The Physics of Lightning

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Lab: H2

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Introduction

Lightning has been around for over 3 billion years (Rakov et al. 2003). Man has always seen lightning as a powerful and mysterious force. Many ancient cultures had gods who controlled lightning. For example, the Greek god Zeus, the Roman god Jupiter, and the Norse god Thor, all supreme gods in their respective cultures, controlled and created lightning (Rakov et al. 2003). The first official experiment with lightning was conducted by Benjamin Franklin in 1774. Franklin is credited with inventing the first application of electricity with the lightning rod. However, most experiments and findings on the understanding of lightning did not happen until the modern era (Uman,2001). Today, there is much knowledge on how lightning works. Despite this, lightning is still seen as powerful force by many. The following paragraphs will describe the physics of lightning.

Types of Lightning

There are 4 main types of lightning. The most common type of lightning is intracloud lightning (Uman 2001). Intracloud lightning is the transfer of electric charge from one part of the cloud to another (Uman 2001). About 50% of all lightning is this type. The second main type of lightning is cloud-to-ground lightning. This is the transfer of charge from a cloud to the ground. This is the most studied type of lightning because of it's the easiest to photograph and study using optical instruments. Figure 1 on the next page shows an example of this type of lightning. The third main type of lightning is cloud-to-cloud lightning, or the transfer of electrical charge from one cloud to another (Uman 2001). The final type is cloud-to-air lightning, or the transfer of electric charge from a cloud to the air. Intracloud, cloud-to-cloud, and cloud-to-air lightning are often combined and called cloud lightning (Uman 2001).

Figure 1: Cloud-to-ground lightning (Ken Costello 2012)

There are other types of lightning besides these main four. These types are far less common than the 4 mentioned above. Ball lightning is lightning that looks like a ball. Its size can vary from the size of a pea to the size of a truck. As of right now, scientists do not know what causes ball lightning (Mollet et al. 2012). Blue jets are narrow cones that are ejected above clouds during thunderstorms. They are ejected at speeds of 100 km/s and disappear around altitudes of about 40 or 50 km (Mollet et al. 2012). Figure 2 below shows what blue jet lightning looks like.

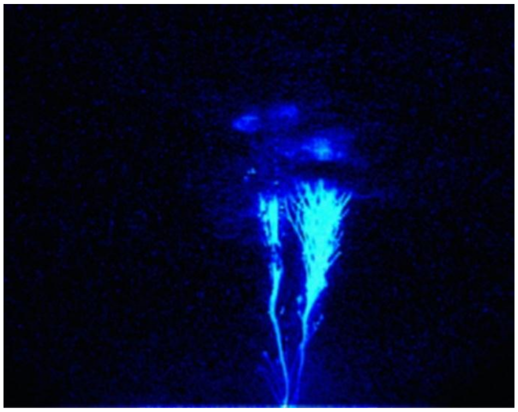

Figure 2: Jet Blue Lightning (Red Orbit 2012)

Red sprites are massive but weak flashes that occur above thunderclouds and usually happen at the same time as cloud-to-cloud and intracloud lightning. Their structures vary from long, vertical spots to bright groups at the tops of clouds. They are brightest when at altitudes of 65-75 km, and can be seen at altitudes as high as 95 km and as low as 40 km (University of Alaska 2004). Red sprites are usually found in groups of 2 or more. Red sprites can extend horizontally for as far 50 km and occupy volumes of more than10, 000 cubic km (University of Alaska 2004). Evidence shows that sprites usually occur in decaying portions of thunderstorms and are correlated with large positive cloud-to-ground lightning strokes (University of Alaska 2004). Figure 3 below shows what red sprite lightning looks like.

Figure 3: Red Sprite Lightning (Strange Strange Strange 2012)

Bipolar lightning is the rarest form of lightning. Bipolar lightning involves the polar reversal of the current in waveform (Rakov 2012). The currents in bipolar lightning varies from 350 A to 1500 A and around 12 C to 35 C of charge is transferred per lightning flash (Rakov 2012). Very little is known about bipolar discharges. There are three types of bipolar lightning. The first type is a polarity reversal occurring during a slowly-changing current component, such as the initial continuous current. The polarity reversal may happen multiple times and may involve an appreciable no-current interval between different polarity parts of the waveform of lightning (Rakov 2012). The second type of bipolar lightning is characterized by different polarities of the initial stage current and of the following return stroke or strokes (Rakov 2012). The third and final type of bipolar discharges involves return strokes of opposite polarity (Rakov 2012).

