Chapter 15
Energetic Radiation and Lightning

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Abstract Until very recently, lightning was thought to be an entirely conventional discharge, involving only low-energy (a few eV) electrons. This picture changed with the discovery of intense x-ray emission from natural cloud-to-ground lightning, rocket-triggered lightning and thunderstorms. Indeed, the intensity of the x-rays generated by thunderstorms can be so large that bright bursts of these x-rays are observed from space, 600 km above the storms, as terrestrial gamma-ray flashes (TGFs). This energetic emission cannot be produced by conventional discharges in air, and so the presence of x-rays implies that runaway electrons, accelerated in air by strong electric fields, play a role in thunderstorm and lightning processes. In this chapter, an overview will be given of the x-ray observations of thunderstorms and lightning. In addition, the physics of runaway electrons will be presented, including some recent theoretical advances.

Keywords Lightning · Thunderstorms · X-rays · Energetic radiation · Atmospheric electricity

15.1 Introduction

15.1.1 Overview

Despite many reports of x-ray emission from thunderstorms and lightning made over the years (e.g., Shaw, 1967; Parks et al., 1981; McCarthy and Parks, 1985; D'Angelo, 1987; Suszcynsky et al., 1996; Eack et al., 1996; Brunetti et al., 2000 Chubenko et al., 2000), until recently, most researchers believed that lightning was an entirely conventional, albeit large, discharge that did not involve high-energy processes that might produce energetic radiation such as x-rays. Beginning in 2001,

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this view changed when Moore et al. (2001) showed that energetic radiation is produced during natural lightning and when Dwyer et al. (2003, 2004a) demonstrated that rocket-triggered lightning also produces large quantities of energetic radiation and that this radiation was predominantly made of hard x-rays. Because the only viable mechanism for explaining the x-ray emission from lightning is through the production of runaway electrons (Gurevich et al., 1992 Gurevich and Zybin, 2001), these x-ray measurements demonstrate that lightning is not just a conventional discharge. Runaway electrons are created when the electric force experienced by fast electrons is greater than the effective frictional force produced by the motion of the electrons through air, allowing the electrons to run away and gain large amounts of energy (Wilson, 1925). As the runaway electrons collide with air they copiously emit x-rays and gamma-rays via bremsstrahlung, the measurement of which can be used to infer properties of both the runaway electrons and the lightning that produced them.

15.1.2 Runaway Electron Production

The principle behind runaway electrons is illustrated in Fig. 15.1, which shows the effective frictional force and electric force experienced by an energetic electron moving through air at 1 atmosphere pressure. As can be seen, electrons with initial kinetic energies greater than K_{th} will gain more energy from the electric field than they lose from collisions with air and will run away. Such energetic seed electrons, with $K > K_{th}$, are readily supplied by the interaction of atmospheric cosmic-rays

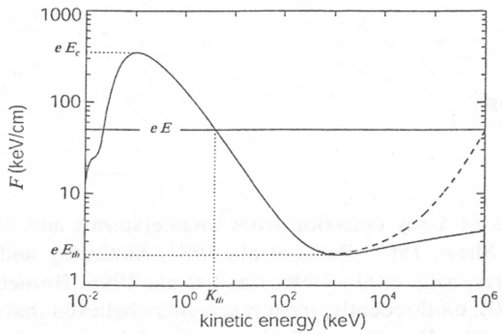

Fig. 15.1 The effective frictional force experienced by a free electron moving through air at STP as a function of kinetic energy. The *solid curve* is due to inelastic scattering of the electron with air atoms, and the *dashed curve* includes the effects of bremsstrahlung emission. The *horizontal line* shows the electric force from a 5000 kV/m electric field. Runaway electrons occur for kinetic energies greater than the threshold energy, $K > K_{th}$. E_c is the critical electric field strength, for which low-energy free-electrons will also run away, and E_{th} is the minimum field needed to produce runaway electrons. The figure is from Dwyer (2004)

with the atmospheric constituents. Once an electron runs away, it will collide with air atoms producing energetic "knock-on" electrons with $K > K_{th}$. These secondary electrons may also run away, resulting in an avalanche of relativistic electrons that grow exponentially with time and distance as long as the electric field $E > E_{th}$. This way of generating runaway electrons is called the Relativistic Runaway Electron Avalanche (RREA) mechanism, sometimes referred to as "runaway breakdown."

