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Figures

Figure 1: Simple example of transient signal event detected in the VIRTIS Visible data

Figure 2: Histogram showing the wavelength distribution of the signal peaks found in the data

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

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 constrains for future research

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

by

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Abstract

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

1. Introduction

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

1.1. Observations of Lightning on Venus

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

Ksanfomaliti 1983].

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

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

1.2. Predictions of lightning emission on Venus

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

Other Transient Luminous Events (TLEs) like Sprites, Elves and Halos (streamer type electrical discharges) are likely to appear at higher altitudes and could be potentially more amenable to remote sensing. TLEs are secondary phenomena that occur in the upper atmosphere in association with underlying lightning, and will hence also be of interest in this project. Current estimations indicate that they could occur above 85 km, with a dominant emission around 280-420 nm, peaking at 337 nm, corresponding to the second positive band of N_2, with no presence of oxygen emissions. [Dubrovin 2010]

2. Analysis

2.1. VIRTIS Visible Night Side Data Set

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

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

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

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

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 0.6µm and 0.75µm, 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 detector and producing a signal that mimicked to some extent that of lightning. Even if some criteria were imposed in the algorithm to ignore some events that were obviously not physically possible (e.g. oblique traces on the detector not aligned with the optics) the high number of transient events detected in the archive made it impossible to understand whether any of these detected signals were caused by physical events in the Venusian atmosphere or simply caused by random cosmic rays. In other words, we could not establish which of these detections where simply random events, hence a statistical analysis was required.

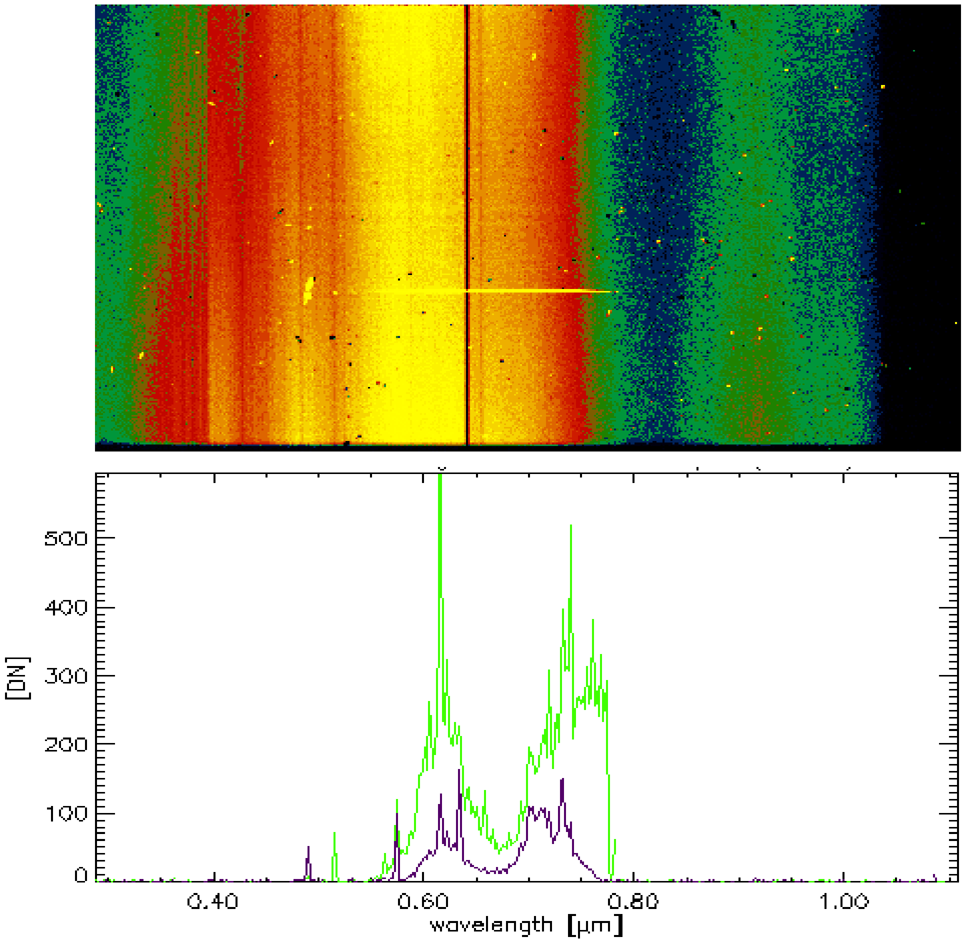

Figure 1: Simple example of transient signal event detected in the VIRTIS Visible data. Image above shows the 2-dimensional frame as acquired by the VIRTIS-M-Visible detector. Color is equalized for better visualization, showing low background signal from the sun scattered by the clouds and an interesting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

