AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2013JD021011

Key Points:

- X-rays from natural downward negative cloud-to-ground lightning
- No X-rays from upward positive and negative leaders
- Background radiation during thunderstorms

Correspondence to:
J. Montanyà,
montanya@ee.upc.edu

Citation:
Montanyà, J., F. Fabró, O. van der Velde, D. Romero, G. Solà, J. R. Hermoso, S. Soula, E. R. Williams, and N. Pineda (2014), Registration of X-rays at 2500 m altitude in association with lightning flashes and thunderstorms, *J. Geophys. Res. Atmos.*, *119*, 1492–1503, doi:10.1002/2013JD021011.

Received 8 OCT 2013
Accepted 7 JAN 2014
Accepted article online 9 JAN 2014
Published online 7 FEB 2014

Registration of X-rays at 2500 m altitude in association with lightning flashes and thunderstorms

Joan Montanyà[1], Ferran Fabró[1], Oscar van der Velde[1], David Romero[1], Gloria Solà[1], Juan Ramon Hermoso[1], Serge Soula[2], Earle R. Williams[3], and Nicolau Pineda[4]

[1]Electrical Engineering Department, Universitat Politècnica de Catalunya, Barcelona, Spain, [2]Laboratoire d'Aérologie, Université de Toulouse, CNRS, Toulouse, France, [3]Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, [4]Meteorological Service of Catalonia, Barcelona, Spain

Abstract Electric fields and high-energy radiation of natural lightning measured at close range from a mountaintop tower are discussed. In none of the 12 negative cloud-to-ground upward flashes were X-rays observed. Also no energetic radiation was found in one negative upward leader at close range (20 m). In the first of two consecutive negative cloud-to-ground flashes, X-rays were detected during the last ~1.75 ms of the leader. During the time of energetic radiation in the flash an intense burst of intracloud VHF sources was located by the interferometers. The X-ray production is attributed to the high electric field runaway electron mechanism during leader stepping. Even though the second flash struck closer than the previous one, no X-rays were detected. The absence of energetic radiation is attributed to being outside of the beam of X-ray photons from the leader tip or to the stepping process not allowing sufficiently intense electric fields ahead of the leader tip. High-speed video of downward negative leaders at the time when X-rays are commonly detected on the ground revealed the increase of speed and luminosity of the leader. Both phenomena allow higher electric fields at the leader front favoring energetic radiation. Background radiation was also measured during thunderstorms. The count rate of a particular day is presented and discussed. The increases in the radiation count rate are more coincident with radar reflectivity levels above ~30 dBZ than with the total lightning activity close to the site. The increases of dose are attributed to radon daughter-ion precipitation.

1. Introduction

The suggestion that energetic radiation could be produced by thunderstorms was set first by C.T.R Wilson. Today, three main fronts are pushing the boundaries of the understanding of the high-energy radiation related to thunderstorms. One is the study of the energetic fluxes during thunderstorms [e.g., *Chilingarian et al.*, 2010] in which the thunderstorm electric fields seem to modulate the energetic particles received at ground. The second is the study of the origin of the intense radiation named terrestrial gamma ray flashes (TGFs) detected from space discovered about 20 years ago [*Fishman et al.*, 1994]. Currently, upward lightning leaders reaching higher parts of the cloud or even leaving it seem to be the most probable candidate for the TGF emissions [*Williams et al.*, 2006]. But in addition to these two phenomena, the unambiguous production of high-energy emission from natural cloud-to-ground (CG) lightning was established by *Moore et al.* [2001] in their experiments at South Baldy Peak (3288 mean sea level (msl)). At that time, the measurement of energetic bursts of radiation at close distances from three downward negative CG lightning flashes suggested that the phenomenon was related somehow with the stepping process. Four years later, *Dwyer et al.* [2005a] clearly showed the coincidence of X-ray pulses and leader steps during five negative CG flashes occurring in Florida (sea level). This work reinforced the idea that the stepping process would involve a mechanism for energetic radiation, similar to the one of dart leaders in rocket triggered lightning [*Dwyer et al.*, 2003]. The particular fast electric fields produced by downward negative stepped leaders, already reported many years ago [*Krider and Radda*, 1975], were measured and ranged simultaneously with X-rays by *Howard et al.* [2008]. The authors found that the electric field changes produced by leader steps and the X-rays are colocated in space within 50 m and X-rays are emitted up to 1.3 μs after the field changes. They reported the case of one natural CG flash and hypothesized that the electrostatic field change is responsible for the X-ray emissions. In the same year, *Yoshida et al.* [2008] published observations of upward leaders of both polarities that produced increases in X-ray counts. Later, *Howard et al.* [2010] related the observations of leader electric fields close to the return stroke and generation of energetic radiation. The authors pointed out that the X-rays seemed to be beamed but this was not in agreement with previous work by *Saleh et al.* [2009] who found isotropic radiation. Meanwhile in Europe, *Montanyà et al.* [2012] succeeded in measuring electric fields and X-rays from a close negative CG flash and reported the characteristics of the measured bursts. The latest works reporting data from natural lightning are from *Schaal et al.* [2012] with a sample of two flashes and *Mallick et al.* [2012] with a larger sample of 8 flashes and 15 subsequent strokes. In that work they found an efficiency of X-ray detection of 88% for the first stroke and 47% for subsequent strokes within 2 km. The authors noted that not all leaders of the same flash produced detectable X-rays. A similar effect is reported for leader steps for the same leader to ground. The energy of the radiation seems to be related with the stroke peak current but not with the amplitudes of the d*E*/d*t* pulses produced by the leader steps. Finally, the authors pointed out that leaders of subsequent strokes were more prolific producing detectable X-rays. These observations are in support of the theory [*Cooray et al.*, 2009, 2010] that the high-temperature and low-density channels traversed by subsequent leaders favor the cold runaway breakdown.

