Observation of Elves with the Fluorescence Detectors of the Pierre Auger Observatory

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Abstract: We report the observation of elves using the Fluorescence Detectors of the Pierre Auger Observatory in Malargüe, Argentina. Elves are transient luminous phenomena originating in the D-layer of the ionosphere, high above thunderstorm clouds, at an altitude of approximately 90 km. With a time resolution of 100 ns and a space resolution of about 1 degree, the Fluorescence Detectors can provide an accurate 3D measurement of elves for thunderstorms which are below the horizon. Prospects for the implementation of a dedicated trigger to improve detection efficiency and plans to perform multi-wavelength studies on these rare atmospheric phenomena will be given.

Keywords: elves, lightnings, ionosphere, thunderstorms, fluorescence detectors, Pierre Auger Observatory

1 Introduction

There is an electrodynamic coupling between electromagnetic fields produced by lightning discharges and the lower ionosphere. This coupling gives rise to distinct sets of observed phenomena, including various transient luminous events (TLEs) such as the so-called “Sprites” and “Elves”. Sprites are luminous discharges located at altitudes between 40 and 90 km. They are due to the heating of ambient electrons, and last a few to tens of milliseconds. This characteristic makes them easily detectable with high speed cameras. Elves are optical flashes produced by heating, ionisation, and subsequent optical emissions due to intense electromagnetic pulses (EMPs) radiated by both positive and negative lightning discharges. Elves are confined to 80-95 km altitudes, and extend laterally up to 600 km \cite{1}. Their duration, much shorter (< 1 ms) than that of sprites, made them somewhat harder to study. The first clear observation of elves was made using a high speed photometer pointed at altitudes above those of sprites \cite{2}. More sophisticated instruments, such as “Fly’s Eye” \cite{3} and PIPER \cite{4}, consisting of linear arrays of horizontal and vertical photometers with a time resolution of ~ 40 \mu s, have been used in the last decade to study the rapid lateral expansion of these high altitude optical emissions, and to test the excitation mechanism. Data from space on elves were acquired by the ISUAL/Formosat-2 mission, from 2004 to 2007 \cite{5}. These data allowed one to conclude that elves develop on oceans or coastal regions ten times more frequently than on land. The satellite data were acquired with six PMTs and two 16-channel multi-anode PMTs, with time resolutions of 100 and 50 \mu s, respectively.

Further advancements in the understanding of these phenomena may be achieved using the fluorescence detector (FD) of the Pierre Auger Observatory \cite{6}. The FD comprises four observation sites located atop small hills at the boundaries of the Auger surface array. Each FD building contains six independent telescopes, each with a field of view (FOV) of 30° × 30° in azimuth and elevation. The combination of the FOV of the six telescopes covers 180° in azimuth. Incoming light enters through a UV-transmitting filter window, and is focused by a mirror onto a camera, which is formed by 22 × 20 hexagonal photomultiplier tubes (PMTs). The wavelength of detected light ranges from 300 to 420 nm. Light pulses in each photomultiplier are digitized every 100 ns. The PMT processed data are passed through a flexible multi-stage trigger system, which is implemented in firmware and software. The resulting data are stored in 100 \mu s-long traces.

The FD geometry and time resolution are ideal for studying fast developing TLEs. However, the trigger chain contains a dedicated selection algorithm for rejecting lightning, which makes the FD a rather inefficient elf detector. Nevertheless, a few events which accidentally passed the rejection have been detected while searching for non-conventional cosmic ray shower events.
2 Observations

The first event was noticed serendipitously during an FD data taking shift. This unusual event presented a well-defined space-time structure: a luminous ring starting from a cluster of pixels, and expanding in all directions.

A search for events with a similar space-time evolution in the data collected by Auger since 2004 has identified two more events. These events are listed in the Table 1. The presence of dust and poor local weather conditions, recorded by the Auger atmospheric monitoring devices [7], complicate the reconstruction of the first and the last event, but do not prevent one from recognizing the same overall features of the phenomenon. Most of the details which are given in this paper refer to the analysis of the second event.

In Fig. 1, the photon time distributions for the three events are shown. Events which do not pass the whole trigger selection, but trigger a minimum of adjacent PMTs (second level trigger, or T2) leave some basic information in a log file, such as the GPS time and the number of PMTs hit. From these logs it is possible to observe that all the selected events last much longer than 70 μs, and are actually detected in adjacent FD bays, or even in other eyes, as summarized in table 2. The number of buffered pages shows, in units of 0.1 ms, the time duration of the detected event.

![Figure 1: Photon counts at 370 nm obtained from the sum of all photomultiplier ADC traces of the three events in Table 1. Since these events are not totally contained inside the camera FOV, the gray areas denote a region with possible signal losses.](image)

<table>
<thead>
<tr>
<th>Site-Bay</th>
<th>GPS time</th>
<th>GMT time</th>
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<tbody>
<tr>
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<td>18 May 2005 01:15:29</td>
</tr>
<tr>
<td>CO − 3</td>
<td>860806213</td>
<td>17 April 2007 00:49:59</td>
</tr>
<tr>
<td>LL − 1</td>
<td>861081389</td>
<td>20 April 2007 05:16:15</td>
</tr>
</tbody>
</table>

Table 1: Three elve candidates seen by Auger fluorescence detectors and their arrival times.

