On the mechanism of X-ray production by dart leaders of lightning flashes

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ABSTRACT

Radiation with energies up to about 250 keV associated with the dart leader phase of rocket-triggered lightning were reported by Dwyer et al. (2003). The mechanism of X-ray generation by dart leaders, however, is unknown at present. Recently, Cooray et al. (2009a) developed physical concepts and mathematical techniques necessary to calculate the electric field associated with the tip of dart leaders. We have utilized the results of these calculations together with the energy dependent frictional force on electrons, as presented by Moss et al. (2006), to evaluate the maximum energy an electron will receive in accelerating in the dart-leader-tip electric field. The main assumptions made in performing the calculations are: (a) the dart leader channel is straight and vertical; (b) the path of the electrons are straight inside the channel; and (c) the decay of the channel temperature is uniform along the length of the dart leader. In the calculation, we have taken into account the fact that the electric field is changing both in space and time and that the gas in the defunct return stroke channel is at atmospheric pressure and at elevated temperature (i.e. reduced gas density). The results of the calculation show that for a given dart leader current there is a critical defunct-return-stroke-channel temperature above which the cold electron runaway becomes feasible. For a typical dart leader, this temperature is around 2500 K. This critical temperature decreases with increase in dart leader current. Since the temperature of the defunct return stroke channel may lie in the range of 2000–4000 K, the results show that the electric field at the tip of dart leaders is capable of accelerating electrons to MeV energy levels.

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1. Introduction

Until recently, it was the general consensus that high energy processes that lead to the production of X-rays are not associated with lightning discharges. This view was changed when Moore et al. (2001) provided first convincing evidence that energetic X-rays are produced during natural lightning. In a later study, Dwyer et al. (2003) reported that dart leaders in rocket triggered lightning is a strong source of X-rays. They observed that about 73% of the dart leaders produced X-ray emissions within 0–80 µs prior to return strokes. Studies conducted subsequently by Dwyer et al. (2004) showed that X-rays from dart leaders occur in bursts of microsecond duration with the energy of individual X-ray photons reaching energies up to about 250 keV. Dwyer et al. (2005) demonstrated the occurrence of X-rays from stepped leaders of natural lightning confirming the results obtained previously by Moore et al. (2001). Most recently, Saleh et al. (2009) reported X-rays from a rocket-triggered lightning dart stepped leader consistent with electrons with a characteristic energy of the 1 MeV. At present, the only mechanism that can explain the production of X-rays by lightning discharges is the electron runaway mechanism. The electron runaway mechanism can be divided into relativistic runaway electron avalanche model (RREAM) and cold electron runaway mechanism (CERM). In RREAM, relativistic electrons produced either by cosmic rays or radioactive decay become runaways when the background electric field exceeds a certain threshold (Gurevich et al., 1992). This threshold electric field in normal atmospheric air is about a factor of ten less than the electric field necessary for conventional electrical breakdown. Through collisions these runaway electrons produce more energetic electrons, which also become runaways leading to an avalanche of runaway electrons, the number of which increases exponentially with time and distance. When these runaway electrons interact with air they produce X-rays through Bremsstrahlung. Note that according to this mechanism the initial acceleration of seed electrons to relativistic energies happens elsewhere, and it is not mediated by the lightning process itself. In CERM, electric field generated by the lightning process itself accelerates low-energy electrons to energies large enough for them to become runaways. The electric field that is needed to
facilitate CERM is about ten times higher than the electric field necessary for conventional breakdown. Since electron avalanche formation usually limits the electric field in air to values close to the critical electric field necessary for conventional breakdown, such large fields can only exist in air for a fraction of a microsecond before they will be relaxed by conventional electron avalanche processes. Recently, Cooray et al. (2009b) showed that the electric fields generated during the encounter of positive and negative streamers in long sparks are capable of driving electrons to relativistic energies by CERM.

In a recent study Dwyer (2004) showed that RREAM is not consistent with the observed spectra of energetic electrons generated by dart leaders. If CERM is active in dart leaders, it in turn requires rather high fields (on the order of ten times the conventional breakdown values) acting for a short duration in dart leaders. In a recent study, Cooray et al. (2009a) showed that the electric fields associated with the current generation at the tip of dart leaders can reach values in excess of conventional breakdown electric fields in the low dense air of the defunct return stroke channel through which the dart leader propagates. They also suggested that these electric fields could be the source of X-ray production in dart leaders. In this paper we will further investigate this possibility.