A hypothesis why stepped leaders are the source of energetic radiation already was exposed by *Suszcynsky et al.* [1996], based on the references therein, in which the authors pointed out that the negative stepped leader is a runaway-dominated discharge. The Runway Air Breakdown theory was proposed to explain the expected emissions during the negative stepped leader to ground. Later, after *Moore et al.* [2001] linked the measured X-rays emission with the stepping process, *Dwyer* [2004] argued that the relativistic runaway electron avalanche (RREA) model for runaway breakdown could not explain the observed energy spectrum and flux of the X-rays emission from dart leaders in rocket triggered lightning. Moreover, the RREA needs energetic seed electrons to develop [*Gurevich et al.*, 1992] that are supposed to be a result from interactions of cosmic rays. Subsequently, the cold runaway electron model was proposed [*Gurevich*, 1961; *Dwyer*, 2004]. That model exploited the fact that the electric field in the leader front is very large and on the order of the critical field E_c that allows electrons to run away. At that moment it was increasingly clear that the localized intense field at leader fronts could play a fundamental role in the energetic production without the necessity for energetic cosmic ray-derived seed electrons. This concept is named the high-field runaway electron mechanism [*Gurevich et al.*, 2007; *Dwyer*, 2008] and the candidate to explain the observed X-rays in lightning and in laboratory sparks [*Stankevich and Kalinin*, 1967; *Dwyer et al.*, 2005b; *Kostyrya et al.*, 2006; *Dwyer et al.*, 2008; *Nguyen et al.*, 2008; *Rahman et al.*, 2008; *Rep'ev and Repin*, 2008; *Nguyen et al.*, 2010; *March and Montanyà*, 2010, 2011; *Shao et al.*, 2011, *Oreshkin et al.*, 2012, *Kochkin et al.*, 2012]. This mechanism requires an electric field much larger than the conventional breakdown threshold E_k [*Moss et al.*, 2006]. But a field of $E{\sim}10\ E_k$ would only produce energetic electrons in the streamer zone of the leader of about 2–8 keV [*Moss et al.*, 2006]. To explain the energies observed at the ground [e.g., *Montanyà et al.*, 2012], a second mechanism shall play the role to accelerate runaway electrons to higher energies. According to *Gurevich et al.* [2007] the energetic thermal electrons could serve as seed energetic electrons for the named strong runaway breakdown. But *Celestin and Pasko* [2011] demonstrated how exponential growth of streamers under strong fields can produce energetic electrons up to ~100 keV that can be further accelerated to MeV energies in the negative stepping leaders. Experiments performed by *March and Montanyà* [2010] showed the importance of the voltage growth rate in the production of X-rays in long sparks in air. This was consistent with the very well-studied runaway and X-ray generation from pulsed nanosecond discharges in open air [e.g., *Babich and Loiko*, 2010, and related references therein]. These fast discharges allowed high overvoltage to be applied to the air gap. The overvoltage Δ is defined as the $U_{\max}/U_{\mathrm{st}} - 1$ where $U_{\max}$ is the maximum applied voltage to the gap and U_{st} is the quasi-stationary self-breakdown voltage.