How Lightning Happens

Lightning is caused by the build-up of electric charge in clouds (University of Alaska Fairbank 2012). Positive and negative charges separate, with the negative charges usually going towards the bottom of the cloud and positive charges going to the top. After a certain amount of time, the negative charge leaps, going to either another cloud or to the ground. The discharge of electric charge in a cloud-to-ground discharge is called a flash. On average, each flash lasts about 0.5 seconds and is composed of three or four current pulses called strokes. There are a few milliseconds between each stroke. These strokes cause lightning to "flicker" (Rakov et al. 2004). The strength of an electric field in an area determines the likely hood that the charge will move towards the ground. Generally, the stronger the electric field is, the more likely that the charges will move towards the ground (University of Alaska Fairbank 2012).

In negative ground-to-charge lightning, there is a separation of charge in the cloud which causes the creation of the step leader (Rakov et al. 2003). Step leaders are paths of iodized air. Step leaders may not follow a straight path or ionize air equally in all directions because they usually follow the path that gives them the best chance to reach the earth the fastest (How Stuff Works 2012). Impurities in the air and the shape of the electric field affect the path that the leaders take because it makes it harder for the air to break down (How Stuff Works 2012). The shape of the electric field depends on where the charged particles are. In the case of a cloud-to-ground discharge, the charges are located at the bottom of the cloud and on the surface of the earth below the cloud. If the cloud is parallel to the earth's surface, and the area is small enough that the curvature of the earth is negligible, the two charge locations will behave as two charged parallel plates (How Stuff Works 2012). The electric flux created by the separation of the charges will be perpendicular to the cloud and earth.

`As of right now, it is unknown what causes this charge separation. One theory is the drop break-up theory (Saunders 2008). When water droplets collide, the larger droplets become positively charged while the remaining parts are negative. When a bubble bursts over the ocean, positive charged droplets form and can be carried up into clouds via air currents (Saunders 2008). One problem with this theory is that the break-up of individual water droplets in clouds is a rare occurrence because surface tension keeps most of the droplets together in the presence of turbulence (Saunders 2008).

Another theory is ion charging. There are 3 types of ion charging. The first type of ion charging involves the fact that water molecules collect more easily on negative ions than positive (Saunders 2008). The negative ions cause the water molecules to have a charge separation. However, unrealistically high super saturations of several hundred percent are required to activate droplet growth on the ions (Saunders 2008). The second type of ion charging involves cloud particles being polarized in a pre-existing electric field (Saunders 2008). The electric field causes the particle to have a positive half and a negative half. As the particle falls, the positive half attracts negative ions. This causes the particle to have a negative charge. However, this process is limited because the negative charge will attract positive ions (Saunders 2008). In addition to this, the electric field is too weak to cause electrical breakdown (Saunders 2008). The final type of ion charging is thunderstorm charging. Polarized drops are charged when smaller droplets that are released from their sides (Saunders 2008). This causes smaller droplets to have a positive charge and the larger droplets to have a negative charge. The positively charged droplets are carried up while the negatively charged droplets fall. This charge separation increases the strength of the electric field. However, in stronger fields, the collision usually results in the combing of the water droplets.

Another theory is the convective mechanism theory. Natural convection currents move charges throughout the cloud (Saunders 2008). Cloud particles collect these charges while they move through the cloud, resulting in the initial electrification of the cloud. The negatively charged particles in the cloud attract positive ion on the ground. These positive charges are captured by droplets and moved to the top of the cloud. In turn, this positive region attracts negative ions to the cloud that are captured by falling particles whose charge then strengthen the negative charge of the bottom of the cloud. The cycle continues and causes the strength of the electric field to increase greatly. One problem with this theory is that it is unlikely that this process would lead to an electric field strong enough to initiate lightning (Saunders 2008).

