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Highlights

- Full analysis VIRTIS-Venus Express Visible dataset in the night side of Venus
- Most comprehensive search of lightning conducted so far with Venus Express data
- Thousands of signal detections, but they can all be explained by cosmic rays
- Statistical analysis shows random wavelength distribution consistent with cosmic rays
- No clear evidence of lightning in the data, adds constraints for future research

1 **No statistical evidence of lightning in Venus night-side atmosphere**
2 **from VIRTIS-Venus Express Visible observations**

3 by

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15 **Keywords:** Lightning, Venus, Venus atmosphere, image processing, spectroscopy

16

17 ***Abstract***

18 In this study we describe a dedicated analysis of luminous transient events on Venus night side
19 atmosphere with the visible channel of the VIRTIS instrument, this being the most comprehensive
20 search of lightning conducted so far with Venus Express data. Our search results in thousands of
21 signal detections, but unfortunately they can be all explained by cosmic rays impinging on the
22 detector, and further statistical analysis shows that all of the events are randomly distributed along
23 the spectral dimension, therefore not showing any clear evidence of signal coming from lightning
24 emission in the Venus atmosphere. This does not exclude the existence of lightning, but imposes
25 some constraints on their occurrence that are important for future research.

26 ***1. Introduction***

27 Lightning is of great interest in the field of planetary science since each electrical discharge produce
28 a channel of high-pressure, high-temperature gas that enables chemical reactions that would not
29 occur under normal atmospheric conditions. These reactions can potentially alter the chemical
30 composition and physical properties of planetary atmospheres. Lightning can also have important
31 implications for energy/radiation balance, for example through the production of nitrogen oxides
32 that on Earth are associated with ozone production [Yiung 2009]. Additionally, the presence of
33 lightning can be a hazard to planetary probes such as landers or balloons [Russell 2006] that need
34 to be taken into account for exploration programmes.

35 ***1.1. Observations of Lightning on Venus***

36 Lightning is known to occur in the atmospheres of Earth, Jupiter, Saturn, Uranus and Neptune. Its
37 occurrence on Venus has been observed multiple times in the past. Most of the postulated events of
38 Venus lightning come from electromagnetic pulse detections, reported in the framework of the
39 Venera, Pioneer Venus Orbiter and Galileo missions. For instance, it has been detected with an
40 electric antenna at various low frequencies [Taylor 1979; Scarf 1980; Russell 1991], with radio
41 waves through the ionosphere [Gurnett 1991], with electric signals within the ionosphere [Russell
42 1991], and with electric and magnetic antennas within the atmosphere [Strangeway 1993;

43 Ksanfomaliti 1983].

44 More recently, Venus Express (VEX) was in orbit around the planet since 2006 until 2014,
45 following a 24h polar elliptical orbit that allowed the long term monitoring of the Venusian
46 atmosphere. VEX detected high levels of electromagnetic activity in the atmosphere at ELF
47 frequencies as measured by the flux-gate magnetometer, with an occurrence rate and wave energy
48 similar to terrestrial values arising from lightning activity [Russell 2007; Daniels 2012].

49 Even if these electromagnetic measurements are now well established, the only optical detections
50 to date were obtained decades ago by the Venera 9 mission [Krasnopolsky, 1980] and from the
51 ground [Hansell, 1995]. No optical or infrared lightning emission evidence has been reported so far
52 by any of the instruments of VEX [Erard, 2008]. Therefore a comprehensive study of the VIRTIS
53 spectral data set is granted to improve our understanding of lightning emissions on Venus.

54 ***1.2. Predictions of lightning emission on Venus***

55 Lightning on Earth has the strongest emission lines at 777.3nm and 844.6nm, corresponding to
56 atomic oxygen, which are easily observable from space [Gordillo, 2011]. Laboratory measurements
57 at higher pressures predict that the dominant line at Venus should be the 777.3nm oxygen line
58 [Borucki 1981 and 1996]. However the lightning events on Venus are expected to occur inside or
59 below the cloud layer [Garnett 1991], and because of the height of the clouds, intra-cloud lightning
60 are mostly expected, therefore making the potential detection of lightning from space difficult.