2. Electric field generated by dart leaders

In order to evaluate the electric field in the dart leader, Cooray et al. (2009a) first estimated the spatial and temporal variation of the dart leader current along the channel. Once this is known, the electric field at any point on the channel can be evaluated using Maxwell’s equations. In evaluating the temporal and spatial variation of the dart leader current, Cooray et al. (2009a) used the following procedure. As the dart leader passes through a given section of the defunct return stroke channel, the change in the potential requires a certain amount of negative charge to be deposited on this channel section. As a result, a wave of positive current (or electron deficiency) travels towards the cloud leaving a net negative charge on the newly created channel section. Since this current transports positive charge into the cloud, each newly created dart leader channel section acts as a current source, which effectively drains negative charge from the charge center in the cloud. Based on this scenario, Cooray et al. (2009a) assumed that each newly created dart leader section acts as a current source that injects a current (corona current) into the central core of the dart leader channel. This current travels to cloud along the core of the dart leader channel with the speed of light. They also assumed that the amplitude of the corona current pulse associated with a given elementary newly created channel section decays exponentially with time with a decay time constant τ. The peak amplitude of the corona current generated at a given channel element depends on the amount of charge deposited at that channel element by the dart leader. They obtained this information from a study conducted by Cooray et al. (2007) who derived the distribution of the charge on the dart leader channel as a function of both the height of the dart leader tip from ground and the peak current of the prospective return stroke that will be generated when the dart leader touches the ground. Their study and other references given therein showed that the charge on the leader channel increases linearly with increase in prospective return stroke current. In this respect, it is also important to mention here that Kodali et al. (2005) reported a strong correlation between the dart-leader line charge density and return-stroke peak current, with determination coefficient being 0.7–0.8. Results of Cooray et al. (2009a) showed that the rise-time of the dart leader current varies with the magnitude of τ. They inferred that the rise-time of the dart leader current is about 1 μs based on experimental data on optical radiation of dart leaders (Jordan et al., 1997) and this observation led them to set the value of τ to about 0.5 μs. Another parameter that influences the current distribution along the dart leader channel is the speed of the dart leader. The speeds of dart leaders are known from experimental observations and the typical speed of a dart leader is about $10^7$ m/s (Orville and Idone, 1982; Jordan et al., 1992; Wang et al., 1999).

Consider a given point on the defunct return stroke channel. As the dart leader approaches this point, the electric field at that point increases and it will reach a peak when the tip of the dart leader reaches that point. The electric field at this point starts to decrease as the dart leader continues its forward movement and finally it will decrease to a value comparable to the potential gradient of an arc channel in air. Fig. 1 depicts the electric field at a point located at a height of 250 m above the ground level on the defunct return stroke channel as the dart leader passes through that point. The calculations are presented for three values of leader-tip current decay time constant, τ. In these calculations the speed of the dart leader is assumed to be $10^7$ m/s and the point of origin of the dart leader is fixed at a height of 5 km above ground. Numbers on the horizontal axis show the separation between the tip of the dart leader and the point of observation. The separation is assumed to be negative when the tip of the dart leader is located above the point of observation and positive when it is located below. It is clear from Fig. 1 that the peak electric field produced by the dart leader decreases with increase in rise-time of the dart leader current. Further, the electric field rises very sharply as the dart leader passes through the observation point, reaches a peak soon after that and then decays to a relatively low level. To summarize, the waveforms in Fig. 1 show how the electric field at the point of observation varies as the dart leader tip approaches the point of observation (negative values of separation), pass it (separation equal to zero), and moves further downward, away from the point of observation (separation larger than zero). The same field is experienced by
any other point located in the vicinity of the point of observation in the defunct return stroke channel, but it will occur earlier if the second point is located above the point of observation and after if it is located below. In other words, as the dart leader moves along the defunct return stroke channel, the region of high electric field travels along the channel with the same speed. Note also that the field signatures given in Fig. 1 can be expressed in terms of time by multiplying the numbers on the horizontal-axis by the speed of the dart leader. Fig. 2 shows the electric field at the same point, but as a function of the speed of the dart leader. In these calculations, the value of $\tau$ was fixed at 0.5 $\mu$s. Note that for a given value of $\tau$ the electric field increases with decrease in dart leader speed. As mentioned previously, according to Cooray et al. (2007), the charge on the dart leader channel increases linearly with increase in peak current of the prospective return stroke. The electric field signatures shown in Figs. 1 and 2 correspond to a prospective return stroke current of 12 kA, which is the median value of subsequent return stroke peak currents. A dart leader that will give rise to a 24 kA subsequent return stroke, for example, will produce electric field amplitudes, which are two times the ones given in Figs. 1 and 2. In summary, when the other parameters remain the same, the electric field produced by a dart leader increases with increase in dart leader current, decrease in dart leader current rise time, and with decrease in dart leader speed. Of course the above statement is based on the assumption that there is no connection between the dart leader current amplitude, dart leader speed, and the current rise-time. But the possibility that these parameters are correlated to each other cannot be ruled out (Cooray, 1996). The study conducted by Cooray et al. (2007) also shows that the charge on the dart leader channel decreases with increasing height of the dart leader channel. Thus, the current associated with a dart leader tip increases as the dart leader progressed towards the ground. For this reason, the electric field produced by the dart leader at a given channel segment decreases as the height of that channel element increases. For example, Fig. 3 shows the electric field produced by the passage of the dart leader through channel segments located at different heights. The data illustrate the point mentioned above.

