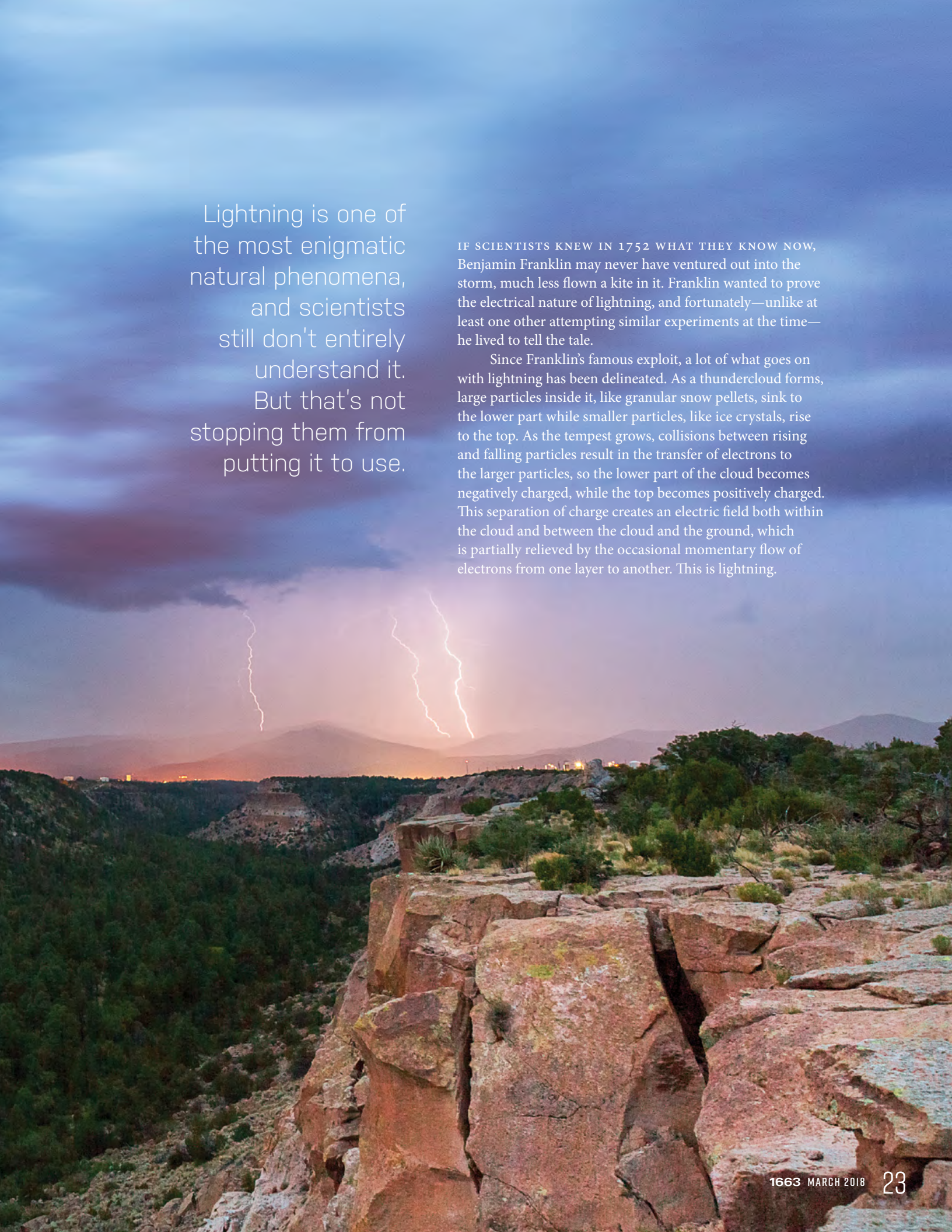
CREDIT: Jim Stein



Lightning is one of the most enigmatic natural phenomena, and scientists still don't entirely understand it. But that's not stopping them from putting it to use.

IF SCIENTISTS KNEW IN 1752 WHAT THEY KNOW NOW, Benjamin Franklin may never have ventured out into the storm, much less flown a kite in it. Franklin wanted to prove the electrical nature of lightning, and fortunately—unlike at least one other attempting similar experiments at the time—he lived to tell the tale.

