Runaway Breakdown and the Mysteries of Lightning

The observed electric fields in thunderclouds are generally too weak to initiate the atmosphere's electrical breakdown. But cosmic rays can play a surprising role in the drama of lightning.

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In 1749 Benjamin Franklin made a fundamental discovery—that lightning is an electrical discharge between a thundercloud and Earth. Such a discharge can only occur if the atmosphere, which is normally an insulator, undergoes electrical breakdown. Therein lies our first mystery.

The conventional breakdown taught in textbooks originates with free electrons heated in an electric field. Fast electrons in the tail of the thermal distribution function have enough energy—about 10–20 eV—to ionize matter and therefore to generate new free electrons. Electrons with lower energies disappear when they recombine with the ionized molecules in the air. When the electric field E exceeds a threshold, $E > E_{thr}$, the generation rate of new electrons from ionization exceeds their recombination rate, and the number of free electrons begins to exponentially increase: Electrical breakdown occurs. Because the electrons responsible for ionization are out in the high-energy tail of the distribution, the mean electron energy ε at which breakdown occurs does not normally exceed several electron volts. For instance, in air, $\varepsilon \approx 2$ eV. For conventional breakdown, E_{thr} is proportional to the number density of molecules. In air at atmospheric pressure, $E_{thr} \approx 2$ MV/m. All electric field measurements in thunderclouds, however, reveal values substantially less than those needed for conventional breakdown.[1] This is the long-standing mystery about lightning's origin.

More mysteries than one

Another mystery appeared with the discovery of strong isolated radio pulses generated during thunderstorms but not connected to lightning discharge.[2] Those roughly 5-μs radio events—called narrow bipolar pulses—can have astonishingly high power emissions, up to 100 GW. A closely related radio effect is the lightning-initiation pulse recently discovered by us and our colleagues,[3] which is always seen as the first isolated pulse at the beginning of a lightning discharge. That type of pulse is also bipolar, but its duration is only about 0.5 μs and its power is less than that of NBPs. What could generate such radio pulses?

Still another mystery arose after the discovery of intense x-ray bursts[4] both inside and beneath thunderclouds. With characteristic x-ray energies around 50 keV, the bursts last about 1 minute and are usually well correlated with lightning events. In addition, the *Compton Gamma Ray Observatory* and the *Reuven Ramaty High Energy Solar Spectroscopic Imager* satellites detected very intense millisecond gamma-ray bursts (0.05–10 MeV) that appeared at altitudes of about 500–600 km in the ionosphere.[5] The data analysis definitely indicated that the bursts were generated during thunderstorms. The existence of analogous gamma-ray emission (2–10 MeV) accompanying lightning was established by Charles B. Moore and colleagues in natural conditions and by Joseph Dwyer and coworkers in rocket-triggered lightning experiments.[6]

All of these results are of supreme interest: The existence of high-energy emissions indicates that relativistic electrons must play a significant role in thundercloud discharge. But that requires a new approach to the problem of lightning development, one based on relativistic kinetic theory. This new approach led to what is now called runaway breakdown (RB), depicted schematically in figure 1.

Runaway breakdown

The phenomenon of runaway breakdown is based on specific features of the interaction between fast particles and matter. The braking force F acting on an energetic particle as it traverses matter is determined by the ionization losses.[7] Figure 2 shows how that force decreases with increasing electron energy ε. The reason can be traced back to the famous experiments of Ernest Rutherford, who found that a fast electron interacts with electrons and nuclei of neutral matter as if they were all free particles; that is, according to Coulomb's law. Coulomb scattering has a Rutherford cross section σ proportional to $1/\varepsilon^2$. Therefore, in the nonrelativistic regime, the braking force is proportional to the molecular density N_m and inversely proportional to the electron energy—that is, $F \propto \varepsilon\sigma N_m \propto 1/\varepsilon$. For a given density of matter—whether a gold brick or Earth's atmosphere—this ionization "Coulomb friction" continues to decrease for about three decades of increasing electron energy. Eventually, the decrease slows down due to relativistic effects. For $\varepsilon \gtrsim 1.5$ MeV, the braking force reaches a minimum F_{min} and then slowly increases logarithmically.

The strong decrease in frictional scattering gives rise to the possibility of accelerated electrons in a thundercloud's electric fields. Indeed, in a constant electric field E that exceeds the critical field E_c, given by $E_c = F_{min}/e$, an electron with a sufficiently high energy $\varepsilon > \varepsilon_c \approx mc^2E_c/2E$ is continuously accelerated by the electric field (see the shaded region in figure 2). Such electrons were first predicted by Charles Thomson Rees Wilson in 1924.[8] Later

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they were called runaway electrons.

Note that at its minimum, the friction force still does not vanish. The finite value of F_{min} is determined by the energy lost by the moving electron as it ionizes molecules along its path. In the absence of an electric field, a 1-MeV electron traversing Earth's atmosphere would lose all its energy to ionization within a few meters. The electron becomes a runaway because of the electric field, and even then only where $E > E_c$.

The phenomenon of RB was predicted in 1992 by one of us (Gurevich), together with Gennady Milikh and Robert Roussel-Dupre.[9] The basic physical process is the generation of new fast electrons from the runaway-particle ionization of neutral molecules. Although the majority of newborn free electrons have low energies, some will have rather high energy, $\varepsilon > \varepsilon_c$. Those will also be accelerated by the field, become runaway electrons, and may in turn generate more free electrons with $\varepsilon > \varepsilon_c$. As a result, an exponentially growing runaway avalanche can occur.