2.3. Statistical analysis of the results

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

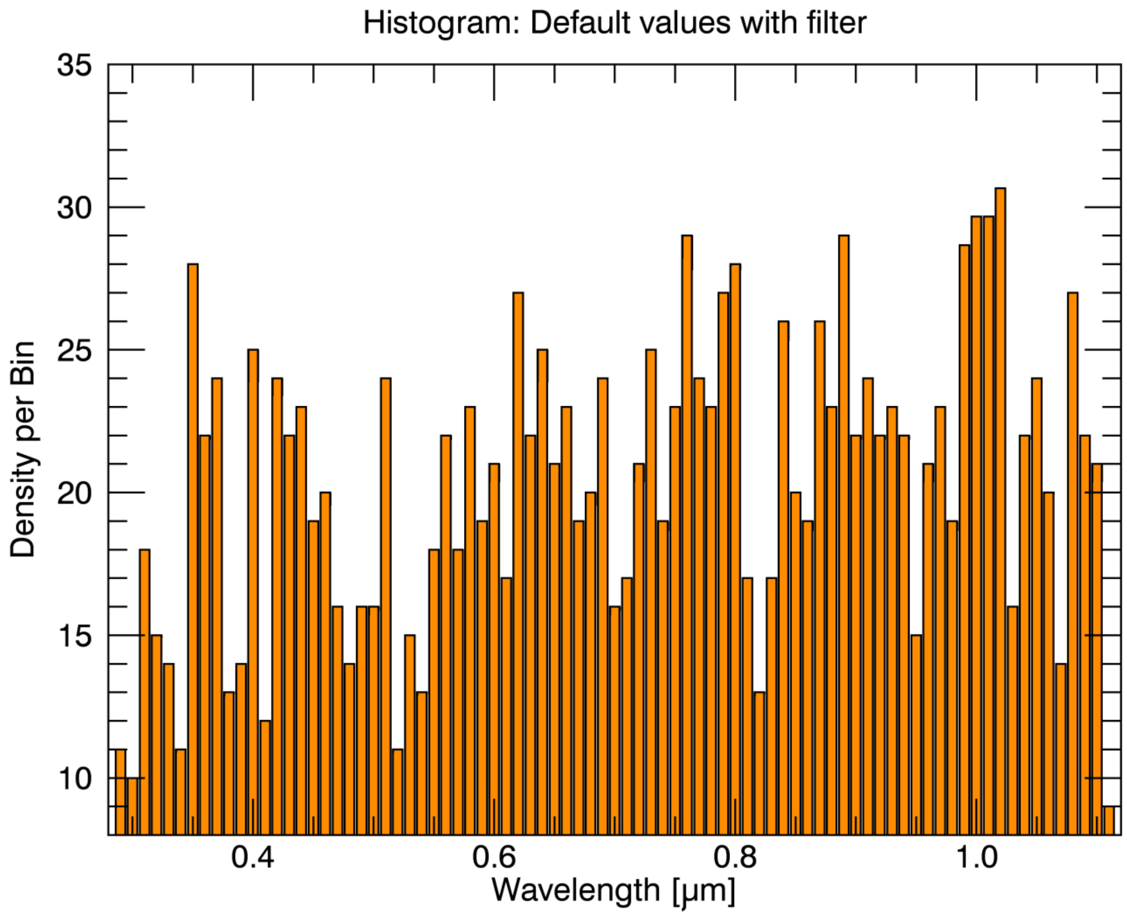

Figure 2: Histogram showing the density distribution of wavelengths of the maximum peaks for all transient events in one of the tests with default search parameters. X axis shows the wavelength in micron. Y axis shows the number of times a maximum peak appears in a given wavelength, with a bin size of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

distributed in wavelength. This test shows a minor peak (around 1μm) 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 of the detection of lightning or any other significant Transient Luminous Events (TLE's) in the night side atmosphere of Venus. As a secondary conclusion of this research, we can also confirm that we have not found evidence of other transitory emissions that could also be expected in the atmosphere~~,~~ such as meteor showers.

3.1. Discussion

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

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

Another explanation for the lack of statistical evidence is that the occurrence of transient emissions on Venus could be too rare to appear relevant in the histograms. This is indeed possible for some momentary events and we believe it is the most likely explanation for the emissions caused by meteor showers as in fact they are expected to be rare [Christou 2010], so even if some of the signal could be present in our data, it might not be statistically significant. However, in the case of lightning this explanation is not in line with the results of the VEX magnetometer that observed high rates in the order of several occurrences per second, similar to Earth [Russell 2006, Daniels 2012]. This possibility is in principle excluded considering the good atmospheric coverage of VIRTIS over the years, with a total integration time of thousands of seconds per 1 degree^2 surface element over the southern hemisphere, therefore we can consider it unlikely that lightning emission is not seen in the data due to their expected frequency of appearance.

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

3.2. Considerations for future research

As a final conclusion of this work, we would like to share some recommendations for future research on this topic. First of all we encourage the analysis of other data sets that could contain additional valuable information in this topic, as for the visible night side data images from the Venus Monitoring Camera, also on-board Venus Express, and in particular the new data from the Akatsuki mission that has recently been inserted into orbit around Venus carrying a high-speed imager to search for lightning flashes. Detailed analysis of these data will very likely bring more enlightenment into the subject. Nonetheless we have demonstrated with our analysis that thousands of signal detections, many of them at the expected wavelength, or many good spectrum profiles is not enough to demonstrate the detection of lightning. For this reason, we want to insist on the importance of the cosmic rays when analyzing any new data in the future, and remark the difficulty to demonstrate that signal detection is actually coming from the planet and is not just a random event. For all these reasons and to avoid questioning future results, we propose that future instrumentation for lightning detection gives high priority to the exclusion of cosmic rays, for example having two distinct detectors, probably sharing the same optics that could measure independently the same signal peak with the same geometry for unambiguous detection.

4. *Acknowledgments*

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