THE DOMINICK LABINO LECTURE

Lightning Makes Glass

by Vladimir A. Rakov

1. Introduction

Mother Nature makes glass each time a large amount of energy is released during a sufficient period of time at the Earth's surface, provided that the soil composition is suitable for making glass. The latter condition is satisfied, for example, by sandy soil, with the resultant natural glass being silica glass named "lechatelierite" after the French chemist Henry Le Châtelier (1850–1936).

There are two phenomena that are responsible for making natural glass on Earth: meteorites and lightning. Glass that is made as a result of the collision of a meteorite with the Earth's surface is called meteoritic glass or tektite. Glass (a glassy object, to be exact) that is made as a result of a cloud-to-ground lightning discharge is called a fulgurite (from the Latin "fulgur," which means lightning). Fulgurites come in a great variety of forms and can be viewed as nature's own works of art.

It is worth noting that lechatelierite (natural silica glass) is not present in obsidian, a glass-like material associated with volcanic activity. On the other hand, volcanic activity is known to generate lightning which, if it strikes sandy soil, may produce a fulgurite. Silica glass also has been made as a result of nuclear explosions. In 1945, the first nuclear bomb (equivalent to 18,000 tons of TNT) was detonated in the New Mexico desert. The explosion formed a crater 800 yards in diameter, glazed with a dull gray-green silica glass. This glass was named "trinitite" after Trinity Site where the first nuclear bomb test was conducted.

Vladimir Rakov, holding lightning-trigger rockets

2. Characterization of Lightning

On average, about 100 lightning discharges occur every second on the Earth. Only about one-third of them involve ground and potentially can make fulgurites. (Others occur in the clouds, between clouds, or between cloud and clear air). The Tampa area in Florida receives more than 12 lightning strikes per square kilometer per year. This is the highest level of lightning activity in the United States. Each cloud-to-ground lightning involves an energy of roughly 10^9–10^{10} Joules. Most of the lightning energy is spent to produce thunder, hot air, light, and radio waves, so that only a small fraction of the total energy is available at the strike point. However, it is well known that this small fraction of the total lightning energy is sufficient to kill people and animals, start fires, and cause considerable mechanical damage to various structures. Lightning is also a major source of electrical disturbances.

The peak temperature of the lightning channel is of the order of 30,000°K, which is five times higher than the surface temperature of the Sun (the temperature of the solar interior is 10^7 K). The lightning peak temperature is considerably higher than silica's melting point, which is somewhere between 1600 and 2000°C, depending on moisture content. But whether or not silica sand melts and glass is produced depends on lightning duration (besides other, not well-understood factors). Since a contact with ground is made, some lightning strokes last for less than a millisecond, while others linger for a significant fraction of a second. Lightning current peaks are usually of the order of tens of kiloamperes, but occasionally may exceed 100 kA. The