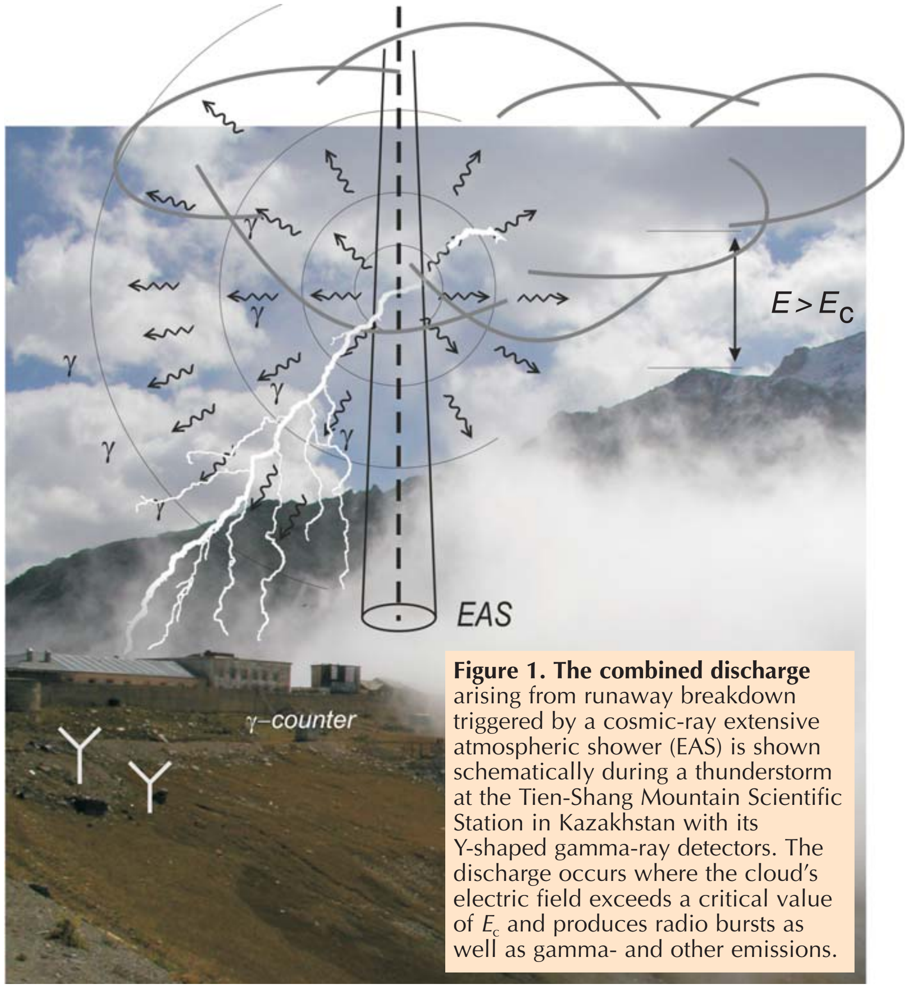


Figure 1. The combined discharge arising from runaway breakdown triggered by a cosmic-ray extensive atmospheric shower (EAS) is shown schematically during a thunderstorm at the Tien-Shang Mountain Scientific Station in Kazakhstan with its Y-shaped gamma-ray detectors. The discharge occurs where the cloud's electric field exceeds a critical value of E_c and produces radio bursts as well as gamma- and other emissions.

Along with the new runaways, a very large number of slow electrons are generated, which ultimately leads to the electrical breakdown of matter—RB. The full relativistic theory of RB was developed[10] by groups at the Lebedev Physics Institute, Los Alamos National Laboratory, Stanford University, and the Sarov Institute of Physics and Engineering. A full review of the theory is given in the final paper of reference 10.

Recall that in air at atmospheric pressure, the threshold field for conventional breakdown is about 2 MV/m. By contrast, the critical field E_c in the same conditions is only about 200 kV/m. Thus, RB occurs in a field that is an order of magnitude smaller than is needed classically.

But the condition $E > E_c$ alone is insufficient for RB. The presence of fast "seed" electrons, having energies above the critical runaway energy of 0.1–1 MeV, is also necessary. Even more important, the spatial scale of the electric field must substantially exceed the characteristic length l_a needed for the exponential growth of a runaway avalanche. That length proves to be very large in gas media: In air at atmospheric pressure, $l_a \approx 50$ m. This is the main reason that the effect is difficult to observe in gases under laboratory conditions.

The situation is radically different, however, in the atmosphere of a thunderstorm. There, the characteristic sizes of clouds are always much greater than l_a and, as we will see, fast seed electrons are also plentiful, effectively generated by cosmic rays. In addition, the maximum value of the electric field in thunderclouds[11] is often close to or even higher than the critical field E_c (see figure 3). Therefore, RB can indeed occur during thunderstorms.

The box on page 40 highlights some significant differences between runaway and conventional breakdown.

RB–EAS discharge

In the atmosphere, RB is stimulated by cosmic-ray secondary electrons.[12] A high-energy cosmic ray interacting with molecules in the atmosphere generates an extensive atmospheric shower (EAS) that consists of a large number of different elementary particles and fragments of nuclei.[13] For RB, the secondary electrons—arising from the mutual transformations of electrons, positrons, and gamma rays in the air via interactions that include bremsstrahlung, e^+e^- pair production, Compton scattering, and ionization—are the most important.

