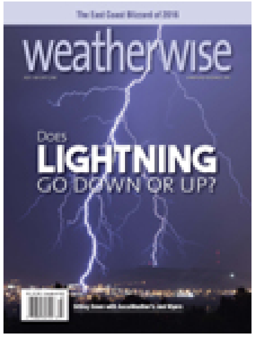

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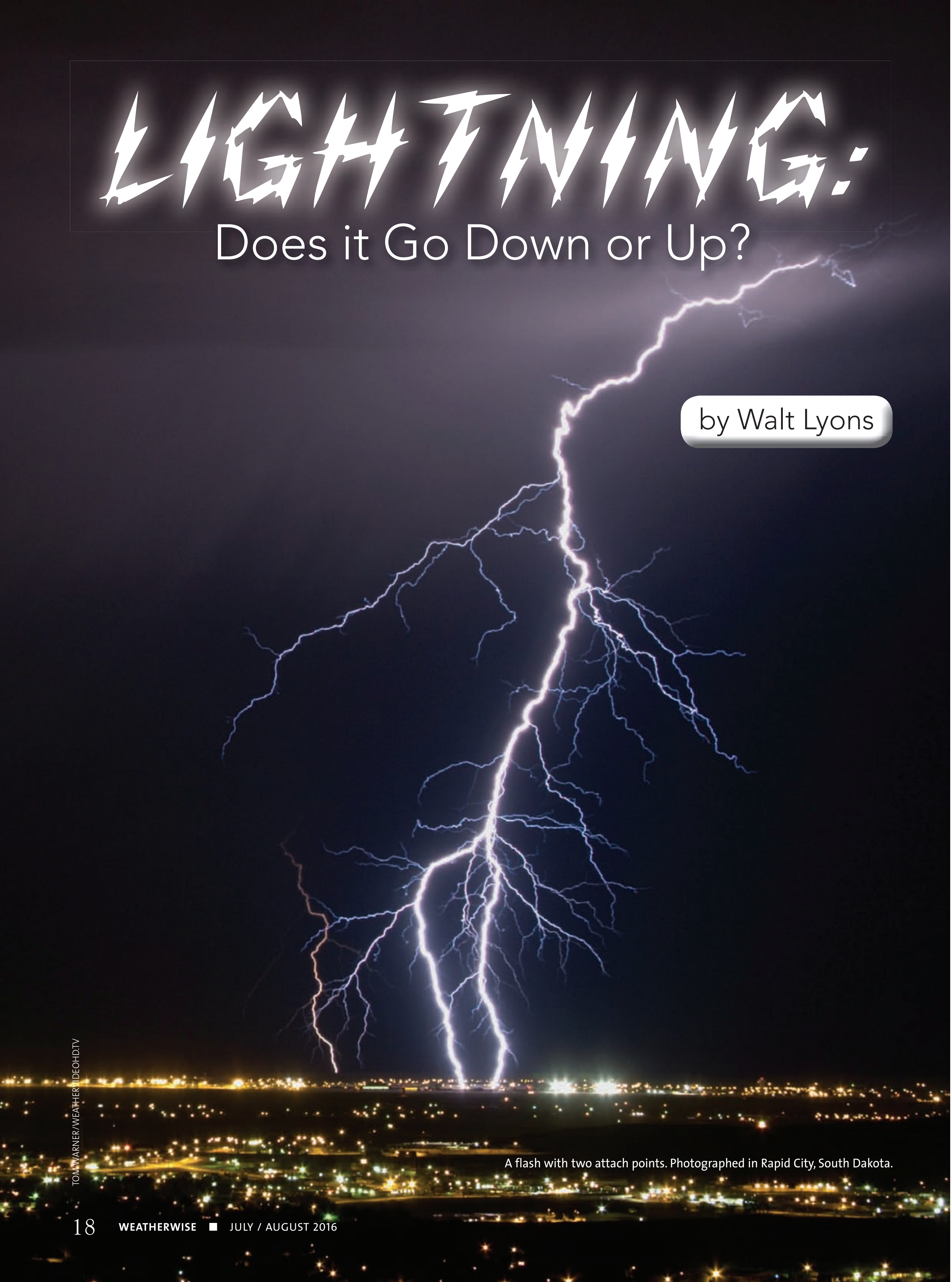
LIGHTNING:

Does it Go Down or Up?

by Walt Lyons



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A flash with two attach points. Photographed in Rapid City, South Dakota.