3. Temperature and density of the defunct return stroke channel

The dart leader travels along defunct return stroke channel. The temperature of this channel depends on several parameters including the time interval from the previous return stroke and the diameter of the channel. Uman and Voshall (1968) have presented calculations to show that after the passage of the subsequent return stroke the decay of the channel temperature depends on the diameter of the channel: the larger the diameter the slower the decay of the temperature. For example, assuming an initial temperature of $10^4$ K they showed that a channel with a 1 cm radius will decay to about $4 \times 10^3$ K in 10 ms; a channel of 2 cm radius will decay to about $5 \times 10^3$ K during the same time interval. The corresponding values at 20 ms are about $3 \times 10^3$ and $4 \times 10^3$ K, respectively. Uman and Voshall (1968) also pointed out that the dart leader probably takes place when the temperature of the defunct return stroke channel is about $2 \times 10^3$–$4 \times 10^3$ K. The reason for this suggestion is the following. The conductivity of air varies with temperature in a non-uniform manner. Above about $4 \times 10^3$ K air is a rather good conductor and below about $2 \times 10^3$ K it is essentially an insulator. If the channel conductivity is high (of the order of $10^4$ S/m) then the mode of charge transfer between the cloud and ground takes place in the form of M-components. If the conductivity is very low then the charge transfer takes place in the form of dart-stepped or stepped leader/return stroke sequences. Thus for the propagation of dart leaders an intermediate temperature in which the air changes from a conductor to an insulator is the most favorable. It is reasonable to assume, therefore, that the temperature of the defunct return stroke

![Fig. 2. The variation of the electric field at a point located 250 m above ground as the dart leader passes through it. The horizontal axis depicts the separation between the tip of the dart leader and the point of observation. This separation is assigned negative values when the dart leader tip is above the point of observation and positive values when it is below. The curves a, b, and c correspond to dart leader speeds of $5 \times 10^6$, $10^7$, and $1.5 \times 10^7$ m/s, respectively.](image-url)
channel during the propagation of dart leaders lies in the range of $2 \times 10^{-4} - 4 \times 10^{3}$ K. Rakov (1998) estimated the conductivity of channel ahead of a dart-leader tip to be about 0.02 S/m.

The critical electric field necessary either for conventional breakdown or for cold electron runaway breakdown depends on the density of air under consideration. Since ample time is available for the pressure of the defunct return stroke channel to reach atmospheric pressure before the occurrence of a dart leader, the air density, $\delta_{0}$, in the defunct return stroke channel during the passage of the dart leader is given by

$$\delta_{\dot{r}} = \frac{\delta_{0} \times T_{0}}{T}$$

where $T$ is the temperature of the defunct return stroke channel during the passage of the dart leader, $T_{0}$ is the standard atmospheric temperature (i.e. $T_{0} = 273$ K) and $\delta_{0}$ is the standard atmospheric particle density (i.e. $\delta_{0} = 2.69 \times 10^{19}$ cm$^{-3}$).