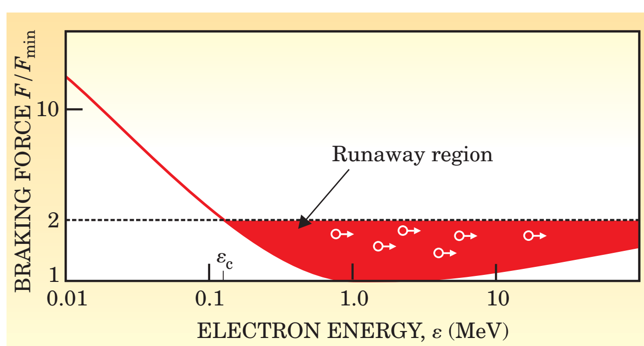


Figure 2. An electron loses energy as it ionizes atoms or molecules on its passage through matter. That braking force decreases with increasing electron energy until relativistic effects set in. With an electric field present, electrons above a certain critical energy ε_c can undergo runaway acceleration, shown schematically in the shaded region for an electrical field that is twice the critical field, $E = 2E_c$. The finite minimal braking force is $F_{min} = eE_c$.

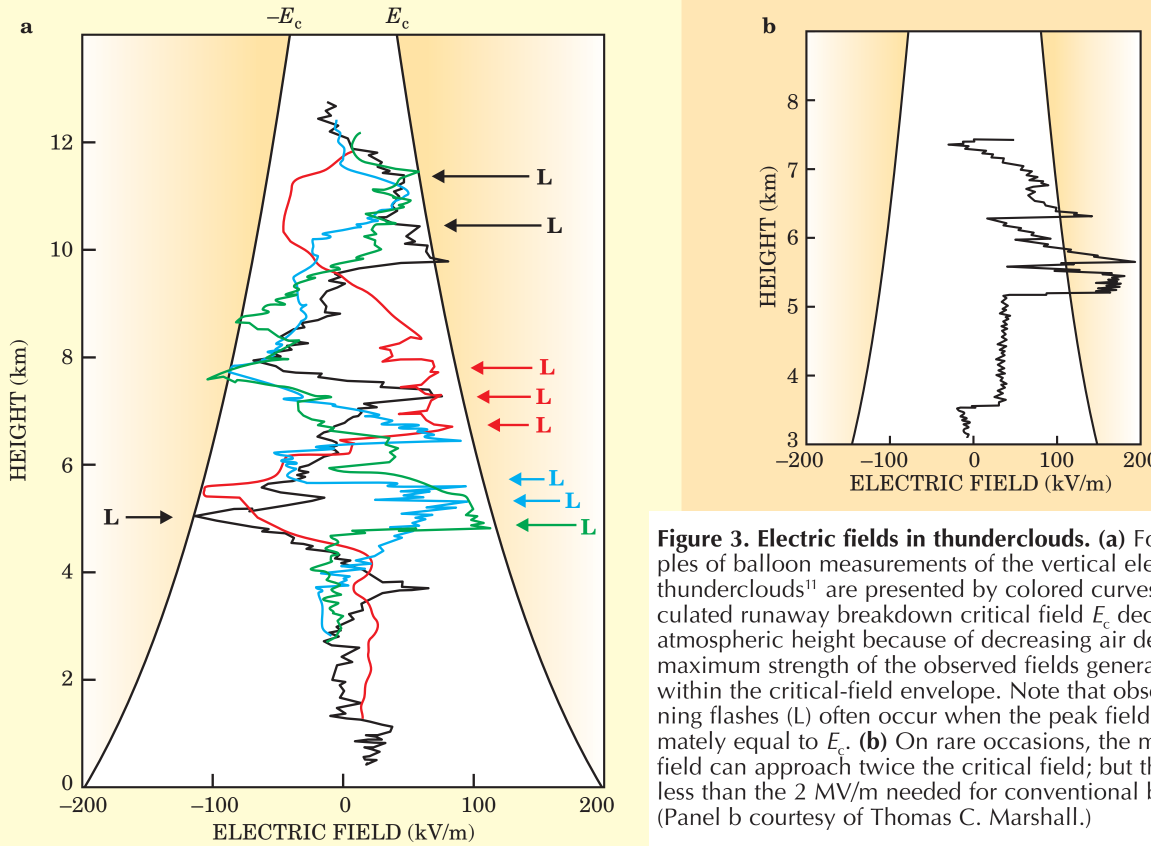


Figure 3. Electric fields in thunderclouds. (a) Four examples of balloon measurements of the vertical electric field in thunderclouds[11] are presented by colored curves. The calculated runaway breakdown critical field E_c decreases with atmospheric height because of decreasing air density. The maximum strength of the observed fields generally falls within the critical-field envelope. Note that observed lightning flashes (L) often occur when the peak field is approximately equal to E_c. **(b)** On rare occasions, the maximum field can approach twice the critical field; but that is still far less than the 2 MV/m needed for conventional breakdown. (Panel b courtesy of Thomas C. Marshall.)

