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REVIEW

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Lightning detection on Venus: a critical review

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Abstract

Claimed detections and nondetections of lightning and related electromagnetic emissions on Venus are qualitatively contradictory. Here, motivated by the commencement of observations by the Akatsuki spacecraft and by studies of future missions, we critically review spacecraft and ground-based observations of the past 40 years, in an attempt to reconcile the discordant reports with a minimal number of assumptions. These include invoking alternative interpretations of individual reports, guided by sensitivity thresholds, controls, and other objective benchmarks of observation integrity. The most compelling evidence is in fact the first, the very low frequency (VLF) radio emissions recorded beneath the clouds by all four of the Veneras 11–13 landers, and those data are re-examined closely, finding power-law amplitude characteristics and substantial differences between the different profiles. It is concluded that some kind of frequent electrical activity is supported by the preponderance of observations, but optical emissions are not consistent with terrestrial levels of activity. Venus' activity may, like Earth's, have strong temporal and/or spatial variability, which coupled with the relatively short accumulated observation time for optical measurements, can lead to qualitative discrepancies between observation reports. We note a number of previously unconsidered observations and outline some considerations for future observations.

Keywords: Venus, Lightning, Electromagnetic emission, Observation

Introduction

As our sister planet Venus attracts particular interest among solar system objects, it is further important to recognize that many Earth-sized planets now being detected around other stars are as likely to be "Venus-like" as they are "Earth-like." Lightning is an important process for several reasons (e.g. Rakov and Uman, 2003). First, it is a striking phenomenon in its own right. Second, it may serve as a diagnostic of other processes, such as volcanism or convection. Third, lightning may be important in atmospheric evolution and prebiotic evolution, notably in fixing nitrogen which is an essential element in living things but is generally chemically inaccessible. Finally, lightning may be a hazard for vehicles exploring a planetary atmosphere.

For these reasons, some effort has been devoted to detecting possible lightning on Venus, as indicated by the literature on the topic (Fig. 1)—major stimuli to the topic have been the Venera and Pioneer Venus results around 1980 and the Venus Express results since 2007. Several previous surveys have reviewed planetary lightning generally (Desch et al. 2003; Yair 2012; Aplin 2013; Aplin and Fischer 2017). Reviews of Venus lightning specifically include Williams et al. 1983, Russell 1991, and Hunten 1995, and the two notably comprehensive reviews in the Arizona Press "Venus" books now two decades old—Ksanfomality et al. 1983, Grebowsky et al. 1997. A comparatively recent Venus-specific review is given in Takahashi et al. (2008), who outlines the potential of new optical measurements on the Japanese Akatsuki Venus Climate Orbiter (Nakamura et al. 2007), which recently began operations at Venus after an extended journey (Nakamura et al. 2014). It may be noted that lightning has been repeatedly observed at Jupiter and Saturn and is not in dispute, and firm nondetections are established at Titan. At Venus, however, there are many superficially conflicting positive and negative reports. This review attempts to assess these reports critically, to develop scenarios that seem most probable in so far as they are consistent with the preponderance of observations.

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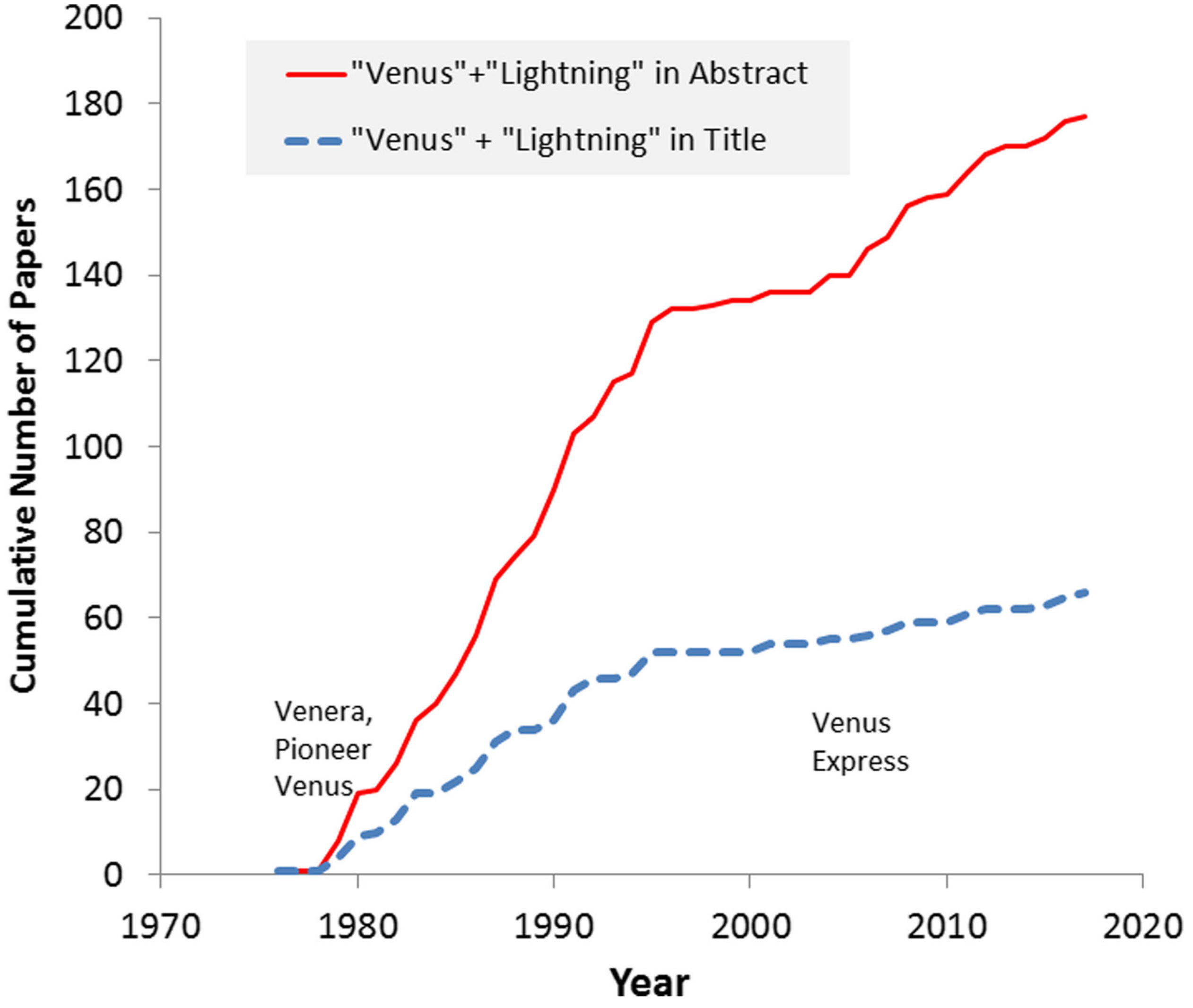

Fig. 1 The growing corpus of scientific literature on the topic (Smithsonian-ADS refereed paper search 9/28/2017). Search keywords "Venus" and "Lightning" were both required in the title or the abstract; the abstract search turns up more general papers as well as Venus-lightning-specific articles. The curves have a plateau in the 1995–2007 period as the Pioneer Venus interpretation debate fizzles out; the pace of papers increases a little after Venus Express data begin to emerge

Broadly speaking, evidence for or against lightning on Venus may be classified in four general categories, which are shown schematically in Fig. 2, against the profiles of electron density in the ionosphere and the temperature of the lower atmosphere. The main cloud layer lies between about 50 and 75 km altitude.

A key point in this review is that it is futile to reconcile observations of claimed flash rates (or nondetection) without considering the robustness of the measurement (e.g., the quantification of false detection rate), the significance of the measurement (the area and duration of the observations), and the sensitivity (the magnitude of lightning discharge that would be detectable). Measurement sensitivity must also take into account the transfer of information from where the electrical discharge occurs to the location of the measurement system: this propagation may be inefficient or even impossible (e.g., blue light from the lower atmosphere is absorbed before reaching space), or may be highly variable as in the case of whistler-mode plasma waves. This information propagation is summarized in Fig. 3.

In this connection, it is interesting to consider that the detection footprints of the various techniques may have a counterintuitive trend—that higher-altitude surveys may sample a smaller area. Specifically, the extremely low frequency (ELF) (~ 100 Hz) whistler-mode electromagnetic detections from orbit sample only an area connected to the spacecraft by appropriate ionospheric and magnetic field conditions and so may sense a range of only a couple of hundred kilometers from the subspacecraft

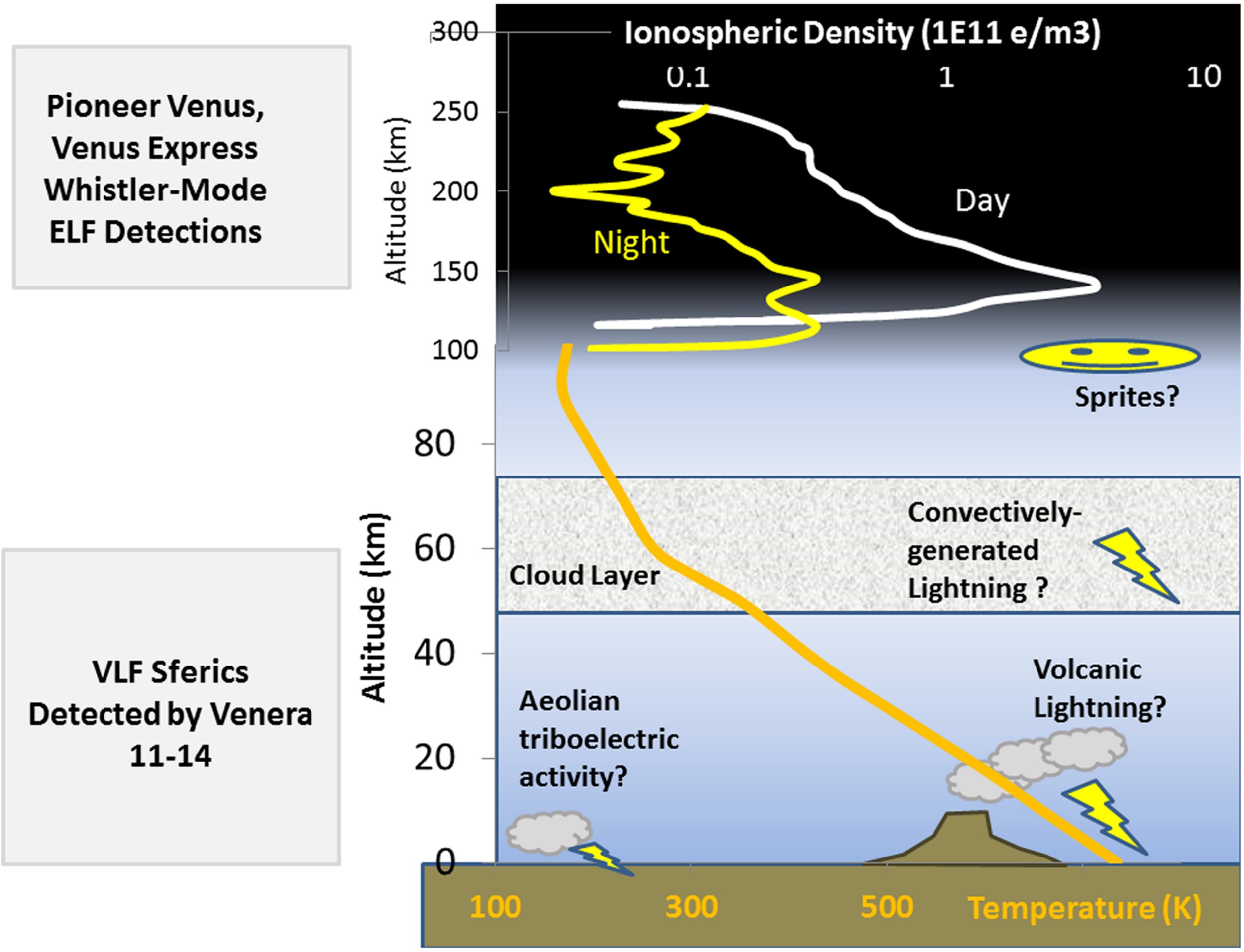

Fig. 2 Structure of the Venus atmosphere showing the ionosphere peaking between 100 and 150 km altitude (with daytime densities exceeding 10^5 cm^{-3}) and the temperature profile with the main cloud layer around 60 km altitude. Possible sites of electro-optical activity are noted—eolian and volcanic discharges near the surface, convective lightning in the cloud layer, and possible transient luminous events like sprites in the mesosphere. The corresponding altitudes of positive indications of lightning are noted at left

point. However, very low frequency (VLF) (10–80 kHz) measurements by descent probes at low altitude may detect discharges at ranges of thousands of kilometers, due to ducted propagation by super-refraction in the lower atmosphere (Croft 1983) and/or by "skybounce"—reflection from the ionosphere (e.g., Simões et al. 2008)—see also discussion in Ksanfomality et al. (1983). Similar VLF detectors are now used routinely by networks on Earth to map and track lightning activity over planetary-scale distances (see, e.g., Wood and Inan 2002 or the World-Wide Lightning Location Network WWLLN at https://webflash.ess.washington.edu).

A key challenge is in the interpretation of electrical or magnetic signatures claimed to be whistler-mode emissions from lightning discharges. For the Pioneer Venus electric field data at least, several alternative explanations were offered, and much of the 1980s literature is cluttered with this debate. In part, a difficulty is that such observations somewhat transcend scientific disciplinary boundaries—atmospheric scientists are generally unfamiliar with plasma physics, and it is difficult for nonpartisan observers to gauge the robustness of different interpretations. What is clear, however, as we discuss later, is that such electromagnetic signatures are observed fairly consistently, and that lightning discharges are one possible origin.