61 Other Transient Luminous Events (TLEs) like Sprites, Elves and Halos (streamer type electrical
62 discharges) are likely to appear at higher altitudes and could be potentially more amenable to
63 remote sensing. TLEs are secondary phenomena that occur in the upper atmosphere in association
64 with underlying lightning, and will hence also be of interest in this project. Current estimations
65 indicate that they could occur above 85 km, with a dominant emission around 280-420 nm,
66 peaking at 337 nm, corresponding to the second positive band of N₂, with no presence of oxygen
67 emissions. [Dubrovin 2010]

68 **2. Analysis**

69 **2.1. VIRTIS Visible Night Side Data Set**

70 The Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) has a mapping channel
71 (VIRTIS-M), which is a scanning slit spectrometer with high-resolution imaging (3.3° FOV,
72 $250\mu\text{rad}$ per pixel) in the visible-infrared range ($0.28\text{--}5\mu\text{m}$) at moderate spectral resolution (10nm
73 in IR and 2nm in VIS). VIRTIS is also equipped with a high-resolution spectroscopy channel
74 (VIRTIS-H) in the $2\text{--}5\mu\text{m}$ range, although this is not used in this study. The scientific objectives of
75 VIRTIS range a large diversity, from the study of the thermal emission of the surface up to the
76 composition and dynamics of the upper atmosphere [Piccioni 2007].

77 The use of VIRTIS for a lightning search is limited by the technical design of the instrument, a “line
78 scanner” that was not meant for detection of transient events. In VIRTIS, any kind of short
79 temporary signal causes a variation only in a few pixels of a single acquisition of the detector. This
80 makes it very difficult to identify lightning in the data, and initial attempts with data from the
81 infrared arm of the instrument were inconclusive [Erard 2008]. Moreover, it is likely that singular
82 events will be filtered out by the calibration pipeline. Therefore any dedicated lightning study
83 requires analysis of the raw data, avoiding the data processing steps that could eliminate valuable
84 traces of lightning signal [Cardesin 2010].

85 VIRTIS has an extensive coverage of the atmosphere from 0.3 to 5 microns, but our analysis is
86 focused in the visible channel as it is expected that lightning have a stronger signal in the visible
87 wavelengths [Borucki 1996]. The lightning search is performed only in the night side images to
88 increase the signal to noise ratio, and to avoid any signal from the sun reflected by the cloud tops.
89 The signal received from the night atmosphere in the visible range is almost negligible, so this
90 maximizes the chances to detect any trace of signal from transient lightning events.

91 The exposure times of the instrument may range from a few milliseconds up to 18 seconds. In our
92 study, all exposure times were taken into account but the long exposures of several seconds are the
93 most useful ones as they maximize the chances of detecting a transient event during the exposure.

