, where τ is the luminous efficiency of the bolide. For meteors with mass m up to a few kg and entry velocities $v < 25.372$ km/s, τ may obey the following equation (e.g., Popova et al. 2005):

$$\ln \tau = 0.567 - 10.307 \ln v + 9.781(\ln v)^2 - 3.0414\,(\ln v)^3 + 0.3213(\ln v)^4 + 0.347 \tanh(0.38 \ln m)\,. \tag{5}$$

We defined v as the average entry velocity (25 km/s) for meteors ranging in mass from 10^{-1} to 10^2 kg. We then found the best-fit power law that relates τ (dimensionless) and E_O (J), following Brown et al. (2002):

$$\tau = 0.01442\, E_O^{0.0846}, \tag{6}$$

which predicts luminous efficiencies from ~0.05–0.08 over this size range (Figure 2c). By incorporating Eqn. (6) into Eqn. (4), we then find that

$$log_{10}N = 10.43 - 0.82\ log_{10}E_O. \qquad (7)$$

However, not all the optical energy is emitted near 777 nm, to which Akatsuki's LAC filter and the search for flashes at Mt. Bigelow were restricted. Only a small fraction of the total optical energy is due to the excited oxygen triplet:

$$E_{OI} = f_{OI}E_O, \qquad (8)$$

where $0 < f_{OI} < 1$. In terms of E_{OI}, the power law for the rate of meteor fireballs at Venus is:

$$log_{10}N - 10.43 - 0.82log_{10}\frac{E_{OI}}{f_{OI}}. \qquad (9)$$

The factor f_{OI} is uncertain and variable for meteor fireballs at Earth (e.g., Vojáček et al., 2022). The uncertainty is even greater for meteors at Venus, but we expect relatively high values of f_{OI} because of the relative abundance of oxygen atoms in carbon dioxide. If we assume a certain value of f_{OI}, then we can estimate the rate of meteor fireballs with different brightnesses at Venus—and thus if the observed flashes plausibly originated from meteors, not lightning.

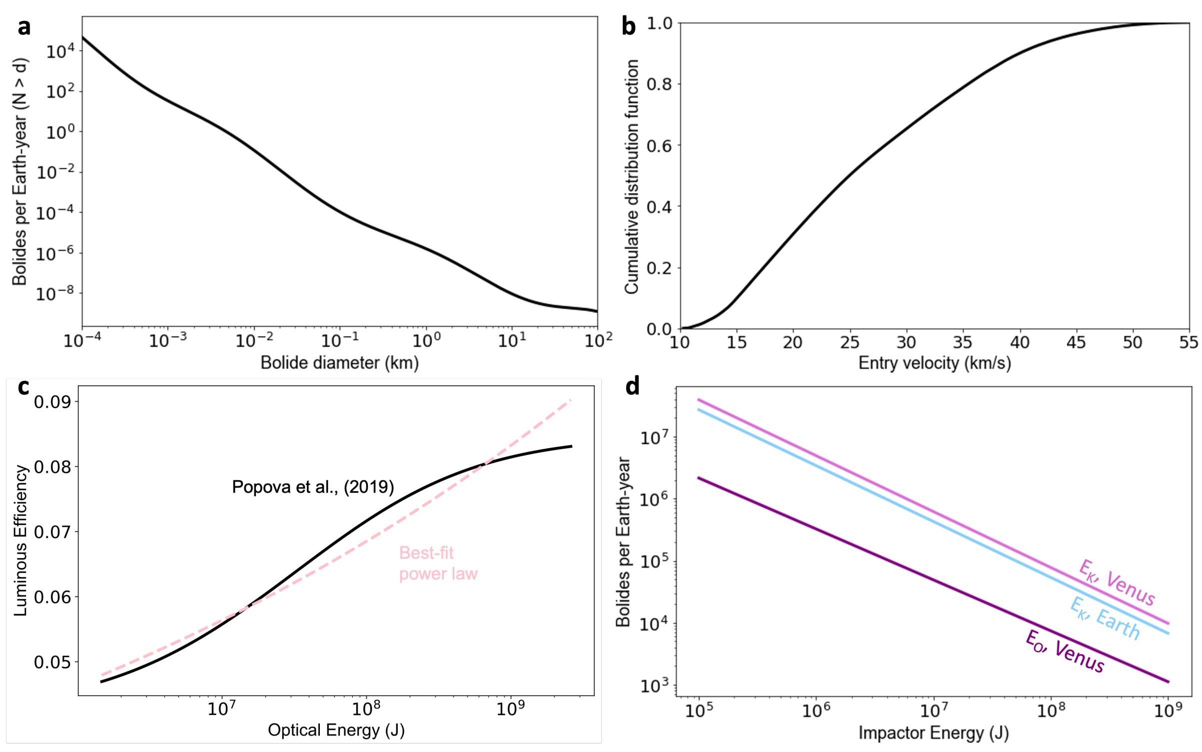

Figure 2. The number, velocity, and energy of bolides colliding with Venus can be modeled from previous work. In **(a)** we plot the number of bolides above a certain diameter colliding with Venus per Earth-year (e.g., Le Feuvre & Wieczorak, 2011). In **(b)** is the cumulative distribution function for bolide entry velocity. The average entry velocity for meteors at Venus is 25 km/s. In **(c)** we plot the best-fit power law for the luminous efficiency of meteors that we found using equations from Popova et al. (2005). Luminous efficiency—the amount of kinetic energy converted to optical energy—increases as entry mass and entry velocity increase. In **(d)** we plot

the number of bolides with a certain energy colliding with Earth and Venus per Earth-year. Impactors at Venus have higher kinetic energy due to their higher average entry velocity. E_O is the optical energy emitted per bolide; only a fraction of kinetic energy is converted to optical energy during ablation, as defined by the luminous efficiency in **(c)**.

2.3 Experimental simulations of meteor plasma

No one has yet measured the emission spectrum of a meteor fireball at Venus. In the absence of direct observations, we can turn to laboratory experiments for hints about what fraction of the total optical energy might be emitted near 777 nm. Many groups have used laser-induced breakdown spectroscopy (LIBS) to simulate a meteor fireball (e.g., Krivkova et al., 2021; Ferus et al., 2018; Dell'Aglio et al., 2010). A high-power laser can ablate a meteorite in a similar fashion to meteor ablation during high-speed collisions with atmospheric molecules. Experimental studies relevant to terrestrial meteors typically conduct LIBS experiments on meteorites in a vacuum or under ambient atmospheric conditions. However, for application to Venus meteors, we would prefer to invoke LIBS experiments conducted on rock and mineral samples surrounded by (predominantly) carbon dioxide at a pressure of a few mbar. Coincidentally, air at the surface of Mars has approximately the same composition and pressure as air at an altitude of ~100 km above the surface of Venus.

Because of this similarity, we utilized results from the LIBS experiments that were conducted to calibrate the ChemCam instrument package on the Mars rover Curiosity (Wiens et al., 2013). We used data from the Los Alamos National Laboratory ChemCam experiments, where samples were measured in 5 locations. For each sample, 50 laser pulses were taken at each location and averaged together. After the data were collected, the spectra were cleaned and calibrated. We used the cleaned and calibrated dataset to estimate the fraction of optical energy near 777 nm. We analyzed 5 different samples to determine an average fraction of optical energy. Olivine ($[Fe,Mg]_2SiO_4$) and pyroxene ($[Fe,Mg]SiO_3$) are common in stony meteorities as chondrules. We also analyzed spectra from samples of diopside ($CaMgSi_2O_6$), llanite (a rhyolite), and basalt. Diopside and llanite provided comparative results despite not being as common in meteorites as the other materials. The calibration samples did not include water ice, but we expect that a comet's fireball would produce even more OI emission than a rocky meteor. To calculate f_{OI} for each mineral or rock, we calculated the area under the spectral curve for the entire spectrum from 350–800 nm, as well as the area within the OI peak from 771–800 nm. We then divided the area under the OI peak by the total area of the spectrum, producing f_{OI}.

3 Results

3.1 Meteor fireballs are not (always) blackbodies

Many studies assume that ablating meteors in Venus's atmosphere would emit as blackbodies (e.g., Takahashi et al. 2021). If a meteor ablating at ~6000 K emitted as a blackbody, then only a very small amount of the total optical energy (<1%) would be contained in the excited oxygen line at ~777 nm or in the bandpass of the instruments designed to detect this line. The small amount of observed energy would require a very large, and thus very infrequent, meteor to cause the observed amount of optical energy. However, recent studies have shown that small meteors, such as the one observed by Madiedo et al. (2013) in the Geminid meteor shower on Earth, do not always emit as blackbodies (**Figure 3**). By calculating the area under the spectral curve, we determine that ~7% of the total optical energy produced by this meteor was contained in the excited atomic oxygen line.

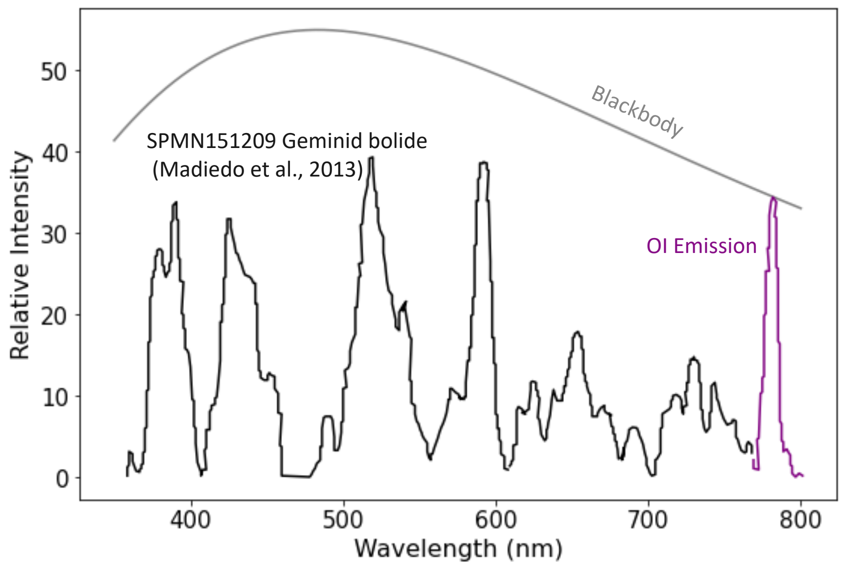

Figure 3. Two spectra with the same amount of optical energy near 777 nm, but very different amounts of total optical energy. A Geminid meteor produced a spectrum (black and purple) distinctly different than a blackbody curve (gray) for an effective ablation temperature of 6000 K. At Venus, due to the large relative abundance of oxygen, ~5–30% of a small meteor's optical emission may be contained in the OI triplet (purple).

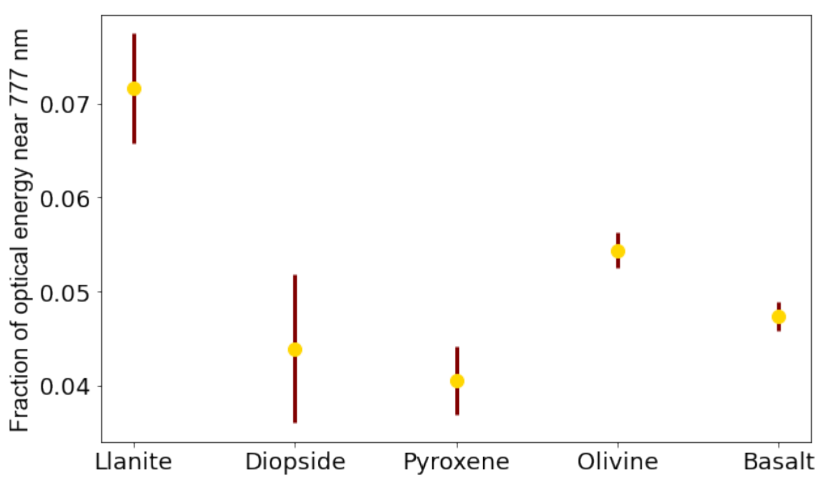

Figure 4. Fraction of total optical energy emitted in the 777 nm bandpass, based on inspection of LIBS spectra from the ChemCam calibration database, which provide a potential analogue for the emission spectra of meteors. Near the surface of Mars, the atmosphere is CO_2-dominated with pressures of a few millibars—exactly the conditions at altitudes near ~100 km in the atmosphere of Venus where small meteors burn up. We find that ~4–7% of the total optical energy contained in these spectra is typically emitted near 777 nm. For minerals and rock types that are common in meteors, as well as the more silicic llanite, this plot shows the mean (gold) and standard deviation (maroon) of that fraction for 5 samples in the database.