One final theory is the inductive charging theory. The inductive process relies on the pre-existing electric field to induce charges so that particle rebounds can separate charge and strengthen the field (Saunders 2008). Initially, the electric field is formed from the positive particles in the atmosphere and the negative charge of the ground below the cloud. The cloud particles have a high enough electrical conductivity that there is time for the induced charges to form in the particles in response to the external electric field (Saunders 2008). Because water droplet collision generally lead to coalescence, the inductive process rebounds ice/ice and ice/water collisions. When the smaller particles rebound from the larger ice particles in the electric field, they take positive charges with them, leaving the ice particles negative. The airstream moves the smaller, positively charged particles up while gravity moves the larger, negatively charged particles down. One problem with theory is that when the larger droplets collide, they only partially coalesce (Saunders 2008). This causes induced charge to separate so that the electric field is reduced (Saunders 2008).

Each stepped leader lasts about 1 microsecond and occurs once every 50 microseconds (Uman 2001). Each stepped leader transfers about 10 C of negative charge in about 10 milliseconds going about 200,000 m/sec (Uman 2001). During this transfer, the stepped leader branches out forming geometric patterns.

As the stepped leader gets closer to the ground, the electric field increases until it reaches the point where the initiations of multiple upward leaders are formed (Uman 2001). This is more common when the area contains natural formations (Uman 2001). These upward leaders travel until they meet the downward leaders. This entire process is called the attachment process. The meeting of these leaders results in a return stroke of energy. This stroke neutralizes the charge of the stepped leaders by transporting the charge to the ground. Return strikes can have an initial velocity between 1/3 to ½ the speed of light (Uman 2001). During this process, the nearby air is heated to temperatures of 300,000 K because of the energy released from the return strike (Uman 2001). This causes the channels to expand rapidly, resulting in a stock wave. This stock wave is called thunder (Uman 2001).

If all the charge is transferred to the ground, the flash ends. If addition charge still remains in the channel, a dart leader forms and moves up and down the channel, going at a velocity of about 3,000,000 m/sec. During the time between the first return strike and the start of the dart leader, J- and K-process occur in the cloud. J-processes are processes that occur in clouds that cause the movement of charge in a cloud (Rakov et al. 2003). J-processes happen in about 10 milliseconds. K-processes are transients that occur during slow J-processes (Rakov et al. 2003). These processes cause excess negative charge to move down channels created by step leaders. However, it is not known if there is a relation between these processes and the start of the dart leader (Rakov et al. 2003). The dart leader carries a charge of about 1 C and has a current of 1000 A and causes any subsequent return strikes (Uman 2001). The diagram below shows visible how lightning works.

