33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

Observation of Elves at the Pierre Auger Observatory

AURELIO TONACHINI[1] FOR THE PIERRE AUGER COLLABORATION[2].

[1] *Università degli Studi di Torino and INFN Sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy*
[2] *Full author list: http://www.auger.org/archive/authors_2013_05.html*

auger_spokespersons@fnal.gov

Abstract: The 'elves' are transient luminous events generated by the sudden excitation of the lower ionosphere, caused by lightning. Exploiting a time resolution of 100 ns and a space resolution of about 1°, the Fluorescence Detectors of the Pierre Auger Observatory in Argentina can provide 2D imaging of elves, originating at distances of several hundred kilometers, with unprecedented accuracy. Using 60 elves event candidates from prescaled data taken in the period 2008-2011 by the Fluorescence Detectors of the Pierre Auger Observatory, we have redesigned the third level trigger of the experiment, in order to acquire elve data with much higher efficiency in the coming years of operation. Preliminary results from the first months of data taking with the upgraded trigger will be given.

Keywords: Pierre Auger Observatory, fluorescence detectors, TLE, elves, ionosphere, thunderstorms, lightning

1 Introduction

Transient luminous events (TLEs) like elves, sprites, halos and jets are luminous emissions detectable well above thunderstorms. Lightning discharges generate electromagnetic pulses (EMPs) which accelerate free electrons. TLEs are different kinds of optical flashes due to the interaction of these electrons with atmospheric species. Elves appear as rapidly expanding rings of light, and are a consequence of the heating and ionization of the lower boundary of the ionosphere. The light emission attains diameters of several hundred kilometers [1], while the typical duration is less than 1 ms.

The wavelength range of light emission in elve events extends from UV to near-infrared. Prompt emissions are due to the electron impact with nitrogen and oxygen molecules. These emissions are followed by chemical reactions which produce a dim chemiluminescence [2].

The first clear detection of elves, made using a high speed photometer pointed at altitudes in coincidence with the observation of sprites [3]. The following observations from ground were made with linear arrays of photomultiplier tubes (PMTs) [4, 5]. In particular, the PIPER instrument [6] adopts two or more orthogonal arrays of PMTs with a time resolution of 40 μs. The arrays can be combined in order to reconstruct 2D images.

The ISUAL mission, which ran from 2004 to 2007 onboard the FORMOSAT-2 satellite, studied systematically TLEs from space. The data collected allowed one to study the global rate and occurrence conditions [7]. The global elve occurrence rate estimated by ISUAL is 35 events per minute. Elves are thus identified as the dominant kind of TLEs. There is also a clear relation between their occurrence and the temperature of the sea surface, which favors the warmest zones of the Earth. The elve occurrence rate, in fact, increases dramatically when the sea surface temperature exceeds 26° Celsius. Globally, it has been shown that there are ten times more elves above the Ocean than on land.
Further progress in understanding and modeling elves may be achieved using the data recorded by the air fluorescence detector (FD) of the Pierre Auger Observatory [8]. The observatory is located near the city of Malargüe, Argentina (69° W, 35° S, 1400 m a.s.l.). The FD comprises four observation sites overlooking a 3000 km^2 water Cherenkov surface array. Each site is in turn made of six independent telescopes, each one with a field of view (FOV) of 30° × 30° in azimuth and elevation (see Fig. 1). In each site, thus, the combination of the FOV of six telescopes covers 180° in azimuth. Since elves detectable by the Pierre Auger Observatory are located far away from the observatory, there is a good probability to see them simultaneously with two or more FD sites (stereo mode).

