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Implications of x-ray emission from lightning

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[1] *Dwyer et al.* [2003, 2004a] recently reported measurements of bursts of x-rays, with energies up to ~250 keV, originating from dart leaders and possibly the return strokes of rocket-triggered lightning. In this paper, these x-ray observations are compared with the relativistic runaway electron avalanche (RREA) model. It is found that for dart leaders the standard RREA model is inconsistent with the observed spectrum and flux of the x-ray emission. This result implies that the cold runaway electron model may be applicable to dart leaders. In this model, runaway electrons are directly accelerated out of the bulk electron population, produced by the ionization of the neutral atoms. However, this mechanism requires an electric field an order-of-magnitude larger than the conventional breakdown field. Because the flux of runaway electrons is very sensitive to the electric field strength, x-ray observations of lightning provide a novel tool for determining the fields associated with the leaders. *INDEX TERMS:* 0654 Electromagnetics: Plasmas; 3300 Meteorology and Atmospheric Dynamics; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3359 Meteorology and Atmospheric Dynamics: Radiative processes. **Citation:** Dwyer, J. R. (2004), Implications of x-ray emission from lightning, *Geophys. Res. Lett.*, *31*, L12102, doi:10.1029/2004GL019795.

1. Introduction

[2] Three recent papers [*Dwyer et al.*, 2003, 2004a, 2004b] have reported measurements of energetic radiation during rocket-triggered lightning made at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL [*Rakov and Uman*, 2003]. The following is a summary of the results presented by *Dwyer et al*. based upon the observation of 63 dart leader/return stroke sequences: The majority of the observed x-ray emission is spatially and temporally associated with the dart leaders and possibly the early stages of the return strokes, originating from the lowest 50 m or so of the lightning channel. The emission intensifies as the leader approaches the ground, with the maximum occurring immediately before or at the very beginning of return stroke. At 15 m from the channel, the energy spectrum of the x-rays typically extends up to about 250 keV, with the majority of the emission well below this energy. The x-ray emission occurs in association with over 80% of the dart leader/return stroke sequences, showing that it is a common feature of triggered lightning. Because triggered lightning strokes are similar to the subsequent strokes in natural lightning, it is likely that such x-ray emission also occurs during natural lightning. Furthermore, *Moore et al.* [2001] has reported x-ray emission from the stepped leaders of natural lightning, so it is plausible that the mechanism for producing the x-ray emission from dart leaders is applicable to stepped leaders as well.

[3] At present, the only viable models for explaining these x-ray observations of lightning involve runaway electrons. The mechanism for producing runaway electrons is illustrated in Figure 1, which shows the effective frictional force due to collisions of electrons with air as a function of the electron's kinetic energy. For kinetic energies $K > K_{\mathrm{th}}$, the rate of energy gain from the electric field, eE, exceeds the rate of energy loss due to collisions, making it possible for electrons to acquire large amounts of energy. Note that the effective frictional force shown in Figure 1 depends linearly on the air density. Therefore, the electric field necessary for electrons to runaway also depends linearly on the density and so is lower at high altitudes. For electric field strengths much less than the critical field, E_{c}, only relativistic electrons can run away. Alternatively, for large electric fields ($E > 0.5E_{\mathrm{c}}$), because K_{th} decreases with increasing E, the high-energy tail of the bulk free-electron population can run away as well. However, unless this electric field enhancement occurs very quickly, ionization and charge transport should neutralize the field, preventing this "cold" runaway from occurring.

[4] In recent years, the relativistic runaway electron avalanche (RREA) model has gained great popularity, becoming the standard runaway breakdown model for atmospheric processes [*Gurevich et al.*, 1992; *Gurevich and Zybin*, 2001]. In this model, energetic electrons, e.g., from atmospheric cosmic-rays or radioactive decay, run away when the field exceeds E_{th}, which is about a factor of 100 smaller than E_{c}. These runaway electrons will produce more energetic seed electrons, with $K > K_{\mathrm{th}}$, via hard elastic scattering with electrons in the air molecules. These seed electrons subsequently run away, producing more energetic seed electrons and so on, resulting in an avalanche of high-energy electrons that increases exponentially with time and distance. The runaway electrons in the avalanche produce large quantities of ionization plus x-rays through bremsstrahlung interactions with air.

