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Investigating multiple ELVES and halos above strong lightning with the fluorescence detectors of the Pierre Auger Observatory

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ELVES are being studied since 2013 with the twenty-four FD Telescopes of the Pierre Auger Observatory, in the province of Mendoza (Argentina), the world's largest facility for the study of ultra-high energy cosmic rays. This study exploits a dedicated trigger and extended readout. Since December 2020, this trigger has been extended to the three High Elevation Auger Telescopes (HEAT), which observe the night sky at elevation angles between 30 and 60 degrees, allowing a study of ELVES from closer lightning. The high time resolution of the Auger telescopes allows us to upgrade reconstruction algorithms and to do detailed studies on multiple ELVES. The origin of multiple elves can be studied by analyzing the time difference and the amplitude ratio between flashes and comparing them with the properties of radio signals detected by the ENTLN lightning network since 2018. A fraction of multi-ELVES can also be interpreted as halos following ELVES. Halos are disc-shaped light transients emitted at 70-80 km altitudes, appearing at the center of the ELVES rings, due to the rearrangement of electric charges at the base of the ionosphere after a strong lightning event.

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1. Introduction

The Pierre Auger Observatory is the world's largest infrastructure for the study of ultra-high energy cosmic rays. Besides its main activity, the Observatory has started a program of cosmo geophysics studies, which exploit some of the unique features of its detectors. ELVES (Emission of Light and Very low-frequency perturbations due to Electromagnetic pulse Sources) are transient luminous events occurring at the base of the ionosphere when a strong electromagnetic pulse (EMP) is emitted by lightning. This phenomenon, theoretically predicted a few years before [1], was photographed for the first time in 1990 from the Space Shuttle [2]. For an observer on the ground, ELVES appear as rapidly expanding rings, smoothly fading towards the horizon, and can be observed at distances farther than 250 km from our fluorescence detector (FD) [3]. The center of the expanding rings is not above the vertical of the causative lightning, but at the point of minimum light path between source and observer, as we explained in our previous papers [4, 5]. By projecting the traces observed at ground to the emission layer at the base of the ionosphere and properly correcting for the time delay in each pixel, we observe the resulting light front expanding outwards with respect to the lightning center.

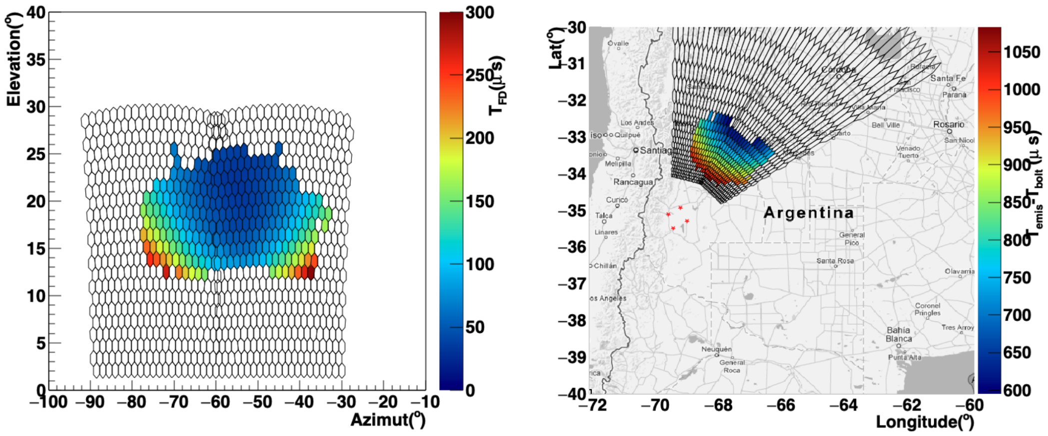

Figure 1: Time evolution of an ELVES : (a) in the camera (b) at the emission layer.