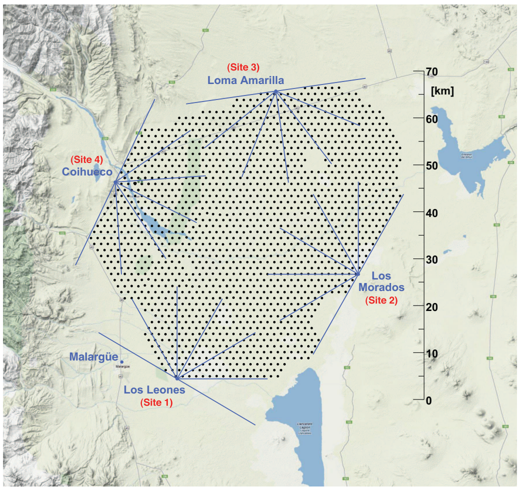

Fig. 1: Map of the Pierre Auger Observatory. The surface detector (small dots) is overlooked by the fluorescence detector. The blue lines show the field of view of each FD telescope.

In each telescope, incoming light passes through a large UV filter window before being focused by a 10 square meter mirror on a grid of 440 photomultiplier tubes (PMTs). The range of wavelengths passing the filter goes from ~290 to ~410 nm. Signals in each PMT are digitized at 10 MHz.

The FD geometry, resolution, and its 100 ns sampling rate make Auger telescopes suitable for studying such fast developing TLEs as elves. Furthermore, the location of the Pierre Auger Observatory allows the detection of elves both on land and above the Pacific Ocean, allowing one to study in detail the difference among the two classes in terms of occurrence rate and signal development.

2 Design of the elve trigger

The event selection of the FDs is based on a three-stage trigger. The first level trigger operates at pixel level, and keeps the PMT trigger rate at 100 Hz by adjusting the threshold. The second level trigger checks the 22×20 pixel camera for five-pixel track segments. This basic selection is passed by both cosmic ray showers and elve-like events. The third level trigger (TLT) is software based. It is designed to efficiently filter out lightning events, and is based on the number of triggered pixels of one camera at the same time (called multiplicity). To achieve a very high efficiency a dedicated study with a sample of true showers and lightning events was performed. The multiplicity-based TLT was installed in the end of 2007 as a replacement of a previous and less efficient version.

Before that time, three elves passed by chance the lightning cuts, and were tagged as cosmic ray showers. After their serendipitous discovery, these events were studied in detail from the point of view of the evolution of the signal in time and space [9].

Based on these events a deep search in a prescaled sample (1 in a 100) of minimum bias events has been done. The result after many iterations was a set of conditions that selects elves very efficiently. Each event that is preliminarily classified as lightning noise is thus analyzed in order to recognize if the light front expands radially. Firstly, a fast pulse analysis is done on the triggered pixels. Once the first triggered pixel is identified, pulse start times of the triggered pixels falling on the same row and the one of the pixels falling on the same column are checked.

For the sample of pixels of the same column, the algorithm requests that at least three pixels before *and* three pixels after the central one have a pulse. Moreover, 80% of them must show an increasing pulse arrival time.

For the sample of pixels of the same row, instead, the algorithm just requests three pixels to the left of the central one *or* three pixels to the right of it. Any of the two arms must show an increasing pulse arrival time in 80% of the pixels.

Considering that elves release a large amount of light compared to cosmic rays, an additional cut on the pulse amplitude has been introduced in order to remove unwanted noise: among the triggered pixels, at least one must have a pulse amplitude greater than 50 ADC channels.

Running this selection procedure over the prescaled data recorded from 2008 to 2011, 58 elves have been found. 39 of them have the centre contained inside the camera, and thus are well reconstructable (see Table 1). In the remaining 19 candidates, the centre occurs in an adjacent bay (which has been randomly discarded) or outside the field of view. An example of an elve detected with the FD is shown in Fig. 2.

As expected, the elve rate is not uniform over time, but shows a substantial increase in the warmest months, when usually violent thunderstorms take place (Fig. 3). For the events with the centre well visible within the FD camera,

FD site	Elves	Centre contained
1. Los Leones	21	17
2. Los Morados	6	3
3. Loma Amarilla	12	9
4. Coihueco	19	10
Total	**58**	**39**

Table 1: Number of elves found in the FD prescaled data, grouped by site. the site number refers to Fig. 1.