94 The analysis has been done with the whole VIRTIS archive for the full lifetime of the mission. This

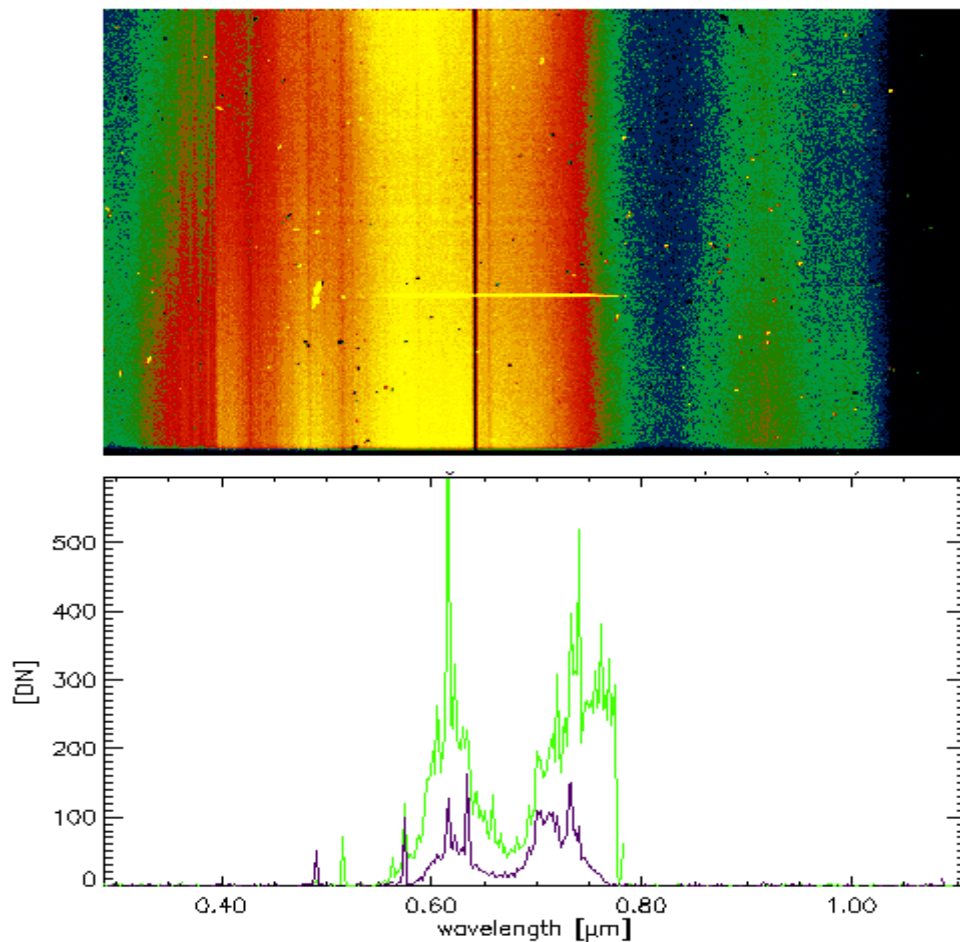
means that more than 10,000 spectral images have been processed for detection of transient events. Due to the geometry of the Venus Express polar orbit with the apocenter over the south pole [Titov 2006], the coverage is much better in southern latitudes, especially at high latitudes near the south pole, where the accumulated integration time over the whole lifetime of the missions goes beyond 5000 seconds. This accumulated exposure time is significantly lower at low latitudes (1000s around the equator) and very low in the northern hemisphere (60s or less).

2.2. *Search Algorithm*

A specific search algorithm for transient events was developed for this study. The algorithm considers each observation file and aims to detect signal variation peaks within each data frame acquisition with respect to the adjacent frames. This algorithm was used in all raw VIRTIS-M Visible data in the Venus night side, and was executed numerous times with configurable parameters and filters for various geometrical and operational parameters. Default search parameters constrained local time (night side 5h-19h to remove dayside background), latitude (-85° to 85° , to exclude straylight from terminator at the poles), various integration times (long exposures from 0.2 to 20s), and minimum detection thresholds (50 digital counts at least to ignore random noise). Besides this default analysis of the archive, a total of 12 additional tests were performed including different criteria to focus on limbs, pure nadirs, terminator and polar observations, single emission lines, including special filtering for solar straylight, various thresholds and other combinations of geometrical and observational parameters.

This search algorithm successfully identified transient events in the VIRTIS data and produced thousands of detections for each search of the data archive depending on the detailed parameters. A single example of the events that could be detected in the data is shown in Figure 1, where a significant peak is detected with hundreds of digital counts over the background signal, and having maximum peaks around $0.6\mu\text{m}$ and $0.75\mu\text{m}$, somehow close to the expected wavelength range predicted for lightning. However when looking at all the results, we observe all kinds of spectrum profiles and maximum peaks distributed over all wavelengths, which was incoherent with the existence of lightning in the data if arising from lightning. Careful visual analysis of the identified events showed that many of the detections were most likely caused by cosmic rays impacting the

123 detector and producing a signal that mimicked to some extent that of lightning. Even if some
 124 criteria were imposed in the algorithm to ignore some events that were obviously not physically
 125 possible (e.g. oblique traces on the detector not aligned with the optics) the high number of
 126 transient events detected in the archive made it impossible to understand whether any of these
 127 detected signals were caused by physical events in the Venusian atmosphere or simply caused by
 128 random cosmic rays. In other words, we could not establish which of these detections were simply
 129 random events, hence a statistical analysis was required.