The events triggered by Auger are produced by lightning sources far enough from the FD, such that the earth's curvature prevents the direct light from reaching our sensors. Since 2013, we developed a dedicated trigger and readout scheme to study these events using the twenty-four FD Telescopes [6–8]. Since 2017, we have extended the length of recorded traces to up to 0.9 ms to fully measure the doughnut-shaped region of maximum emission. Such an upgrade has opened perspectives for observation of other types of Transient Luminous Events (TLEs from now on), such as the halos, which will be reported in the following sections. In December 2020, we implemented the ELVES trigger and readout in the data taking of the three additional high-elevation telescopes (HEAT).

2. Correlation of multiple ELVES with lightning waveforms from ENTLN

The time resolution of the Auger Observatory, coupled with its 2D imaging capability, allows us to study in detail the fine structure of the light emission in ELVES events, often characterized by two or more distinct flashes. While double ELVES have been reported many times in the literature [9–11], Auger has been the first experiment to report the observation of a triple ELVES event [12].

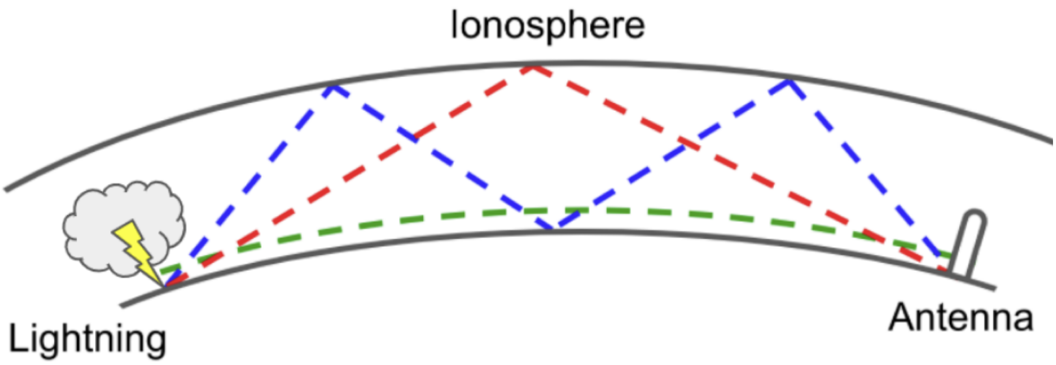

Figure 2: Propagation of radio waves between earth and ionosphere: surface wave (green), 1st sky wave (red), 2nd sky wave (blue).

The strong electromagnetic pulse (EMP) which produces the ELVES can also be detected at the round by networks of radio antennas; the EMP propagates towards the antennas either following the surface of the earth (with a shorter attenuation length) or repeatedly bouncing between the base of the ionosphere and the ground, as in a resonant cavity, as shown in Fig.2.

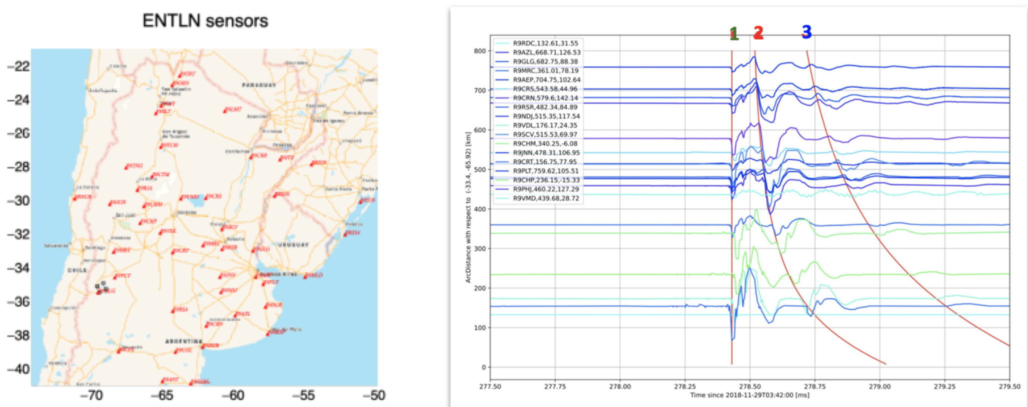

Figure 3: Map of the ENTLN stations in Argentina (left); ENTLN traces sorted as a function of Arc Distance from the lightning location (right).