For sufficiently strong electric fields, $E \geq E_c$, a large number of low-energy electrons, from the bulk free-electron population, will gain energy and run away without the need for externally supplied seed particles, *e.g.* from cosmic-rays. This mechanism is called the cold runaway electron mechanism (Gurevich, 1961; Dwyer, 2004; Moss et al., 2006). A third source of energetic seed particles comes from a positive feedback effect involving backward propagating x-rays and positrons, called the relativistic feedback mechanism (Dwyer, 2003, 2007), which is discussed in Section 15.3.4. An advantage of the relativistic feedback mechanism is that it works for relatively low electric fields ($E_{th} < E < E_c$) and allows the discharge to become self-sustaining, without the need for an external source of energetic particles.

15.1.3 Lightning Initiation

The physics of lightning initiation remain poorly understood despite many decades of research on the topic (Rakov and Uman, 2003). It is currently thought that in order to form a lightning leader, at someplace in the thundercloud, the electric field must reach a large enough value for conventional breakdown to occur. In dry air at sea-level the conventional breakdown threshold, E_b, is about 2.6×10^6 V/m (Raether, 1964). When precipitation is present, this threshold is reduced to about $1.0–1.4 \times 10^6$ V/m, depending upon the size and shape of the precipitants (Solomon, Schroeder and Baker, 2001; Cooray, 2003). However, decades of in situ electric field measurements have failed to find electric field strengths near the conventional breakdown threshold, even when the effects of precipitation are included (MacGorman and Rust, 1998). On the other hand, the thunderstorm electric fields are often observed to exceed the threshold field to create runaway electron avalanches, E_{th}(Marshall and Rust, 1991; Marshall et al., 2005), opening the possibility that runaway electrons play some role in lightning initiation. For instance, Gurevich et al. (1999) suggested that the RREA mechanism acting on extensive cosmic-ray air showers could produce enough ionization to initiate lightning. On the other hand, Dwyer (2005) suggested that runaway electron avalanches produced by the ambient cosmic-ray background, with a possible contribution from relativistic feedback, could locally enhance the electric field to the point where lightning initiates. Unfortunately, not all of the details of these models have been worked out. In particular, it is still not clear how the relatively diffuse discharge created by the runaway electrons can result in a hot lightning leader channel, measuring just centimeters across. As a result, it remains an open question whether or not runaway electrons are important for lightning initiation.

15.2 X-ray and Gamma-Ray Observations

15.2.1 Observations of x-rays from Rocket-Triggered Lightning

In 2003, Dwyer et al. reported the measurement of intense bursts of energetic radiation from rocket-triggered lightning (Dwyer et al., 2003). These results, which were later confirmed and expanded upon by Dwyer et al. (2004a), were significant because they allowed, for the first time, detailed and repeatable investigations of the x-ray emissions from lightning. An example of the x-ray observations of triggered lightning is presented in Fig. 15.2, from Dwyer et al. (2004a), which shows the response of a NaI(Tl)/photomultiplier tube (PMT) detector. The detector was housed in a heavy aluminum box, designed to keep out RF noise, moisture and light. Because the instrument was required to operate in the close vicinity of lightning, no conducting power or data cables entered or exited the box. The detector and electronics were internally powered by a 12 V battery, and switched on and off using fiber optics. Fiber optics were used to transmit the anode signal from the PMT to a shielded trailer, where the waveform was digitized and recorded. For this observation, the instrument was located 40 m from the triggered lightning channel at the University of Florida/Florida Tech International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. The ICLRT is a well instrumented

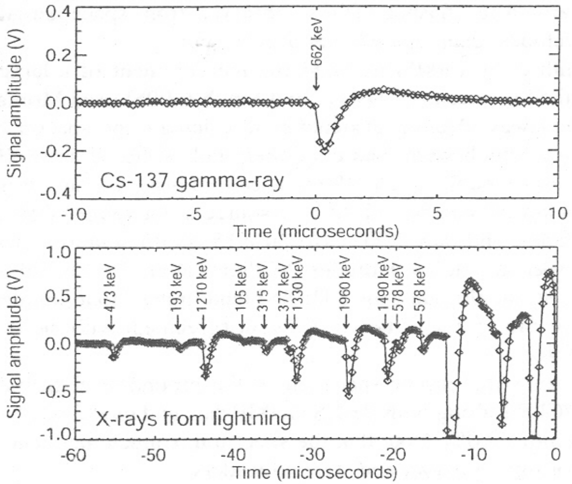

Fig. 15.2 *Top panel:* waveform from one of the NaI(Tl)/PMT detectors for a single 662 keV gamma-ray from a Cs-137 radioactive source placed temporarily on top of the instrument. The *diamonds* show the data as recorded by the acquisition system, and the *solid line* shows the detector response as calculated from the NaI decay-time and the RC-times in the front end electronics. *Bottom panel:* waveform for a time period just prior to a return stroke (at $t = 0$) of triggered lightning. The detector response (*solid line*) is plotted over the measured data (*diamonds*). The *arrows* indicate the times and deposited energies of the energetic radiation. The figure is from Dwyer et al. (2004a)

facility capable of measuring electric currents, electric and magnetic fields and optical emission (Jerauld et al., 2003).