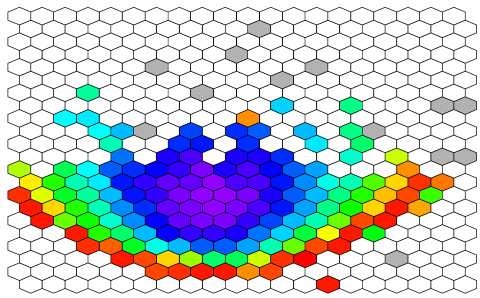

Fig. 2: Pixels of an FD telescope triggered by an elve. The event expands radially from its centre, as shown by the colour scale (pulse start time increases from violet to red).

the direction of the electromagnetic pulse which triggered the elve is easily reconstructable. Fig. 4 shows that most of the events detected so far come from the warmest regions of Argentina, while none of these events took place above the sea.

The elve trigger, as described in the previous section, has been fully integrated in the TLT as of March 2013. During the data taking periods of March and April 133 events were tagged as elve candidates, and only six of them (4.5%) are false positives.

3 Elve reconstruction

The light observed with the FDs is emitted by the D region of the ionosphere, which has been excited by elec-

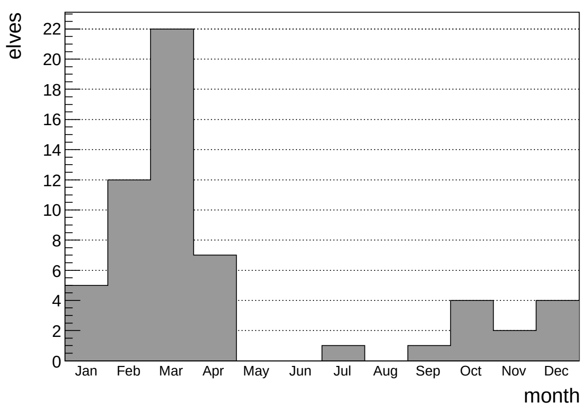

Fig. 3: Elve rate per month from the 58 events found in the prescaled data. Most of the events were detected during austral summer.

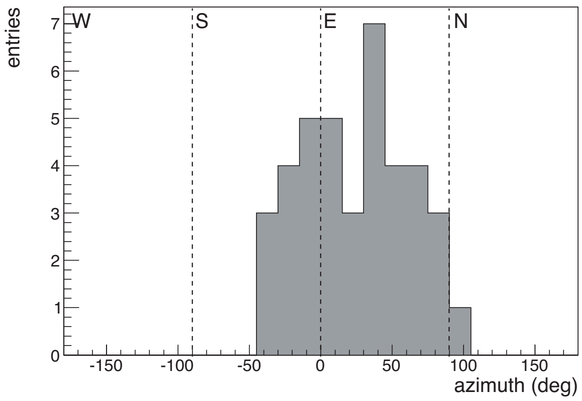

Fig. 4: Azimuth direction of the EMP location. The direction is in degrees anticlockwise with respect to the East. Most of the events came from the North-East. None of them came from the direction of the Pacific Ocean .

trons accelerated by a lightning-launched electromagnetic pulse. The signal travels from the source to the ionosphere at nearly the speed of light; fluorescence light is emitted at altitudes around 90 km and travels towards the detector. The light observed by different PMTs of a fluorescence detector in the same time frame corresponds to paths traveled in the same amount of time. One can describe this as the intersection of an expanding ellipsoid, with the EMP source and the FD at the foci, and a sphere concentric to the Earth with a radius given by the D layer altitude plus the Earth radius (see Fig. 5). In this model, the first light is observed at t_0, when the ellipsoid is tangent to the sphere. If the altitude of the D layer were well known, one would have a strong geometrical constrain on the position of the EMP source. In reality, this altitude fluctuates by several kilometers. Fig. 5 illustrates how the position of the EMP found in such a way is sensitive to this fluctuation. For $t > t_0$ one observes a closed curve, whose lateral expansion is symmetric. The front moving towards the FD appears to move faster than that moving in the opposite direction, since at higher elevation angles the portion of D region observed with the same field of view is less.

