Runaway breakdown and electrical discharges in thunderstorms

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[1] This review considers the precise role played by runaway breakdown (RB) in the initiation and development of lightning discharges. RB remains a fundamental research topic under intense investigation. The question of how lightning is initiated and subsequently evolves in the thunderstorm environment rests in part on a fundamental understanding of RB and cosmic rays and the potential coupling to thermal runaway (as a seed to RB) and conventional breakdown (as a source of thermal runaways). In this paper, we describe the basic mechanism of RB and the conditions required to initiate an observable avalanche. Feedback processes that fundamentally enhance RB are discussed, as are both conventional breakdown and thermal runaway. Observations that provide clear evidence for the presence of energetic particles in thunderstorms/lightning include γ-ray and X-ray flux intensifications over thunderstorms, γ-ray and X-ray bursts in conjunction with stepped leaders, terrestrial γ-ray flashes, and neutron production by lightning. Intense radio impulses termed narrow bipolar pulses (or NBPs) provide indirect evidence for RB particularly when measured in association with cosmic ray showers. Our present understanding of these phenomena and their enduring enigmatic character are touched upon briefly.

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1. Predecessors of Runaway Breakdown

[2] The many interesting things that happen when an electric field is applied across a gas have occupied the attention of physicists for more than a century since 1900 when Townsend discovered the laws governing ionization and the gaseous discharge in a uniform electric field. These studies have led to such fundamental discoveries as cathode rays and X-rays, the fundamental properties of electrons and atoms, and optical and mass spectrometry. Gas discharge phenomena are now thought of as part of the field of plasma physics [*MacDonald*, 1967; *Brown*, 1959; *Gurevich et al.*, 1997b].

[3] An avalanche breakdown in gases occurs when a large electric field accelerates free electrons to energies high enough to cause ionization during collisions with atoms. The number of free electrons is thus increased rapidly as newly generated particles become part of the process. The conditions at which the gas "breaks down" or at which sparking begins was naturally studied early and extensively, and such studies have occupied a central place in gas discharge phenomena over the years. However, a new type of breakdown which plays an important role in thunderstorms was discovered only recently [*Gurevich et al.*, 1992]. This process is triggered by seed relativistic electrons that can multiply rapidly in an applied electric field while at the same time freeing large number of low-energy electrons, hence the term runaway breakdown (RB), and it requires a break even field an order of magnitude less than that needed to initiate conventional breakdown. The purpose of this paper is to describe the known properties of RB along with its manifestation in the atmosphere. Before discussing the physics of RB, we describe its predecessors, those studies that ultimately led to the discovery of RB.

[4] Let us first discuss conventional air breakdown from the standpoint of kinetic theory. When an electric field is applied to air having some seed electrons their distribution function changes from a Boltzmann distribution to that having a plateau and high-energy tail as shown in Figure 1a. These distributions are computed for different intensities of the applied electric field. The higher the field intensity, the smaller is the lower energy boundary of the tail. Electrons with energy greater than the oxygen ionization threshold at approximately 12.2 eV are involved in the avalanche breakdown. However, a competition exists between ionization and dissociative attachment of electrons to molecular oxygen. The cross sections of these processes are shown in Figure 1b. Attachment has a relatively low cross section, although it peaks at a low energy of 5.2 eV. The rates of ionization and attachment equate at $E = E_{\mathrm{th}}$, where E_{th} = 3 MV/m is the threshold field of air breakdown at standard temperature and pressure (STP).

[5] Consider now what happens if the external electric field significantly exceeds the breakdown threshold. As shown by experiments in tokomaks [*Sharma and Jayakumar*, 1988] it

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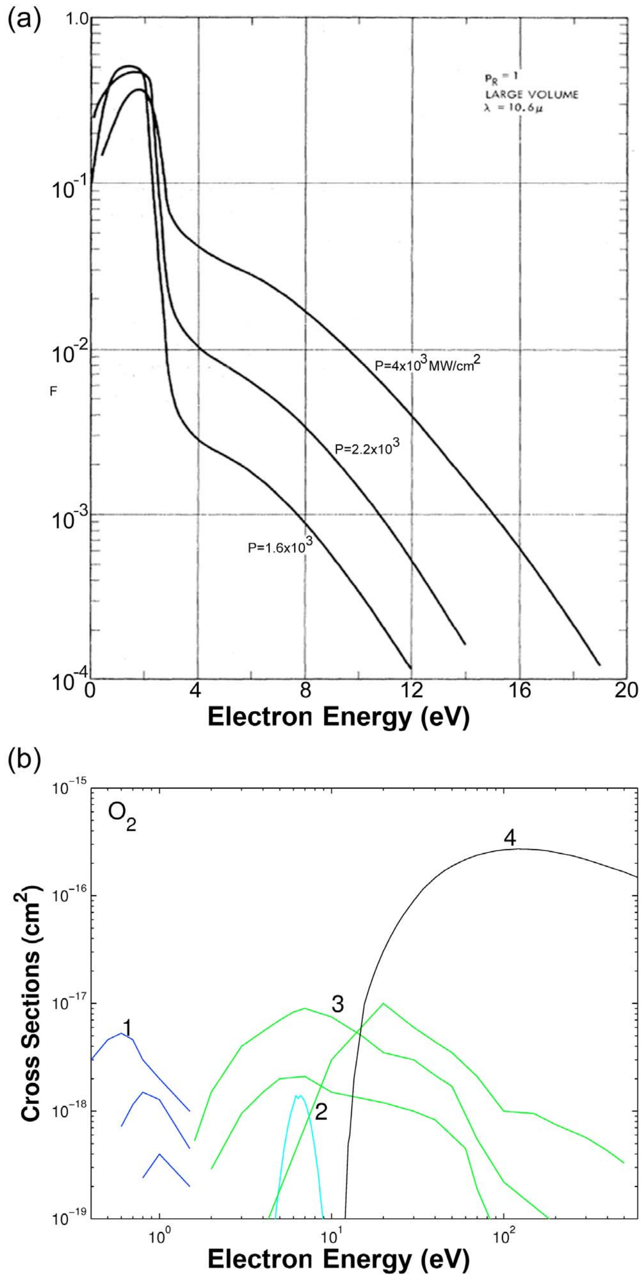

Figure 1. (a) The electron distribution functions in air computed for three different values of incident power density [adapted from *Kroll and Watson*, 1972]. (b) Cross-section for inelastic collisions of electrons with molecular oxygen [adapted from *Tsang et al.*, 1991]: trace 1, the excitation of the vibrational levels, trace 2, dissociative attachment; trace 3, excitation of electronic levels; trace 4, the ionization cross section.

can lead to thermal runaway when the accelerated plasma hits the facility walls. The concept of electron runaway acceleration in the presence of a uniform, steady electric field was developed by *Gurevich* [1961], *Dreicer* [1960], and *Lebedev* [1965]. The runaway phenomenon is a consequence of the long range, small angle scattering among charged particles undergoing Coulomb interactions. The scattering cross section decreases with velocity as $\sigma_{tr} \sim 1/v^4$. As a result, for a given electric field value the threshold energy can be found beyond which the dynamical friction cannot balance the acceleration force due to the electric field, resulting in continuous electron acceleration.

[6] In the weakly ionized plasma an important role is played by the electron-neutral collisions. Thus the cold electrons undergo the dynamical friction force, the latter playing a fundamental role in breakdown studies,

$$F = m\nu_{en}\, \mathrm{v}, \tag{1}$$

where ν_{en} is the electron-neutral collision frequency. The friction force is shown as the trace 1 in Figure 2 as a function of the electron kinetic energy, where it increases with ε. However, at high-electron velocity, when the electron energy exceeds the ionization potential ($\varepsilon > \varepsilon_i$), the interactions of the fast electrons with the nuclei and atomic electrons obey the Coulomb law. Correspondingly the dynamical friction force decreases with the electron energy [*Bethe and Ashkin*, 1953],

$$F = m\nu(v)v = \frac{4\pi e^4 n}{mv^2} \ln \Lambda, \tag{2}$$

where n is the electron density and $\ln\Lambda$ is the Coulomb logarithm. This force is shown as trace 2 in Figure 2. *Gurevich* [1961] first introduced the critical electric field for thermal runaway. Its value is

$$E_{cn} = \frac{4\pi e^3\ ZN_m}{\varepsilon_i} k_n, \tag{3}$$

here N_m is the density of the neutral molecules and Z is the mean molecular charge, which for air is 14.5, and k_n is the numerical factor, determined by the type of the neutral gas. In fact, for hydrogen, $k_n \sim 0.33$, and for helium, $k_n \sim 0.30$.