To illustrate the response of the instrument to x-rays, the top panel of the figure shows the signal from one 662 keV gamma-ray from a Cs-137 radioactive source placed temporarily on top of the instrument. The solid black curve shows the fit of the response function as derived from the electronics and the 0.23 μs NaI decay-time. The bottom panel of Fig. 15.2 shows x-rays from a stroke of rocket-triggered lightning measured during the dart leader phase. In the figure, the return stroke occurred to the right at time $t = 0$. The solid black curve is the fit of the response functions with the x-ray's deposited energies and times indicated by the arrows. The background rate during this time period was measured to be 120 counts/s for energies above 100 keV, making the odds that even one very small pulse in the 60 μs time window shown in Fig. 15.2 was due to background at less than 1 in 100. As can be seen, some of the pulses have rather large deposited energies, more in line with the energies of gamma-ray photons. However, by operating several detectors simultaneously and placing bronze and lead attenuators of varying thicknesses over the scintillators and PMTs, it was found by Dwyer et al. (2004a) that the pulses are not usually individual gamma-rays but were instead composed of fast bursts of x-rays, mostly in the 30–250 keV range, although occasionally individual x-rays in the MeV range are observed. Using bronze collimators, the x-rays were also observed to be spatially and temporally associated with the dart leaders and possibly the beginning of the return strokes.

15.2.2 Observation of X-rays from Natural Cloud-to-Ground Lightning

During the summers of 2004 and 2005, a total of 9 natural cloud-to-ground lightning flashes, all of which lowered negative charge to the ground, struck the ICLRT or its immediate vicinity, with significant x-ray emission measured. Figure 15.3, from Dwyer et al. (2005a), shows data for a natural lightning flash on 24 August 2004, for the stepped leader phase just prior to the first return stroke. The bottom panel is the electric field changes produced by the stepped leader as it propagates to the ground. The individual steps appear as sudden drops in the electric field waveform, caused by the leader bringing negative charge closer to the ground. The top panels show the x-ray waveforms from a NaI/PMT x-ray detector, similar to that described above. As can be seen, the x-ray pulses are very closely associated with the leader steps. This is significant because the stepped leader process determines how and where lightning propagates, and, as this figure illustrates, runaway electrons are being produced during the step formation.

The x-ray emission from natural lightning stepped leaders is remarkably similar to the x-ray emission from triggered lightning dart leaders, implying that both the dart leader and stepped leader x-ray emission share a similar production mechanism. Since nearly all dart leaders emit similar x-rays, this implies that nearly all dart leaders in fact involve stepping to some degree, but that the steps are so short that

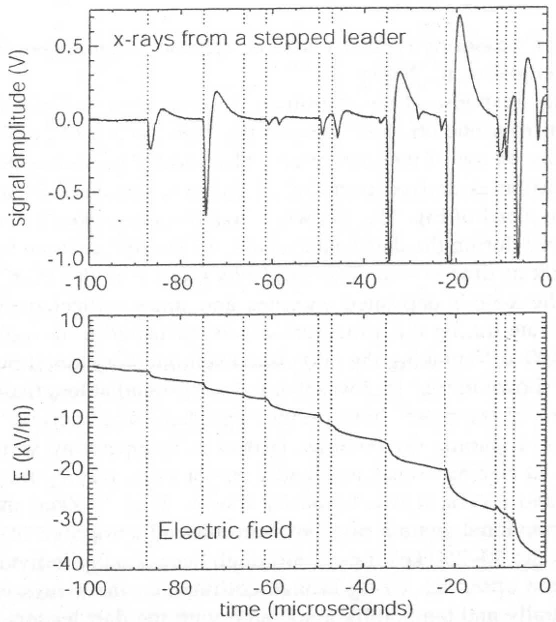

Fig. 15.3 X-rays (*top panel*) and electric field (integrated *dE/dt*) waveforms (*bottom panel*) for a natural cloud-to-ground lightning flash. The lightning struck within 50 m of the electric field antenna and about 260 m from the x-ray detector. Time zero in the plot corresponds to the beginning of the return stroke. The start times of the steps are denoted by vertical *dotted lines*. The figure illustrates that the x-ray pulses occur during the formation of the stepped-leader steps, and, therefore, the x-ray emission is related to the stepping process, which determines where lightning will go and how it branches. The Figure is taken from Dwyer et al. (2005a)