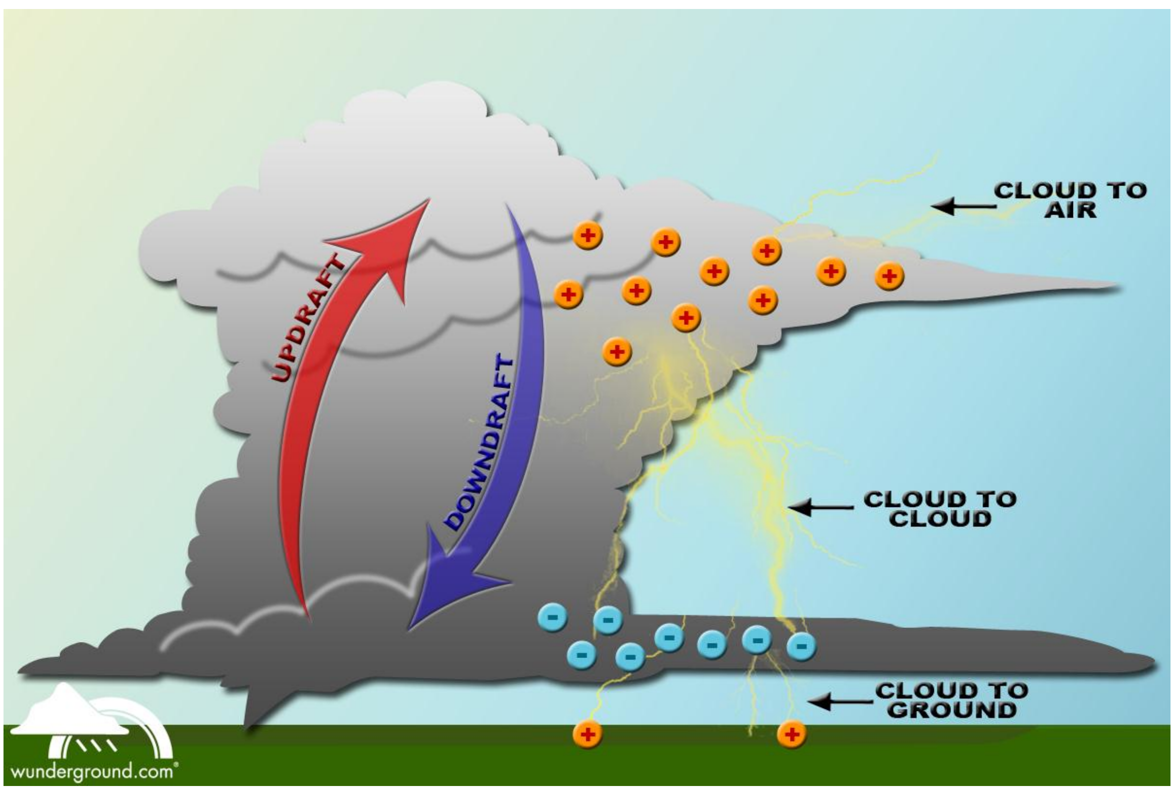

Figure 4: Diagram of how lightning forms (Wunderground.com 2012)

There is usually about a few milliseconds between successive return strikes. However, if a continuing current is flowing in the channels, this time difference increases to a few tenths of a second (Uman 2001). It is estimated that ½ to ¼ of all cloud-to-ground discharges involve a continuing current. Continuing currents have a magnitude of around 100 A and transfer about 10 C directly to the ground from the cloud and produces M-components (Uman 2001). M-components are the brightening lights that appear under clouds during continuing current flows (Milikh et al. 1995).

Positive Lightning vs. Negative Lightning

90% of all lightning is negative lightning. The other 10% is positive lightning (Uman 2001). Despite being transferred the same way, positive and negative lightning have many differences. First, negative lightning is the transfer of negative and positive lightning involves the transfer of positive charge. Second, negative lightning usually has two or more return strikes. Positive lightning usually only has return strike (Rakov 2012). Third, positive lightning almost always contains a continuing current flow. The current can range from 10,000 A all the way to 40,000 A and can carry 10 C to 1000 C of charge (Rakov 2012). However, only 25% to 50% of negative lightning involves a continuing current. These continuing currents only have a magnitude of 100 A and only carry about 10 C of charge (Rakov 2012). In addition to this, the continuing current of positive lightning lasts 4 times longer than that of negative lightning (Rakov 2012).

Forth, based on observations, the return strikes of positive lightning are often preceded by a large amount of intracloud discharge activity lasting about 100 milliseconds (Rakov 2012). Fifth, it is common for positive lightning to have several long horizontal channels stretching several kilometers (Rakov 2012). Finally, positive lightning almost always move continuously or in stepped fashion. In contrast, negative lightning appears to be stepped once it starts moving in non-iodized air. Also, positive lightning doesn't radiate at VHF as negative leaders. VHF is a wave frequency ranging from 30 MHz to 300 MHz (Rakov 2012).

Flash Ground Density

Flash ground density is the number of flashes of lightning per squared kilometer per year (National Weather Service Weather Forecasting Office 2012). This value is hard to measure and varies greatly from area to area. In order to find this value easily, an equation was created involving thunder days. The thunder day value is the number of day per month or year on which thunder was here (Uman 2001). These values are readily available because weather stations gather their values. The equation is $N=aT^b$ where N is lightning flash density, T is the thunder day value, and a and b are empirical constants that vary from region to region (Uman 2001). The value of a is usually between 0.1 and 0.2. The value of b is usually 1.

Conclusion

Lightning is a powerful force. This is seen in the large currents and the amount of charge that is transferred per flash. Despite having a good understanding of how lightning works, there are many things that scientist still do not known about lightning. For example, there is much debate on how charge separation in thunderclouds occurs. Just like in ancient times, lightning is still a powerful and mysterious force.

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