We used LIBS data from the calibration of Curiosity's ChemCam instrument to estimate meteoritic emission in the OI emission line for ablating bolides at Venus. To better constrain the amount of energy in the excited oxygen triplet for different materials, we analyzed common meteoritic materials for the fraction of optical energy contained around 777 nm (**Figure 4)**. We found that, for common meteoritic materials such as olivine, pyroxene, and basalt, the value of f_{OI} ranges from ~0.04–0.07 (Figure 4). Based on these laboratory experiments and the observations of some terrestrial meteors, we thus expect that fireballs from small meteors at Venus are an order-of-magnitude brighter than blackbodies near 777 nm. However, the emission spectrum of an individual meteor will depend on many factors, including its composition, mass, entry velocity, entry angle, and irregularities that cause it to fragment and/or spin as it ablates.

3.2 Meteor fireballs in surveys from Akatsuki and the Mt. Bigelow 61-in. telescope

Figure 5 plots the number of flashes per Earth-year expected for a certain amount of optical energy produced by the ablating bolide, based on the amount of optical energy contained in the OI filter centered near 777 nm (f_{OI}). For higher values of f_{OI}, we expect to see more flashes of a given brightness in one Earth-year. As detailed above, a meteor fireball that emits as a blackbody should have f_{OI} ~0.007. Observations of terrestrial fireballs and LIBS experiments suggest that f_{OI} ~0.05–0.10 is more realistic for small meteors. We estimate that an upper limit for f_{OI} is ~0.3, perhaps for a comet that hit Venus at high velocities. We compare these expectations to the flash rates inferred from the two surveys with relatively reliable detections.

The one optical flash detected by Akatsuki's LAC (so far) had a brightness that is consistent with a meteor fireball. That is, if f_{OI} ~0.07, then we expect to witness the same number of flashes in one Earth-year from these meteors as the expected number from Akatsuki's estimated global flash rate. However, this result is somewhat conditional on the true detection limit for Akatsuki's LAC. Even if LAC's detection limit is higher than claimed by Takahashi et al. (2018) (i.e., equal to the flash brightness in the worst case), a meteor is still statistically probable within the 95% confidence intervals for $f_{\mathrm{OI}} > 0.10$. However, Takahashi et al. (2018) also claimed that the detection limit for Akatsuki's LAC is perhaps as low as $E_{\mathrm{OI}} \sim 5 \times 10^5$ J, or even lower. In that case, observing at least one flash from a meteor fireball is not surprising.

Meteor fireballs are perhaps also bright and frequent enough to explain the observations from the Mt. Bigelow 61-in. telescope. If the dimmest observed flash were observed at exactly the detection limit of that survey, then we would only predict the observation of seven meteor fireballs if ~30% of the total optical energy were concentrated in the OI filter. However, Hansell et al. (1995) estimated that their detection limit was much lower, which is also consistent with f_{OI} ~0.05–0.10, exactly what we expect for fireballs at Venus. Yair et al. (2012) also conveyed a personal communication about "repeated attempts by large-mirror ground telescopes to repeat the Hansell et al. (1995) observations," which apparently have not yielded any additional detections. If the effective area-time product for ground-based surveys is higher than Table 1 indicates, then the extrapolated number of flashes per Earth-year would decrease—and thus agree even better with the predicted rate of meteor fireballs at Venus. Finally, recent papers noted that the observations at Mt. Bigelow were not conducted at a high enough sampling rate to take more than one image per flash, leaving some ambiguity about whether a cosmic ray or electrical noise produced one or more of the flashes (e.g., Takahashi et al. 2018). If one or two of the claimed flashes did not originate from Venus, then the observed rate would agree perfectly with what we predict for meteor fireballs and with the current results from Akatsuki. Using Eq. 1

and 2, we calculate that the upper limit on the global, yearly rate of lightning in the clouds is $N \leq 11975$ ($< 4 \times 10^{-4}$ Hz), with 95% confidence—if none of the observed flashes originate from lightning.

Our study focuses on reproducing the hypothesized lightning flash rates at Venus with an alternative source of optical energy in the form of ablating meteors tens of km above the cloud layer. However, the shapes of any observed light curves would provide additional constraints. The shape of the light curve observed by Akatsuki was positively skewed (e.g., Takahashi et al. 2021), which the team argued as most consistent with lightning. Models predict a negatively skewed light curve from the ablation of a spherical meteor that does not fragment. However, ablating meteors probably are non-spherical and also fragment and spin as they descend through the atmosphere, making it difficult to predict the shape of an individual bolide-produced light curve. We did not construct any models for the light curves of meteors at Venus—but such efforts will only become more important as the number of time-resolved observations increases. Preliminary work suggests that Venusian meteors are indeed brighter than terrestrial meteors (e.g., McAuliffe & Christou, 2006; Christou & Gritsevich, 2023).

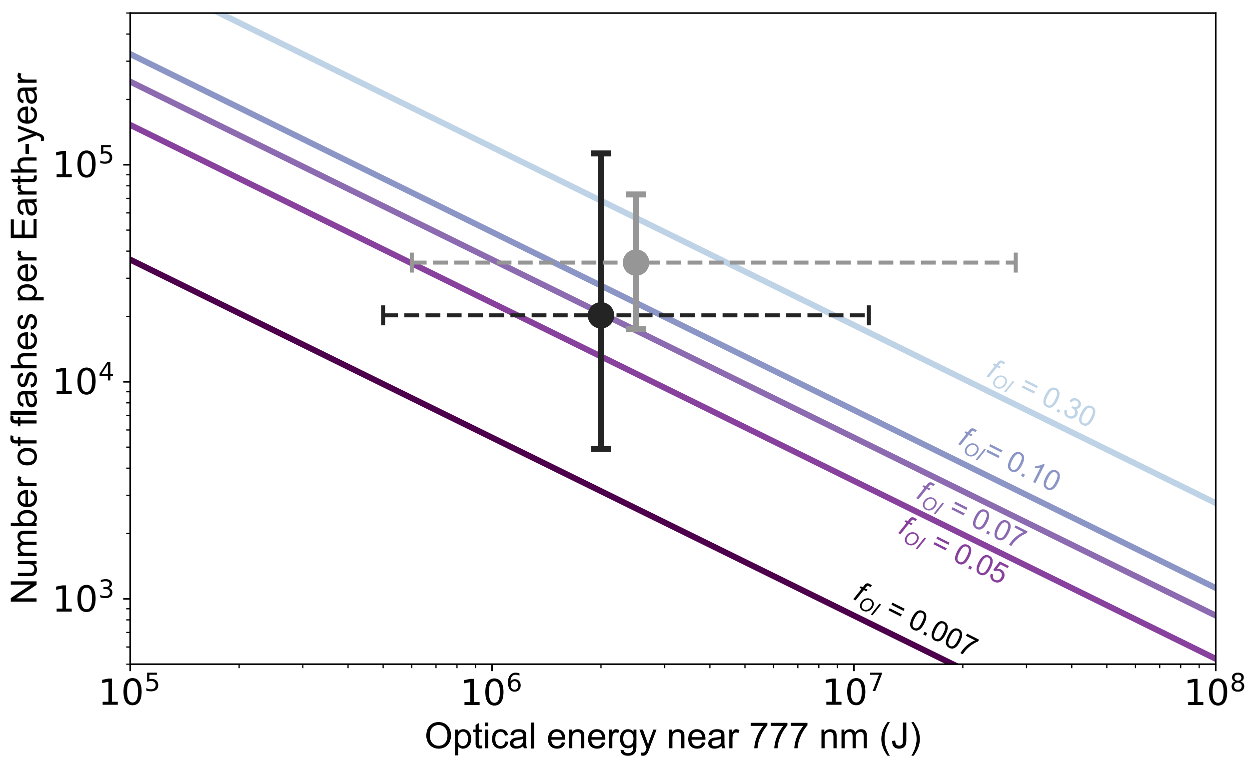

Figure 5. Estimate of the expected number of optical flashes at Venus in one Earth-year (N) that would release at least a certain amount of energy near 777 nm (E_{OI}). The black and grey circles show the global rates inferred from Akatsuki and Mt. Bigelow, respectively. The vertical bars denote the 95% confidence intervals on the global rate. The horizontal, dashed bars reflect uncertainty about the detection limits of both surveys. On the right, the dashed bars extend to the optical energy near 777 nm from the dimest flash that each survey detected, which is the highest possible detection limit. The circles are centered at the claimed detection limits for Akatsuki (e.g., Takahashi et al., 2018) and the Mt. Bigelow survey (Hansell et al., 1995). On the left, the dashed bars extend to the lowest plausible values of the detection limit claimed for each survey.

4 Discussion

4.1 Sub-cloud lightning is possible

Regardless of whether lightning exists high in Venus's atmosphere, lightning could occur close to the surface from either volcanic or aeolian processes (**Figure 6**). On Earth, volcanic lightning often occurs in the ash plume associated with an explosive eruption. The particles in the plume can become charged through several mechanisms, but fracto-electrification and tribo-electrification are considered the most important because they are closely related to explosive eruption dynamics (e.g., Cimarelli & Genareau, 2022). Material is fractured into ash-sized particles during an explosive eruption, which can release electrons and positive ions and charge the fragmented particles themselves (fracto-electrification). Ash particles of various compositions within the plume will then collide with each other, charging the particles through friction (tribo-electrification) (e.g., Cimarelli & Genareau, 2022). At the surface, winds carrying small particles can also create charges through tribo-electrification. This process could be a common phenomenon on Venus because wind speeds are close to the transport threshold (e.g., Lorenz, 2018). The Venera landers observed the movement of surface material, which implies that wind may be capable of charging particles on Venus's surface (e.g., Lorenz, 2018).

Previous studies disregarded volcanic lightning on Venus as impossible due to the supposed lack of explosive volcanism. Borucki (1982) argued that if volcanism caused the then-claimed observation of 30 lightning flashes in 3 years by the Pioneer Venus Orbiter, there would have been 10 eruptions per year. If explosive volcanism were occurring at this rate, then it would release particles into the atmosphere that could be detected. However, the cloud-particle-size spectrometer on Pioneer Venus did not detect particles of the size expected to result from explosive volcanism. Borucki (1982) therefore concluded that, even if Venus were volcanically active, explosive volcanism was not common and thus not a probable source of lightning. They also argued that lightning would have to occur in the clouds because the lower atmosphere would absorb energy at the wavelengths produced by lightning (e.g., Borucki, 1982). However, those specific detections are now attributed to cosmic rays (e.g., Lorenz, 2018). The electromagnetic observations that yield the highest inferred rates of lightning only constrain the source of those signals to below the ionosphere—compatible with a near-surface origin.

New evidence of explosive volcanism on Venus has recently emerged. For example, Ganesh et al. (2021) modeled the formation of several proposed pyroclastic deposits on Venus. These pyroclastic flows would have formed through the collapse of ash plumes created during explosive eruptions. Their models of collapsing plumes provided good matches to deposits at several locations on Venus hypothesized to be associated with explosive volcanism. Recently, a volcano that changed shape over the course of eight months during the Magellan mission was identified (e.g., Herrick & Hensley, 2023). This is evidence of active volcanism on Venus in recent years, which further supports the position that the possibility of volcanic lightning should not be disregarded. Of course, new observations from future geophysical orbiters such as VERITAS and EnVision are needed to unveil the volcanic history of Venus.