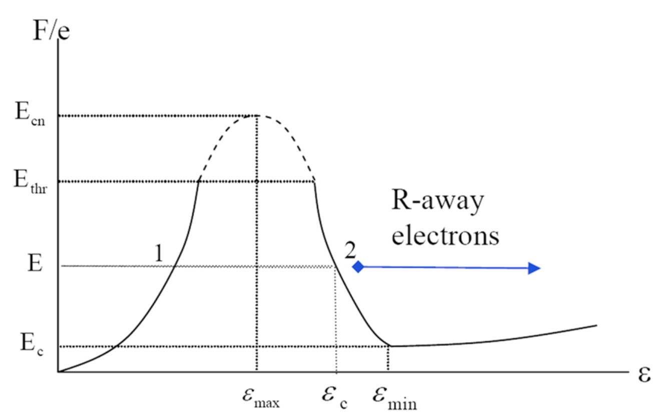

Figure 2. Schematic of the dynamical friction force in air as a function of electron energy. Traces 1 and 2 correspond to low- and high-energy electrons, respectively. E_{cn} is the critical field for thermal runaway, E_{th} is the breakdown threshold, and E_c is the critical field for relativistic breakdown.

[7] If the electric field is larger than E_{cn}, the entire population of electrons is accelerated and gains energy. If the field is less than E_{cn}, only a few electrons having energy higher than ε_c are accelerated,

$$\varepsilon > \varepsilon_c = \frac{2\pi e^3\ ZN_m\ \ln\Lambda_n}{E}, \tag{4}$$

where $\Lambda_n \sim \varepsilon_c/Z\varepsilon_i$. These are the runaway electrons in the neutral gas, and according to *Gurevich* [1961], their flux is given by

$$S_r = n\nu_e \exp\{-\frac{E_{cn}}{4E}A\},\ (A = 30 \text{ for air}). \tag{5}$$

We emphasize that the amplitude of the electric field leading to the electron runaway is limited, since only for nonrelativistic electrons does the dynamical friction force drop when the electron energy increases [*Bethe and Ashkin*, 1953]. For relativistic electrons the friction force reaches its minimum at the energy $\varepsilon_m \sim 1.4$ MeV and then slowly (logarithmically) increases with ε (see Figure 2). The minimum of the friction force F_{min} is related to the minimum value of the electric field E_c, which still generates the runaway, this field is called critical field, and its value is

$$E_c = \frac{4\pi Z\ e^3 N_m}{mc^2} a \tag{6}$$

in the air, $a \sim 11.2$. Notice that the following relations hold

$$\frac{E_{cn}}{E_c} \approx \frac{mc^2}{30\varepsilon_i} \approx 200, E_{cn} \approx 10E_{th}, E_c \approx E_{th}/20. \tag{7}$$

Therefore, in the air, the runaway electrons could appear in a wide range of electric field $E_c < E < E_{cn}$, which spans almost 3 orders of magnitude.

[8] This basic kinetic description of electron acceleration, energy loss, and ionization that occurs throughout the energy range from zero to tens of MeV forms the basis for understanding electrical breakdown in gases and various materials. The specifics of the electron-neutral interactions that govern electron transport at high energy (>1–10 keV) and the associated production of secondary electrons allow for quantification of the RB mechanism. Details are provided below along with a historical overview of advances made in understanding the role of RB in thunderstorm electrical processes.

2. Basic Mechanism and Advances in Understanding of Runaway Breakdown

[9] The basic mechanism by which relativistic electrons avalanche and break down dielectrics such as neutral gases was first described by *Gurevich et al.* [1992]. Preceding this work were the measurements of enhanced X-ray fluxes in thunderstorms and the corresponding theoretical analyses by *McCarthy and Parks* [1992] that clearly pointed to a need for multiplication of the energetic electrons to account for the high measured fluxes of bremsstrahlung photons. In addition to acceleration and runaway in thunderstorm electric fields *Wilson* [1924] also hinted at potential multiplication of the energetic electrons by secondary ionization, however, the details of this process and its implications for lightning discharges were not worked out until 1992 (see paper by *Williams* [2010]).

[10] As noted in the previous section the quantitative studies of runaway acceleration by both *Dreicer* [1960] and *Gurevich* [1961] in the context of fusion plasmas also helped to set the stage for the development of the RB mechanism. Using the insight provided in these works and in the 1992 paper, the detailed kinetic theory of RB was formulated by *Roussel-Dupré et al.* [1994] and subsequent work that significantly improved and refined the computed avalanche rates [*Symbalisty et al.*, 1998; *Lehtinen et al.*, 1999; *Gurevich and Zybin*, 2001; *Babich et al.*, 1998, 2001a] in basic agreement with the initial estimates obtained in 1992. A recent more detailed review and extended analysis at low electron energies is provided in *Roussel-Dupré et al.* [2008].

[11] One of the important quantitative aspects of RB is the steady-state rate at which the energetic population of electrons multiplies for different applied electric field strengths. A plot of the avalanche times (τ) (sometimes referred to as "the characteristic e-folding time") as a function of the overvoltage $\delta_0 = E/E_c$ for air at STP as computed by *Roussel-Dupré et al.* [2008] is reproduced in Figure 3a along with the corresponding mean energy ε_m, Figure 3b, and the energy spread about the mean ε_{sig}, Figure 3c, of the electron population. A general form that yields agreement to within 2% throughout the range $1.5 < \delta_0 < 25$ for each of these quantities can be written,

$$Y = \frac{A}{(\delta_0 - 1.28)^B} \exp\Big[C\ln(\delta_0 - 1.28)^2 + D\ln(\delta_0 - 1.28)^3 + E\ln(\delta_0 - 1.28)^4\Big], \tag{8}$$

where Y represents either τ, ε_m, or ε_{sig} and A-E are the corresponding fit parameters determined by a polynomial least squares fitting routine. The fit parameters are provided in Table 1.

[12] The results for $\delta_0 > 10$ do not include contributions that may come from the conventional avalanche of low-energy (<100 eV) electrons. The coupling that exists between the low-energy electrons and the relativistic runaway electrons for applied fields that exceed the conventional breakdown threshold is discussed below in more detail [cf., *Colman et al.*, 2010]. Note that the mean energy of the electrons can exceed 7 MeV with a spread greater than 12 MeV. The electron distribution function is shown in Figure 4 for an over-voltage of $\delta_0 = 4$ as a function of electron energy ε and the angle θ of motion of the electrons relative to the direction of the electric field. Note the collimation of the electrons along the electric field at high energies. These electrons constitute a particle beam propagating antiparallel to the electric field. The steady state form of the distribution function is achieved when the rate at which particles accelerate to higher energies $R = ec(E - E_c)/\varepsilon_m$ is equal to the avalanche rate, $R_a = 1/\tau$. From this equality one obtains a simple expression for the mean energy of the electrons in terms of the avalanche time, $\varepsilon_m = ce(E - E_c)\ \tau = ceE_c(\delta_0 - 1)\tau$. In units of eV this expression becomes $\varepsilon_m = 2.2 \times 10^5 (\delta_0 - 1) l_{av}$, where l_{av} is the avalanche length (taken to be $c\tau$)