Since Franklin's famous exploit, a lot of what goes on with lightning has been delineated. As a thundercloud forms, large particles inside it, like granular snow pellets, sink to the lower part while smaller particles, like ice crystals, rise to the top. As the tempest grows, collisions between rising and falling particles result in the transfer of electrons to the larger particles, so the lower part of the cloud becomes negatively charged, while the top becomes positively charged. This separation of charge creates an electric field both within the cloud and between the cloud and the ground, which is partially relieved by the occasional momentary flow of electrons from one layer to another. This is lightning.

Where a lightning flash occurs, the air is literally ripped apart—because air is a poor electrical conductor, for an electrical discharge like lightning to pass through it, the air molecules have to be broken down into ionized plasma—and the temperature spikes to five times hotter than the surface of the sun. A typical lightning bolt comprises two distinct kinds of electrical discharges: leaders, which form the main zigzag, and streamers, which are barely visible tendrils that sprout from the leaders. Leader discharges and streamer discharges are different in terms of charge, length, and duration, with streamers being smaller than leaders in all regards.

Despite breakthroughs in lightning science since Ben Franklin's day, there are still a lot of questions with respect to this most dynamic phenomenon of the natural world. Like what actually initiates a lightning bolt? The electric field in the cloud is not large enough to cause a spontaneous spark. The following three projects at Los Alamos are helping scientists understand the cause of lightning as well as how it can be put to use.

Project One: Searching for a spark

For decades at least, scientists have been trying to shed light on the source of lightning initiation. One theory is positive streamers, which are, in lightning lingo, brief and thread-like ionized paths that usually form inside the cloud, relatively high up, between the negatively and positively charged regions. (They also form between the cloud and the ground, which is temporarily positively charged, having had its electrons pushed away by the negatively charged cloud looming overhead). Scientists first thought that negative streamers initiate lightning, but that theory requires an electric field much greater than what's been measured. Initiation by positive streamers, on the other hand, demands a considerably lower electric field (though still too high), but observations show positive streamers forming after the leader forms, not before.

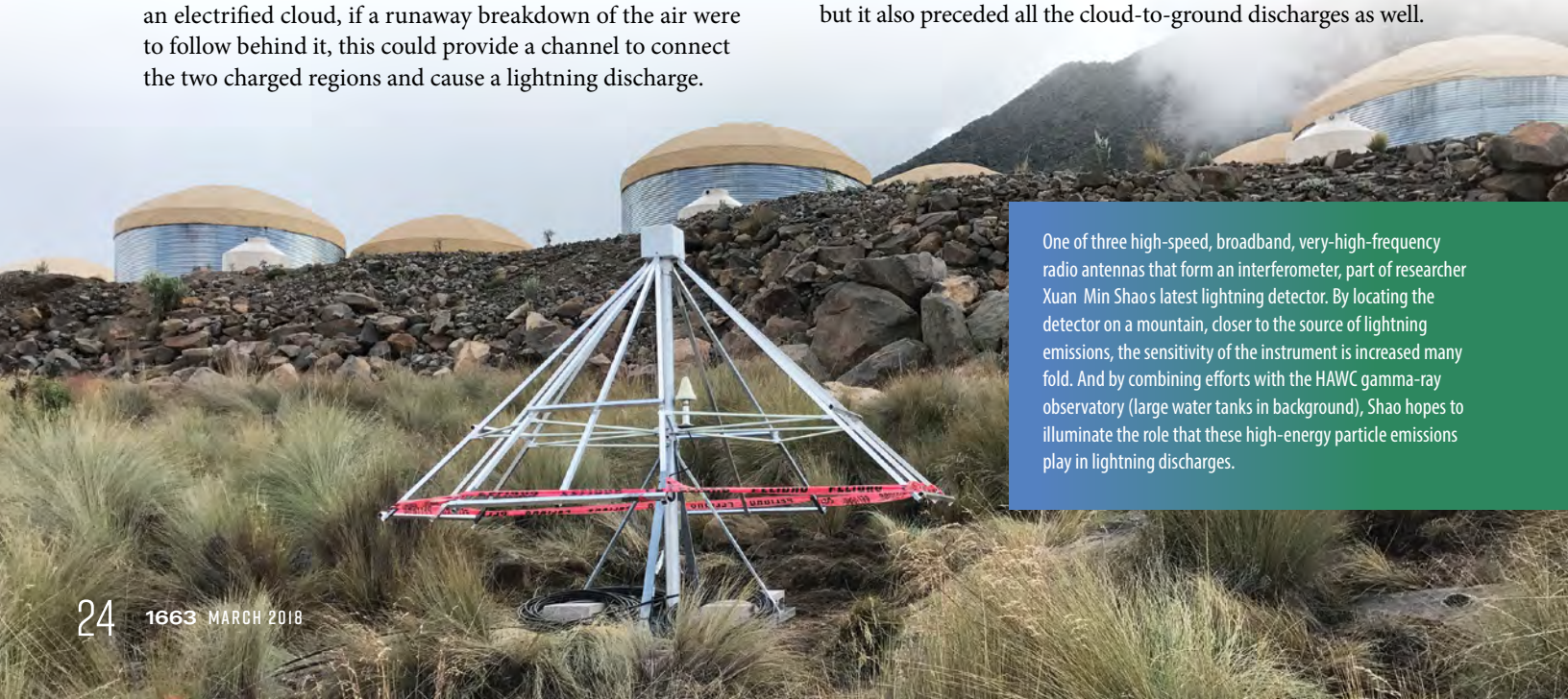
Another theory is cosmic rays. These very-high-energy particles continually bombard the planet, and may, so the theory goes, make the air in their wakes electrically conductive for a fraction of a second. As a cosmic ray travels through an electrified cloud, if a runaway breakdown of the air were to follow behind it, this could provide a channel to connect the two charged regions and cause a lightning discharge. This theory doesn't require as strong an electric field as the positive streamer theory, but as yet, runaway air breakdown has not been observed in association with cosmic rays traveling through thunderclouds.