Because the primary cosmic ray is highly relativistic, the newborn particles all travel at velocities close to the speed of light along the primary's direction. As a result, the velocity dispersion along the axis of the EAS is very small. However, the electromagnetic cascade of particles is spread out in the transverse direction, as follows from the decay of neutral pions into two momentum-conserving gamma rays. As a result, particles in the electromagnetic cascade of an EAS form a pancakelike structure, typically just a few meters along the direction of the primary cosmic ray's motion, but about 100–150 m across. The total number of secondary electrons n_s in an EAS is proportional to the primary's energy ε_p: For $\varepsilon_p = 10^{15}$ eV, $n_s \approx 10^6$, and for $\varepsilon_p = 10^{19}$ eV, $n_s \approx 10^{10}$. The average energy of EAS secondary electrons is about 30 MeV. Thus, given the high flux of cosmic rays, copious numbers of energetic electrons are always present in Earth's atmosphere.

Now consider what happens when an EAS crosses a thundercloud, as depicted in figure 1. In the region where the thundercloud's electric field is close to the critical value E_c, the number of fast secondary electrons in the "pancake" grows exponentially in a runaway avalanche (see figure 4a), and that increase rapidly grows with the maximum value of the electric field, E_m, in the thundercloud. Simultaneously, a tremendous number of thermal electrons are generated. Together, they produce an RB–EAS discharge[14] that is naturally accompanied by exponential growth, not only of the number of energetic electrons but also of positrons and gamma rays.

A calculated gamma-ray distribution is shown in figure 5. The secondary, higher-altitude maximum reflects the possibility of a self-consistent discharge developing inside the thundercloud where the electric field remains higher than E_c. The electrical discharge can spread within the cloud because of gamma-ray diffusion, pair production, and Compton scattering. The main energy source remains runaway electrons and their multiplication.

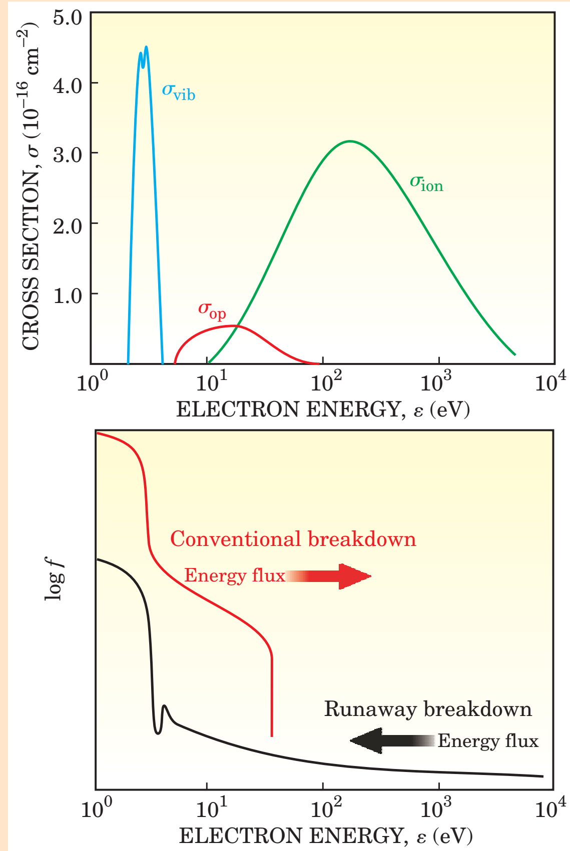
Figure 4b shows the total energy W dissipated by runaway electrons in an RB–EAS discharge. Most of that energy is used to ionize air molecules and thereby create a huge number ($\sim 10^{18}$–10^{21}) of slow thermal electrons, which are especially important. Under the action of the thundercloud's electric field, the thermal electrons, despite their short lifetimes, create a strong unipolar electric current pulse, which generates a bipolar radio pulse (figure 6a). That pulse can be seen from a large distance and can attain gigantic power, 300 GW and higher in some special conditions, which makes it the most powerful radio pulse created by a natural source at Earth's surface.

Now let's compare some recent observations with the theory.

Lightning initiation

The theory predicts that at the onset of lightning, the RB–EAS discharge should generate a few-megahertz bipolar radio pulse lasting about 0.5 μs. To check that prediction, we built a radio interferometer with high time resolution (as fast as 10 ns) and a wide bandwidth (0.1–30 MHz).[3] Nearly 1200 lightning events have now been recorded in different regions of Russia and Kazakhstan. Indeed, the results show that an isolated bipolar radio pulse is always present at the initiation of lightning (see figure 6b for an example). The pulse width is about 0.4–0.7 μs for low-altitude lightning (4–6 km). Typical pulse field amplitudes are 0.05–1.0 V/m. With typical distances to the source of 10–100 km, the electric current pulse is about 0.1–1 kA. The bipolar radio bursts reflect the fact that the underlying current pulse can have either

Conventional and Runaway Breakdown



Some of the significant differences between conventional and runaway breakdown can be understood in part from the figure shown at the right. With or without breakdown of any sort, free electrons in air lose energy mainly in three ways: They can excite molecular vibrations, emit light, or ionize atmospheric molecules. The top panel shows the cross sections for these processes. The bottom panel shows the qualitative behavior of the electron distribution functions *f* for conventional (red) and runaway (black) breakdown. The direction of energy flow is shown by arrows.