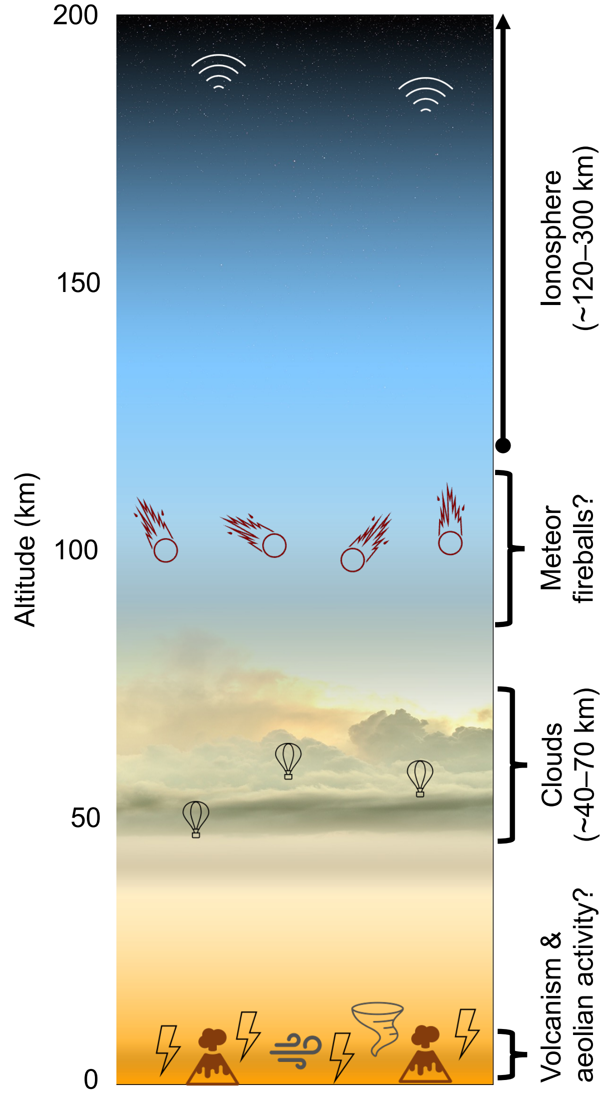

Figure 6. A cartoon of possible phenomena in Venus's atmosphere. Small meteors may burn up far above the clouds, while near-surface lightning could generate the putative whistler-mode waves from far below the clouds. Adapted from Figure 6 in O'Rourke et al. (2023).

4.2 Lightning is not a hazard to missions in the clouds

Many missions to Venus passed through its clouds. No mission has, to our knowledge, been struck by lightning, but lightning nonetheless poses a potential risk to any mission. Starting with Venera 7, ~14 probes have delivered data from below the clouds (e.g., Taylor et al., 2018). Two balloons floated at an equilibrium altitude of ~53 km as part of the Soviet VeGa mission, reporting data for ~47 hours before running out of battery power (e.g., Sagdeev et al., 1986; Moroz, 1987; Crisp et al., 1990). Given these past experiences, lightning is not an obvious hazard to atmospheric probes or short-lived balloons. However, future missions may include extended stays in the clouds to answer high-priority scientific questions (e.g., O'Rourke et al., 2021; Arredondo et al., 2022; Cutts et al., 2022). For example, Phantom is an exciting, well-developed concept that features an aerial platform that dwells in the clouds for at least ~30 Earth-days, and plausibly ~100 Earth-days or longer (e.g., Byrne et al., 2023). Scientists have also proposed sending flotillas of long-lived balloons to search for active biology (Hein et al., 2020) or seismic and volcanic activity (Krishnamoorthy & Bowman, 2023; Rossi et al., 2023). Is lightning a threat to long-duration missions in the clouds of Venus?

We can use simple statistics to estimate the hazard from lightning to various types of missions. Say that T_M is the duration of the mission (in seconds); Γ_L is the overall rate of lightning in the clouds (in strikes per second); and R_H is the radius within which a lightning strike is potentially hazardous (in meters). The estimated number of lightning strikes within the hazardous radius during the mission is then

$$\lambda_L = T_M \Gamma_L \left(\frac{R_H}{2R_V}\right)^2, \tag{10}$$

where $R_V = 6052$ km is the radius of Venus, assuming that $R_H << R_V$. If lightning strikes happen without spatial bias but with timing that obeys Poisson statistics, then we can calculate the probability that a hazardous strike will occur near the mission:

$$P_H = 1 - e^{-\lambda_L}. \tag{11}$$

Mission designers often consider a hazard with a probability of $P_H < 10^{-6}$ to be negligible. We considered three possible rates of lightning in the clouds. Overall, our study is compatible with the hypothesis that cloud-based lightning is vanishingly rare ($\Gamma_L \leq 10^{-9}$ Hz). If the optical flashes observed by Akatsuki and ground-based telescopes originated from cloud-based lightning, then $\Gamma_L \sim 1.2 \times 10^{-4}$ Hz (Lorenz et al., 2022). If the claimed whistler-mode waves were attributed to cloud-based lightning, then we fear that $\Gamma_L \sim 320$ Hz (Hart et al., 2022). Of course, as on Earth, we would expect to find lightning on Venus concentrated in particular regions at any given time. However, we can use the assumption of global homogeneity to estimate relative hazards. If lightning were ubiquitous in the clouds, then requiring a mission to survive a strike could seem prudent. However, no caution is necessary if there is no (or very rare) lightning.

Figure 7 shows the probability of a hazardous lightning encounter for four classes of missions. First, probes can pass quickly through the clouds. For example, the DAVINCI mission notionally plans to descend from ~70–40 km in ~34 minutes between the deployment and release of its parachute (Garvin et al., 2022). If lightning were indeed ≥ 7 times as common on Venus as Earth (Hart et al., 2022), then we might expect ~40 strikes within ~100 km of DAVINCI (and all past probes). However, the expected number of strikes near a probe is < 1 using the flash rate inferred from Akatsuki's search. Second, the VeGa mission was the archetype of a short-lived balloon, operating for ~47 hours. Again, the flash rate inferred from Akatsuki is compatible with the non-detection of lightning (i.e., $\lambda_L \sim 10^{-3}$ for $R_H \sim 100$ km). Third, we assume that a long-lived balloon has a lifetime of ~30 Earth-days. The chances of a nearby strike ($R_H < 100$ km) are then only 1-in-50, according to the optical flash rate from Akatsuki. This contrasts with the analysis in Hart et al. (2022), which implies that such a mission could operate in the vicinity of >50,000 strikes. Finally, we imagined a flotilla of 10 balloons that each have lifetimes of ~100 Earth-days. Using the flash rate from Akatsuki, it is more likely than not that at least one of those balloons encountering a strike within ~90 km. However, perhaps such a moderately distant strike would seem more exciting than dangerous. Ultimately, especially given the possibility that meteor fireballs produced all the optical flashes observed at a Venus, there is as of yet no affirmative evidence that lightning is common enough in the clouds to pose a hazard to even fleets of long-lived aerial platforms.

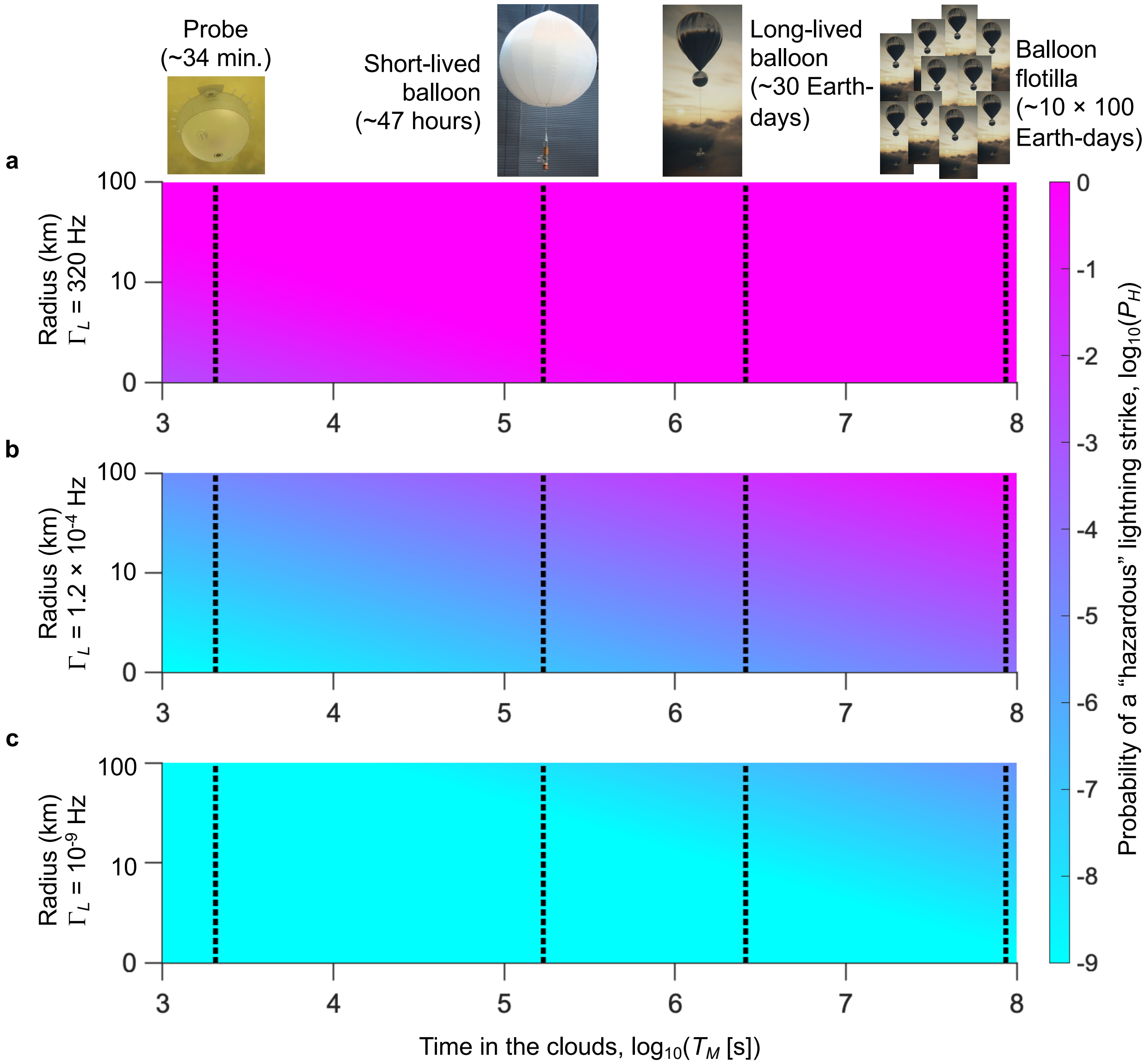

Figure 7. Relative risk of lightning to various mission architectures. Lightning is only a hazard to missions in the clouds if lightning exists in the clouds. We have calculated the probability that a lightning strike would occur within a certain horizontal distance (vertical axes) as a function of the total time that a mission spends within the clouds (horizontal axes). Although that time varies by five orders of magnitude for different types of missions, estimates for the rate of lightning in the clouds span ~10 orders of magnitude. In (**a**) we use the rate of lightning inferred from studies of putative whistler-mode waves (Hart et al., 2022). In (**b**) we use the global rate derived from Akatsuki's observation of a single flash so far, assuming that flash originated from lightning (Lorenz et al., 2022). In (**c**) we use the highest rate that implies that even a balloon flotilla experiences a negligible risk ($P_H < 10^{-6}$) from lightning, which agrees with the hypothesis that no flashes from lightning have ever been seen at Venus.

4.3 The search must go on

In our work we have developed a production function for meteor fireballs in the atmosphere of Venus, which should be revisited as flash rates become better determined by future observations. While we found that small meteors ablating high (~100 km) in the atmosphere are plausible explanations for the observed optical flashes, more optical flash observations would serve to sharpen our statistics and provide tighter quantifications of flash rates. Spectrally resolving optical flashes at Venus could verify our study's estimate that meteor fireballs at Venus have strong emission near 777 nm. Additionally, determining the altitude of recorded optical flashes would allow us to conclude whether they originated above or within the cloud layer, providing more evidence of their source. Meteor fireballs and sprites would occur tens of kilometers above the clouds. Only a very rare, huge meteor would reach the clouds.

The "gold standard" approach to lightning detection would be simultaneous optical and radio observations (e.g., Aplin & Fischer, 2017; Cartier, 2020). Lightning above the lower cloud deck could produce an observable optical flash, whistlers at kHz frequencies, and sferics at MHz frequencies. In contrast, meteors would not produce strong radio emissions. Meteors themselves make important contributions to atmospheric chemistry (e.g., Pätzold, et al., 2009; Carrillo-Sánchez et al., 2020) and produce infrasonic signatures that aerial platforms could observe (e.g., Silber et al., 2018; 2023). Lightning below the clouds may produce radio emissions but not optical flashes visible from space. If the diagram of transient phenomena on Venus shown in Figure 6 were correct, then we would expect optical flashes consistent with the power laws derived in this study, plus non-simultaneous radio emission in the form of whistlers and sferics.