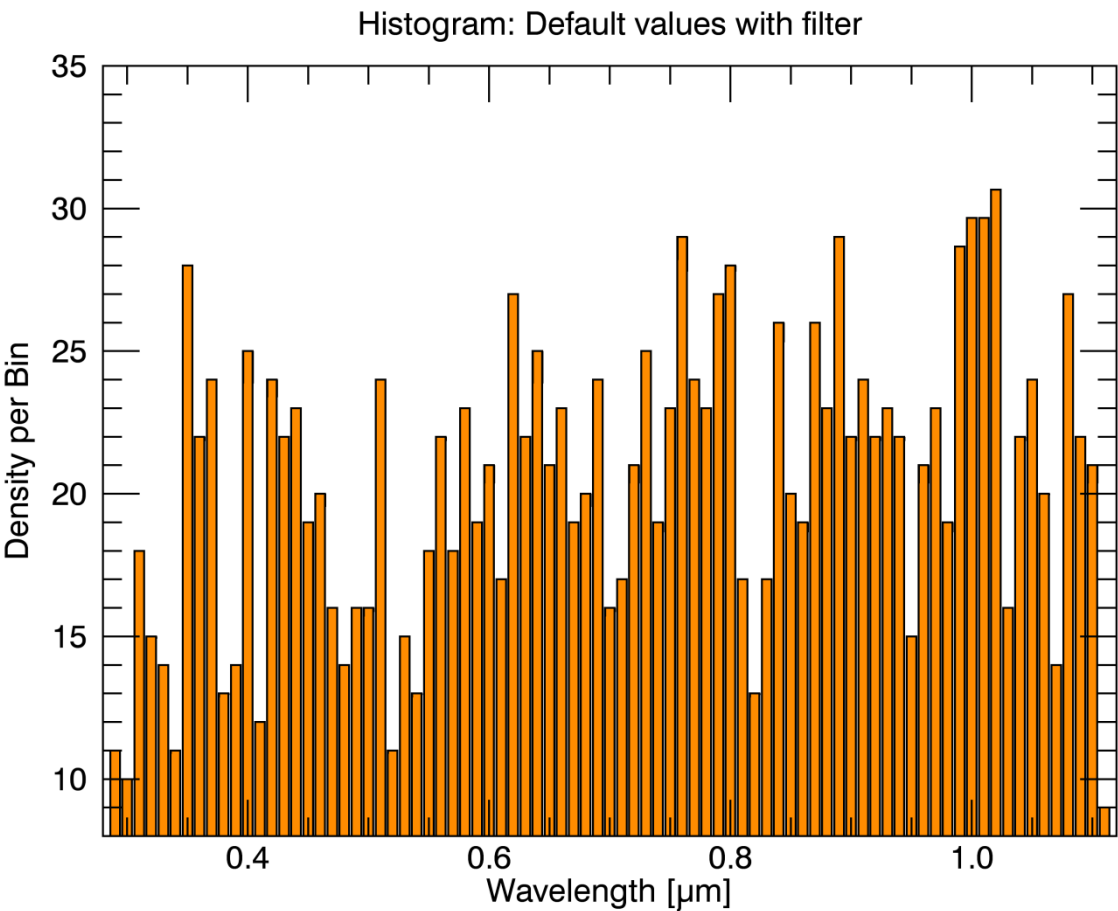


130

131 Figure 1: Simple example of transient signal event detected in the VIRTIS Visible data. Image
 132 above shows the 2-dimensional frame as acquired by the VIRTIS-M-Visible detector. Color is
 133 equalized for better visualization, showing low background signal from the sun scattered by
 134 the clouds and an interesting peak that covers two samples (Y-axis) and extends along the
 135 spectral direction (X-Axis). The plot below shows the spectrum profile of the two samples
 136 where a peak is detected, with background signal subtracted. (Digital Number units with
 137 respect to wavelength in microns)