In air, conventional electric breakdown requires an electric field that exceeds a threshold of about 2 MV/m. Conventional breakdown does not require high-energy electrons in order to get started: The electric field is high enough to surmount collisional losses of the thermal electrons and generate a net energy flux from the bulk thermal population into suprathermal particles. Conventional-breakdown electrons are concentrated in the low-energy range $0 \le \varepsilon \le 10$ eV, above which the distribution function falls very rapidly. Because of this, electrons lose their energy mostly to optical emission and the excitation of molecular nitrogen vibration levels. Only part of the tail of the distribution function works for ionization; there is no gamma-ray emission.

In runaway breakdown (RB), the critical electric field E_c is one tenth of the conventional threshold field. The low-energy electrons cannot get enough energy from this field to overcome the collisions with air molecules. But for relativistic electrons, the energy losses can be less than the work done by the electric field, as depicted in figure 2 on page 38. Those fast electrons gain still more energy from the electric field and thus stimulate RB. In the runaway regime, the distribution function falls with electron energy only as $\varepsilon^{-1.2}$. The energy flows from energetic (relativistic) electrons to low-energy (thermal) electrons. Energy is lost mostly in the ionization process; less than 1% of the energy goes into optical emission. Thus, RB is not as bright as conventional breakdown, although, as explained in the text, gamma-ray emission takes place. Recombination occurs only for low-energy electrons—less than about 2 eV—in three-body collisions with molecular oxygen. Since the ionization is very effective and the recombination is relatively weak, the number of free thermal electrons becomes very large, about a million for each runaway electron under quasi-stationary conditions.[18]

negative or positive polarity, as shown in figure 6a.

The observed emission is omnidirectional, which means that the current is generated by thermal electrons moving at only about 10^6 cm/s in the thundercloud's electric field. To produce the observed radio pulse, the density of free electrons generated by the "ionizer" must grow very rapidly. The analysis of the observational data showed that the ionizer's speed is nearly the speed of light, consistent with the notion of a cosmic-ray stimulated RB process.

Of course, we don't know what actually initiates lightning, but the recent observations have demonstrated that RB–EAS discharge could be the trigger. The observed values of the pulse's maximum electron current can be reached if the cosmic-ray energy ε_p is approximately 10^{16}–10^{17} eV and the maximum thunderstorm electric field E_m/E_c is approximately 1.2–1.5. A preliminary analysis of lightning statistics shows that the flux of cosmic-ray particles with $\varepsilon_p \approx 10^{16}$ eV is indeed sufficient.[3]

Narrow bipolar pulses

The astonishing natural phenomenon of a narrow bipolar pulse (NBP) is an isolated discharge in a thunderstorm's atmosphere that generates enormously powerful radio emission but lasts only a few microseconds. NBPs are observed in two forms, shown in figure 6c: negative and positive. In recent years, intensive measurements of NBPs have been made with the Los Alamos Sferic Array (spread across several hundred kilometers), the *FORTE* satellite, the National Lightning Detection Network, and other installations (see D. A. Smith's papers in reference 2).

NBP emission has a low frequency (0.2–0.5 MHz) and a high amplitude ($E \approx 10$–100 V/m). The measurements allow one to estimate the underlying electric current pulses for NBPs: They are unipolar, have characteristic widths of about 5 μs, and have maxima of about 30–100 kA. The data show that, as with the much shorter lightning-initiation pulses, the electric current is gener-

Derived Energies and Currents

Observation	Energy of primary cosmic ray particle, ε_p	Maximum electron current, J_m
Radio–Extensive atmospheric shower simultaneity	10^{14}–10^{15} eV	1–10 A
Lightning initiation	10^{16}–10^{17} eV	0.1–1 kA
Narrow bipolar pulses	10^{17}–10^{19} eV	10–100 kA

