Destructive power of a Thunderstorm
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Measurement of the Electrical Properties of a Thundercloud Through Muon Imaging by the GRAPES-3 Experiment

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(Received 6 January 2019; revised manuscript received 21 January 2019; published 15 March 2019)

The GRAPES-3 muon telescope located in Ooty, India records rapid (∼10 min) variations in the muon intensity during major thunderstorms. Out of a total of 184 thunderstorms recorded during the interval of April 2011–December 2014, the one on December 1, 2014 produced a massive potential of 1.3 GV. The electric field measured by four well-separated (up to 6 km) monitors on the ground was used to help estimate some of the properties of this thundercloud, including its altitude and area that were found to be 11.4 km above mean sea level and ≥380 km², respectively. A charging time of 6 min to reach 1.3 GV implied the delivery of a power of ≥2 GW by this thundercloud that was moving at a speed of ∼60 km h⁻¹. This work possibly provides the first direct evidence for the generation of gigavolt potentials in thunderclouds that could also possibly explain the production of highest-energy (100 MeV) gamma rays in the terrestrial gamma-ray flashes.

DOI: 10.1103/PhysRevLett.122.105101

Thunderstorms are a spectacular manifestation of the discharge of massive electric potentials that develop in thunderclouds during severe weather conditions. The first authoritative study of thunderstorms by Franklin dates back to the 1750s [1]. A major advance in their understanding occurred in the 1920s when their dipole structure was identified [2]. However, actual structure is more complex. The separation of electric charges in thunderclouds occurs when supercooled water droplets make grazing contact with hail pellets (graupel) polarized by the fine-weather electric field (120 V m⁻¹) on Earth’s surface. The rebounding droplets acquire a positive charge and are carried by a convective updraft toward the cloud top, whereas negatively charged graupel fall toward the cloud base due to gravity. This creates a vertical field that increases the polarizing charge on the graupel, thus accelerating this process and reinforcing the vertical field that grows exponentially until air insulation breaks down and triggers a lightning discharge [3]. Because the thickness of thunderclouds extends to several kilometers, potentials of ≥1 GV could be generated [2].

A unique signature of massive electric potentials generated in thunderclouds was the discovery of terrestrial gamma-ray flashes (TGFs) containing MeV photons by the BATSE instrument aboard the Compton Gamma Ray Observatory. The source of the TGFs was identified to be thunderstorms in the lower tropical atmosphere [4]. The detection of highest gamma-ray energy of 100 MeV by the AGILE satellite would, however, require bremsstrahlung of very high-energy electrons and the presence of potentials of hundreds of megavolts [5]. The maximum thunderstorm potential measured in balloon soundings is only 0.13 GV [6], which is well short of the magnitude needed to produce 100 MeV gamma rays [5] and the magnitude of 1 GV predicted by Wilson [2]. MeV gamma rays produced in thunderstorms have been detected on the ground, both through triggered and natural lightning discharges, showing a close connection of the TGFs detected from space and from the ground [7,8]. Early studies of the changes in muon intensity $I_\mu$ at low energies (90 MeV) were shown to be correlated with the electric field of thunderstorms [9,10] and confirmed by the results from Norikura [11] and elsewhere [12].
The Gamma Ray Astronomy at PeV EnergieS Phase-3 (GRAPES-3) muon telescope (G3MT) in Ooty [11.4°N, 2200 m above mean sea level (amsl)] studies the astrophysics of cosmic rays (CRs) through the measurement of $I_{\mu}$ produced by CRs. Its detection element is a proportional counter (PRC) made from steel pipes ($6 \times 0.1 \times 0.1$ m). The G3MT consists of four PRC layers under a 2 m thick concrete roof, resulting in a threshold of $E_{\mu} = 1$ sec($\theta$) GeV for muons with a zenith angle of $\theta$. This four-layer configuration enables muon reconstruction in two mutually perpendicular planes, and the two PRC layers in the same projection plane separated by $\sim 0.50$ cm permit the muon direction to be measured with $\sim 4^\circ$ accuracy, as shown in Fig. 1(a). Thus, the G3MT measures $I_{\mu}$ in 169 directions over a field of view; hereafter, FOV = 2.3 sr, as shown in Fig. 1(b) [13]. Although, the solid angle of 169 directions differ significantly, but the area of thundercloud covered varies by only 19%. Because $\sim 2.5 \times 10^6$ muons are recorded every minute, $I_{\mu}$ gets measured to 0.1% precision [14,15].

During thunderstorms, the G3MT detects rapid changes ($\sim 10$ min) in $I_{\mu}$. Because the muon energies exceed 1 GeV, the presence of large electric potentials is implied. To probe this phenomenon, electric field monitors, hereafter referred to as “EFMs” (Boltek model EFM-100 [16]), were installed in April 2011 at four locations: at GRAPES-3 and at three others a few kilometers away, as shown in Fig. 1(c). The data collected during April 2011–December 2014 showed that 184 thunderstorms were detected both by the G3MT and EFMs. The seven largest events with a muon intensity variation of $\Delta I_{\mu} \geq 0.4\%$ were shortlisted. However, except for the event on December 1, 2014 discussed here, the EFM profiles of the remaining six events were extremely complex, which made the association of $\Delta I_{\mu}$ and the electric field of a specific thundercloud difficult.

Thunderclouds are known to have a complex multipolar structure [3]; but here, it is assumed to be dipolar because the implications of such a structure can be easily simulated and a quantitative comparison of the simulation output with experimental data could be used to obtain the average properties of the thundercloud by treating it as a parallel plate capacitor that can provide an approximate estimate of its properties. To simulate the muon response to thundercloud potential $V$, a uniform vertical electric field $E_z$ for the following three cloud thickness cases $D_i$ was investigated, where $V = E_z D_i$: (1) $D_1 = 2$ km for the field between 8 and 10 km amsl, (2) $D_2 = 7.8$ km for the field between the ground and 10 km amsl, and (3) $D_3 = 10$ km for the field between 10 and 20 km amsl. The dependence of $\Delta I_{\mu}$ on $V$ was obtained from Monte Carlo simulations, which are described in the next paragraph and found to be the same for cases (1) and (2). For case (3), $\Delta I_{\mu}$ was 15% smaller than cases (1) and (2). Thus, case (3), apart from being unrealistic, also required potentials higher than the other two cases. Thus, a uniform electric field applied between 8 and 10 km was used to provide a conservative estimate of the thundercloud potential $V$.

The conversion of observed $\Delta I_{\mu}$ into equivalent potential $V$ is derived from Monte Carlo simulations using the CORSIKA code [17] that, in turn, relies on the choice of hadronic interaction generators. Here, FLUKA [18] and SIBYLL [19] were used for the low- (<80 GeV) and high-energy (>80 GeV) interactions, respectively. When two
other popular high-energy generators (namely, QGSJET [20] or EPOS [21]) were used, an identical dependence of $\Delta I_\mu$ on $V$ was obtained. This is because the affected muons are produced by low-energy ($< 80$ GeV) CRs where the high-energy generators are not used. But, when the other two low-energy generators, GHEISHA [22] or UrQMD [23], were used, significant differences were observed. Compared to FLUKA, GHEISHA was, on average, 15% higher; and for UrQMD, it was 6% higher. FLUKA was chosen because it provided the lowest, and therefore the most conservative, estimate of the thundercloud potential. Next, the Monte Carlo simulation of muons detected by the G3MT in each of the 169 directions were carried out: first, with $V = 0$; and then, by applying a $V$ in the range of $−3$ to 3 GV in 0.1 GV steps over a height from 8 to 10 km amsl, as explained above. For each direction, the number of muons above the corresponding threshold energy was calculated. A high-statistics muon database of $10^7$ for $V = 0$ and $10^6$ muons for each nonzero $V$ was created. This allowed the simulated $\Delta I_\mu$ to be measured to 0.1% accuracy, which was much smaller than the error of 0.4–2.7% in real data.

The solar wind introduces a diurnal variation in $I_\mu$ that was removed by modeling with a higher-order polynomial after excluding thunderstorm affected 18 min data. The change in $I_\mu$ during 18 min is shown in Fig. 2. A cluster of 45 contiguous directions enclosed by a dark boundary displays a peak decrease of 2% (209 significance) in $I_\mu$, as shown in Fig. 3. During 10:42-10:59 UT, a clear decrease is visible to the right of the dark boundary in Fig. 2.

The simulated dependence of $I_\mu$ for 45 directions on applied potential $V$ is shown in Fig. 4. A positive $V$ at the thundercloud top relative to the bottom would lead to energy-loss of eV for $\mu^+$ and the same gain for $\mu^-$. Because of the ratio $\mu^+/\mu^- > 1.0$, the loss of detected $\mu^+$ exceeds the gain of $\mu^-$. Thus, the sum of muons of both polarities decreases for positive $V$ and, beyond 1 GV, the slope gradually increases due to the rapid increase in decay probability of $\mu^-$, as seen in Fig. 4. This dependence is used to convert the measured $\Delta I_\mu$ into equivalent $V$ that peaks at $(0.90 ± 0.08)$ GV, as shown in Fig. 5.

The EFM records of the electric field (sample rate = 20 s$^{-1}$) show a smooth profile with rms = 0.01 kV m$^{-1}$ in all four cases, which is same as the EFM resolution. This suggests the absence of major lightning. Hereafter, the mean electric field (min$^{-1}$) is used for comparison with muon data (min$^{-1}$). Because all EFM profiles were similar and their amplitudes varied 22% around a mean of 3.3 kV m$^{-1}$, they were normalized to 3 kV m$^{-1}$, as shown in Fig. 6. EFM1, after a delay of 4 min, was followed by EFM2 and EFM4; both of which overlapped. EFM1, which was closest to the G3MT, was delayed by 6 min relative to EFM4, indicating a thundercloud velocity of $\sim 1$ km min$^{-1}$, moving from EFM4 toward EFM1, as shown schematically in Fig. 1(d).