By comparing the radio waveforms with the UV light emissions of the ELVES, we can study the mechanism underlying the production of multiple ELVES. The Earth Networks Lightning Network (ENTLN) has installed more than 35 antennas, shown in Figure 3 left, in the austral summer 2018-9 [13, 14]. Each antenna has a bandwidth of up to 24 MHz. The ENTLN time resolution is 1 μs. Besides lightning locations, energy and polarization, ENTLN provide waveforms of each antenna, shown in Figure 3, right. Using lightning longitude and latitude provided by the ELVES reconstruction algorithm to calculate the time offset between the antenna traces, we observe that signals align consistently. By sorting the signals with the distance of the antenna from the lightning source, one can distinguish the surface wave (1, in green), the first sky wave (2, in red), directly related to the ELVES emission, and even the second sky wave (3, in blue).

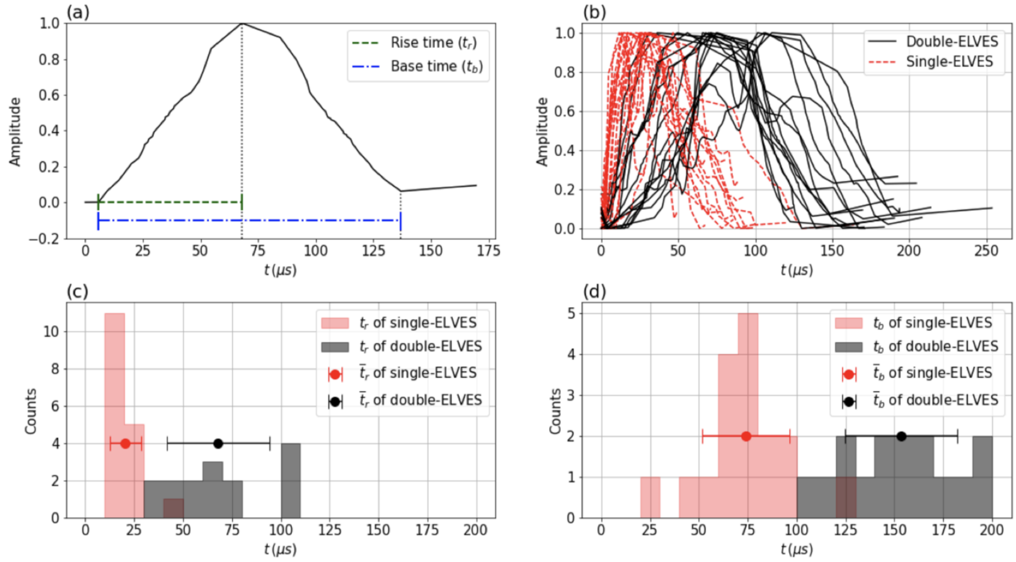

Figure 4: ENTLN traces: (a) definition of risetime and basetime in the waveforms; (b) single ELVES in red and double ELVES in black; distribution of (c) risetimes and (d) basetimes.

The night between April 27 and 28, 2020 contains the largest number of multiple ELVES candidates, produced by one mesoscale convective system developing around 0 UTC at 35°S, 66°W, and a second one, farther away, initiated at 34°S, 62°W, both evolving in a SE direction. We have used the events from this night to search for features that allow us to distinguish double ELVES from single ELVES in the waveforms. All ENTLN traces have been parameterized using the risetime and the basetime as defined in Fig.4(a). The waveforms observed with antennas between 300 and 400 km from the ELVES source are shown in Fig.4(b), in red for single ELVES and black for double ELVES. The lower plots show the distribution of risetimes (c) and basetimes (d) for single and double ELVES, which are consistent with the model described in ref.[10]. Further work is needed to check whether the ratio between the light intensity of the first flash and the one of the second are consistent in each pixel with the prediction of this model.

3. Triple ELVES

Terrestrial Gamma Ray Flashes (TGF) are among the most exciting recent discoveries [15] in lightning science as they prove that electrons can be accelerated to relativistic energies in thunderstorm clouds. TGFs were observed by satellites and were therefore directed towards outer space: the natural question is whether downward going TGFs exist and in what conditions they can be produced. The first ground-level TGF was observed during a rocket-triggered lightning flash in the summer of 2003 [16]. The search for natural downward TGFs took longer, and only recently the two largest cosmic ray observatories, namely Telescope Array [17] and the Pierre Auger Observatory [18, 19], claimed the observation of this phenomenon.