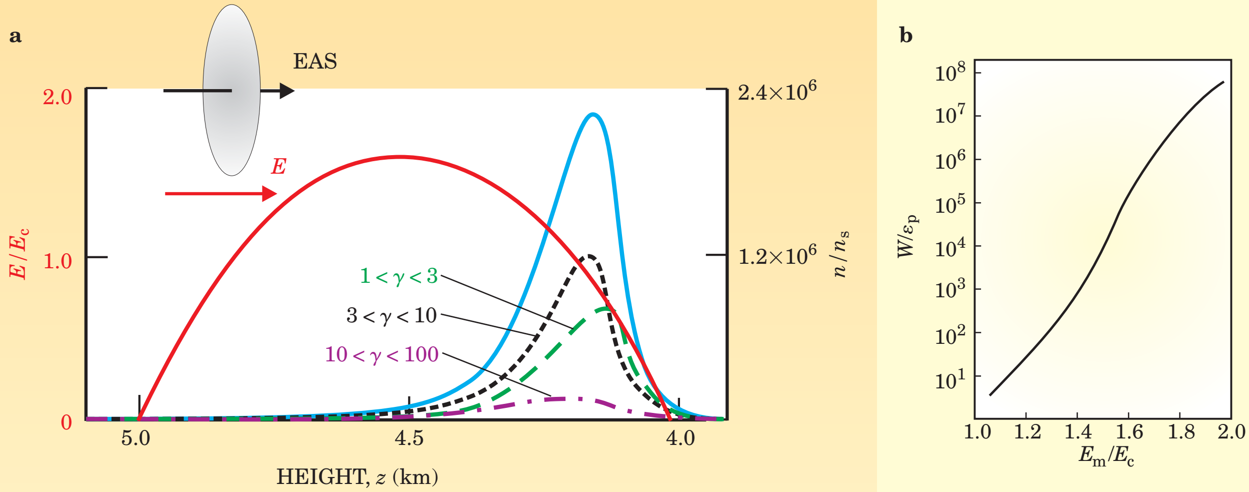


Figure 4. Runaway breakdown. (a) The calculated number of relativistic electrons n, normalized to the number of cosmic-ray secondary electrons n_s, is greatly amplified when an extensive atmospheric shower enters the atmosphere and the RB–EAS discharge takes place. The model thunderstorm's electric field $E(z)$ is shown in red. The directions of the pancakelike EAS and the electric field E are shown. The thundercloud's maximum electric field E_m was chosen at $z_0 = 4.5$ km to be 1.6 times the critical field E_c for runaway acceleration to occur. The height dependence of the relativistic electrons is shown for various ranges of the relativistic factor γ and for the total (solid blue line). **(b)** The full energy W dissipated by runaway electrons in an RB–EAS discharge due to the work of the thundercloud's electric field. That energy grows rapidly with maximum electric field because of the rapid increase in the number of runaway electrons and in fact exceeds the energy ε_p of the triggering cosmic-ray particle by 3–5 orders of magnitude. (Adapted from ref. 14.)

ated by thermal electrons and the ionizer moves at a very high speed.[2,15]

The optical emission of an NBP discharge is very low, at least an order of magnitude less than a usual lightning flash, although the power of NBP radio emission is an order of magnitude higher. Detailed studies of radio pulse propagation and ionospheric reflection have localized NBP discharges in the atmosphere with great accuracy: They are high-altitude discharges mainly in the 10–20 km range. There is a sharp peak at 18 km for negative NBPs and at 13 km for positive ones (Smith et al., 2004, in reference 2).

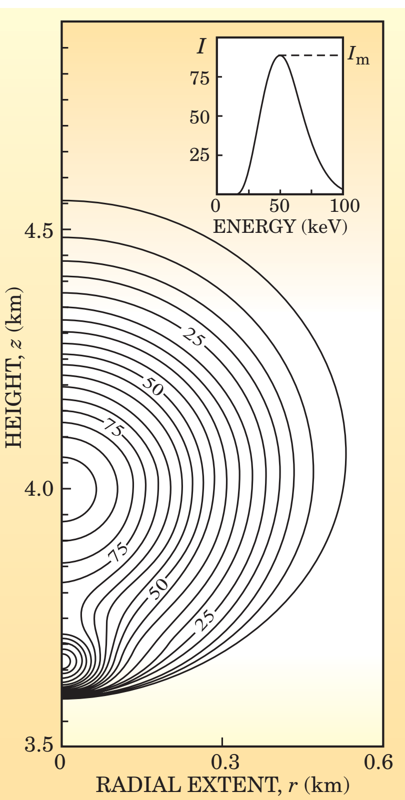


Figure 5. Gamma-ray emission is widespread around the main discharge area. The contour curves show the maximum gamma spectrum intensity I_m in a vertical plane when the primary cosmic-ray particle passes the point $z = 3.6$ km. Two maxima are clearly seen, one near that primary and the other inside the thundercloud ($z \approx 4$ km). The inset shows the characteristic form of the gamma-ray spectrum. The spectrum falls at low energies due to photoionization and at high energies due to Compton losses.

The very high power of NBP radio pulses is a consequence of the coherence of the emission process: The power grows with the square of the current. Hence, a pulse with a current exceeding 100 kA can emit a power of 100–300 GW and an energy of 0.2–1 MJ. We see that, for an NBP, the thunderstorm's electric field puts a gigantic amount of work into generating radio emission.

The detailed analysis of observational data allowed Abram R. Jacobson to speculate about a possible connection between NBPs and RB.[15] An actual comparison with the RB–EAS discharge theory[14] shows a reasonable agreement for $E_m \approx 1.4–1.5\ E_c$.

Radio–EAS simultaneous measurements

So far, we have discussed only radio observations. To verify the theory and to better understand the main physical processes, it is important to see if radio emission and EASs occur simultaneously. Such experiments were conducted[16] at an altitude of 3300–3500 m at the Tien-Shang Mountain Scientific Station, shown in figure 1. A special trigger array using Geiger–Müller counters was set up. The array could detect pulses of gamma emission from EASs generated by cosmic-ray particles having energies ε_p between 2×10^{14} and 10^{15} eV. The average time interval between EASs observed by the array was 2.5 s.

A signal from that EAS antenna triggered the radio receivers. During two thunderstorms, 150 gamma and radio pulses were observed simultaneously, to within 50 μs. During quiet times with no thunderstorms, radio pulses were absent but EASs were always seen.

The observed radio pulses were bipolar with full widths of 0.4–0.7 μs. The underlying electric current pulses were estimated to have maxima of a few amperes.