4. Acceleration of electrons in electric fields

A free electron located in a gaseous medium when exposed to an electric field will experience a force equal to $-eE$, where $E$ is the applied electric field and $e$ is the electron charge. Under the influence of this force and governed by the Lorenz force and Newton’s second law the electron will continue to accelerate. As the electron accelerates through the gaseous medium it will collide with atoms and molecules and this causes the electron to lose energy. Thus, this interaction of the electron with atoms and molecules will generate a ‘Frictional (or drag) Force’ that will oppose the force exerted on the electron by the electric field. For a given electron energy, the drag force decreases linearly with decreasing density. Let us denote the energy lost by an electron per unit length due to this frictional force as $F_{d}$. The unit of this parameter is eV/m. Fig. 4 (adapted from Moss et al., 2006) shows how this frictional force (in eV/cm) varies as a function of the energy of the electron. It is important to point out that this diagram corresponds to standard atmospheric density. Note that the maximum value of this frictional force, about $2.5 \times 10^{5}$ eV/cm, corresponds to electron energy of about 100 eV. After reaching a peak at this electron energy the frictional force decreases with increase in electron energy and reaches a minimum when the electron energy is about $10^{6}$ eV. It is interesting to note that the frictional force can be expressed as an electric field that opposes the acceleration of the electron caused by the applied field. For example, the peak frictional force experienced by an electron having energy 100 eV can be translated to an opposing electric field of magnitude of about 250 kV/cm. If the magnitude of the background electric field that accelerates the electron is larger than the opposing electric field, the gain in the energy of the electron per unit length will be larger than the losses and the electron will continue to gain energy and become a runaway. As one can see from Fig. 4, once the electron exceeds the threshold energy of about 100 eV, the external electric field necessary to push the electron to runaway status decreases with increase in the energy. For example, a $10^{4}$ eV electron will become a runaway in a background electric field of about 32 kV/cm. In evaluating the energy gained by electrons that are moving in the electric field created by the dart leader, we will use the frictional force diagram depicted in Fig. 4, but adjusted for the actual gas density.

5. Acceleration of electrons in the dart leader channel

5.1. General considerations

The electric fields generated at a given point on the defunct return stroke channel as the dart leader passes through that point are shown in Figs. 1–3. Recall that as the dart leader sweeps through the channel each point on the defunct return stroke channel will experience similar field pulses (with different peak amplitudes, of course) at different times. Therefore, the electric field in the dart leader channel varies both in time and space (i.e. along the channel). Thus the electric field experienced by an electron located in the dart leader channel depends both on time and the location of the electron. Since the location of a dart leader created by the dart leader changes its position with time it is necessary to keep track of the location of the electron as it moves along the channel in order to estimate the electric field acting on it at a given time. Moreover, as the electron accelerates its speed can approach values for which one cannot neglect the relativistic correction. Thus in the analysis the speed of an electron having a given kinetic energy $E_{k}$ is estimated using the formula

$$E_{k} = \frac{m_{0}c^{2}}{\sqrt{1-(v/c)^{2}}} - m_{0}c^{2}$$

where $v$ is the speed of the electron, $m_{0}$ is the rest mass of the electron, and $c$ is the speed of light.

Since, as mentioned in the previous section, the drag force acting on an electron depends on the gas density, the amount of energy gained by electrons during the passage of the dart leader depends on the electric field as well as the gas density of the defunct return stroke channel. Since the electric field is changing both in space and time the energy gained by an electron and whether it will be pushed into the runaway mode depends also on the initial location of the electron. Let us consider one particular case as an illustration. Recall that the curve marked by ‘a’ in Fig. 1 shows how the electric field at a point located 250 m above ground varies as the dart leader tip passes through it. Consider the instant of time at which the location of the dart leader tip coincides with this point. What are the magnitudes of the electric field at this instant of time at points located in the vicinity of this point? Since the dart leader sweeps through the defunct return stroke channel at a more or less constant speed, an instant snapshot of electric fields at points in the vicinity of our point of interest is also given by the curves shown in Fig. 1 (here we assume that the peak field is more or less the same in adjacent

