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Science Update

Catching Elves in Argentina

The world's largest cosmic ray detector accidentally spotted elves, an unusual lightning phenomenon high in the atmosphere. Now it's intentionally looking for more.

Argentina's Pierre Auger Observatory was designed to detect high-energy cosmic rays, but it's also good at spotting elves created by high-energy lightning. Credit: Steven Saffi, CC BY-SA 2.0

By Kevin-Druis Merenda, Roberto Mussa, and Lawrence Wiencke 5 June 2020

The Pierre Auger Observatory in Argentina was not designed to catch elves, but in recent years it has been doing exactly that. Through a bit of serendipity, we discovered that the world's largest cosmic ray detector provides new capabilities to observe rare, ring-shaped emissions of ultraviolet (UV) and visible light high above thunderstorms [*Aab et al.*, 2020]. Studying these elves, short for emissions of light and very low frequency perturbations due to electromagnetic pulse sources [*Fukunishi et al.*, 1996], could reveal new insights into the physics and effects of strong lightning, including lightning of the highest energy.

Lightning Science Strikes

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Where Elves Come From

Lightning produces familiar large bolts and flashes, but strong lightning—lightning carrying more than about 100 kiloamperes of current—can also generate expanding rings of light overhead, at the base of the ionosphere, a plasma layer roughly 85 kilometers above Earth's surface [*Inan et al.*, 1991]. These "airglow enhancements," first recorded by a camera aboard the space shuttle *Discovery* in 1989 [*Boeck et al.*, 1992], appear when a fast change in the electrical current generated by lightning produces an electromagnetic pulse (EMP). When the pulse intersects the base of the ionosphere, it transfers energy to free electrons in this plasma. The energized free electrons can then excite electronic transitions when they collide with atmospheric molecules. As these excited molecules relax again to lower-energy states, they emit a wide-frequency spectrum of light in a process known as fluorescence; in particular, some nitrogen molecules will emit UV light.

> *The expanding ring of light emissions arise as the roughly spherical electromagnetic pulse crosses the much flatter base of the ionosphere.*

The expanding ring of light emissions arise as the roughly spherical EMP crosses the much flatter base of the ionosphere. By looking at the patterns in the light emissions, we can reconstruct the geodetic location, altitude, and time of the lightning stroke, as well as more fundamental physics about the stroke itself and about the ionosphere. This fundamental information has a variety of practical applications. For example, engineers test ways of protecting aircraft from severe weather using measurements of the amount of current in a lightning stroke and how long it took for the current to ramp up during the stroke process. In addition, GPS signals are corrected for attenuation caused by the boundary between the mesosphere and the ionosphere. As the brightness of elves is dependent on the concentration of free electrons and molecules in the ionospheric plasma, their observation may potentially be used to validate previous electron density measurements at the base of the ionosphere.

The World's Largest Cosmic Ray Observatory

The accidental elves catcher, the Pierre Auger Observatory, was built by a collaboration of almost 500 physicists from 19 countries; construction was completed in 2008. Occupying 3,000 square kilometers, it is the largest cosmic ray observatory on Earth and was designed to open a new window on the cosmos by measuring the highest-energy subatomic particles known to exist [*Aab et al.*, 2015]. The energy in these tantalizing cosmic rays, which originate from faraway sources outside our solar system, can exceed 10^{20} electron volts. This is roughly the kinetic energy of a tennis ball in play at the U.S. Open, but this energy is carried by a single proton or nucleus.