A further point centers on the definition of "lightning." It is only in the last couple of decades (long after the Venus lightning debate began in earnest with Pioneer Venus) that a fuller range of optical phenomena associated with atmospheric electrical discharges has been recognized on Earth, namely sprites, elves, blue jets, and other emissions. Given the different environment on Venus, it seems highly likely that not only are lightning bolts (if they occur in the conventional sense) possibly different in character, but these other types of luminous events may be present and have

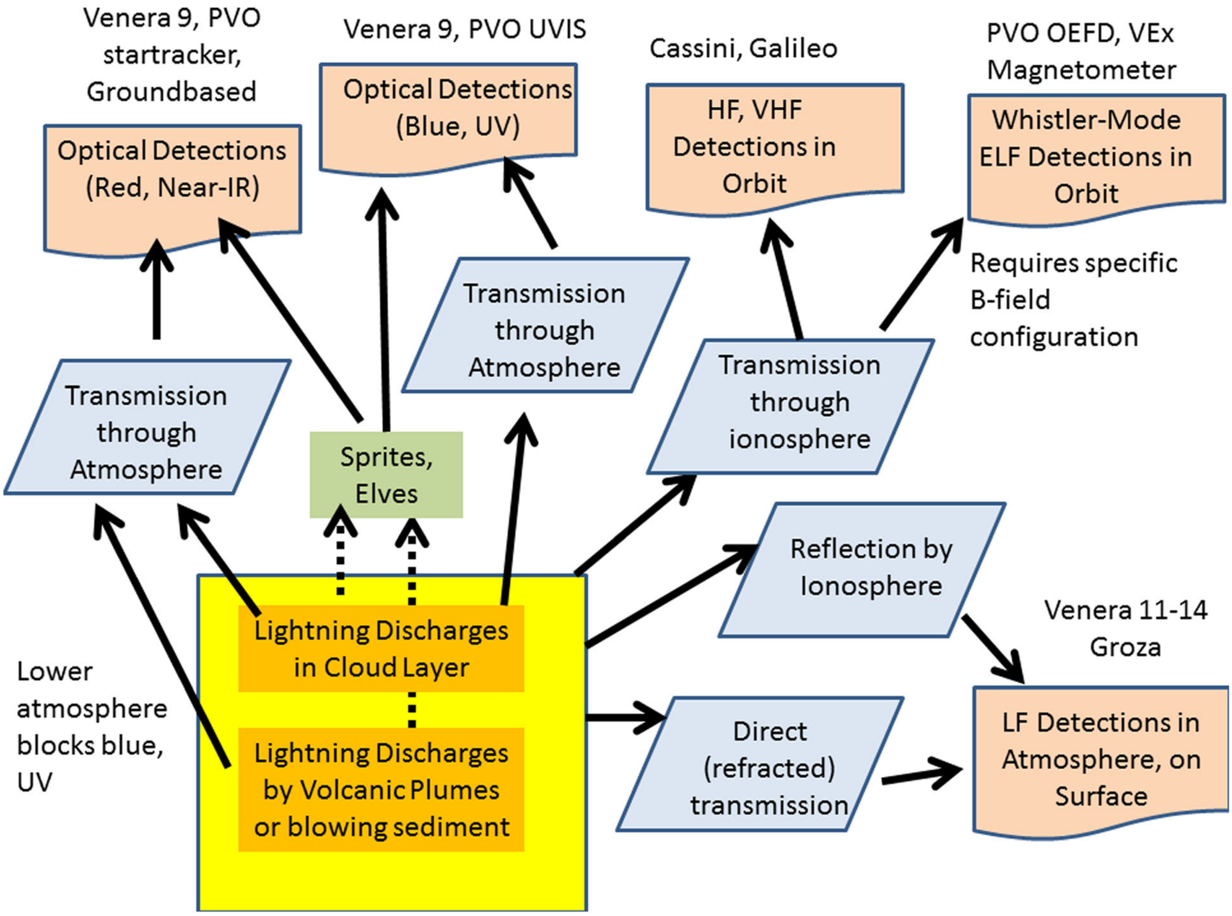

Fig. 3 A schematic of lightning sources and detection mechanisms, noting that detections rely on signal propagation mechanisms that may not be effective for all combinations

similar or different features compared with the Earth. For the purpose of this review, we consider “lightning” to be any optical emission associated with an electrical discharge, thus including ionosphere/mesosphere glows such as sprites as well as “conventional” lightning flashes.

It is interesting to lay out the development of Venus lightning studies in parallel (see Table 1) with progress in studying lightning at Earth. In fact, many significant terrestrial developments have been made since the first observations of possible lightning on Venus—notably the development of terrestrial networks of radio systems able to provide real-time and essentially global surveillance of lightning activity. Indeed, not only have these developed from national-scale systems such as the US National Lightning Detection Network NLDN to the global WWLLN, but even an amateur network exists (“Blitzortung.org”) using simple VLF detectors linked to servers that locate strikes by time of arrival (see Fig. 4).

More pertinents, perhaps, from an analogy standpoint are the observations of terrestrial lightning from space. Vanguard III, only the 12th satellite to reach the orbit and only 2 years after Sputnik 1, carried a proton precession magnetometer, in which some VLF whistler-mode signals were detected (Cain et al. 1961). Orbital measurements of whistlers were more robustly observed and directly attributed to “fractional hop” whistler waves launched from near the sites of lightning discharges, by the Canadian satellite Alouette (Barrington and Belrose 1963), and by the small US satellites Injuns 3 and 5 (see, e.g., Gurnett and O’Brien 1964). A global map of lightning is derived from the detection of VLF sferics measured in 1972 by the British satellite Ariel 4 (Bullough et al. 1975).

Optical detections of lightning were made by photometers on the Orbiting Solar Observatory (OSO-B or OSO-2, Vorpahl et al. 1970) and then mapped in more detail by OSO-5 (Sparrow and Ney 1971). These photometers were saturated by moonlight (and sunlight) and therefore were restricted to observations during the new moon. The field of view of these instruments was of the order of a few square degrees (a few $\times 10^4 \text{km}^2$), and in ~200 h of observation spread over 15 months, about 7000 lightning strokes were detected in about 1000 storms, revealing

Table 1 Timeline of lightning studies. Venus dates correspond to relevant publications, rather than data acquisition, generally only a year or so earlier

	Venus	Earth
1959–1964	Mariner 2 encounter with Venus; hot greenhouse atmosphere identified	Whistlers first observed by satellites—Vanguard III, Alouette, Injuns 3 and 5
1967	First in situ measurements—Venera 4	
1970–1		Optical flashes mapped by OSO-2 and OSO-5 satellites
1972	Venera 8 reaches surface	
1975	Veneras 9 and 10 landers + Orbiters. V-9 orbiter records possible flashes	RF lightning emissions mapped by UK satellite Ariel 4
1979	VLF Discharges measured by Venera 11, 12 landers	
1979–80	Pioneer Venus Orbiter detects electric ELF whistlers	
1983	Veneras 13 and 14 confirm VLF discharges	
1986	VEGA balloons float in Venus atmosphere	
1989		NLDN provides continuous US continental-scale lightning mapping
1989	Magellan spacecraft launched	Sprites first photographed
1994		Terrestrial gamma-ray flashes (TGFs) discovered
1997		FORTE satellite: both optical and RF detections TRMM satellite studies storms and lightning
2004		DEMETER satellite. World-Wide Lightning Network (WWLN) established
2007	Venus Express detects magnetic ELF Whistlers	
2008		C/NOFS satellite
2010	Akatsuki launched	
2016		GOES-16 with Geostationary Lightning Mapper

graphically the enhancement of lightning activity over land relative to the oceans at the same latitude. Surveillance by flash meters on US VELA satellites (installed to detect the optical emission from nuclear detonations) revealed a small population of particularly intense lightning discharges (Turman 1977) and later dedicated lightning sensors on the Defense Meteorological Support Program (DMSP) satellites gave additional information on the optical power distribution of lightning flashes overall (Turman 1978; see also Christensen et al. 1979).

Modern satellite sensors dedicated to lightning mapping (e.g., the Lightning Imaging Sensor (LIS) on the Tropical Rainfall Mapping Mission (TRMM), the Optical Transient Detector (OTD) (see, e.g., Finke 2009), and more recently, the global lightning imager on GOES-16 have yielded systematic observations of activity, enabling correlation with geographical or convective parameters. There have also been satellite missions dedicated to the study of lightning-related phenomena, notably the Fast On-orbit Rapid recording of Transient Events (FORTE) and Communications/Navigation Outage Forecasting System (C/NOFS), both of which carried optical flash detectors (photodiodes) as well as antennas to measure electromagnetic signatures. These observations (e.g., Fig. 5), and those from a related instrument (Global Lightning and Sprite Measurements on Japanese Experiment Modules JEM-GLIMS on the International Space Station, e.g., Sato et al. 2015), have given us simultaneous views of different phenomena associated with discharges, phenomena which have only been studied separately at Venus. There is also a powerful synergy between the ground-based networks and spacecraft sensors since they can perform intercalibrations to assess detection thresholds and efficiencies.

Venus observation review

In this section, we review pertinent details of the various Venus observations, arranged chronologically. The key parameters are summarized in Table 2.

Veneras 11–14 lander electromagnetic observations

Observations by the Veneras 11 and 12 probes, which descended to Venus' surface in December 1978, were the first strong report of lightning on Venus (Ksanfomality et al. 1979). Note that although the Venera 9 orbiter observations (see next section) were acquired earlier, their interpretation as lightning was not developed (Krasnopolsky 1979; submitted November 10, 1979) until after Ksanfomality's Venera 11/12 paper was published in the May/June 1979 issue of (originally submitted in February 1979).

The Veneras 11 and 12 probes carried an instrument suite called "Groza" (thunderstorm—a clear indication of the purpose of the system) which comprised a magnetic field antenna (a loop) to detect sferics and a microphone to detect thunder. Signals in two wavebands (at 10 and 36 kHz) were recorded. Veneras 13 and 14 carried an improved instrument (Groza-2) which also included a seismometer, Fig. 6.

The acoustic element of the instrument was not useful for detecting thunder during descent, in that, aeroacoustic noise of the air rushing past provided too strong a background for sensitive detection. On the surface, some lander-generated noise was identified, and the background signal level was in fact used to estimate the wind speed on Veneras 11 and 12, but no thunder was detected.

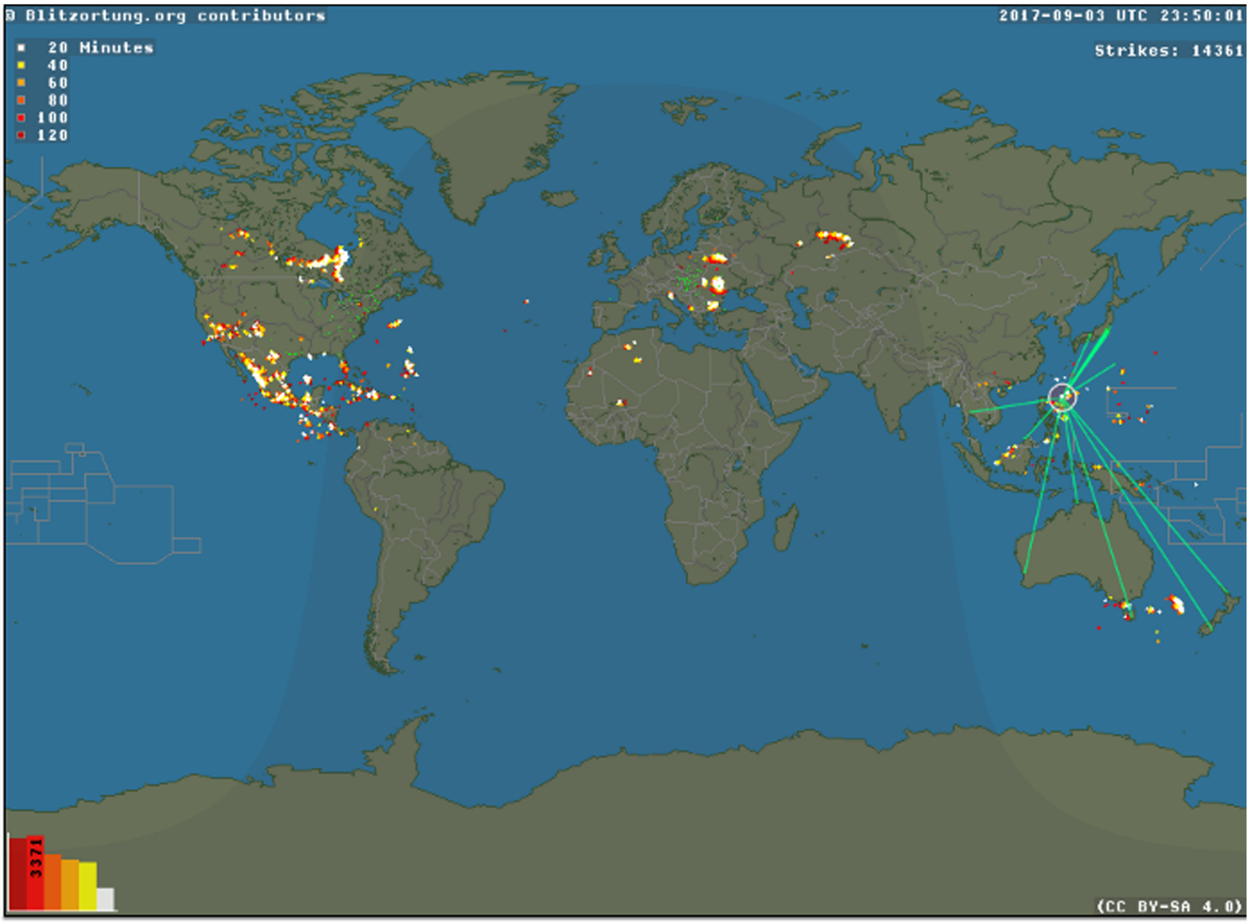

Fig. 4 Map of lightning activity in a 2 h period, detected more or less globally (coverage in South America and Africa by this amateur network is somewhat sparse of stations, which need only a small VLF receiver and an internet connection). A single recent strike is detected (lines) by stations from Japan to Australia and New Zealand, allowing its location in the Philippines—some 8000 km from New Zealand—to be reconstructed (circle) within a second or so. It is also apparent from this plot that there may often exist regions thousands of kilometers across where no lighting is present at a given time. Creative Commons license—by contributors to the Blitzortung network

The electromagnetic field sensor detected substantial activity, which showed a different vertical profile for each lander (suggesting that the signals were not artifacts). Usually, these have been displayed together with scales adjusted; it is instructive here to show them on a common scale Fig. 7.