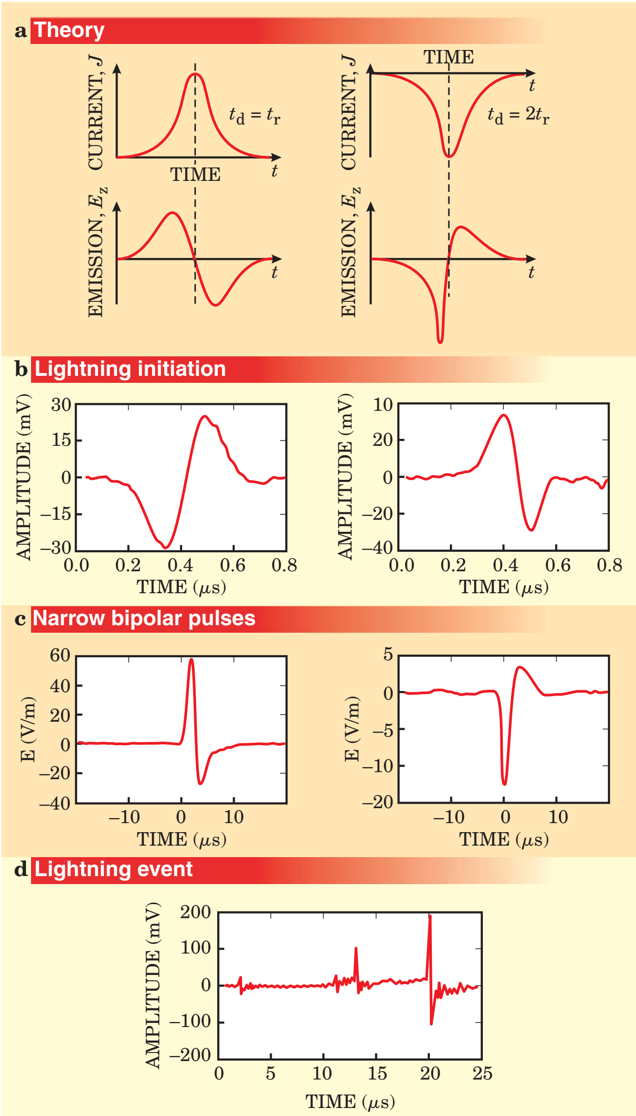


Figure 6. Radio emission associated with the runaway breakdown discharge. **(a)** Theoretical curves for positive (left) and negative (right) electric current pulses. The current's rise time t_r is determined by the RB process and is inversely proportional to the density of air molecules. The current's decay time t_d is determined by the electrons' recombination in three-body collisions and is inversely proportional to the square of the density of air molecules. Thus, the pulse's duration lengthens with height in the atmosphere; its shape also changes as its decay time grows. The unipolar current pulse generates a bipolar pulse of radio emission. The radio-pulse amplitude is fully determined by the current and thus has analogous power and height dependences. **(b)** Observations of isolated bipolar radio pulses characterizing the lightning initiation process. The pulses were at altitudes of 4–6 km.[3] **(c)** Observations of both positive and negative narrow bipolar pulses (from Smith et al., 2002, in ref. 2), at heights of 13–18 km. The changes in duration and form of the narrow bipolar pulses with respect to the lightning initiation pulses agree with the theory. **(d)** The first three radio pulses of a typical lightning event.

There is reasonable agreement between the radio observations and the prediction of the RB–EAS theory, assuming that the maximum electric field in the thundercloud, E_m, is about 1.2–1.4 E_c.

Pulling it all together

The table on page 40 shows the rough proportionality between electron current maxima and cosmic-ray energies that results from comparing data with the theory. To make the comparison, the rather high values of 1.2–1.5 were assumed for E_m/E_c. Direct observations at both low and high altitudes usually give lower values, but the higher values have been seen at altitudes of 4–6 km (see figure 3b). We note that NBPs are seen in the most active storm regions, and some researchers[2] assume that a strong positively charged layer can exist at heights around 15–16 km.

As we have seen, evidence shows that the RB–EAS discharge could serve to trigger lightning. Still, much more has to be done both experimentally and in the theory. For example, it is possible that RB can help solve yet another lightning mystery: How does the conductivity grow by several orders of magnitude to allow the widely dispersed electric charge in a thundercloud to gather—in what is known as a "stepped leader"—and be transported in a few milliseconds, either to Earth or to another cloud? Recently, Dwyer and his colleagues observed energetic microsecond bursts of gamma emission generated by runaway electrons; the bursts were well correlated with the leader steps in cloud-to-ground lightning.[17] According to Dwyer's suggestion, the runaways arise in a small local region where electric fields could be extremely strong.

Intense radio pulses are of great significance. The RB–EAS theory predicts a strong growth of the radio pulse power with the cosmic-ray particle energy. Those radio pulses could be easily observed at great distances, up to 1000 km. We suppose that such pulses would also look like NBPs. Detailed studies of this phenomenon could lead to a new method for radio detection of very high-energy cosmic-ray particles, ($\varepsilon \geq 10^{17}$ eV).

Being a relativistic kinetic process, the RB–EAS discharge is accompanied by an exponential growth in the number of positrons and gamma rays, which opens a wide opportunity for experimental studies—for example, of the 511-keV e^+e^- annihilation line. Of special interest are the extremely strong pulses of gamma emission, predicted by the theory, that accompany NBP events. That effect should be carefully studied experimentally, because it takes place around the height where commercial airplanes fly. For gamma pulses generated at heights of 15–20 km, satellite measurements would be convenient. Moreover, satellite studies could help establish the origin of very strong millisecond pulses of gamma emission observed by David Smith and his colleagues[5] and the possible connection of those pulses with high-altitude lightning and discharges between thunderclouds and the ionosphere (see the article "Sprites, Elves, and Glow Discharge Tubes" by Earle Williams in PHYSICS TODAY, November 2001, page 54).