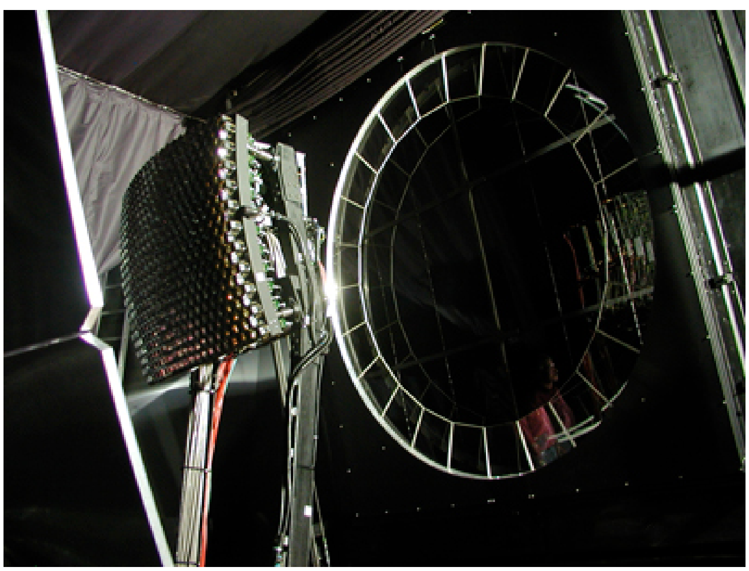
The efforts of the Pierre Auger Collaboration have led to discoveries about the origins and nature of these elusive particles [*Aab et al.*, 2017a, 2017b] and to contributions to the emerging field of multimessenger astrophysics [*Abbott et al.*, 2017]. At the time of its construction, we did not foresee that the Auger Observatory could also catch elves. Furthermore, we discovered that the Auger Observatory can catch them across an area that's 1,000 times larger than the 3,000-square-kilometer area it uses to catch cosmic rays. In the case of the Auger Observatory, this larger area overlaps with a region known for its high rates of strong lightning and large convective storms.

A Large Net to Catch Rare Events

The highest-energy cosmic rays are rare—on average, only one 10^{20}-electron-volt ray lands in a 10-square-kilometer area (about 3 times as large as New York City's Central Park) per century. The Auger Observatory catches these rays indirectly by measuring the UV light and the particles they give off, essentially using the atmosphere as a large particle physics–type calorimeter. High-energy cosmic rays deposit their energy in the troposphere through the creation of cascades of secondary lower-energy particles, including many electrons.

The surface detector (SD) of the Auger Observatory, comprising a gridded array of more than

A thunderstorm looms on the horizon near the hillside site of one of the Pierre Auger Observatory's fluorescence detectors (the same site depicted in the figure at the beginning of this article). Credit: Pierre Auger Observatory, CC BY-SA 2.0

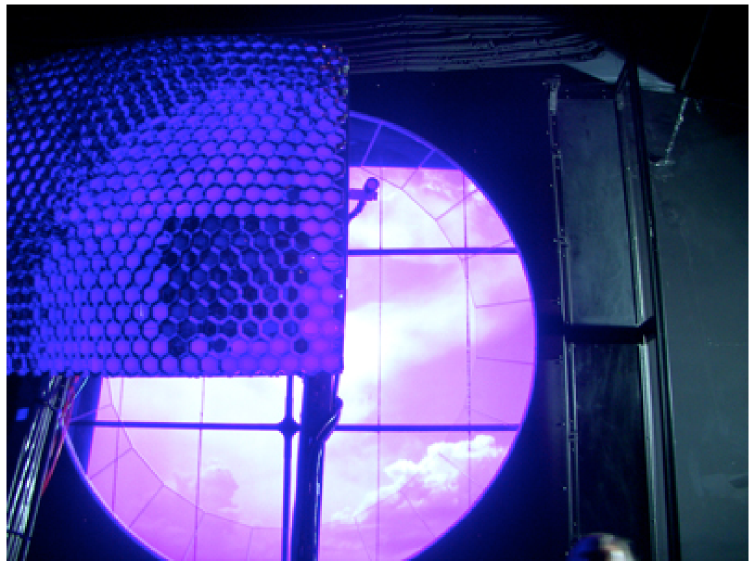


One of the 24 fluorescence detector (FD) telescopes, showing (left to right) the edge of the mirror, the custom camera, and the light aperture. Credit: Pierre Auger Observatory, CC BY-SA 2.0

1,600 instrumented water tanks separated from each other by 1.5 kilometers, samples the footprint of these cascades as they hit the ground. The fluorescence detector (FD), consisting of 24 telescopes arranged at four sites around the perimeter of the SD array, views the atmosphere above the SD [*Abraham et al.*, 2010]. Unlike astronomical telescopes, the FD telescopes have much wider fields of view, about 30° × 30°, and they point in fixed directions just above the horizon.