5 Conclusions

For decades, searches have been conducted for concrete proof of lightning in the atmosphere of Venus. Proving or disproving its existence would have vast implications for scientists' understanding of Venus's atmospheric chemistry, weather patterns, and even the potential for life in the clouds. Though multiple pieces of evidence such as whistler-mode waves and optical flashes have been put forward as proof of lightning, the presence of cloud-based lightning remains an open question. In this study, we have investigated whether small meteors may have produced optical flashes in the atmosphere of Venus that were interpreted as lightning. We calculated the rates of expected optical flashes from ablating bolides, and compared those to the rates inferred from optical surveys. We also calculated the risk posed to cloud-based missions considering the estimated lightning rates from these optical surveys. We find that based on observations of meteor fireballs at Earth, ablating fireballs at ~100 km altitude may be responsible for most, or even possibly all of the observed flashes. Lightning thus does not seem like a threat to missions that pass through (e.g., probes) or even linger within (e.g., aerial platforms) the clouds. Future optical surveys should find more meteor fireballs at rates and brightnesses that match our power laws. Simultaneous optical and radio measurements would help in the hunt for definitive evidence of lightning.

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Open Research

Software (other than for typesetting) was not used for this research. Datasets for this research are available in these in-text data citation references: Wiens et al. (2013).

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Meteors May Masquerade as Lightning in the Atmosphere of Venus

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Key Points:

- We investigate whether meteor fireballs could have produced the optical flashes that have been detected at Venus and attributed to lightning
- We find that flashes from meteor fireballs are statistically likely to occur at the observed rates and brightness
- There is no affirmative evidence that lightning is a hazard to missions that pass through or dwell within the clouds of Venus

Abstract

Lightning in the atmosphere of Venus is either ubiquitous, rare, or non-existent, depending on how one interprets diverse observations. Quantifying when and where, or even if lightning occurs would provide novel information about Venus's atmospheric dynamics and chemistry. Lightning is also a potential risk to future missions, which could float in the cloud layers (~50–70 km above the surface) for up to an Earth-year. Over decades, spacecraft and ground-based telescopes have searched for lightning at Venus using many instruments, including magnetometers, radios, and optical cameras. Two optical surveys (from the Akatsuki orbiter and the 61-inch telescope on Mt. Bigelow, Arizona) observed several flashes at 777 nm (the unresolved triplet emission lines of excited atomic oxygen) that have been attributed to lightning. This conclusion is based, in part, on the statistical unlikelihood of so many meteors producing such energetic flashes, based in turn on the presumption that a low fraction (< 1%) of a meteor's optical energy is emitted at 777 nm. We use observations of terrestrial meteors and analogue experiments to show that a much higher conversion factor (~5–10%) should be expected. Therefore, we calculate that smaller, more numerous meteors could have caused the observed flashes. Lightning is likely too rare to pose a hazard to missions that pass through or dwell in the clouds of Venus. Likewise, small meteors burn up at altitudes of ~100 km, roughly twice as high above the surface as the clouds, and also would not pose a hazard.

Plain Language Summary

Artists depicting the atmosphere of Venus love to include lightning bolts to emphasize its hellish environment. Even though missions like DAVINCI would most likely be safe from strikes as they descend quickly through the atmosphere, long-lived aerial platform missions supported by large balloons floating in the cloud layer ~50–70 km above the surface might not be so fortunate. Do engineers need to build aerial platforms with the toughness (and thus expense) required to survive a lightning strike? Quantitative estimates of lightning strike frequency are inconsistent based on different forms of evidence. Observations of certain electromagnetic signals, interpreted as lightning in the clouds, suggest a strike rate several times that of Earth's lightning. In comparison, optical flash rates at Venus, as observed at the Mt. Bigelow observatory in Arizona and by the Akatsuki mission currently orbiting Venus, suggest a far lower flash rate. In this study, we argue that these optical flashes were plausibly produced by meteor fireballs ~100 km above the surface, not by lightning in the clouds. If so, then lightning poses no significant threat to balloon missions in the clouds of Venus. Lightning may still exist at the surface, produced by aeolian processes or explosive volcanism.

1 Introduction

Venus is a natural laboratory for studying the atmosphere of a non-Earth-like planet. While Venus is unique among terrestrial planets in our Solar System, it is an analogue to a common class of exoplanets (e.g., Kane et al., 2019; Way et al., 2023). For example, Venus's present-day atmosphere is far more massive than the atmospheres of Earth and Mars (e.g., Taylor et al., 2018)—dominated by carbon dioxide and perpetually shrouded in clouds rich in droplets of sulfuric acid at altitudes from ~47–70 km (e.g., Titov et al., 2018). Exoplanets born near their parent stars may outgas thick, CO_2-dominated atmospheres shortly after they accrete (e.g., Hamano et al., 2013; Gillmann et al., 2022; Miyazaki & Korenaga, 2022) or, later, if they experience a runaway greenhouse (e.g., Krissansen-Totton et al., 2021; Way et al., 2022).

Venus's clouds are super-rotating, moving westward much faster than the solid body (e.g., Read & Lebonnois, 2018). This attribute can be exploited for exploration: a surface station would take ~243 Earth-days to experience a sidereal day, but an aerial platform in the clouds could circumnavigate Venus at the equator every ~5–7 Earth-days (e.g., Cutts et al., 2022; O'Rourke et al., 2023). Likewise, many terrestrial exoplanets may have superrotating atmospheres (e.g., Imamura et al., 2020; Lee et al., 2020). As the number of observed exoplanets grow, so does the complexity of work to understand their evolution and current environments, and the need to study Venus. Lightning is an important aspect of terrestrial atmospheres, in part for its ability to instigate non-equilibrium chemistry (e.g., nitrogen fixation) relevant to biology and life detection (e.g., Ardaseva et al., 2017). Venus offers a natural laboratory for studying lightning on a major class of exoplanets.

On Earth, lightning flashes occur hundreds of times each second across the globe (e.g., Desch et al., 2002), illuminating areas where the atmosphere is dynamically active. Lightning flashes occur after a significant charge separation has been built up in the atmosphere (e.g., Yair, 2012; Aplin, 2006; Dwyer & Uman, 2014). Once released, lightning dissipates an enormous amount of energy, a fraction of which flashes as optical energy. In Earth's atmosphere, lightning strikes are most often facilitated via the interactions between liquid water and water ice particles, where the polarity of the molecules contributes to the buildup of this charge difference. Volcanic plumes (e.g., Nicoll et al., 2019; Mather & Harrison, 2006) and dust storms (e.g., Aplin, 2006) can also produce lightning by triboelectric charging, in which ash and dust particles are the medium of charge buildup.

On Venus, lightning could arise from mechanisms analogous to those seen on Earth. Sulfuric acid molecules in the clouds may have sufficient polarity to produce charge separation if both solid and liquid phases exist, though this is debated (e.g., McGouldrick et al., 2011). The frequency of volcanic events on Venus today is uncertain. However, Venus and Earth could have similar rates of volcanic activity overall (e.g., Byrne & Krishnamoorthy, 2021). Radar images from Magellan revealed ~10^5 volcanoes on the surface larger than 5 km in diameter (Hahn & Byrne, 2023). Magellan may also have observed active volcanism (e.g., Herrick & Hensley, 2023). At least some volcanic eruptions were explosive in the past (e.g., Ganesh, 2022; Ganesh et al., 2022; Ganesh et al., 2021; Airey et al., 2015). Lightning produced by either volcanic or atmospheric processes would provide a probe into Venus's current and past evolution. Lightning strikes could also excite global Schumann resonances at frequencies of tens of Hz, enabling electromagnetic sounding of Venus's lithosphere from an aerial platform (e.g., Grimm et al., 2012). Finally, lightning on Venus would create unique chemical environments in the atmosphere (e.g., Krasnopolsky, 2006; Delitsky & Banes, 2015). Almost anyone studying Venus, especially those planning future missions, should feel motivated to find lightning, if it exists.

The existence of lightning in the atmosphere of Venus has been heavily debated for decades based on interpretations of different types of evidence. Numerous attempts to collect concrete evidence of lightning have been made, with varying results (e.g., Lorenz, 2018; Lorenz et al., 2019 and references therein). Most of the claimed detections rely on observations of radio, magnetic, and acoustic signals. The Venera 11–14 landers observed near-continuous signals at ~10–80 kHz during their descents, which resembled electrical activity (sferics) associated with lightning on Earth (Ksanfomality, 1980). The Pioneer Venus Orbiter detected electric fields thought to be associated with lightning flashes (e.g., Taylor et al., 1979). The Venus Express magnetometer detected magnetic bursts near periapsis that were interpreted as whistler-mode waves—circularly polarized electromagnetic waves with frequencies up to several hundred Hz at Venus, which follow local magnetic field lines—produced by lightning below the ionosphere (e.g., Russell et al. 2006). Most recently, Hart et al. (2022) claimed that Venus has a flash rate several times higher than for lightning on Earth. However, there have also been non-detections of lightning that are in tension with these predictions, including with the radios of Cassini (Gurnett et al., 2001) and the Parker Solar Probe (Pulupa et al., 2021). All claimed detections have been controversial, with spacecraft and plasma noise proposed as candidates to create some of the signals (e.g., Lorenz, 2018).

A second approach to detect lightning at Venus is searching for optically bright flashes, similar to what we associate with lightning here on Earth. Laboratory experiments simulating lightning discharge conducted in a carbon dioxide-dominated atmosphere show a distinctive peak at the excited atomic oxygen triplet near 777 nm (e.g., Borucki et al., 1985, 1996; Qu et al., 2023). Because of the increased abundance of oxygen (in carbon dioxide) at Venus, emission from the OI triplet should be relatively strong compared to at Earth (e.g., Borucki et al., 1985). Numerous searches for lightning have been conducted via optical flash detection at this wavelength, including with the Venera 9/10 Orbiter Spectrometer (Krasnopolsky, 1979), the Pioneer Venus Star Tracker (Borucki et al., 1991), and Venus Express Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) (Moinelo et al., 2016), none of which returned clear detections. Other endeavors, such as the observations made by the Mt. Bigelow 61-in. telescope (Hansell et al., 1995) and the Akatsuki Lightning and Airglow Camera (LAC) (Takahashi et al., 2021; Lorenz et al., 2022), were more successful, with several distinct light flashes recorded (see Section 2.1 below). Theory and simulations predict that the clouds would only absorb ~60% of the optical energy from lightning near the cloud base, although the photons would be scattered horizontally to a width of ~200–300 km (e.g., Williams et al., 1982; Williams & Thomason, 1983). In contrast, only ~0.01% of the visible photons from near-surface lightning could escape to space. Ultimately, orbiting spacecraft or ground-based telescopes could detect lightning that occurs as low as the lower cloud deck.

However, these optical flashes may have alternative sources beyond lightning. On Earth, satellites that observe lightning also observe meteor fireballs. As bolides ablate in the atmosphere, some of their kinetic energy is released as optical energy, which can be observed at visible wavelengths. Observations of small meteors reveal that they, like lightning, emit a distinctive peak around 777 nm (e.g., Madiedo et al., 2023). While slower meteors generate a Planck continuum, the OI emission line is especially strong for faster meteors (e.g., Vojáček et al., 2022). At Venus, we might expect even stronger OI emission.

In this study, we investigate the rate of fireballs from cm-sized meteors ablating in the upper atmosphere of Venus as alternative explanations for observed optical flashes. First, we calculate the global rate of optical flashes inferred from the Mt. Bigelow and Akatsuki detections (Section 2.1). Then, we adapt a power law for impactors at Earth (e.g., Brown et al. 2002) to calculate the flux of small impactors at Venus. We derive a power law for the number of impactors with a certain amount of optical energy in the OI emission line (Section 2.2). Next, we compare those to the rate of observed flashes from Akatsuki and Mt. Bigelow (Section 3). While these optical flashes are likely to come from the cloud layers (if produced by lightning) or even higher in the atmosphere (if produced by ablating meteors or transient luminous events like sprites, elves, and haloes), we also discuss the prospects for lightning elsewhere on Venus, such as volcanic or aeolian lightning near the surface (Section 4.1). Finally, we assess whether cloud-based lightning would threaten future probes or aerial platforms (Section 4.2).

2 Methods

To begin unravelling the mystery of lightning at Venus, we predict the rate of optical flashes produced by meteor fireballs. We compare those rates to those inferred from the Akatsuki (Takahashi et al., 2021; Lorenz et al., 2022) and Mt. Bigelow (Hansell et al., 1995) surveys. If the observed flashes occur at a rate consistent with that predicted for meteor fireballs, then one could conclude that meteor fireballs are a plausible explanation for all the flashes. However, if the observed flashes are much more frequent, then some of them probably originated from lightning.