Earth is one of four planets in our solar system—along with Venus, Jupiter, and Saturn—that experiences giant atmospheric electrical discharges, or lightning. Only on our planet, however, are there sentient creatures pondering the origin and nature of these atmospheric pyrotechnics. This is most appropriate, given that the energy of ancient lightning flashes might have produced some key amino acids comprising the organic molecules that allowed for the evolution of these curious Homo sapiens.

One question often asked by humans: which way does lightning travel? Does it come down from the cloud, or go up from the ground? The answer is: Yes. And no. Also both ways. And very often sideways. It turns out, it's complicated! Fortunately, lightning researchers, aided by new high-speed camera systems, have begun to clarify the amazingly complex physics that transpire within fractions of a second.

It Started with Ben

Humans, awed and terrified by lightning, long believed it to be spears of fire hurled from above by angry gods. According to lore, the god Teschup punished the Hittites with lightning, as did Typhon punish the ancient Egyptians, Zeus the Greeks, Jupiter the Romans, Thor the Norse, and the Thunderbird and Wakinyan the Native Americans. Then arrives Benjamin Franklin, who speculated that lightning was merely a gigantic spark. In 1750, Franklin proposed the so-called sentry box experiment, which was designed to draw the electricity from the sky to a protruding metal conductor. The experiment was actually first performed in France in May 1752, unbeknownst to Franklin, under the direction of one Thomas-François D'Alibard, and then in Russia in 1753 by Georg Richmann, resulting in his death while conducting the inherently dangerous experiment. Franklin himself conducted the experiment with a slightly safer methodology, involving the famous kite in June 1752. Drawing a spark of the "electrical fluid" down from the cloud to his knuckle from a key suspended from the wet kite string confirmed that lightning was indeed electricity. And Franklin's lightning rods proved a terrific way to channel that energy from your roof harmlessly into the ground. For the next 100 years or so, lightning research progressed rather slowly. The advent of photography spurred further probing of the flashes that had proved maddeningly difficult to investigate. According to the George Eastman House Museum in Rochester, New York, the first lightning photographs were captured between 1882 and 1890 by one William N. Jennings, who proved it could be done. Into the 20th century, ingenious photographers teased out the workings of a phenomenon that takes place often much faster than the blink of an eye (about 100 milliseconds or thousandths of a second) or, for that matter, the click of a shutter. So-called streak photography could employ rotating banks of cameras, single cameras moving horizontally during a flash, or film strips pulled past open shutters. These efforts revealed that the lightning "bolt" was really a rapidly evolving sequence of distinct processes.

Dissecting the Lightning Discharge

While lightning is often called a "bolt," that term is purely colloquial and not used in technical discussions. Any form of lightning can be referred to as a discharge. But what causes a white-hot channel of electricity to discharge deep inside a cold cloud mass? Franklin knew thunderclouds contained vast pockets of electrical charge, with the lower portion usually having an excess of negative charge. But why? It turns out that ice is required to make the fire of lightning. When convective cloud updrafts exceed

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Figure 1. About three quarters of all lightning discharges wend their way through the sky without ever striking the ground.

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Figure 2. Selected frames from a Phantom high speed camera at 7200 frames per second showing a network of negative stepped leaders approaching a hilltop as an upward leader from a radio tower prepares to attach, completing the circuit with the upward return stroke.

around 15 mph, they usually penetrate well above the atmospheric freezing level. As updrafts propel storms ever higher, a deep volume of cloud spanning temperatures from +14°F to –40°F contains a myriad of supercooled water droplets, ice crystals, and graupel (soft hail) particles, which comingle and bounce off one another. This process results in (usually heavier) particles gaining negative charge and lighter ones becoming positively charged. Gravity separates the two within the updrafts, with the positive charges typically found high above a lower negative region. An intensifying electrical field results.