they are usually not resolved in optical records. Consequently, it may be possible to unify the different kinds of negative leaders observed in nature, which may appear optically different depending on the conditions along their propagation path (Rakov and Uman, 2003), into one basic type, with one underlying mechanism for propagation. Moreover, because x-ray emission is observed from nearly all lightning, triggered and natural, that strikes within a hundred meters or so of the detectors, x-ray emission and hence runaway electrons commonly occur in most lightning. As a result, successful models of lightning must also explain how this high-energy emission occurs.

15.2.3 Observation of Gamma-Ray Flashes from Thunderclouds

In addition to x-ray emission from lightning, Dwyer et al. (2004b) reported the observation of an intense gamma-ray flash observed on the ground at sea level,

produced in association with the initial-stage of rocket-triggered lightning at the ICLRT. The flash, which lasted about 300 μsec, was observed simultaneously on three NaI(Tl)/PMT detectors that were located 650 m from the triggered lightning channel with gamma-ray energies extending up to more than 10 MeV. The beginning of the gamma-ray flash occurred at about the same time as the upward propagating positive leader, initiated from the top of the rocket and extended triggering wire, would have reached the overhead cloud charge at 6–8 km above the ground. It is possible that when the leader reached this charge, an intense discharge was initiated, producing runaway electrons and the accompanying gamma-rays. The gamma-ray flash, therefore, may represent a new kind of event, different from the leader emission.

If the gamma-rays were indeed produced at a height of 6–8 km above the ground, atmospheric attenuation would greatly reduce the gamma-ray intensity on the ground. Interestingly, the amount of atmosphere above 6 km is about the same as the amount below that altitude, raising the possibility that similar gamma-ray events, directed upwards, might also be observable from space, since the attenuation of the gamma-rays in the upward and downward directions would be the same. Indeed, intense gamma-ray flashes have been reported using BATSE data from the Compton Gamma Ray Observatory (CGRO) (Fishman et al., 1994). These flashes were originally inferred to be associated with high-altitude discharges such as red-sprites (Nemiroff, Bonnell, and Norris, 1997), largely because of their correlation with thunderstorms and lightning (Inan et al., 1996). It is an intriguing possibility that terrestrial gamma-ray flashes (TGFs) observed from space actually originate from the thunderclouds, deep in the lower atmosphere.

Recently, Smith et al. (2005) reported the measurement of a large number of TGFs by the RHESSI spacecraft. Dwyer and Smith (2005) used Monte Carlo simulations of the runaway electron avalanches to calculate the spectra of terrestrial gamma-ray flashes, which were then compared with RHESSI and CGRO/BATSE observations. It was found that the RHESSI spectrum is not consistent with a source altitude above 24 km but can be well fit by a source in the range of 15–21 km (also see Carlson, Lehtinen, and Inan, 2007). Because 15 km is not unusual for the tops of thunderstorms, especially at low latitudes (Williams et al., 2005), and is lower than typical minimum sprite altitudes, the RHESSI data implies that thunderstorms and not sprites may be the source of these TGFs, in agreement with the suggestion by Dwyer et al. (2004b).

Figure 15.4 shows the energy spectrum of the ground-level gamma-ray event measured at the ICLRT along with RHESSI TGF data and model results as reported by Dwyer and Smith (2005). Note that the spectrum is much harder than the spectrum measured for lightning dart and stepped leaders.

Last year, Tsuchiya et al. (2007) reported gamma-ray emission from winter thunderstorms in Japan that lasted up to 40 s and had energies up to 10 MeV. The duration of this emission is substantially longer than the millisecond long emission observed from lightning and terrestrial gamma-ray flashes. The timescale observed is more reminiscent of the in situ x-ray enhancements observed of Eack et al. (1996), which lasted about 1 min and those observed by McCarthy and Parks (1985) and