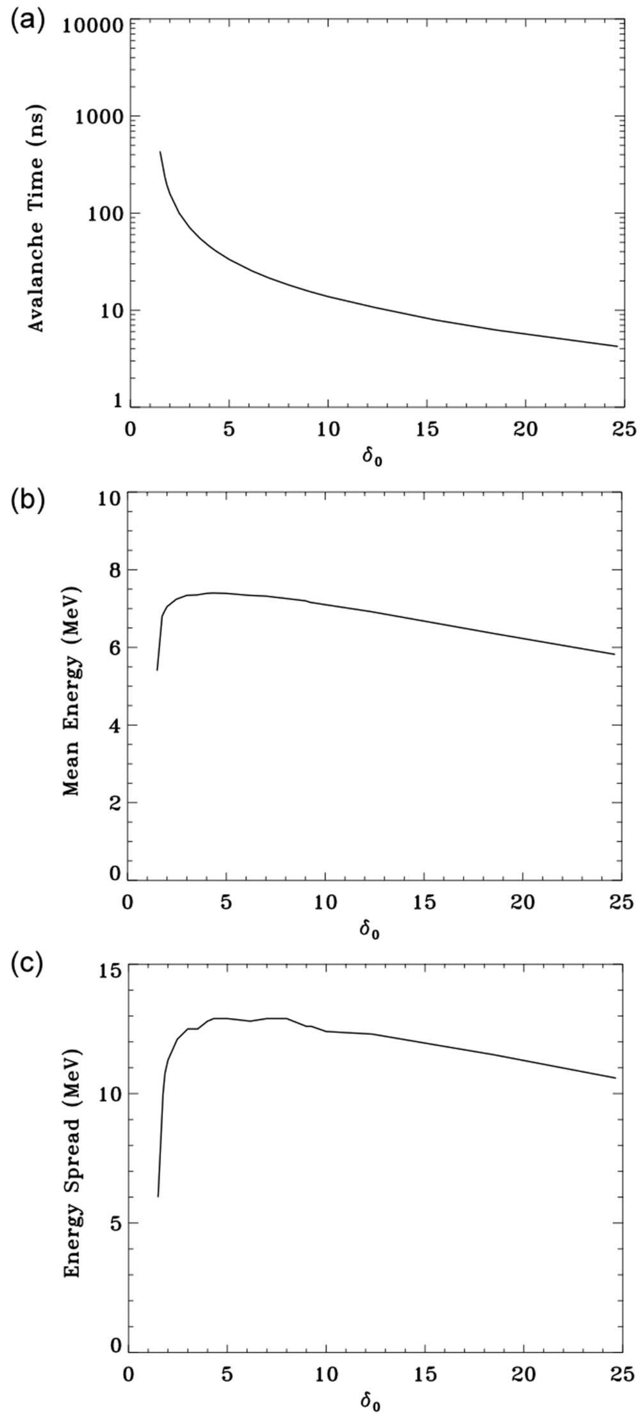

Figure 3. (a) Avalanche time in ns. (b) Mean electron energy in MeV. (c) Electron energy spread in MeV as a function of the over-voltage $\delta_0 = E/E_c$. All calculations were performed for air at STP.

in meters. A check of this result against equation (8) confirms the basic physical assumption for a steady state solution.

[13] At this stage in the development of the RB mechanism, the details of the electron distribution function were understood for the case of a steady, uniform, externally applied electric field. The basic properties of RB in this case include a threshold field (~280 kV/m at STP) for initiation of an avalanche that is approximately a factor of 10 less than conventional breakdown, high mean energies ~7 MeV, bremsstrahlung radiation to 20 MeV and possibly higher, and spatial avalanche scales from 2 to 70 m at STP. Subsequently our theoretical understanding of RB was advanced through studies of the spatial evolution of a runaway discharge including the effects of diffusion [*Gurevich et al.*, 1994], calculations of the X-ray emissions produced by RB in thunderstorms [*Gurevich et al.*, 1997a], and applications of RB to the development of discharges driven by the thunderstorm electric field. The latter included models for sprites [*Taranenko and Roussel-Dupre*, 1996; *Roussel-Dupré and Gurevich*, 1996, *Yukhimuk et al.*, 1999], blue jets [*Yukhimuk et al.*, 1998], and intracloud discharges [*Roussel-Dupré et al.*, 2003]. We note that the mechanism of RB encompasses both an avalanche of relativistic electrons and the copious production of low-energy secondary electrons that contribute significantly to the total electrical current and play an essential role in the evolution of an RB discharge [cf., *Gurevich et al.*, 2004b].

[14] The application of RB to the modeling of high-altitude discharges necessitated a more detailed analysis of the effect of an externally applied magnetic field on the kinetics of the runaway process and the corresponding avalanche rates [*Gurevich et al.*, 1996; *Lehtinen et al.*, 1999]. Depending on the angle relative to the electric field, the magnetic field suppresses RB as the electrons become magnetized and are accelerated by only a fraction of the total electric field strength. These effects become important in the atmosphere above approximately 20 km altitude where MeV electrons become magnetized.

[15] In 1999 Gurevich et al. suggested that cosmic rays and extensive air showers could play an important role in providing the seed energetic electrons needed to initiate a strong RB discharge. The number of seed electrons per unit area increases with the energy of the primary cosmic ray particle as

$$\rho_e = 0.4\,\frac{n_0}{R^2}\left(\frac{R}{r}\right)^2\left(1+\frac{r}{R}\right)^{-3,5}\text{with } n_0 = 0.3\,\frac{\varepsilon_{cr}}{\beta\sqrt{\ln(\varepsilon_{cr}/\beta)}},$$

where we have taken $s = 1$ in equation (2) of *Gurevich et al.* [1999a], $R \sim 115$ m in air, ε_{cr} is the incident cosmic ray particle energy, r is the distance from the shower axis, and $\beta = 72$ MeV for air. The frequency of these showers is given by $5 \times 10^3\ (10^{13}/\varepsilon_{cr})^2$ km^{-2} sr^{-1} s^{-1} and the minimum energy to initiate RB was estimated to be ~10^{15} eV. The frequency of EAS at these energies fits well with the measured rate of intracloud lightning for typical charge layer dimensions. In addition, the production of radio frequency (RF) radiation by an RB discharge was analyzed and found to possess a characteristic bipolar temporal signature [cf., *Roussel-Dupré and Gurevich*, 1996; *Gurevich et al.*, 2003]. This fact was exploited by *Gurevich et al.* [2004a] to look for a correlation between cosmic ray showers and the initiation of intracloud lightning.

[16] The large scale lengths associated with RB in gases make it difficult to reproduce in the laboratory. Two experiments [*Gurevich et al.*, 1999b; *Babich et al.*, 2004a] have been conducted with some success but interpretation of the results requires careful analysis of the experimental setup and associated diagnostics. A more straightforward experimental

Table 1. Fit Parameters for τ, ε_m, or ε_{sig} With Results in ns, MeV, and MeV, Respectively

	A	B	C	D	E
τ	117.154	0.90331769	−0.028990976	−0.0054570445	0
ε_m	7.2369	−0.047166287	−0.044739548	0.023395940	−0.0066729225
ε_{sig}	12.0186	−0.13104670	−0.11326119	0.051383081	−0.010414670

configuration with larger scale lengths is needed in order to systematically study the RB mechanism under controlled conditions that yield reliable/repeatable results. Acquiring an appropriate facility may well require some technological breakthroughs so, for now, we are left with the natural environment to provide us with validation and further details regarding RB.

[17] In 2003, Dwyer pointed to the important role played by secondary emissions (γ-rays and positrons) in enhancing the RB process by providing additional seed energetic electrons in the source region in the same way that photon and ion feedback mechanisms at the cathode work in conventional breakdown experiments conducted in the laboratory [e.g., *Morrow*, 1985a, 1985b; see also *Dwyer*, 2008].

[18] To better understand how the RB mechanism operates in air and appreciate the overlap that exists among the processes of RB, thermal runaway, and conventional breakdown we refer the reader to a companion paper published in this special issue [*Colman et al.*, 2010]. Figure 5 shows a more detailed plot of the energy loss rate for electrons in air with the vibrational transitions of Oxygen and Nitrogen included. For an applied field above the high-energy minimum at $\varepsilon_m \sim 1.4$ MeV and below the maximum at $\varepsilon_p \sim 100$ eV, it is possible to divide the energy space into two regimes we shall call thermal, where $\varepsilon < \varepsilon_1$, and runaway, where $\varepsilon > \varepsilon_2$. ε_1 is the energy below ε_p at which the electric field equals the energy loss rate and similarly for ε_2 which lies above ε_p. These two kinetic regions interact with each other by means of two mechanisms. Thermal electrons can leak into the runaway regime by tunneling through the intermediate energy region between ε_1 and ε_2 and runaway electrons produce thermal electrons by direct ionization. These two populations of electron feed back on each other such that one or the other controls the growth rate of both populations. When the applied field is below the threshold for avalanche of the thermal population, the runaway electrons define the rate of growth of both populations. When the applied field is above the threshold for conventional breakdown and the avalanche rate of the thermal electrons exceeds the runaway avalanche rate then the thermal electrons will ultimately define the growth rate of both populations. There is a time delay however before the thermal population can leak sufficiently into the runaway regime to dominate the runaway population. A quantitative treatment of this kinetic interaction is provided by *Colman et al.* [2010]. As noted previously, both Dreicer and Gurevich addressed the thermal runaway process while *Moss et al.* [2006] and *Gurevich et al.* [2007] described and referred to a strong runaway breakdown regime where the electric field exceeds the threshold for conventional breakdown ($E > E_c$) and placed his results in the context of lightning stepped leader development.