2.1 Searches for optical flashes at Venus

Table 1 summarizes five searches for optical flashes at Venus, following Table 1 in Lorenz et al. (2019). Here, our first goal is to use these observations to place statistical constraints on the global, yearly rate of optical flashes at Venus.

Two surveys yielded the most believable detections of optical flashes at Venus. The Akatsuki mission entered orbit at Venus in December 2015 (e.g., Nakamura et al., 2016) and initiated a search for optical transients with its Lightning and Airglow Camera (LAC) in 2016 (e.g., Takahashi et al., 2018). LAC uses a filter centered at 780.6 nm with a bandwidth (full width at half maximum) of 9.0 nm, which is sufficient to capture the emission from the OI triplet at 777 nm. The sampling rate is 31.25 kHz with a spatial resolution of ~175 km at a distance of ~5000 km (Takahashi et al., 2018). LAC is only operated during the spacecraft's orbit when Venus blocks sunlight from directly hitting its sensor. In its first years of operation, the LAC team confirmed that the triggering system functioned correctly and detected several cosmic rays (Takahashi et al., 2018). After three years, LAC operated for a total of 16.8 hours, covering an area-time product of $\sim 82 \times 10^6$ km^2-hr, without any detections of a flash attributable to lightning or meteors (Lorenz et al. 2019). By late 2020, LAC accumulated an area-time product of $>100 \times 10^6$ km^2-hr and detected a single optical flash that lasted ~100 ms with a total optical energy near 777 nm of $E_{OI} \sim 1.1 \times 10^7$ J (Takahashi et al., 2021), which is several times brighter than the detection limit of $E_{OI} \sim 5 \times 10^5$ J to 2×10^6 J (Takahashi et al., 2018). As of late 2022, LAC reached an area-time product of at least $\sim 200 \times 10^6$ km^2-hr without any additional detections of lightning-like flashes, as shown in Table 1 (Lorenz et al., 2022).

In the early 1990s, a ground-based telescope observed several candidate flashes at Venus. That search used a 1.5-m telescope on Mt. Bigelow, Arizona to image the night side of Venus with a sampling rate of 18.8 Hz over several nights. The instrument used a narrowband filter centered at 777.4 nm, with a bandwidth of 0.7 nm (Hansell et al., 1995). Overall, this survey detected seven flashes, each in a single frame of the imaging sequence collected in ~53 ms. Takahashi et al. (2018) argued that using only one frame per flash admits the possibility that cosmic rays or unknown electrical noise could have produced some flashes. Table 2 of Hansell et al. (1995) reports the "associated optical energy" for each flash, which equals 2.5 times the optical energy measured near 777 nm. This factor of 2.5 (=1/0.4) was inserted based on the assumption that Venusian lightning would emit ~40% of its total optical energy near 777 nm (e.g., Borucki et al., 1981). Therefore, associated optical energies of $\sim 0.1\text{–}2.1 \times 10^9$ J are equivalent to $E_{OI} \sim 4\text{–}84 \times 10^7$ J near 777 nm. Hansell et al. (1995) inferred a detection limit of

E_{OI} ~0.6–2.5 × 10^6 J for 50–95% detections. Overall, the area-time product from this ground-based survey reached at least ~800 × 10^6 km^2-hr (Hansell et al., 1995), counting additional nights of non-detections by that group that were not published (Lorenz et al., 2019). Other groups may have conducted similar searches using ground-based telescopes with no detections (Yair et al., 2012), but those efforts have not been published or included in Table 1.

Three other attempts to observe optical flashes at Venus were less successful. The Pioneer Venus Star Tracker (Borucki et al., 1991) and Venus Express VIRTIS (Moinelo et al., 2016) accumulated area-time products of ~10^5 and 14 × 10^6 km^2-hr, respectively, with no detections. The Venera 9/10 Orbiter Spectrometer recorded a burst of light lasting ~70 s, almost immediately after it began observations (Krasnopolsky, 1979; 1983). Some authors attribute this observation to lightning (e.g., Hart et al., 2022), while others argue that instrument anomalies or even spacecraft debris are a more likely explanation (e.g., Lorenz, 2018; Lorenz et al., 2019). The total area-time product associated with Venera 9/10 was relatively tiny, only ~2.5 × 10^3 km^2-hr (Lorenz et al., 2019). Ultimately, we might not be surprised that the two surveys with by far the largest coverage are the ones that yielded the most reliable detections.

Table 1. Two surveys produced relatively reliable detections of optical flashes in the atmosphere of Venus. Three other surveys, which had much lower coverage, did not return any uncontested detections.

Search	Coverage (10^6 km^2-hr)	Number of lightning-esque flashes	Equivalent global, yearly rate (95% confidence intervals)	Detection threshold (J)	Energy of the dimmest flash near 777 nm (J)
Mt. Bigelow	800	7	35423 (17476, 66808)	2.5 × 10^6 (95%) 0.6 × 10^6 (50%)	2.8 × 10^7
Akatsuki	200	1	20241 (4902, 112770)	0.5–2 × 10^6	1.1 × 10^7
Venera 9/10 Orbiter Spectrometer	0.0025	0	0 (< 5 × 10^9)	3 × 10^7	-
Venus Express VIRTIS	14	0	0 (< 9 × 10^5)	Unknown	-
Pioneer Venus Star Tracker	0.1	0	0 (< 10^8)	2 × 10^8	-

To compare with the power laws derived in the next subsection, we need to translate these observations into statistical constraints on the global rate of flashes at Venus. Say that a survey observes a given area (A_S) for a given time (T_S). Its area-time product is $A_S T_S$. If N is the total number of bright flashes (i.e., with optical energies above a certain detection limit) across Venus during one Earth-year, then the expected number of flashes observed by that survey is

$$\lambda_S = N\left(\frac{A_S}{A_V}\right)\left(\frac{T_S}{T_Y}\right), \tag{1}$$

where $A_V = 4.6 \times 10^8$ km^2 is the surface area of Venus and $T_Y = 8.8 \times 10^3$ hr is the duration of an Earth-year. We assume that Poisson statistics govern optical flashes (from lightning or meteors), meaning that the probability of observing an integer number of flashes (k) during a survey is

$$P(k \mid \lambda_S) = \frac{\lambda_S^k e^{-\lambda_S}}{k!}. \tag{2}$$

Here, we know that $k = 1$ and 7 for the Akatsuki and Mt. Bigelow surveys, respectively. We want to calculate the probability density function for λ_S and thus N according to both surveys. By Bayes' theorem, $P(\lambda_S \mid k) \propto P(k \mid \lambda_S)$. We then convert λ_S to N using Eq. 1 and renormalize the probability density function so it integrates to 1 from N equals zero to infinity.

Figure 1 shows our statistical constraints on the global, yearly rate of optical flashes at Venus. For surveys with $k = 0$, we can say that $\lambda_S \leq 3$ with 95% confidence. The upper limits on λ_S are thus ~9×10^5, ~10^8, and ~5×10^9, respectively, from the non-detections by Venus Express VIRTIS, the Pioneer Venus Star Tracker, and the Venera 9/10 Orbiter Spectrometer (assuming Venera 9/10 saw only spacecraft debris or an instrument anomaly). For surveys with more reliable detections of optical flashes ($k \geq 1$), the most likely value of λ_S is simply k. Using Eq. 1, the most likely values of N are 20241 and 35423 for Akatsuki and Mt. Bigelow, respectively. With Eq. 2, we calculated the 95% ("two-sigma") confidence intervals associated with each survey: (4902, 112770) for Akatsuki and (17476, 66808) for Mt. Bigelow. The 68.3% ("one-sigma") confidence intervals are (14325, 66808) and (14325, 54509), respectively. These surveys are both consistent with a global flash rate of $N \sim 10^4$–10^5 per Earth-year. However, we report these estimates separately because each survey may have a different (albeit similar) detection limit.

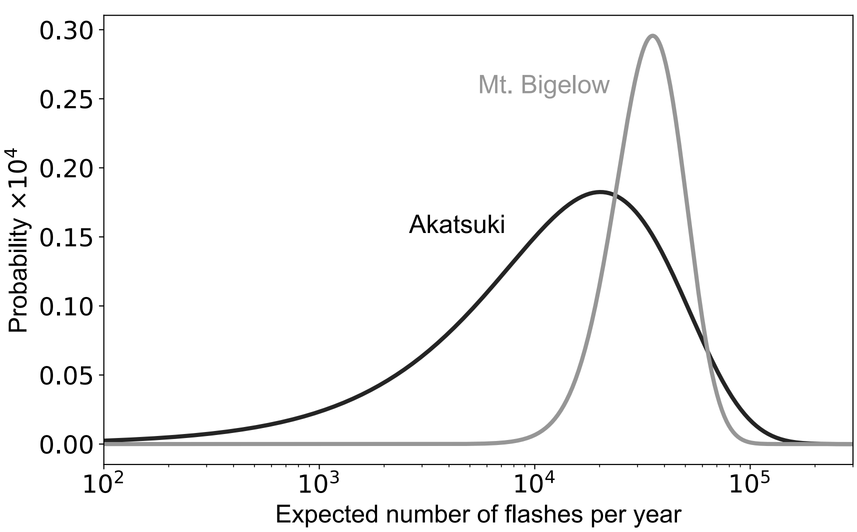

Figure 1. Probability density functions for the global, yearly rate of bright flashes at Venus (i.e., the expected number across the entire planet in one Earth-year with optical energies above the

detection limit of each instrument), estimated from the coverage and detections in surveys from Akatsuki and Mt. Bigelow.

2.2 Impactor production functions and luminous efficiency

To quantify the number of bolides that enter Venus's atmosphere in one Earth-year, we turned to existing studies of meteors at Earth (**Figure 2**). Le Feuvre & Wieczorek (2011) developed a 10^{th}-order power law to describe impactor flux at Venus over a wide range of bolide diameters (Figure 2a). However, our study requires only a log-linear power law, for simplicity, to describe the flux of small impactors at Venus. We thus start with power laws developed by Brown et al. (2002), which were the basis for the low-mass end of the expression derived in Le Feuvre & Wieczorek (2011). Based on the observations described in Section 2.1, we are interested in meteors that could produce flashes with optical energies ~10^7 J. As discussed below, the kinetic energy of those meteors should be at least an order of magnitude higher (~10^8 J). Depending on the impact velocity, the masses of meteors potentially relevant to the detected optical flashes are thus roughly ~0.1–1 kg.

We start with an established relationship between the frequency and kinetic energy of small bolides that collide with Earth (Brown et al., 2002):

$$\log_{10} N_E = 11.93 - 0.90 \log_{10} E_K\,, \tag{3}$$

where N_E is the cumulative number of bolides that strike Earth in one Earth-year with a kinetic energy of at least E_K (in Joules). This equation is the same as Eq. 2 by Brown et al. (2002), who expressed E_K in units of kiloton-TNT equivalent.

Next, we write the equivalent equation for Venus. On average, bolides strike Venus with faster velocities and thus higher kinetic energies. Le Feuvre & Wieczorek (2011) found that the average impact velocity at Venus is 25.0 km/s, whereas the average velocity for Earth is 20.3 km/s (Brown et al., 2002). From Table 3 in Le Feuvre & Wieczorek (2011), the impact rate at Venus per unit area is higher by a factor of 1.75/1.58 = 1.11 than the impact rate at Earth. However, Venus also has less surface area than Earth, by a factor of $(6052/6371)^2 = 0.902$. Overall, we can combine these factors to write the power law for the bolide flux at Venus:

$$\log_{10} N = 12.09 - 0.90 \log_{10} E_K\,, \tag{4}$$

where N is now the cumulative number of bolides that strike Venus in one Earth-year with kinetic energies of at least E_K (in Joules).