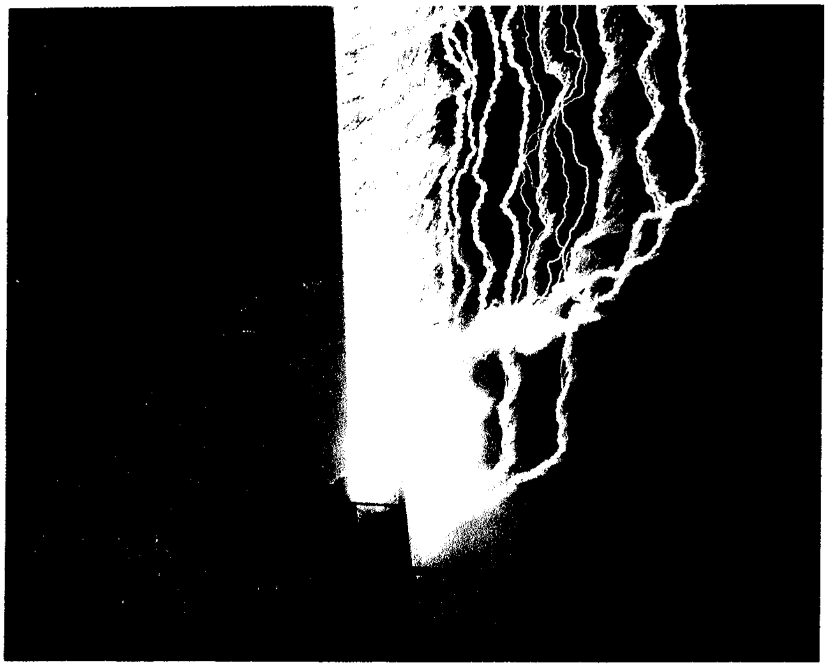
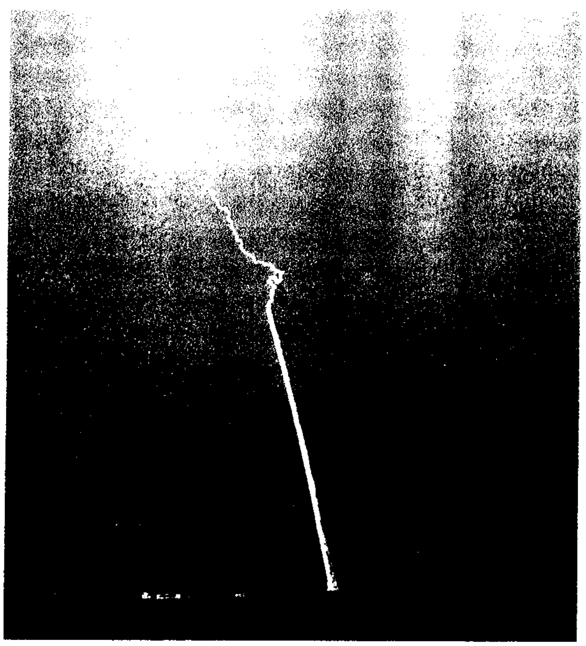


Figure 1: Photographs of lightning flashes triggered in 1997 at Camp Blanding, Florida.

A close-up view of a strike to the test power system



A distant view of a strike to the test runway

long-lasting current components are typically in the range of tens to hundreds of amperes. The latter are thought to be responsible for making fulgurites.

In the case of natural lightning, it is usually unknown when and where the discharge is going to occur. These uncertainties are largely removed when lightning is artificially initiated (triggered) from an overhead natural thundercloud with the so-called rocket-and-wire technique. (For details, visit our web site: http://www.eel.ufl.edu/~lightning). Some of the most interesting fulgurites have been created in triggered-lightning experiments.

About 30 to 40 lightning discharges are triggered every summer at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. The Center is located approximately midway between Jacksonville and Gainesville, Florida, and is a unique facility for studying various aspects of atmospheric electricity, lightning, and lightning protection. The Center is operated by the University of Florida (UF). Examples of still photographs of lightning flashes triggered at Camp Blanding, Florida, are shown in Figure 1. During the summers of 1995 through 1998, over 30 scientists and engineers (excluding UF faculty, students, and staff) from 13 countries, and representing four continents, performed experiments at the Center. Many triggered-lightning discharges at the Center that terminated on ground (as opposed to termination on well-grounded objects or systems) created fulgurites.

3. General Information on Fulgurites

The earliest discovery of a fulgurite was reportedly made in 1706 by Pastor David Hermann in Germany. Most people have never seen a fulgurite, and if they have, they might not have recognized it for what it was. All fulgurites can be divided in two classes: sand fulgurites and rock fulgurites. Sand fulgurites are usually hollow, glass-lined tubes with sand adhering to the outside. Rock fulgurites are formed when lightning strikes the bare surface of rocks. This type of fulgurite appears as thin glassy crust with which short tubes, or perforations lined with glass in the rock, may be associated. Glass of this type may be relatively low in silica, and exhibit a wide variety of colors, depending on the composition of the host rock. Rock fulgurites are found on the peaks of mountains.