[19] In conclusion to this section we briefly summarize the main features of Runaway Breakdown (RB). It is triggered

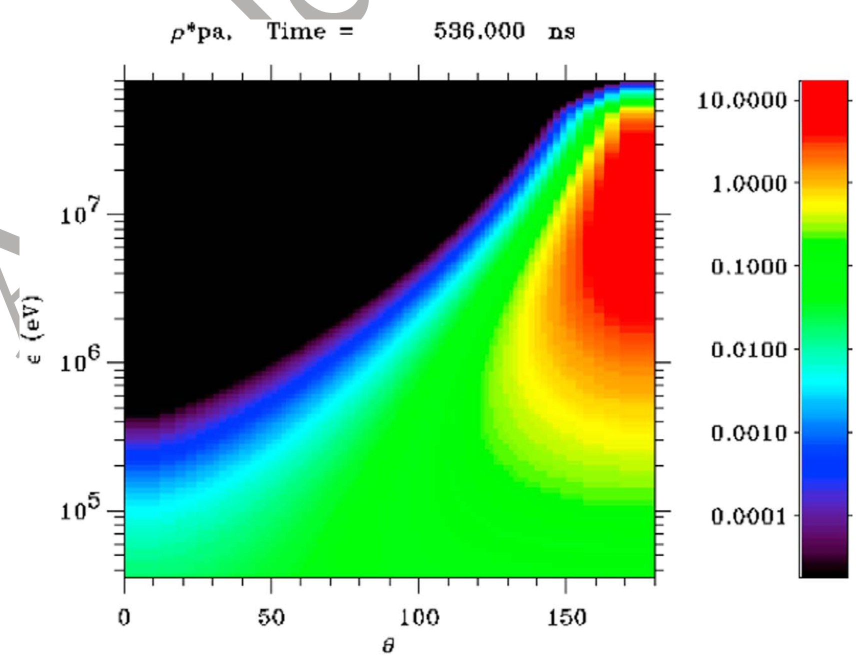

Figure 4. Electron distribution function for $\delta_0 = 4$ as a function of electron energy ε in eV and the angle θ of motion of the electrons relative to the direction of the electric field.

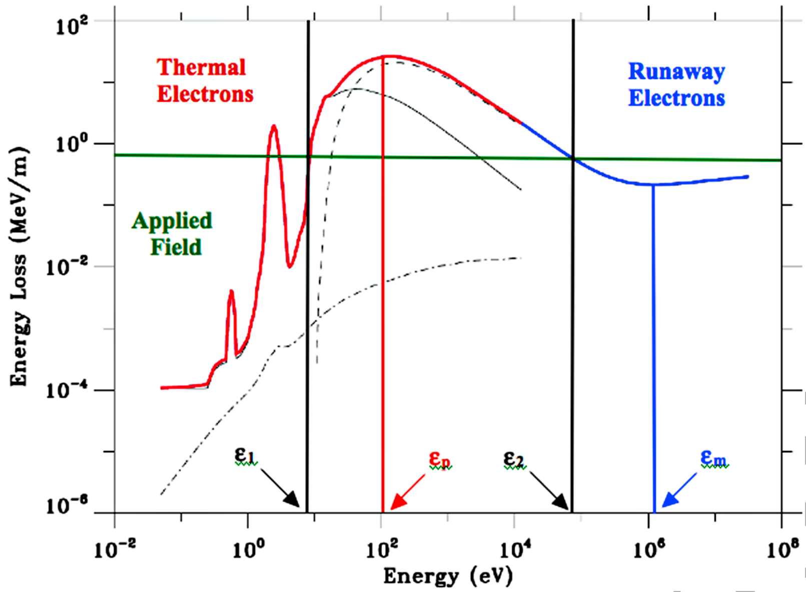

Figure 5. Energy loss rate for electrons in air as a function of electron energy. The red curve is derived from detailed cross sections for elastic, rotational, vibrational, electronic, and ionizing electron-neutral collisions in air. The solid, dashed, and dash-dotted curves represent the energy loss rate due to inelastic (sum of rotational, vibrational, and electronic processes), ionizing, and elastic collisions, respectively. The blue curve is the Bethe energy loss formula invoked at energies above 10 keV. The green line represents the magnitude of an applied electric field. ε_1, ε_2, ε_p, and ε_m are defined in the text.

by seed relativistic electrons and needs a break even field an order of magnitude less than the conventional breakdown threshold. The exponential growth of RB is determined by the electrons in 3–200 keV energy range, although the high-energy "tail" extends up to tens of MeV. This tail determines the γ- and X-ray fluxes. The main population of electrons generated by RB has low energy (1–3 eV) and these electrons produce the electric current, electric field attenuation and radio emission. Finally, unlike the conventional breakdown, our present understanding suggests that RB does not happen in alternating or stochastic electric fields.

3. Manifestation of Runaway Breakdown in the Atmosphere

[20] As mentioned in section 3, until recently laboratory studies of RB have not yielded definitive results. A new perspective is related to laboratory experiments based on long sparks in air. They successfully detected X-ray bursts having a broad energy spectrum up to a few MeV which are presumably caused by RB [*Dwyer et al.*, 2005; *Rahman et al.*, 2008]. The reported breakdown field was about 1.1 MV/m which is less than that of the conventional breakdown although still much higher than that of RB thus leaving some uncertainty about its RB nature. However in the RB studies one can still mostly rely on the natural phenomena that occur in thunderstorms and manifest themselves by generating X-ray and γ-ray emissions, as well as neutrons. The observations of emissions generated by RB in thunderstorms will be reviewed in this section.

[21] Earlier attempts to detect X-rays due to thunderstorm activity were focused on that caused by a strong current due to the return stroke [*d'Angelo*, 1987; *Hill*, 1963]. Those attempts were unsuccessful since the electron temperature in the lightning channel does not exceed a few thousand K. Thus the hot, thermal component of the lightning channel is not a suitable source for X-ray production.

3.1. Intracloud X-ray Pulses

[22] A breakthrough occurred when *McCarthy and Parks* [1985, 1992] conducted observations while flying an aircraft through thunderclouds with onboard X-ray detectors. It was reported that (1) X-ray fluxes increased by 1–3 orders of magnitude in all energy channels available (from 5 keV up to 110 keV), (2) the horizontal scale of the radiating region can exceed several hundred meters, and (3) the elevated X-ray production precedes a lightning flush by a few seconds and ceases immediately after a lightning flash.

[23] The last finding was of special importance. It showed that an, as yet, unknown mechanism of X-ray production existed, which was not related to lightning flashes. Furthermore, McCarthy and Parks correctly attributed the observed X-ray fluxes to bremmstrahlung by high-energy electrons. They also assumed that the observed X-rays could be caused by cosmic ray secondary electrons accelerated by the thunderstorm electric field. However, the number density of energetic electrons available from cosmic ray secondaries is more than an order of magnitude less than that required to produce the observed X-ray fluxes. A magnification mechanism was missing, which role is played by runaway breakdown.

[24] These experiments attracted interest to the direct X-ray measurements in thunderclouds. *Eack* [1996] was the first to fly a meteorological balloon equipped with a spe-

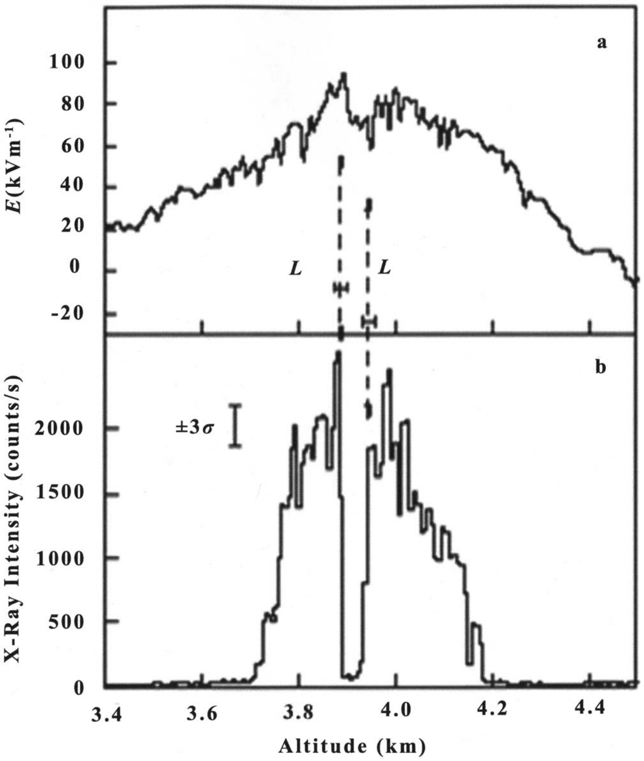

Figure 6. Balloon measurements of (top) *E* field and (bottom) X-rays [adapted from *Eack*, 1996].

cially designed light X-ray detector into a large thunderstorm [see also, *Eack et al.* 1996]. The balloon also carried an electric field meter.