![Figure 2: Schematic view of an EMP generated by a thunderstorm in S, which interacts with the D region of the ionosphere. The light emitted by the ionosphere (in red) is detected by the fluorescence detector at O. The observed signal time t is the combination 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.](image)

3 Front propagation reconstruction

If the events observed are elves, the signals recorded correspond to the optical emission of the D region of the ionosphere, as a consequence of its interaction with a lightning-launched electromagnetic pulse (EMP).
3.1 Geometrical model

The EMP source is confined inside the troposphere, while the optical emission takes place at 80-95 km altitudes. The observed light develops over times comparable with the time needed to travel from the source $S$ to a point in the D region, and from there to the observer $O$ at the speed of light (see Fig. 2). In fact, the light detected at time $t$ may come from any of the points belonging to the intersection of the D region with an ellipsoid whose foci are $O$ and $S$. The first light arrives at a time $t_0$ defined by the ellipsoid tangent to the D region. The tangent point $P$ is found from observations, and puts constraints on the location of the source $S$. Indeed, it can be demonstrated geometrically that the line tangent at $P$ to an ellipse with foci $O$ and $S$ forms equal angles with the lines $OP$ and $PS$. Thus, once defined $P$, the locus of the foci $S_i$ is a line.

At a time $t_i > t_0$ the intersection of the ellipsoid with the D region corresponds to a closed curve: this is actually observed by the fluorescence detectors. The lateral expansion of this curve is expected to be symmetric, while the front moving towards the FD is expected to move faster than that moving in the opposite direction.

3.2 Signal treatment

The pixels considered in each event are the ones which have an FD first level trigger trace. Each trace is formed by 1000 time bins of 100 ns each. Signal bounds are searched in each trace by maximizing the signal over noise ratio. This allows one to roughly define the pulse start and stop times. Afterwards the signal is smoothed by applying a 2.1 $\mu$s running average in order to decrease short time signal fluctuations. The pulse start position is then moved back until the signal is less than $3\sigma$ above the noise. The error associated with this point is determined by searching the time where the signal is less than $3\sigma$, and then taking the time difference with respect to the start point (see Fig. 3).

The pulse start times measured by each photomultiplier are plotted in Fig. 4 as a function of PMT pointing directions. This development has been compared with the geometrical model discussed before. Once the pixel which recorded the minimum pulse start time was found, the direction of the start point $P$ was varied by $\pm 2^\circ$ in both elevation and azimuth angles. For each $P$ the altitude of the D region and the direction of the EMP source with respect to the FD have been varied within 80 to 100 km and $+5^\circ$ and $-5^\circ$ respectively, in order to find the parameters which better fit the elve development.

4 Results

The best fit to the pulse start times of the event studied is obtained for a source elevation angle of $-1.15^\circ$ and a D layer altitude of 92 km a.s.l. The direction (elevation, azimuth) of the first light is $(14.6^\circ, -52.1^\circ)$. The source linear distance from the fluorescence detector of the Auger Observatory is about 580 km. A comparison of the times expected from a theoretical model with these parameters and the real data is shown in Fig. 5. The time residuals are plotted in Fig. 6.

The location of the event is strengthened by the presence of a large cloud perturbation seen by GOES geostationary satellites in the same region [8]. Moreover, a coincidence with a strong lightning pulse detected by the World Wide Lightning Location Network (WWLLN) [9] has been found.

Figure 3: A signal measured with a single photomultiplier (gray graph). To reduce noise fluctuations, a moving average is performed on the original trace (black thick graph). The start point (blue square point) is defined from this graph when the signal is $5\sigma$ above the baseline (dotted line).

Figure 4: Interpolated tridimensional curve representing the time of arrival of photons at the FD diaphragm as a function of elevation and azimuth angle. Pulse start times belong to the event detected at GPS 860806213. This event triggered 143 pixels.
Figure 5: Best fit (red curve) compared to real data (black squares) for the column and the row of pixels passing through the centre of the event. $\delta \phi$ is the azimuth direction of the pixel with respect to the centre.

Figure 6: Difference between measured pulse start times and simulated ones as a function of the pixel pointing directions ($\mu$s). Differences are confined within 2 $\mu$s, with the exception of one pixel which recorded a trace delayed by 7 $\mu$s.

5 Final remarks

It has been shown that the fluorescence detector of the Pierre Auger Observatory may represent an interesting opportunity to study the elve evolution with an unprecedented time resolution. However, in order to transform the FD in an efficient elve detector it is necessary to design a dedicated software trigger. This would allow one not only to increase the FD efficiency, but to record subsequent signal traces up to the expected length of these optical flashes ($\sim$ 1 ms).

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References