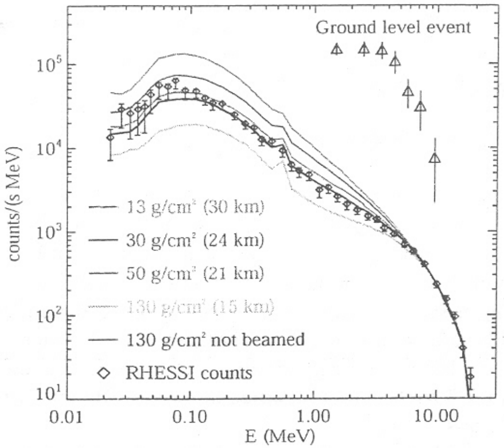

Fig. 15.4 Energy spectrum of the gamma-ray flash observed on the ground at the ICLRT as compared to the terrestrial gamma-ray flash (TGF) spectrum as measured from space by RHESSI (Dwyer and Smith, 2005). The *solid curves* are the x-ray emission spectra, corrected for the instrumental response, as calculated by the Monte Carlo simulation of runaway breakdown at four atmospheric depths. An atmospheric depth of 13 g/cm^2 corresponds to an altitude of 30 km, 30 g/cm^2 corresponds to 24 km, 50 km g/cm^2 corresponds to 21 km, and 130 g/cm^2 corresponds to 15 km. For four of these spectra, the runaway breakdown is assumed to be beamed along the vertical direction. Also shown is the spectrum for a source at 15 km but for runaway breakdown that is isotropic in the upper cone with a half width of 45° (labeled non-beamed)

Parks et al. (1981), which lasted for up to 20 s. These observations may indicate that the RREA mechanism, acting on the cosmic-ray background, is taking place in the regions of the thunderstorms with large electric fields, $E > E_{\rm th}$. At this time, it is still not clear how these results are related to TGFs or the ground level gamma-ray event discussed above.

15.2.4 X-rays from Laboratory Sparks

Until recently it was generally believed that electrical discharges in air involved only low-energy electrons having energies of at most a few tens of eV (Raether, 1964; Bazelyan and Raizer, 1998). The recent and surprising discovery that both natural and triggered lightning discharges emit x-rays, demonstrated that some kinds of discharges in air produce high-energy electrons traveling close to the speed of light and having energies of at least hundreds of keV and sometimes up to tens of MeV. Initially, the x-ray observations of lightning seemed to support the generally-accepted notion that lightning was different from laboratory sparks, the latter being assumed to involve only conventional breakdown and not runaway electrons as with lightning.

In 2005, Dwyer et al. reported the x-ray observations of long high-voltage laboratory sparks in air that demonstrate that these laboratory discharges do indeed produce x-rays similar to the x-ray emission seen from lightning (Dwyer et al., 2005b). These results imply that runaway electrons are also occurring in these relatively small high-voltage sparks and, hence, that such sparks are more than just a conventional breakdown. This finding implies that the physics used for decades to describe discharges in air may be inadequate, even for relatively small sparks.

X-ray observations were made during fourteen 1.5–2.0 m high-voltage discharges in air at 1 atmosphere pressure produced by a 1.5 MV Marx circuit at Lightning Technologies Inc. in Pittsfield, MA. All 14 discharges generated x-rays in the ~30–150 keV range. The x-rays, which arrived in discrete bursts, less than 0.5 microseconds in duration, occurred from both positive and negative polarity rod-to-plane discharges as well as from small, 5–10 cm series spark gaps within the Marx generator. Figure 15.5 shows examples of this x-ray emission, which is

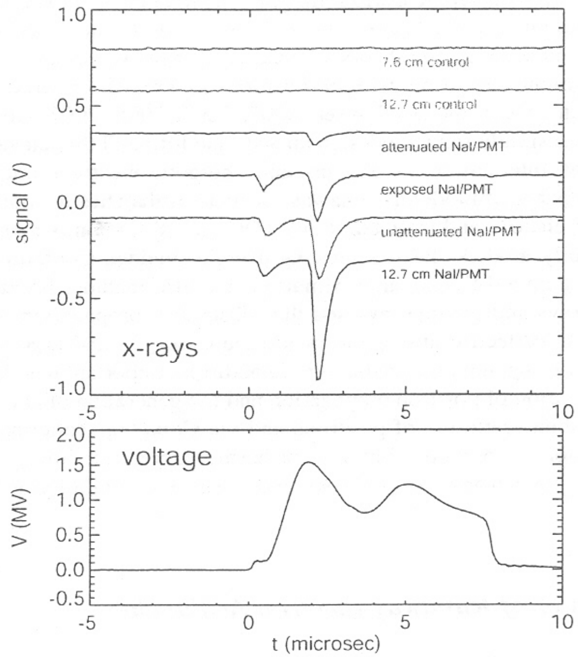

Fig. 15.5 X-ray waveforms from 4 NaI/PMT detectors and two control detectors (with no NaI) plus the gap potential for a 1.5 MV spark. A change in pulse size of –0.25 V corresponds to a deposited energy of 662 keV in all detectors. In the upper panel, from top to bottom, respectively, the signals are from the two control detectors (no NaI), an attenuated detector (0.32 cm thick bronze cap), a detector covered by a wire mesh, and two un-attenuated detectors (no bronze cap). The bottom panel shows the gap voltage, measured with a resistive divider. The figure is from Dwyer et al. (2005b)