Thundercloud movement in the FOV may be studied by the displacement of its muon image ($\Delta I_\mu$) in short 2 min exposures. Because short exposures reduce muon statistics thus, regions that showed ($I_\mu$) decrease in (a) contiguous directions or (b) isolated directions over $\geq 2$ successive

![FIG. 2. Muon intensity variation during 18 min thunderstorm. Forty-five out of 169 thunderstorm affected contiguous directions are enclosed by the dark boundary. Color-coded percent variation shown by a bar on the right. Thundercloud angular size in N-S = 74.6°.](image)

![FIG. 3. Maximum muon intensity variation $\Delta I_\mu = −2\%$, starting at 10:42 Universal Time (UT) and lasting 18 min, seen during thunderstorm of December 1, 2014. Vertical bars represent $1\sigma$ error.](image)

![FIG. 4. Dependence of $\Delta I_\mu$ on electric potential (in gigavolts) across atmospheric layer of 8–10 km amsl, based on simulations for 45 directions shown in Fig. 2.](image)
exposures were selected. In Fig. 7, $\Delta I_e$ for the first exposure starting at 10:42 UT is shown for the full FOV in the first top panel labeled 1. A decrease in four directions enclosed by a dark boundary is visible, and the potential needed is shown in the bottom panel 1 of Fig. 7 that shows maximum $V = 1.8$ GV during 10:41–11:00 UT. From the second panel onward, only 91 affected directions in the east are displayed. In the top panel labeled 2, 12 affected directions require maximum $V = 1.4$ GV. This decreases to 1 GV for panels labeled 3 (23) and 4 (32). Then, it increases to 1.1 and 1.2 GV for panels labeled 5 (28) and 6 (23), respectively. Finally, it reaches 1.4 GV for panels labeled 7 (16) and 8 (13). Integer values in the parentheses next to each panel number indicate the number of affected directions, which are highlighted by the dark boundaries in the corresponding top panels.

Successive panels in Fig. 7 show the western boundary of the muon image moving from east to west in the northern FOV. For example, it moved from direction A in the top panel labeled 1 to B in the top panel labeled 4 in 6 min, implying an angular velocity of $6.2^\circ$ min$^{-1}$, as depicted in Fig. 1(d). A movement of $6.2^\circ$ min$^{-1}$ of the muon image is seen in the southern FOV from C to D in the top panels labeled 3 and 6, respectively. A similar movement is also reflected in the progressive shift of the peak voltage in the eight bottom panels of Fig. 7. If this angular velocity ($6.2^\circ$ min$^{-1}$) is combined with the linear velocity ($1$ km min$^{-1}$) from the EFMs, then a height of 11.4 km asml is obtained, which is comparable to a typical thundercloud height (12 km) [3]. The 1 km min$^{-1}$ velocity and 11.4 km height are consistent with the velocity and height of a subtropical jet stream in south India [24].

In north-south direction, the muon image covers the full FOV that corresponds to an angular size of 74.6°, as seen in Fig. 2. This implies a radius of $\geq 11$ km, which is very similar to average thundercloud radius ($\sim 12$ km) [25] and yields a total area of this thundercloud of $\geq 380$ km$^2$. A thundercloud with infinitesimally thin charged regions, separated by 2 km, acts as a parallel-plate capacitor of a capacitance of $\geq 1.7 \mu F$. But, in reality, the thickness of the charged regions is comparable to their separation that reduces capacitance by $\sim 50\%$ to $\geq 0.85 \mu F$. $V = 1.3$ GV would require a total charge of $Q \geq 1100$ C and energy of $\geq 720$ GJ stored in this thundercloud. A 1.3 GV potential across the thundercloud with its two charged regions with a thickness 2 km each and a distance of 2 km between them implies an average field of 2.2 kV cm$^{-1}$, which is lower than the breakdown field at high altitudes [3]. The mean time to reach the maximum potential shown in the eight bottom panels in Fig. 7 is 6 min. Thus, the thundercloud would have delivered a power of $\geq 2$ GW, which is comparable to the single biggest nuclear reactors [26], as well as hydroelectric and thermal power generators [27]. The separation of 2 km used is reasonable because it extends the thundercloud top into the tropopause that defines the limit of cumulonimbus clouds producing major thunderstorms in the atmosphere [3]. Because the capacitance, total charge, energy stored, and power delivered by a thundercloud vary inversely with the separation of its charged layers, these parameters can be easily calculated for any other separation.

The potential can be measured by integrating the electric field over the thundercloud height. However, in general, the field measured by instruments aboard aircraft and balloons spans a region much smaller than the thundercloud height, and therefore cannot provide a reliable estimate of the potential. On the other hand, the parameter $\Delta I_e$ depends on the thundercloud potential and is virtually independent of its electric field and-or height. This makes muon telescopes with a giga-electron-volt threshold such as the G3MT ideal for measuring gigavolt potentials in thunderclouds. However, such high potentials cannot be indefinitely sustained, and a breakdown of air would result in acceleration of electrons to giga-electron-volt energies. It is conceivable that bremsstrahlung emission from giga-electron-volt electrons could produce photons ranging from
a few to beyond 100 MeV in a short flash of terrestrial gamma rays.

Conclusions.—The GRAPES-3 muon telescope is well suited to measure the electric potential developed in thunderclouds, as shown for the December 1, 2014 event in which a peak electric potential of 1.3 GV was measured. This value is an order of magnitude larger than the previously reported maximum of 0.13 GV. This is possibly the first direct evidence for the generation of gigavolt potentials in thunderclouds, which is consistent with the prediction of Wilson 90 years ago [2]. The existence of gigavolt potentials could explain the production of highest-energy gamma rays in terrestrial gamma-ray flashes discovered 25 years back [4]. It is shown that \( \geq 2 \) GW of power, which are comparable to the single biggest nuclear reactors [26], as well as hydroelectric and thermal power generators [27], were delivered by this thunderstorm that was estimated to be moving at a speed of 60 km h\(^{-1}\) near the top of the troposphere. Despite a simplified structure of the thundercloud used here, the present work provides reasonable insights into the physical state of the thunderstorms.

D. B. Arjunan, V. Jeyakumar, S. Kingston, K. Manjunath, S. Murugapandian, S. Pandurangan, B. Rajesh, K. Ramadass, V. Santhoshkumar, M. S. Shareef, C. Shobana, and R. Sureshkumar are thanked for assistance in running the GRAPES-3 experiment. The GRAPES-3 experiment was built with the generous support of TIFR and the Department of Atomic Energy, of the Government of India. This work was partially supported by grants from ISEE, Nagoya University, Chubu University, and the Ministry of Education and Science, Japan. We thank the three anonymous referees whose prompt, critical, and constructive comments led to a significant improvement in the final Letter and its early publication.


A thunderstorm probed with atmospheric muons had an electric potential exceeding one billion volts, much higher than values measured previously.

Researchers have documented a thunderstorm producing an electric potential of about 1.3 billion volts (GV), 10 times greater than the largest value ever reported. The team’s new thunderstorm monitoring method makes use of the muons raining down on Earth, produced by cosmic rays hitting the atmosphere. A thundercloud’s potential can reduce the energies of the charged particles and decrease the likelihood that they will be detected beneath the storm. The new measurement indicates that thunderstorms with several-billion-volt potentials are possible, voltages high enough to explain the mysterious flashes of high-energy gamma rays sometimes observed during thunderstorms.

Since Benjamin Franklin flew a kite on a stormy afternoon in 1752, we have known that thunderstorms include electrical phenomena—lightning and thunder are the manifestations of sudden discharges between charged regions of the atmosphere. To study the electrical structure of thunderclouds, researchers send airplanes or balloons into the centers of thunderstorms. These tests have found electric potentials exceeding tens of millions of volts, with the largest value, 130 megavolts, seen during a mountain storm in New Mexico in the 1990s [1]. Aircraft and balloons, however, can only probe the small region of the storm through which they fly and cannot measure the potential across the entire cloud.
The method devised by Sunil Gupta of the Tata Institute of Fundamental Research in Mumbai, India, and colleagues is based on probing the effect of thunderstorms on particle detections by G3MT, a muon telescope in Southern India (part of the GRAPES-3 cosmic-ray detection facility). The telescope detects muons generated in the atmosphere by cosmic rays—charged particles that mainly come from outside of the Solar System. Researchers at several other muon telescopes have previously observed thunderstorms correlated with changes in the measured numbers of muons (the flux). Now Gupta’s team has taken the next step and developed a quantitative method. “We realized that GRAPES-3 is an ideal tool for measuring thunderstorm potentials, in particular for the biggest storms,” says Gupta.

The majority of the muons detected by G3MT are positively charged antimuons, which usually lose energy as they respond to the complicated arrangement of charges of a thundercloud. With reduced energies, the muons are less likely to be picked up by the detector, which only measures particles with energies above a certain threshold. So the storm registers as a reduction in detected muon flux that can be as large as a couple of percent. With over one million muons reaching G3MT every minute, the system can measure muon-flux changes with 0.1% precision. The telescope can also distinguish among 169 discrete directions in the sky.

From flux measurements, Gupta and his colleagues can estimate the thunderstorm potential using computer simulations based on a simplified description of the thunderstorm. They treat it as a giant capacitor made of two parallel plates 2 km apart generating an upward-pointing electric field.

Between 2011 and 2014, the researchers gathered data on 184 thunderstorms, shortlisting the seven largest events. Six of those, however, had a complex temporal profile, which made it hard to compute the potential. The researchers focused on the seventh storm, which occurred on 1 December 2014, and derived a peak, record-breaking electric potential of 1.3 GV.

“This muon-based technique provides a unique, albeit indirect, way to probe the electric fields in the largest natural particle accelerators on Earth—lightning and thunderstorms,” says Michael Cherry, who studies high-energy cosmic rays and gamma rays at Louisiana State University in Baton Rouge. The analysis depends on Monte Carlo simulations and on simplifying assumptions that may not apply to all storms, he says, but the value derived clearly indicates much larger potentials than those previously measured by balloons. He suggests that launching a balloon or a drone during a thunderstorm while observing muons could provide a test of one key model parameter: the 2-km separation distance between the plates of the thundercloud-equivalent capacitor.

The new finding may also help researchers solve an atmospheric puzzle, says Gupta. Since 1994, satellite measurements have revealed gamma-ray flashes coming from altitudes of tens of kilometers. Researchers speculate that these flashes could be produced by electrons accelerated by thunderstorms, but previous measurements hadn’t found sufficiently large thunderstorm potentials. However, the newly observed potentials in the gigavolt range are much closer to the values required to produce the
observed gamma rays. Gupta's team is now setting up gamma-ray detectors around GRAPES-3, hoping to provide conclusive evidence by catching gamma-ray flashes in coincidence with a gigavolt-level thunderstorm.

This research is published in *Physical Review Letters*.

–Matteo Rini

Matteo Rini is the Deputy Editor of *Physics*.

References

Supercharged thunderstorm reaches a record 1.3 billion volts

Lighting bolts sizzle over Johannesburg, South Africa. Credit: Mitchell Krog/Getty

Thunderstorms can reach voltages ten times greater than those previously recorded, a new measurement suggests.