Electrons in cosmic ray cascades absorb energy from the cosmic ray, and these energetic electrons can excite other electrons in atmospheric nitrogen atoms into higher-energy states. Much like what happens in elves, when these excited electrons in nitrogen atoms return to their ground state, they fluoresce, giving off some of their extra energy as UV light. The FD telescopes at the Auger Observatory operate at night to record this UV fluorescence, which is obscured by sunlight during daylight hours. The amount of UV light emitted from the cascades is nearly proportional to the energy of the incoming cosmic ray. The FD records the evolution of cosmic ray cascades in the troposphere and provides the energy calibration reference (the mathematical relation between the energy of the cosmic ray and the number of photons that the camera records) for the Auger Observatory.

To capture the faint UV light from the cosmic rays, the light aperture of each FD telescope is relatively large (2.2 meters in diameter) and is covered by a UV-transmitting optical filter that screens out visible light in the atmosphere. A custom camera consisting of 440 photomultiplier tubes at the mirror focus generates images of 20 × 22 pixels at the rate of 10 million frames per second. This impressive acquisition rate enables us to observe cosmic ray showers, the cascades of relativistic particles crossing the sky at the speed of light, in detailed "slow motion."



The light aperture of each FD telescope is covered by an optical filter that transmits light in the 300- to 420-nanometer region of the ultraviolet spectrum. Credit: Pierre Auger Observatory, CC BY-SA 2.0

If the Auger Observatory is focused on seeing cosmic rays, how do elves appear in our cameras? A cosmic ray shower looks something like a meteor moving at the speed of light, but elves appear as expanding wavefronts propagating down across the focal plane of the camera (Figure 1). The brightest edge of the front appears to travel through the atmosphere faster than the speed of light! Is this a violation of relativity, or of causality? Not at all: Such an artifact is known in physics as the "shadow effect," and it is clearly visible thanks to the high time resolution and large light-gathering power of this instrument.