[5] In the following sections, the x-ray emission from the dart leaders will be compared with the predictions of the RREA model. It will be shown that the RREA model does not produce enough x-rays to account for the observations and that the energy spectrum of the x-rays predicted by the RREA model is not consistent with the observed spectrum.

2. X-ray Flux From the RREA Model

[6] As an illustration, Figure 2 shows the results of a detailed Monte Carlo simulation of the runaway breakdown of air in the high electric field associated with a dart leader,

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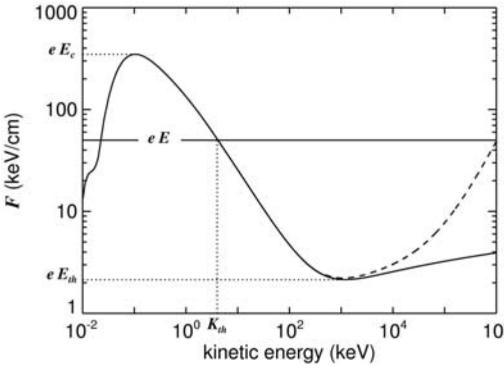

Figure 1. The effective frictional force experienced by a free electron moving through air at STP as a function of kinetic energy [*International Commission on Radiation Units and Measurements*, 1984]. The solid curve is due to inelastic scattering of the electron with air molecules, and the dashed curve includes the effects of bremsstrahlung emission. The horizontal line shows the electric force from a 50 kV/cm electric field. Runaway electrons occur for kinetic energies greater than the threshold energy, $K > K_{\text{th}}$. E_{c} is the critical electric field strength for which all free-electrons will run away, and E_{th} is the minimum field needed to produce runaway electrons.

using the geometry for which x-rays were observed by *Dwyer et al.* [2004a]. The 3-D simulation includes, in an accurate form, all the relevant physics for describing the interactions of photons and energetic electrons with air [see *Dwyer*, 2003]. In the simulation shown in Figure 2, a highly optimistic electric field configuration was used in order to enhance the amount of runaway breakdown. The electric field from the dart leader was modeled using a spherically symmetric surface charge centered 60 m above the ground with a radius of 10 m. The charge was chosen to give a 2 MV/m field at the surface. An image charge was placed at −60 m, and a large scale vertical electric field of 1 MV/m was added, bringing the total field at the leading edge of the leader to 1.2 times the breakdown field. Even with this exaggerated field, many times larger than previously inferred for triggered lightning dart leaders [*Miki et al.*, 2002; *Jordan et al.*, 1997], the simulation does not produce enough x-ray emission to account for the observations. Indeed, even if the avalanche happened to directly hit the detector along its field of view, the simulation produces a total x-ray energy per unit area of only 1.3 MeV/m^2, while *Dwyer et al.* reported that it frequently surpassed 2×10^4 MeV/m^2. Using an average x-ray energy of 100 keV, consistent with the *Dwyer et al.* observations, this measurement corresponds to 2×10^5 photons/m^2, which is several orders of magnitude larger than the 1.2 photons/m^2 produced by the simulation.