Sunil Gupta at the Tata Institute of Fundamental Research in Mumbai, India, and his colleagues used an instrument called a muon telescope to measure storms’ electric potential — the voltage between the top and bottom of a thundercloud.

Muon particles are generated when cosmic rays smash into Earth’s atmosphere. As muons cross a storm’s electric potential, they lose energy, which causes some of the particles to fall below a muon telescope’s detection threshold. A storm with a higher voltage causes each muon traversing it to experience a greater energy drop. This means that a telescope’s detector sees a lower rate of incoming muons when storm voltage is greater.

Gupta’s team used the GRAPES-3 facility in Ooty, India, to record muons as they reached the ground during 184 thunderstorms. Using computer simulations, the researchers estimated that the electric potential of one storm in 2014 reached 1.3 billion volts, the largest value ever recorded.

This observation might explain the flashes of highly energetic γ-ray radiation
observed during storms; scientists have theorized that only extreme voltages can produce such flashes.


Physics
Massive voltages in thunderclouds can slow down subatomic particles

By Sid Perkins Mar. 14, 2019, 11:50 AM

The electric potentials that build up in thunderclouds can exceed 1.3 billion volts, about 10 times the voltages previously measured, Science News reports. Besides being the driving forces for lightning, electric potentials in thunderclouds also tend to decelerate negatively charged subatomic particles known as muons, which rain down from the upper atmosphere where they are created when cosmic rays collide with gas molecules. The new finding, based on analyses of a severe thunderstorm that occurred in southern India in December 2014 and reported in a forthcoming issue of Physical Review Letters, may help explain how strong storms can be a source of brief flashes of gamma rays, researchers say.

*Clarification, 20 March, 10:10 a.m.: To avoid confusion with astronomical processes, the description of the gamma rays generated by thunderstorms has been modified.*
Most powerful thunderstorm ever measured produced 1.3 billion volts

PHYSICS 20 March 2019

By Chelsea Whyte

A thunderstorm in India produced an electric potential of 1.3 billion volts – 10 times the highest voltage previously recorded. The finding could help explain how high-energy gamma rays are produced during storms.

Inside a thundercloud, positively charged water droplets are carried upward while negatively charged hail pellets are drawn down. This difference in charge between the top and the bottom of the cloud creates a vertical electric field that intensifies as the cloud gets larger. In
thunderclouds that are several kilometres thick, the electric potential can reach billions of volts. That is what happened in December 2014, when the record-breaking voltage was detected in a storm over Ooty in India. It was caused by clouds 11 kilometres above sea level covering an area about 22 kilometres across, though there was no lightning detected.

“Thunderstorms are really big places, and it’s hard to get enough instruments inside them to measure the whole thing,” says Joseph Dwyer at the University of New Hampshire, who wasn’t involved in the work. “The act of making the measurement with a balloon or airplane can collapse the electric field and artificially initiate lightning.”

Instead of going up into the complex mess of clouds, Sunil Gupta at the Tata Institute of Fundamental Research in India and his colleagues measured the electric potential with messengers in the form of muons — subatomic particles generated in the atmosphere by powerful cosmic rays from outside the solar system. They pass through the thundercloud in a few microseconds and experience the electric potential produced inside.

Read more: Lightning storms triggered by exhaust from cargo ships

The team calculated the storm’s power using G3MT, a muon telescope in southern India. As short-lived muons pass through the electric field, they gain energy and more of them make it to the sensors on the ground than usual. Measuring this flux in muons allowed the team to simulate the voltage produced by the thunderstorm overhead.

The reason the calculations were so delayed was because Gupta and his colleagues don’t normally study thunderstorms. It was only when they were combing through data from the telescope that they decided to model the storm.

The high potentials inside storm clouds could explain the puzzle of how thunderstorms initiate terrestrial gamma ray flashes (TGFs). “These gamma rays can blast their way through the atmosphere and temporarily blind a satellite, but they come from garden variety thunderstorms,” says Dwyer. This new measurement suggests that the potentials are larger than we had thought, which means there is more energy to impart to electrons within the thundercloud.

Gupta says electrons with an energy of 1.3 billion volts can easily radiate gamma rays of more than 100 million volts, and explain the production of the highest energy terrestrial gamma ray flashes we see.

Maribeth Stolzenburg at the University of Mississippi doesn’t agree. “It is surprising to me that this largest thundercloud potential on record occurs in the absence of major lightning. After 30 years of studying thunderstorms, I find this very hard to understand,” she says. “It is additionally perplexing because there is a claim made in the paper that this large potential estimate can somehow explain the production of TGFs. As far as I am aware, the present understanding of TGF production is closely tied to the initiation stage of particular intracloud lightning flashes.”


More on these topics: electromagnetism weather
As clouds gathered over the city of Philadelphia in 1752, Benjamin Franklin stood outside with a simple kite-borne experiment and proved the electric nature of lightning. Now, more than 250 years later, scientists have uncovered a shocking secret about the awesome power of thunderstorms.

With the help of charged particles originating from space, a team in India has accurately measured the electric properties of a giant thundercloud, determining that the behemoth contained 10 times more energy than any previously investigated storm. Along with discovering a novel connection between cosmic and terrestrial events, the findings might help solve a 25-year-old mystery in high-energy physics.

Thunderstorms 101 At any moment, about 2,000 thunderstorms are occurring worldwide. Learn how thunderstorms form, what causes lightning and thunder, and how these violent phenomena help balance the planet's energy and electricity.

Since 2001, physicists in Udagamandalam, India, have been using the Gamma Ray Astronomy PeV EnergieS phase-3, or GRAPES-3, telescope to monitor subatomic particles called muons. Cascades of these naturally occurring particles rain down on Earth when cosmic rays from the distant universe hit our upper atmosphere. (Here's how scientists recently used muons to discover a previously unknown void inside the Great Pyramid of Giza.)

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Intriguingly, the highly sensitive GRAPES-3 instrument often detected slight decreases in the muon shower's intensity between April and June, and again between September and November—just when the subtropical region receives its highest rainfall.

The GRAPES-3 muon telescope.

Photograph by GRAPES-3 collaboration

“This was more of an amusing episode for us than anything serious,” says study coauthor Sunil Gupta, a high-energy physicist at the Tata Institute of Fundamental Research in Mumbai, India, whose team described their work last month in Physical Review Letters. “We were studying high-energy cosmic rays and interplanetary space, and not so much the thunderstorms.”
Packing a punch

Muons carry negative charge, meaning their paths are distorted by electric fields. Gupta wondered if that property could be used to calculate how much energy the thunderclouds contained.

Back in 1929, Nobel prize-winning physicist Charles Thomson Rees Wilson measured the electric field inside a thundercloud and found it to be a surprisingly large 12,700 volts per inch. This implied that the storms, which can stretch for miles, should have enormous total electric potentials of around a gigavolt, or the equivalent of nearly a billion AA batteries.

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But measuring voltage across an object usually requires placing two wires at either end, and nobody had figured out how to do that for a large and amorphous thing like a cloud. Airplane and balloon experiments, which have flown through thunderstorms taking readings at various locations, found electric potentials of tens of millions of volts, with the largest previously recorded event having 130 million volts.

Study coauthor Balakrishnan Hariharan devised a model that determined how powerful an electric field would need to be to alter the number of muons detected in GRAPES-3. Working backward, the team could then use their muon observations to estimate the electric field inside the clouds above the experiment.

In the GRAPES-3 data, the researchers saw the electrical effects of 184 thunderstorms over the course of three years. The muons indicated that one particular leviathan, which appeared on December 1, 2014, briefly contained an electric potential of nearly 1.8 gigavolts. That's enough energy to run all of New York City for half an hour, Gupta says.
“To achieve such high voltages on the ground is almost impossible,” he adds. “But nature seems to know how to do it almost effortlessly.”

**Dangerous discharge**

Because the muon-based measurements can see large areas of the clouds, they are more accurate than plane- or balloon-borne experiments. That means prior data likely delivered underestimates, and many thunderstorms should have billions of volts of energy inside them. This, in turn, might illuminate the origins of a long-standing head scratcher in atmospheric physics.

In 1994, NASA’s Compton Gamma Ray Observatory, which was built to monitor powerful flashes of light occurring in distant galaxies called gamma-ray bursts, noticed a few high-energy eruptions coming from Earth's atmosphere. Nobody has since been able to give a full explanation for why our planet should produce events similar to some of the most powerful phenomena in the cosmos.

Though lightning had been suspected to play a role, the thundercloud energies observed in previous experiments were not great enough to explain the terrestrial gamma-ray flashes. (Find out how thunderstorms can shoot antimatter into space.)

Now, GRAPES-3’s gigavolt measurements are the first to suggest that such storms contain enough power to produce this enigmatic effect. Gupta says the team would like to include a gamma-ray detector in their instruments in future to help solidify the connection. They would also like to study how quickly the voltage in a thunderstorm is dissipated through lightning strikes.

“We want to look for the discharge,” he says. “Because that’s what causes most of the damage.”

For now, the existing measurements have already impressed other researchers.

“It’s an application that nobody has thought of before,” says Michael Cherry, who studies high-energy cosmic rays and gamma rays at Louisiana State University in Baton Rouge and was not involved in the recent work.

Most researchers in the community would have previously been skeptical that ultra-powerful cosmic rays could be affected by comparatively mundane lightning, he adds. But the results suggest that lightning is one of the most powerful natural particle accelerators that Earth-bound physicists can access.

“These high-energy processes don’t have to be studied in an exotic source like a distant black hole or supernova,” Cherry says. “We can study them by looking up close and personal at nearby lightning.”

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Reality Check: You Can’t Actually Name Stars for David Bowie
Advances in science are often the result of combining ideas and information from scientific disciplines that seem to be otherwise unrelated. A familiar example might be how scientists came to understand the double helix of DNA, which required mixing biology and x-ray crystallography.

And now, a new scientific duo will allow us to study one of the most fascinating phenomena in the Earth’s atmosphere: lightning storms. Radiation from space and meteorology have revealed that the electricity of lightning storms can be far more powerful than anyone ever expected.

Don Lincoln

With the ability to generate as much power as a modern nuclear power plant, lightning storms are a glorious display of the power of nature, which have awed humanity for millennia. Whether they were thought to be Thor fighting the Frost Giants or understood using the more modern idea of electricity, voltages and electric fields, it is hard to compete with a wave of lightning rolling across the sky, accompanied by a cacophonous rumble of thunder.

Meteorologists have long studied what produces a thundercloud. Friction between water droplets and air separate electric charges into positive and negative, with one set rising to the top of the clouds and others descending to the bottom. This separation of charges results in huge electric potential, such that air, which is normally an insulator, becomes a conductor and the clouds discharge, emitting a thunderous stroke of light and sound.