![Fig. 4. Magnitude of the ‘drag force’ as a function of electron energy. The diagram corresponds to normal atmospheric density (adapted from Moss et al., 2006).](http://jilawww.colorado.edu/www/research/coldidata.html)
points). This is shown on an expanded distance scale in Fig. 5. First of all, note that in order for low energy electrons to be pushed into the runaway mode the dart leader has to generate a peak electric field above a certain critical value. Assume that the electric field of all, note that in order for low energy electrons to be pushed into the runaway mode the dart leader has to generate a peak electric field above a certain critical value. Assume that the electric field depends on the initial location of the electron. Consider an electron located at point C on the channel at the instant of time shown in Fig. 5. The peak electric field of the dart leader has already passed this point and the electric field at the location point of the electron is not large enough to push it into the runaway mode. Consider an electron located at point B. Even though the peak of the dart leader field has already passed this point, the electric field acting on the electron could still be large enough to accelerate the electron to energy large enough to overcome the peak drag force. Once on the ‘right hand side’ of the global peak in Fig. 4, the electron may continue to gain energy and its speed may reach a value larger than the speed of the dart leader. The electron will then move towards the tip of the dart leader. During its journey it will first experience an increase in electric field but as it continues to move the electric field acting on it will decrease with time. Even though the field acting on the electron is decreasing at this stage, it may still continue to gain energy from the field because the drag force acting on the electron also decreases with the increase in energy of the electron. If the electron continues to gain energy (depending on the way in which the electric field of the dart leader varies in space and time), it will very soon reach a speed comparable to speed of light and move out from the tip of the dart leader into a region with very low electric field. Throughout their propagation, the electrons may emit X-rays via Bremsstrahlung interactions with air atoms. The slowing down of the electron in this low electric field will probably lead to the generation of Bremsstrahlung. Now, consider an electron located at point A (see Fig. 5) on the channel at the given instant. The electric field at this point is rather low at this instant of time and the drag force overwhelms the accelerating force. Thus the electron cannot gain much energy from the electric field. However, as time passes and the dart leader advances forward and the electric field experienced by the electron increases with time. After a certain time interval the high field region will reach the location of the electron and if the peak electric field is large enough it may drive the electron into the runaway mode. After that the electron will behave in a manner described in Section 4.

5.2. Results

As mentioned in the previous section, even if the peak electric field generated by the dart leader is large enough to accelerate electrons into runaway mode, whether an electron will reach the runaway mode or not depends on the initial location of the electron with respect to the tip of the dart leader. Since our calculations show that the maximum energy gain by a runaway electron is more or less similar if the electron is located anywhere between points A and B (see Fig. 5), all the results presented here are calculated by assuming that the initial location of the electron is at point B; point B in turn is assumed to be located 5 cm behind the location of the peak electric field. Figs. 6–11 depict the energy gained by electrons in the electric fields created by dart leader associated with prospective return stroke currents of 12, 24 and 45 kA. The rise time of the dart leader current was fixed at 1 μs (i.e. \( \tau = 0.5 \mu s \)) and the speed of the dart leader is assumed to be \( 10^7 \text{ m/s} \). The energy is plotted as a function of the temperature of the defunct return stroke channel. Once in the runaway mode the energy gained by an electron depends on how far it will travel along the dart leader channel. In generating the data in Fig. 6 the simulation was continued until the electron has traveled all the way across the tip and came out into the low field region in front of the dart leader tip. In Figs. 7–11 the energy gained by the runaway electron after it has traveled a distance of 1 m, 10, 5, 2, and 1 cm are depicted.