For reasons still under active scientific scrutiny, a bidirectional electrical breakdown eventually occurs between the two charge centers. At one end, negative lightning leaders propagate into positive charge volumes, and, at the other end, positive leaders penetrate negatively charged regions. Almost like a tree growing a vast network of branches and roots, the leader channels travel vertically but mostly sideways. Such discharges often remain buried deep inside the cloud and thus are termed intra-cloud (IC) lightning (Figure 1). About 75% of all lightning events are ICs. In very tall, severe storms and tall, tropical cumulonimbi, IC discharges can comprise more than 90% of the lightning.

Globally about 25% of lightning discharges are cloud-to-ground (CG) flashes. They strike something—or somebody. If positive charge is lowered to the ground, the event is called a positive cloud-to-ground (+CG). However, on average about 90% of CGs lower negative charge to earth. These –CGs have been extensively investigated over many decades using standard and

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Figure 3. Moving a camera horizontally during a lightning strike while leaving the shutter open reveals the multiple return strokes in a typical negative CG.


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Figure 4. Around half of lightning flashes to ground connect to more than one location, on some occasions up to several miles away.

streak photos, movie film, and video (typically 30 frames per second). Most recently, special high-speed cameras have been capturing from 1,000 to 10,000 or more frames per second. Successive images freeze activity in steps of 1.0 to 0.1 milliseconds or even shorter.

Once a discharge initiates deep within a thunderstorm cell, perhaps –four to five miles above the surface, some lightning channels may head downward, branching and splitting as they go. Videos show that the progress of the negative leader is one of starts and stops. Pushing ahead for some 150 feet over a millionth of a second, then pausing for around 50 milliseconds, it continues its earthward journey in a multitude of steps. As these negatively charged stepped leader tips come closer to the ground, we might be tempted to think lightning starts "looking around for a target to hit." But downward leaders are clueless. They don't start out with a pre-ordained target to zap. Rather, the lowering negative charge attracts the existing positive charge near the ground, which then concentrates on pointy objects, ranging from trees to steeples to golfers to blades of grass. As the stepped leader channels approach ground, the surface electric field further intensifies. One or more ground objects then launch upward positive leaders (sometimes called streamers). Now a race is on to see which upward leader can connect to which downward stepped leader. When a connection (or attachment) is made some 100 to 300 feet above ground, the magic happens. A giant cloud-to-earth electrical circuit is completed. A massive wave of energy races up the leader's channel from the ground into the cloud. This is the return stroke (Figure 2). Only one or two centimeters wide, it transports tens to hundreds of coulombs of charge with currents of many thousands of amperes, while reaching temperatures over 50,000°F—many times hotter than the surface of the sun. The return stroke releases enormous amounts of energy of all kinds: heat, light, acoustic [thunder], and radio waves, which can be detected thousands of miles away.

But have you ever noticed how many CG flashes appear to flicker? It turns out after the initial return stroke, the typical –CG can repeat the process. Successive leaders (called dart leaders, as their motion is less jerky) usually, but not always, follow the initial channel to ground. A typical –CG flash may have four or five distinct strokes, but as many as 46 have been documented. Successive strokes in a –CG tend to follow the same channel to ground, zapping the same point multiple times (Figure 3). But around half of CGs can have multiple attach points, or create totally separate channels to ground, some up to several miles away (Figure 4). This just further ups the odds of hitting something.


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Figure 5. An initial positive CG to ground (right side) induces an upward Lightning Triggered Upward Lightning from a radio tower on a hillside in Rapid City, South Dakota.

The individual –CG return strokes last only several millionths of a second, separated by tens of milliseconds. Some channels may not turn off completely, allowing weaker continuing currents to burn for many milliseconds. Even with all this happening, the typical "garden variety" –CG multi-stroke lightning flash is usually over in less than a half second. And amazingly, with today's high-speed camera technology, we can now see all this happening (see a collection of such videos at: https://www.weathervideohd.tv/wvhd.php?mod=clipbin&share=ff2b3f81x20e).