By sending airplanes and weather balloons into the center of lightning storms, scientists were able to measure just how large the voltages can be in thunderclouds, with the largest value reaching 130 million volts. That record stood for a long time -- until now.

A new technique for studying the inside of a lightning storm has been developed that exploits radiation from space to peer inside an entire thunderstorm and measure all of the voltages in the storm, rather than just those in a few clouds.
This 'supercluster' of galaxies lets us peek into the universe's past
You might not know it, but the entire Earth is under assault. A constant barrage of particles called cosmic rays hits the Earth's atmosphere. Cosmic rays are usually just protons boiled off from the Sun, which hit atoms in the Earth's atmosphere. These collisions smash apart the atoms' nuclei and the result are many particles -- one proton in and many out. This is due to Einstein's theory of relativity.
The energy of these highly energetic cosmic rays converts into an array of subatomic particles. Those particles go on and hit other atoms in the atmosphere, making even more particles. Eventually they decay, and what filters down to the Earth's surface is a steady rain of an unstable subatomic particle called a muon.
In addition to being created in cosmic ray collisions, muons can also be made in particle accelerators. They are much like the more familiar electron. Most importantly, they have an electrical charge, which can be affected by electrical fields like the ones that exist in thunderstorms.
Because we can measure cosmic rays both on a clear day and during a thunderstorm, we can use these two different conditions to gauge the electric fields inside the storm.
The GRAPES-3 experiment is located in India and was built to study the properties of muons originating from cosmic rays. It is an array of 400 muon detectors, spread over 25,000 square meters (6.2 acres).
A dark matter hurricane is headed our way
The GRAPES-3 experimenters noticed that when a thunderstorm passed over their detector, the number of muons they observed got smaller compared to the rate before the thunderstorm arrived. The very strong electric fields inside the storm can deflect the muons so they entirely miss the detector -- that was the reason the muon rate dropped. The effect was very small (rarely did they observe a change of more than 0.4%), but the detector is sophisticated enough to measure that accurately.
They set out to study this in more detail, first by adding electric field measuring devices around the perimeter of their detector. Then they waited.
Over three and a half years, from April 2011 to December 2014, they...
observed 184 thunderstorms, with seven of them being big enough to alter their detected rate of muons by a large amount. For six of those seven storms, the electric field measuring devices indicated a very complicated electrical situation, which was hard to characterize properly. But a storm that occurred on December 1, 2014 was both big enough and simple enough for the scientists to simulate. The instrument that spots killer asteroids and star-eating black holes
What they found astonished them. In this monster storm, their calculations indicated that the voltage in the storm was 1.3 billion volts, about ten times more than the biggest voltage measured previously. This equates to more than two billion watts of power, which is comparable to a large and modern nuclear or hydroelectric plant.
Such an enormous voltage, while very surprising, was a welcome result, as it answered some key questions. For instance, scientists have long known that powerful equatorial thunderstorms can generate gamma rays, which is a kind of nuclear radiation. How they did so was a mystery -- it is impossible for storms harboring 130 million volts of electrical potential to make the observed gamma rays. But with voltages of 1.3 billion volts, gamma rays are easily explainable.
The incredible magnitude of the voltage, compared to prior measurements, can be explained by the fact that the weather balloons and airplanes, previously used sample only a small part of the storm. Using cosmic ray muons, scientists are able to study the entire storm at one time.
So, with any such scientific announcement, the most important question to ask is, "Is this a reliable measurement?" In this case, some caution is warranted. The study presenting these extraordinary findings will be published in the journal Physical Review Letters, which is one of the most prestigious scientific journals of its kind, and it has undergone stringent peer review. On the other hand, the measurement reports only a single thunderstorm, and the specific model used in the theoretical calculation was a simple one. It's clear that a more refined model could give a different result.
Still, the technique is fascinating. Even if a more refined study results in a different numerical value for the electrical potential inside the storm, it is quite likely that the approach of using cosmic ray muons to study thunderstorms will continue to be developed.
Science is often the most fascinating and productive when techniques from different disciplines are combined. Cross-disciplinary studies have often revolutionized our understanding of perplexing scientific mysteries. It could well be that cosmic rays and thunderstorms
Billion-volt thunderstorm studied using muons

A thundercloud with a record-breaking voltage of 1.3 GV has been observed by physicists in India and Japan. Sunil Gupta at the Tata Institute of Fundamental Research in Mumbai and colleagues calculated the voltage from changes in the intensity of atmospheric muons detected by the GRAPES-3 muon telescope. The existence of such high voltages could explain the origin of the mysterious, high-energy gamma-ray flashes, which are occasionally seen in cloud tops during thunderstorms.

Thunderstorm clouds are normally studied by flying weather balloons and aeroplanes straight through their centres. Indeed, a balloon was used several decades ago to measure the previous record high voltage of 130 MV – which was observed inside a thunderstorm over New Mexico. Such a voltage is high enough to create atmospheric particle accelerators that can generate X-rays and low-energy gamma rays. However, it is not high enough to create high-energy (about 100 MeV) gamma rays that are sometimes detected during thunderstorms.
In the 1920s, Scottish physicist and meteorologist Charles Wilson predicted that thunderstorms could induce far larger potentials; on scales of billions of volts. Voltages this large could only form across storm clouds that are several kilometres high and his prediction had been untested because balloons and aeroplanes are not able to measure voltages on such length scales.

Deflecting fields

Gupta and colleagues have got around this problem by using the GRAPES-3 muon telescope at Ooty in southern India to measure voltages across entire clouds. The telescope detects muons created when cosmic rays smash into the atmosphere. Muons are charged particles and are therefore deflected by the electric fields associated with huge voltages in thunderclouds. This means that fewer muons should be detected by GRAPES-3 when thunderclouds are nearby – which the team verified by studying 184 thunderstorms over three years.

Japanese team sees gamma-ray pulse before lightning flash

To understand their results, the team modelled a thundercloud as a colossal parallel-plate capacitor– with the plates representing positively- and negatively-charged cloud layers that are separated by several kilometres. Using this model to interpret muon observations gathered during a storm in December 2014, they concluded that a voltage of 1.3 GV had developed between cloud layers – confirming Wilson’s prediction.

The voltage appears to be large enough to create flashes of gamma rays with energies as high as 100 MeV – which the team could not detect with their set-up. The researchers now plan to install gamma-ray detectors close to GRAPES-3, allowing them to pick up gamma rays in coincidence with gigavolt-scale thunderstorms.

The study is described in Physical Review Letters.
How Much Electricity Can Thunderstorms Produce?

Researchers used a cosmic ray detector to clock one storm in at a shocking 1.3 billion volts

Illustration of the GRAPES-3 Muon telescope in a lightning storm.
(PRANAY GODAWAT/GRAPES-3 EXPERIMENT)
Thunderstorms are surely powerful, but quantifying their electrical potential is challenging. A new study, however, was able to look deep within one giant storm using a telescope designed to study cosmic rays, finding that it contained a shocking 1.3 billion volts, according to a new study in the journal *Physical Review Letters*.

Matteo Rini at *Physics* reports that in the past researchers have flown airplanes or released balloons into storm clouds to try and measure their electric potential. The largest reading taken with those methods clocked in at 130 million volts during a storm over New Mexico in the 1990s.

But researchers at the Tata Institute of Fundamental Research in Mumbai, India, decided to probe thunderclouds using something more sophisticated than a balloon: muon detectors. Muons are charged particles produced in the upper atmosphere of the Earth when cosmic rays that constantly bombard our planet interact with various particles. That means there’s a steady rain of these energetic muons constantly falling across the earth. When something gets in their way, however, muons lose energy, and the loss of energy can be detected using special equipment.

The GRAPES-3 telescope at The Tata Institute tracks muons, detecting over one million muons per minute. But George Dvorsky at *Gizmodo* reports that the team added electric field monitors to the detector and began watching storms passing overhead. By looking at the reduction in energy of the muons passing through the cloud, the team can calculate the amount of electrical potential within the storm.

Between 2011 and 2014, the team captured data on 184 storms. They narrowed that list to the seven largest storms. Six of those, however, were complex storms and computing their electrical potential had various problems. A massive storm in December 1, 2014, however, had the right profile for a calculation.

The storm moved along at 40 miles per hour at an altitude seven miles above the Earth’s surface and and covered about 146 square miles. Calculations based on the number of muons the storm repelled show it had a potential of 1.3 billion volts, 10 times more than the previous highest reading for a thunderstorm.

“Scientists estimated that thunderclouds could have gigavolt potential in the 1920s,” co-author Sunil Gupta of Tata tells Tia Ghose at *LiveScience*. “But it was never proven — until now. The amount of energy stored here is enough to supply all the power needs of a city like New York City for 26 minutes. If you could harness it.”
Gupta says the chances of finding a way to use all that electrical potential is unlikely—the energy is so intense it would melt anything we used to conduct it.

Michael Cherry, a cosmic and gamma-ray researcher at Louisiana State University in Baton Rouge tells Rini at Physics that the muon-detecting technique is a good start, but that it relies on some simplified models of storms to derive its calculations. In the future, he says, sending drones or balloons into storms in combination with the muon detector could help refine the readings.

The fact that storms can climb into the gigavolt range does help solve one mystery. Since the 1990s satellites have recorded gamma-ray flashes emanating from the higher reaches of the atmosphere known as Terrestrial Gamma Ray Flashes. If thunderstorms do have electrical potential in the gigavolt range, it means they are powerful enough to accelerate electrons to speeds that can smash certain atoms to pieces, producing the flashes.

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Current Issue | April 2019
Muons reveal the whopping voltages inside a thunderstorm

Science News

Earth,
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Physicists used subatomic particles to probe the inner workings of a cloud

By

Emily Conover
7:00am, February 15, 2019

STORM SURGE Subatomic particles called muons can expose a thunderstorm (like this one) storing up a huge electric potential — more than a billion volts.

Ian Froome/Unsplash

An invisible drizzle of subatomic particles has shown that thunderstorms may store up much higher electric voltages than we thought.

Using muons, heavier relatives of electrons that constantly rain down on Earth’s surface, scientists probed the insides of a storm in southern India in December 2014. The cloud’s electric potential — the amount of work
necessary to move an electron from one part of the cloud to another — reached 1.3 billion volts, the researchers report in a study accepted in *Physical Review Letters*. That's 10 times the largest voltage previously found by using balloons to make similar measurements.

High voltages within clouds spark lightning. But despite the fact that thunderstorms regularly rage over our heads, “we really don't have a good handle on what's going on inside them,” says physicist Joseph Dwyer of the University of New Hampshire in Durham who was not involved with the research.