Ksanfomality et al. (1979) and Ksanfomality (1980) claim that some of the detected bursts showed a periodicity commensurate with the slow rotation of the Venera 11 lander during the latter part of the descent, consistent with spin modulation due to the directionality of the antenna as it swept past a distant (i.e., of small extent in azimuth) source. However, this suggestion does not seem quite consistent with the measurements of the probe rotation from angular velocity sensors (~ 7°/s—see Fig. 4 of Karyagin et al. 1980); the combination of this rate (50 s period) and the bi-lobed sensitivity pattern of the antenna should lead to a 25 s period modulation of a distant source, not the 40–80 s modulation observed. Furthermore, inspection of the radiation pattern of the antenna (Fig. 10 of Ksanfomality et al. 1983) suggests that the sensitivity varies with azimuth by a factor of 2–3, yet the observed change in signal amplitude appears rather larger. Thus, an alternative interpretation advanced in the present review is that in fact the pseudo-periodic variations are bursts of the original emission (implying only one to four sources were being observed, each generating one or a few bursts), rather than spin modulation of a single continuous source.

On Venera 12, one electromagnetic burst was recorded after landing. The burst (see Fig. 10 later in this article) lasted the entire observation window of 8 s, these windows being repeated at 3–4 min intervals. This sparse sampling only constrains the burst to have a duration of between 8 and 360 s. No bursts were recorded on the surface by other landers (a total observation period of about 2 h.)

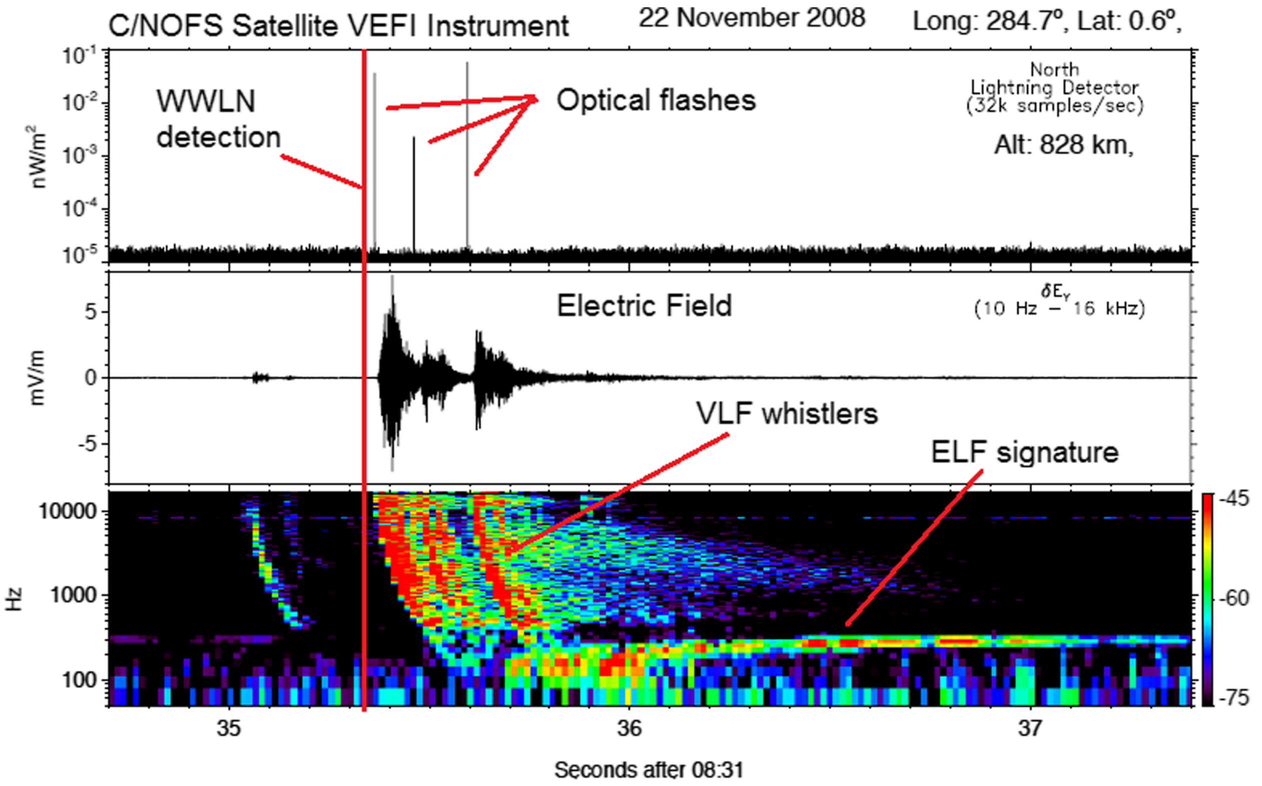

Fig. 5 A single (multiple) lightning flash recorded by the C/NOFS satellite on Earth in multiple ways that have only separately been seen on Venus. Three brief optical flashes (top) are recorded, the first near-synchronous with a stroke detection by the ground-based VLF World-Wide Lightning Network (WWLN), shown in the red line. Electric field antennas on the satellite then showed a waveform (middle) that can be decomposed in the spectrogram (bottom) into whistlers in the VLF range (kHz to 10 s of kHz), similar to the VLF noise recorded by the Venera landers, and ELF waves of a few hundred Hertz (which may be whistler-mode) in the ionospheric plasma, similar to those recorded by Pioneer Venus and Venus Express. Figure courtesy Bob Holzworth

The near-continuous activity generally observed by the probes during most of the descent (the Venera 11 instance above notwithstanding) implies that if the activity is typically in 5–70 s bursts, the observation (instrument plus signal propagation characteristics) was sensitive enough to detect bursts from long enough distances that a sufficient number of sources was detectable at any moment to prevent gaps being observed between bursts. If we ignore for a moment that the probes were descending, we can consider each record as a time series. For Venera 11 (see, e.g., Fig. 2. of Ksanfomality et al. 1983), the activity was moderate (~ 20 uVm^{-1} Hz$^{-0.5}$) between 0530 and 0545 h (60 to 30 km) and strong (~ 100 uVm^{-1} Hz$^{-0.5}$) from then until 0605 (15 km) then moderate to the surface. For Venera 12 (ibid, Fig. 3) some sporadic activity (with 1–2 min variations) was seen for the first 15 mins of descent, then essentially zero for the next 25 min, then moderate activity for the last 20 min of descent.

Considering the first part of Venera 11, if a single source causes ~ 5 bursts of ~ 30 s duration (as indicated in the high-resolution record 0606–0611 previously interpreted as spin modulation—Ksanfomality et al. 1983; Fig. 8), then the continuous record seen 0546–0552 (ibid, Fig. 5) implies two or more sources within range, such that the bursts overlap.

Note that in addition to the averaged field strength (recorded with a 0.25 s time constant, and in some cases in the papers cited above plotted after averaging over 20 s periods), the radio system was also equipped with a pulse counter. This indicated (Ksanfomality et al. 1979) pulse rates (threshold not specified) from 1or 2 per second to 10 or 20 for part of Venera 11's descent, and the text indicates even higher levels were seen. Pulse counter data is also presented in Ksanfomality et al. (1982) for Venera 14, with a threshold of some 200 μV/m/Hz$^{0.5}$—at this quite high threshold, the rates were 0 to 2 pulses per 10 s above about 25 km, with some periods of 5–7 pulses per 10 s below that level.

The possibility of some artifact (e.g., noise generated by aerodynamic flutter during descent) does not appear to have been discussed in detail in the literature. However, a slow systematic (smooth) altitude dependence would be expected, as the vehicles' terminal velocity slowed as they reached the denser lower atmosphere—such a dependence

Table 2 Key characteristics of Venus lightning observations

Study[a]	Platform	Instrument	Signature	Instrument designed for lightning?	Detections	Amplitude or Sensitivity	Controls	Other explanations for data	Area observed	Duration
Krasnopolsky 1979, 1983a,b	Veneras 9 and 10 orbiter	Visible spectrometer	Spikes in optical intensity	No (spectral scanner)	1 burst of ~ 2 flashes/s over 70 s	1E8 W 3E7 J/ flash	Dark sky	Debris from spacecraft?	1500 km^2	2 spacecraft × 25,000 s (night)
Ksanfomality et al. 1979, Ksanfomality et al. 1982, Ksanfomality et al. 1983	Veneras 11 and 12 lander. Veneras 13 and 14 lander	Groza (V11, 12) Groza-2 (V13, 14) magnetic and acoustic sensors	10 and 36 kHz impulses	Yes	Near-continuous noise (few to ~ 40 pulses per second)	Tens of μV/μ/Hz$^{0.5}$	–	Spacecraft noise: but time (altitude) dependence argues against	Few million km^2 (?) Depends on propagation	4 spacecraft, ~ 1 h each descent
					One burst (V12) 150 pulses in 8 s	20–40 μV/ μ/Hz$^{0.5}$	–	As above	1 million km^2 (?)	4 s/c × 8 s every 3–6 min for ~ 1 h
Scarf et al. 1980, 1987	Pioneer Venus Orbiter	Electric field detector	E-field bursts at 100 Hz	(Yes)	4240 bursts	> 20 μV/μ/Hz$^{0.5}$	–	Plasma noise. Spacecraft noise	Unknown	257 h
Borucki et al. 1991	Pioneer Venus Orbiter	Star scanner	Optical pulses	No		2E8 J	Statistics of off-disk pulses	Cosmic rays	~1 million km^2	~ 80 s
Huestis and Slanger 1993	Pioneer Venus Orbiter	UV spectrometer	Spikes in optical intensity	No (spectral scanner)	1 event	> 70 kR	–	Meteor trail was preferred explanation	< 1000 km^2	~ 600 orbits, 10 min each
Gurnett et al. 1991	Galileo flyby	Radio	Electric field	Yes	9 impulses	10–16 V^2 m^{-2} Hz^{-1}	Observations before/after encounter	Plasma noise, spacecraft noise	Disk	53 min
Belton et al. 1991	Galileo flyby	CCD Camera	Bright spots on image	Yes	Nondetection	4 × 1E9 J	–	N/A	Part of disk	
Hansell et al. 1995	1.54 m ground-based telescope	CCD camera	Bright spots on image	Yes	7 flashes	7E7–1E9 J	Dark frames	Cosmic rays	~ 70% of disk	3.75 h
Gurnett et al. 2001	Cassini flybys	Radio and plasma wave	Electric field	Yes	Firm nondetection		Earth lightning	N/A	~ Disk	
Russell et al. 2007a, 2007b. Hart et al. 2013	Venus Express	Magnetometer	Bursts at 64 Hz	Indirectly	~ 700 s of activity per 225 days (10 min/day)	~ 0.1–1 nT	Variation with altitude	Plasma, spacecraft noise	~ 200 km	
Moinelo et al. 2016	Venus Express	VIRTIS near-IR spectrometer	Bright spectra	No	Nondetection	Not stated	–	N/A	(varies)	~ 50,000 s total

[a] In many cases, many papers examine the same data (especially Pioneer Venus and Venus Express, see main text)—here lists only the papers from which the table entries have been derived