In recent years, the less common +CG strike has been the object of much study. While less than 10% of the global CG population, +CG strike can dominate in some severe supercell storms in which the storm polarity appears inverted (negative charge above positive), in some winter snow squalls, and in the trailing stratiform regions of large mesoscale systems. Positive CGs tend to have higher peak currents, and they transfer much more charge to the ground since their continuing currents can be stronger and longer lived. They usually only have one return stroke, but the process of a downward leader attaching to an upward leader from the ground resulting in an upward propagating return stroke is still found. Positive CGs are often associated with vast horizontal displays of intracloud lightning, popularly termed "spider lightning" or "anvil crawlers"—discharges that can at times propagate for over 100 miles. Some +CGs are so powerful they can induce phantasmagorical electrical discharges called "red sprites" high above thunderstorms in the mesosphere, which propagate both downward and upward from an ignition point around 47 miles altitude.

But Does Lightning Go Down or Up?

We can pretty much dismiss the notion of a dyspeptic deity riding a chariot through storms while hurling jagged darts of flame down from the sky. But the "cloud-to-ground" terminology does suggest that the action of lightning is cloud to ground. And as we have seen, high-speed cameras document that both negative and positive CGs do indeed start with a downward network of branching leaders propagating ever closer to earth. One of those downward leaders will attach to an upward ground leader. So far this has taken tens to hundreds of milliseconds. In the next several microseconds, the dramatic return stroke races back up the "lucky" downward leader channel—the event people clearly see and associate with lightning. The panel of images obtained by a Phantom high-speed camera at 7,200 frames per second illustrate classic –CG downward-stepped leaders approaching a radio tower from which an upward leader emerges, followed by the brilliant return stroke as the attachment occurs. Indeed, it can be said that CG lightning goes both ways—down and then up. So, it seems the question has been answered.

But as it turns out, there is a less common variation on the theme—one that more or less reverses the directions involved. Ground-to-cloud lightning? Sort of. It is well known that the taller an object, the more likely it is to be involved in a lightning strike. Sometimes it's an antenna poking above the roof lines of a suburban neighborhood, a cellphone tower, or even a several-hundred foot tall TV broadcast tower.

But the taller the object is, especially for structures more than around 300 feet, the more the basic character of the lightning event changes. The Empire State Building in New York City is struck many times each year—in one storm, eight times in 24 minutes. But researchers have long known that these events were different. In such cases, the initial leader did not come downward from the cloud above, but rather up from the tip of the structure. High-speed cameras have now clearly documented that such upward lightning starts with an initial continuing current as a leader ascends into the charged clouds above. In many, but not all, cases, return-stroke–like currents can then flow back down, causing the appearance of flickering.

And, of course, to make things even more complicated, there are two flavors of "upward" lightning. Researcher Tom Warner of ZT Research in Rapid City, South Dakota, has documented that, especially during summer storms, it appears the most frequent mode for upward lightning starts when a regular +CG strikes the ground, sometimes as far away as 30 miles. This momentarily enhances the electric field atop tall conducting structures in the region, allowing upward leaders to be launched (Figure 5). This process is called "lightning-triggered upward lightning." One "normal" +CG can potentially trigger upward tower discharges over a surprisingly large area. Multiple radio and TV antennae or numerous turbines in a wind farm can unleash spectacular simultaneous lightning-triggered upward lightning displays (Figure 6).

Sometimes, when there is not quite enough charge in the clouds to initiate "regular" CG electrical breakdown, the electrical field enhancement at the tip of a tall tower is sufficient for self-initiated upward lightning. These leaders can be seen reaching upward and outward on a journey to meet up with pockets of opposite polarity charge in the clouds overhead (Figure 7).

And then there is the rare thundersnow. Lightning, which is normally a summertime