We see that processes taking place in quite different physical regions can act in concert to determine the state of our electric environment. Consider too that the atmosphere is a rather dense medium, where the free path of a thermal electron is measured in microns and its lifetime in nanoseconds. Yet giant macroscopic processes, kilometers across, are determined by purely relativistic kinetic effects that occur in relatively weak electric fields. There is a clear need for a detailed scientific program that will allow the continuation and extension of investigations into this truly wonderful physical phenomenon.

Finally, we note that according to the theory, RB is also possible in a condensed medium. The critical electric field value is $E_c = 1.8\,\rho$ MeV/cm, and the avalanche length is $l_a = 6.1\,\rho^{-1}$ cm, where ρ is the condensed matter density in grams per cubic centimeter. An MeV electron beam crossing a dielectric plate of size L where the condition $E > E_c$ is fulfilled will generate a flux of gamma emission and energetic electrons that grows exponentially with L/l_a. The realization of RB in condensed matter may give rise to many very interesting prospects. We hope that efforts in this direction will be undertaken.

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References

1. D. R. MacGorman, D. Rust, *The Electrical Nature of Storms*, Oxford U. Press, New York (1998).
2. D. M. LeVine, *J. Geophys. Res.* **85**, 4091 (1980); D. A. Smith et al., *J. Geophys. Res.* **104**, 4189 (1999); D. A. Smith et al., *J. Geophys. Res.* **107**, D134183 (2002); D. A. Smith et al., *Radio Sci.* **39**(1), RS1010 (2004).
3. A. V. Gurevich, L. M. Duncan, A. N. Karashtin, K. P. Zybin, *Phys. Lett. A* **312**, 228 (2003).
4. M. D. McCarthy, G. K. Parks, *Geophys. Res. Lett.* **12**, 393 (1985); K. B. Eack et al., *J. Geophys. Res.* **101**, 26637 (1996). A. P. Chubenko et al., *Phys. Lett. A* **275**, 90 (2000); M. B. Brunetti et al., *Geophys. Res. Lett.* **27**, 1599 (2000); T. Torii et al., *J. Geophys. Res.* **107**, 4324 (2001); V. V. Alexeenko et al., *Phys. Lett. A* **301**, 299 (2002); A. P. Chubenko et al., *Phys. Lett. A* **309**, 90 (2003).
5. G. J. Fishman et al., *Science* **264**, 1313 (1994). D. M. Smith et al., *Science* **307**, 1085 (2005).
6. C. B. Moore, K. B. Eack, G. D. Aulich, W. Rison, *Geophys. Res. Lett.* **28**, 2141 (2001); J. R. Dwyer et al., *Science* **299**, 694 (2003); J. R. Dwyer, *Geophys. Res. Lett.* **31**, L12102 (2004); J. R. Dwyer et al., *Geophys. Res. Lett.* **31**, L05118 (2004).
7. H. A. Bethe, *Ann. Phys.* (Leipzig) **5**, 325 (1930).
8. C. T. R. Wilson, *Proc. Cambridge Philos. Soc.* **22**, 34 (1924).
9. A. V. Gurevich, G. M. Milikh, R. A. Roussel-Dupre, *Phys. Lett. A* **165**, 463 (1992).
10. A. V. Gurevich, K. P. Zybin, *Phys. Lett. A* **237**, 240 (1998); A. V. Gurevich, H. Carlson, Y. V. Medvedev, K. P. Zybin, *Phys. Lett. A* **275**, 101 (2000); R. A. Roussel-Dupre, A. V. Gurevich, A. V. Tunnel, G. M. Milikh, *Phys. Rev. E* **49**, 2257 (1994); E. M. D. Symbalisty, R. A. Roussel-Dupree, V. B. Yuhimuk, *IEEE Trans. Plasma Sci.* **26**, 1575 (1998); N. G. Lehtinen, T. F. Bell, U. S. Inan, *J. Geophys. Res.* **104**, 24699 (1999); L. P. Babich, I. M. Kutsyk, E. N. Donskoy, A. Y. Kudryavtsov, *Phys. Lett. A* **245**, 460 (1998); A. V. Gurevich, K. P. Zybin, *Phys. Usp.* **44**, 1119 (2001).
11. T. C. Marshall, M. D. McCarthy, W. D. Rust, *J. Geophys. Res.* **100**, 7097 (1995). T. C. Marshall et al., *Geophys. Res. Lett.* **32**, L03813 (2005).
12. A. V. Gurevich, K. P. Zybin, R. A. Roussel-Dupre, *Phys. Lett. A* **254**, 79 (1999).
13. T. K. Gaisser, *Cosmic Rays and Particle Physics*, Cambridge U. Press, New York (1990).
14. A. V. Gurevich, Y. V. Medvedev, K. P. Zybin, *Phys. Lett. A* **329**, 348 (2004).
15. A. R. Jacobson, *J. Geophys. Res.* **108**, D244778 (2003).
16. A. V. Gurevich, et al., *Phys. Lett. A* **325**, 389 (2004).
17. J. R. Dwyer et al., *Geophys. Res. Lett.* **32**, L01803 (2005).
18. A. V. Gurevich, Y. V. Medvedev, K. P. Zybin, *Phys. Lett. A* **321**, 179 (2004). ■