Since lightning leaders are the candidates to be the source for the energetic radiation detected at ground and from space, some important characteristics of positive and negative leaders are listed as follows: (i) the electric field in the positive streamer zone of a leader is about ~3 times lower that for negative streamer zone [*Bazelyan and Raizer*, 2000]; (ii) high voltage experiments with long gaps (>100 m) showed that the electric field required for propagation of positive and negative leaders are nearly identical [*Bazelyan and Raizer*, 2000]; (iii) positive streamers propagate against the electrons drift, whereas negative streamers propagate in the same direction as electron drift [e.g., *Raizer*, 1991]; (iv) positive leaders do not propagate in a stepping manner as negative leaders do [e.g., *Rakov and Uman*, 2007]; (v) branches of negative leaders appear to be brighter than in positive leaders and positive downward leaders appear to be less branched when approaching to the ground [e.g., *Montanyà et al*., 2012]; (vi) positive leaders can experience sudden negative recoil leaders, whereas negative leaders do not experience recoils [e.g., *Mazur*, 2002]; (vii) speeds of positive leaders are in the range of $2 \cdot 10^4$ m s^{-1}, while negative leaders propagate an order of magnitude faster 1–5 10^5 m s^{-1} [e.g., *Proctor et al*., 1988; *Mazur et al*., 1998; *Shao and Krehbiel*, 1996; *van der Velde and Montanyà*, 2013], although faster positive upward leaders have been observed in rocket triggered lightning [e.g., *Yoshida et al*. 2010] and propagating horizontally in natural lightning [e.g., *van der Velde and Montanyà*, 2013]; (viii) propagation of negative leaders generates strong RF emissions in the Very High Frequency (VHF) and higher frequencies, whereas propagation of positive leaders is much quieter [*Mazur and Ruhnke*, 1993; *Shao and Krehbiel*, 1996]; and (ix) upward positive leaders do not experience the final jump near the ground as the downward leaders do, downward positive leaders clearly accelerate when approaching to the ground, whereas negative downward leaders are more irregular [*Campos et al*., 2013].

We present observations of different type of lightning flashes occurring at close ranges. The case of a negative CG flash in which X-rays were detected is compared with a closer flash that occurred 1 min later and did not produce X-rays. The cases of two upward events of both polarities without the evidence of X-rays are also presented and discussed. One of the objectives of the paper is to investigate, based on the observations, the most favorable conditions for a lightning leader to produce energetic radiation. The background radiation count rate of a day with several storms is shown as an example. Before the observations and discussions, the instruments and data are described in the next section.

2. Instruments and Data

The Eagle Nest tower is located at the south side of the Pyrenees at an elevation of 2537 m msl. This location belongs to the so-called Ebro Valley Laboratory in the northeast of Spain. Despite the low height of the tower (22.5 m), it often receives lightning during summer and winter seasons. Several instruments are installed at the tower and in its vicinity. One of the instruments is located at only 20 m from the tower tip. It has two ∅76 mm NaI(Tl)/photomultiplier tube scintillator detectors placed within an aluminum shielded box with a 5 mm wall thickness. The detectors are pointing upward behind two apertures covered by 1 mm aluminum foil. One detector is used with a multichannel analyzer in order to compute the background of high-energy counts accumulated in periods of 1 min. The second is used to record transient bursts of pulses produced by close lightning. The output of this detector is digitized together with an electric field antenna and a GPS time synchronization signal. The electric field antenna is a flat plate with a 3 ms time constant. The antenna is also used to trigger a high-speed camera operating at ~3000 fps with a fisheye lens pointing upward. When winter comes, the instrument is usually removed from the Eagle Nest site. During winter and spring of 2012 the instrument was operative at the observatory of Pic du Midi de Bigorre (2877 m msl, southern France). A radio/TV tower of ~100 m is on top of the peak and it is often hit by lightning. The instrument was installed in a platform ~100 m from the tower base.

Both sites are well covered by the LINET VLF/LF lightning detection network [see *Betz et al*., 2004, 2008] which was used to identify CG strokes and intracloud (IC) emissions, the latter named hereafter as IC strokes. Only the Eagle Nest site is covered by the four-station VHF interferometer network named XDDE. This network locates VHF sources in 2-D produced by IC activity [see *Montanyà et al*., 2007; *Lojou and Cummins*, 2006].