[25] It was found that on a number of occasions the X-ray flux strongly increases for about 1 min in all three energy channels (30–120 keV) available. This is illustrated in Figure 6 which shows vertical profiles of X-ray intensity and electric field strength. A significant increase in X-ray counts near 4 km height is revealed and lasted for about 1 min. Simultaneously the electric field strength increased as well. In Figure 6, two arrows marked by letters L show lightning flashes, which precede significant decreases in the X-ray flux. Note also that *Marshall et al.* [1995] used balloons to measure the strength of thunderstorm electric field. Figure 7 shows the results of the field measurements made along the balloon orbit as well as the curves which show the height profile of the critical field of the runaway breakdown. It is seen that the electric field can reach the RB threshold E_c. Here the arrows show that when the field reaches E_c it correlates with a lightning flush. *Marshall et al.* [1995] concluded from analysis of a number of thunderstorm electric field soundings that lightning may occur whenever the electric field exceeds the E_c value. Thus lightning may limit the electric field inside thundercloud to values less than E_c, which indicates that RB could be a trigger mechanism for lightning. As suggested by *Gurevich and Milikh* [1999] RB leads to the charge transfer, by both ion and electron, which in turn reduces the thundercloud electric charge, and thus leads to redistribution of the electric field producing a characteristic flat-type electric field maximum observed earlier in thunderclouds [*Marshall et al.*, 1995].

[26] These observations reveal that RB could occur inside thunderclouds at a few kilometers in height. To study such an effect one can either fly detectors through a thundercloud or just install them high up in the mountains and wait till a thunderstorm occurs. In fact, we discuss next three different observations of RB obtained in the mountains. The first one was conducted by the carpet air shower array at Baksan, North Caucasus at 1.7 km altitude during a thunderstorm on 9 July 2000 [*Alexeenko et al.*, 2002]. Shown in Figure 8 (top) are the electric field strength and so-called soft component of cosmic rays which describes electrons in the energy range 10–30 MeV. Figure 8 reveals that a noticeable (≤20%) enhancement of the soft component of cosmic rays lasted about 0.5 min before the lightning flush and coincides with the flash. At the same time the hard component with energies exceeding 70 MeV (third plate from the top) was not affected. Finally, Figure 8 (bottom) shows an increase of the electric current due to thermal electrons generated by the RB. Notice that a peculiarity of RB is that the production of relativistic particles is accompanied by the production of thermal electrons having a velocity about 2 orders of magnitude less than that of relativistic electrons. However, since the total number of thermal electrons is 5–6 orders of magnitude higher than that of relativistic electrons the electric current is predominantly determined by thermal electrons.

[27] The second experiment also conducted inside a thunderstorm at a mountain observatory located 2.7 km above sea level provides proof of the existence of RB. During this experiment *Tsuchiya et al.* [2009] detected simultaneous bursts of runaway electrons and γ-rays which preceded lightning flashes.

[28] The last and the most sophisticated experiments among those reviewed here were conducted by Gurevich and his team during 2002–2009 at the Tien-Shang Mountain at 3.4–4 km above sea level [*Gurevich et al.*, 2009]. They

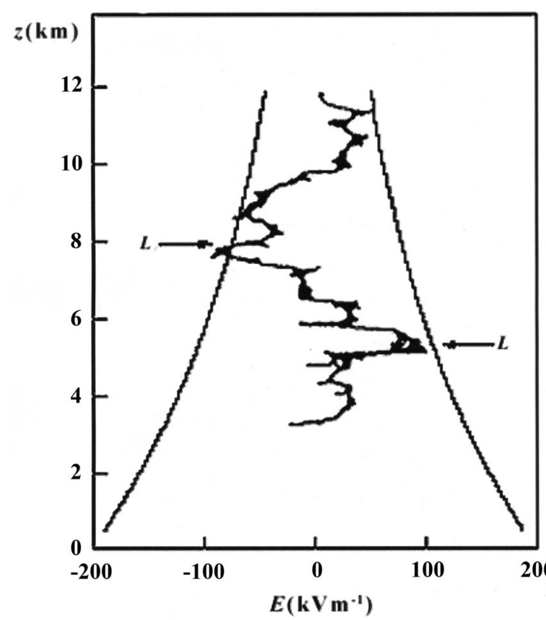

Figure 7. Balloon measurements of the electric field [adapted from *Marshall et al.*, 1995]. The arrows marked L shows lightning strokes.

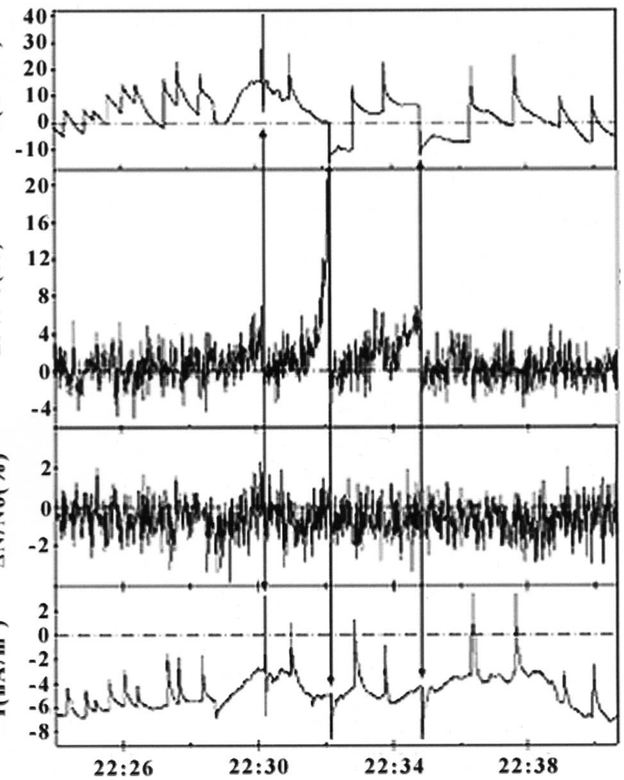

Figure 8. Observations by the Carpet air shower array at Baksan, North Caucasus during the thunderstorm on 9 July 2000. (top plate) The electric field and (second from the top) the soft component (electrons, 10–30 MeV) of cosmic rays. The arrows show lightning strokes [adapted from *Alexeenko et al.*, 2002].

looked for RB triggered by electron secondaries produced by Extensive Atmospheric Showers (EAS) (see Figure 9). Thus, they used an array of Geiger-Muller counters which detect γ-rays caused by particles with energy in the range of 2×10^{14}–10^{15} eV. A signal from the EAS triggered the radio receiver which detects a radio pulse caused by currents of both relativistic runaway electrons and thermal electrons which is produced by the RB.

[29] As a result hundreds of simultaneous γ and radio pulses were detected during thunderstorms. In the absence of thunderstorms no radio pulses were observed although EASs were always seen.

[30] The observed radio pulses were bipolar widths ranging from 0.4 to 0.7 μs. As we discuss later on in this section, this time scale corresponds well to RB development and duration at typical charge layer heights. Besides, the intensity of the radio pulses due to RB corresponds to an external electric field $E = (1.2 - 1.4)E_c$.

[31] A model of the X-rays due to RB inside thunderclouds was developed by *Gurevich et al.* [1997a]. The model first estimates the total flux of ambient cosmic ray secondary electrons. Then it computes the magnification of this flux due to RB and finally finds the spectral density of the bremmstrahlung emission. The latter is shown in Figure 10 computed for the height 4 km at an electric field twice the value of the critical field for RB. *Gurevich and Milikh* [1999] studied X-ray propagation in the atmosphere by taking into account Compton scattering and loss due to photo ionization. The computed energy spectrum was then checked against the spectrum observed by *Eack* [1996]. He observed an X-ray event of 1 min duration, i.e., much longer than any lightning flash. It is shown in Figure 11 where the model X-ray fluxes were integrated over three energy channels (30–60, 60–90, and 90–120 keV). The red points in Figure 11 show the balloon measurements, the blue points show the model spectrum at 70 m from the source, and the green points show the model at 420 m from the source. The latter case is in a good agreement with the observations.