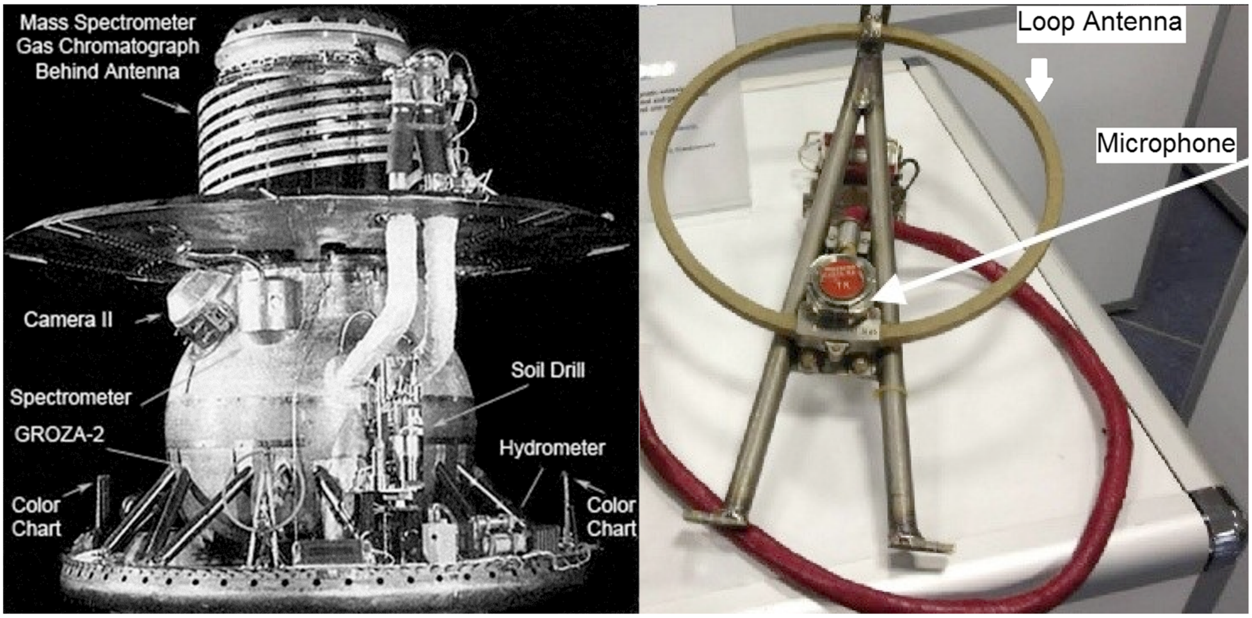

Fig. 6 The Venera 13 lander (left) with major systems noted (figure courtesy W. Huntress)—the GROZA-2 label points to the location of the loop antenna mounted externally just above the shock-absorbing landing ring. The disk structure near the top stabilized the probe during descent after the parachute was released. The GROZA-1 instrument is shown at the right (figure courtesy L. Ksanfomality) showing the loop antenna and mounting strut, together with a microphone for detecting thunder—note the heavy-duty insulation on the cable to protect it from the hot corrosive Venus atmosphere

was not observed. Further, it is seen (e.g., Ksanfomality et al. 1983, Fig. 10) that the signals do not cease abruptly at impact but rather fall off within the last few hundred meters of descent, more consistent perhaps with terrain obscuration of signal propagation. (The possibility of near-surface atmospheric composition changes causing radio absorption cannot be completely excluded, however). Finally, specifically to test whether charging of the vehicle itself could be responsible for the observed signals, a discharge current meter was installed on the Groza-2 experiments on Veneras 13 and 14 (see Ksanfomality et al. 1982)—those results do not appear to indicate any strong local contribution to the observed discharges but may be consistent with the presence of charged dust in the Venus lower atmosphere (Lorenz 2018).

It is useful to put the Groza experiments in context with a similar investigation, the Lightning and Radio Emission Detector (LRD) on the Galileo Probe (e.g., Lanzerotti et al. 1992; Rinnert et al. 1989, 1998). It was noted that the noise background of this instrument was found to be higher in flight (due to the operation of a nearby radiometer instrument with an electric motor) than in laboratory/field tests.

It may also be noted that the LRD instrument detected between 10 and several hundred RF pulses per second throughout the descent (over 150,000 pulses total), whereas no optical lightning detections were claimed (the few hundred counted optical pulses being attributed to spin-modulated sunlight early in descent, or to cosmic rays—see Rinnert et al. 1998). This underscores the comparative long-range ability of electromagnetic vs optical sensing (and makes the optical nondetection of the VEGA balloon at Venus perhaps unsurprising). The LRD used a ferrite coil antenna (i.e., sensing the magnetic component of the signal, like the Groza instruments) and counted pulses in narrow bands at 3, 15, and 90 kHz, with the lowest frequencies seeing highest activity; sensed pulse amplitudes reached a few tens of nanotesla. The LRD detected appreciable azimuthal anisotropies (i.e., preferred source directions).

Terrestrial tests of the LRD showed that intensity fell off with increasing frequency approximately as f^{-2}; such a strong fall-off was also seen at Jupiter (Rinnert et al. 1985). The Groza instrument at Venus found a spectral index varying between 0.5 and 2, typically 1. This fall-off seems consistent with an interpretation of the signals as due to electrical discharges. Note that the sometimes challenging units of electromagnetic observations have perhaps limited external scrutiny into these results—for example, even though a magnetic antenna was used, (Ksanfomality et al. 1979, Ksanfomality et al. 1983 hereafter referred to as K83) expresses the Groza signals as electric field intensity—e.g., the 10 kHz signals on Venera 12 (K83 Fig. 3) reaching a value of ~ 15 μV/m/$\mathrm{Hz}^{0.5}$ (recorded over a bandwidth of 1.6 kHz) or a peak field of 0.6 mV/m. For classic electromagnetic propagation in free space, the electric field E relates to the magnetic field B as $E = cB$, with c being the speed of light—note that this relation does not hold for the

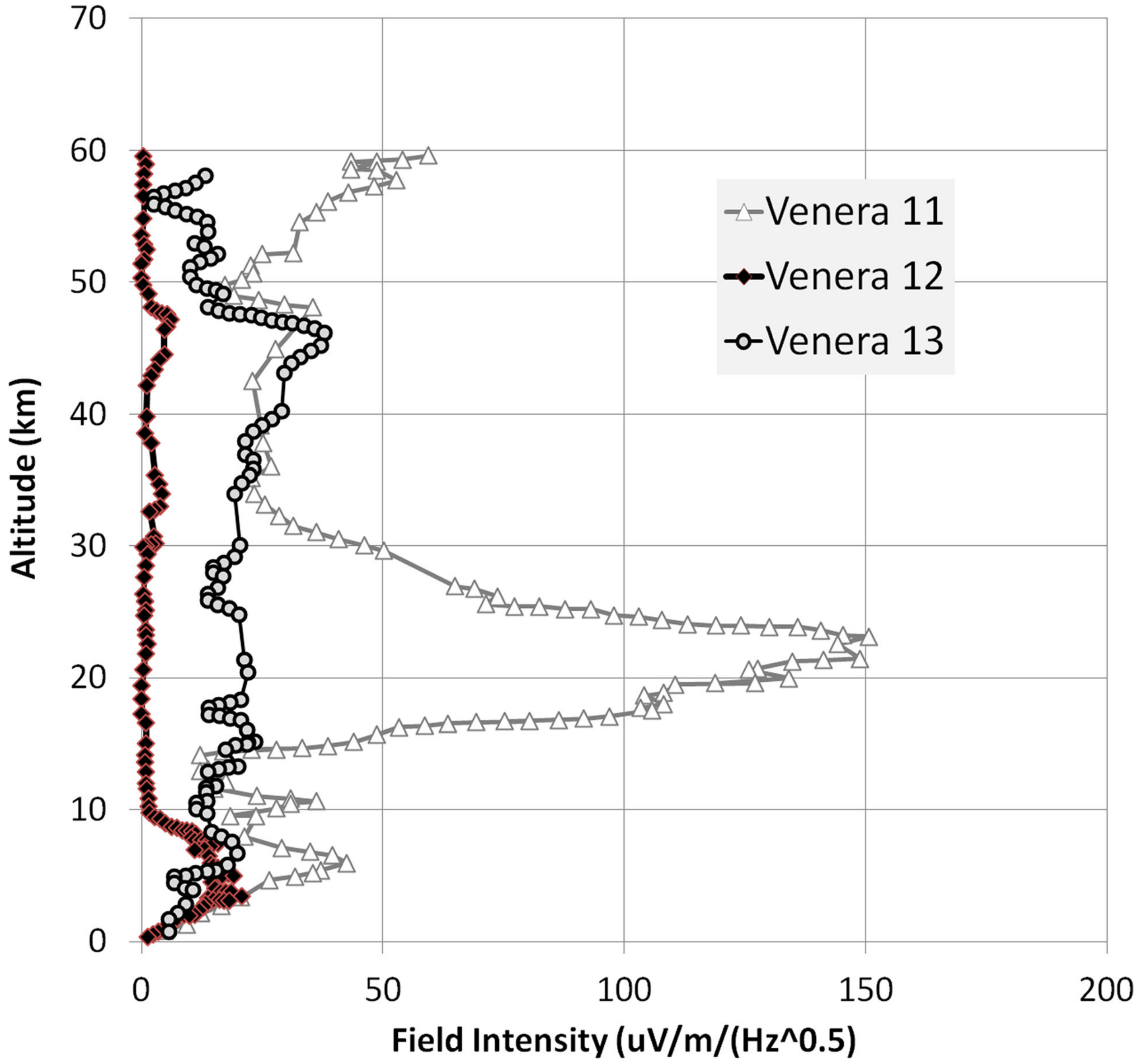

Fig. 7 The electromagnetic field intensity (5 kHz bandwidth centered on 10 kHz) from Veneras 11–13 (Ksanfomality et al. 1982,1983) averaged over 20 s intervals, plotted on a common scale which shows the dramatically different character of the Venera 11 profile with the 30–15 km altitude range (about 20% of the descent duration) having several times higher intensity than the rest. Previous presentations have tended to rescale each profile, de-emphasizing this difference

whistler-mode propagation in a plasma), and so, this corresponds to 0.002 nT, or 5×10^{-5} nT/Hz$^{0.5}$. The Galileo sensors at Jupiter, by contrast, recorded a power spectral density of up to 10^{-3} nT^2/Hz or $\sim 1 \times 10^{-6}$ nT/Hz$^{0.5}$ at a similar frequency (15 kHz), a significantly lower level than Venus. On the other hand, a handful of waveforms were recorded by Galileo, the largest having a peak amplitude of a couple of tens of nanotesla (Lanzerotti et al. 1996; Rinnert et al. 1998).

In many respects, the Groza records are among the richest datasets pertaining to possible Venus lightning. Their presentation in various graphical forms in Ksanfomality et al. 1979 and 1983 is useful, but the examination with new statistical methods would benefit from access to original digital data, which is unfortunately not publicly accessible (sadly, also true of the Galileo LRD experiment).

Note that Ksanfomality's papers (1982, 1983) describe anomalies encountered by the Pioneer Venus probes as circumstantial support for electrical activity. While at the time, the possibility of some kind of discharge had been considered one possible explanation for these anomalies (the failure of external temperature sensors

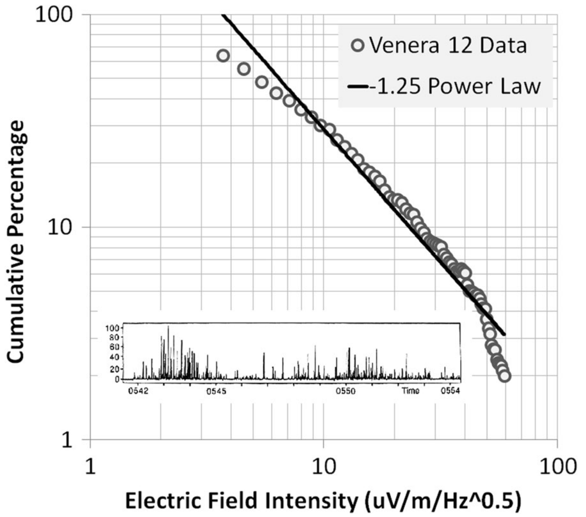

Fig. 8 Amplitude distribution of pulse heights (inset) recorded at a high data rate during part of the Venera 12 descent (see, e.g., Ksanfomality et al. 1983). About 30% of the time, the amplitude was at the noise level of ~ 5 uV/m/Hz$^{0.5}$—spikes of ~ 100 occur less than 1% of the time. The data (analyzed here by digitizing the plotted figure) do not permit robust discrimination of a power law from a broken power law or an exponential; the single power law with an exponent of − 1.25 is shown as an example, although there is some hint of a steeper slope at the high end of the curve (right). The distribution arises either from an intrinsic amplitude distribution, or because discharges occur at a variety of ranges, or both. The distribution is also broadly consistent with the aggregate of results shown in Fig. 7

on all four probes, at the same altitude of ~ 12 km) these anomalies have since been attributed to a failure of electrical insulation in the Venus environment at this altitude (e.g., Seiff 1995; Harland and Lorenz 2006) and so should not be considered as indicating electrical activity (although they do not exclude it either).

Venera 9 and 10 orbiter spectrometer

These observations, initially reported in Krasnopolsky (1979), are discussed at rather more length in Krasnopolsky (1983a, 1983b, 2006). As this UV-visible-NearIR spectrometer scanned over 10 s from 300 to 800 nm, observing a 160 × 9 km patch of the Venus nightside, the recorded light level saw several irregular jumps—seven such scans had these jumps. Interpreting this as a time series rather than a spectrum, there was a 70 s series of flashes, about two per second, each lasting about 250 ms, each of about 3×10^7 J of optical energy. Although claimed to be "similar to the duration of a flash on Earth," these durations (much longer than the instrument response time of 5 ms) are puzzling. The observation was at 9° S around 7 pm local solar time; the "thunderstorm region" is described as being of 50,000 km^2 area, presumably derived by mapping the instrument footprint migration during the 70 s.

One point to note is that in fact, this event was seen during the very first night observation of the instrument, perhaps when instrument anomalies would be more likely to occur. A further consideration is that while no localized Venus emission interpreted as lightning was recorded by the instrument on Venera 10, the light was unexpectedly measured off-disk and was interpreted as a dust trail from a comet Krasnopolsky and Krysko, 1979. The presence of a dust trail (something no mission to Venus before or since has indicated) cannot be ruled out entirely but is at least superficially improbable. Instead, it is possible that both this observation and/or the Venera 9 "lightning" burst may have been caused by light reflected from some material (e.g., thermal blanket) released from the spacecraft: a tumbling reflector could give quasiperiodic flashes with durations consistent with the 0.25 s durations observed. The star tracker on Magellan was spoofed by particles shed from its that spacecraft's thermal blankets when solar wind conditions led to surface charging (e.g., Harland and Lorenz 2005). It is also reported that the Venera 9 instrument temperatures increased from 20 to 60 °C, during its 2-month mission, a factor which degraded the sensitivity of the spectrometer instrument (Krasnopolsky 1983a).

