Lightning: A Striking Example of Physics in Nature

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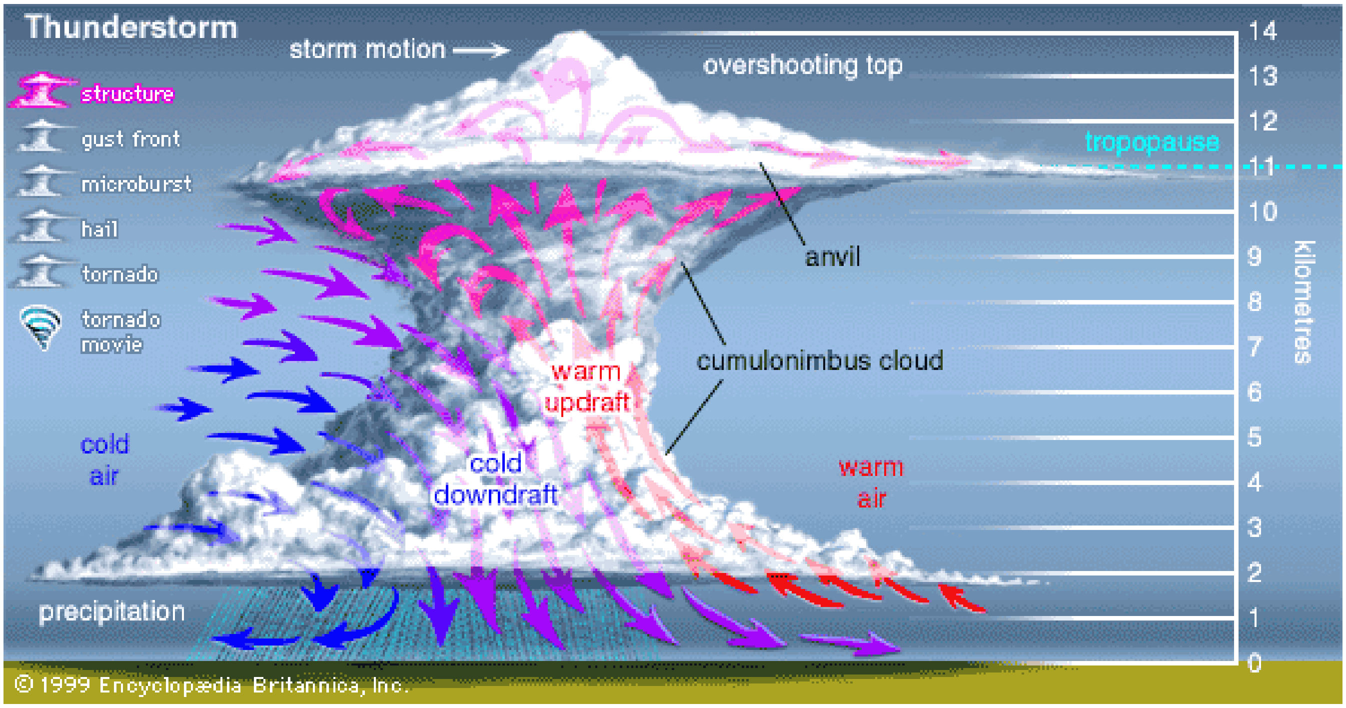
Due to the advent of modern science, the physical structure of lightning has been revealed. The progression from suspected supernatural causes for lightning strikes to a modern logical approach to electric charge parallels the rise of contemporary civilization (Rakov 2003, 1-3). However, lightning is not a single phenomenon, but a collection of various different types of electrical discharge all governed by the same physical principles (National Weather 2010). These include cloud to ground lighting, intra-cloud lightning, upper atmospheric lightning, and as yet unexplained lightning phenomena. The massive transfers of charge between bodies represent electrostatics on a global scale.