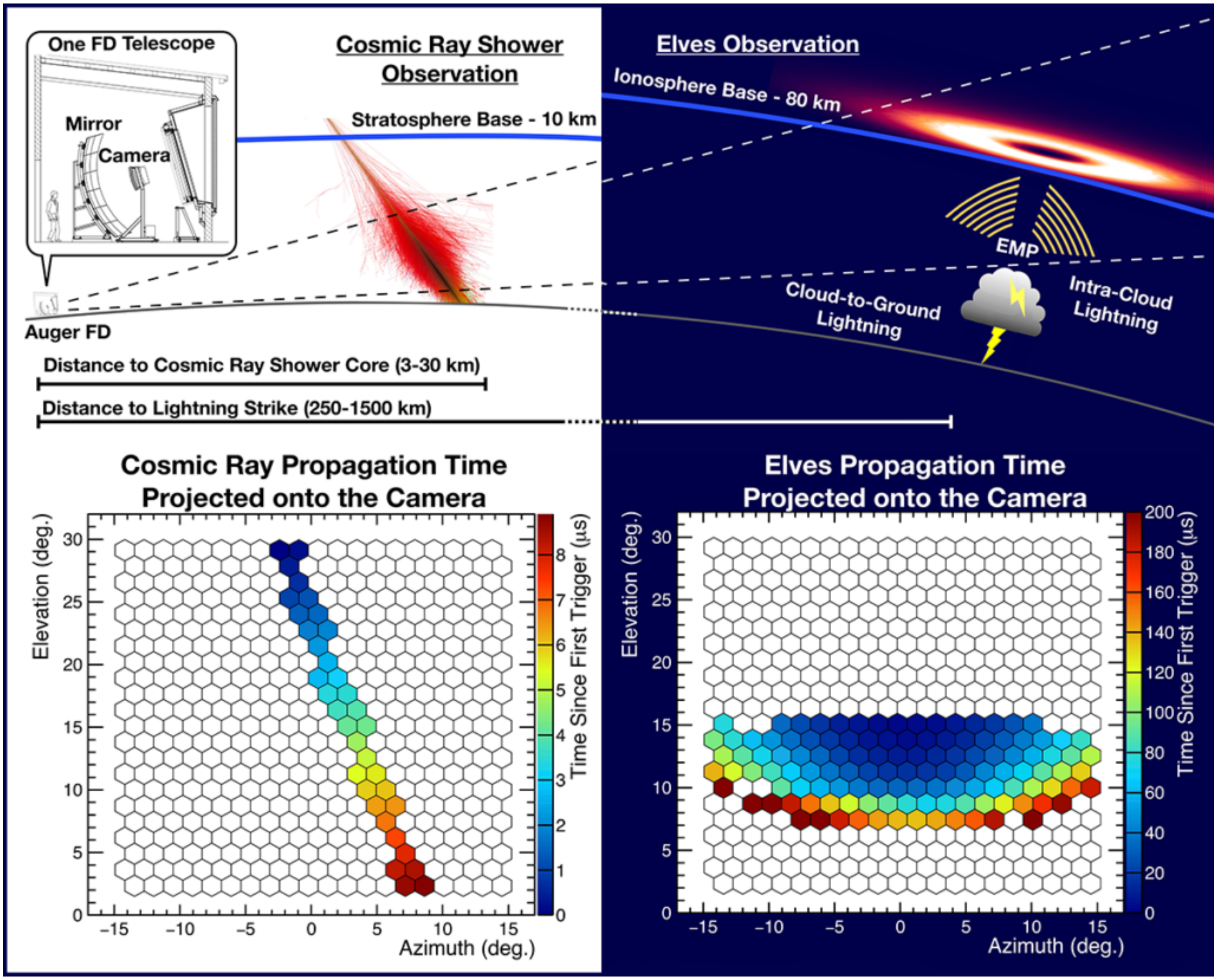


Fig. 1. A diagram of one telescope of the Auger FD and the setup for the observation of elves from storms that occur below the horizon (top). A plot showing the propagation time of the light pattern for a cosmic ray air shower (bottom left). A plot displaying the propagation time of the light pattern for an elves in one telescope of the Auger FD (bottom right).

Observations of Elves: From Accidental to Intentional

The first serendipitous observations of three elves candidates occurred between 2005 and 2007 during the construction of the detector [*Mussa et al.*, 2012; A. Aab et al., The Pierre Auger Observatory: Contributions to the 33rd International Cosmic Ray Conference (ICRC 2013), EarthArXiv, http://arxiv.org/abs/1307.5059]. A "lightning veto" algorithm had been built into the data collection software to filter out flashes of light coming from lightning strokes close to the detector. This algorithm prevented all but a few elves from being recorded, keeping just the signals from light arriving from cosmic rays.

The Auger Observatory's footprint for catching elves is about 3 million square kilometers, the largest ground-based area ever used for detecting elves.

After we realized that the Auger FD was able to detect elves, we had to develop a simple selection algorithm to recognize the propagation pattern of light arriving from elves, as well as a data-collecting format dedicated to their intentional observation. The Auger Observatory started taking data with these new selection criteria in January 2014. We and our colleagues recently published a map that we made using the data from 2014 to 2016 to show that the Auger Observatory's footprint for catching elves is about 3 million square kilometers, the largest ground-based area ever used for detecting elves [*Aab et al.*, 2020].

By studying data from the Tropical Rainfall Measuring Mission, scientists identified northern and central Argentina as having the highest rate of lightning flashes in the tallest thunderstorms on Earth [*Zipser et al.*, 2006]. Studying these tall, intense storms over Argentina is expected to provide the scientific community with insights into extreme weather patterns in the rest of the world, such as severe convective cells that form over the Colorado Rockies in summer.