![Fig. 5. Electric field at different points on the channel at the instant of time when the location of the dart leader tip coincides with a point located 250 m above ground. Dart leader current rise-time was assumed to be 1 μs (\( \tau = 0.5 \mu s \)) and prospective return stroke current peak was assumed to be 12 kA. The points marked on the curve are the locations of initial electrons used in the calculation. See text for details.](image)

![Fig. 6. The energy gained by electrons while accelerating in the dart leader field as a function of the temperature of the defunct return stroke channel. The initial location of the electron is at point B depicted in Fig. 5. This point is located 5 cm away (to the right) from the peak field. The simulation was continued until the electron has accelerated across the whole front of the dart leader field and emerged out from the tip of the dart leader. The speed of the dart leader and the current rise-time are \( 10^7 \text{ m/s} \) and 1 μs, respectively. The prospective return stroke current associated with the dart leader is (a) 12 kA, (b) 24 kA, and (c) 45 kA.](image)
Fig. 12 depicts the energy gained by electrons when exposed to the dart leader fields occurring at different heights along the channel. The data given are the energy gained by runaway electrons in moving a distance of 1 m. In all these calculations our energy resolution is on the order of few tens of eV.

6. Discussion

The data given in Figs. 6–12 show very clearly the importance of the temperature of the defunct return stroke channel in deciding whether the electrons could be accelerated to relativistic energies by the electric field produced by the dart leader channel. The reason for this is the fact that, for a given electron energy, the...
located at different heights along the defunct return stroke channel. The initial location of the electron is at point B depicted in Fig. 5. This point is located 5 cm away (to the right) from the peak field. The energy corresponds to the energy gained by the electrons in accelerating 1 cm along the dart leader channel. In the calculations the electron accelerated across the whole front of the dart leader field and emerged out from the tip of the dart leader. The speed of the dart leader and the current rise time are $10^7$ m/s and 1 μs, respectively. The prospective return stroke current associated with the dart leader is (a) 12 kA, (b) 24 kA, and (c) 45 kA.

Fig. 11. The energy gained by electrons while accelerating in the dart leader field as a function of the temperature of the defunct return stroke channel. The initial location of the electron is at point B depicted in Fig. 5. This point is located 5 cm away (to the right) from the peak field. The energy corresponds to the energy gained by the electrons in accelerating 1 cm along the dart leader channel. In the calculations the electron accelerated across the whole front of the dart leader field and emerged out from the tip of the dart leader. The speed of the dart leader and the current rise time are $10^7$ m/s and 1 μs, respectively. The prospective return stroke current associated with the dart leader is (a) 12 kA, (b) 24 kA, and (c) 45 kA.

Fig. 12. The energy gained by electrons while accelerating 1 m in the dart leader field as a function of the temperature of the defunct return stroke channel. Different curves depicts the energy gained by electrons when exposed to the electric fields created by dart leaders as it passes through points located at different heights: (1) 2.5 km, (2) 2.0 km, (3) 1.5 km, (4) 1.0 km, (5) 0.5 km, (6) 0.25 km, (7) 0.1 km. The calculations are conducted in a manner similar to the previous cases by placing the electron 5 cm behind the location of the maximum electric field. The speed of the dart leader and the current rise-time are $10^7$ m/s and 1 μs, respectively. Different curves correspond to points of observations located at different heights along the defunct return stroke channel.

drag force acting on the electrons decreases with decreasing air density. The density of the defunct return stroke channel decreases with increasing temperature (the pressure remains atmospheric) and therefore in a given dart leader electric field the possibility of accelerating electrons to runaway mode increases with increasing temperature. The data presented here show that the temperature has to be larger than a critical value for electrons to be runaway. Our calculations show that for electrons to runaway the peak electric field, $E_{dr}$, of the dart leader has to be such that

$$E_{dr} \frac{\delta E}{\delta r} \geq 2.55 \times 10^7 \text{ V/m}$$  

Note that this is approximately equal to the critical electric field necessary to overcome the maximum drag force experienced by an accelerating electron at normal atmospheric density (see Fig. 4).