A third theory that is gaining traction is fast positive breakdown, that is, air breakdown by fast positive streamers. Regular positive streamers are typically slow and weak, whereas fast positive streamers, as their name suggests, are much faster and stronger. They are known to occasionally occur immediately after especially energetic lightning discharge processes, yet their physics isn't well understood. Recently, Los Alamos physicist Xuan-Min Shao and his collaborators observed fast positive streamers occurring in virgin air, immediately before lightning. This prompted a hypothesis for how fast positive streamers might initiate lightning: Although the overall charge of the cloud is inadequate, small regions of very strong electric field may enable the spontaneous formation of fast positive streamers, which could break the air down and result in leader formation.

"These patches of intense electric field, combined with the presence of water droplets and ice crystals in the cloud—which may further increase the field strength—could be enough to get a fast positive streamer started," says Shao.

Most lightning is intracloud lightning, which never comes anywhere near the ground, so to test their theory, Shao and his collaborators are focusing on the sky. They deployed a lightning-mapping array on top of a mountain in Central New Mexico. The array, based on a concept originally introduced by Shao, included a high-speed broadband very-high-frequency (VHF) radiation interferometer, which is the only kind of detector with sufficient temporal and spatial resolution to pick up fast positive breakdown. It works by comparing phase differences between VHF signals received from pairs of spatially separated antennas. The differences are used to back-calculate the direction of the source of the signal, thereby generating a two-dimensional lightning map.

After observing hundreds of lightning discharges the researchers are confident that they're on to something: not only did fast positive breakdown precede all the intracloud discharges, but it also preceded all the cloud-to-ground discharges as well.



One of three high-speed, broadband, very-high-frequency radio antennas that form an interferometer, part of researcher Xuan Min Shao s latest lightning detector. By locating the detector on a mountain, closer to the source of lightning emissions, the sensitivity of the instrument is increased many fold. And by combining efforts with the HAWC gamma-ray observatory (large water tanks in background), Shao hopes to illuminate the role that these high-energy particle emissions play in lightning discharges.

No other phenomenon has yet been observed to correlate so well. More research is needed before it can be called a smoking gun, but it's looking good so far.

Recently, Shao built and deployed another detector, with the goal of further clarifying how fast positive breakdown works. In addition to visible light and VHF electromagnetic radiation, lightning also produces very-high-energy gamma rays, but the role that they play in the electric charging or discharging of thunderclouds is unclear. The new lightning-detection system includes the same type of VHF interferometers used previously, but this one also has a small gamma-ray detector and a tool to measure VHF polarization, which will reveal the direction of electron movement in a lightning discharge. In addition, the new array has a heavy-hitting neighbor: the High-Altitude Water Cherenkov Gamma-ray Observatory (HAWC, discussed in more detail in "Dark Matter Gets a Little Darker" on page 2). Located atop a mountain in Mexico, HAWC is a collaborative project between Los Alamos and numerous other entities (led by Los Alamos astrophysicist Brenda Dingus), built to study some of the most energetic phenomena in the universe, and Shao's new lightning detector is cozied up right next to it. The plan is that when lightning strikes, HAWC will pick up the gamma emissions (with a million times more sensitivity than the small gamma-ray detector built into Shao's array) while the lightning-detector will provide location, frequency, energy, and timing information.