When lightning strikes sandy soil, the air and moisture present in soil are rapidly heated, and the resultant explosion-like expansion forms the central tubular void. As stated before, quartz sand melts at a temperature of about 1600–2000°C depending on moisture content, and molten glass is pushed to the periphery of the void. Subsequent relatively rapid cooling causes the glass to solidify. A general condition for sand fulgurite formation appears to be the presence of a relatively dry dielectric such as quartz sand overlying a more conducting soil layer or the groundwater table, with the depth of the latter probably determining the limit for vertical extent of the fulgurite formation.

The diameter of fulgurites ranges from a quarter of an inch to three inches, and the color varies, depending on the type of sand from which they were formed. Sand fulgurites are usually tan, grayish, or black, but almost translucent, white fulgurites have been found in Florida panhandle beaches. The inner surface is glassy and exhibits numerous bubbles. The walls are usually about 0.5–2 mm thick, but may be paper thin. There appears to be no relation between tube diameter and wall thickness. Sand fulgurites are quite fragile and very difficult to excavate in one piece. An example of a sand fulgurite is shown in Figure 2.

Since fulgurites are real glasses, they are very resistant to weathering and are usually well preserved for a long period of time. For this reason they are used as paleoenvironmental indicators. For example, many fulgurites are found in the Sahara desert, where presently there is little lightning activity, confirming that very different conditions existed in this region in prehistoric times. A fossil fulgurite thought to be 250 million years old has been reported there.

Fulgurites have been produced artificially by passing laboratory arc current through sand. It has been found by researchers at the Technical University of Ilmenau, Germany, that currents higher than 50 kA and lasting for some hundreds of microseconds, typical of impulsive components of the lightning current, are incapable of making a fulgurite (only some very thin fragments). On the other hand, relatively low magnitude currents of some hundreds of amperes, lasting for some hundreds of milliseconds, yielded well-formed fulgurites with diameters of 7 to 15 mm. It has been also observed that the higher the current, the larger the cross-sectional dimensions of the fulgurite.

Different forms of fulgurites were obtained in dry and wet sand. Fulgurites in wet sand were more curved and had more irregular outer surface. The latter feature was attributed to the pressure of vaporized moisture that squashed the fulgurite when the arc pressure in the central tubular void disappeared, while the glass was still plastic.

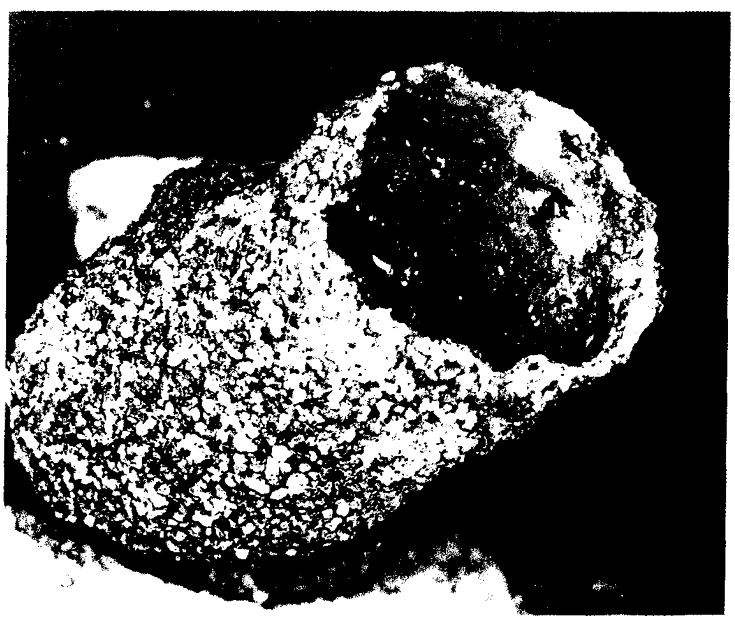


Figure 2: A sand fulgurite made by triggered lightning in 1993 at Camp Blanding

Cable A

Cable B

Cable C

Figure 3: Lightning damage to underground power cables. Note fulgurites in A and B