Balloons and aircraft can monitor only part of a cloud at a time, making it difficult to get an accurate measurement of the whole thing. But muons zip right through, from top to bottom. “Muons that penetrate the thunderclouds are a perfect probe for measuring the electric potential,” says physicist Sunil Gupta of the Tata Institute of Fundamental Research in Mumbai, India.

**BEARING FRUIT** The GRAPES-3 experiment (shown) measures muons that rain down on Earth. The pitter-patter of the electrically charged subatomic particles drops off during thunderstorms, unmasking the electrical inner workings of clouds.

Gupta and colleagues studied the muons' behavior with the GRAPES-3 experiment in Ooty, India, which observes around 2.5 million muons every minute. During thunderstorms, that rate drops, as muons, which are electrically charged, tend to be slowed by a thunderstorm's electric fields. That means fewer particles carry enough energy to register in the scientists' detectors.

Using computer simulations of a thunderstorm, the researchers determined the electric potential necessary to explain the drop in muons spotted during the 2014 storm. The team also estimated the storm's electric power: It was similar to the output of a large nuclear reactor, at around 2 billion watts.

The result is “potentially very important,” Dwyer says. But “with anything
that's new, you have to wait and see what happens with additional measurements.” And the researchers’ simulated thunderstorm was simplified, he says. It consisted of one region of positive charge, and another negatively charged region, whereas real thunderstorms are more complex.

If confirmed, though, such high voltages inside a thunderstorm could explain a puzzling observation: Some storms send bursts of high-energy light, called gamma rays, upward (SN: 5/30/15, p. 12). But scientists don't fully understand the processes that could create such energetic light. If thunderstorms indeed reach the billion-volt level, that could account for the mysterious light.

Citations


Further Reading


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How a Space Telescope's Accidental Discovery Overturned Everything we Thought we Knew About Lightning Storms

The GRAPES-3 muon telescope in Ooty, India was designed to study the cosmos—events that took place millions of years ago at distances that confound the human imagination. What researchers didn't expect was that it would also shed light not just on cosmic history, but on a mystery much closer to home: the massive power hidden in a thundercloud.

Benjamin Franklin was the first to produce a definitive study on a thunderhead's electric charge*. With his famous kite-in-a-thunderstorm experiment, along with many others, he showed that thunderclouds separate electric charge, piling up negative charge at their lower edges and positive charge at the top. (It's since been found that although this is the case most of the time, occasionally the charges are switched.) This charge imbalance creates an electric potential difference—also known as a voltage—across the cloud vertically, much like a giant battery. In 1929, Scottish physicist Charles Wilson estimated this voltage to be well over one gigavolt, or one billion volts—an astounding figure. While it was initially accepted with enthusiasm, this estimate eventually fell out of favor as field measurements repeatedly struggled to break one-tenth that amount.

That shouldn't really come as a surprise, though, says Sunil Gupta, corresponding author on a new article in the American Physical Society's journal Physical Review Letters. After all, voltage is usually determined by connecting the positive and negative sides with a terminal and measuring the current that flows across it, powered by the potential difference. “But how do you put a terminal across a two- or three-kilometer high thundercloud?” he asks rhetorically. You simply can't.

Instead, researchers usually use balloon-borne instruments to measure the local electric field at many points throughout the thundercloud, and from that extrapolate the overall voltage. But balloons are slow and can take hours to transverse a cloud, and thunderstorms have short lifetimes. “They weren't using the right tool,” Gupta says. In contrast, he and his colleagues think that they've found the ideal tool, one that can flit through a thundercloud in a matter of microseconds: high-energy, electron-like particles known as muons.

This story begins the same way so many others do in the scientific community: an unexpected experimental measurement. Although the project would eventually develop into a collaboration among twenty-two researchers at six institutions dotted across India and Japan, it started with one team from the Tata Institute of
Fundamental Research in Mumbai, and another from Osaka City University. The two institutes were initially united in a collaborative survey of muons, with the hope that it would provide some insight into the cosmos.

Muons themselves do not come from space, but astronomers find them useful as a proxy for cosmic rays, which do. Cosmic rays are an assortment of high-energy particles—primarily composed of protons and helium nuclei, but also containing representatives of most of the periodic table—that bombard Earth's atmosphere from outer space.

After being ejected from stars, supernovae, and more exotic objects such as quasars, these particles travel over light years of empty space, practically unimpeded. But when they enter the atmosphere, they're confronted with a wall of air molecules, and quickly interact with these particles' nuclei to produce a whole spectrum of secondary particles, including muons. Except for muons, these secondary particles never reach the ground; they're either too light or too highly charged to carry much momentum in a straight line. Muons, however, have the charge of an electron but more than 200 times its mass, which means they can hurtle down toward Earth at incredible speeds, without being deflected much by the charged particles they pass on the way. "Almost like a shower of particles moving at nearly the speed of light propagating towards Earth," Gupta explains.

It was this shower of particles that the team originally set out to survey with the GRAPES-3 muon telescope. However, they were surprised to find that during certain times of year the muon intensity tended to dip (or, more rarely, spike) as much as 2% for a brief period. "Now, for most experiments 2% is a very small number... you generally don't worry about it," Gupta admits. But outside of these anomalies, the fluctuations in the number of muons measured was comparatively tiny, only about 0.2% off the mean. That means that such an enormous variation is extremely unlikely to be due to chance; in fact, "it will likely not happen even in the lifetime of the universe," Gupta says. There had to be some other explanation.
After a little head-scratching, they realized that those times corresponded to peak thunderstorm season in their location—and, in fact, the changes to muon intensity always occurred in conjunction with a storm! Gupta is quick to point out that they weren't the first to observe such a phenomenon: “The thunderstorm connection was well known,” he says, “but the direct relationship between the two was not established.” In other words, although thunderstorms and muons were linked in research literature, it wasn't clear why thunderstorms would have such a large effect on the number of muons reaching the ground—or what it could tell us.

GRAPES-3, however, has something that other muon telescopes don’t: the ability to tell with high accuracy the muon's direction of travel based on their angle of impact. “We gained direction,” Gupta says of the telescope's unique construction, “and that turned out to be a critical difference in studying this phenomenon.” It’s the same difference, he says, as the one between an optical telescope and a solar panel; both register photons hitting their surfaces, but only one can reconstruct an image of the sky. Similarly, the team could use GRAPES-3 data to reconstruct a map of muon intensities across a thundercloud, something that hadn’t been done before.
These muon maps gave the research team a more complete picture of the thunderstorm's anatomy, allowing them to accurately compare muon intensities under a thundercloud to those in clear skies. This was key, because muons have a special property: as charged particles, their energy changes when they pass through an electric potential like that of a thundercloud. And since the GRAPES-3 receiver has a threshold energy of about 1 GeV, that change in energy can affect whether a muon is detected at all. It seems like a perfect explanation for the observed drop in muon intensity, since some muons presumably lost enough energy passing through the thundercloud that they no longer registered.

Well, it's almost a perfect explanation. You see, muons come in two flavors: positively charged and negatively charged. Assuming the typical thundercloud charge distribution (positive on top, negative on bottom), a negatively charged particles with an energy of, say, 1.3 GeV would lose enough energy that it would fall below the threshold—but on the other hand, a positively charged muon of 0.7 GeV could gain enough energy to be detected, resulting in a zero net change.

“This is where nature comes to our rescue,” Gupta says with a chuckle. This conundrum is very real, but only assuming an equal number of positive and negative muons (and an even distribution of energies). However, since many of the cosmic rays that produce the muons in the first place are the positively-charged protons, there is actually an imbalance in muon charges that results in a 10-20% excess of positive muons. Without this convenient fact, the researchers could never have measured a difference in muon intensity.

Yet they did, and from those measurements they managed to extrapolate a function that maps an observed change in muon intensity to the voltage that would have caused it. After analyzing the numerous thunderstorms caught by GRAPES-3, they were delighted to find that one thundercloud was particularly powerful, clocking in at 1.3 gigavolts—right on target with Wilson's prediction from nearly a century ago! To put that in perspective, after making some reasonable assumptions about the cloud's size and shape, the researchers estimate that it contained over 720 gigajoules of power. "That's a massive amount of power," says Gupta, "If you could tap this power... it is enough to sustain New York City for 26 minutes. It's really unbelievable."

The team has already measured several more thunderstorms with similar voltages, indicating that their 1.3 gigavolt monster was not an anomaly. "It's not a one-off thing," Gupta says of the remarkable potential. Unfortunately, it's unlikely that we'll ever be able to harness the remarkable power held in thunderstorms, but Gupta is already hoping that this study will help explain other phenomena—like the mysterious high-energy gamma rays that populate the atmosphere. "The story has just begun," he promises.

—Eleanor Hook
Thunderstorms are more powerful than you could possibly imagine. (PASCAL POCHARD-CASABIANCA/AFP/Getty Images)

Lightning strikes are more powerful than you probably realise. A single lightning bolt, for example, unleashes about a billion joules of energy – about the same contained within 111,100 AA batteries. It's easily enough energy to transform rocks into a glassy substance that, long after a thunderstorm has passed by, can be used to work out how powerful that storm might have been.

Thunderstorms themselves are furious, ephemeral globs of sheer power that scientists are only beginning to fully comprehend. Now, as first spotted by ScienceNews, scientists in India have measured the strongest thunderstorm to date, coming it at 1.3 billion volts. Although there are likely stronger thunderstorms out there that have evaded detection, this is an indubitably potent electrical beastie – and, as a new study reports, it was recorded with the help of a telescope looking for a very specific type of subatomic particle.

Let's backtrack for a bit. First, what does 1.3 billion volts mean? It's certainly not the same as joules, which is a unit of energy. If you can remember back to your high school physics days, a volt is a unit of electric potential, or the difference in electric potential between two conducting points.
Still sounds like jibberish? How about this: imagine you have a water tank, filled up to the brim, with an outlet pipe attached to it. This is analogous to an electric circuit. The amount of water in that tank is equal to the electric charge present. How it flows through that outlet pipe is equal to the electrical current of the circuit. The pressure the water in the tank is putting on that outlet pipe? That's the voltage. In crude terms, it’s a measure of how much the current really wants to flow out of that pipe.

Systems in the universe tend towards balance. Say you have two water tanks, attached at their bases with a pipe, and you fill them both up with equal amounts of water. The pressure (voltage) between the two is the same, and the water (the charge) won’t flow between the two tanks, which means there is no current. Balance exists.