The data presented above also show that the energy gained by runaway electrons increases with increase in distance of travel along the dart leader channel. If the distance of travel is about 1 cm the energy gain in the case of a typical dart leader is about 30 keV. This energy will increase to about 50, 125, 250, and about 900 keV when the distance of travel increases to 2, 5, 10 cm, and 1 m respectively. A runaway electron that travels all the way across the front of the dart leader electric field can gain energies of about 2–3 MeV. Therefore, the 250 keV electron energies inferred by Dwyer et al. (2004) can be accounted for by this model. However, one issue is whether the electrons can travel a significant distance along the channel before scattering out. The central core of the dart leader where electrons are accelerated has a radius of about 1 cm. In the calculations presented above it is assumed that the electron takes a straight path through the channel so that it will remain inside the channel irrespective of the distance traveled. In reality, however, the path of the electrons may deviate from a straight path due to scattering. The deviation from a straight path due to scattering will increase with increase in distance of travel. Therefore, it is doubtful whether an electron can continue to travel inside the thin dart leader channel for several meters without coming out of it. On the other hand, even though the density of air outside the channel is about an order of magnitude higher than the air inside the channel, the electric field of the dart leader may still be able to sustain the energy gain by electrons. For instance, if inside the channel the STP equivalent electric field is 260 kV/cm and the density outside the channel is a factor of ten higher, then the STP equivalent electric field is 26 kV/cm just outside the channel. As can be seen in Fig. 4, the threshold energy for electrons to runaway at 26 kV/cm is about 10 keV. As a result, an electron traveling 1 cm in the channel, the same distance as the radius of the channel, the electron will gain 30 keV and exit with enough energy to continue to run away.

Note that the temperature necessary to initiate electron runaway decreases and the energy gained by the runaway electrons increases with increase in dart leader current (and with increase in prospective return stroke current). The reason for both these observations is the increase in the dart leader electric field with increase in current. Fig. 12 depicts the energy gained by electrons in traveling 1 m as a function of channel temperature when they are exposed to the electric fields that will occur at different heights along the channel. Observe that the minimum temperature required to initiate runaway increases with increase in height while the energy gained by runaway electrons decreases with height. The reason for this is the decrease in the peak value of the dart leader electric field with height. If the temperature of the defunct return stroke channel is uniform along the channel, the probability of electrons moving into runaway mode increases as the dart leader approaches the ground. Thus some dart leaders may generate energetic radiation only when they have reached relatively low altitudes.

In the analysis presented here we have assumed that the lightning channel is straight. However, in reality the channel is tortuous. The tortuosity makes a modulation of the electric field
along the channel due to the changes in the direction of current flow. Thus the tortuosity of the channel may lead to turn on and off of the energetic radiation due to the modulation of the electric field experienced by the electrons in the channel.

An effect similar to the one described above can also occur due to the variations in defunct return stroke channel temperature along the channel. Video records of the decaying lightning channel show that some regions of the channel remain more luminous than the other parts as the channel decays. This phenomenon is described in the lightning literature as bead lightning. Similar behavior is also observed in laboratory discharges. The reason for this phenomenon could be two-fold. First, there may exist a natural process that could modulate the temperature of the decaying channel as a function of height. Second, this observation could be purely due to the channel bends associated with a tortuous channel. An observer may see the luminosity of the channel at the bends to last longer than the other points because, depending on the orientation of the channel, light coming from a longer channel section could reach the observer through these points. Irrespective of these special effects, the decay of the channel is mediated partly by turbulent mixing of cool air with the hot channel. It is reasonable, therefore, to assume that decaying of the channel is not uniform along the whole channel. This situation too leads to the on and off of the X-ray emissions or give it a pulsed behavior because in some parts of the channel the temperature could be above the critical value necessary for electron runaway and in other parts it may be below it.

7. Conclusions

We have calculated the electric field associated with the tip of dart leaders and used this field, together with the energy dependent frictional force on electrons, to evaluate the maximum energy an electron will receive in accelerating in this electric field. The main assumptions made in the calculation are: (a) the dart leader channel is straight and vertical; (b) the path of the electrons are straight inside the channel; and (c) the decay of the channel temperature is uniform along the length of the dart leader. In the calculations, we have taken into account the fact that the electric field is changing both in space and time and that the gas in the defunct return stroke channel is at atmospheric pressure and at elevated temperature (i.e. reduced gas density). The results of the calculations show that if the temperature of the defunct channel is higher than about 2500 K, a typical dart leader with prospective return stroke current of 12 kA could accelerate electrons into energies in the range of MeV. The critical temperature decreases with increase in dart leader current (the peak of the prospective return stroke current). Below this critical temperature, runaway mode is arrested and the maximum energy gained by electrons is less than a few tens of electron volts. The results show that the electric field at the tip of dart leaders is capable of accelerating “cold” electrons to MeV energy levels.

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