remarkably similar to the x-ray bursts previously observed from lightning. The figures were taken from Dwyer et al. (2005b). These results have now been verified by Rahman et al. (2008), using a 1 MV Marx generator at Uppsala University, Sweden. The discovery of x-rays from laboratory sparks opens up the possibility of using laboratory sparks to study the poorly understood phenomenon of runaway electron production by lightning.

15.3 Theory and Modeling

15.3.1 Runaway Electron Simulations

Because the interactions of high-energy electrons and photons with air are well understood and simple to calculate, Monte Carlo codes, in which individual particle trajectories and interactions are simulated, are particularly useful for studying runaway electrons. One such Monte Carlo simulation, developed over the last 7 years at Florida Tech, shall be described here. This 3-D (plus time) Monte Carlo simulation has been used to investigate the theory of relativistic runaway electron avalanche (RREA) development and to model specific runaway breakdown processes, with results reported in several papers (Dwyer, 2003, 2004, 2005, 2007; Coleman and Dwyer, 2006). The simulation includes, in an accurate form, all the relevant physics for describing the interactions of photons and energetic electrons and positrons with air and is capable of modeling runaway electron avalanches for both spatially and time varying electric and magnetic fields (Dwyer, 2003). Unlike earlier work, this simulation fully models elastic scattering using a shielded-Coulomb potential, rather than relying on a diffusion approximation, and also includes bremsstrahlung production of x-rays and gamma-rays and the subsequent propagation of the photons, including photoelectric absorption in nitrogen, oxygen and argon, Rayleigh and Compton scattering and pair production. In addition, important new features include the incorporation of positron propagation and the generation of energetic seed electrons via Bhabha scattering of positrons and via Compton scattering and photoelectric absorption of energetic photons. Furthermore, bremsstrahlung production from all secondary electrons and positrons and positron annihilation gamma-rays are included.

15.3.2 Properties of Runaway Electron Avalanches

As relativistic runaway electrons propagate through air in an electric field with $E > E_{\text{th}}$, an avalanche of runaway electrons develops. The number of runaway electrons, produced by N_{o} energetic seed electrons, is given by

$$N_{RE} = N_o \exp\left(\int_0^L \frac{dz}{\lambda(z)}\right) \tag{15.1}$$

where L is the length of the electric field region, and λ is the characteristic length for an avalanche to develop. This avalanche length, λ, is found by the Monte Carlo simulations (Dwyer, 2003; Coleman and Dwyer, 2006) to be well fit (300 kV/m)$n \leq E \leq$ (3000 kV/m)n, by the empirical formula

$$\lambda(z) = 7300\text{kV}[E(z) - (276\text{kV/m})n]^{-1}, \tag{15.2}$$

where n is the density of air relative to that at STP. The Monte Carlo simulation also shows that when elastic scattering is included, the threshold for runaway electron avalanche development is E_{th} = (284 kV/m)n, slightly higher than the value shown in Fig. 15.1, which only includes the effects of inelastic scattering. For $E <$ (300 kV/m)n, the length-scale needed to produce substantial numbers of runaway electrons is several kilometers, too long to be applicable for thunderstorms and lightning. Simulations show that the average kinetic energy for the runaway electrons in the avalanche is about 7.3 MeV, which justifies the use of the term relativistic in the names of the mechanisms.

From Eqs. (15.1) and (15.2), an upper limit on the number of runaway electrons is given by

$$N_{RE} \leq N_o \exp(V/7.3\text{MV}), \tag{15.3}$$

where V is the total voltage drop in the avalanche region. The upper limit in Eq. (15.3) is very robust, and is independent of the air density and the spatial variation of the electric field.