In 2019 the experiment ASIM[20] on the ISS reported [21] the first simultaneous observation of a TGF and an ELVES event, confirming that these two processes are correlated. However, it is still unclear which specific feature of the ELVES light emission can be associated with the generation of a TGF. If TGFs are produced from the top of high thunderstorm clouds, triple and even quadruple ELVES have been suggested as possible signatures: the narrowest time gap between the pulses, associated with ground reflection of the EM pulse, should vary with the arc distance R_{EB} (see Fig.5, right) of the point of light emission from the vertical of the lightning source, and should depend on its height h_b.

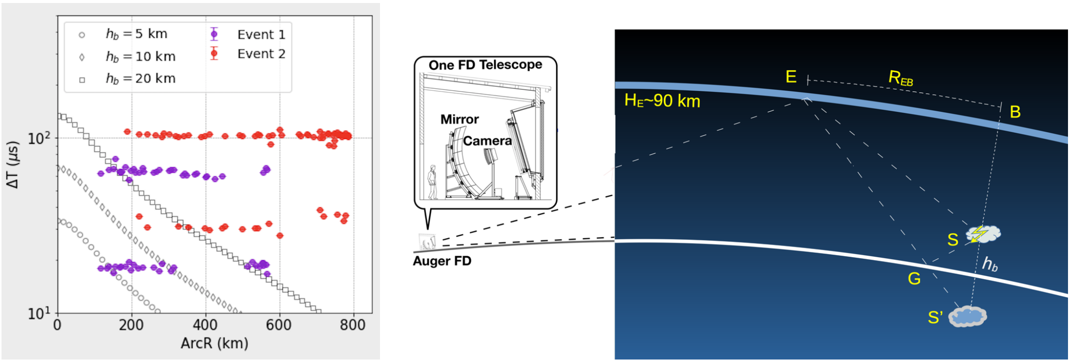

Figure 5: Left: time gaps between flashes in two typical triple ELVES events vs arcdistance R_{EB} from the vertical of the source and the point of light emission; Right: geometrical model for the calculation of the time gap.

The time resolution of Auger FD can be exploited to detect multiple flashes and study the dependence of the time gap on the emission point E. In order to calculate the dependence of the time gap from the height of the source we can use the method of the mirror images and assume that the second flash originates from a point below the earth surface, at a distance $R_{\text{earth}} - h_b$ from the center of the earth, as shown in the right side of Fig.5. The distribution of time gaps $t_2 - t_1$ and $t_3 - t_1$ for all the pixels in two typical events is shown in the left figure. The distribution of $t_3 - t_1$ (the largest gaps) is similar to the one of ELVES doublets. If the second flash were due to ground reflection, the $t_2 - t_1$ values (the closest gaps) should have followed one of the colored curves, depending on the source height h_b.

4. Reconstruction of ELVES seen by HEAT

Starting in January 2021, the ELVES trigger has also been implemented in the three HEAT telescopes located near the Coihueco FD site, the westernmost and highest in altitude (about 1.7 km asl) of the Observatory, ideally located to overlook most of the storms. These three fluorescence detectors are meant to extend the dynamic range of the Observatory, detecting lower energy cosmic ray showers.The three detectors are identical in size and aperture to the other 24 FD telescopes, but the optical axis of their mirrors can be tilted to an elevation angle of 45 degrees, instead of 16.5 degrees.

In the standard Auger FD, triggering of ELVES from lightning closer than 250 km is prevented by the arrival of the direct light from the thunderstorm at the ground, which overwhelms the emission from the base of the ionosphere and, due to multiple scattering, does not follow the time pattern typical of individual ELVES. Given the large elevation angle, the HEAT telescopes can observe the light from closer lightning, as the direct light from the bolt is prevented from reaching the camera by the tilted entrance window. Such a feature allows the observation of the region of maximum emission. The field of view of these three detectors is shown in Figure 6: the red hexagons show the pixel edges in operation mode, and the green hexagons show them in the calibration mode to cross-calibrate the observed events with the ones seen in Coihueco. The right plot shows the longitude and latitude of the pixels' field of view projected at the base of the ionosphere.