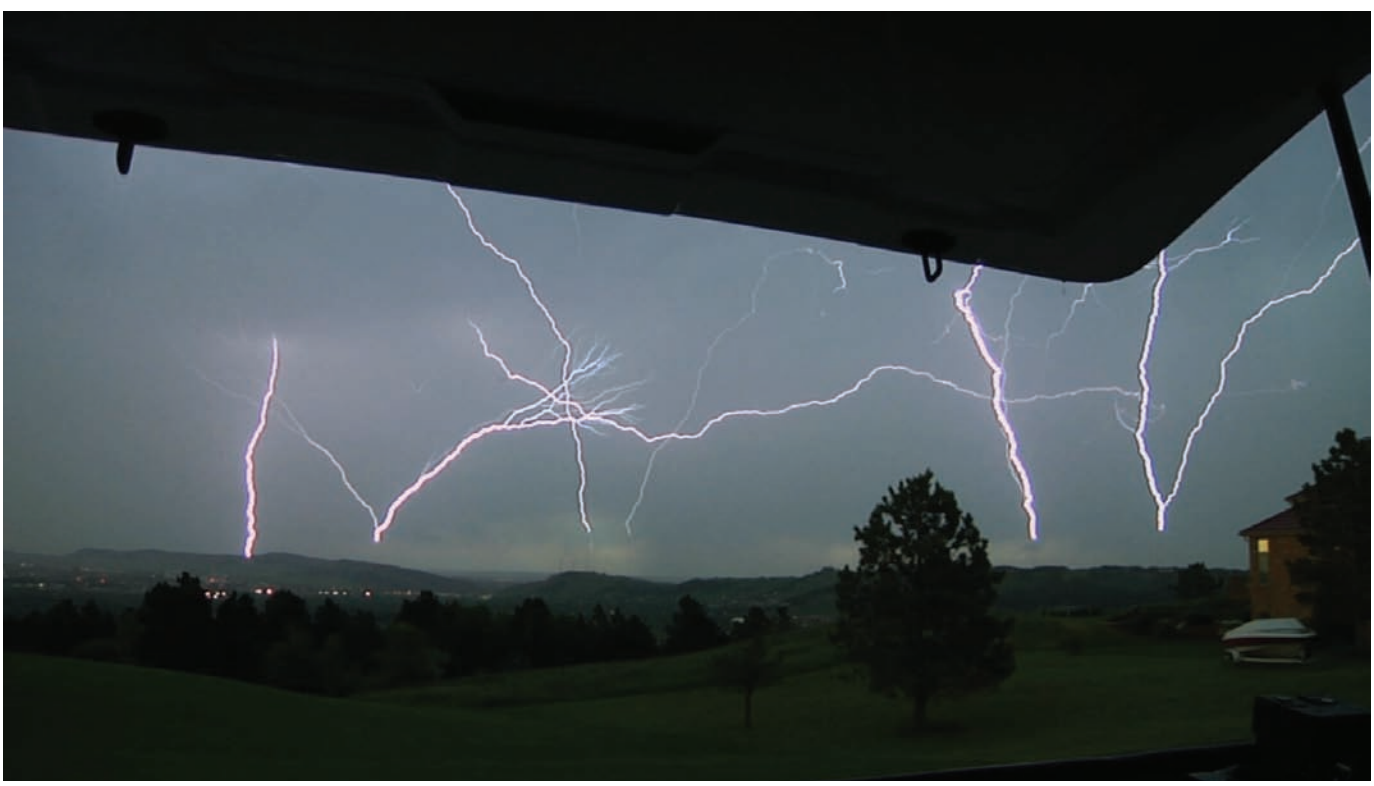

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Figure 6. Single video frame captured by lightning research vehicle shows a single positive CG (left) triggering upward lightning discharges from five broadcast towers.

phenomenon, can occur in the midst of a howling blizzard. It appears that many thundersnow events are actually self-initiated upward lightning from the tops of tall structures. In the Groundhog Day Blizzard of February 2011 that stretched from Missouri into Ontario, Canada, hundreds of self-initiated upward leaders launched from wind turbines, electrical transmission lines, and skyscrapers, such as the Willis and Trump Towers in downtown Chicago, Illinois.

So how can you tell if what you are seeing is up or down lightning? In a photograph, one can distinguish between regular CGs and the upward varieties by noting the direction of the branching leaders. If the leader branches splay downward and outward, it is cloud-to-ground flash (Figure 8). If they expand upward and outward resembling a tree, it is an upward event (Figure 7)

TOM WARNER/WEATHERVIDEOHD.TV

Figure 7. Upward lightning discharge from a tall tower branches upwards and outwards.

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Figure 8. A high speed camera captures numerous downward spreading stepped leaders approached the surface to meet an upward leader rising from the ground in this negative CG strike.