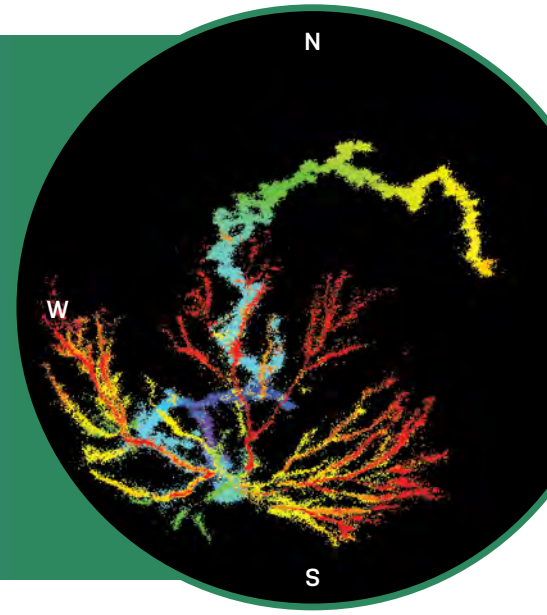
Where **lightning flashes,** the air is **ripped apart** and the **temperature** rises to **hotter than** the surface of **the sun.**

Conveniently, HAWC also detects cosmic rays, so the new setup may be able to shed new light on the cosmic ray question: do cosmic rays disrupt the air's molecular structure enough to initiate a lightning discharge? If they do, Shao's lightning-detection system, working with HAWC, will see it.

Advanced lightning mapping and high-energy particle observations will answer key scientific questions about not just lightning, but other bright flashes as well—the physical signatures of lightning are very similar to those of atmospheric nuclear explosions. By studying lightning, something that is happening all the time across the globe, Los Alamos scientists can learn more about nuclear explosions, which are, needless to say, much rarer, thereby serving the Laboratory's nuclear explosion detection and forensics missions.

Project Two: Illuminating the ionosphere

Thunderstorms happen in the atmospheric layer called the troposphere. Above the troposphere lies the stratosphere, then the mesosphere, then the thermosphere; each layer is defined by distinct temperature changes. But atmospheric layers can be defined by other criteria too: the ionosphere, for example, overlaps parts of both the mesosphere and thermosphere, but is defined by the presence of air ionization due to solar radiation.