3. Detection of X-Rays in Cloud-to-Ground Flashes

3.1. X-Rays From Negative Downward Leaders

On 5 July 2012, two negative CG flashes struck ground in the vicinity of the Eagle Nest tower. The single ground stroke of the first flash occurred at 18:36:28.558 UT at a distance of ~1 km. The peak current of the return stroke was reported by LINET as −81 kA and a similar peak current was reported by the XDDE. The electric field signature of the leader and the return stroke are depicted in Figure 1a. The negative leader approaching the ground produced a positive increase of the electric field which was measurable for ~ 1.75 ms before it was truncated by the negative step change due to the return stroke. It is just during this millisecond that a total of 17 X-ray pulses were detected by the NaI(Tl) scintillator (Figure 1b). The maximum energy deposited by the pulses was 806 keV and the median time between pulses was 120 μs with a minimum of 3 μs. In this case, the number of detected X-rays is much lower than in the reports of *Montanyà et al*. [2012], *Moore et al*. [2001], and *Dwyer et al*. [2005]. Moreover, the detected pulses here were not organized in short bursts related

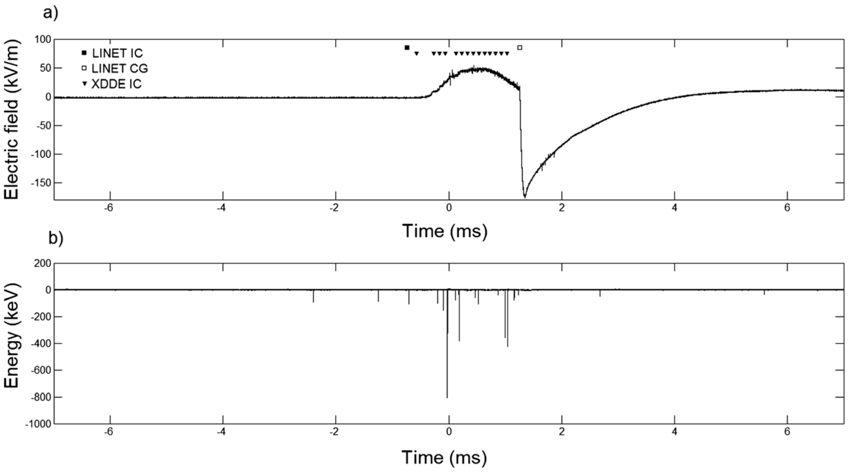

Figure 1. Negative CG flash of 5 July 2012 at 18:36:28.559 UT. (a) Electric field. The black square: IC VLF detection of LINET; black triangles: IC VHF detections of the XDDE; white square: CG VLF detection of LINET. (b) Energy pulses of X-rays.

to leader steps as in the previous reports. The lack of structure in the pulses possibly resulted because only the intense portion of X-rays generated by the distant leader (~1 km) arrived at the detector.

In less than 1 min, at 18:37:22.592 UT, a second negative flash struck ground closer to the tower than the previous one (~0.7 km). LINET reported a peak current of −45 kA for the first return stroke current. As plotted in Figure 2, no noticeable X-ray pulses were detected during the downward leader phase. In Figure 2b, an intense pulse of ~900 keV appeared when the electric field started to increase due to the leader proximity, but it cannot be concluded that this was related to the leader. It is interesting to note that the electric field of the leader at the site was more intense and lasted longer compared to the previous flash. This effect can be explained because the stroke was closer to the antenna. But even though the stroke was closer than before, no burst of X-rays was detected.

Although both flashes occurred within a very short time interval and the electric field signatures were similar, the characteristics of the VHF sources mapped by XDDE are very different for the two events. As Figure 1a displays, between 1.7 ms and ~90 μs before the return stroke the XDDE detected a burst of VHF sources (black triangles). Surprisingly, this is at the same time when the electric field of the leader is measured at ground and during the burst of X-rays. In contrast, during the leader phase of the second flash no similar VHF sources (Figure 2a) were detected and also burst of X-rays was measured. In both cases, LINET reported VLF detections