Don't Become a Fulgurite

When the huge current of a lightning strike enters soil, it can fuse the sand into a glass-like tube of "fossilized" lightning called a fulgurite. A sign posted in Colorado's Great Sand Dunes National Park warns hikers: "Don't Become a Fulgurite." Being struck, whether by a positive or negative CG or upward lightning, is a bad thing. All discharges attaching to the earth pack currents that can be deadly for living creatures (not to mention the microprocessors in your TV or computer.) Satellite measurements have fixed the average global lightning flash rate at about 45 per second, or 1.4 billion per year, of which 25% reach the ground. While roughly 70–75% of the planet's lightning occurs in the more tropical regions between 35 degrees north and south latitude, many continental and mid-latitude regions receive their fair share. Florida and the Gulf Coast region have well-known "lightning alleys," with hot spots of over 30 flashes for each square mile each year. Some mesoscale convective systems rumbling across the Central Plains and Midwest can unleash more than 100,000 flashes. The United States absorbs some 25 million CG flashes (and about 125–150 million strokes) each year. And the question of whether the lightning goes up, down, or both becomes pretty academic if you are a victim.

The United States lightning death rate fortunately has been steadily falling over the last century due to fewer people working outside jobs and greatly increased lightning safety awareness. Recently, fatality rates have been about 25–35 per year (with perhaps 10 times that being injured). Global lightning-caused death rates have been estimated at between 6,000 and 24,000 per year.

So what are your chances of being struck by lightning? Much, much higher than winning the Powerball lottery. The National Weather Service calculates that an American's lifetime odds of being involved in a strike are one in 12,000. And if one assumes a that typical person a has a circle of 10 family members and/or close friends, that means the odds of someone near and dear to you being struck drops to a little over one in 1,000. In other words, in a packed NFL stadium crowd, one should find around 70 people who will at some point have to cope with a loved one who became a candidate for fulgurite status. And while you statistically have "only" about a 10% of being killed outright, lifelong neurological and physiological disorders plague many survivors. And do note, lightning victims do not carry any


MIKE O'NEILL/WEATHERVIDEOHD.TV

Figure 9. Classic "bolt-from-the-blue" in which lightning strikes ground well outside of the main storm core, near Darwin, Australia.

dangerous residual electrical charge. If lightning strikes near you, help the "dead" first: Many who are struck will lie paralyzed in cardiac arrest after their bodies' electrical system was "short circuited." Immediate CPR can return many lightning strike victims from death's door.

How do you know when to take cover from lightning? If you hear thunder, it is time to take action. While you can see lightning—under ideal conditions, for over 100 miles—you can only hear thunder for up to five to 10 miles away in quiet rural areas. If you hear thunder, be on alert. Lightning has been known to strike 10 miles or more from its parent storm cloud (Figure 9)—the proverbial "bolt from the blue." Since thunder travels at the speed of sound, for each five-second delay between seeing the flash and hearing the bang, there is one mile of separation between you and a life-threatening experience. If you see a flash, be aware it is common for the next one to be a CG, which can easily hit up to six miles away—like maybe where you are standing. And it need not be raining. It might even be sunny! Many fatalities occur before the rain starts or after it ends. Thus the venerable 30/30 rule: If the interval between any lightning and thunder is 30 seconds or less, get inside and stay there until 30 minutes after the last thunder is heard.

People who fear the sound of thunder or lightning suffer from phobias called brontophobia and keraunophobia. However, while phobias are by definition irrational, respecting lightning for the damage it can inflict is very rational. Being inside a solid building or enclosed metal vehicle largely shields one from lightning. "When Thunder Roars, Go Indoors" has become a wise and practical mantra during lightning conditions. Being the source of an upward leader for an approaching downward stepped leader…is not fun—really. W

Certified Consulting Meteorologist WALT LYONS is a past president of the American Meteorological Society. His career path has included establishing lightning detection networks and investigating sprites, elves, halos, and gigantic jets high above thunderstorms. He is president of the educational Web site http://www.WeatherVideoHD.tv.

Special thanks to Tom Warner of ZT Research for his many scientific and video contributions.