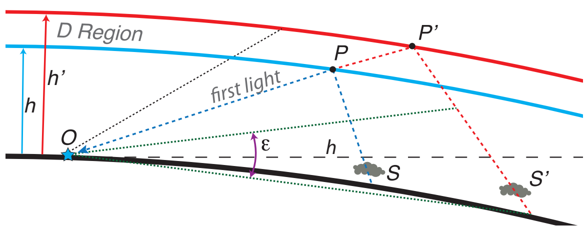

Fig. 5: Schematic view of an EMP generated by a thunderstorm at S, which interacts with the D region of the ionosphere. The light emitted by the ionosphere (in blue) is detected by the fluorescence detector at O. The observed signal time t is the sum of the time needed by the pulse to move from S to the interaction point P and the time needed by the emitted light to travel from P to O. If the D region is higher, the first light is emitted by P' instead of P, and the source S' is much farther. The D region altitude can be retrieved from the overall development of the elve.

3.1 Signal processing

For those PMTs that pass the first level trigger, a trace of 1000 bins of 100 ns each is recorded. A pulse search is run on each trace, and the pulse start and end are found by maximizing the signal to noise ratio. For reconstructing the development of elve events it is particularly important to have a precise determination of the starting time of the signal. For this reason, small pulses whose maxima are below three standard deviations with respect to the background or very short pulses ($\Delta t < 3\mu$s) are not considered.

For the other ones, a 2.1 μs running average is applied in order to smooth the traces. The pulse start time previously determined is then moved back until the smoothed signal is less than 5σ above its pedestal. The uncertainty associated with this point is determined by searching for the time at which the signal falls below 3σ, and taking the time difference with respect to the start point.

Once the first triggered pixel is found, the duration of the pulse recorded is measured. This pulse width can be related either to the duration of the EMP, or to the thickness of the light emitting layer.

3.2 Elve location

In order to have a precise measurement of the azimuthal direction of the EMP source, a parabolic fit of the lateral expansion is done considering all triggered pixels with elevation within 0.75° (half the PMT field of view) with respect to the first triggered PMT elevation.

Once the azimuth and elevation of the first light are determined, the model still depends on two parameters: the D layer height h, and the elevation ε of the EMP source with respect to the horizon. In order to determine the exact location of the source and the D layer altitude at the same time, h is variated between 50 to 110 km, and ε between -8.0° and +5.0°. For each step in h and ε the model is used to calculate the expected times of the light pulses observed by the PMTs, which are then compared to the values recorded by the triggered PMTs.

4 Results

The reconstruction algorithm has been tested on the 39 elves contained in the prescaled data. The distance of the EMP source to the fluorescence detector varies from about

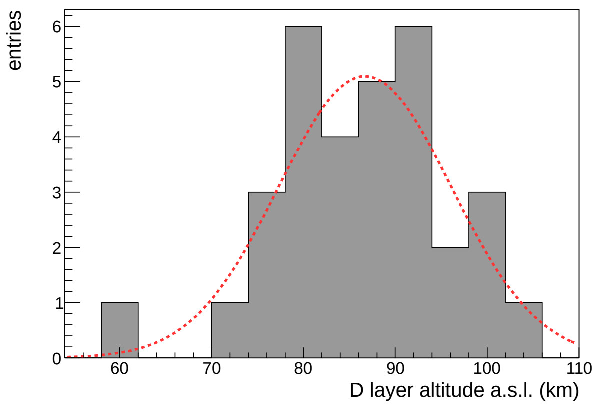

Fig. 6: The distribution of the D layer altitudes has mean value at ∼86 km and RMS of 9 km.