[7] While one simulation cannot be used to rule out the RREA model, the argument that the RREA model does not produce enough runaway electrons and x-rays can be shown to be independent of the details of the electric field configuration as follows: The number of runaway electrons, produced by N_o energetic seed electrons, is given by

$$N_{RE} = N_o \exp\left(\int_0^L \frac{dz}{\lambda(z)}\right), \tag{1}$$

where L is the length of the electric field region, and λ is the characteristic length for an avalanche to develop. The elementary theory of runaway breakdown [*Gurevich and Zybin*, 2001] gives

$$\lambda(z) = \frac{10.8MV}{E(z)}, \tag{2}$$

where E is the electric field magnitude, which is assumed to be in the z-direction and independent of x and y over the width of the avalanche. A more accurate expression for λ is found using a detailed 3-D Monte Carlo simulation of the runaway breakdown of air [*Dwyer*, 2003]. For 300 kV/m $\leq E/n \leq$ 2500 kV/m, λ is well fit by the empirical formula

$$\lambda(z) = 7200kV[E(z) - (275kV/m)n]^{-1}, \tag{3}$$

where n is the density of air relative to that at STP. The Monte Carlo simulation also shows that when elastic scattering is included, the threshold for runaway breakdown E_{th}/n = 284 kV/m, slightly higher than the value shown in Figure 1, which only includes the effects of inelastic scattering. For E/n < 300 kV/m, the length-scale needed to produce substantial numbers of runaway electrons is several kilometers at STP, too long to be applicable to the dart leader observations.

[8] From equations (1)–(3), the number of runaway electrons is then given by

$$N_{RE} \leq N_o \exp(V/7.2MV), \tag{4}$$

where V is the total voltage drop in the avalanche region. The upper limit in equation (4) is very robust: It is valid for

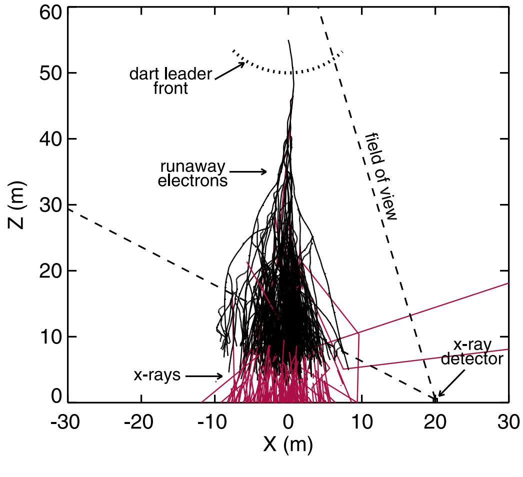

Figure 2. Monte Carlo simulation of the RREA model of runaway breakdown, showing runaway electrons (black trajectories) and x-rays (red trajectories) for the configuration observed by *Dwyer et al.* [2004a]. The simulation is run until all x-rays and electrons either hit the ground or are absorbed. However, in order to show the spray of x-rays at the bottom, the electrons are only plotted for the first 1.5×10^{-7} s of the avalanche. The field of view of the lowest two collimated detectors described by *Dwyer et al.* [2004a] is also shown. These two detectors had the biggest x-ray signals for all the events observed.

both expressions for λ given by equations (2) and (3), and is independent of the air density and the spatial variation of the electric field.

[9] For negative cloud-to-ground lightning, the electric potential of the dart leader is about 15 MV [*Rakov and Uman*, 2003]. Plugging 15 MV into equation (4) gives $N_{\rm RE} \leq 8\ N_{\rm o}$. In other words, at best, very little multiplication is occurring during the avalanche. *Dwyer et al.* [2004a] estimated that the peak flux of x-rays is at least 10^{12} photons/($\rm m^2$ s) at the dart leader front. For energetic electrons moving through 50 m of air, the number of emitted x-rays (>30 keV) is much less than the number of electrons. Therefore, conservatively, the number of energetic seed electrons that must be injected into the acceleration region is $N_{\rm o} > 10^{11}\ (\rm m^2\ s)^{-1}$. The number of energetic seed electrons that were present at the time of the triggered lightning events was measured on the ground to be $<250\ (\rm m^2\ s)^{-1}$, which agrees with the accepted value of the cosmic-ray flux at sea level but contradicts the value required by the RREA model.