3.2. Terrestrial γ-ray Flashes

[32] The Earth's atmosphere becomes transparent to γ-rays with energies greater than ~1 MeV above about 25 km altitude. As a result, strong γ-ray bursts originating at high tropospheric altitudes and perhaps somewhat below the tropopause can be seen from space-based platforms and can in turn provide some diagnostic information about the source. Indeed, TGFs were first discovered by the Burst and Transient Source Experiment (BATSE) on the Compton γ-ray Observatory (CGRO) [*Fishman et al.*, 1994] and are presently being monitored by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite, which has observed some 10–20 TGFs per month [*Smith et al.*, 2005]. The Fermi γ-ray Space Telescope has also recently detected TGFs [see *Fishman et al.*, 1994]. The BATSE experiment consisted of eight large area detectors (2000 cm^2 each, NaI crystals) situated on the corners of the CGRO. The large number of counts (>100) registered per event permitted a crude spectral measurement (four broad channels from 20 keV to >300 keV) for each event while the distributed sensors with overlapping fields of view permitted a rough geolocation of the source. RHESSI on the other hand consists of a nine germanium crystals that collect photons over 2π sterradians. RHESSI counts each photon

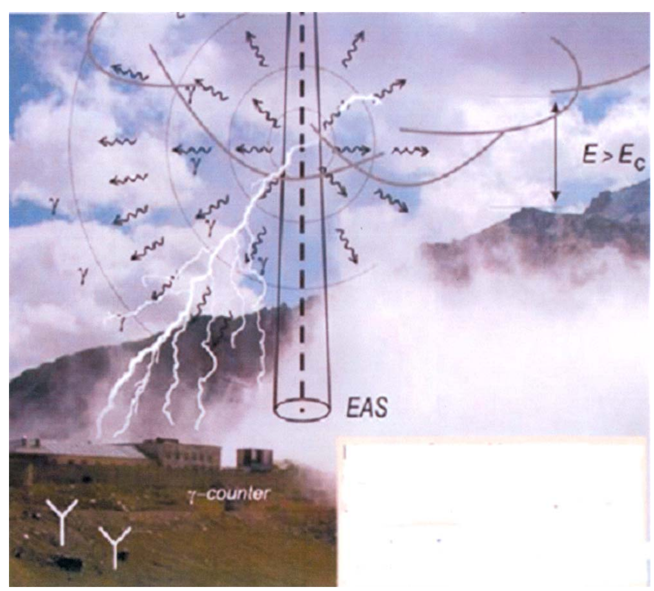

Figure 9. Schematics of simultaneous measurements of radio pulses and extensive atmospheric showers conducted at the Tien-Shang Mountain [adapted from *Gurevich and Zybin*, 2005].

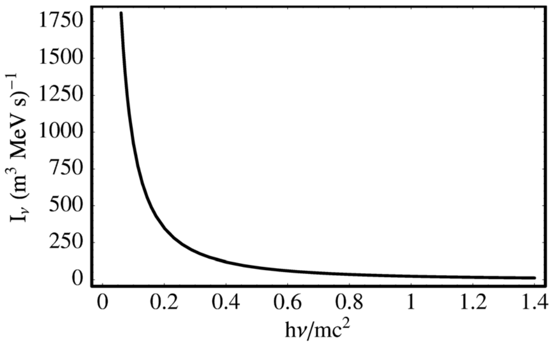

Figure 10. Model of spectral density of the bremmstrahlung emission due to RB in thundercloud at 4 km at $E = 2E_c$ [adapted from *Gurevich et al.*, 1999a].

and is able to produce a spectrum from ~20 keV to 20 MeV with a resolution of up to a few kiloelectron volts. Because of the much smaller detector volume however the count rate is low (tens of photons per event) and a full spectrum is obtained only after summing over tens of events.

[33] *Cummer et al.* [2005] found a number of correlations between TGF events and VLF signals radiated by lightning. The parental lightning had charge moment changes under 100 C km, which is much smaller than needed to initiate a sprite. Interestingly, some TGFs preceded the lightning flashes although absence of GPS at RHESSI leads to a significant timing inaccuracy. More details can be found in the paper by *Smith et al.* [2010].

[34] TGFs are thought to be a manifestation of some form of RB that develops above a thunderstorm [*Bell et al.*, 1995; *Inan et al.*, 1996; *Roussel-Dupré and Gurevich*, 1996]. *Nemiroff et al.* [1997] presented first some temporal and spatial characteristics of TGFs measured by BATSE. The spectra measured by RHESSI reveal energies up to 30 MeV [*Smith et al.*, 2005], in agreement with energies predicted by the RB mechanism triggered by cosmic rays [*Dwyer and Smith*, 2005; *Carlson et al.*, 2007; *Babich et al.*, 2007a]. The time duration of individual events ranges from hundreds of microseconds to milliseconds. The geographical distribution of TGFs roughly corresponds to that of lightning over continents at low latitude and also to the distribution of sprites [*Chen et al.*, 2005]. However TGF emissions are rarely detected over the Southern United States where many sprites are observed at ground level [*Smith et al.*, 2005]. The energy range from 100 keV to several MeV of the TGF spectrum is sensitive to the TGF emission altitude, due to the cascading of the high-energy photons to lower energies. The analysis of the RHESSI spectra suggests that their source is in the range of 15–21 km, implying that thunderstorms and not sprites may initiate TGFs [*Dwyer and Smith*, 2005]. In their recent paper, *Hazelton et al.* [2009] used lightning sferics to identify storms near TGFs detected by RHESSI. They found that lightning flashes closer than 300 km of the subsatellite point produced much harder spectrum of TGFs than that located at larger distance. Moreover presented in the paper model shows that most likely the sources were at 15 km altitude and have a wide-beam geometry. Some analyses, however, of BATSE spectra have suggested that the source of TGFs could extend continuously from 15 to 60 km altitude rather than in a narrow altitude range [*Østgaard et al.*, 2006]. More recently *Østgaard et al.* [2006] have addressed dead time issues, associated with the BATSE detector, that suggests a pile up of high-energy photons. The net result is inference of a softer spectrum than actually exists and therefore a higher source altitude. *Dwyer* [2008] analyzed different mechanisms which produce TGFs. He mentioned that RB when acting on the external source of cosmic secondary electrons is insufficient to account for TGF fluxes. He suggested two alternative mechanisms, thermal runaway and relativistic feedback.

[35] However, those two mechanisms have limited applications. Let us consider first the relativistic feedback. Figure 12 shows ratio of electron positron pair production length (l_{pair}) to the electron avalanche length (l_{av}) for two different photon energies 10 MeV (the trace 1) and 20 MeV (the trace 2). It was computed for STP by using the kinetic avalanche time (Figure 3a from this paper) and the cross section of electron positron pair production [*Hubbell et al.*, 1980]. Figure 12 reveals that at $\delta_0 > 2$ the ratio l_{pair}/l_{av} exceeds 25–30. From the other hand, the size of the avalanche region cannot exceed 25–30 avalanche lengths, otherwise the electric field causing RB will be eliminated. Thus, the mean free path of 10–20 MeV photons with respect to pair production exceeds the size of avalanche region at $\delta_0 > 2$.

[36] Therefore, the photons will escape the area of RB, and the positrons produced by the high-energy photons will not participate in the feedback process. Interesting that detailed Monte Carlo computation [*Babich et al.*, 2005] showed that the positron feedback is negligible at $\delta_0 > 3$, although it plays a significant role at moderate field ($\delta_0 < 2$).

[37] In order to generate a huge amount of γ-rays such as required to produce TGFs, a strong electric field is needed in

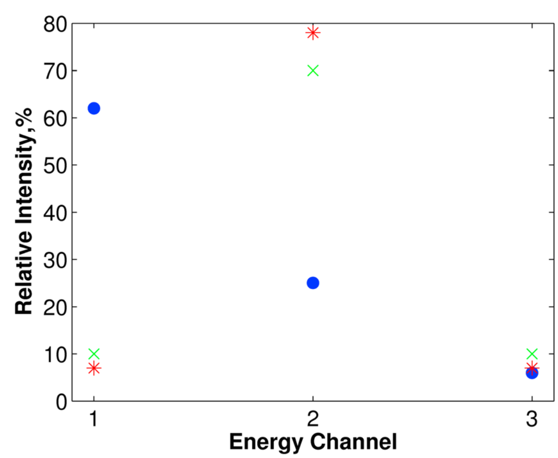

Figure 11. The computed energy spectrum for the X-ray emission given in Figure 10. The X-ray fluxes were integrated over three energy channels (30–60, 60–90, and 90–120 keV). The stars show the balloon measurements, the blue points show the spectrum at 70 m from the sources, and the crosses show the spectrum at 420 m from the source. The stars show the balloon measurements by *Eack* [1996].

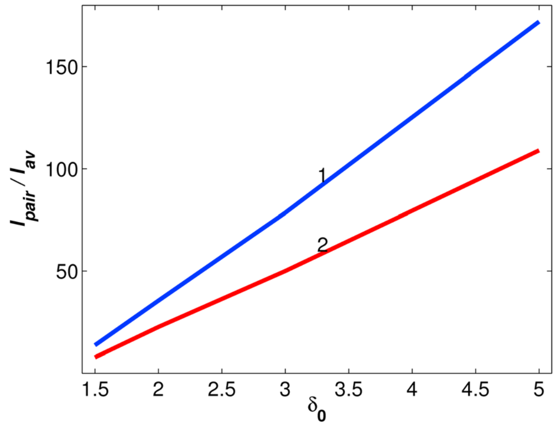

Figure 12. The ratio of the pair production length to the avalanche length as a function of δ_0 computed for two different photon energies 10 MeV (trace 1) and 20 MeV (trace 2).

which case the feedback is not playing a role. *Babich et al.* [2001b, 2004b, 2008] have addressed this point with detailed Monte Carlo simulations and were the first to identify the total number of electrons needed to reproduce the BATSE and RHESSI measured fluxes. Their simulations assumed an average figure for the background of seed energetic electrons and did not include the effects of either thermal runaway or feedback. However, a moderate field supplemented by the feedback mechanism could still play a role in the TGF production, but it requires that RB occurs in a thick layer having a vertical scale of a few kilometers. Therefore, we agree with the conclusion made by *Babich et al.* [2005] that "significantly more work is required to establish the existence and role of feedback in RB under thunderstorm electrical conditions".