When considered qualitatively, "Venera 9 saw lightning, but some aspects of the observation are puzzling." A quantitative perspective, however, is much more illuminating. An important quantity recently explained (Krasnopolsky, personal communication, June 2017) to the author of the present paper is the duration of subsequent nightside observations (for Veneras 9 and 10 combined) where no lightning features were observed, 50,000 s. Thus, one "burst" of 70 s of emission was seen in about 14 h of observation of an area ~ 1500km^2, the activity being present ~ 0.1% of the time.

Krasnopolsky claims that the spikes are enveloped somewhat by the optical sensitivity of the instrument (i.e., fewer/weaker flashes at the ends of the passband, whereas electrical noise or cosmic rays might be expected to be uniform with time/wavelength), supporting an external optical origin of the signal. However, this is also fully consistent with the sunlight reflections-from-debris hypothesis suggested above. If the signal was really due to lightning, it imposes an altitude constraint for the optical emission (as noted by Krasnopolsky 2006) in that the blue end of the spectrum at 20 km or below (i.e., volcanic lightning) would be attenuated severely by the atmosphere, and thus, whatever light was observed by Venera 9 had to come from above the deep atmosphere. However, since lightning emission has a highly nonuniform line emission spectrum (e.g., Borucki et al. 1985, 1996), the somewhat uniform peak amplitudes observed by Venera 9 seems perhaps more consistent with periodically reflected sunlight.

Pioneer Venus electric field detector

The Pioneer Venus Orbiter was placed in December 1978 into an elliptical polar orbit around Venus with a 24 h period. It carried an electric field instrument which measured the power of electric field variations in four narrow wavebands. Taylor et al. (1979) and Scarf and Russell, 1983 reported that signals seen over nightside periapses, most prominently in the 100 Hz band, could be interpreted as whistler-mode emissions from lightning. These signals were "impulsive" in the sense of being short compared with the 0.5 s sampling interval and the 0.7 s decay time of the instrument. Because the spacecraft environment was noisy in sunlight, these signals could only be reliably detected at night, and they were detected only at low altitude (e.g., Scarf et al. 1980), which given the parameters of the orbit, meant low latitudes.

A variety of plasma phenomena can occur in space, and alternative explanations were offered for these signals and an extensive debate in the literature ensued. We do not recapitulate the blow-by-blow debate here but refer the reader to comprehensive reviews by Russell (1991) and Grebowsky et al. (1997) Fig. 9.

For the present discussion, we may note that while all observations (electromagnetic or optical) may suffer noise or artifacts, there are features of the signals that are claimed to be consistent with a lightning origin, notably their altitude dependence.

Scarf et al. (1987) reported identifying 4240 bursts in the first 2124 orbits, at altitudes between 150 and 2900 km, indicated by them as a total observation period of 257 h. Then, whatever phenomenon a "burst" actually corresponds to—perhaps passage over a thunderstorm—there were about 15 per hour. Note that the "new" burst definition used by Scarf et al. (1987), counting short events distinctly, corresponds to a rate five times higher than that used previously (assessing whether a signal existed in a 30 s window or not.) A more elaborate analysis was made by Ho et al. (1991) who attempted to deconvolve the response time of the instrument—in effect counting any 0.5 s window with measureable "extra" energy as an event—see Fig. 10. This yielded the rather high rate of ~ 0.14 events per second.

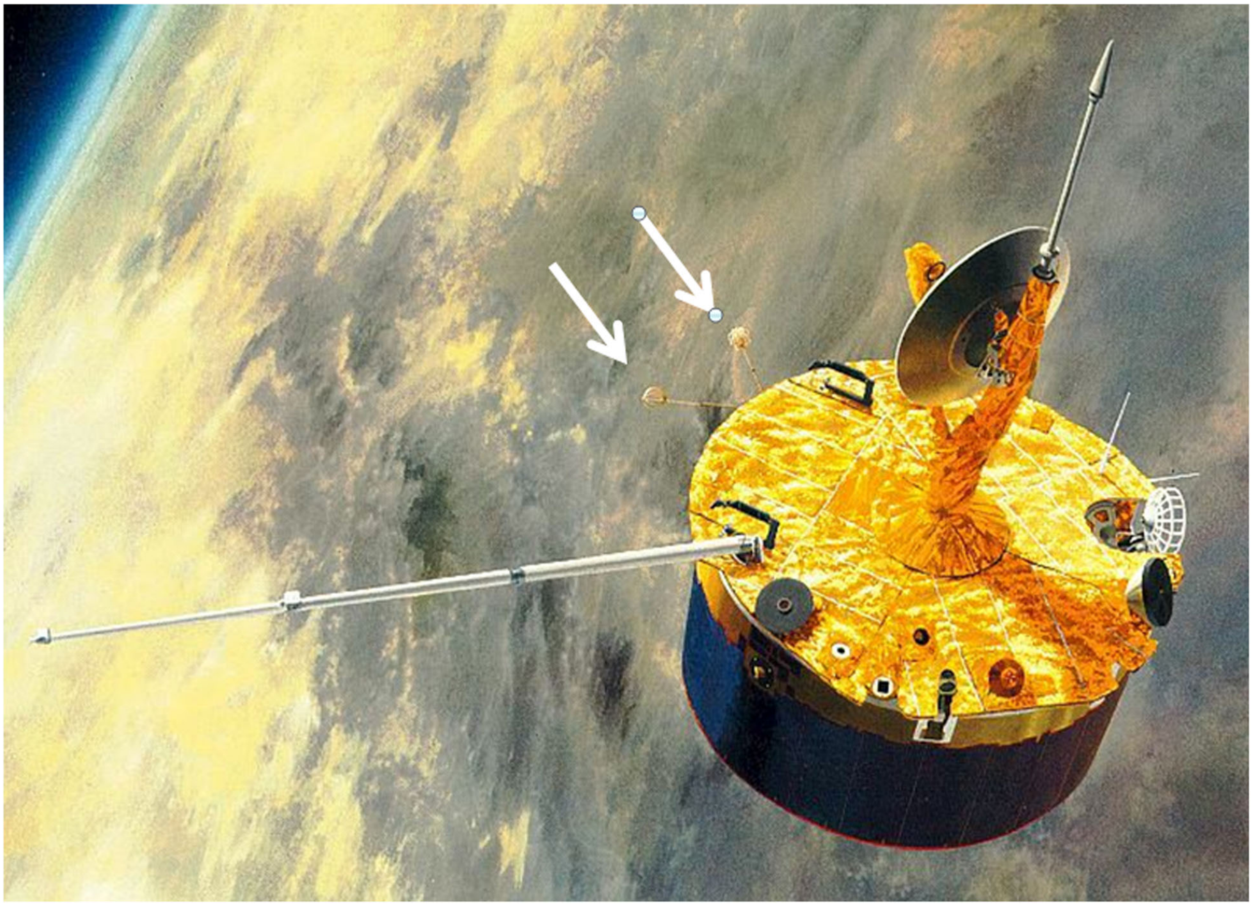

Fig. 9 NASA artists impression of the Pioneer Venus orbiter. The Orbiter Electric Field Detector (OEFD) measures the potential between two wire mesh sphere electrodes (arrowed)

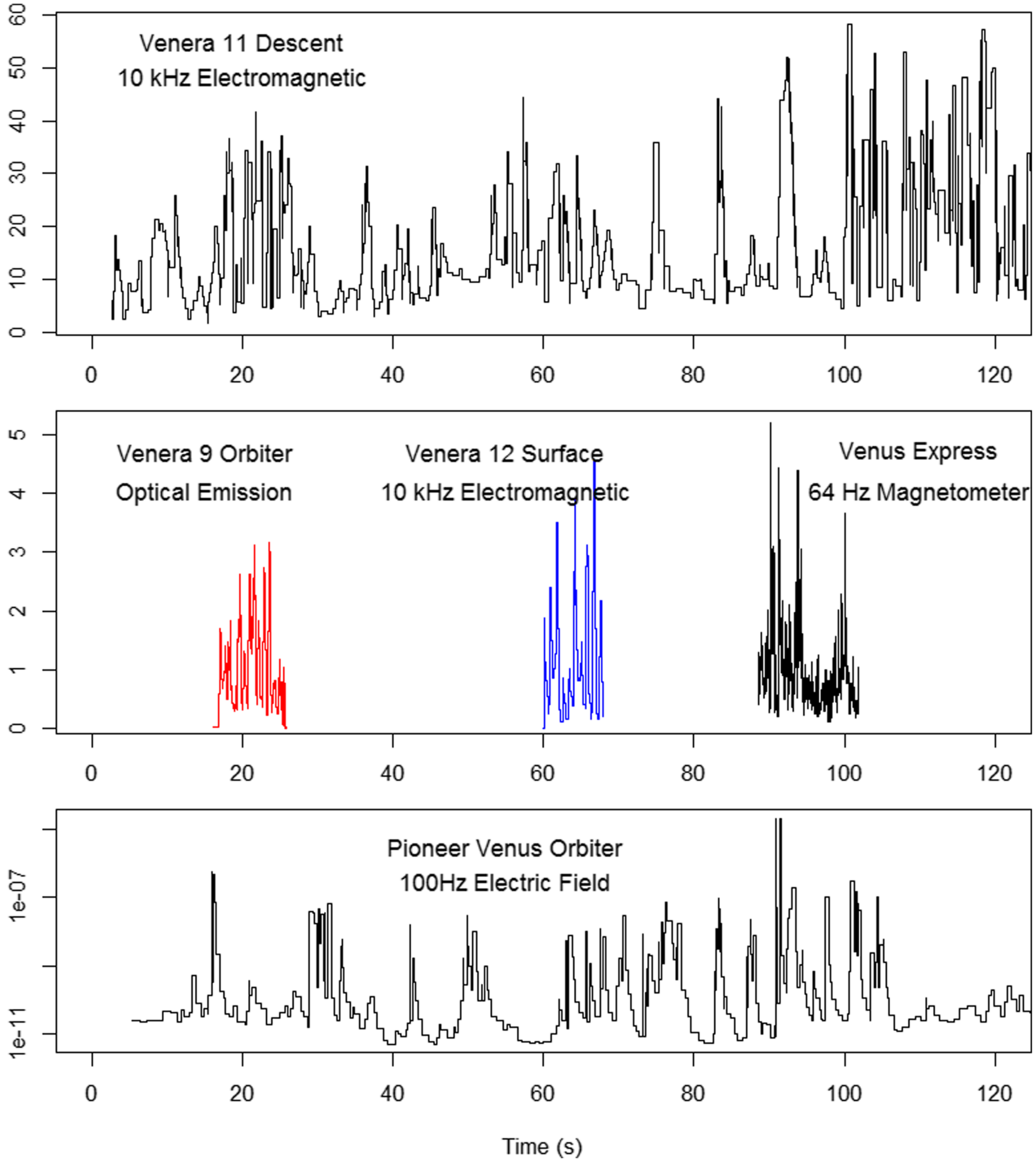

Fig. 10 Several different Venus lightning detections plotted with arbitrary vertical scales, but on the same abscissa, showing the characteristic variability on second and sub-second timescales. It is evident too that the rate of events (bursts/pulses/flashes/strokes) is strongly dependent on the time resolution adopted

Although some claims of geographical association of whistler detections with elevated terrain (presumed to be volcanic) were made (e.g., Scarf et al. 1987), sampling biases may not have been fully taken into account, and this correlation is now considered weak at best—one refutation is by Taylor Jr and Cloutier (1986).[1] Considerably more robust, however, is the finding that activity appeared to be concentrated in the dusk-midnight sector, with much less in the midnight-dawn sector. Note that whereas on Earth, most convection occurs in the afternoon when solar heating is strong, on Venus convection may instead be driven by cloud-top cooling (e.g., Imamura et al. 2014) at night. This latter scenario would probably cause peak convective lightning activity in the dusk-midnight sector, as observed.

Pioneer Venus optical

Borucki et al. (1981, 1991) examined data from the star scanner on the Pioneer Venus Orbiter—an instrument and data-mining analysis much like that of Sparrow and Ney (1971) at Earth. Borucki et al.'s nondetection of events (or rather a detection rate that did not exceed the false alarm background due to energetic particles) in fact derived from only 450 s of effective search time (Borucki et al. 1981; another 88 s, but covering a wider area, was added in further analysis, Borucki et al. 1991). The short observation period results from the fact that the observations relied on lightning emissions not being observed directly but rather scattered into the detector as stray light—even the "ashen light" from the Venus nightside saturated the detector when observed directly. Despite this short observing time, the area-time product of a few $\times 10^7$ km^{2}s was enough to derive a useful upper limit on the flash rate of $1–4 \times 10^{-7}$ flashes/km^2/s.

Pioneer Venus ultraviolet spectrometer

An optical anomaly was noted (Huestis and Slanger 1993) in the analysis of data from the Pioneer Venus Orbiter ultraviolet spectrometer, whose primary purpose was to investigate the nightglow between 150 and 360 nm wavelength. In one observation (orbit 75), three successive scans were observed to have a strong emission (at wavelengths matching the N-O band system). These short-wavelength scans had an interval of 24 s, as the spacecraft spun with a 12 s period and short-wavelength (155–258 nm) and long-wavelength (258–360 nm) scans were interleaved. No anomalous brightness in the two intervening long-wavelength scans was observed. One could interpret this as a 72 s long event with only shortwave emission in narrow bands, or perhaps just coincidence that the 3–5 major flashes (discarding those with only one or two photons—see their Fig. 9) over a 72 s period just happened to occur during the shortwave scans. It should be noted that the "strong emission," corresponding to 70 kR (kiloRayleighs—where one $R = 10^{10}$ photons/m^2/s), was indicated by only about 60 photons in each scan, compared with a typical 30 photons due to the airglow.

