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9 Figures

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

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

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15 Keywords:

16 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

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

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## 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 N<sub>2</sub>, 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 ( $3.3^\circ$  FOV,  
72  $250\mu\text{rad}$  per pixel) in the visible-infrared range ( $0.28\text{-}5\mu\text{m}$ ) at moderate spectral resolution ( $10\text{nm}$   
73 in IR and  $2\text{nm}$  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

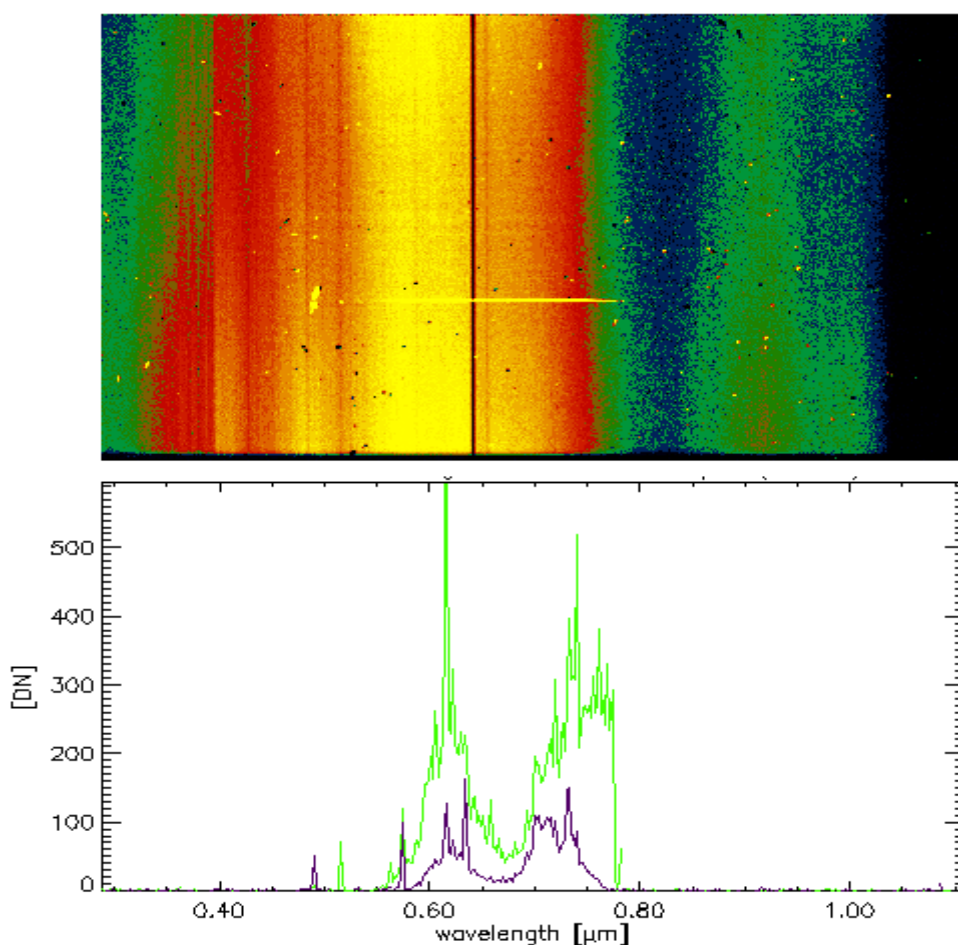
95 means that more than 10,000 spectral images have been processed for detection of transient  
96 events. Due to the geometry of the Venus Express polar orbit with the apocenter over the south  
97 pole [Titov 2006], the coverage is much better in southern latitudes, especially at high latitudes  
98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

## 101 **2.2. Search Algorithm**

102 A specific search algorithm for transient events was developed for this study. The algorithm  
103 considers each observation file and aims to detect signal variation peaks within each data frame  
104 acquisition with respect to the adjacent frames. This algorithm was used in all raw VIRTIS-M  
105 Visible data in the Venus night side, and was executed numerous times with configurable  
106 parameters and filters for various geometrical and operational parameters. Default search  
107 parameters constrained local time (night side 5h-19h to remove dayside background), latitude (-  
108  $85^\circ$  to  $85^\circ$ , to exclude straylight from terminator at the poles), various integration times (long  
109 exposures from 0.2 to 20s), and minimum detection thresholds (50 digital counts at least to ignore  
110 random noise). Besides this default analysis of the archive, a total of 12 additional tests were  
111 performed including different criteria to focus on limbs, pure nadirs, terminator and polar  
112 observations, single emission lines, including special filtering for solar straylight, various  
113 thresholds and other combinations of geometrical and observational parameters.

114 This search algorithm successfully identified transient events in the VIRTIS data and produced  
115 thousands of detections for each search of the data archive depending on the detailed parameters.  
116 A single example of the events that could be detected in the data is shown in Figure 1, where a  
117 significant peak is detected with hundreds of digital counts over the background signal, and having  
118 maximum peaks around  $0.6\mu\text{m}$  and  $0.75\mu\text{m}$ , somehow close to the expected wavelength range  
119 predicted for lightning. However when looking at all the results, we observe all kinds of spectrum  
120 profiles and maximum peaks distributed over all wavelengths, which was incoherent with the  
121 existence of lightning in the data if arising from lightning. Careful visual analysis of the identified  
122 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.