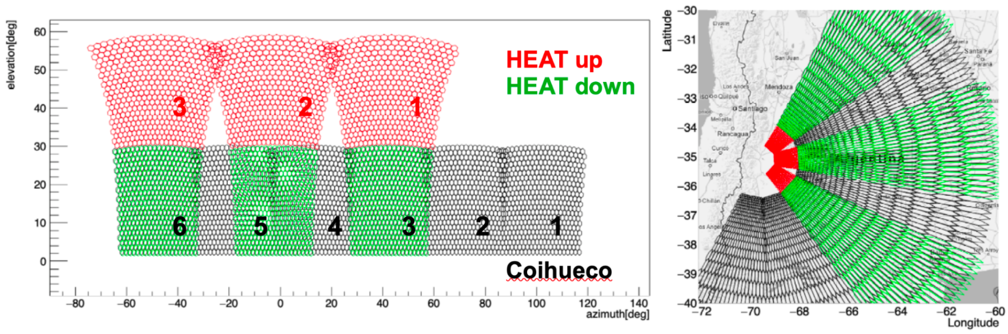

Figure 6: Field of view of the HEAT telescopes in operation mode (red) and in calibration mode (green), compared to the Coihueco telescopes.

The HEAT electronics is two times faster than that of the standard FDs, and each trace is made of 2000 bins to cover the same time window of the FD traces (100 μs). The ELVES trigger is programmed to acquire a maximum of three consecutive pages for a total trace length of 300 μs. In comparison, ELVES traces in standard FD reach up to 900 μs [9]. Because of the tilted geometry, HEAT can only see a portion of the full ELVES. Very few events simultaneously trigger HEAT and the standard FD telescopes.

The best fit of the lightning location is calculated correcting each trace for the average light path from source to FD of each pixel. The right plots of Fig.7 show the time residuals as a function of the azimuth of the ionospheric emission region observed by a given pixel. The distribution of residuals of best fit (left) obtained using the light pulses from all the FD pixels is compared with the one (right) obtained optimizing the alignment of the ENTLN waveforms. The two solutions, shown in the left figure, together with the map of light emission, are only 5 km apart, indicating that the HEAT events can localize the lightning source with resolutions below one km.

5. Halos observation and models

Since 2017, the ELVES triggers in Auger are acquired with trace lengths up to 900 us, in order to study the full region of maximum emission around the vertical of the lightning source. This study is challenged by two factors: (a) the farthest part of the ring is significantly attenuated by the distance, and (b) the light pulse in a given pixel is naturally much broader and, therefore, may fail

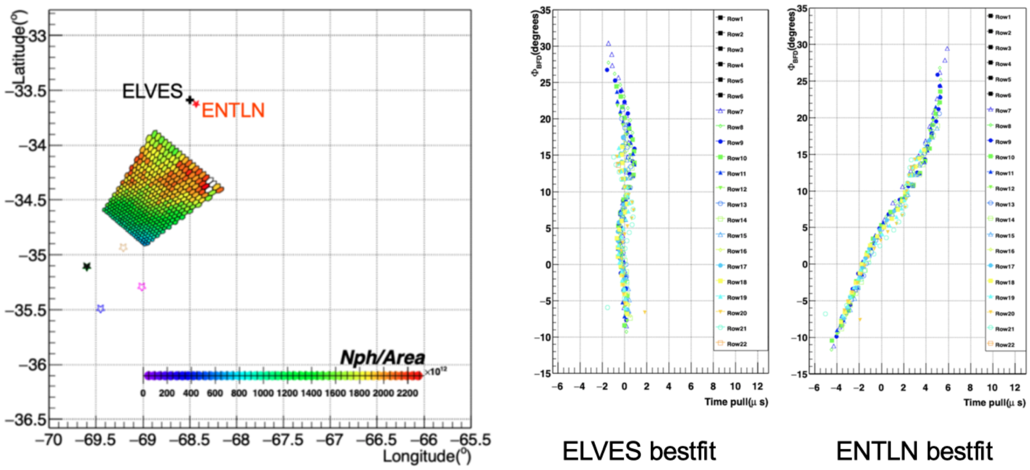

Figure 7: Left: intensity of light emission for one typical ELVES visible from HEAT; the lightning location determined with our algorithm (black dot labeled ELVES) is compared with the one determined using the radio antennas (red dot labeled ENTLN).