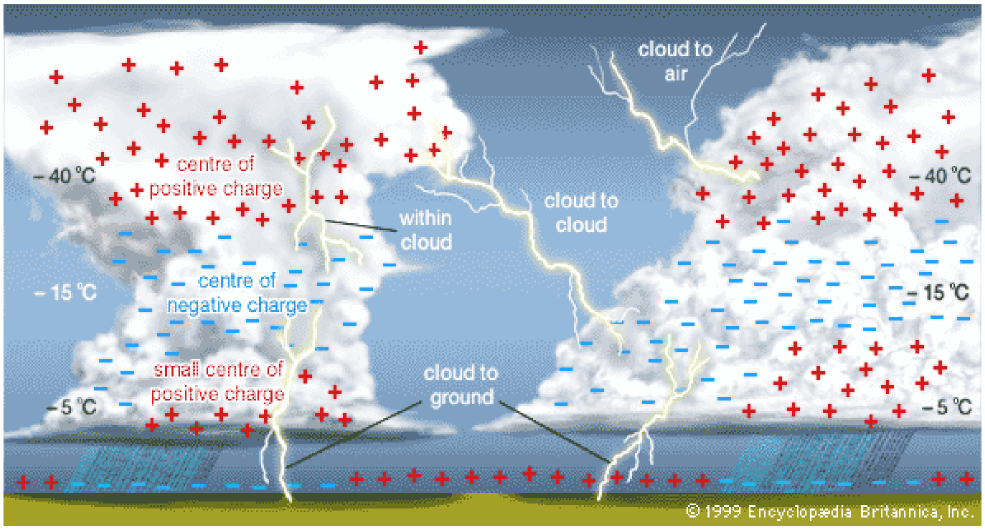
Currently, the best understood form of lightning is cloud to ground lightning (Buzzel 2010). This is due to a difference in charge between the clouds and the ground (How 2010). As a thunderstorm progresses, the lower portion of the clouds become negatively charged while the upper portion acquires a positive charge, resulting in an atmospheric capacitor (How 2010). This is thought to be due to a noninductive charging mechanism in which updrafts and downdrafts promote the collision of particles in the cloud (Bruning 2010). The collisions that occur in regions between -10°C and -30°C create negative charges, while the collisions that occur in regions slightly below 0°C or warmer cause positive charges to accumulate (Bruning 2010). The unfrozen positively charged particles are then carried to the top of the cloud by updrafts, as they have less mass than the heavier frozen particles (How 2010). This process leads to a separation of charge leading to partition of charge within the cloud. (How 2010). However, there are also a small number of positive charges near the base of the cloud that are not explained by this model (Britannica 2010). Also, the overall negative charge at the base of the cloud repels the negative charge in the Earth’s surface, causing it to become positively charged (How 2010). This process creates two oppositely charged areas in proximity to one another, setting the stage for a negative cloud to ground lightning strike (Rakov 2003, 108). In fact, this difference in charge is observed even when no thunderstorm is present, and is known as the global electric circuit (Rakov 2003, 6). The Earth's atmosphere exhibits a positive charge while the Earth's surface contains a negative charge (Rakov 2003, 6). This creates an electric field near the Earth's surface around 100 V m^{-1} (Rakov 2003, 8). It seems that during thunderstorm activity, this electric field is greatly amplified, allowing for the spectacular electric events that would not take place under normal conditions.



Cloud Airflow Diagram

(Britannica 2010)

The actual negative cloud to ground lightning strike is initiated by a process known as the preliminary breakdown (Rakov 2003, 108). There is no firm agreement on the mechanism of this charge transfer, but it may be due to "a discharge bridging the main negative and lower positive charge regions" and lasts on the order of several milliseconds (Rakov 2003, 11). This process creates paths of ionized air, known as step leaders, which extend toward the earth (How 2010). Their movement is governed by the electric flux of the region, which directs the step leaders along the path of least electrical resistance (How 2010). Interestingly, this path may not be the shortest distance between the cloud and the ground, but varies with the electric flux in individual regions of the atmosphere (How 2010). This step leader extends toward the ground in a series of discreet steps, around 30 meters in length, which are separated by 10-50 microseconds each, at an overall speed of 1.5x10^5 m/s. (Britannica 2010). Also, it is composed of a central current carrying portion, with a radius of 0.5-1.0 cm, which is surrounded by a charged corona sheath with a radius of 0.5-5 meters (Britannica 2010). As the step leader nears the Earth’s surface, a connective discharge travels from the ground and forms a connection with the step leader (Cummins 1998, 465). This is caused by the massive difference in electric potential between the ground and the step leader, from 50 to 500 MV (Rakov 2003, 111). The connection formed creates a path of ionized air between the earth and the cloud, allowing current to flow between the two bodies (How 2010). This electrical conduit allows for the return stroke to take place, which is often perceived as lightning as it is much brighter than the step leader (Britannica 2010). Generally, five coulombs of charge are transferred in this process, producing temperatures of 30,000°C (Britannica 2010). This intense transfer of charge causes the return stroke to propagate toward the cloud at one third of the speed of light, and also leads to an expansion of the central current carrying portion of the lightning (Britannica 2010). As charge travels upward, the lightning bolt illuminates more intensely as the charge passes the former step leader branches (Rakov 2003, 1111). Overall, negative cloud to ground lightning serves to relieve the difference in electric potential between the two regions, and acts similar to static electricity in that is produced by a Van de Graff generator.