Huestis and Slanger (1993) offered a meteor trail (900 km long!) as a possible explanation, considering this more plausible than a lightning or auroral origin. Their interpretation seems improbable but cannot be excluded. The observation seems incompatible with a direct lightning origin (even though Borucki et al. (1996) conclude that discharges in the Venus atmosphere would produce some UV light, it would be scattered or absorbed before reaching an orbiting detector if launched from the clouds.) The possibility, however, of it being due to upper atmosphere luminosity from electrical discharge (i.e., sprites, elves, etc.—phenomena which only became well-known in the 1990s, after this observation and analysis were completed) might bear reexamination. Indeed, Pérez-Invernón et al. (2016) present models of posssible mesospheric optical signatures of lightning (i.e., transient luminous events (TLEs, such as sprites and elves) but curiously do not cite the Huestis and Slanger work. They note that in addition to the green and red oxygen lines, nitrogen emission would occur in the UV and near-IR. As an example, a lightning discharge with a total released energy of 2×1010 J would launch 2×10^{20} green photons and 3.7×10^{19} photons 120–280 nm, much of which would be in the PV UVS passband.

UV observations were made (lasting a few tens of minutes around periapsis) over the first 2 years; only this single anomaly was reported. Thus, this single "burst" of ~ 72 s was the only one in ~ 1 million seconds of observation.

Pioneer Venus gamma ray detector

The Pioneer Venus Orbiter in fact carried an instrument whose purpose was not to study Venus at all; the Orbiter Gamma-Ray Burst Detector (OGBD) was flown to help measure astrophysical gamma-ray bursts, by using time-of-arrival differences between it and other spacecraft in the solar system to triangulate the source direction. This instrument operated for some 14 years until 1993 when Pioneer Venus' orbit decayed. It was only a year afterwards that terrestrial gamma-ray flashes (TGFs) associated with lightning on Earth were discovered Fishman et al. 1994.

Lorenz and Lawrence (2015) reviewed the OGBD dataset archived on the National Space Science Data Center (NSSDC) to assess whether there was evidence of an enhancement of gamma-ray flux near Venus, but unfortunately, those data were too coarsely binned in time to permit any conclusion. Should high-time-resolution records be discovered (in contrast to astrophysical bursts, TGFs are only milliseconds long), the question might bear reexamination. The authors also modeled the propagation of gamma rays through the Venus atmosphere, to assess the altitude above which gamma rays would need to be released to be usefully detectable. They found that gamma rays from sources at 65–75 km altitude (depending on energy) are attenuated by a factor of 100. Radiation and particle transport studies were performed by Bagheri and Dwyer (2016), with similar results. Should gamma-ray instrumentation be flown on a future Venus orbiter (e.g., to measure sulphur in the clouds), a high-time-resolution capability would be desirable to detect possible lightning flashes.

VEGA balloon

The two VEGA balloons deposited into Venus' atmosphere in 1985 floated for ~ 48 h at an altitude of 50–55 km. Each gondola was equipped with a photodiode light gauge, including an electronic high-pass filter to detect flashes. No flash detections were reported: Sagdeev et al. (1986) notes that the intermediate-brightness flash counter on VEGA 2 did increment once, indicating a possible flash, but the measurement is suspicious because it was made near the terminator (where varying cloud-top altitudes could cause strong changes in ambient illumination) and that the lower-level threshold counter should also have incremented but did not. The VEGA data have recently been restored and made available for the NASA Planetary Data System (PDS)—Lorenz et al. (2018); it may be noted that the VEGA-2 lander pressure-temperature profile therein is the only high-quality in situ atmospheric dataset that reaches all the way to the surface of Venus.

Although the observation period was relatively long, it may be noted that the observation was mostly in the midnight-dawn sector of the Venus day (on Earth, the period least likely to see lightning). Furthermore, the detection area would have been relatively small, only a few tens of kilometers across at most, i.e., area of ~ 1000 km^2. The platform is pseudoLagrangian, being advected with the air mass. Thus, if one adopts the proposition that some air masses have lightning and some do not (e.g., due to moisture content), then the range of locations sampled is very small (in contrast, e.g., to an orbiter survey of similar duration). Thus, the nondetection is a rather weak constraint on lightning on Venus.

Galileo radio

Gurnett et al. (1991) reported the detection of nine electric field impulses over a period of 53 min during the Galileo spacecraft's Venus flyby in 1991 at about 4–5 R_V (Venus radii), i.e., a range of about 20,000 km. Although at the time, they reported that "lightning is the most likely source," the lead on this investigation has informed us (Gurnett, personal communication, 23 May 2017) that he no longer believes lightning to be responsible, noting that impulsive signals could arise from (1) spacecraft electronics, (2) plasma waves, (3) dust impacts, (4) thermal stresses that cause discontinuous mechanical motions that are coupled to the antennas via microphonic effects, and (5) other unknown effects. Although control observations were carried out during two 1 h intervals (when no impulses were seen), these were well before the Venus flyby and well after the Venus flyby. Notably, the high-voltage component of a plasma instrument (PLS) was active during the close approach period but was off during the control intervals. Thus, it is possible that the operation of the PLS high voltage unit close to Venus was responsible for the signals interpreted at the time as lightning. It may also be noted that if the impulses really were due to lightning, the observed rate is much lower than would be observed for terrestrial lightning at a comparable radial distance.

Galileo optical

Belton et al. (1991) examined nightside images of Venus acquired by the Galileo spacecraft during its flyby en route to Jupiter. Ten images were devoted to this lightning search; however, since exposure times were less than a second, the nondetection is not a strong constraint.

Mt. Bigelow ground-based optical

Hansell et al. (1995) installed the CCD detector at the 153 cm telescope located on Mt. Bigelow, Arizona (more popularly known locally as the "61-inch."), and searched for light flashes on the nightside of Venus. Their study carefully employed coronagraphic optics, using two masks designed in accordance with the specific geometry for each individual night of viewing. An occulting mask was used in the imaging plane, and a Lyot mask was used to block diffracted light by the edges and support structure of the secondary mirror. The CCD detector was operated at 18.8 frames/s for ~ 30 pixel images of Venus. The observations were made at mainly 777.4 nm (i.e., in the near-infrared—an atomic oxygen line expected from laboratory simulations of lightning discharge in a carbon dioxide atmosphere by Borucki et al. 1996); a few observations were made at 656.3 nm as a control. For eight nights in 1993, the total viewing time was 3 h at 777.4 nm and 45 min at 656.3 nm. The dusk side of Venus was facing Earth. Seven events met the stringent criteria (including the requirement that an event must be seen on more than one pixel) that the experimenters used for isolating lightning flashes, as shown in Fig. 1. Six events were detected in the 777.4 nm line. The seventh occurred while observations were being made at 656.3 nm. The 777.4 nm flashes occur at a rate of 2.7×10^{-12} flashes/km^2/s and imply Venus lightning flashes with optical energies from 7×10^7 to 2×10^9 J.

Although the statistics are rather poor, Hansell et al. (1995) did note that three of the flashes occurred within 10 min of each other, while some nights had no flashes at all, suggesting a possibly clustered behavior. However, the locations of flashes were distant from each other, suggesting this may have been a sporadic coincidence. The detection of a flash at 656.3 nm (the hydrogen-alpha line, not initially expected to yield lightning detections) was interpreted as being due to light from a carbon emission line at 658 nm identified in laboratory experiments simulating lightning discharge in various planetary atmospheres (Borucki et al. 1985; Borucki et al. 1996).

A remark on the flash duration is in order. Krasnopolsky's (1979) detections—see earlier—were about 250 ms long, not typical of terrestrial flashes (as had been claimed). The Hansell et al. (1995) data analysis procedure entailed subtracting a running average image (of the two frames before and the two frames after) from each image. Thus, if a flash were of 250 ms duration, it would have spanned all five frames, and the bias (average) image would contain just as much energy as the frame under study. In other words, the analysis procedure excluded long pulses of light. Note also that the analysis procedure excluded single-pixel events. The only events recorded, then, had an apparent span of many hundreds of kilometers, although the sources may have been rather smaller but blurred by the Earth's atmosphere (observations of Venus are necessarily made with Venus low in the sky and thus at large air masses, susceptible to seeing conditions). Note that some other phenomena do have durations of 250 ms (e.g., blue jets), and meteor fireballs or trails can have durations of the order of a second or longer (e.g., McAuliffe and Christou 2006).

Note that Hansell and colleagues repeated the experiment the following year (Hansell, personal communication, 2010), although since this was a null result and the concluding part of work for a thesis (Hansell, University of Arizona, 1996), no journal publication was made. This experiment used a dichroic splitter so that both the 778 nm and hydrogen-alpha line would be observed simultaneously. The same processing applied to the earlier imaging campaign failed to yield any detections at either wavelength, although it should be noted that the new observation was made on the sunrise side of Venus' dark disk (i.e., local solar times between about midnight and 6 a.m., where the electromagnetic results from Pioneer Venus seem to show a pronounced decrease in activity.)

Cassini radio

The Cassini flybys (Gurnett et al. 2001) provided a much better search for lightning at Venus than was available from the Galileo flyby. The reasons are as follows. First, the flyby altitudes for Cassini, 284 and 598 km, were much closer than for Galileo, which would make the lightning signals stronger by a factor of 1600 to 10,000 in power. Second, because Cassini had longer antennas, its sensitivity was better than for Galileo, by at least a factor of 10. Third, the integration time constant of the Cassini receiver (1 ms for some of the observations) is much better suited to detect the very short impulses from lightning than the Galileo receiver, which had an integration time constant of about 100 ms. Furthermore, the ability of the Cassini instrument to detect lightning was explicitly demonstrated during the Cassini-Earth flyby in August 1999, during which over 1000 impulses consistent with lightning were detected at radial distances inside 14 R_E. That no impulses significantly above the receiver noise level were detected during either of the Cassini-Venus flybys (total observing time of several hours while viewing essentially the entire planet) allows us to make the very strong statement that "lightning similar to terrestrial lightning did not exist at Venus during the two Cassini flybys." Crudely, one might interpret the null result as indicating a flash rate lower than about one-thousandth of Earth's. Of course, this does not rule out the possibility that episodes of terrestrial-like lightning could occur at Venus during other times, such as occurs for the very episodic lightning at Saturn (intense lightning activity was observed in association with a large storm on that planet, around the equinox season in 2009, but relatively little activity has been detected by the 2004–2017 Cassini mission either optically or by radio before or since this one storm—see, e.g., Fischer et al. 2011).

Venus Express magnetometer

The most persuasive *recent* evidence for lightning are the transient AC magnetic field pulses observed by Venus Express (Russell et al. 2008a). Like other electromagnetic evidence, these suffer from the ambiguity of having alternative explanations (spacecraft artifacts, plasma noise, etc.), but the recurrent nature of the signals (having been observed hundreds of times) and the fact that their polarization and detection appear consistent with whistler-mode ELF emissions lend some support to the claim that they have a lightning-like origin.

Specifically, they have been observed close to the periapsis of Venus Express (~ 250 km altitude; due to Venus Express's orbit, this happens nearly over the north pole), when magnetic field lines are inclined in such a way as to link the spacecraft with Venus' atmosphere. The signals are detected at 64 Hz (the sample rate of the magnetometer is limited to 128 Hz) and have a typical amplitude of 0.1 nT, sometimes reaching 1.5 nT (Daniels et al. 2012).

Hart et al. (2013) describe the bursts as lasting between 6 s and up to a minute. Note, however, that the spacecraft is moving at almost 10 km/s, so in 1 min, the vehicle traverses about 600 km. If the range sensed by the whistler-mode observation is only a couple of hundred kilometers, then it may be that the upper bound on burst duration is truncated not by the intrinsic duration of bursts of activity but by the duration of the visibility window of a given source.

Hart et al. (2013) report that bursts occupied about 1% of the time the spacecraft spent at about 250 km altitude, the occurrence falling off to higher altitudes (~ 0.3% at 390 km), but also towards lower altitudes.

Russell et al. (2008b) note that in the first Venus year of operation, there were 12,223 s of useful data, during which 61 bursts were detected, i.e., one per 200 s. They assumed that the magnetic field permitted detection only 25% of the time. They also make the reasonable (but unsupported) assumption that the detection samples a region 200 km in radius (roughly the spacecraft altitude above the ionosphere) or 0.027% of the surface and extrapolate to a rate of 18/s globally.

Some care is needed in that different definitions of the event or "burst" have been used. Daniels et al. (2012) show magnetometer waveforms and hodograms and describe the "components" as lasting around 100 ms (since the data are generated from heavily bandpass-filtered signals between 42 and 60 Hz, 100 ms corresponds to only a few "wiggles" of the signal) whereas Russell et al. (2007a) describe them as 0.2–0.5 s. They show the peak rate of bursts defined that way as ~ 0.0045 per second at 200–225 km altitude, whereas the "reduced" burst rate, defined as the number of 5 s intervals containing such a signal as 0.0014 per second—thus on average, when a 5 s burst occurs, it contains ~ 3 smaller pulses.

These rates, based on several years of operation, are a disconcerting order of magnitude less than the initial report of Russell et al. (2007a). That study used 37 orbits (days) of data selected when the background noise due to the spacecraft reaction wheels was particularly low, such that bursts with a peak-to-peak amplitude of 0.2 nT can be picked out. Reader attention is needed to note that the Daniels et al. (2011) counts of 0.2 nT are for 0.2 nT half amplitude—i.e., events double in amplitude compared with Russell et al. (2007a). Lightning events, like many other phenomena in nature, have highly skewed populations, and any attempt to compare counts without taking the detection threshold into account is hopeless (see, e.g., Lorenz 2009 for a similar problem with dust devils). Daniels et al. (2011) break their counts up into several amplitude bins—> 0.4 nT events make up only 10% of the total of > 0.2 nT events, so one might similarly extrapolate that > 0.1 nT events are ten times more abundant, consistent with the Russell et al. (2007a) numbers. Russell et al. (2011) describe bursts as about 4 s long and having a rate of 0.05/s at peak. Thus, even considering observations from a single instrument, the event rate may vary by a factor of ~ 40 (0.0014 to 0.05/s) depending on the threshold and time window considered! The same caution applies to optical detections—see Fig. 11 and associated discussion later.