The location of the Auger Observatory, on a dry highland with relatively low cloud coverage, makes it an ideal spot to study the transient luminous events produced by these strong thunderstorms at far distances. Earth's curvature prevents arrival of the direct light from the lightning bolts and allows for clean observations of light emissions from the base of the ionosphere. In addition, FD sites facing west exploit the Andes mountain range, which screens direct light from rare storms above the Pacific Ocean that produce elves visible from as far away as 1,000 kilometers.

By combining the detailed measurements of elves from the Auger Observatory with data from other lightning experiments across Argentina, we hope to contribute to current research in atmospheric electricity physics. In one of the first analyses, we used a time correlation to match lightning strokes recorded by the World Wide Lightning Location Network with elves detected at the Auger Observatory, and we demonstrated that these elves are created by high-energy lightning strokes. Thus, the Auger Observatory is naturally selecting intense electrical events in the severe Argentinian thunderstorms that occur during the austral summer.

Elves Reveal Unexplained Features

Within our 3-year data set, 18% of the approximately 1,600 elves have more than one peak in the signal recorded by the cameras at Auger. Elves with one peak in their emissions pattern are created by a cloud-to-ground lightning stroke, whereas, in accordance with classical electromagnetism theory, elves with two peaks in their emissions pattern are expected to be created by a lightning stroke that is not touching the ground—an intracloud lightning stroke. The first reported observation of elves with two peaks in their photo traces was in 1999, in New Mexico [*Barrington-Leigh and Inan*, 1999].

The very low frequency of the EMP emitted by a lightning stroke allows it to reflect many times between the ground and the ionosphere, and to propagate over thousands of kilometers. The ultrafast (10-megahertz) data acquisition rate and the light-collecting power of the Auger FD enables us to see very fine structure in the light emissions of elves. As a result, some of our events have more than two peaks in their photo traces.

We believe that elves with more than two peaks in their photo traces are also created by intracloud activity, but because of the timing between peaks, we are not convinced that they are created solely by multiple reflections of the EMP in the waveguide created between the ground and the ionosphere. Using standard physical models, we can estimate that any two peaks in one elves event cannot be separated by more than 40–50 microseconds. However, for an event on 4 March 2016 (Figure 2), the Auger Observatory detected three distinct peaks recorded by more than 40 photomultiplier tubes across two FD sites. The third peak in the photo trace occurred 100 microseconds after the second peak. Consequently, other processes in the physics of atmospheric electricity must be responsible for creating elves with complex light emission curves.