Cloud Charge Structure

(Britannica 2010)

While watching a thunderstorm, it is apparent that some lightning flashes are perceived as lasting longer than others. After the initial transfer of charge is complete, the lightning flash may either dissipate or exhibit several more charge transfers (Rakov 2003, 111). In the case of additional transfers of charge, the ionized pathway is traversed by a dart leader (Rakov 2003, 111) This dart leader travels continuously and is usually not branched, a contrast to the step leader (National Weather 2010). The dart leader will then cause another return stroke (Cummins 1998, 465). Moving at a speed of 10^7 m/s, it carries around one coulomb of charge, significantly less than the initial stroke (Rakov 2003, 112). It can also branch off from the initial step leader, producing a lightning flash with a forked appearance (Britannica 2010). This process can be repeated several times, producing “a typical CG flash contain[ing] several strokes and last[ing] about half a second”(Cummins 1998, 465). All of these lightning flashes occur so quickly that the human eye perceives them as a single, long lasting, and sometimes flickering entity (How 2010). Due to the high speed of multiple lightning

Positive Cloud to Ground Lightning

(Mother 2009)

strokes, their appearance can be deceiving.

Positive cloud to ground lightning is a less common but perhaps more dangerous phenomena. Known colloquially as a “bolt from the blue”, these extremely powerful bolts are emitted from the upper portion of the cloud and can strike objects up to 30 miles away (Mother 2009). In fact, “the highest directly measured lightning currents (near 300 kA) and the largest charge transfers to ground (hundreds of coulombs or more) are thought to be associated with positive lightning” (Rakov 2003, 214). As the top of the cumulonimbus storm cloud is positively charged, it is thought that the charge difference produced by this portion of the cloud and the ground triggers positive ground to cloud lightning (Rust 1986, 42). Also, the likelihood of this type of lightning is increased by the presence of strong horizontal winds on the upper portion of the cloud (Rust 1986, 4) This separates the upper layer of the cloud from the lower layer, allowing the positively charged upper layer to have unimpeded access to the ground (Rust 1986, 42). A positively charged leader, traveling from the top of the cloud to the ground, generally guides this form of lightning (Rakov 2003, 222) Also, positive ground to cloud lightning differs in another respect, as it generally only exhibits one return stroke that has a continuing flow of current through it (Rakov 2003, 222). While this form of lightning is fairly rare, it has destructive implications for structural integrity and personal safety.

Interestingly, upward lightning can sometimes be triggered by tall manmade structures, generally over 200 meters in height (Rakov 2003, 260). During the progression of

Upward Lighting

(Britannica 2010)

the lightning, there is usually a step leader which travels upwards toward the cloud, while the return stroke travels downward toward the earth (Rust 1986, 41). This is opposite of the direction of propagation of the negative cloud to ground lightning (Rust 1986, 41). In fact, the branches of the step leader extend in an upward direction, leading to the electrical discharge appearing to dissipate upwards into the atmosphere (Britannica 2010). However, this form of lightning can be either positive charged, negatively charged, or bipolar, although it is generally negatively charged (Rakov 2003, 241, 247). Also, tall, metallic manmade objects exhibit higher peak currents relative to the ground, which may be due to an enhancement in the lightning's electromagnetic field (Rakov 2003, 260). It is astounding that common manmade structures such as radio towers can have such a significant impact on weather behavior.