**YOU MAY ALSO LIKE**

In order to have a change in voltage, you need to change the pressure between the two tanks and create an imbalance. How do you do that? Simply add more water (more charge) to one tank. That imbalance ups the pressure (voltage) on the system, which causes a flow of water (current) to happen. This exists until the pressure is equalised by having a balanced charge on both sides.

[Image: https://youtu.be/w82aSjLuD_8]

That’s the long and short of it. A thunderstorm can described in a similar manner: there is a tank of charge somewhere in that storm that has a lot of pressure to get somewhere else. In this case, that means there is a huge amount of positive charge in the upper section of the cloud column, and a huge amount of negative charge in the lower section – two “water” tanks, with a massive “pressure” difference.
Because the atmosphere is a very good insulator, it's not easy for the charge to flow from one point to the other and bring balance to this circuit. That means a huge difference in charge can accumulate in a thunderstorm cloud. When the voltage (pressure) between these two points (tanks) becomes too great, you get a bolt of lightning, and charge rapidly flows from one point to the other.

With all that in mind, hopefully you can understand that 1.3 billion volts is, well, a huge amount of electrical “pressure.” As a point of comparison, an average electrical fence to keep livestock from escaping a field has a measly voltage of around 6,000 volts.

Thunderstorms are always high-voltage creations, but this one is a record-breaker – ten times larger than the second-most high-voltage thunderstorm on record, according to an accompanying article in Physics. So how exactly was it detected?

Direct voltage measurements can be taken from within thunderstorms through the use of specially designed aircraft, drones or weather balloons. These only provide snapshots of the voltage in certain parts of the thunderstorm though; they often leave much of the fluffy-looking electric circuit unexplored.

This time around, a subatomic particle detection facility based in Ooty, India threw its hat into the ring. The Indian-Japanese GRAPES-3 experiment – the Gamma Ray Astronomy Peta-electron-volt EnergieS, 3rd establishment – looks for interactions between our atmosphere and bursts of radiation usually emerging from deep space known as cosmic rays. These interactions produce (among other things) muons, unstable and far heavier cousins of electrons.

https://youtu.be/lQGFvKAujb8
Muons normally rain down from the upper atmosphere at an extraordinarily high rate. When they encounter the strong electrical disturbances we call thunderstorms, however, the paths of these electrically charged subatomic particles are perturbed. The stronger the voltage of a thunderstorm, the more the path of various muons will change. In other words, different amounts of muons reach detectors looking out for them if they are beneath a thunderstorm.

With this knowledge in mind, the team used the G3MT muon telescope attached to GRAPES-3 to estimate the voltage of 184 thunderstorms above it that took place between 2011 and 2014. As reported in the new Physical Review Letters paper, a storm on December 1, 2014 messed around with the muon flux so much that, according to the team's calculations, required an electrical potential of 1.3 billion volts.

Some researchers have pointed out that this indirect method of voltage measurement isn't 100 percent precise, and it seems curious that it's far higher than the sorts of values weather balloons and the like have come up with in the past. Saying that, it's a technique that could be further corroborated if, in the future, direct measurements are taken at the same time as the muon flux is recorded by telescopes like G3MT.

In any case, as pointed out by the aforementioned Physics article, this work could help solve a longstanding mystery. Since the mid-1990s, satellites have detected sudden releases of gamma rays – very energetic bursts of electromagnetic radiation – coming from somewhere in the lower-to-mid atmosphere. It's largely been suspected that these were generated by extremely powerful lightning bolts in thunderstorms, but direct proof has remained somewhat elusive.

As a point of contention, scientists haven't managed to find thunderstorms with high enough voltages required to create such outbursts, known as terrestrial gamma ray flashes, or TGFs. This new paper, though, seems to have found a thunderstorm whose voltage is in the right ballpark.

That's not all: back in 2015, Hurricane Patricia threw researchers a bone too. This extremely powerful cyclonic terror, while throwing everything it had at Mexico, was being watched by the Airborne Detector for Energetic Lightning Emissions, or ADELE. This piece of tech, attached to a Hurricane Hunter aircraft, picked up on a beam of positrons – the antimatter equivalent to electrons – flying out of Patricia's pandemonium.

This was only possible thanks to the colossal electrical field present within the hurricane, with its huge voltage permitting some extremely energetic lightning to form. Acting as a natural particle accelerator, one of these bolts jettisoned a bunch of electrons into space while sending a mirrored beam of antimatter down to Earth. This is precisely what models expected to happen during TGFs.

So, whether it's through the detection of positrons or muons, the fog of mystery around TGFs is clearing. In the process, scientists are finding out that the tumbling clouds above us are more powerful than any of our ancestors could have possibly imagined.
India's telescope detects monstrous thundercloud

News

K. S. Jayaraman

doi:10.1038/nindia.2019.37 Published online 26 March 2019

A record-breaking thunderstorm electric potential of about 1.3 billion volts detected by a telescope in south India's hill resort Ooty has stunned scientists. The thunderstorm potential – 10 times greater than the largest value ever reported – has been recorded by the GRAPES-3 Muon Telescope (G3MT) operated by Mumbai-based Tata Institute of Fundamental Research (TIFR)¹. Lightning and thunderstorms, spectacular manifestations of sudden discharge of charged clouds have fascinated mankind. But they also cost thousands of human lives every year worldwide. Researchers have earlier flown airplanes and balloons into the centers of thunderstorms to study their electrical structure, but they could only probe the small region and not the entire cloud.

¹ © G3MT experiment
Physicist Sunil Gupta of TIFR devised a method that makes use of muons – heavier cousins of electrons – to measure the electric potential of thunderclouds. Muons are produced by cosmic rays and constantly rain down on the Earth's surface penetrating the clouds.

The G3MT) in Ooty – an array of 400 muon detectors, spread over 6.2 acres – can observe around 2.5 million muons every minute. That rate drops during thunderstorms since the electrically charged muons are slowed down by a thunderstorm's electric fields, resulting in fewer particles getting picked up by the detector. In other words, the number of muons (flux) detected by the telescope is related to the electrical voltage of a thundercloud.

From muon flux measurements, Gupta and his colleagues were able to estimate the electric potential of thunderstorms using computer simulations, treating a thundercloud as a giant capacitor made of two parallel plates 2-km apart that generates an upward-pointing electric field.

Between 2011 and 2014, the researchers gathered data on 184 thunderstorms, but what astonished them was the one on 1 December 2014 that was accompanied by a big drop in muon flux. Using computer simulations, the researchers calculated the electrical potential in the storm to be 1.3 billion volts.

The team also estimated the monster storm's electric power to be around two billion watts – similar to the output of a large nuclear reactor. "That's a massive amount of power." says Gupta, Unfortunately, it's unlikely that we'll ever be able to harness the remarkable power held in thunderstorms."

Scottish physicist C T R Wilson, who won the Nobel Prize in 1927 predicted that thunderclouds may generate giga-volt electric fields. "So it is pleasing that a modern cosmic ray detector has verified this experimentally," Subir Sarkar, head of Particle Theory Group of the University of Oxford, told Nature India.

In 2015 the same detector had detected a gigantic breach in the Earth's magnetic field, triggered by a solar storm. "These discoveries illustrate the significant advantage of studying cosmic ray muons as probes of the upper atmosphere," Sarkar says.

Sunil Gupta, who devised the method to use muons to measure thunderclouds.

The finding may also help researchers explain the mystery of high energy gamma-ray flashes sometimes observed during
thunderstorms and first discovered 25 years back, Gupta says. Tariq Aziz, a retired professor of high energy physics at TIFR, agrees. "Possibly the discovery will go far beyond explaining gamma ray flashes in understanding cosmic phenomenon at grander scale."

Gupta's team is now setting up gamma-ray detectors around G3MT, hoping to catch the terrestrial gamma-ray flashes in coincidence with a gigavolt-level thunderstorm.

The highest energy observed to date in a terrestrial gamma-ray flash (TGF) is 100 MeV, says Narayana Bhat, an astrophysicist at the University of Alabama in Huntsville, USA “Such high electric potentials required to accelerate electrons to GeV energies has not been measured so far nor was it thought possible to generate such high fields. This paper demonstrates the presence of such gigavolt electric potentials in the terrestrial atmosphere for the first time,” he says.

Bhat says the clever ground based experimental technique as opposed to using balloon-borne instruments used to demonstrate the existence of such potential is unique and powerful.

References

Researchers use muon detector to measure electric potential in a thunderstorm

A team of researchers from several institutions in India and Japan has found that it is possible to use a muon detector to measure electric potential in thunderstorms. The paper is published in the journal Physical Review Letters. The researchers explain that they noticed muon detection levels drop during thunderstorms, and used that information to calculate electric potential in thunderstorms.

Lightning bolts that flash across the sky are ample evidence that storms produce electricity. Over the past several decades, scientists have sent balloons and planes into storms to learn more about what goes on inside of them. But the sensors used in such efforts have only been able to capture data about very small parts of storms. In this new effort, the researchers developed a way to capture one critical measurement of an entire storm—it’s electric potential.

The electric potential of a storm is defined as the collective amount of work that would be required to move its electrons from one part of a cloud to another. In thunderstorms, the electric potential arises as positively charged water droplets rise and negatively charged droplets sink, and the air between them becomes conductive. Because of their electrical activity, thunderstorms can have an impact on muons, forcing them to lose energy, which prevents muon detectors from detecting them.
Muons are one of a type of tiny particles that result when cosmic particles slam into the atmosphere and break apart into millions of bits of debris—they constantly rain down from above. Scientists have built muon detectors to study them. One such facility is the GRAPES-3, located in India. It has 400 muon detectors located on the ground, covering approximately 25,000 square meters. Together, they detect millions of muons every minute. The researchers with this new effort began monitoring changes in detection levels when they noticed that the levels fell when thunderstorms were overhead. They report that they monitored and studied changes to such levels over the time period April 2011 to December 2014. During one particularly large storm that occurred on December 1, 2014, muon levels dropped a full 2 percent.

As part of their research, the team built a storm simulator to calculate the total electrical potential of a storm based on the drop in muons detected. They report that their simulator showed the December storm had a 1.3-billion-volt electric potential.

**Explore further:** Russian scientists on the verge of solving the 'muon puzzle'

**More information:**
DOI: 10.1103/PhysRevLett.122.105101

**Journal reference:** *Physical Review Letters*

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A Single Thundercloud Carries 1 Billion Volts of Electricity

By Tia Ghose, Associate Editor

March 22, 2019 11:50am ET

Credit: Vasin Lee/Shutterstock
When Benjamin Franklin tied a key to a kite and flew it into a lightning storm, he briefly became an appliance plugged into the strongest power generator on Earth.