When a meteor ablates in a planet's atmosphere, only a fraction of the total kinetic energy is converted to optical energy. We can relate kinetic and optical energy with $E_O = \tau\, E_K$, where τ is the luminous efficiency of the bolide. For meteors with mass m up to a few kg and entry velocities $v < 25.372$ km/s, τ may obey the following equation (e.g., Popova et al. 2005):

$$\ln\tau = 0.567 - 10.307\ln v + 9.781(\ln v)^2 - 3.0414\,(\ln v)^3 + 0.3213(\ln v)^4 + 0.347\tanh(0.38\ln m)\,. \tag{5}$$

We defined v as the average entry velocity (25 km/s) for meteors ranging in mass from 10^{-1} to 10^2 kg. We then found the best-fit power law that relates τ (dimensionless) and E_O (J), following Brown et al. (2002):

$$\tau = 0.01442\,E_O^{0.0846}, \tag{6}$$

which predicts luminous efficiencies from ~0.05–0.08 over this size range (Figure 2c). By incorporating Eqn. (6) into Eqn. (4), we then find that

$$log_{10}N = 10.43 - 0.82\ log_{10}E_O. \tag{7}$$

However, not all the optical energy is emitted near 777 nm, to which Akatsuki's LAC filter and the search for flashes at Mt. Bigelow were restricted. Only a small fraction of the total optical energy is due to the excited oxygen triplet:

$$E_{OI} = f_{OI}E_O, \tag{8}$$

where $0 < f_{OI} < 1$. In terms of E_{OI}, the power law for the rate of meteor fireballs at Venus is:

$$log_{10}N - 10.43 - 0.82log_{10}\frac{E_{OI}}{f_{OI}}. \tag{9}$$

The factor f_{OI} is uncertain and variable for meteor fireballs at Earth (e.g., Vojáček et al., 2022). The uncertainty is even greater for meteors at Venus, but we expect relatively high values of f_{OI} because of the relative abundance of oxygen atoms in carbon dioxide. If we assume a certain value of f_{OI}, then we can estimate the rate of meteor fireballs with different brightnesses at Venus—and thus if the observed flashes plausibly originated from meteors, not lightning.

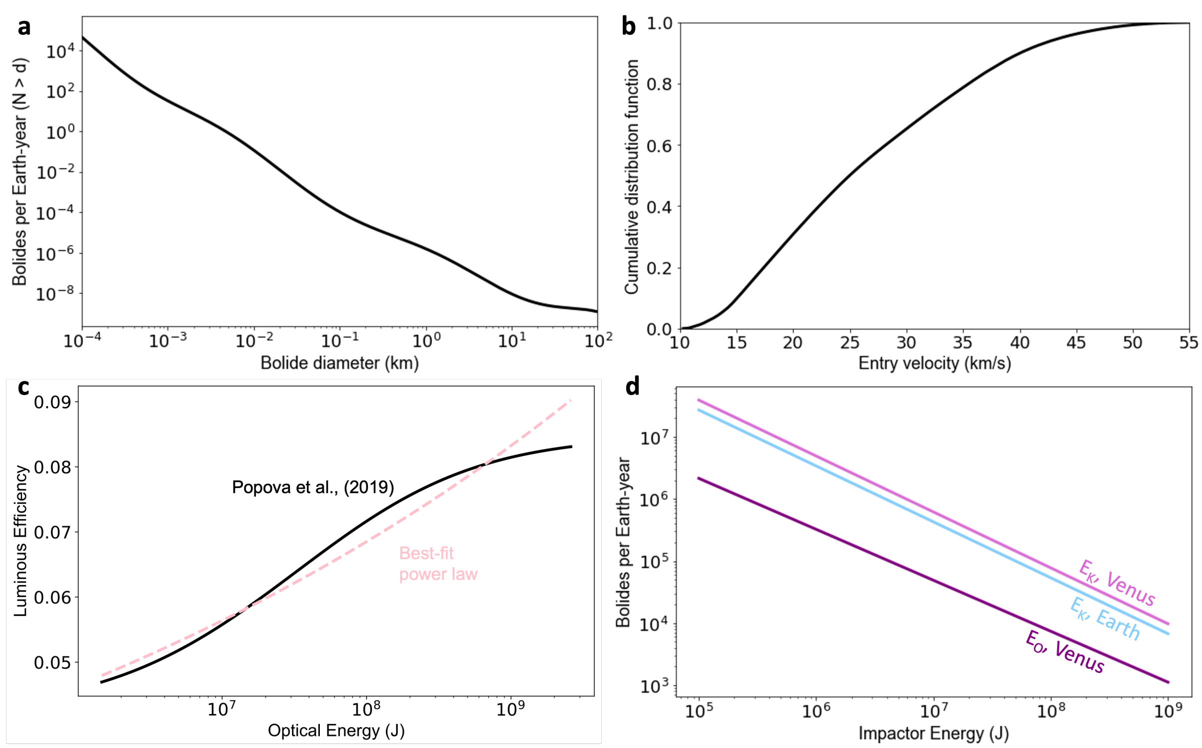

Figure 2. The number, velocity, and energy of bolides colliding with Venus can be modeled from previous work. In **(a)** we plot the number of bolides above a certain diameter colliding with Venus per Earth-year (e.g., Le Feuvre & Wieczorak, 2011). In **(b)** is the cumulative distribution function for bolide entry velocity. The average entry velocity for meteors at Venus is 25 km/s. In **(c)** we plot the best-fit power law for the luminous efficiency of meteors that we found using equations from Popova et al. (2005). Luminous efficiency—the amount of kinetic energy converted to optical energy—increases as entry mass and entry velocity increase. In **(d)** we plot

the number of bolides with a certain energy colliding with Earth and Venus per Earth-year. Impactors at Venus have higher kinetic energy due to their higher average entry velocity. E_O is the optical energy emitted per bolide; only a fraction of kinetic energy is converted to optical energy during ablation, as defined by the luminous efficiency in **(c)**.

2.3 Experimental simulations of meteor plasma

No one has yet measured the emission spectrum of a meteor fireball at Venus. In the absence of direct observations, we can turn to laboratory experiments for hints about what fraction of the total optical energy might be emitted near 777 nm. Many groups have used laser-induced breakdown spectroscopy (LIBS) to simulate a meteor fireball (e.g., Krivkova et al., 2021; Ferus et al., 2018; Dell'Aglio et al., 2010). A high-power laser can ablate a meteorite in a similar fashion to meteor ablation during high-speed collisions with atmospheric molecules. Experimental studies relevant to terrestrial meteors typically conduct LIBS experiments on meteorites in a vacuum or under ambient atmospheric conditions. However, for application to Venus meteors, we would prefer to invoke LIBS experiments conducted on rock and mineral samples surrounded by (predominantly) carbon dioxide at a pressure of a few mbar. Coincidentally, air at the surface of Mars has approximately the same composition and pressure as air at an altitude of ~100 km above the surface of Venus.

Because of this similarity, we utilized results from the LIBS experiments that were conducted to calibrate the ChemCam instrument package on the Mars rover Curiosity (Wiens et al., 2013). We used data from the Los Alamos National Laboratory ChemCam experiments, where samples were measured in 5 locations. For each sample, 50 laser pulses were taken at each location and averaged together. After the data were collected, the spectra were cleaned and calibrated. We used the cleaned and calibrated dataset to estimate the fraction of optical energy near 777 nm. We analyzed 5 different samples to determine an average fraction of optical energy. Olivine ($[Fe,Mg]_2SiO_4$) and pyroxene ($[Fe,Mg]SiO_3$) are common in stony meteorities as chondrules. We also analyzed spectra from samples of diopside ($CaMgSi_2O_6$), llanite (a rhyolite), and basalt. Diopside and llanite provided comparative results despite not being as common in meteorites as the other materials. The calibration samples did not include water ice, but we expect that a comet's fireball would produce even more OI emission than a rocky meteor. To calculate f_{OI} for each mineral or rock, we calculated the area under the spectral curve for the entire spectrum from 350–800 nm, as well as the area within the OI peak from 771–800 nm. We then divided the area under the OI peak by the total area of the spectrum, producing f_{OI}.

3 Results

3.1 Meteor fireballs are not (always) blackbodies

Many studies assume that ablating meteors in Venus's atmosphere would emit as blackbodies (e.g., Takahashi et al. 2021). If a meteor ablating at ~6000 K emitted as a blackbody, then only a very small amount of the total optical energy (<1%) would be contained in the excited oxygen line at ~777 nm or in the bandpass of the instruments designed to detect this line. The small amount of observed energy would require a very large, and thus very infrequent, meteor to cause the observed amount of optical energy. However, recent studies have shown that small meteors, such as the one observed by Madiedo et al. (2013) in the Geminid meteor shower on Earth, do not always emit as blackbodies (**Figure 3**). By calculating the area under the spectral curve, we determine that ~7% of the total optical energy produced by this meteor was contained in the excited atomic oxygen line.

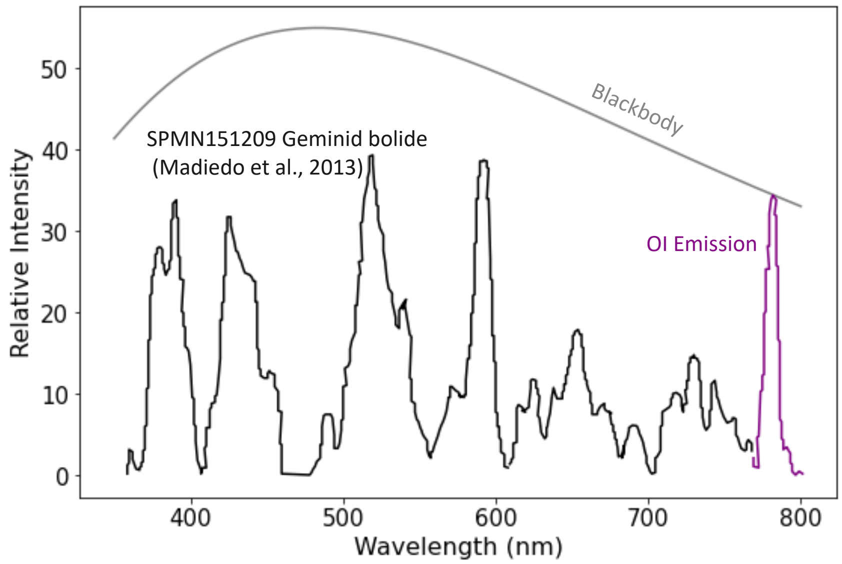

Figure 3. Two spectra with the same amount of optical energy near 777 nm, but very different amounts of total optical energy. A Geminid meteor produced a spectrum (black and purple) distinctly different than a blackbody curve (gray) for an effective ablation temperature of 6000 K. At Venus, due to the large relative abundance of oxygen, ~5–30% of a small meteor's optical emission may be contained in the OI triplet (purple).

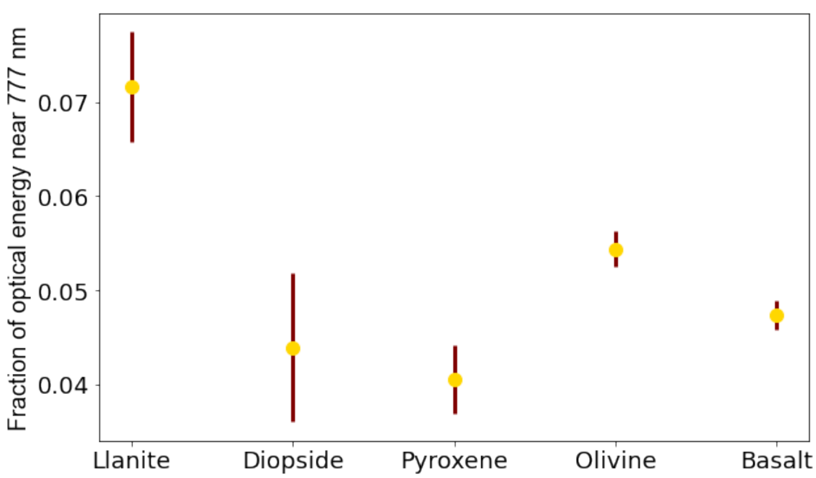

Figure 4. Fraction of total optical energy emitted in the 777 nm bandpass, based on inspection of LIBS spectra from the ChemCam calibration database, which provide a potential analogue for the emission spectra of meteors. Near the surface of Mars, the atmosphere is CO_2-dominated with pressures of a few millibars—exactly the conditions at altitudes near ~100 km in the atmosphere of Venus where small meteors burn up. We find that ~4–7% of the total optical energy contained in these spectra is typically emitted near 777 nm. For minerals and rock types that are common in meteors, as well as the more silicic llanite, this plot shows the mean (gold) and standard deviation (maroon) of that fraction for 5 samples in the database.

We used LIBS data from the calibration of Curiosity's ChemCam instrument to estimate meteoritic emission in the OI emission line for ablating bolides at Venus. To better constrain the amount of energy in the excited oxygen triplet for different materials, we analyzed common meteoritic materials for the fraction of optical energy contained around 777 nm (**Figure 4)**. We found that, for common meteoritic materials such as olivine, pyroxene, and basalt, the value of f_{OI} ranges from ~0.04–0.07 (Figure 4). Based on these laboratory experiments and the observations of some terrestrial meteors, we thus expect that fireballs from small meteors at Venus are an order-of-magnitude brighter than blackbodies near 777 nm. However, the emission spectrum of an individual meteor will depend on many factors, including its composition, mass, entry velocity, entry angle, and irregularities that cause it to fragment and/or spin as it ablates.