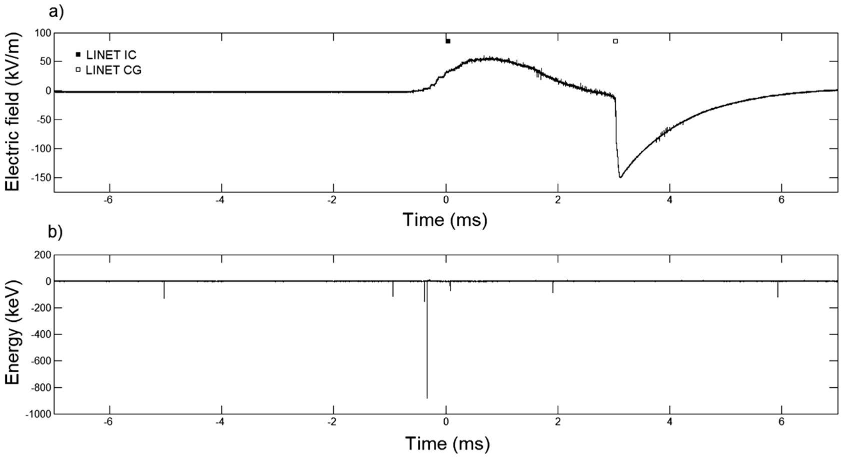

Figure 2. Negative CG flash of 5 July 2012 at 18:18:37:22.592 UT. (a) Electric field. The black square: IC VLF detection of LINET; white square: CG of VLF detections of LINET. (b) Energy pulses of X-rays. No X-rays are straightforward associated to the leader before the return stroke.

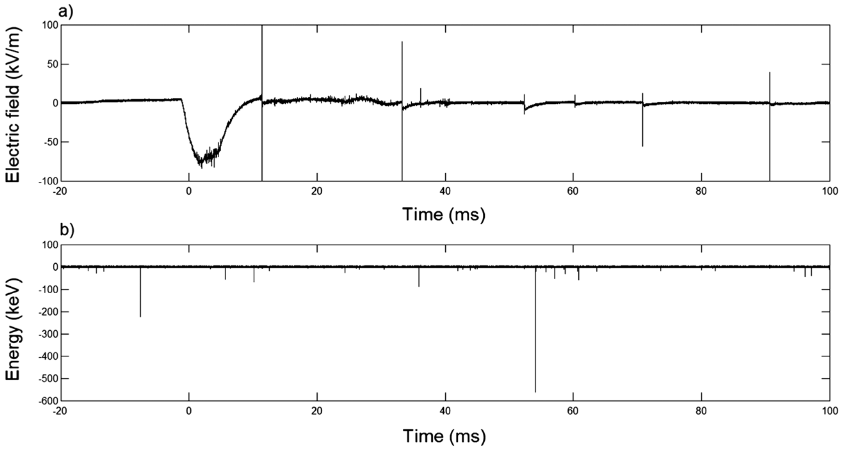

Figure 3. Example of a negative upward CG flash (upward positive leader). (a) Electric field of the event. The electric field associated to the upward leader propagation before its first stroke is comprised between −1.2 ms to 11 ms. The peak current of the first stroke, at 11 ms, was −7.3 kA. (b) Energy pulses of X-rays. No X-rays are associated with this flash.

classified as IC (black squares) before the leader connected to the ground. These were located at altitudes of 10.4 km and 11 km for the first and the second flash, respectively. Both had a positive polarity (9.7 kA and 7.5 kA).

3.2. No X-Rays From Positive Upward Leaders

An upward negative flash is characterized by the inception of a positive upward leader that delivers negative charge to ground [*Berger*, 1967]. Figure 3 displays a typical upward positive leader event. The leader produced the slow negative increase of the electric field between −1.2 ms and 11 ms (Figure 3a). At 11 ms, a negative CG stroke of −7.3 kA was reported by LINET. CG strokes were reported by LINET in most of these flashes. In each of the 12 observed flashes, X-rays cannot be attributed to the upward leaders.

3.3. No X-Rays From a Negative Upward Leader

On 7 June 2011, an intense negative CG stroke of −91 kA struck ground ~3.5 km from the Eagle Nest tower. Figure 4 presents the electric field and X-rays during this event. After 72 ms, the electric field of that flash