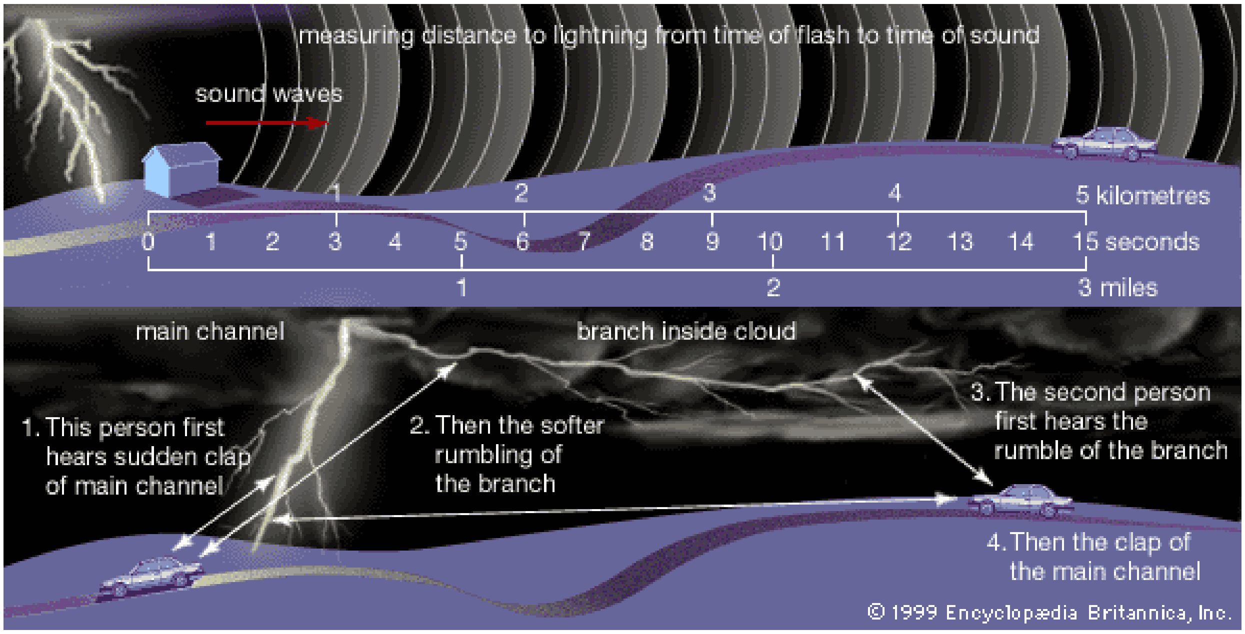
Perhaps the most common, but least noticeable, form of lightning is intra-cloud lightning (Mother 2009). This lightning is driven by charge differences within the cloud, and is most likely to occur at the upper or lower regions of the middle negative section of the storm (Rakov 2003, 322). This charge difference is caused by the same ice particle based interactions that played a role in negative cloud to ground lightning (Williams 1999, 254). Intriguingly, greater updrafts result in larger ice particles, increasing the electrification of the cloud (Williams 1999, 254). This leads to an increase in intra-cloud lightning frequency and intensity within more severe storms (Williams

Intra-cloud Lightning

(Mother 2009)

1999, 254). Generally, intra-cloud lightning progresses in two distinct phases (Rakov 2003, 341). During the first phase, a negatively charged step leader extends across the cloud, is accompanied by a large electric pulse (Rakov 2003, 341). This step leader may be bidirectional, with both positive and negative ends extending toward oppositely charged regions of the cloud (Rakov 2003, 341). As the connection between the two ends of the step leader is severed, the second stage begins (Rakov 2003, 341). This involves charge being transported to the origin of the lightning from more distant areas of the cloud (Rakov 2003, 341). Importantly, while this form of lightning has little effect on ground structures, it is capable of affecting aircraft, causing "temporary loss of vision, punctur[ing] the aircrafts skin, or damag[ing] electronic navigation and communications equipment" (Willits 2004, 6-43) Intra-cloud lightning remains a mysterious yet important factor in storm formation.