3. X-ray Spectrum From the RREA Model

[10] A more serious difficulty for the RREA model is the energy spectrum of the emitted x-rays, which typically does not extend much above 250 keV for dart leaders [*Dwyer et al.*, 2004a]. Because a bremsstrahlung spectrum reaches up to the energy of the source energetic electrons, 250 keV can also be taken as a reasonable upper energy for the runaway electrons.

[11] As can be seen in Figure 1, over a broad range of energies the effective frictional force due to collisions, *f*, is approximately equal to the minimum ionizing value. Furthermore, once created, runaway electrons quickly accelerate, becoming minimum ionizing on a small length scale compared to λ. As a result, when calculating the average energy of runaway electrons, the effective frictional force can be approximated by $f(z) \approx f_{\rm o} \times n(z)$, where $f_{\rm o}$ is a constant between 214 and 300 kV/m. Using equation (1), the average kinetic energy of the runaway electrons in the avalanche, measured at the bottom of the avalanche region ($z = L$), is then

$$\overline{K} \approx [(eE(z) - f(z))\lambda(z)]_{avg}, \qquad (5)$$

where the right hand side is averaged over the initial positions of all the runaway electrons in the avalanche.

[12] Using the expression for λ in equation (2) gives $\overline{K} \approx$ 10.8 MeV when the average field is much bigger than (300 kV/m) × *n*. Using, instead, the empirical formula for λ in equation (3) gives the more accurate value of $\overline{K} \approx$ 7.2 MeV, which is valid as long as the average field is bigger than about (400 kV/m) × *n*. For the RREA model, 7.2 MeV is therefore the characteristic energy of the runaway avalanche and is independent of the details of the electric field configuration, the temperature, the density or the length of the avalanche region. This result has been verified by detailed Monte Carlo simulations, which show that the average runaway electron energy is within 10% of 7.2 MeV for the fields 400 kV/m $\leq E/n \leq$ 2500 kV/m. At very low fields, $\overline{K}$ is reduced slightly. For example, $\overline{K}$ = 5340 ± 30 keV for E/n = 300 kV/m, and $\overline{K}$ = 5250 ± 50 keV for E/n = 290 kV/m, still in the multi-MeV range. Consequently, these runaway electrons will produce bremsstrahlung with most of the x-ray energy occurring above 250 keV.

[13] Because the avalanche of runaway electrons also produces a large number of low-energy electrons below the runaway threshold, when these electrons are taken into account, the average energy of all free electrons produced in the avalanche is substantially lower. However, as will be shown below, these low-energy electrons do not contribute significantly to the bremsstrahlung emission at the bottom of the avalanche region.

[14] The differential energy spectrum of secondary electrons produced by a fast runaway electron is given by the Møller scattering cross-section and is proportional to K^{-2}, where *K* is the kinetic energy of the secondary electron. The instruments used by *Dwyer et al.* were covered with a 0.3 cm thick aluminum window and so were not sensitive to x-rays below about 30 keV. Integrating the secondary electron spectrum from 30 keV to 250 keV and again from 250 keV up gives $N_{LE} \approx 7.6 N_{RE}$, the number of low-energy free electrons, compared to the number of runaway electron. For E/n > 300 kV/m, the runaway threshold, $K_{\rm th}$, is below 234 keV. Electrons below this threshold will quickly lose energy and stop, and electrons above this energy will rapidly gain energy, obtaining an average of 7.2 MeV. Because the runaway electron threshold rapidly decreases as the electric field increases, 7.6 can be taken as an upper limit on the ratio of low-energy electrons to runaway electrons.

[15] The average distance traveled by the energetic runaway electrons is λ in the avalanche region plus an additional 10–100 m to stop after the runaway electrons leave the high field region, if the acceleration region is not immediately above the ground. On the other hand, the average distance traveled by the low-energy electrons that do not run away is very small and in all cases is less than 1 m. As a result, conservatively, the runaway electrons always travel at least 3 times farther than the low-energy electrons.