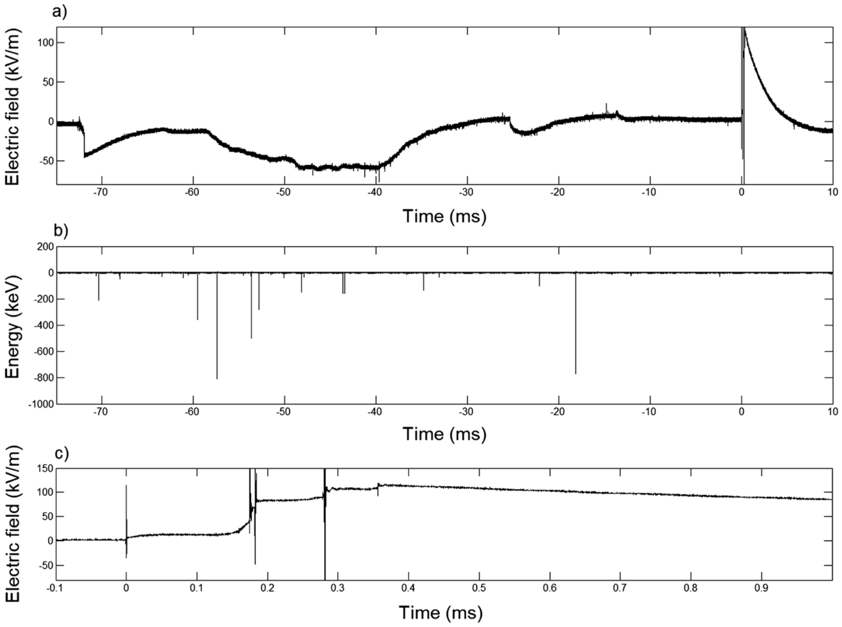

Figure 4. Electric field and X-rays associated to a negative upward leader event. (a) Electric field of the event. The nearby −CG is the negative change at −72 ms and the upward leader at the tower started at 0 ms. (b) Energy pulses of X-rays. (c) Detail of the electric field produced by the upward leader showing five steps. No X-rays are associated with the upward negative leader.

triggered a short-lived upward negative leader at the tower. Between the nearby negative CG flash at −72 ms and the leader at 0 ms, the electric field in Figure 4a shows variations due to IC activity. Figure 4c displays the electric field of the leader which presents four steps. In this case, no X-rays were recorded at the detector located about 20 m from the tower tip.

3.4. Discussion

3.4.1. Upward Lightning

In none of 12 events X-rays have been related to upward positive leaders. Positive upward leaders seem to be less favorable to produce X-rays. The low electric field threshold for positive streamer propagation and the continuous propagation of the leader limits the electric field and consequently the energy of thermal electrons [*Moss et al*., 2006]. Moreover, *Dreicer* [1959] showed how the critical electric field for electron runaway is proportional to the plasma density and inversely proportional to its temperature. As electrons are accelerated toward the streamer front and thus into more dense plasma with low electric field that will slow them down. This argues against X-ray emission by positive leaders. However, *Yoshida et al*. [2008] reported increases of count rates related to upward positive leaders. Additionally, they found increases of count rates attributed to IC events prior to the upward leaders from the towers. These are unique observations, since similar results have not been published yet. Due to strong photon attenuation at sea level, energetic emissions produced by IC lightning would require extremely high energies at the source in order to be detectable at the ground. Even though our sites are at altitudes of 2537 m msl and 2877 m msl, no energetic detections produced by IC flashes above the stations have been recorded yet. The lack of energetic sources of the upward negative leader described in section 3.4 requires a nonunique explanation. Upward negative leaders from ground objects are not common since they require higher inception fields than positive leaders and positive charge above. In the case presented in section 3.3, the upward negative leader was triggered in response to an intense negative CG stroke followed by IC activity. The leader was short lived (Figure 4c), but it appeared very bright in the video images. Two possibilities are considered: the first one is that the leader produced X-rays and the second did not. Under the first possibility, if the leader produced X-rays, they were not detected as the beam was apparently directed away from the sensor. In the first calculations of bremsstrahlung, *Bethe and Heitler* [1934] indicated that the radiation of fast electrons is emitted primarily in the forward direction. Recently, calculations of angular distribution of emitted bremsstrahlung photons for different photon and electron energies have been treated by *Köhn and Ebert* [2013]. The results show that the radiation for highly energetic electrons that can be treated relativistically is forward directed (e.g., a 10 MeV electron has a scattering angle slightly higher than 1°), whereas for lower energies the scattering becomes more isotropic. But three factors contribute to broaden the X-ray flux angle from the source. First, the runaway electrons would follow the electric field lines which have certain divergence from the leader tip [e.g., *Babich et al*., 2013]. Second, Coulomb scattering would have significant incidence on the angular scattering of electrons [e.g., *Lehtinen et al*., 1999; *Dwyer et al*., 2010; *Celestin and Pasko*, 2011]. And third, Compton scattering would decrease the energy of photons considerably and will tend to be isotropic especially for low energies [e.g., *Gurevich and Milikh*, 1999; *Dwyer*, 2003; *Saleh et al*., 2009; *Celestin and Pasko*, 2012]. As result, if the negative upward leader produced X-rays, the lack of detections would suggest that the flux was not pure isotropic. But in order to prove it, future Monte Carlo simulations will certainly help to quantify the amount of photons scattered toward the detector due to Compton scattering. On the other hand, the possibility in which the leader did not produce X-rays would be supported by assuming that the electric field at the leader tip of the upward negative leader was not enough to allow electrons to run away. As very well indicated by *Kunhardt and Byszewski* [1980], the electric field profile ahead of the streamer front must be high enough to allow electrons to run away; otherwise, runaway electrons can be quickly trapped. In the first stages of an upward-directed negative leader, since the bulk of the cloud charge is far aloft, the electric field ahead of the leader tip would rapidly decrease, thereby preventing electron runaway. The reverse would occur with downward-directed negative leaders approaching the ground and bringing the cloud potential to their tips enhancing the electric field due to the charge image effect.