[38] The thermal runaway has its own limitations, namely it requires enormous electric fields which can be formed only on a short spatial scale such as in a streamer tip, although it can be involved in the production of TGFs in conjunction with RB. Furthermore extensive atmospheric showers can play an important role in TGF production [*Gurevich et al.*, 2004a]. Although *Dwyer* [2008] does not share this idea because he believes it is not supported by the time structures and fluencies of TGFs. It should be noted that the reliability of the models of the time structures of a few tens of photons scattering through the entire atmosphere is quite limited.

[39] Further work is needed to evaluate the effect of summing multiple RHESSI events to obtain a spectrum and the corresponding impact on determination of a source altitude. The possibility of two kinds of TGFs corresponding to low- and high-altitude sources cannot be completely ruled out. A lightning leader as a source of TFFs is predicted by *Moss et al.* [2006], who show that thermal electrons can be accelerated in the leader streamer zone up to energies of several hundreds of kiloelectron volts and possibly up to several tens of MeV. This mechanism then predicts that some TGFs can be produced by high-altitude lightning processes. The region from 15 to 21 km lies just above thunderstorm cloud tops where a screening layer of charge forms and the question of how a runaway discharge forms or emerges from the cloud into this region to produce bremsstrahlung photons (or TGFs) was addressed in the above cited theoretical works related to sprites and predicted by *Yukhimuk et al.* [1998] in discussing blue jets. *Gurevich et al.* [2004c] proposed a mechanism of TGF generation by joint effect of RB and EAS. *Milikh et al.* [2005] mentioned that when RB occurs at the height $z > 15$–20 km the relativistic electrons are magnetized, and their trapping can promote propagation of the electromagnetic pulse associated with thunderstorms as a whistler mode. Much work remains to either confirm previous work or identify the actual source of TGFs.

[40] Important theoretical models of TGFs were presented by the Stanford group, who discussed TGF production by RB due to quasi-electrostatic thundercloud fields [*Lehtinen et al.*, 1996, 1999, 2001], as well as by the return stroke from lightning [*Inan and Lehtinen*, 2005].

3.3. γ Bursts Due to Lightning Stepped Leaders

[41] So far, we discussed high-energy radiation generated by the RB which precedes lightning flashes although the ground based observations showed that lightning itself can also be a source of γ-rays. *Moore et al.* [2001] first reported X-rays associated with lightning stepped leaders. This experimental result was supported by *Dwyer* [2003], who detected X-ray bursts in the range 30–250 keV with a typical duration of less than 1 μs. It was assumed that the source of those bursts are the electric field changes accompanying stepping of the leader [*Dwyer et al.*, 2005]. Recently *Howard et al.* [2008] experimentally proved that the sources of X-rays are collocated in space with the leader step electric field changes. Besides, the X-rays were delayed by 0.1–1.3 μs with respect to those field changes. The delay shows the time needed to develop the RB.

[42] Theory which described this effect was introduced by *Moss et al.* [2006] and *Gurevich et al.* [2007]. Interestingly these two groups used different methods (analytical model by Gurevich and Monte Carlo model by Moss) but came to similar conclusions. Namely, that in a streamer tip such as in a streamer zone of lightning leader where the electric field can reach 150 kV/cm, a thermal runaway could occur which can accelerate electrons up to a few kiloelectron volts. Those electrons could in turn trigger RB instead of relativistic seed electrons due to galactic cosmic rays. The estimates show that a significant amount of thermal runaway electrons $N_R = \int S_R V\, dt \simeq 3 \times 10^{12}\ e\lambda$ can be produced in a small volume $V = 10$ cm $\times$ 3 cm^2 within $dt = 0.3$ μs. Note that in RB the spatial size scales as $\lambda_{av} = \lambda^o_{av}/\delta^2$, $\delta = E/E_c = 70$–100. Thus λ_{av} could be as low as a few centimeters and thus can be developed in a streamer zone of a lightning stepped leader.

[43] Furthermore, the model [*Gurevich et al.*, 2007] shows that γ-ray emission generated by the RB due to a single lightning step can reach energies of 0.01–1 kJ over 0.1–0.5 μs. Thus for 2–50 steps the γ-burst can reach an energy of 1–10 kJ. Finally, such a RB generates currents of 0.3–5 kA, which is in line with the observations of lightning stepped leaders.

3.4. Neutron Bursts Due to Lightning

[44] The possible significance of neutron production by lightning was noted by *Fleischer et al.* [1974]. Not only does

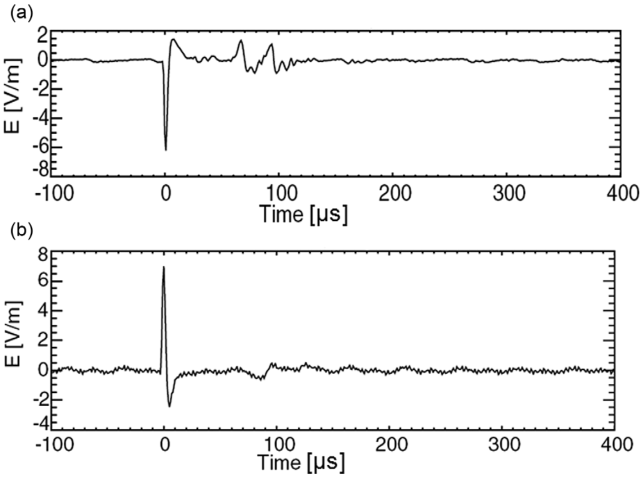

Figure 13. (a) Positive NBP and (b) negative NBP observed by Los Alamos Sferic Array adapted from *Smith et al.* [2002].

the generation of neutrons provide valuable information about the discharge mechanism itself but an enhanced neutron flux would also have important consequences for ^{14}C dating through the neutron capture reaction n(^{14}N, ^{14}C)^{1}H. The implications of the latter are that the ages of various materials would be underestimated unless the historical occurrence rate and geographical distribution of lightning were taken into consideration.

[45] The first estimates of neutron yield from lightning were obtained by scaling the reaction ^{2}H(^{2}H,n)^{3}He in electrical explosions of nylon threads enriched by deuterium [*Libby and Lukens*, 1973; *Stephanakis et al.*, 1972]. *Fleisher et al.* [1974] then performed neutron-monitoring experiments in association with laboratory discharges that simulated the plasma conditions thought to exist in the lightning channel. They found no evidence for neutron production but instead set upper limits on the number of neutrons generated by lightning to 4×10^8 thermal neutrons and/or 7×10^{10} 2.45 MeV neutrons per flash.

[46] The first direct measurements of the neutron flux in the thunderstorm environment [*Fleisher*, 1975] yielded null results. Positive results were not obtained until 10 years later [*Shah et al.*, 1985] when Shah and his colleagues reported observing statistically significant enhancements in the neutron flux in correlation with thunderstorm EMP. They estimated the average neutron yield to range from 10^7 to 10^{10} neutrons per lightning discharge assuming the reaction ^{2}H(^{2}H,n)^{3}He with neutron energy ε_n = 2.45 MeV. From the measured delay times relative to EMP they deduced plausible yields extending to 2×10^{12} assuming ε_n as low as 0.023 eV. *Shyam and Kaushik* [1999] and *Kuzhewskij* [2004] have also communicated statistically significant single events, in which neutron bursts associated with atmospheric lightning discharges were detected near sea level in India and Moscow. Results of these successful experiments were interpreted as stemming from the nuclear fusion reaction ^{2}H(^{2}H,n)^{3}He within the lightning channel.

[47] Recently, *Babich and Roussel-Dupré* [2007] showed that the prevailing neutron generation theory based on synthesis of deuterium nuclei in the lightning channel is not feasible. Instead, this phenomenon is most likely connected with photonuclear reactions (γ,n) associated with an electrical breakdown driven by relativistic runaway electrons (i.e., RB). Neutron production by photonuclear reactions in air requires photon energies exceeding 10 MeV, a value that is consistent with the upper energies of the bremsstrahlung spectrum produced in a runaway breakdown avalanche. The neutron yield of photonuclear reactions that accompany atmospheric γ-ray bursts associated with lightning discharges of various forms was estimated by *Babich and Roussel-Dupré* [2007] to lie between $\sim 10^{13}$ and 10^{15} per discharge. More detailed calculations are presented by *Babich et al.* [2007a, 2007b, 2008].