All of these forms of lightning have been observed to produce a shockwave, known as thunder (Britannica 2010). This is the result of the electrical current heating the surrounding air to around 30000 ° C, causing a pressure of around 1000 kilopascals (Britannica 2010). The resulting superheated air rapidly expands, which results in an audible sound wave (National Oceanic 2008). Since sound travels at a much slower rate than light, the thunder is perceived after the flash from the lightning bolt, with the lapse in time increasing with the distance of the observer from the lightning bolt (Britannica 2010). In fact, the time difference between viewing the lightning strike and hearing thunder can be utilized in order to approximate the distance of the observer and the lighting, as every five seconds of difference approximates to one mile (Britannica 2010). Interestingly, the characteristics of the sound change with distance as well, as thunder in close proximity to the observer is usually preceded by a sharp clap followed by lower pitched rumbling sound (National Oceanic 2008). On the other hand, many of the higher pitched frequencies that produce the sharp clap are absorbed by the surrounding environmental features, giving it a lower rumbling sound without the sharp clap when it is heard by an observer from a distance (National Oceanic 2008). Intriguingly, inaudible shockwaves below 20 Hz are also produced by a reduction in size of a portion of the charged cloud when its charge is removed via lightning (Rakov 2003, 374). These shockwaves are known as infrasonic thunder and require greater amounts of energy than acoustic thunder to produce (Rakov 2003, 374) Thunder is one of the most physically noticeable aspects of any lightning strike, and provides a clear distinction between the speed of electromagnetic and acoustic waves.



Thunder Shockwave

(Britannica 2010)

As various types of electrically charged lightning exist, several forms defy conventional theories on lightning. A prime example of this is bead lightning, in which the lightning bolt appears to dissipate and leave behind glowing beadlike structures (Buzzel 2010). This may be due to several physical factors, including viewing angle and obscuration by rain and clouds (Rakov 2003, 665). Also, magnetism may play as role as a high current in a small radius could cause the magnetic force to vary over the length of the lightning bolt (1, 665). This causes a pinching force on certain regions, which could result in the beadlike structure (Rakov 2003, 655). Also, it could be due to" a series of spherical arcs" formed by lightning or certain regions of the lightning bolt which are exceptionally large, leading to longer dissipation times (Rakov 2003, 666). An even more obscure form of lightning is ball lightning, which is characterized by a floating, spherical orb (Buzzel 2010). Its physical properties appear to remain constant during its lifespan, yet it can move randomly and even pass through objects such as metal screens (Rakov 2003, 662-663). Currently, no definitive scientific theory has been found to adequately describe either ball or bead lightning (Rakov 2003, 664). All of these forms of lightning are rarely observed in nature, and illustrate the need to better apply theoretical physical principles in order to understand these weather phenomena.

Most forms of atmospheric electrical discharge that have been extensively researched deal with easily observed cloud to ground or ground to cloud lightning strikes. However, several forms of mysterious upper atmospheric discharges exist. These include blue jets, sprites, and elves (Weather 2010). Blue jets appear as cylindrically shaped emissions from the tops of storm clouds, rising at speeds around 100,000 m/s and stretching 45-50 km (University 2004). These jets have an extremely short visible duration, around 200 ms. Currently, no theory that sufficiently explains the

Sprite

(Weather 2009)

properties of blue jets has been developed (Rakov 2003, 484). On the other hand, sprites exhibit a low intensity, generally red, discharge above active thunderstorms (Rakov 2003, 485). They are fairly compact, with a radius of only 5 meters, can travel up to 95 kilometers in altitude, and can project thin wispy structures as low as 30 kilometers in altitude (Weather 2010). They have been liked to heavily charged positive cloud to ground lightning, and may occur as often as once every 200 lightning events (Weather 2010). Elves are considerably different from blue jets and sprites, as they propagate in a circular manner and extend through very high regions of the atmosphere (Rakov 2003, 492). In fact, these large saucer shaped pulses can travel to 95 kilometers in altitude and extend 400 kilometers in altitude (Weather 2010). It is thought that these events are related to return strokes, which accelerate electrons via their electromagnetic fields (Rakov 2003, 497). This causes the electrons in atmospheric nitrogen to fluoresce due to the excited states of their electrons, yet the emission of visible light is of an extremely short duration (Rakov 20034). All of these upper atmospheric lightning forms demonstrate the polarity of a charged cloud and the ever mysterious nature of atmospheric electric discharge.