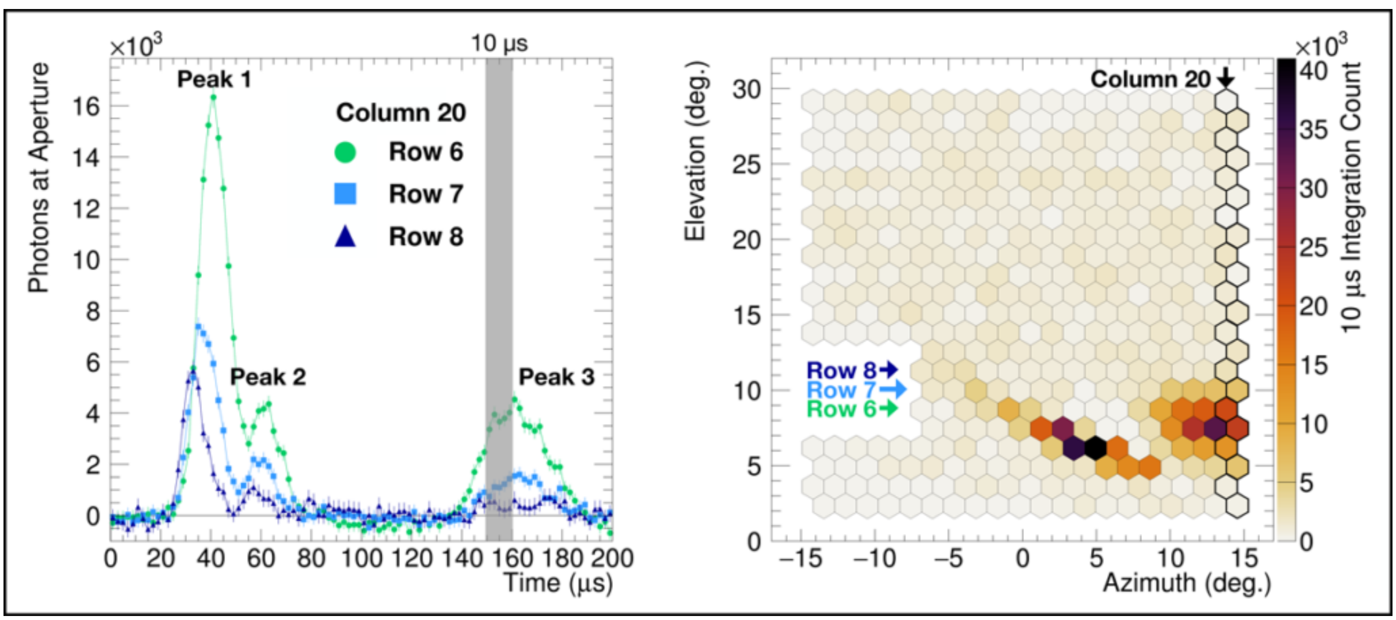


Fig. 2. On 4 March 2016 at about 2:00 a.m. local time, FD telescopes recorded an elves event with three distinct peaks in the numbers of photons detected (left). One frame of the acquired movie for this event represents all pixels in one FD telescope, showing the third peak propagating across the camera after the first two peaks (right).

Among such processes, we cannot exclude multiple initial breakdown pulses, energetic intracloud pulses, compact intracloud discharges, or even gigantic jets as sources for such elves. For example, an energetic intracloud pulse is a type of high-energy electrical discharge associated with the creation of terrestrial gamma ray flashes. The ramp-down of the electrical current in one of these pulses could be sufficiently rapid to create an additional EMP.

Recent research provides clues as to the most likely source of complex elves. This year, researchers reported the first coincident observation of a terrestrial gamma ray flash and an elves event by the Atmosphere-Space Interactions Monitor (ASIM) aboard the International Space Station [*Neubert et al.*, 2020]. These observations, coupled with the large number of superbolts recorded over northern Argentina [*Holzworth et al.*, 2019], suggest that energetic intracloud pulses could be a reasonable candidate mechanism for creating the elves with complex emissions patterns detected by the Auger Observatory.

A New Look at Earth's High-Energy Physics

> *The Auger Observatory has unexpectedly shed light on the dynamics of plasma accelerators on our planet, such as those hiding behind the flash of a lightning bolt.*

The Auger Observatory was designed to investigate and discover the most powerful particle accelerators in the universe, which can boost cosmic rays above 10^{20} electron volts. But it has also unexpectedly shed light on the dynamics of plasma accelerators on our planet, such as those hiding behind the flash of a lightning bolt. We are continuing to analyze data collected by the observatory to pursue more detailed reconstructions of elves created by intracloud discharges and to study the brightness and sizes of elves.

We welcome all collaboration in interpreting elves with multiple peaks. We are also interested in coincident observations with satellite instruments, such as ASIM. The Pierre Auger Observatory will continue year-round operations with full horizon coverage until at least 2030.

Acknowledgments

This article was written by the authors on behalf of the entire Pierre Auger Collaboration. The full list of members taking part in the collaboration is available on the Pierre Auger Observatory's website.

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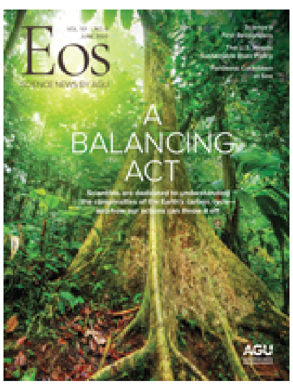

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