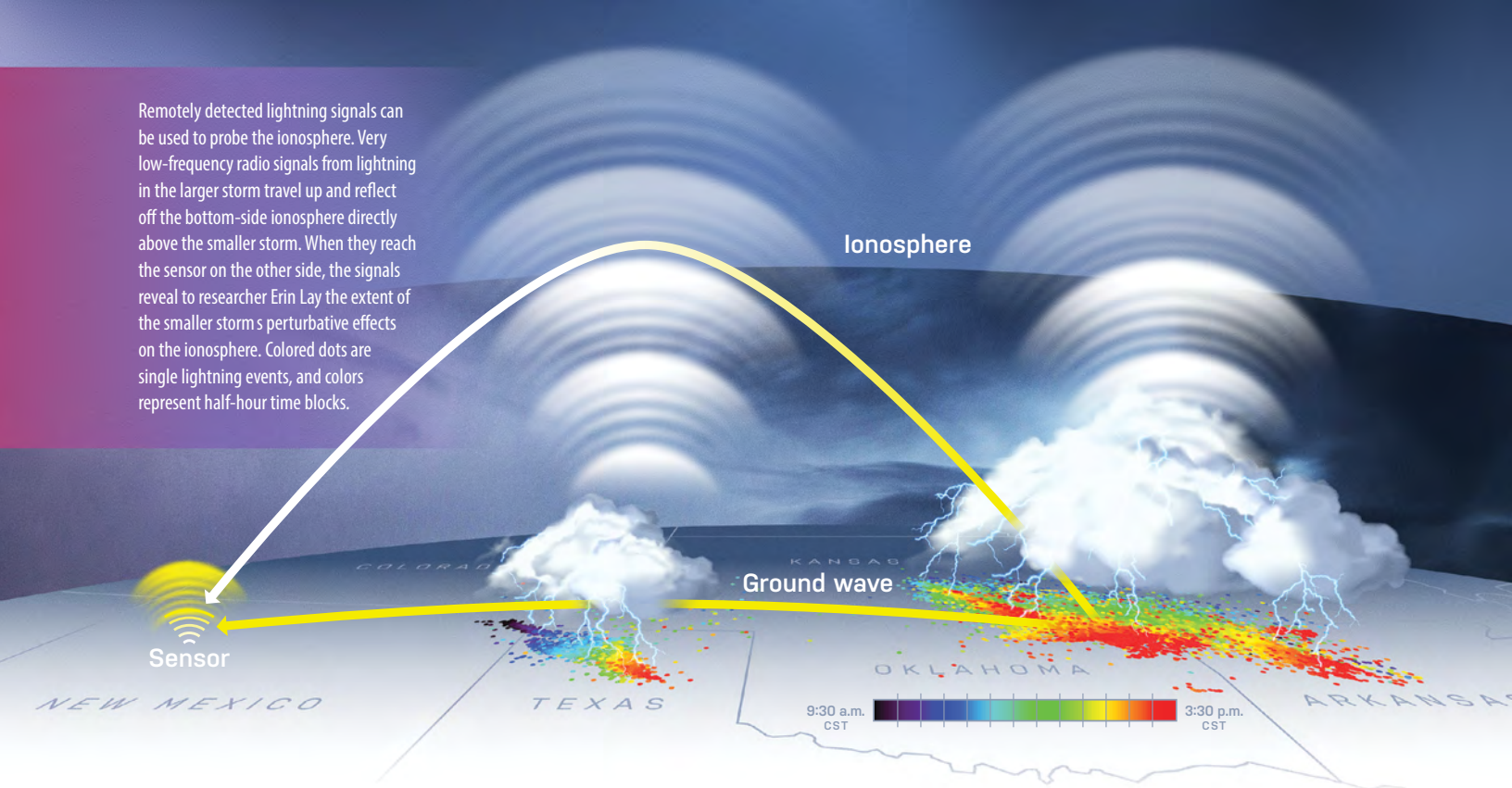
A worms-eye view of a single intracloud lightning discharge in the sky above Los Alamos in May 2017. By comparing phase differences between very-high-frequency radio signals received from spatially separated antennas, the direction of the signal source was calculated. This two dimensional map spans horizon to horizon, and illustrates the timing (blue to red) of the discharge as it propagated over the course of 0.33 second.

The ionosphere is interesting because it is a plasma, having had the electrons knocked off of enough atoms to result in significant concentrations of ions and free electrons. One of the reasons people study the ionosphere is that it is a key player in sending radio waves beyond the horizon to distant places. The radio waves are sent up from a transmitter, then reflect off of the bottom of the ionosphere and bounce back to Earth-bound receivers situated far from the transmitter.

"The bottom-side ionosphere acts as a guide for electromagnetic waves," Los Alamos atmospheric physicist Erin Lay explains. "It bends them and guides them around the planet. And if it's altered in some way, then how it bends and guides the waves will be altered as well."

Lay specializes in signal propagation through the ionosphere. To understand a received signal and be able to distinguish the source, one has to know what it propagated through. One of the technologies most dependent on the waveguide aspect of ionospheric wave propagation is the very-low-frequency (VLF) communications used by submarines. They need to reliably receive signals from very far away, and anything that interferes with that could spell trouble.

A source of VLF radiation, and one of the most frequent sources of ionosphere perturbations is lightning—specifically, the electric field changes produced by lightning discharges in thunderstorms churning way down in the troposphere. The convection (vertical circulation and heat transfer) and buoyancy (upward force) in a thundercloud produce acoustic waves and buoyancy waves (often called gravity waves, and not to be confused with the astrophysical phenomenon of gravitational waves), which go out in all directions. As these waves propagate upward, toward the ionosphere, their magnitude grows exponentially due to decreasing atmospheric density. But because the electron density of the bottom-side ionosphere is so low, it's hard to measure the perturbative effect of acoustic and gravity waves on the lower ionosphere. Together, Lay and Shao developed a technique to get past that



Remotely detected lightning signals can be used to probe the ionosphere. Very low-frequency radio signals from lightning in the larger storm travel up and reflect off the bottom-side ionosphere directly above the smaller storm. When they reach the sensor on the other side, the signals reveal to researcher Erin Lay the extent of the smaller storm s perturbative effects on the ionosphere. Colored dots are single lightning events, and colors represent half-hour time blocks.

difficulty, using lightning itself as a kind of radar. Radar works by sending out a signal, then receiving the signal back after it bounces off of something, and interpreting the difference between the two signals to understand the sizes and locations of the things from which the signal bounced.