15.3.3 Modeling Lightning Leader Emission

For negative cloud-to-ground lightning, the electric potential of the dart leader is roughly 15 MV (Rakov and Uman, 2003). Plugging 15 MV into Eq. (15.3) gives $N_{\text{RE}} \leq 8N_{\text{o}}$, indicating that very little avalanche multiplication is likely to occur for lightning dart leaders. This presents a big problem for the RREA model to explain the observed x-ray emission from lightning, since more than 10^{12} x-ray per m^2 per second were estimated by Dwyer et al., 2004a to be emitted by the dart leader during the last 10 microseconds or so. The number of runaway electrons that produce those x-rays is likely to be much larger. Considering that the atmospheric cosmic-ray flux is only about 200 m^{-1} s^{-1} at sea level, an avalanche multiplication factor of 8, as estimated above, is many orders of magnitude too small to account for the large fluxes of x-ray observed (Dwyer, 2004). A more dramatic problem occurs for the x-ray observation from laboratory sparks. In this case, the maximum voltage produced by the Marx generator was only 1.5 MV, resulting in almost no runaway electron avalanche multiplication as described by the RREA model.

It should be stressed that the x-ray emission from lightning cannot result from the thermal radiation of lightning, since even the maximum temperature of lightning (30,000 K during the return stroke) is many orders of magnitude too cold to account for the hard x-ray energies (>100 keV) observed. The production of runaway electrons in air is still the only viable mechanism for explaining the x-ray emission, which then leads to the question of the origin of the seed particles that run away, the cosmic-ray and natural background fluxes being too small to account for the observations. As described above, an alternative is the so-called cold runaway electron mechanism, for which very large electric fields $E > E_c$ are required. This mechanism allows the high-energy tail of the bulk free electron population to run away, possibly with some additional energy gain from regions where the electric fields remain above E_{th}. It is possible that such large electric fields, $E > E_c$, are briefly generated at the tips of streamers or possibly by leaders. If so, then the electric field produced by streamers is at times larger than previously inferred (Bazelyan and Raizer, 1998). Once the mechanisms for producing the runaway electron are understood it may be possible to use the x-ray measurements to determine the electric field strengths produced by breakdown process, measurements that would be very difficult to carry out otherwise.

15.3.4 Positron and x-ray Feedback

In 2003, Dwyer presented a new runaway breakdown mechanism in which x-rays and positrons generate a positive feedback effect that greatly increases the flux of runaway electrons and x-rays (Dwyer, 2003). This mechanism is illustrated in Fig. 15.6, from Dwyer (2003), which shows partial results of the Monte Carlo simulation described above. In the figure, one high-energy (1 MeV) seed electron is injected at the top center of the region containing a uniform electric field. This

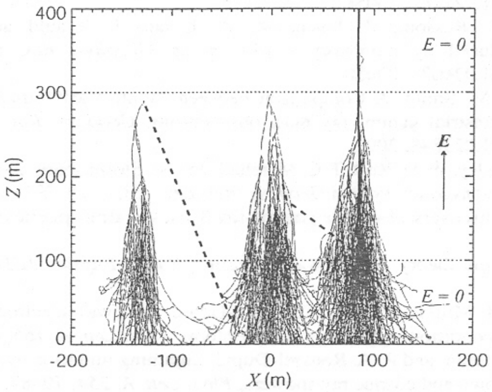

Fig. 15.6 Partial results of the Monte Carlo simulation showing the runaway breakdown of air. The light tracks are the runaway electrons, the *dashed lines* are the x-rays and the dark track is a positron. The entire avalanche is initiated by One, 1 MeV, seed electron injected at the top center of the volume. The *horizontal dotted lines* show the boundaries of the electric field volume ($E =$ 1000 kV/m). For clarity, only a small fraction of the runaway electrons and x-rays (gamma-rays) produced by the avalanche are plotted

electron runs away, producing an avalanche of relativistic electrons (light tracks). Bremsstrahlung x-rays (dashed lines) are produced when the runaway electrons collide with air. The x-ray (or gamma-ray) on the right side of the figure produces a positron (dark trajectory on right) via pair production. This positron runs away, traveling to the top of the figure and producing more runaway electrons via hard elastic scattering, resulting in the secondary avalanche on the right. The x-ray on the left side of the figure Compton scatters to the top and produces another seed electron via the photoelectric effect (shown) or via Compton scattering. This seed electron then runs away producing the secondary avalanche on the left. These secondary avalanches, in turn, produce more feedback electrons via the two mechanisms described above, allowing the whole process to increase exponentially.