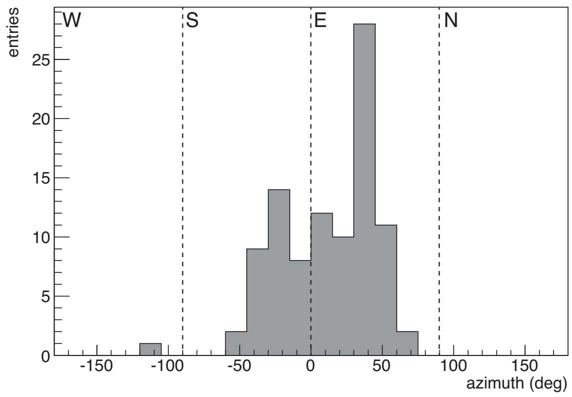

Fig. 7: Azimuth direction of the EMP location for the events recorded in March and April 2013. The direction is in degrees anticlockwise with respect to the East. Most of the events came from the East with a slightly different distribution with respect to Fig. 4.

FD site	Elves	Reconstructed	Stereo
1. Los Leones	41	29	26
2. Los Morados	8	2	7
3. Loma Amarilla	32	26	13
4. Coihueco	52	40	22

Table 2: Number of elves found in the FD measured data, grouped by site. The site number refers to Fig. 1. Three of these elves were seen by three FDs simultaneously.

200 km to 900 km. The elevation angle of the first light observed varies respectively from $\sim 23^{\circ}$ to $\sim 10^{\circ}$. The D layer altitude, measured for each elve, is distributed as shown in Fig. 6, with mean at $\sim$86 km.

The same algorithm was used to process the signals of elves recorded with the new third level trigger of the fluorescence detector. Table 2 reports the number of events detected by each FD site. Many events have been observed simultaneously by more than one detector (stereo mode). Events have been seen at elevations as low as 6°, corresponding to distances as far as 1000 km from the Pierre Auger Observatory. Most of the events occurred in East direction, while no events have been detected above the Pacific Ocean so far (see Fig. 7).

Fig. 8 shows the distribution of the pulse durations measured from the signal recorded by the first triggered PMT of the elves.

5 Conclusions

A dedicated trigger for recording elves has been recently implemented as part of the third level trigger of the fluorescence detector of the Pierre Auger Observatory. 133 events have been already collected, with a low number of false positives. For the first time a detector is recording 2D images of elves with a time resolution 50 times better than the previous observations. Moreover, many events are recorded simultaneously by two or more detectors placed at several tens of kilometers one from the other, thus providing a stereo view of elves.

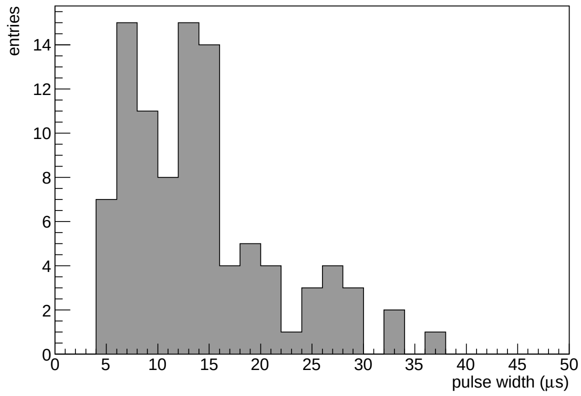

Fig. 8: Pulse width distribution for the events recorded in March and April 2013. This observable can be related to the EMP duration or the thickness of the excited layer in the ionosphere.

References

[1] U. S. Inan, T. F. Bell, J. V. Rodriguez, Geophys. Res. Lett. **18** (1991) 705
[2] C. L. Kuo et al., J. Geophys. Res. **117** (2012) A07320
[3] H. Fukunishi et al., Geophys. Res. Lett. **23** (1996) 2157
[4] U. S. Inan et al., Geophys. Res. Lett. **24** (1997) 583
[5] R. T. Newsome and U. T. Inan, J. Geophys. Res. **113** (2010) A00E41
[6] R. Marshall, R. Newsome, U. Inan, IEEE T. Geosci.Remote **46** (2008) 3885
[7] A. B. Chen et al. J.Geophys.Res. **113** (2008) A08306
[8] The Pierre Auger Collaboration, Nucl. Instrum. Meth. A **620** (2010) 227
[9] A. Tonachini for the Pierre Auger Collaboration, Proc. 32nd ICRC, Beijing, China **11** (2011) 401, arXiv:1107.4806