138 **2.3. Statistical analysis of the results**

139 The purpose of this statistical analysis was to identify any non-random pattern in the wavelengths
140 of the transient events that were previously detected. Whereas the cosmic rays are random by
141 nature and may occur at any wavelength depending on where they fall within the detector, all
142 lightning emissions are expected to emit with a fixed spectral signature, most likely peaking at the
143 predicted 777.3 nm, although for the scope of this study the whole visible range was studied. The
144 statistical analysis was performed by constructing histograms with the wavelength of the maximum
145 peak for each transient event detected, so we could determine whether one wavelength was more
146 prominent than others.



147
148 Figure 2: Histogram showing the density distribution of wavelengths of the maximum peaks
149 for all transient events in one of the tests with default search parameters. X axis shows the
150 wavelength in micron. Y axis shows the number of times a maximum peak appears in a given
151 wavelength, with a bin size of 10nm. The histogram for this test shows more than 1,700
152 transient events in the data and we can observe that maximum peaks are randomly

distributed in wavelength. This test shows a minor peak (around $1\mu\text{m}$) but careful analysis of the data showed that this can be explained by anomalous measurements or instrumental effects.

In order to illustrate the first study with default search parameters explained in the previous section (night side images with long exposure times, ignoring poles, etc.), we obtained more than 1,700 transient events in the data, but when performing the statistical analysis of the maximum peaks with the wavelength histogram shown in Figure 2, we can observe that the peaks were randomly distributed along the spectrum and therefore all events can simply be explained by random cosmic rays with no repetition pattern. In some other test cases we have seen noticeable peaks that could imply a wavelength pattern, but careful analysis of the data showed that these peaks were always explained by instrumental effects or anomalous features that could not be identified as lightning (e.g. straylight, cosmic rays, etc.).

To summarize, histograms were created for all of the tests with various search parameters (different thresholds, various geometrical conditions) even focusing on particular areas and observation types (high latitudes, limb observations, long nadir exposures, etc.), and although some minor peaks appeared, in general none of the histograms showed any clear indication of lightning.

3. Summary and Conclusions

In this study we have developed a dedicated search algorithm for the detection of transient events in the VIRTIS data and we have analyzed one by one all of the visible hyperspectral images in the data archive focusing in the night side atmosphere, which makes this study the most comprehensive search for lightning performed so far with Venus Express optical data. This detailed analysis has been performed with various search filters based on geometrical parameters and several detection thresholds. In total, 13 tests with different parameters were performed and thousands of transient events were detected in the data, but all the events could easily be explained simply by the effect of random cosmic rays on the visible sensor, instrumental effects or anomalous features. Statistical analysis of the detections showed a random wavelength distribution of the peaks, which matches the expected behavior of cosmic events. Therefore there is no clear evidence

181 of the detection of lightning or any other significant Transient Luminous Events (TLE's) in the
182 night side atmosphere of Venus. As a secondary conclusion of this research, we can also confirm
183 that we have not found evidence of other transitory emissions that could also be expected in the
184 atmosphere, such as meteor showers.

185 **3.1. Discussion**

186 For clarity, the absence of statistical evidence for lightning in this analysis does not imply that it
187 does not occur in the atmosphere of Venus. Our study therefore does not directly contradict any of
188 the detections previously reported in literature. We however consider that the lack of evidence in
189 VIRTIS visible data can be very useful to constrain the expected lightning rate and intensity, and
190 this might improve the chances to find optical evidence in the future. In a similar way, the fact that
191 meteor shower emissions do not appear to be statistically relevant in our research does not imply
192 their complete absence, as they are indeed expected to occur in the atmospheric layers as observed
193 in the Earth.