3.2 Meteor fireballs in surveys from Akatsuki and the Mt. Bigelow 61-in. telescope

Figure 5 plots the number of flashes per Earth-year expected for a certain amount of optical energy produced by the ablating bolide, based on the amount of optical energy contained in the OI filter centered near 777 nm (f_{OI}). For higher values of f_{OI}, we expect to see more flashes of a given brightness in one Earth-year. As detailed above, a meteor fireball that emits as a blackbody should have f_{OI} ~0.007. Observations of terrestrial fireballs and LIBS experiments suggest that f_{OI} ~0.05–0.10 is more realistic for small meteors. We estimate that an upper limit for f_{OI} is ~0.3, perhaps for a comet that hit Venus at high velocities. We compare these expectations to the flash rates inferred from the two surveys with relatively reliable detections.

The one optical flash detected by Akatsuki's LAC (so far) had a brightness that is consistent with a meteor fireball. That is, if f_{OI} ~0.07, then we expect to witness the same number of flashes in one Earth-year from these meteors as the expected number from Akatsuki's estimated global flash rate. However, this result is somewhat conditional on the true detection limit for Akatsuki's LAC. Even if LAC's detection limit is higher than claimed by Takahashi et al. (2018) (i.e., equal to the flash brightness in the worst case), a meteor is still statistically probable within the 95% confidence intervals for $f_{OI} > 0.10$. However, Takahashi et al. (2018) also claimed that the detection limit for Akatsuki's LAC is perhaps as low as $E_{OI} \sim 5 \times 10^5$ J, or even lower. In that case, observing at least one flash from a meteor fireball is not surprising.

Meteor fireballs are perhaps also bright and frequent enough to explain the observations from the Mt. Bigelow 61-in. telescope. If the dimmest observed flash were observed at exactly the detection limit of that survey, then we would only predict the observation of seven meteor fireballs if ~30% of the total optical energy were concentrated in the OI filter. However, Hansell et al. (1995) estimated that their detection limit was much lower, which is also consistent with f_{OI} ~0.05–0.10, exactly what we expect for fireballs at Venus. Yair et al. (2012) also conveyed a personal communication about "repeated attempts by large-mirror ground telescopes to repeat the Hansell et al. (1995) observations," which apparently have not yielded any additional detections. If the effective area-time product for ground-based surveys is higher than Table 1 indicates, then the extrapolated number of flashes per Earth-year would decrease—and thus agree even better with the predicted rate of meteor fireballs at Venus. Finally, recent papers noted that the observations at Mt. Bigelow were not conducted at a high enough sampling rate to take more than one image per flash, leaving some ambiguity about whether a cosmic ray or electrical noise produced one or more of the flashes (e.g., Takahashi et al. 2018). If one or two of the claimed flashes did not originate from Venus, then the observed rate would agree perfectly with what we predict for meteor fireballs and with the current results from Akatsuki. Using Eq. 1

and 2, we calculate that the upper limit on the global, yearly rate of lightning in the clouds is $N \leq 11975$ ($< 4 \times 10^{-4}$ Hz), with 95% confidence—if none of the observed flashes originate from lightning.

Our study focuses on reproducing the hypothesized lightning flash rates at Venus with an alternative source of optical energy in the form of ablating meteors tens of km above the cloud layer. However, the shapes of any observed light curves would provide additional constraints. The shape of the light curve observed by Akatsuki was positively skewed (e.g., Takahashi et al. 2021), which the team argued as most consistent with lightning. Models predict a negatively skewed light curve from the ablation of a spherical meteor that does not fragment. However, ablating meteors probably are non-spherical and also fragment and spin as they descend through the atmosphere, making it difficult to predict the shape of an individual bolide-produced light curve. We did not construct any models for the light curves of meteors at Venus—but such efforts will only become more important as the number of time-resolved observations increases. Preliminary work suggests that Venusian meteors are indeed brighter than terrestrial meteors (e.g., McAuliffe & Christou, 2006; Christou & Gritsevich, 2023).

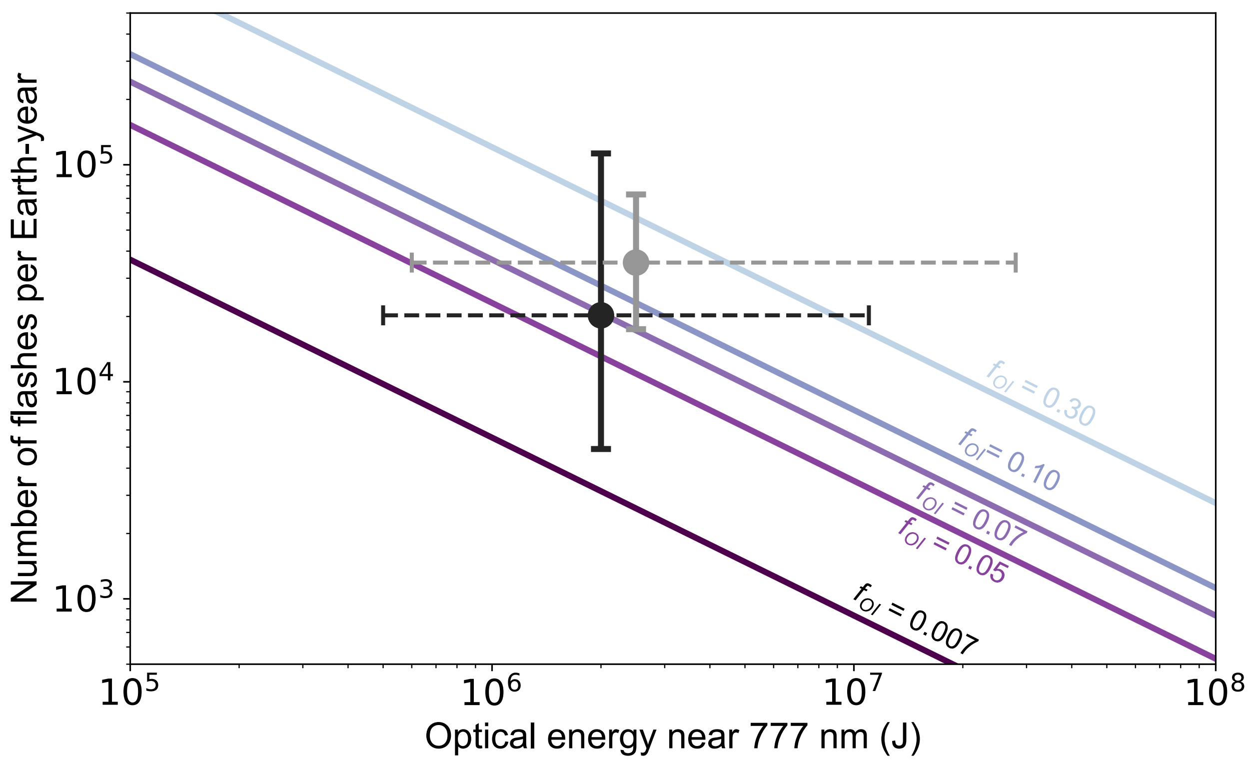

Figure 5. Estimate of the expected number of optical flashes at Venus in one Earth-year (N) that would release at least a certain amount of energy near 777 nm (E_{OI}). The black and grey circles show the global rates inferred from Akatsuki and Mt. Bigelow, respectively. The vertical bars denote the 95% confidence intervals on the global rate. The horizontal, dashed bars reflect uncertainty about the detection limits of both surveys. On the right, the dashed bars extend to the optical energy near 777 nm from the dimest flash that each survey detected, which is the highest possible detection limit. The circles are centered at the claimed detection limits for Akatsuki (e.g., Takahashi et al., 2018) and the Mt. Bigelow survey (Hansell et al., 1995). On the left, the dashed bars extend to the lowest plausible values of the detection limit claimed for each survey.

4 Discussion

4.1 Sub-cloud lightning is possible

Regardless of whether lightning exists high in Venus's atmosphere, lightning could occur close to the surface from either volcanic or aeolian processes (**Figure 6**). On Earth, volcanic lightning often occurs in the ash plume associated with an explosive eruption. The particles in the plume can become charged through several mechanisms, but fracto-electrification and tribo-electrification are considered the most important because they are closely related to explosive eruption dynamics (e.g., Cimarelli & Genareau, 2022). Material is fractured into ash-sized particles during an explosive eruption, which can release electrons and positive ions and charge the fragmented particles themselves (fracto-electrification). Ash particles of various compositions within the plume will then collide with each other, charging the particles through friction (tribo-electrification) (e.g., Cimarelli & Genareau, 2022). At the surface, winds carrying small particles can also create charges through tribo-electrification. This process could be a common phenomenon on Venus because wind speeds are close to the transport threshold (e.g., Lorenz, 2018). The Venera landers observed the movement of surface material, which implies that wind may be capable of charging particles on Venus's surface (e.g., Lorenz, 2018).

Previous studies disregarded volcanic lightning on Venus as impossible due to the supposed lack of explosive volcanism. Borucki (1982) argued that if volcanism caused the then-claimed observation of 30 lightning flashes in 3 years by the Pioneer Venus Orbiter, there would have been 10 eruptions per year. If explosive volcanism were occurring at this rate, then it would release particles into the atmosphere that could be detected. However, the cloud-particle-size spectrometer on Pioneer Venus did not detect particles of the size expected to result from explosive volcanism. Borucki (1982) therefore concluded that, even if Venus were volcanically active, explosive volcanism was not common and thus not a probable source of lightning. They also argued that lightning would have to occur in the clouds because the lower atmosphere would absorb energy at the wavelengths produced by lightning (e.g., Borucki, 1982). However, those specific detections are now attributed to cosmic rays (e.g., Lorenz, 2018). The electromagnetic observations that yield the highest inferred rates of lightning only constrain the source of those signals to below the ionosphere—compatible with a near-surface origin.

New evidence of explosive volcanism on Venus has recently emerged. For example, Ganesh et al. (2021) modeled the formation of several proposed pyroclastic deposits on Venus. These pyroclastic flows would have formed through the collapse of ash plumes created during explosive eruptions. Their models of collapsing plumes provided good matches to deposits at several locations on Venus hypothesized to be associated with explosive volcanism. Recently, a volcano that changed shape over the course of eight months during the Magellan mission was identified (e.g., Herrick & Hensley, 2023). This is evidence of active volcanism on Venus in recent years, which further supports the position that the possibility of volcanic lightning should not be disregarded. Of course, new observations from future geophysical orbiters such as VERITAS and EnVision are needed to unveil the volcanic history of Venus.

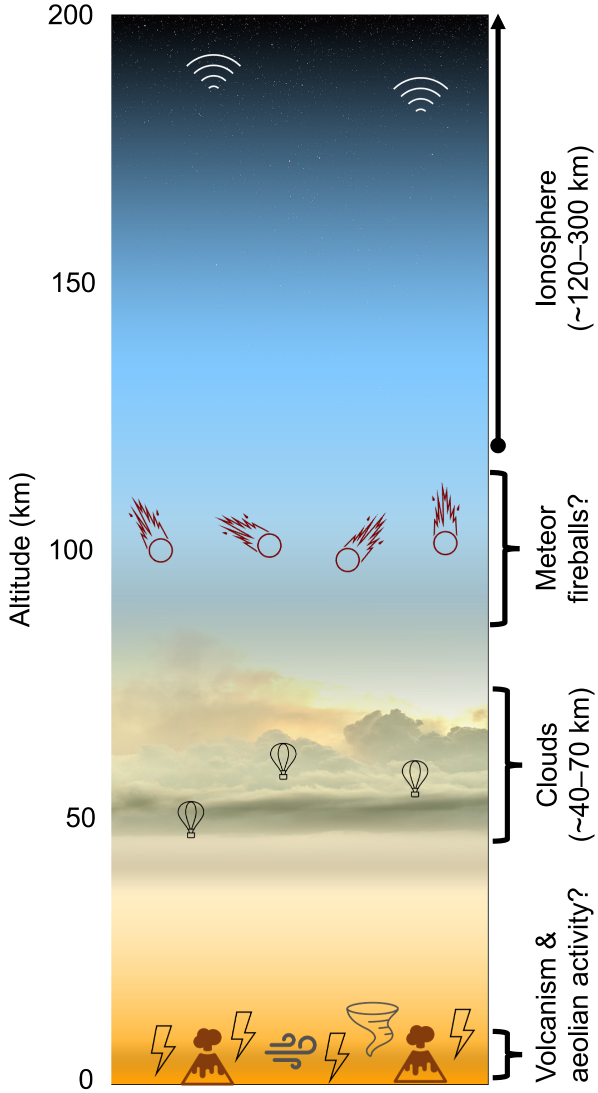

Figure 6. A cartoon of possible phenomena in Venus's atmosphere. Small meteors may burn up far above the clouds, while near-surface lightning could generate the putative whistler-mode waves from far below the clouds. Adapted from Figure 6 in O'Rourke et al. (2023).