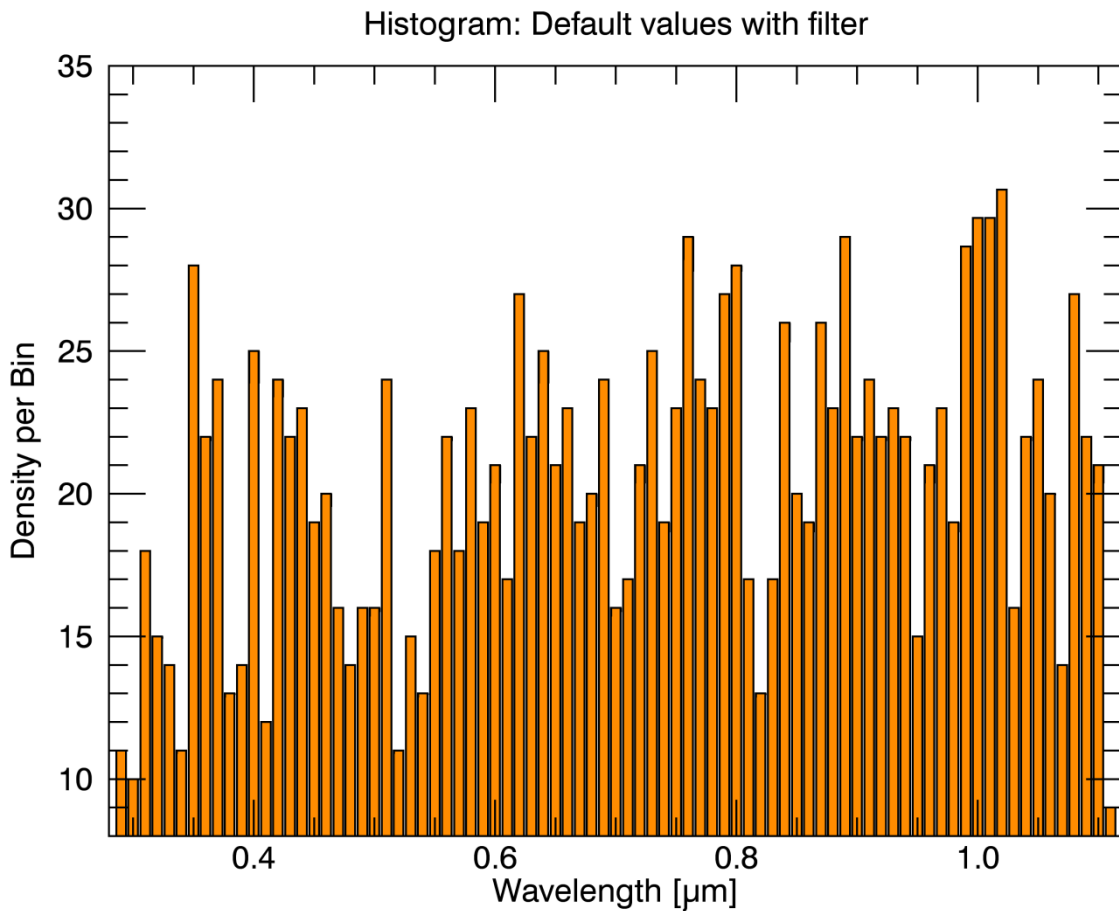


130

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

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

156 In order to illustrate the first study with default search parameters explained in the previous  
157 section (night side images with long exposure times, ignoring poles, etc.), we obtained more than  
158 1,700 transient events in the data, but when performing the statistical analysis of the maximum  
159 peaks with the wavelength histogram shown in Figure 2, we can observe that the peaks were  
160 randomly distributed along the spectrum and therefore all events can simply be explained by  
161 random cosmic rays with no repetition pattern. In some other test cases we have seen noticeable  
162 peaks that could imply a wavelength pattern, but careful analysis of the data showed that these  
163 peaks were always explained by instrumental effects or anomalous features that could not be  
164 identified as lightning (e.g. straylight, cosmic rays, etc.).

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

### 170 **3. Summary and Conclusions**

171 In this study we have developed a dedicated search algorithm for the detection of transient events  
172 in the VIRTIS data and we have analyzed one by one all of the visible hyperspectral images in the  
173 data archive focusing in the night side atmosphere, which makes this study the most  
174 comprehensive search for lightning performed so far with Venus Express optical data. This detailed  
175 analysis has been performed with various search filters based on geometrical parameters and  
176 several detection thresholds. In total, 13 tests with different parameters were performed and  
177 thousands of transient events were detected in the data, but all the events could easily be explained  
178 simply by the effect of random cosmic rays on the visible sensor, instrumental effects or anomalous  
179 features. Statistical analysis of the detections showed a random wavelength distribution of the  
180 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 lightning [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 degree<sup>2</sup> 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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246 Magnetometer.

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