Perhaps most remarkably, lightning represents basic electrostatic physical principles on a global scale. From capacitance to attraction between oppositely charged particles, this weather phenomenon is only a grander expression of electric discharges that can be produced in a small laboratory. Notably, the present knowledge concerning lightning reveals a practical side to human nature, as much of the current research is based on cloud to ground lighting strikes. However, as mankind further expands atmospheric activities, such as commercial spaceflight and increased air traffic, research into more obscure forms of lightning, such as sprites and blue jets, will become essential to promote safety. Overall, the study of lightning provides a natural basis for theoretical predictions and practical benefit for humanity.

Works Cited

Bruning, E., W. Rust, D. MacGorman, M. Biggerstaff, and T. Schuur. 2010. Formation of Charge Structures in a Supercell. Monthly Weather Review 138: 10, (October 1): 3740-3743,3746-3761. http://www.proquest.com/ (accessed November 25, 2010).

Buzzel. 2010. “Different Types of Lightning.” Accessed November 24, http://www.buzzle.com/articles/different-types-of-lightning.html.

Cummins, Kenneth L., E. Philip Krider, and Mark D. Malone. 1998. “The U.S. National Lightning Detection Network and Applications of Cloud-to-Ground Lightning Data by Electric Power Utilities.” IEEE Transactions on Electromagnetic Compatibility 40 4:465-480. Accessed November 23, 2010. http://www.atmo.arizona.edu/students/courselinks/spring07/atmo589/articles/Cummins_IEEE1998.pdf.

Encyclopedia Britannica Online. 2010 ed. “Thunderstorm.” Accessed November 25. http://www.britannica.com/EBchecked/topic/594363/thunderstorm/218332/Thunderstorm-electrification?anchor=toc218332.

How Stuff Works. 2010. “How Lightning Works.” Accessed November 24, http://science.howstuffworks.com/nature/natural-disasters/lightning.htm.

Mother Nature Network. 2009. “Types of Lightning.” Last modified June 17, http://www.mnn.com/earth-matters/translating-uncle-sam/stories/types-of-lightning.

National Oceanic and Atmospheric Administration. 2008. “Lightning Basics.” Last Modified July 7, http://www.nssl.noaa.gov/primer/lightning/ltg_basics.html.

National Weather Service Forecast Office. 2010. “What is Lightning?.” Last modified August 31, http://www.srh.noaa.gov/mlb/?n=what_is_lightning.

Rakov, Vladimir A., and Martin A. Uman. 2003. Lightning Physics and Effects. New York: Cambridge University Press

Rust, David W. 1986. The Earth's Electrical Environment. Washington D.C.: National Academy Press. http://books.google.com/books?hl=en&lr=&id=7j4rAAAAYAAJ&oi=fnd&pg=PA41&dq=positive+cloud+to+ground+lightning&ots=sFpy4GlRhZ&sig=P6NmK9Cc2_FPsUwLjiDbNR-_yMc#v=onepage&q=positive%20cloud%20to%20ground%20lightning&f=false.

University of Alaska. 2004 "Red Sprite and Blue Jets." Last modified May 12, http://elf.gi.alaska.edu/#chrspr

The Weather Doctor. 2010. "Blue Jets, Red Sprites, and Elves." Accessed November 23, http://www.islandnet.com/~see/weather/elements/bluejets.htm.

Williams, Earl, Bob Boldi, Anne Matlin, Mark Weber, Steve Hodanish, Dave Sharp, Steve Goodman, Ravi Raghavan, Dennis Buechelr. 1999. "The Behavior of Lightning Activity in Severe Florida Thunderstorms" Atmospheric Research 51 (1999) 245–265 http://www.srh.weather.gov/media/mlb/pdfs/tli_svr.pdf.

Willits, Pat. 2004. Guided Flight Discovery Private Pilot. Englewood, CO: Jeppesen Sanderson