to meet the conditions for the first level trigger. Nevertheless, this allowed us to detect other TLEs that are correlated with ELVES but brighter, such as the halos. Halos are created by the quasi static component of the EMP, which produces the ELVES at heights around 80 km. Halos are typically brighter than ELVES and have diameters around 80km. Halos, which are ten times less frequent than ELVES[24], are often followed by sprites when the originating lightning leader has a positive charge. Halos can be easily resolved from ELVES after correcting the traces of each pixel for the time delay of the full light path from source to the FD site.

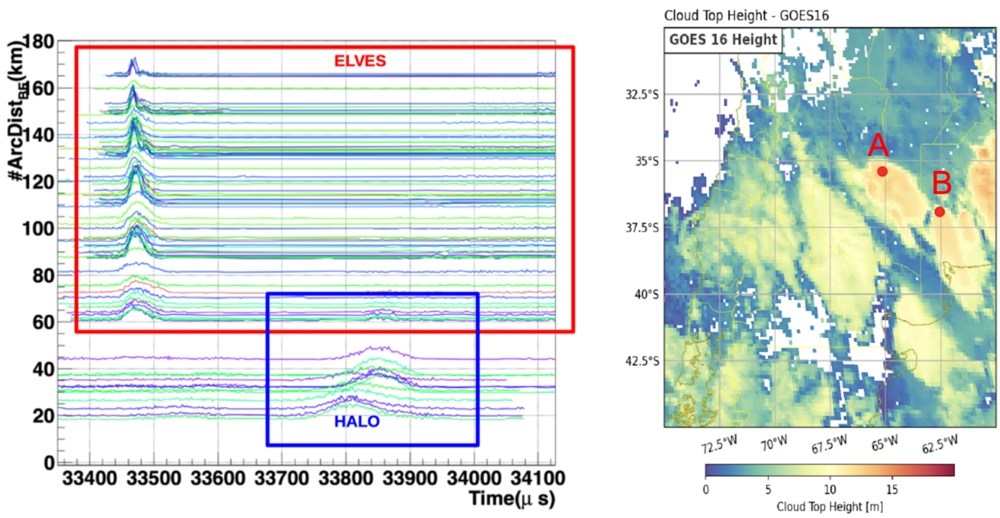

Figure 8: Left: traces of a typical ELVES event followed by a halo; Right: location indicated by a red dot labeled A of the ELVES-halo pair shown in the left figure, and of another ELVES (red dots) of two elves-halo pairs occurring within 65 s.

A typical event is shown in Fig.8, left: the traces with arcdistance 60 to 160 km peaking about time 33480 μs form the ELVES ring. The bump closer to the lightning center is the halo, occurring about 400 μs later. The right plot shows the GOES-16 image on the cloud's top heights. The red dot labeled with an A identifies the location of the source of the ELVES just described. The second one, labeled with a B, occurred only 65 seconds later and is again an ELVES-halo pair. Both points are at the highest tips of two distinct thunderstorms.

6. Conclusions

The study of multiple ELVES is deeply interconnected with the study of other phenomena occurring inside the lightning, such as the TGFs. The challenge to improve the reconstruction of double and triple ELVES led us to incorporate HEAT telescopes to observe events from closer lightning, to study ENTLN radio signals correlated with our events, and to re-discover the halos, as multiple ELVES with distinctive features and different underlying mechanisms. Furthermore, the comparison with satellite databases will allow us to gain further insight into the local conditions inside strong thunderstorms leading to the production of such events.

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The Pierre Auger Collaboration

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