194 The absence of evidence for lightning in the VIRTIS-M-VIS data can be interpreted in several ways.
195 The most probable explanation is that the lightning emission is too low or it is absorbed by the
196 ever-present cloud layer. The electromagnetic intensity of the lightning events has been analyzed in
197 the past by the VEX magnetometer and found to be similar to the ones on Earth [Russell 2006,
198 Daniels 2012]. There have been previous optical detections for lighting [Hansell 1995] and several
199 studies for the absorption and angular dispersion of simulated lightning photons predict that the
200 emissions could be visible at the cloud tops from space-borne instrumentation [Thomason &
201 Krider, 1982; Koshak 1994]. The results of our study could then imply that the upwards
202 propagation of lightning emissions could be totally absorbed by the cloud column, so based on this
203 result one could constrain the reference altitude of the original lightning emissions below the
204 clouds making a radiative transfer analysis using some of the expected wavelength of the emissions
205 and setting a reference energy level as observed on Earth. However this exercise is out of the scope
206 of this research and it is proposed as future work.

207 Another explanation for the lack of statistical evidence is that the occurrence of transient emissions
208 on Venus could be too rare to appear relevant in the histograms. This is indeed possible for some

209 momentary events and we believe it is the most likely explanation for the emissions caused by
210 meteor showers as in fact they are expected to be rare [Christou 2010], so even if some of the signal
211 could be present in our data, it might not be statistically significant. However, in the case of
212 lightning this explanation is not in line with the results of the VEX magnetometer that observed
213 high rates in the order of several occurrences per second, similar to Earth [Russell 2006, Daniels
214 2012]. This possibility is in principle excluded considering the good atmospheric coverage of
215 VIRTIS over the years, with a total integration time of thousands of seconds per 1 degree² surface
216 element over the southern hemisphere, therefore we can consider it unlikely that lightning
217 emission is not seen in the data due to their expected frequency of appearance.

218 An additional justification for our results could have potential implications in the geographical
219 location of the lightning emissions. As we have only analyzed the night side of the atmosphere, we
220 cannot exclude that these and other electromagnetic events could be happening only on the dayside
221 of Venus where unfortunately they would be masked by the solar illumination reflected by the
222 cloud tops and not be visible in our search. This implication regards also the possibility of lightning
223 occurring near the terminator or the poles, as the signal could be hidden by the solar radiation
224 coming from the dayside, again making it difficult to detect in the data.

225 **3.2. *Considerations for future research***

226 As a final conclusion of this work, we would like to share some recommendations for future
227 research on this topic. First of all we encourage the analysis of other data sets that could contain
228 additional valuable information in this topic, as for the visible night side data images from the
229 Venus Monitoring Camera, also on-board Venus Express, and in particular the new data from the
230 Akatsuki mission that has recently been inserted into orbit around Venus carrying a high-speed
231 imager to search for lightning flashes. Detailed analysis of these data will very likely bring more
232 enlightenment into the subject. Nonetheless we have demonstrated with our analysis that
233 thousands of signal detections, many of them at the expected wavelength, or many good spectrum
234 profiles is not enough to demonstrate the detection of lightning. For this reason, we want to insist
235 on the importance of the cosmic rays when analyzing any new data in the future, and remark the
236 difficulty to demonstrate that signal detection is actually coming from the planet and is not just a

237 random event. For all these reasons and to avoid questioning future results, we propose that future
238 instrumentation for lightning detection gives high priority to the exclusion of cosmic rays, for
239 example having two distinct detectors, probably sharing the same optics that could measure
240 independently the same signal peak with the same geometry for unambiguous detection.