Venus Express near-infrared

Moinelo et al. (2016) examined nighttime data from the visible (280–1100 nm) channel of the VIRTIS imaging spectrometer on Venus Express. Their search resulted in thousands of transient signal detections, but these could all be explained by cosmic rays impinging on the detector, and analysis showed that the events were randomly distributed along the spectral dimension, rather than being associated with some expected line emission from Venus' atmosphere. The total observing time was ~ 50,000 s (Moinelo, personal communication, 2017).

Ground-based optical (II)

García Munõz et al. (2011) utilized narrowband fast imaging of the Venus disk from an array of ground-based telescopes. The search targeted the oxygen emission line at 777 nm which should be a prominent line in lightning (as on Earth—most terrestrial spaceborne sensors use a filter to isolate this wavelength to improve the signal to noise). Two sites (Calar Alto and Observatorio del Teide) and three instruments (AstraLux, FastCam, and Wide FastCam) were used for observations during November 2010 to January 2011. The analysis of the night-side imaging of Venus showed no signal of optical emissions. It is likely that many other optical surveys with negative results also exist since nondetections tend not to be reported (e.g., an anonymous reviewer of this paper suggested that the late D. Sentman at University of Alaska made such observations but no formal publication resulted).

Implications and discussion

Synthesis of observations

In Tables 3 and 4, we review the evidence outlined in the previous section. While indeed the reports are not mutually consistent with a simple picture of Earth-like lightning, some conclusions can be drawn, most notably that some sort of atmospheric electricity effect is present but that it yields neither optical flashes nor VLF radio emissions observable from space in anything like the frequency that occurs for Earth.

In principle, it might be possible to aggregate the observational constraints and apply them to models of lightning distribution (spatial, temporal, and amplitude) to test various hypotheses. For example, if lightning is exclusively due to volcanoes, sources will be geographically fixed and will have no local time dependence (although various observation efficiencies, e.g., the ionosphere, may have such dependence). However, the data at hand do not seem adequate to justify such an exercise—the Venera lander datasets are too brief, the Pioneer Venus results already dismissed as equivocal, while the Venus Express magnetometer results are confined to near the north pole and are likely conditioned more by propagation conditions than by local time or geographic effects on their sources.

Observations similar to those of Hansell et al. (1995) would be useful to repeat, even with telescopes of

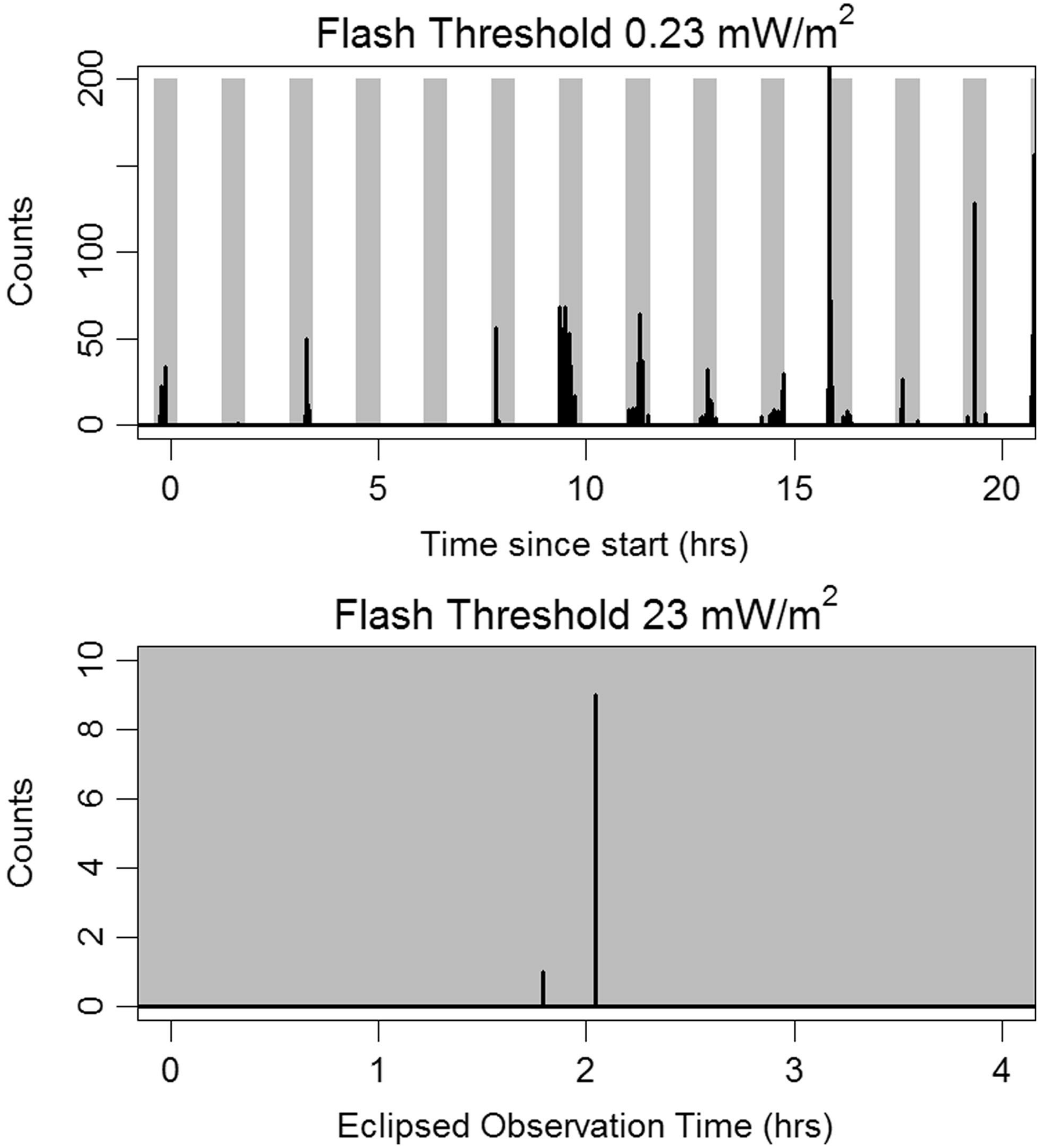

Fig. 11 Optical flashes recorded by one of the two photodiode detectors on the C/NOFS satellite (downloaded from https://cdaweb.sci.gsfc.nasa.gov/index.html/). The top panel shows data for the lowest (most sensitive) threshold brightness—flashes are only detectable in the gray eclipse periods. The counts are the number of samples (~ 4000) per 0.5 s integration period that exceed a flux threshold, here 0.23 mW/m^2—count rates are as high as a couple of hundreds. The bottom panel concatenates several eclipse periods together into an observation comparable in length with Hansell et al.'s (1995) telescopic Venus survey which detected seven flashes in about 4 h. With a 100 times higher threshold than the top panel, only a handful of counts are now obtained, and periods of 2 h or more exist with no counts at all (note that the instantaneous field of view of this sensor is only ~ 1000 × 2000 km)

Table 3 Summary of characteristics of Venus electrical activity

Property	Estimate and confidence	Support	Comment
Rate of bursts	15/h ~ 1/min ~ 18/h	PV E-field bursts [30 s] (Scarf et al. 1987) Venera 11 bursts 13–17 km Venus Express bursts (see text)	
Rate of pulses (during burst)	~ 0.14/s ~ 0.1–0.7/s 2–20/s	PV E-field pulses (Ho et al. 1990) Venera 14 descent pulses (> 200 μV/m/Hz$^{0.5}$) Venera 11 descent pulses (unknown threshold)	
Duration of burst events	Well-determined: 5–100 s	• Venera 12 surface burst > 8 s, less than 3–6 min • VEx magnetometer bursts 6 s to > 60 s • Venera 9 burst 70 s • PV E-field bursts	Overlaps between bursts on Veneras 11–14 descent do not constrain burst duration
Flash duration	Unclear	• Venera 9 claims ~ 250 ms (long for terrestrial lightning) but instrument response? • Hansell ground-based detections < 100 ms (but 5-frame running mean bias subtraction reduces sensitivities to flashes > 50 ms, and discards transients > 250 ms altogether) • Veneras 11–14 pulses 10–60/s, means up to ~ 8–50 ms long	Venus Express, Pioneer Venus ELF signatures longer than "flash" due to propagation delay, so no constraint (see Fig. 5 bottom panel)
Geographic distribution	Global?	• PV OEFD detections mostly mid-latitude (claimed association with highlands specifically was not substantiated by data, but not excluded either • VEx MAG detections only made near north pole (low altitude required for observation) • Venera lander detections made at low latitude, but long detection range gives little localization	
Source region size	< few hundred kilometers	• Spin modulation of Venera 11 source • PV, VEx cover ~ 600 km in 60 s • Hansell flashes cover 3–15 pixels (2.2 arcsec pixels each ~ 600 km across)	
Local time distribution	Strongest observed in evening (18–24 h). But few dayside observations	• Strongly indicated by distribution of PV OEFD and VEx MAG bursts • Statistics of optical detections too poor to provide useful constraints	Evening cooling of cloud-tops drives convection?

Table 4 Summary of hypotheses regarding Venus lightning

Scenario	Support	Comment/challenge	Conclusion
There is no electrical activity on Venus	• Sensitive Cassini search yielded null result • Various optical searches have yielded null results • A priori theoretical difficulty of charge separation	• Requires alternative mechanisms (e.g., local plasma noise) for all orbital electromagnetic evidence (Pioneer OEFD, VEx magnetometer) • Also requires alternative mechanism for atmosphere/surface electromagnetic evidence (Veneras 11–14) • Implies Venera 9 optical detection spurious (not improbable per the present paper) • Implies ground-based optical detection spurious	Unlikely
Sporadic electrical discharges occur with characteristics different from Earth	• Consistent with electromagnetic signatures • Occasional optical detections	• If optical signals are present at all, perhaps they are transient luminous events (TLE's, i.e., sprites or similar) • Cassini radio nondetection was "unlucky"—ionospheric conditions?	Not excluded
Frequent lightning similar to Earth	• Venera 9 original interpretation	• Sensitive Cassini search yielded null result, but detected ample activity at Earth with similar observation • Orbital electromagnetic signatures imply lower rates • Various optical searches have yielded null results or low flash rates • A priori theoretical difficulty of charge separation	Unlikely

somewhat smaller aperture (which are quite abundant). Modern digital video cameras allow high frame rates suitable for detecting transients, and the computer storage and processing hardware and software—demanding in the mid-1990s for this application—are easy to acquire. Notably, software to detect bright transients in planetary video sequences has been developed and made publicly available (e.g., http://pvol2.ehu.eus/psws/jovian_impacts/) and has been successful in detecting impact flashes on Jupiter and the moon (e.g., Hueso et al. 2013).

Chemical evidence for lightning

On Earth, lightning was the principal mechanism of nitrogen fixation prior to the evolution of nitrogen-fixing bacteria and the Haber process. It has been long noted (e.g., Krasnopolsky 1983; Bar-Nun 1980) that the abundance of NO or other nitrogen-bearing species could be profoundly influenced by lightning, and the observed abundance has been taken as at least circumstantial evidence for lightning. Krasnopolsky (2006) suggested an abundance of 5.5 ± 1.5 ppb below 60 km by ground-based telescopic observations and argued that this was consistent with a global flash rate is ~ 90 flashes/s for a flash energy ~ 10^9 J (of course, the chemistry only constrains the product of flash rate and energy—larger but rarer flashes would yield the same production.). The production of NO by shock chemistry associated with meteors has not been evaluated but could conceivably reduce the apparent need for lightning to yield the observed NO abundance.

Lightning and volcanos

In many respects, the study of present-day volcanism on Venus has parallels with the study of lightning. While the past modification of the Venus surface by volcanism is indisputable, the detection of the present-day activity is not. Such detection would of course be a scientifically appealing discovery, and a number of claims have been made. However, the indirect evidence (of changes in the sulphur dioxide abundance in the atmosphere) has alternative explanations. The claimed direct evidence of microwave (Bondarenko et al. 2010) and near-infrared (e.g., Shalygin et al. 2012) emission is subject in both cases to high false-positive susceptibility due to the background subtraction or modeling required to isolate a volcanic signature, and the claims are not widely considered adequate evidence to assert discovery.

In fact, the investigations of lightning on Venus and of present-day volcanism have not only scientific and sociological similarities but also intersections. It is often pointed out that lightning discharges occur in the ash plumes of volcanos on Earth, and in fact, the lightning networks such as WWLN are now used to remotely monitor volcanic activity, as in the case of the 2015 eruption of the Chilean volcano Calbuco (Van Eaton et al. 2016).

Some geographical associations of electric field signatures in Pioneer Venus data with regions on Venus were taken as circumstantial support of a volcanic lightning interpretation. However, the logic was in fact somewhat circular, and the associations were not statistically robust (e.g., Taylor Jr and Cloutier (1986). That said, such an association is not excluded either (e.g., Russell 1991).

Observations on future missions able to locate the sources of electrical discharges without strong latitude, local solar time, or ionospheric propagation biases would be useful in assessing the possible association of lightning with highlands or volcanos specifically. Note, however, that a surface-fixed source of “lightning,” even associated with a surface feature interpreted to be volcanic, is not a guarantee that active volcanism is occurring. A correlation could emerge in another way, for example, in that atmospheric motions that manifest near the Venus cloud tops are now known to occur in a surface-fixed reference frame, due to gravity waves excited by topography (e.g., Fukuhara et al. 2017).