[16] Integrating the bremsstrahlung cross-sections [*Koch and Motz*, 1959] above and below 250 keV gives the relative amount of emission in these two regions. Including the low-energy electrons, as discussed above, and using the most optimistic assumptions to enhance the low-energy emission, the total energy flux of x-rays exiting the bottom of the source region above 250 keV will be at least 10 times greater than the amount between 30–250 keV, and the number of photons emitted above 250 keV will be no less than 70% the number between 30–250 keV. Including details such as the dependence of the runaway electron threshold on the electric field strength only increases the relative amount of emission above 250 keV. Indeed, Monte Carlo simulations for electric fields 290 kV/m < E/n < 2500 kV/m confirm these results. For E/n > 2500 kV/m, $K_{\rm th}$ is below 30 keV, which corresponds to the minimum x-ray energy measured. Therefore, for E/n > 2500 kV/m, only the runaway electrons will contribute to the x-ray emission and the relative amount of x-ray emission above 250 keV will be even larger.

[17] Another feature that suppresses the amount of low-energy x-ray emission is while all the runaway electrons reach the bottom of the high field region, regardless of

where they are generated, the low-energy electrons are spread out, mostly over the range of λ from the bottom. If λ is large, such as occurs for smaller E fields, then most of the low-energy x-rays below 250 keV will not make it to the bottom of the avalanche region and consequently will not be observed.

[18] These results for the relative amount of x-ray emission above and below 250 keV are in direct contradiction with the dart leader observations, which showed that almost the entire energy deposited in the detectors came from x-rays with energies below 250 keV [*Dwyer et al.*, 2004a]. According to the model, the number of emitted photons above 250 keV is comparable to that below 250 keV, so the lack of high-energy x-rays cannot be explained away as due to poor counting statistics. Since these results are independent of the air density, the presence of a low-density channel through which the dart leader may be propagating does not help the RREA model. Also, the conclusions are not sensitive to spatial dependencies of the electric field.

4. Cold Runaway Electron Model

[19] To the author's knowledge, the only viable alternative to the RREA model is the so-called cold runaway electron model, which describes the production of runaway electrons out of the bulk free-electron population [*Gurevich*, 1961]. These low-energy electrons, which are produced via ionization of the air molecules, e.g., by the leader, are accelerated to high energies by strong electric fields, $E > 0.5\ E_c$. Because, unlike the RREA model, the cold runaway electron model does not require the direct production of energetic seed electrons by the runaway electrons, the average energy of the runaway electrons can have any value [*Babich*, 2003], and, in particular, can be $\sim$250 keV as required by the observations. As a result, the energy spectrum measured by *Dwyer et al.* strongly favors the cold runaway electron model. On the other hand, this model requires the electric field to be very large, within a factor of two of the critical field and many times the breakdown field. While such a large electric field would go against the conventional wisdom about dart leaders, which states that the electric field at the leader front should not be much bigger than the breakdown field [*Bazelyan and Raizer*, 2000], it has not been ruled out observationally. However, it does remain a theoretical challenge to explain how such large electric field enhancements could occur.

5. Summary

[20] It has been found that the RREA model of runaway breakdown is not consistent with the observed energy spectrum and flux of the x-ray emission from rocket-triggered lightning. The RREA model may still be applicable in other cases such as energetic emission inside thunderclouds [e.g., *Eack et al.*, 1996] and the occasional bursts of MeV gamma-rays observed during rocket-triggered lightning [*Dwyer et al.*, 2004b]. However, because the average runaway electron energy of several MeV and the resulting x-ray spectrum are basic properties of the RREA model stemming from fundamental interactions of the runaway electrons, it is difficult to envision how the model could be modified to fit the dart leader data. The observations instead favor the cold runaway electron model, implying that the electric field in the region close to the leader front must be very large, on the order of the critical field. Because runaway breakdown is sensitive to the electric field configuration, once the correct runaway breakdown mechanism for lightning has been established, it should be possible to use x-ray observations of lightning to infer electric fields at the leader fronts, measurements that are otherwise extremely difficult to make.

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