3.5. Narrow Bipolar Pulses

[48] Narrow bipolar pulses (NBP) are the electromagnetic signature of a distinct class of impulsive and energetic intracloud discharges that occur in some thunderstorms. NBP were observed by broadband field-change antennas [*Smith et al.*, 2002; *Eack*, 2004] and by the FORTE satellite [*Jacobson*, 2003]. They are characterized by strong VHF emission having peak power 100–300 GW and bipolar waveforms. A positive polarity NBP exhibits a radiation field waveform that begins as a positive electron field peak, while followed by a negative overshoot. A negative polarity NBP begins as a negative electric field peak followed by a positive overshoot (see Figure 13). This indicates that a positive NBP results from a dipole discharge in which positive charge is located over negative charge, while a negative NBP results from an inverted dipole with a negative charge over positive. The positive NBP are scattered between 15 and 20 km, while their spatial distribution peaks at 17 km. The negative NBP are spread between 7 and 15 km, with the distribution peak at 13 km [*Smith et al.*, 2002].

[49] NBP has a mean duration of 5–10 μs with full width at half maximum 2–5 μs and mean relaxation time of 2–5 μs. An average NBP has a peak current of 30–100 kA, while the corresponding dipole moment changes up to 2 C km. The discharges responsible for NBP propagate at an average velocity of 1.5×10^8 m/s [*Eack*, 2004].

[50] NBP is observed in the frequency range 200–500 kHz. The amplitude of the effective electric field at the distance R from the source is $E \sim 10 - 30(\frac{100\ \mathrm{km}}{R})$V/m. Notice that NBP is always accompanied by intensive radio emission in a wide frequency range up to 500 MHz. Detailed studies of HF emission in the frequency range 26–48 MHz conducted by the FORTE satellite [*Jacobson*, 2003] found that this emission has an integrated ERP ≥ 40 kW. It was related to a strong intracloud pulse. These pulses are accompanied by an optical emission with an intensity 2 orders of magnitude less than that in conventional flashes. Finally there are indications that NBP have been correlated with TGF [*Stanley et al.*, 2006; *Shah et al.*, 1985].

[51] *Jacobson* [2003] was the first to suggest that NBP have relevance to RB, while the first quantitative model of NBP was presented by *Gurevich and Zybin* [2004]. According to this model NBP are generated by runaway breakdown triggered by extensive atmospheric shower. The latter is caused by cosmic particle having energy

10^{14}–10^{19} eV. This type of very intensive RB was termed RB-EAS.

[52] The presented model successfully explained the observed time scales of RB-EAS. In fact, at the altitudes of interest the avalanche time is of about 1–5 μs, which fits well with the NBP rise time. The fall of NBP corresponds to the relaxation of the runaway discharge, which is due to the electron attachment to molecular oxygen in triple collisions. The electron attachment time is $\tau_{att} \sim (5 \times 10^{18}\ \mathrm{cm}^{-3}/Nm)^2\ \mu\mathrm{s}$. For the considered height range 13–18 km the value of τ_{att} fits well with the observed fall time of NBP.

[53] The electric current generated by RB-EAS discharge is unipolar. For given external field, its maximum is proportional to the number of thermal electrons, which in turn is proportional to the number of runaway electrons determined by the energy of the cosmic ray particle. As shown by *Gurevich and Zybin* [2004], the current is $J_m \sim (\varepsilon_p/10^{17}\ \mathrm{eV})$ kA. This current emits the bipolar radio pulse.

[54] Notice that the size of the pulsed current region is determined by the EAS scale length of 300–400 m, which is less than the wavelength λ = 600–1500 m of the NBP radiated VLF emission with the frequency 200–500 kHz. Therefore the VLF emission is radiated coherently, its power $P = 2J^2/3c$ is growing as J^2, and it can reach 100–300 GW. Respectively the energy of such pulses can reach MJ. In contrast to the coherent VLF emission, the HF emission from NBP is incoherent, its power is less than 10 MW, and the radiated energy does not exceed 100 J.

[55] Recently *Dwyer et al.* [2009] claimed that according to their estimates the model [*Gurevich and Zybin*, 2004; *Gurevich et al.*, 2004c] requires either unrealistically high-electron avalanche multiplication or ultrahigh-energy air showers. Thus, the subject requires more theoretical studies.

4. Conclusions

[56] The introduction of runaway breakdown and its potential initiation by cosmic rays to our studies of lightning and the thunderstorm electrical environment has provided us with an entirely new perspective on how the Earth's atmosphere couples to the cosmos. In many respects our atmosphere can be thought of as a giant scintillator or "cloud" chamber that is continuously lit up by the passage of energetic radiation from space. Thunderstorms provide an electrically active region that can locally enhance the RF and optical output of the atmospheric scintillator in a dazzling display, one that has fascinated man for millennia. Indeed Wilson would have been proud to see us return to his original ideas and to his invention as a metaphorical if not scientifically useful substitute for the Earth's atmosphere. This notion has far reaching implications both for the potential utility of lightning as a diagnostic to probe the mysteries of energetic cosmic ray showers and therefore the universe and for understanding the very nature of the lightning discharge and its effects on the atmosphere and human activity.

[57] Runaway breakdown could have manifestations in many planetary and astrophysical phenomena and yet we are only beginning to unravel how it actually operates in the natural environment or how it is initiated. Because of its intrinsically large scales (tens to hundreds of meters at atmospheric pressure) the mechanism is very difficult to produce in existing laboratory configurations. On the other hand immense electrical generators such as thunderstorms do provide the requisite conditions and there is every indication that this process is at work in many forms of lightning.

[58] But is this picture correct or even partially so? The question of what we know so far about RB was addressed in some detail in this paper. But where do we go from here?

5. Some Outstanding Issues

[59] A great deal of progress has been made in the last decade and a half on our basic understanding of RB and its potential role in affecting thunderstorm electrical activity and in initiating or driving lightning discharges of various types including stepped leaders, intracloud lightning, and high-altitude discharges. Both theory and observation have worked together over the years, one guiding and/or correcting the other, to provide an emerging, albeit rudimentary, image of how nature operates in the thunderstorm environment. Much scientific research remains however before the picture is completed. Some of the outstanding issues that merit further investigation include the following:

[60] 1. A comprehensive model for TGF generation is needed which should include three main elements, and should address some relevant questions: (1) description of RB based on a kinetic model; (2) self-consistent description of the thundercloud electrodynamics, namely, how the thunderstorm electric field affects RB, including the feedback due to electron avalanche which produces charge separation; and (3) model of generation of γ-rays due to RB and their propagation in the atmosphere.

[61] Among the questions that arise with regards to TGFs are as follows: (1) What role is played by EAS? (2) What role is played by meteorology, namely what geographic locations are preferential for TGF generation, and is there an optimal height for generating TGF? (3) Can TGFs be initiated at the height where relativistic electrons become magnetized? In this case the effects due to the geomagnetic field should be taken into account. (4) Are TGFs and NBPs related? (5) Do red sprites or blue jets produce TGFs? (5) Are TNFs produced in conjunction with TGFs?

[62] 2. A model for γ-bursts produced in stepped leaders is needed which should include two main elements and should address some relevant questions: (1) kinetic theory of RB at high electric field $E/E_c > 10$ and (2) theoretical description of stepped leaders including model of the formation of self-consistent governing fields [see *Raizer et al.*, 2010].

[63] Questions include the following: (1) Is there a feedback between RB and leader formation? (2) Is the electric field formed in the stepped leader sufficient to cause RB?

[64] Solution of the above problems will require theoretical and experimental efforts.

[65] 3. The feedback mechanism identified by Dwyer needs further elaboration in the context of the thunderstorm environment and the presence of EAS: Self-consistent electromagnetic and kinetic calculations with the thunderstorm electric field, EAS initiation, RB, and feedback included are needed.

[66] Relevant questions include the following: (1) If feedback limits the thunderstorm electric field to the threshold for RB then why do we observe lightning at all?

(2) Are the electrical conditions in the thunderstorm such that a strong RB develops before feedback can limit the field? (3) Do EAS locally enhance the ambient thunderstorm field sufficiently to initiate a discharge?

[67] 4. High current discharges and development of plasma instabilities: A detailed kinetic theory for the development of RB at high current levels has yet to be developed and is needed.

[68] Relevant questions include the following: (1) What are the current levels achieved in an RB discharge? (2) Are they sufficient to drive plasma instabilities? (3) What instabilities develop? (4) Are they observed in lightning discharges?

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