4. Fulgurites Created at the ICLRT at Camp Blanding, Florida

4.1 Underground Power Cable Project (1993–94)

In 1993, an experiment, sponsored by Electric Power Research Institute (EPRI), was conducted by Power Technologies, Inc. to study the effects of lightning on underground power cables. In this experiment, three 15 kV coaxial cables with polyethylene insulation between the center conductor and the outer concentric shield (neutral) were buried 5 m apart at a depth of 1 m, and lightning current was injected into the ground at different positions with respect to these cables. One of the cables (Cable A) had an insulating jacket and was placed in PVC conduit. Another one (Cable B) had an insulating jacket and was directly buried, and the third one (Cable C) had no jacket and was directly buried. About 20 lightning flashes were triggered directly above the cables, which were unenergized.

The underground power cables were excavated by the University of Florida in 1994. The damage found ranged from minor punctures of the cable jacket to extensive puncturing of the jacket and melting of nearly all the concentric neutral strands near the lightning attachment point. Some damage to the cable insulation was also observed. In the case of the PVC conduit cable installation, the side wall of the conduit was melted, distorted, and blown open, and the lightning channel had attached to the cable inside and damaged its insulation. Photographs of the damaged parts of the cables are shown in Figure 3.

Five fulgurites were found during the excavation of the underground cables. The excavation process was a slow, methodical one, and covered an area with dimensions of 4 m by 20 m. Various techniques developed in paleontology were used to remove the fulgurites. The fulgurite excavated over Cable B was nearly vertical, with a length of approximately 1 m, and an average diameter of 1.5 cm at the top and about 0.4 cm at the cable. This fulgurite was the most complete fulgurite excavated as part of the underground power cable project. It was unearthed in one piece with very little reconstruction necessary. This fulgurite is presently on exhibit at the Electric Power Research Institute (EPRI) in Palo Alto, California.

4.2 World-Record Fulgurite (1996)

After the excavation of fulgurites produced as part of the underground power cable project, we started checking for fulgurites at all known lightning strike points at the Camp Blanding facility. Each year, we trigger on average 30 to 40 discharges, some of which strike ground as opposed to terminating on the rocket launcher. Additionally, the facility receives about five lightning strikes that occur naturally, irrespective of our lightning triggering activity. Our surveillance cameras and observer reports allow us in many cases to find the strike point on the ground. Such strike points usually appear as holes in the ground with the surrounding grass being killed (as becomes apparent within a few days). When the strike point on the ground is found and flagged, it is impossible to predict if a fulgurite has been created, and, if so, what its shape and dimensions are.

One such find in 1996 led to many days of careful digging and resulted in the unearthing of a fulgurite having two mostly vertical branches, one about 16 feet and the other about 17 feet long. It was recognized by the Guinness Book of Records as the world's longest excavated fulgurite. The 17-foot branch of the world-record fulgurite is shown in Figure 4. The successful excavation would not have been possible without special tools and the paleontological skills of Mr. Dan Cordier and Mr. Mike Stapleton. The world-record fulgurite was carefully separated into sections and covered in plastic material used in paleontological digs. Each section was measured with special instruments and labeled for subsequent reassembling. At this time, the world's longest fulgurite is looking for a home—a museum with sufficient space to display this magnificent subterranean creation of atmospheric electricity. We have dug up about ten other fulgurites at Camp Blanding that are on average 4–5 feet long.