Franklin knew, as most people do, that thunderstorms are incredibly powerful. Researchers have tried to estimate precisely how powerful for more than a century, but have always come up short — even the most sophisticated airborne sensors are inadequate because thunderclouds are just too big and unpredictable to measure.

Using an array of sensors designed to measure electric fields and the intensity of muons — heavy particles that constantly rain down from Earth's upper atmosphere, decaying as they pass through matter — the team measured the voltage of a large thundercloud that rolled over Ooty for 18 minutes on Dec. 1, 2014. The researchers found that, on average, the cloud was charged with about 1.3 gigavolts of electricity, which is 1.3 times 10^9 volts — roughly 10 million times more voltage than is supplied by a typical power outlet in North America.

"This explains why thunderclouds are so destructive," study co-author Sunil Gupta, a cosmic ray researcher at India's Tata Institute of Fundamental Research, told Live Science. "If you dissipate this massive amount of energy through anything, it is going to cause severe devastation."

It's raining muons

Gupta and his colleagues primarily study muons — electron-like particles that are created when cosmic rays bash into various atoms in Earth's atmosphere. These particles have about half the spin of electrons but 200 times the weight, and are very good at penetrating matter. A muon raining down from the atmosphere can travel deep into the ocean or miles underground in just a fraction of a second, as long as it has enough energy.

Muons lose their energy when something gets in their way — say, a pyramid, for example. In early 2018, scientists discovered two previously unknown chambers inside the Great Pyramid of Giza by setting up muon detectors around the structure and measuring where the particles lost (and didn't lose) energy. Muons passing through the pyramid's stone walls lost more energy than muons passing through the large, empty chambers. The results allowed the researchers to create a new map of the pyramid's interior without setting foot inside of it.

Gupta and his colleagues used a similar method to map the energy inside the Ooty thundercloud. Instead of contending with stone, however, muons falling through the
cloud faced a turbulent electric field.

"Thunderstorms have a positively charged layer on top and a negatively charged layer on bottom," Gupta said. "If a positively charged muon hits the cloud as it rains down from the upper atmosphere, it's going to be repelled and lose energy." [Infographic: How Lightning Works]

Using an array of muon-detecting sensors and four electric field monitors spread over several miles, the researchers measured the average drop in energy between muons that passed through the thundercloud and those that didn't pass through it. From this energy loss, the team was able to calculate how much electric potential the particles had passed through in the thunder cloud.

It was massive.

"Scientists estimated that thunderclouds could have gigavolt potential in the 1920s," Gupta said, "But it was never proven — until now."

Mapping the thunder

Once the researchers knew the cloud’s electric potential, they wanted to go a step further and measure precisely how much power the thundercloud carried as it roared over Ooty.

Using the data from their widely dispersed electric field monitors, the team filled in some important details about the cloud — that is was traveling at roughly 40 mph (60 km/h) at an altitude of 7 miles (11.4 kilometers) above sea level, had an estimated area of 146 square miles (380 square km, an area about six times the size of Manhattan), and reached its maximum electrical potential just 6 minutes after appearing.

Armed with this knowledge, the researchers were finally able to calculate that the thunderstorm carried about 2 gigawatts of power, making this single cloud more powerful than the most powerful nuclear power plants in the world, Gupta said.

"The amount of energy stored here is enough to supply all the power needs of a city like New York City for 26 minutes," Gupta said. "If you could harness it."

With current technology, that's an unlikely prospect, Gupta noted: The amount of
energy dissipated by such a storm is so high that it would probably melt any conductor.

Still, the violently powerful potential of thunderstorms could help settle a cosmic mystery that scientists like Gupta and his colleagues have asked for decades: Why do satellites sometimes detect high-energy gamma rays blasting out of Earth's atmosphere, when they should be raining down from space?

According to Gupta, if thunderstorms can indeed create an electric potential greater than one gigavolt, they could also accelerate electrons quickly enough to break apart other atoms in the atmosphere, producing gamma-ray flashes.

This explanation requires more research to verify its accuracy, Gupta said. In the meantime, be sure to marvel at the next thundercloud you see, for it is an unfathomably mighty force of nature — and, please, think twice before flying a kite.

Originally published on Live Science.

Author Bio

Tia Ghose, Associate Editor

Tia has been Live Science's associate editor since 2017. Prior to that, Tia was a senior writer for the site, covering physics, archaeology and all things strange. Tia's work has appeared in Scientific American, Wired.com, and the Milwaukee Journal Sentinel. Tia grew up in Texas and has an undergraduate degree in mechanical engineering from the University of Texas at Austin, a master's degree in bioengineering from the University of Washington and a graduate certificate in science writing from the University of California Santa Cruz. When she's not editing stories, Tia enjoys reading dystopian fiction and hiking.
GRAPES-3 muon telescope discovers record 1.3 gigavolt potential in a thundercloud

Public Release: 20-Mar-2019

Tata Institute of Fundamental Research

IMAGE: GRAPES-3 muon telescope (foreground) with an artist's view of lightning strikes.

Credit: Pranay Godawat/ GRAPES-3 experiment

Thunderstorms are a spectacular manifestation of electrical discharges of thunderclouds, and have fascinated humans through millennia. There is a dark side of thunderstorms as thousands of lives are lost every year worldwide, making them a leading cause of death by natural disasters. The technique of muon imaging developed by GRAPES-3 collaboration showed that huge voltages develop in supercharged thunderclouds. The voltage produced by a thundercloud on 1 December 2014 in Ooty measured 1,300,000,000 Volts (1.3 GV) across its height, which is 10 times larger than the previous record voltage of 0.13 GV. This verifies the 90-year-old prediction of 1,000,000,000 Volts (1 GV) by C.T.R. Wilson. Such massive voltages are essential for the production of high-energy (100 MeV) gamma rays in the Terrestrial Gamma Ray Flashes (TGFs) emanating from thunderstorms, first discovered 25 years ago.
The GRAPES-3 muon telescope is a sensitive instrument operated by the Cosmic Ray Laboratory of the Tata Institute of Fundamental Research in Udhagamandalam (Ooty) for a collaboration of several institutes and universities from Japan and India. Embedded within an array of plastic scintillator detectors that together constitute GRAPES-3, the experiment is designed to study muons produced by cosmic rays from outer space. The muon intensity changes due to the presence of electric potential in thunderclouds. Therefore, this change in the muon intensity measured by the GRAPES-3 muon telescope can be exploited to estimate the electric potential in the thundercloud.

The data collected by the GRAPES-3 muon telescope show that this particular thunderstorm was a massive (400 sq. km.) cloud, storing about a trillion Joules of energy. Moving at a speed of 60 km per hour at an altitude of 11.4 km -- where passenger jets fly -- such thunderstorms could pose a serious threat to passenger safety. The >2 GW power supplied by the strong thermal currents sustaining this thunderstorm is comparable to the existing single biggest nuclear reactors or hydroelectric- or thermal power generators. If only this huge energy could be harnessed in some way, it would be sufficient to power a large metro like New York, London or Mumbai for its duration of 18 minutes.
Indian Scientists Measure 1.3-Billion-Volt Thunderstorm, the Strongest on Record

A thunderhead (not the one measured in this study) seen from the International Space Station over the Senegal-Mali border. Photo: NASA/ISS 16 (Wikimedia Commons)

Scientists in India observed the highest-voltage thunderstorm ever documented with the help of a subatomic particle you might not hear much about: the muon.

The researchers operate the GRAPES-3 telescope, which measures muons, particles that are similar to electrons but heavier. Specifically, the Gamma Ray Astronomy at PeV EnergieS Phase-3 (GRAPES-3) muon telescope measures high-energy particles from outer space called cosmic rays. It typically picks up 2.5 million muons each minute, mapped on a 13-by-13 grid across the sky. But during thunderstorms, it experiences quick changes to the amount of muons it receives. The GRAPES-3 researchers added electric field monitors to the experiment, and devised a way to turn these muon fluctuations into measurements of the voltage of passing storms.

A storm on December 1, 2014, led to a relatively enormous 2 percent decrease in the amount of muons that the experiment received. According to their methods, published in Physical Review Letters, this would be equivalent to a 1.3-billion-volt electric potential in the thunderhead. This doesn't refer to a single lightning bolt, but rather the strength of the electric field caused by positively charged water molecules carried by convection to the top of the cloud while negatively charged ice remains lower down. For comparison, most lightning bolts have 100 million volts of electric potential between their ends. Subway tracks carry less than 1.000 volts.
That voltage measurement is 10 times higher than the previous most powerful observed storm on Earth. Storms with these strengths may be behind some of the other high-energy phenomena we've covered, like terrestrial gamma-ray flashes.

It's important to point out that models aren't always accurate, and require human assumptions. Michael Cherry, physics professor at Louisiana State University in Baton Rouge, told the science publication Physics that it was a unique but indirect way to measure the electric fields in thunderstorms, and the assumptions used in the analysis might not apply to every storm. He suggested that balloons or drones could be used to make measurements that refine the model.

But this mega measurement could help explain an important mystery. We've reported that satellites have measured terrestrial gamma ray flashes, or bolts of gamma rays. It's assumed that storms cause these TGFs, but there haven't been thunderstorms on record strong enough to generate the gamma rays observed by experiments like the AGILE satellite. But 1.3 billion volts would certainly be strong enough.

Provided the model is accurate, this would be the largest voltage ever measured in a thundercloud. And if the cloud were to discharge that electricity near you, well, you'd die in more ways than one.
At 1.3 gigavolts, this cloud had ten times higher potential than the previous record in a cloud

For the first time in the world, researchers at the GRAPES-3 muon telescope facility in Ooty have measured the electrical potential, size and height of a thundercloud that passed overhead on December 1, 2014. At 1.3 gigavolts (GV), this cloud had 10 times higher potential than the previous record in a cloud. This is not because clouds with such high potentials are a rarity, but rather, because the methods of detection have not been successful so far.

Cloud structure

Clouds have negative charges along their lower side and positive charges on top and
can be several kilometres thick. If balloons are used to measure the potential difference between the top and bottom, they will take hours to traverse the distance. Unfortunately, thunderstorms last only for about 15-20 minutes, and this method fails.

The Ooty group did not really set out to measure the cloud’s potential. Sunil Gupta from TIFR, Mumbai and corresponding author of the paper published in Physical Review Letters, says that he was first intrigued by the way the muon intensity dipped briefly in a manner correlated with the thunderstorm. Though it was known that thunderstorms had an effect on muon intensity, it had not been probed in detail earlier. Dr Gupta urged the researchers in his team to study this carefully.