Triboelectric discharges on Venus surface

It is striking that on only two occasions when small-scale surface changes could have been observed on Venus, namely in the roughly 1 h intervals between the successive image panoramas on each of the Veneras 13 and 14 landers, sediment transport was observed on one of these (Lorenz 2016). In contrast, typically one might (depending on location) need to wait for days or months to observe surface movement on Earth; similarly, only a few surface changes were observed on Mars by the Viking landers over several years.

It has been recognized that triboelectric charging may be an important effect on Titan (Lorenz 2014; Mendez-Harper et al. 2017) as well as Mars, in environments where the lack of surface electrical conductivity via liquid water prevents rapid charge leakage. In the dry high-pressure near-surface atmosphere of Venus, it will be even harder for the charge to leak away from triboelectrically charged sediments.

It seems plausible that triboelectric charging associated with eolian sediment transport might occur on Venus; if it does, the proximity of Venus wind speeds to the transport threshold and the surface transport observation on Venera 14 may imply that it is widespread and frequent. It may not be ubiquitous, however. An obvious prerequisite is the availability of sand, dust, or gravel to be transported, and such material may be strongly supply-limited in many places (e.g., Weitz et al. 1994); although ash streaks from a number of volcanos can be recognized, the dominant source of sediment may be ejecta from the ~ 1000 impact craters on Venus. Topographic obstacles may play an important role in funneling winds at a regional and local scale. These caveats aside, while only a couple of sites with Magellan-resolvable sand dunes are known (e.g., Lorenz and Zimbelman 2014), wind streaks are found over all latitudes and longitudes.

Although we have little direct information on Venus' near-surface winds, they are unlikely to be uniform—some places will be windier than others. Notably, slope winds due to diurnal heating will be strongest on large, steep slopes at low latitudes, and an evaluation (Dobrovolskis 1993) suggested two daily peaks in speed will occur, around 0600 and 1800 h local solar time (upslope and downslope respectively). Since sediment transport will be favored downhill, this predicted maximum in particle motion, and thus, triboelectric charging will occur in the evening, consistent with the apparent increase in observed electrical activity then compared with early morning. It should be underscored that the high pressure at Venus' surface is a challenge to the prospect of discharges; however, in that, the breakdown field at these conditions is very high. In this respect, volcanic ash clouds may be more likely to yield discharges, since the charged dust in this case is lofted to a higher altitude where the breakdown field is lower.

Conclusions and recommendations for future surveys

This review reaches much the same conclusion as many before it, namely that more observational data are required to make a robust assessment about atmospheric electrical activity on Venus. To date, the most compelling indications of some kind of persistent atmospheric electrical activity at Venus appear to be the VLF detections by Veneras 11–14. The ELF emissions observed by Pioneer Venus, and perhaps more robustly by Venus Express, appear fully consistent with such electrical activity although they do have potential other explanations. As summarized in Table 3, rates of activity seem broadly coherent among the quite different datasets.

Of the optical observations, the ground-based observation by Hansell et al. (1995) appears the most significant in terms of robustness and area and time observed, although the very small number of flashes is challenging to interpret quantitatively. The Venera 9 observation has a number of aspects that make the interpretation difficult and suggest a possible artifact. Circumstantially, the nondetection, or at least lack of reports of detected flashes, in a number of other datasets (Pioneer Venus star tracker, VEGA, Venus Express) indicates that flashes are not a prominently observable feature of Venus, although in some cases (Pioneer Venus, VEGA), the area and/or duration of the observation is small.

It is clear that a larger area-time product, desirably with a low optical energy detection threshold, is required to assert strong upper limits on, or to obtain secure statistics of, what is likely to be a strongly spatio-temporally variable phenomenon. The present state of the art of optical detections at Venus is somewhat similar to the handful of orbits with a high detection threshold (totaling 4 h), as shown in the lower panel of Fig. 11 for terrestrial data from the C/NOFS satellite—the interpretation of only a few flashes is challenging as any geographical or temporal dependence is not statistically robust. It may be hoped that the Lightning and Airglow Camera (LAC) on Akatsuki may be operated for some time, yielding statistically useful numbers of detections. The rate of optical detections for an instrument at Earth viewing from about 1000 km altitude, and thus viewing about 1 million km^2 (e.g., FORTE, Kirkland et al. 2001) is of the order of 100–200 per hour. The eight initial LAC observations reported by Takahashi et al. (2018) cover a few million km^2 for ~ 20 min, and thus, many detections would have been expected if the optical flashes comparable with terrestrial ones occurred at a terrestrial rate, given a total survey of 10~ 20 million km^2-h. On the other hand, perhaps detectable Venus flashes may be as rare as terrestrial "superbolts" (~ 10^9 J optical energy). Forty such flashes were seen (Turman 1977) in 2 months of long-distance observations, i.e., full-disk ~ 130 million km^2, from the Vela satellites. Thus, the rate of these events is ~ 2×10^{-4} per million km^2-h, and so, an instrument with observing opportunities like LAC (~ 20 min in each 10-day orbit) is unlikely to achieve a detection, even if in operation for a decade. The subtlety of planet-averaged lightning rates not representing the highly clustered (i.e., "conditional") distribution of flashes (e.g., Fig. 4) should be noted—it is not enough to stare with a very sensitive detector at only one place if that place does not see a storm. Thus, there remains high value in obtaining further LAC observations. The question of irregular spatio-temporal sampling of an irregular spatio-temporal phenomenon such as lightning deserves further quantitative exploration, e.g., by Monte-Carlo simulations that can include, e.g., geographical, time of day, or other dependencies, but this is beyond the scope of the present review.

It may be noted that a sufficiently long optical survey may yield optical transient detections even if lightning never occurs on Venus; satellite optical observations (such as Vela, designed to detect nuclear detonations) detect flashes of large meteoroids (bolides) entering the Earth's atmosphere (Brown et al. 2002). The reported events with optical energies of the order of 4×10^9 J occur at a rate of ~ 100/year at Earth, or about 2.5×10^{-5} per million km^2-h, with less energetic events proportionately more often. Thus a 10^6 J optical event might occur at ~ 0.1 per million km^2-h, such that at least a few such events can be expected in some years of LAC observation. Note, however, that the duration of bolide entries is long compared with a lightning flash; in the Venus atmosphere, meteor "flares" are expected to last a couple of seconds (e.g., McAuliffe and Christou 2006), so the triggering logic of an instrument like the LAC, or the exposure time of a camera, cannot be optimal for searching for lightning and for bolides simultaneously.

The superficially bland optical appearance of Venus and its interpretation as a uniform, unchanging atmosphere has given way to a much more variable perspective revealed in the near-infrared (for example by the Akatsuki 2-micron camera—see Fig. 12); thus, it would not be surprising if the vertical motions required for charge separation were as localized as they are on Earth. Not only might the diurnal distribution of lightning production be concentrated (e.g., dusk-midnight) but there may be a geographical preference (e.g., at volcanoes or downwind of large mountainous provinces that may produce uplift in gravity waves). There may also be a meteorological influence on detection efficiency—e.g., lightning emissions may (as on Earth) be more easily detected at the edges of large convective storms, rather than at their center where the obscuring clouds may be thicker.

Above the ionosphere, surveys of whistler-mode signals from orbit have already been comparatively extensive, yielding results that remain broadly consistent from 1 year to the next, and between the Pioneer Venus and Venus Express datasets. While further observations, e.g., from a low circular orbit, would have some value in refining geographical and local time distributions, they are unlikely by themselves to be any more persuasive to the broader community, or informative on the generation mechanism. A combination of an ELF electrical/magnetic detection with another type (most obviously an optical sensor, but possibly gamma ray, or even VHF radio) would be much more compelling (as performed on FORTE and C/NOFS at Earth—see, e.g., Fig. 5) and Suszcynsky et al. 2000. As noted by Russell (2011), a low circular polar orbit is desirable for radar mapping, and a modest lightning instrument would be a valuable but relatively inexpensive augmentation to a radar mapping mission. We may note that such combined optical and RF surveys of lighting (e.g., Light et al. 2001) at Earth have been performed on a rather small satellite platform (e.g., FORTE, 210 kg, flown in 1997).

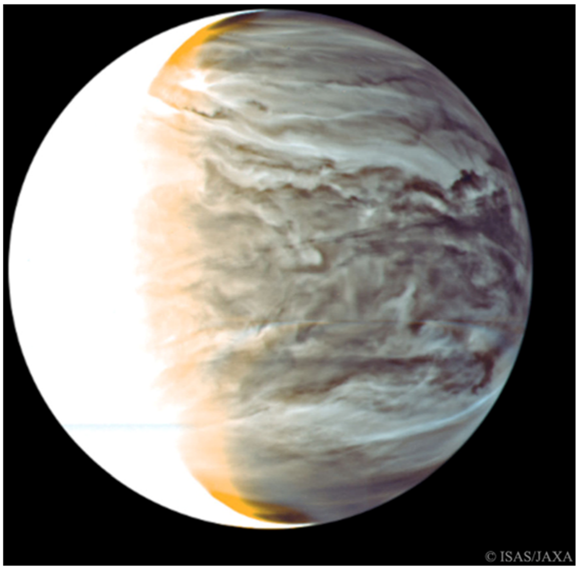

Fig. 12 The deeper view into Venus' clouds afforded by near-infrared windows (this example from the Akatsuki 2-micron camera) shows structures on a range of length scales—if lightning is associated with cloud convection as on Earth, it might be expected that lightning will be similarly patchy (see also Fig. 4)

Both the Pioneer Venus electric and the Venus Express magnetic whistler-mode observations have been made over ~ 10 years for each mission near periapsis (~tens of minutes during each 24 h orbit, or a duty cycle of ~ 2%). Thus, the total observing time is ~ 0.2 years. A radar mapper in a low circular orbit allowing continuous observation would require at least one Venus day (~ 0.7 years) and probably several to sweep through the full range of longitudes and relay the data. Thus, even allowing for lightning observations only at night, piggybacking a lightning payload on a mapping mission will yield a factor of several improvements in observation duration for electromagnetic observations, with better geographical diversity, compared with prior surveys. An optical monitor on a low orbiter, with a ~ 25% duty cycle for night-time only operation, would yield a vastly longer observation time than has been possible to date (typically a few hours).

Below the ionosphere, a long-lived (months?) aerial platform like a balloon would be useful in having a much longer observation period than a surface probe, which will be limited to a few hours. The Venera results suggest that a simple instrument like Groza or the Galileo LRD (an instrument which even with the 1980s technology had a mass of 2.5 kg, a power demand of 3 W and an average data rate of only ~ 1 bit per second—Lanzerotti et al. 1992) would yield rich VLF data from an easily accommodated coil or loop antenna. A modern instrument, operating on a platform near the cloud tops (where temperatures and pressures are benign) could be implemented with a few hundred grams of hardware—it is basically an AM radio, and even only a week of operation would yield a dataset 100 times larger than a probe descent like Venera. Optical detection on an airborne platform would likely have a much shorter range (tens of kilometers) due to atmospheric absorption and scattering but demands so little mass or power that a flash detector should probably be included anyway. A measure of the DC electric field would also be useful to assess fair weather electricity (e.g., the character of the global electric circuit) and possible charging mechanisms; the vertical tether on a balloon is an obvious platform on which to make a simple measurement.

The incremental value of further measurements on short-lived landers or probes is not obvious, unless direction-finding capability (easily implemented, as in some terrestrial sensors, simply by having two coils and measuring the intensity ratio between them) is included. The crude direction-finding implemented by the single coil on the Venera probes with modest directivity coupled with somewhat uncertain spin rate information (Ksanfomality, personal communication, 2017) could not disentangle spin modulation of a finite-extent source from temporal variability in it, nor reliably isolate multiple source regions. A two-axis sensor could resolve these ambiguities, making even a single hour-long probe descent worthwhile, although a long-lived aerial platform would of course be preferable. Desirably, technology developments may eventually permit long-duration operation, and/or multiple platforms can be sent such that useful constraints on temporal or spatial variability can be determined.

Although further spacecraft measurements at Venus are sorely needed, as described above, it is likely that useful insights from ground-based observations can still be made. More sensitive optical surveys can be performed with high-speed cameras that are now readily available, and automated searches with sophisticated statistical tests have been developed (e.g., a lightning search at Jupiter by Luque et al. 2015). Additionally, lightning can be detected by radio methods (e.g., Zarka et al. 2008; Konovalenko et al. 2013) reported observations of Saturn lightning using the large UTR-2 radiotelescope at 20–25 MHz (robust detections were made with fluxes of 100–700 Jansky). A positive simultaneous detection at Venus by both optical and radio means would be powerful evidence of lightning or related activity.

Endnote

[1] Note that this Taylor (Harry H., of Goddard Space Flight Center) is not the same Taylor (William W., of TRW, Inc) who authored the 1979 "discovery" paper.

Abbreviations

C/NOFS: Communications/Navigation Outage Forecasting System (satellite); ELF: Extremely low frequency, a few Hz to a few hundred Hz; FORTE: Fast On-orbit recording of Transient Events (satellite); kR: kiloRayleigh (unit of optical flux); LRD: Lightning and Radio Detector (on Galileo probe); OEFD: (Pioneer Venus) Orbiter Electric Field Detector; OGBD: (Pioneer Venus) Orbiter Gamma-Ray Detector; TGF: Terrestrial gamma-ray flash; TLE: Transient luminous event; VEx: Venus Express; VLF: Very low frequency, typically 3–100 kHz

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Author's contributions

RL conceived and designed the study and wrote the paper. The author read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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