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249 **5. References**

- 250 Borucki, W. J. et al : Optical Search for Lightning on Venus, *Geophysical Research Letters*, Vol. 8,
251 No.3, Pages 233-236, 1981
- 252 Borucki, W. J. et al : Spectral Irradiance Measurements of Simulated Lightning in Planetary
253 Atmospheres, *ICARUS* 123, 336–344, Article No. 0162, 1996
- 254 Cardesin Moinelo, A. et al : Calibration of Hyperspectral Imaging Data: VIRTIS-M Onboard Venus
255 Express, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 48, No. 11, 2010
- 256 Christou, A. A., Annual meteor showers at Venus and Mars: lessons from the Earth. *Monthly*
257 *Notices of the Royal Astronomical Society*, 402: 2759–2770, 2010
- 258 Daniels, J. T. M., Russell, C.T. et al.: Whistler mode bursts in the Venus ionosphere due to
259 lightning: Statistical properties using Venus Express magnetometer observations, *Journal of*
260 *Geophysical Research: Planets*, Volume 117, Issue E4, 2012
- 261 Dubrovin, D. et al : Sprite discharges on Venus and Jupiter-like planets: A laboratory investigation,
262 *Journal of Geophysical Research*, VOL. 115, A00E34, 2010

263 Erad, S. et al : Multivariate analysis of Visible and Infrared Thermal Imaging Spectrometer
 264 (VIRTIS) Venus Express night side and limb observations, Journal of Geophysical Research, Vol.
 265 114, E00B27, 2008

266 Gordillo Vazquez, F.J. et al : Spectrum of sprite halos, Journal of Geophysical Research, Vol. 116,
 267 A09319, 2011

268 Gordillo Vazquez, F.J. et al : Near infrared and ultraviolet spectra of TLEs, Journal of Geophysical
 269 Research, Vol. 117, A05329, 2012

270 Gurnett, D. A., et al : Lightning and plasma wave observations from the Galileo flyby of Venus,
 271 Science, 253, 1522–1525, 1991

272 Hansell, S. A., W. K. Wells, and D. M. Hunten: Optical detection of lightning on Venus, Icarus, 117,
 273 345–351, 1995

274 Koshak, W.J., Solakiewicz, R. J., Phanord, D. D. and Blakeslee R.: Diffusion model for lightning
 275 radiative transfer, Journal of Geophysical Research, Vol. 99, No. D7, 14361-14371, July 20, 1994

276 Krasnopolsky, V. A., Lightning on Venus according to information obtained by the satellites Venera
 277 9 and 10, Kosm. Issled., 18, 429–434, 1980

278 Ksanfomaliti, L. V. et al: Electrical activity of the atmosphere of Venus. I. Measurements on
 279 descending probes, Kosm. Issled., 21, 279–296. 1983

280 Piccioni, G. and 65 colleagues, VIRTIS: The Visible and Infrared Thermal Imaging Spectrometer, in
 281 ESA-SP-1295, 2007

282 Russell, C. T., R. J. Strangeway, and T. L. Zhang, Lightning detection on the Venus Express
 283 mission, Planet. Space Sci. 54, 1344–1351, 2006

284 Scarf, F.L., Taylor, W.W.L., Russell, C.T., Brace, L.H.. Lightning on Venus: orbiter detection of
 285 whistler signals. J. Geophys. Res. 85, 8158–8166. 1980

286 Strangeway, R.J., Russell, C.T., Ho, C.M., Brace, L.H.. Plasma waves observed at low altitudes in
 287 the tenuous Venus night side ionosphere. Geophys. Res. Lett. 20, 2767–2770. 1993

288 Taylor, W.W.L., Scarf, F.L., Russell, C.T., Brace, L.H.,. Evidence for lightning on Venus. Nature

289 279, 614–616. 1979

290 Thomason, L. W. and Krider, E. P., The Effects of Clouds on the Light Produced by Lightning,
291 American Meteorological Society, 0022-4928/82/092051-15, 1982

292 Titov, D. V., Svedhem, H., et al. Venus express: Highlights of the nominal mission, Solar System
293 Research, vol. 43, p. 185-209, 2009

294 Yair, Y., Takahashi, Y., Yaniv, R., Ebert, U., Goto, Y., A study of the possibility of sprites in the
295 atmospheres of other planets. J. Geophys. Research. 114, E9. 2009

296 Zhang, T.L., Baumjohann, W., et al. Magnetic field investigation of the Venus plasma environment:
297 expected new results from Venus Express. Planet. Space Sci. 54, 1336–1343. 2006