3.4.2. Downward Negative Lightning

The observed downward negative leaders of natural negative CG flashes are discussed now. To date, there is not a large catalogue of X-ray measurements produced by natural lightning [*Moore et al*., 2001; *Dwyer et al*., 2005a; *Howard et al*., 2008; *Yoshida et al*., 2008; *Howard et al*., 2010; *Mallick et al*., 2012; *Montanyà et al*., 2012; *Schaal et al*., 2012]; and all the observations, except those of *Yoshida et al*. [2008], corresponds to downward negative stepped leaders and dart leaders. Some of the authors of the present paper experienced difficulty in the task of measuring X-rays from natural lightning. After 4 years of campaigns in the Ebro Valley Laboratory, only two events allowed to measure X-rays. The detection of X-rays from lightning requires being very close to the lightning strike. But, although on several occasions lightning struck at close range ($<$ 1 km) even at 2500 m altitude, no energetic radiation was detected. Notably, in the case of *Suszcynsky and Roussel-Dupre* [1996] in 22 records of lightning flashes within 2 km (10 of those within a distance of about 0.5 km), no energetic radiation was detected. As before, two initial hypotheses arise: the primary one is that all negative leaders produce X-rays, and the secondary one is that not all negative leaders do. If we first consider that all negative leaders produce X-rays, the only explanation would be that measurements must be done in a range such that the instruments are illuminated by detectable radiation. This means that the detectors must be close enough in order not to receive completely attenuated radiation. In such a case, measurements at sea level require very short ranges (i.e., 1 MeV photons have ~100 m of attenuation length at sea level). Thus, measurements at higher altitudes are more favorable considering an attenuation law as $\exp(-(\mu/\rho)R)$ where R is the distance and μ/ρ is the mass attenuation coefficient which depends on the medium density ρ [see *Hubbell and Seltzer*, 2004]. Once the leader is close enough, the detector needs to be within the X-rays flux beam. As pointed out before, energetic photons are forward directed with the runaway electron flux but also broadened as they propagate. Considering a mean energy $\langle\varepsilon\rangle$ distribution of the runaway electrons of ~7 MeV [e.g., *Babich et al*., 2013], the angular distribution would be as narrow as ~2.5° based on *Köhn and Ebert* [2013]. But on the other hand, the divergence of the electric field lines at the leader front, Coulomb, and Compton scattering would contribute to broaden the X-ray propagation. Thus, the chances of detecting emissions are limited to the distance between the leader front and the instrument $R = \sqrt{h^2 + d^2}$ where h is the leader height and d is the horizontal distance. As result, the minimum requirements to detect radiation are (i) $R \leq$ attenuation length for a given photon energy at the source and air density; and (ii) $\operatorname{atan}(d/h) \leq$ half of the angular distribution of the X-ray flux. Other factors may have strong influence (e.g., detector type, size, efficiency, and other electron and photon interaction processes not considered here). In that sense, *Saleh et al*. [2009] found a radial fall off proportional to the $[\exp(-r/120)]/r$, where r is the radial distance. The case in section 3.1 where X-ray pulses were received, a very large angular distribution of ~120° would be required. But according to the received energies, the leader would be tilted toward the detector in its final approach to ground. Another possibility would be that the received energy came from one of the leader branches that usually do not point vertically to ground [*Montanyà et al*., 2012]. In any case, no leaders can be observed in the high-speed video records, only illumination from the cloud can be resolved during the leader phase. For the second event in section 3.1 with no X-rays detected, even the leader struck closer it would be directed outside of the field of view of the instrument. Now, the hypothesis that not all negative leaders produce X-rays is going to be considered. Several arguments can arise to explain such an observation. This would apply to the leader and their branches. As discussed by *Moss et al*. [2006], the generation of thermal runaway electrons would be produced during the stepping process when the time delay of negative corona inception occurs. This delay is produced after the stroke-like current pulse due to the junction between the space leader and the main leader. During that delay, electric fields would be present very close to the leader tip for a short time (~1 μs) allowing thermal runaway electrons. This time agrees with the delays between the electric field pulses and the arrival of X-rays reported by *Howard et al*. [2008]. This situation appears to be very similar to the production of thermal RE by nanosecond discharges where high overvoltage Δ can be applied to the gap [e.g., *Babich and Loiko*, 2010, and related references therein]. In laboratory spark gaps one of the electrodes is connected to the high-voltage source and the other is commonly grounded. In nature, a negative leader has sufficiently large conductivity to be considered as an equipotential [e.g., *Raizer*, 1991]. It is assumed that the leader is connected to the cloud potential and carries it to the ground thanks to its high conductivity. The cloud potential is estimated to be at 20–130 MV [*Marshall and Stolzenburg*, 2001]. The leader driven by the cloud potential may play an important role in allowing high electric fields closely ahead of the leader tip. In that sense, negative leaders associated with low cloud potential respect to ground may not produce enough fields to generate thermal runaway electrons. In the two cases that are presented in section 3.1, one difference is the detected VHF sources by the interferometer network during the last part of the leader simultaneously when X-rays were detected. With our interferometers, it is not possible to unambiguously distinguish if these sources come from the leader tip to ground or from leaders in the cloud. But the large baselines (~150 km) of the XDDE sensors do not favor the detection of VHF sources at low altitudes. If these are cloud sources, these detections may be related with some IC process related to the downward leader.