The avalanches on the left and right illustrate the x-ray feedback and positron feedback mechanisms, respectively. The positive feedback effect from the backward propagating positrons and the back scattered x-rays allow the discharge to become self-sustaining. As the number of runaway electrons increases exponentially with time, the large increase in conductivity will necessarily result in the collapse of the electric field. As a result, unlike the RREA mechanism (*i.e.* so called runaway breakdown), which depends upon an external source of energetic seed electrons, the relativistic feedback mechanism is a true electrical breakdown. Moreover, Dwyer (2003) showed that the relativistic feedback mechanism places a severe limit on the maximum electric field achievable in air, a limit which may be relevant to thunderstorm electrification (also see Babich et al., 2005). In addition, Dwyer (2007) showed that in some cases feedback can increase the flux of runaway electrons and the x-rays they produce by a factor of a 10^{13} over the standard RREA mechanism alone, making this mechanism a good candidate for explaining the ground-level gamma-ray flash and terrestrial gamma-ray flashes, both of which infer large intensities of runaway electrons at the source. However, it is not clear if relativistic feedback plays any role in the runaway electron production associated with lightning leaders, since like the RREA mechanism, relativistic feedback requires sizeable potential differences, more than several tens of MV.

15.4 Conclusions

15.4.1 Open Questions Regarding the X-ray Emission from Lightning

While great progress has been made in recent years measuring properties of the x-ray emission from lightning, a large number of questions remain. The following are just a few questions that may help direct future work:

1. What are the specific runaway electron mechanism(s) involved in the production of x-rays from lightning stepped-leaders, dart leaders and return strokes?
2. Exactly when and where are the x-rays produced?
3. How are the runaway electrons and the x-rays related to the stepping process? Are runaway electrons important for lightning propagation?

4. Are the x-rays from dart leaders related to stepping? Since nearly all dart leaders make x-rays, does this imply that nearly all dart leaders step?
5. What are the properties of the x-rays produced by the return stroke?
6. How does x-ray emission depend upon other observable properties of lightning such as leader speed, electric field strengths, return stroke currents, etc.?
7. How does the x-ray emission change with altitude and distance from the ground?
8. Do runaway electrons play a role in lightning initiation?
9. How and where do TGFs occur and how are they related to the observed long duration x-ray emission?

15.4.2 The Next Step

Starting in 2007, a total of 24 x-ray instruments, making up the Thunderstorm Energetic Radiation Array (TERA), are now operating at the UF/Florida Tech International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL. This array allows a more complete picture to be obtained of the x-ray emission from lightning, allowing us to study the energy spectra and the spatial and temporal properties of the emission. It is also a significant improvement for studying natural lightning, since the detectors now cover a much larger area than before. Such measurements should help us better understand the runaway electron mechanisms involved in lightning propagation and should provide new insight into the physical processes involved in the leader stepping.

15.4.3 Summary

The last few years have been an exciting time for lightning research with several new high-energy phenomena associated with thunderstorms and lightning being discovered. We are learning that many of the established ideas about how lightning and laboratory sparks work are not complete and that more work is needed. We have now firmly established that high-energy electrons and their accompanying x-ray and gamma-ray emission are routinely produced by thunderstorms and lightning in our atmosphere. We have made theoretical progress understanding this emission, but it is my expectation that most of the important work in this exciting field still remains to be done.

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Chapter 16
Schumann Resonance Signatures of Global Lightning Activity

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Abstract This chapter is concerned with the Earth's Schumann resonances (SR) and their application to understanding global lightning. The natural electromagnetic waves in the SR frequency range (5 Hz to approx. 60 Hz) radiated by lightning discharges are contained by the Earth-ionosphere cavity. This cavity excitation by lightning can occur as a single energetic flash (a 'Q-burst'), or as an integration of a large number of less energetic flashes (the 'background' resonances). In principle, continuous observations of SR parameters (modal amplitudes, frequencies, and quality factors) provide invaluable information for monitoring the worldwide lightning activity from a single SR station. Relationships between the variation of SR intensity and global lightning activity are shown. Connections between the change of diurnal modal SR frequency range and the areal variation of worldwide lightning are demonstrated. The temporal variation of the diurnal SR frequency patterns characteristic of the global lightning dynamics is also presented. Distortions of ELF waves propagating between the lightning sources and the observer are theoretically discussed based on the TDTE (two-dimensional telegraph equation) technique, focusing on the role of the day-night asymmetry of the Earth-ionosphere cavity. Theoretical and observational results are compared. Both instruments for SR observations and spectral methods for deducing SR parameters are reviewed. Experimental findings by SR on global lightning variations on different time scales (diurnal, seasonal, intraseasonal, annual, semiannual, interannual, 5-day, long-term) are summarized. The growing use of SR measurements as a natural diagnostic for global climate change is emphasized.

Keywords Schumann resonance · ELF · Global lightning · Earth-ionosphere cavity · Day-night asymmetry · Q-burst · Charge moment · Tropical chimneys · Climate

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