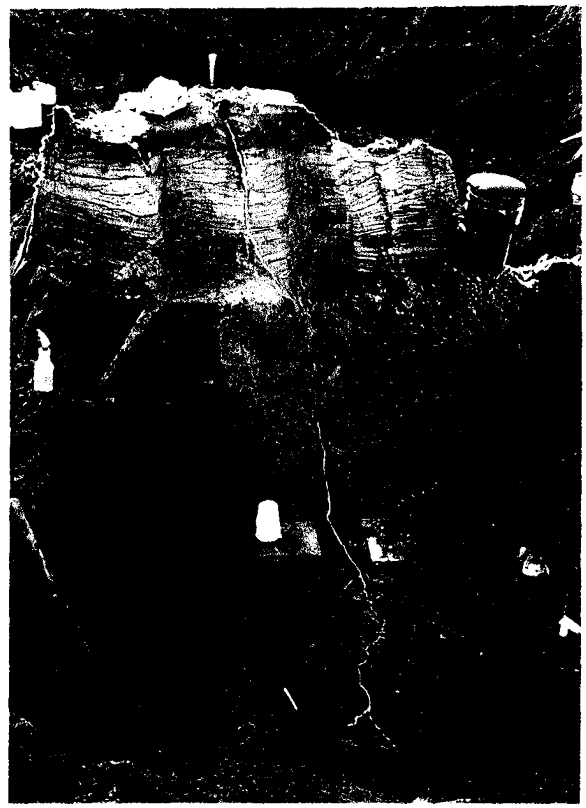


Figure 4: World's longest excavated fulgurite (17 feet), made by triggered lightning in 1996 at Camp Blanding

4.3 Artistic Installation, Petrified Lightning from Camp Blanding (1997–98)

In the summer of 1997, researchers at the International Center for Lightning Research and Testing, Dr. M. A. Uman, Mr. D. J. Cordier, Mr. K. J. Rambo, and Mr. M. V. Stapleton, worked with Mr. Allan McCollum, an internationally recognized artist, to create the fulgurite that became the centerpiece of an artistic installation entitled *Petrified Lightning from Camp Blanding*. The installation was on display at the USF Contemporary Art Museum in Tampa in the fall of 1998, and was accompanied by a simultaneous exhibit and presentation on the project at the Tampa Museum of Science and Industry (MOSI). The project was curated and organized by Margaret A. Miller, Director of the USF Contemporary Art Museum, Jade Dellinger, Independent Curator, and Wit Ostrenko, Executive Director of MOSI.

The Camp Blanding (fulgurite production) stage of the project involved the experimentation with minerals of which the fulgurite was to be made, and with various types of containers that were used to avoid the very difficult excavation process. A fulgurite made of staurolite (75%), ilmenite (15%), and rutile (10%) is shown, as an example, in Figure 5. Allan McCollum selected zircon ($ZrSiO_4$), a heavy mineral that is mined by Du Pont not far from Camp Blanding, and that is primarily used in the refractory industry. Zircon melts at 2100–2300°C, a melting temperature that is slightly higher than for silica.

Zircon sand was packed in a 4-foot section of a PVC pipe 6 inches in diameter, and equipped with two axial metallic electrodes forming a gap of 15 cm or so in the sand. This container was placed in a red

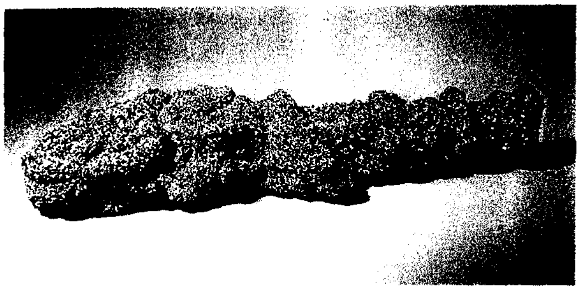


Figure 5: A fulgurite made of staurolite (75 percent), ilmenite (15 percent), and rutile (10 percent) at Camp Blanding

Figure 6: Allan McCollum, *Fulgurites*, 1997–98 (installation view)

trash receptacle located near the base of a rocket launcher used to trigger lightning. Allan McCollum, the artist, helped with the design of the experiment, and was the one to push the rocket-launch button. When lightning was initiated, lightning current passing through the gap produced a zircon sand fulgurite resembling a bone.

A Florida souvenir factory, Sand Creations, produced 10,000 replicas of the fulgurite. The replicas were made from a mixture of zircon (the same mineral from which the original was made) and epoxy. The artistic installation is shown in Figure 6. As another element of the installation, Allan McCollum prepared a series of booklets containing more than 50 texts on fulgurites, lightning, and related subjects. The booklets were presented on tables in a room adjacent to the display of 10,000 replicas of the fulgurite.

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