Lay and Shao's method requires there be two separate storms—one to perturb the ionosphere above it and the other to send lightning VLF signals that reflect off the perturbed region and, once they reach the sensors, reveal the extent of the perturbation they passed through. The proof-of-principle study showed that the already low electron density in the lower ionosphere above the storm was further reduced by 60 percent. This project used a Los Alamos sensor network that Shao helped establish 20 years ago to study lightning and is based on a VLF radio propagation model developed by Shao and his colleagues.

Humans are **fascinated** by lightning, **intimidated** by it, and **motivated to understand** it.

What made the lightning-as-radar project possible was a breakthrough data-processing technique. This technique compares the amplitude of the portion of the lightning radio signal that travels along the ground, undisturbed by the ionosphere, to the amplitude of the signal that is reflected off the ionosphere to reveal how much of the signal was absorbed by the ionosphere. It also uses the time delay between the two signals to indicate the altitude of the bottom-side ionosphere. These measurements reveal to the scientists what the ionosphere looks like above the perturbative storm, just like radar reveals to a pilot what lies beyond the clouds.

Thunderstorms and lightning aren't the only things perturbing the ionosphere that are of interest to scientists. There are other hazardous phenomena, including earthquakes, meteors, and nuclear explosions, whose perturbative potential scientists need to understand. But there's yet another dramatic player in the lightning-as-a-probe ensemble. With temperatures hotter than the surface of the sun and signatures similar to nuclear detonation, what could possibly make studying lightning more dramatic? How about erupting volcanoes?

Project Three: Probing the plume

Los Alamos atmospheric physicist Sonja Behnke was studying lightning when she fell into Alaska's Redoubt volcano. Well, she fell into *volcanology*, to be precise, and it began at Redoubt. As a graduate student, while developing her lightning research, she was offered an opportunity to study volcanic lightning on Redoubt. She accepted and then continued to pursue volcanic lightning during her postdoctoral training, during which a serendipitous series of events helped light her path forward. She joined a team in Florida under aspirations of studying volcanic lightning in Central America. But disappointingly, that project fell through, prompting Behnke to seek out new horizons. Fortune finally landed her at the foot of Sakurajima volcano in Japan, where she studied a peculiar kind of lightning associated with explosive volcanic eruption. Now she is collaborating in the development of a volcano-monitoring system based on that peculiar volcanic lightning.

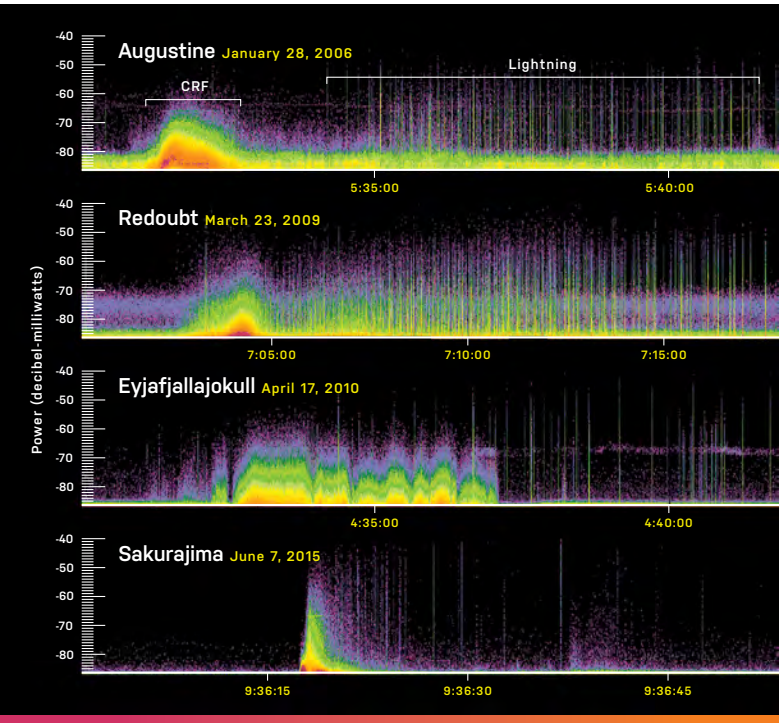
Contrary to popular perception, it's not obvious when a volcano is about to erupt. Volcanoes are often remote, far from human eyes and ears, and their tops can be shrouded in clouds. So, with no one to see or hear an eruption, there's no

one to raise the alarm. And yet, an alarm system is warranted, because when a volcano erupts, even a remote one, it poses a major hazard.