Threshold of detection

Muons and other particles are produced when cosmic rays bombard air particles surrounding the earth. The muons produced can have positive or negative charge. When a positively charged muon falls through a cloud, it loses energy. If its energy falls below 1 giga electron volt (GeV), which is the threshold of detection of the GRAPES-3 muon telescope, it goes undetected. On the contrary, a negatively charged muon gains energy when falling through the cloud and gets detected. Since there are more positive than negative muons produced in nature, the two effects don’t cancel out, and a net change in intensity is detected.

From April 2011 to December 2014, the group studied the variation of muon intensity during 184 thunderstorms. In seven events they came across thunderclouds that corresponded to a large change in muon intensity, of above 0.4%. They also simultaneously monitored the profiles of the clouds using four ground-based electric field monitors. Only the cloud that crossed on December 1, 2014, had a profile that was simple enough to simulate.

Using a computer simulation and the observed muon intensity variations, the group worked out the relationship with the electric potential of the cloud. They calculated that the potential of the cloud they were studying was approximately 1.3 GV. “To best of our knowledge no one has ever measured potential, size and height of a thundercloud simultaneously. That is the reason for all the excitement,” says Dr Gupta.

Clue to puzzle

Dr Gupta and his colleagues surmise that this method can be used to solve a 25-year-old puzzle of terrestrial gamma ray bursts — huge flashes of light that accompany lightnings, but which have not been explained in theory until now.

Learning about the properties of thunderclouds can be useful in navigation of aircraft and preventing short circuits. This serendipitous discovery might provide the means to making headway in this direction.
OOTY: Cosmic Ray Lab breaks new ground with ‘Muon’ telescope

DECCAN CHRONICLE. | B RAVICHANDRAN
Published
Mar 22, 2019, 2:28 am IST

Updated
Mar 22, 2019, 3:44 am IST

Phenomenal detection of high voltage in thunderstorm.

GRAPES-3 Muon Telescope at CRL in Ooty with artist's view of lightning strike. (Credit:Godawat/GRAPES-3)

OOTY: On March 21, the day of spring equinox, wherein day and night are of approximately equal duration, an important day in annals of space research, the Cosmic Ray Laboratory(CRL) of the Tata Institute Fundamental Research (TIFR), located at the Melkavvatti road junction here, made the announcement of its phenomenal discovery on production of unimaginably high voltage in a thunderstorm.

It thus showcased India's strength and capability in probing the atmosphere and space using the cosmic particles and taking the world along it to the next higher level of research in this field.
The CRL by using its ‘muon telescope’ has performed a wonder, answering the nearly century-old question of how to measure the high voltage produced in a thunderstorm. Thus the CRL has developed a tool in ‘muon telescope’ to discover the electrical potential in thunderstorm.

The lightning strikes that kill lives in a flash are caused by high voltage in thunderstorms. But, the actual voltage produced in the thunderstorms has been shrouded in mystery up until now. This mystery remained unresolved because the technology needed to measure this extra-terrestrial high voltage phenomenon was lacking all of these years. Though scientists of yesteryear made valiant attempts, the cutting-edge instrument needed for measuring the thunderstorm voltage was missing for nearly a century.

Scientists at CRL, who in 2016 made a thundering discovery of weakening of Earth’s magnetic shield due to a solar storm, have, now, discovered another startling discovery pertaining to the high voltage in a thunderstorm, which may pave way for applied science to benefit in the years to come.

Dr Sunil K. Gupta, head of CRL, explained that the thunderstorms are an amazing display by nature of thunder and lightning. By the muon imaging, the GRAPES-3 telescope (Gamma Ray Astronomy at PeV Energies Phase-3) at CRL showed a huge voltage of 1,300,000,000 Volts (1.3 GV) (130 crore volts in Indian terms) in a thunderstorm on 1 December 2014 in Ooty. The ‘muon’ is a sub-atomic charged particle that is produced when the cosmic rays travel through the atmosphere, he noted.

This voltage was present for the thunderstorm duration of 18 minutes. This voltage is 10 times larger than the previous record voltage of 0.13 GV. This verified 90-year old prediction of 1,000,000,000 Volts (1 GV) by C.T.R. Wilson (Physics Nobel 1927). Such massive voltages are needed to explain the production of high-energy (100 MeV) gamma rays in Terrestrial Gamma Ray Flashes, first discovered 25 years ago, he pointed out.

The ‘Grapes-3 muon telescope’ is a sensitive instrument operated by the CRL in Ooty, as a collaboration of several institutes and universities from Japan and India. Muon intensity changes due to thunderstorm voltage, which allowed scientists to calculate this voltage of 1.3 GV. Basically, higher the voltage in the thunderstorm, lower will be the muon intensity, he explained.

B. Hariharan used the computer cluster, a state of the art system developed at the CRL in Ooty, to do extensive calculations to establish the exact relation between the muon intensity due to thunderstorm voltage which made the present phenomenal discovery possible. It took over nearly four years to complete and verify this work before making the final announcement of this discovery, he explained.
Breakthrough towards Resolving Century Old Riddle of Deadly Thunderstorms by a Muon Telescope in India

Prof Sunil Gupta  March 19, 2019

View: 9 Comments: 0

Thunderstorms are frightening and a spectacular demonstration of one of the most violent phenomenon in our atmosphere. Nearly three centuries back in 1749, Benjamin Franklin through his famous kite-experiment during a thunderstorm showed that the discharge of electric charges stored in clouds was responsible for the astonishing phenomena of thunder and lightning.

Thunderstorms are very common in our country especially during the Monsoon season and occur frequently in other parts of the world. Spectacular and awe inspiring they may be, but there is a dark side of thunderstorms, as a leading cause of loss of human lives from a natural disaster. In India, alone they cost hundreds of lives every year. Gaining insights into the properties of thunderstorms could be the first step towards predicting their behavior and possibly mitigating their deadly impact on the society.
The cosmic rays discovered more than a century back in 1912 mostly comprise of protons and other heavier nuclei moving near the speed of light. The cosmic rays interact with nitrogen and oxygen in the air to produce several secondary particles. This is due to Einstein’s equation $E=mc^2$ which allows the conversion of energy of cosmic rays into creation of new particles, some of them decay into high energy Muons. The Muons travel down to Earth near the speed of light and get detected by the GRAPES-3 Muon telescope.
Image 2: The GRAPES-3 Moun telescope comprises of 4 supermodules seen as 4 large halls above.

What makes our Muon telescope unique in the world is its capability to accurately measure the Muon intensity along 169 independent directions in the sky rather like a 169 pixel camera that is continuously recording the Muon image of the atmosphere above.

Because of an extremely complex structure and a short life of several minutes, the understanding of the inner working of thunderstorms was slow in coming. The first landmark advance after the work of Franklin was by C.T.R. Wilson (1927 Nobel in Physics) who identified the dipole structure of thunderstorms and predicted 90 years ago that an incredibly large electric voltage of 1,000,000,00 Volt (1 GV) could develop across a powerful thunderstorm! Hariharan and 21 other scientists drawn from six different institutes and universities in India and Japan are members of the GRAPES-3 experiment. By Muon imaging they measured an electric potential (voltage) of 1,300,000,000 Volts (1.3 GV) across a thunderstorm that occurred on 1 December 2014 in result published in Physical Review Letters (https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.105101). This measurements has thus, verified the nearly century old prediction of Wilson.

Remarkably, this voltage is 10 times larger than previous record maximum voltage of 0.13 GV measured by scientists in the USA.
Image 3: Inside view of a Moun telescope supermodule, four layers of proportional counters sandwiched between concrete layers detect Mouns along 169 directions. High energy photons are called gamma rays which possess a million times more energy (MeV) than the ordinary light. Scientific surprises unleashed by this discovery extend beyond just a record-breaking voltage inside a thunderstorm. A quarter of a century ago, a NASA satellite discovered short-lived flashes of gamma rays emerging from the atmosphere and were named Terrestrial Gamma ray Flashes or TGFs for short. Shortly thereafter, the source of the TGFs were found to be large thunderstorms occurring in the lower atmosphere. The energy of these gamma rays was found to be quite large (20 MeV) and soon newer satellites showed the presence of gamma rays of 100 MeV in TGFs. The only known mechanism for the production of such high energy gamma rays is from the interaction of electrons or positrons of still higher energies. It turns out that the existence of GV potentials is absolutely essential for the acceleration of electrons to GeV energies and that could in turn produce 100 MeV gamma rays seen in TGFs and provide a solution to this 25 year old riddle.

The high sensitivity of the GRAPES-3 Muon telescope, when combined with the additional information from a set of four electric field monitors, allowed several of the properties of this thunderstorm to be measured for the first time. This thunderstorm can be considered a giant (400 km2) capacitor, storing an energy of about trillion Joules. It was moving at a speed of 60 km/hour at an altitude of 11.4 km above sea level, exactly where passenger jets fly. The presence of such huge voltages in supercharged thunderclouds makes them a serious threat to the passenger safety.
The 2 GW power supplied by the strong thermal currents sustaining this thunderstorm were comparable to the existing single biggest nuclear reactor, hydroelectric and thermal power generators. If only the energy of this thunderstorm could have been harnessed, it would have powered a large metropolis like New Delhi or Mumbai for its entire duration of 18 minutes.

(The paper does not necessarily represent the organisational stance... More >>

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Author
Prof Sunil Gupta
Researchers have documented a thunderstorm with the most electric potential ever recorded. The powerful storm had an electric potential of about 1.3 billion volts, which is ten times greater than the previous record-setting storm. The storm confirmed that thunderstorms are possible with several-billion-volt potentials.

The researchers say that the incredibly high voltages could explain the flashes of high-energy gamma rays that are sometimes observed in a thunderstorm. To study the structure of thunderclouds normally requires researchers to send balloons or airplanes into the center of the storms.

The catch with using aircraft or balloons to measure these storms is that both measurements are only of a small region of the storm, not the potential across the cloud. An incredibly powerful thunderstorm had an electric potential of 1.3 billion volts.

The researchers probed the thunderstorm using the storm's effect on particle detection by G3MT, which is a muon telescope in Southern India. That telescope can detect muons generated in the atmosphere by cosmic rays. These researchers have developed a quantitative method to measure the potential of thunderstorms.

The G3MT can measure muon-flux changes with 0.1% precision and distinguishes 169 discrete directions in the sky. The team hopes that their findings will solve the mystery around gamma-ray flashes coming from altitudes of tens of kilometers that
have been seen by satellites since 1994. Previous measurements of thunderstorms found that there wasn't a sufficiently large potential for the storms to create the gamma rays. The new findings show that some significant storms have the potential required.