Introduction to the physics of lightning

V.A. Rakov

University of Florida, Gainesville, Florida, USA

An overview of the physics of cloud-to-ground lightning is given, including its initiation, propagation, and attachment to ground. Lightning interaction with the ionosphere and production of energetic radiation (x-rays and gamma radiation) are considered. Discharges artificially initiated (triggered) from natural thunderclouds using the rocket-and-wire technique are discussed with a view toward studying properties of natural lightning. Mechanism and parameters of compact intracloud discharges that are thought to be the most intense natural producers of HF-VHF radiation on Earth are reviewed. Every effort has been made to maintain a balance between completeness and an emphasis on the primary features of modern research.

The primary source of lightning is the cloud type termed cumulonimbus, commonly referred to as the thundercloud. Maximum electric fields typically measured in thunderclouds are 1 to 2 x 10^5 V/m (the highest measured value is 4 x 10^5 V/m), which is lower than the expected conventional breakdown field, of the order of 10^6 V/m. Two mechanisms of lightning initiation have been suggested. One relies on the emission of positive streamers from hydrometeors when the electric field exceeds 2.5 to 9.5 x 10^5 V/m, and the other involves high-energy cosmic-ray particles and the runaway breakdown that occurs in a critical field, assumed to be about 10^5 V/m at an altitude of 6 km. Either of these two mechanisms permits, in principle, creation of an ionized region ("lightning seed") in the cloud that is capable of locally enhancing the electric field at its extremities. Such field enhancement is likely to be the main process leading to the formation (via conventional breakdown) of a "hot", self-propagating lightning channel.

About 90% or more of global cloud-to-ground lightning is accounted for by negative (negative charge is effectively transported to the ground) downward (the initial process begins in the cloud and develops in the downward direction) lightning. Other types of cloud-to-ground lightning include positive downward, negative upward, and positive upward discharges. There are also bipolar lightning discharges sequentially transferring both positive and negative charges during the same flash.

The basic elements of the negative downward lightning discharge are termed component strokes or just strokes. Each flash typically contains 3 to 5 strokes, the observed range being 1 to 26. Roughly half of all lightning discharges to earth strike ground at more than one point with the spatial separation between the channel terminations being up to many kilometers. There are two major processes comprising a lightning stroke, the leader and the return stroke, which occur as a sequence with the leader preceding the return stroke.

The leader creates a conducting path between the cloud charge source region and ground and distributes negative charge from the cloud source region along this path, and the return stroke traverses that path moving from ground toward the cloud charge source region and neutralizes the negative leader charge. Thus, both leader and return stroke processes serve to effectively transport negative charge from the cloud to ground. The leader initiating the first return stroke differs from the leaders initiating subsequent strokes (all strokes other than first are termed subsequent strokes). In particular, the first-stroke leader appears optically to be an intermittent process, hence the term stepped leader, while the tip of a subsequent-stroke leader appears to move continuously. The continuously moving subsequent-stroke leader tip appears on streak photographs as a downward-moving "dart", hence the term dart leader. The apparent difference between the two types of leaders is related to the fact that the stepped leader develops in virgin air, while the dart leader follows the "pre-conditioned" path of the preceding stroke or strokes. Sometimes a subsequent leader exhibits stepping while propagating along a previously-formed channel; it is referred to as dart-stepped leader.

All types of leaders produce x-ray emissions with individual photon energies typically ranging from 30 to 250 keV (the latter being about twice the energy of a chest x-ray), although occasionally photons in the MeV range were observed. These emissions are associated with the descending leader tip and with the ground attachment process. It is likely that x-ray emissions from cloud-to-ground lightning leaders are associated with the so-called cold runaway (also known as thermal runaway) breakdown, in which very strong electric fields (>30 MV/m) cause the high-energy tail of the bulk free electron population to grow, allowing some electrons to runaway to high energies. Such very high fields may be present at streamer heads or leader tips.

When the descending stepped leader attaches to the ground, the first return stroke begins. The first return-stroke current measured at ground rises to an initial peak of about 30 kA in some microseconds and decays to half-peak value in some tens of microseconds. The return stroke effectively lowers to ground the several coulombs of charge originally deposited on the stepped-leader channel including all the branches, as well as any additional cloud charge that may enter the return-stroke channel.

Once the bottom of the dart leader channel is connected to the ground, the second (or any subsequent) return-stroke wave is launched upward, which again serves to neutralize the leader charge. The subsequent return-stroke current at ground typically rises to a peak value of 10 to 15 kA in less than a microsecond and decays to half-peak value in a few tens of microseconds.

The high-current return-stroke wave rapidly heats the channel to a peak temperature near or above 30,000^{o}K and creates a channel pressure of 10 atm or more, resulting in channel expansion, intense optical radiation, and an outward propagating shock wave that eventually becomes the thunder (sound wave) we hear at a distance.

The impulsive component of the current in a return stroke (usually subsequent) is often followed by a continuing current which has a magnitude of tens to hundreds of amperes and a duration up to hundreds of milliseconds. Continuing currents with a duration in excess of 40 ms are traditionally termed long continuing currents. Between 30% and 50% of all negative cloud-to-ground flashes contain long continuing currents. Current pulses superimposed on continuing currents, as well as the corresponding enhancements in luminosity of the lightning channel, are referred to as M-components.

Lightning discharges cause a variety of transient low-luminosity optical phenomena in the clear air between the cloud tops (at altitudes of near 20 km or less) and the lower ionosphere (near 60 to 90 km depending on the time of day). Six general types of such phenomena, collectively referred to as transient luminous events (TLEs), have been observed: red sprites, haloes, blue starters, blue jets, gigantic jets, and elves. They represent a mechanism for energy transfer from lightning and the thundercloud to the regions of the atmosphere between the cloud tops and the lower ionosphere.

There is a special type of lightning that is thought to be the most intense natural producer of HF-VHF (3 – 300 MHz) radiation on Earth. It is referred to as Compact Intracloud Lightning Discharge (CID). CIDs received their name due to their relatively small (hundreds of meters) spatial extent. They tend to occur at high altitudes (mostly above 10 km), appear to be associated with strong convection (however, even the strongest convection does not always produce CIDs), tend to produce less light than other types of lightning discharges, and produce single bipolar electric field pulses (Narrow Bipolar Pulses or NBPs) having typical full widths of 10 to 30 μs and amplitudes of the order of 10 V/m at 100 km, which is comparable to or higher than for return strokes in cloud-to-ground flashes.

Lightning can be artificially initiated (triggered) by launching of a small rocket trailing a thin grounded wire toward a charged cloud overhead. When the rocket, ascending at about 150 to 200 m/s, is about 200 to 300 m high, the field enhancement near the rocket tip launches a positively charged leader that propagates upward toward the cloud. This upward positive leader vaporizes the trailing wire, bridges the gap between the cloud and ground, and establishes an initial continuous current with a duration of some hundreds of milliseconds that transports negative charge from cloud charge source region to the triggering facility. After the cessation of the initial continuous current, one or more downward dart leader/upward return stroke sequences may traverse the same path to the triggering facility. The dart leaders and the following return strokes in triggered lightning are similar to dart leader/return stroke sequences in natural lightning, although the initial processes in natural downward and triggered lightning are distinctly different.

To date, approximately 1,000 lightning discharges have been triggered using the rocket-and-wire technique, with over 300 of them at Camp Blanding, Florida. The results of triggered-lightning experiments have provided considerable insight into natural lightning processes that would not have been possible from studies of natural lightning due to its random occurrence in space and time.