4.2 Lightning is not a hazard to missions in the clouds

Many missions to Venus passed through its clouds. No mission has, to our knowledge, been struck by lightning, but lightning nonetheless poses a potential risk to any mission. Starting with Venera 7, ~14 probes have delivered data from below the clouds (e.g., Taylor et al., 2018). Two balloons floated at an equilibrium altitude of ~53 km as part of the Soviet VeGa mission, reporting data for ~47 hours before running out of battery power (e.g., Sagdeev et al., 1986; Moroz, 1987; Crisp et al., 1990). Given these past experiences, lightning is not an obvious hazard to atmospheric probes or short-lived balloons. However, future missions may include extended stays in the clouds to answer high-priority scientific questions (e.g., O'Rourke et al., 2021; Arredondo et al., 2022; Cutts et al., 2022). For example, Phantom is an exciting, well-developed concept that features an aerial platform that dwells in the clouds for at least ~30 Earth-days, and plausibly ~100 Earth-days or longer (e.g., Byrne et al., 2023). Scientists have also proposed sending flotillas of long-lived balloons to search for active biology (Hein et al., 2020) or seismic and volcanic activity (Krishnamoorthy & Bowman, 2023; Rossi et al., 2023). Is lightning a threat to long-duration missions in the clouds of Venus?

We can use simple statistics to estimate the hazard from lightning to various types of missions. Say that T_M is the duration of the mission (in seconds); Γ_L is the overall rate of lightning in the clouds (in strikes per second); and R_H is the radius within which a lightning strike is potentially hazardous (in meters). The estimated number of lightning strikes within the hazardous radius during the mission is then

$$\lambda_L = T_M \Gamma_L \left(\frac{R_H}{2R_V}\right)^2, \qquad (10)$$

where R_V = 6052 km is the radius of Venus, assuming that $R_H << R_V$. If lightning strikes happen without spatial bias but with timing that obeys Poisson statistics, then we can calculate the probability that a hazardous strike will occur near the mission:

$$P_H = 1 - e^{-\lambda_L}. \qquad (11)$$

Mission designers often consider a hazard with a probability of $P_H < 10^{-6}$ to be negligible. We considered three possible rates of lightning in the clouds. Overall, our study is compatible with the hypothesis that cloud-based lightning is vanishingly rare ($\Gamma_L \leq 10^{-9}$ Hz). If the optical flashes observed by Akatsuki and ground-based telescopes originated from cloud-based lightning, then $\Gamma_L \sim 1.2 \times 10^{-4}$ Hz (Lorenz et al., 2022). If the claimed whistler-mode waves were attributed to cloud-based lightning, then we fear that $\Gamma_L \sim 320$ Hz (Hart et al., 2022). Of course, as on Earth, we would expect to find lightning on Venus concentrated in particular regions at any given time. However, we can use the assumption of global homogeneity to estimate relative hazards. If lightning were ubiquitous in the clouds, then requiring a mission to survive a strike could seem prudent. However, no caution is necessary if there is no (or very rare) lightning.

Figure 7 shows the probability of a hazardous lightning encounter for four classes of missions. First, probes can pass quickly through the clouds. For example, the DAVINCI mission notionally plans to descend from ~70–40 km in ~34 minutes between the deployment and release of its parachute (Garvin et al., 2022). If lightning were indeed ≥ 7 times as common on Venus as Earth (Hart et al., 2022), then we might expect ~40 strikes within ~100 km of DAVINCI (and all past probes). However, the expected number of strikes near a probe is < 1 using the flash rate inferred from Akatsuki's search. Second, the VeGa mission was the archetype of a short-lived balloon, operating for ~47 hours. Again, the flash rate inferred from Akatsuki is compatible with the non-detection of lightning (i.e., $\lambda_L \sim 10^{-3}$ for $R_H \sim 100$ km). Third, we assume that a long-lived balloon has a lifetime of ~30 Earth-days. The chances of a nearby strike ($R_H < 100$ km) are then only 1-in-50, according to the optical flash rate from Akatsuki. This contrasts with the analysis in Hart et al. (2022), which implies that such a mission could operate in the vicinity of >50,000 strikes. Finally, we imagined a flotilla of 10 balloons that each have lifetimes of ~100 Earth-days. Using the flash rate from Akatsuki, it is more likely than not that at least one of those balloons encountering a strike within ~90 km. However, perhaps such a moderately distant strike would seem more exciting than dangerous. Ultimately, especially given the possibility that meteor fireballs produced all the optical flashes observed at a Venus, there is as of yet no affirmative evidence that lightning is common enough in the clouds to pose a hazard to even fleets of long-lived aerial platforms.

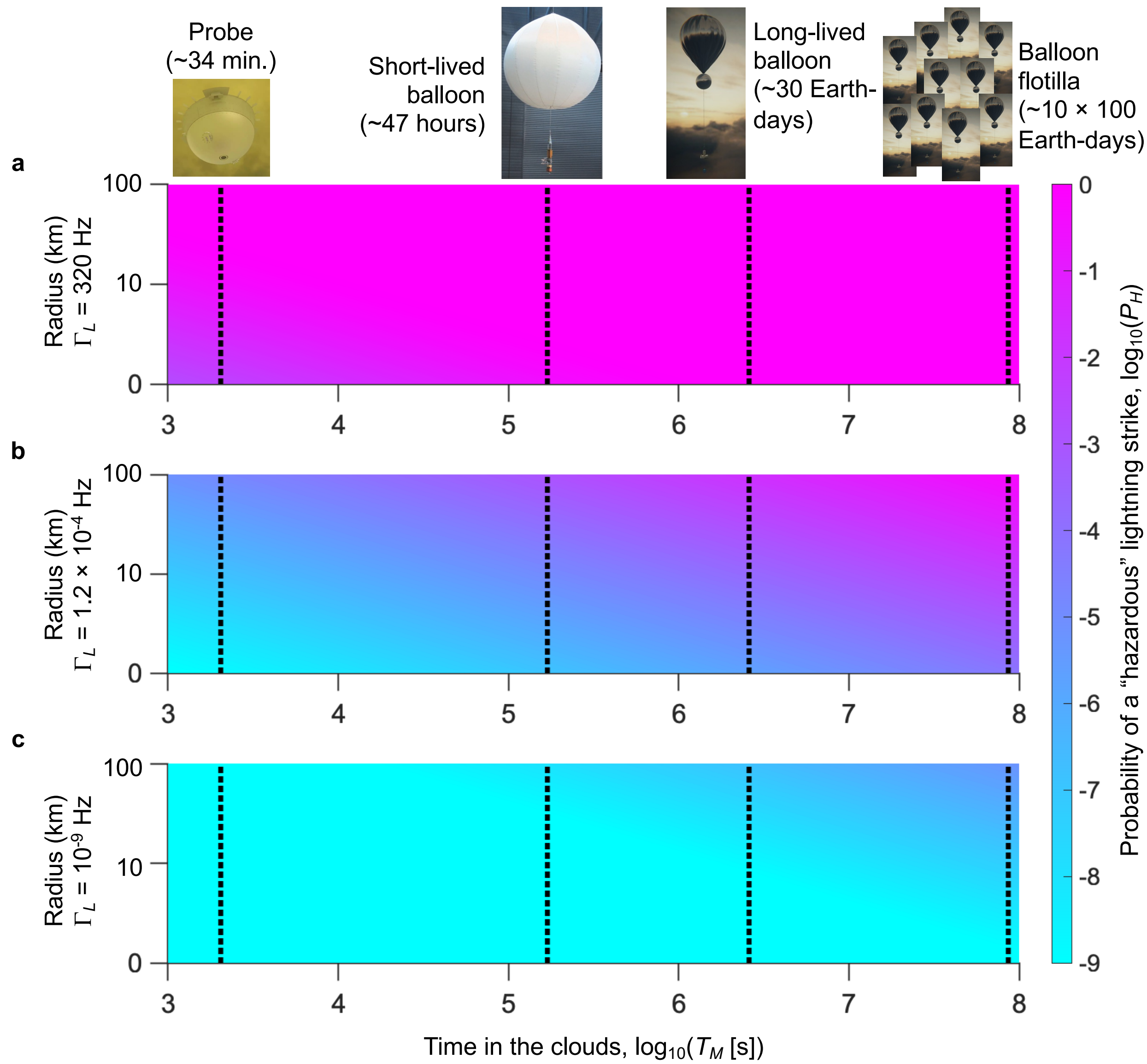

Figure 7. Relative risk of lightning to various mission architectures. Lightning is only a hazard to missions in the clouds if lightning exists in the clouds. We have calculated the probability that a lightning strike would occur within a certain horizontal distance (vertical axes) as a function of the total time that a mission spends within the clouds (horizontal axes). Although that time varies by five orders of magnitude for different types of missions, estimates for the rate of lightning in the clouds span ~10 orders of magnitude. In (**a**) we use the rate of lightning inferred from studies of putative whistler-mode waves (Hart et al., 2022). In (**b**) we use the global rate derived from Akatsuki's observation of a single flash so far, assuming that flash originated from lightning (Lorenz et al., 2022). In (**c**) we use the highest rate that implies that even a balloon flotilla experiences a negligible risk ($P_H < 10^{-6}$) from lightning, which agrees with the hypothesis that no flashes from lightning have ever been seen at Venus.

4.3 The search must go on

In our work we have developed a production function for meteor fireballs in the atmosphere of Venus, which should be revisited as flash rates become better determined by future observations. While we found that small meteors ablating high (~100 km) in the atmosphere are plausible explanations for the observed optical flashes, more optical flash observations would serve to sharpen our statistics and provide tighter quantifications of flash rates. Spectrally resolving optical flashes at Venus could verify our study's estimate that meteor fireballs at Venus have strong emission near 777 nm. Additionally, determining the altitude of recorded optical flashes would allow us to conclude whether they originated above or within the cloud layer, providing more evidence of their source. Meteor fireballs and sprites would occur tens of kilometers above the clouds. Only a very rare, huge meteor would reach the clouds.

The "gold standard" approach to lightning detection would be simultaneous optical and radio observations (e.g., Aplin & Fischer, 2017; Cartier, 2020). Lightning above the lower cloud deck could produce an observable optical flash, whistlers at kHz frequencies, and sferics at MHz frequencies. In contrast, meteors would not produce strong radio emissions. Meteors themselves make important contributions to atmospheric chemistry (e.g., Pätzold, et al., 2009; Carrillo-Sánchez et al., 2020) and produce infrasonic signatures that aerial platforms could observe (e.g., Silber et al., 2018; 2023). Lightning below the clouds may produce radio emissions but not optical flashes visible from space. If the diagram of transient phenomena on Venus shown in Figure 6 were correct, then we would expect optical flashes consistent with the power laws derived in this study, plus non-simultaneous radio emission in the form of whistlers and sferics.

5 Conclusions

For decades, searches have been conducted for concrete proof of lightning in the atmosphere of Venus. Proving or disproving its existence would have vast implications for scientists' understanding of Venus's atmospheric chemistry, weather patterns, and even the potential for life in the clouds. Though multiple pieces of evidence such as whistler-mode waves and optical flashes have been put forward as proof of lightning, the presence of cloud-based lightning remains an open question. In this study, we have investigated whether small meteors may have produced optical flashes in the atmosphere of Venus that were interpreted as lightning. We calculated the rates of expected optical flashes from ablating bolides, and compared those to the rates inferred from optical surveys. We also calculated the risk posed to cloud-based missions considering the estimated lightning rates from these optical surveys. We find that based on observations of meteor fireballs at Earth, ablating fireballs at ~100 km altitude may be responsible for most, or even possibly all of the observed flashes. Lightning thus does not seem like a threat to missions that pass through (e.g., probes) or even linger within (e.g., aerial platforms) the clouds. Future optical surveys should find more meteor fireballs at rates and brightnesses that match our power laws. Simultaneous optical and radio measurements would help in the hunt for definitive evidence of lightning.

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Open Research

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