"Some people think lava is the main hazard," explains Behnke, "but an ash plume poses much more danger, particularly to aircraft. Because it's slow, lava isn't actually much of a hazard, and the kinds of volcanoes that produce lava don't generally produce ash plumes—they are different types of events. An ash plume is fast and sudden and can extend tens of thousands of feet into the air. It's a serious problem."

In 2010, in response to the relatively small eruption of Eyjafjallajökull volcano in Iceland, 20 countries decided that the risk to human lives was great enough to warrant extreme disruption of European air traffic, and ordered their airspace closed to commercial jets. If a jet flies through an ash plume, its engines may fail. The mechanics get mucked up, the air intakes get suffocated, and the entire engine becomes coated in volcanic glass. It's not uncommon for commercial flight paths to pass over volcanoes, and if it's nighttime, or cloudy, a pilot won't see an ash plume—which may not have been there hours or even minutes before.

On Sakurajima, Behnke set up an elaborate lightning-mapping array to collect VHF data that would tell her, in addition to the frequency and duration of radiation emissions, the location and size of the source as well. She knew that the onset of an explosive eruption is accompanied by a powerful burst of continuous radio-frequency (CRF) radiation that lasts too long to come from a normal lightning discharge. The theory was that the source of the CRF burst was, in fact, many small leader discharges happening in rapid succession near the vent of the volcano as the first ash plume bursts forth. If the plume carried an inherent net charge, the theory proposed, then that could facilitate small leader discharges between the plume and the ground. But Behnke's data showed that something else was going on.



Continuous radio-frequency (CRF) emissions at the start of an explosive volcanic eruption are distinct from radio emissions produced by later volcanic lightning discharges. A CRF burst has been measured during every volcanic eruption that researcher Sonja Behnke has studied. She is working on the development of a volcano-monitoring system, based on these CRF emissions, that will help keep aircraft out of dangerous volcanic ash plumes.

The CRF burst was indeed coming from a rapid-fire series of discharges near the vent, but each individual discharge was too brief to be a leader, and the entire burst was happening before any electrical charge in the plume could be detected. Further, leaders, even small leaders, are at least tens of meters in length, while the discharges Behnke measured were only a few meters at most. So Behnke concluded that the CRF burst couldn't come from leaders. She decided streamers, rather—those filamentary streaks that branch off of leaders—were more likely.

Behnke has seen these streamer-like discharges in every volcanic eruption she looked at. They have no counterpart in thunderstorms, are unique to the initial moments of explosive volcanic eruptions, and can be detected up to 100 kilometers away. So the phenomenon is a good candidate for an eruption monitor.

There are other technologies as well: seismometry, infrasound, radar, and satellite imagery are each useful for volcanic monitoring but are each fraught in one way or another. Lightning observation, on the other hand, may just be the stroke of genius needed to protect planes, pilots, and passengers alike.

Lighter and brighter

A lot of lightning studies originated from atmospheric nuclear-detection studies. The two things, are, after all, quite similar. Because of these similarities, it makes sense that Los Alamos scientists would study lightning. It's a tremendously convenient natural proxy.

But aside from mission-driven applications, there's strong basic-science rationale for studying lightning. It is ubiquitous to the human experience; one can't help but be fascinated by it, intimidated by it, and motivated to understand it. As the intrepid Mr. Franklin's derring-do demonstrates, people will go to great lengths to tame nature by figuring out how it works.

In that spirit, Shao, Lay, Behnke, and their contemporaries are inventing tools and venturing into the storm, rather than staying in and peering out the window. Well, actually they *are* staying in, well out of literal storms (putting their instruments in place when there isn't a storm, then waiting for the storm to come), because they know more than Ben Franklin did. But they are intent on taming the figurative storm, the storm of the unknown, and thankfully, their tools are far more sophisticated, and a good bit safer, than a kite with a key on a wire. LDRD

—Eleanor Hutterer