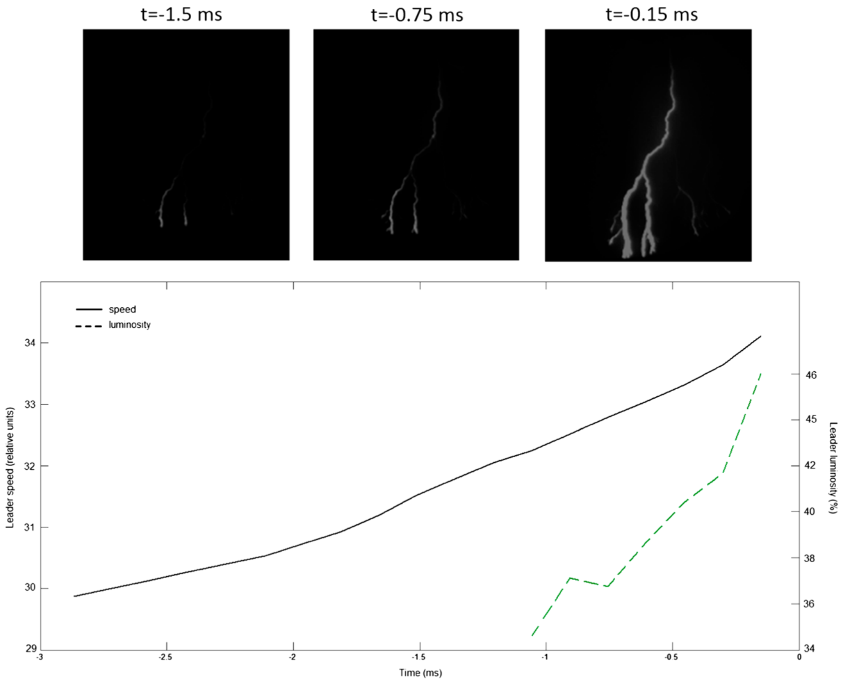

Figure 5. Example of luminosity and speed intensification for a negative downward flash on the sea. (a) Three selected frames before the return stroke at $t = 0$ s. (b) Relative leader velocity and luminosity. Luminosity is expressed in % to pixel saturation.

High-speed video observations of negative stepped leaders show how the leaders notably increase their luminosity during the last milliseconds before connecting to the ground. Figure 5 presents an example of a flash that struck on the sea. The figure displays three frames in which the luminosity of the channel increases before the return stroke ($t = 0$ s). Figure 5b plots the relative speed and the luminosity during the last 2.5 ms. The speed gradually increased during that period while luminosity is highly intensified during the last part of the leader to ground. This effect has been already pointed out by *Schonland et al*. [1935] and more recently studied by *Chen et al*. [1999]. The increase of luminosity is related to the increase of current [e.g., *Bazelyan*, 1995]. *Chen et al*. [1999] indicated that at this stage the leader current is composed of a continuing current and short pulses associated with the step breakdown. Moreover, no significant trend of the step length variation was observed when the leader approaches the ground. Also no relation between the leader length and speed was found. As suggested by *Chen et al*. [1999], the increase of brightness is due to an increase of the electric field surrounding the leader that can accelerate the leader. As the leader propagates toward the ground, the charges pile up within the bright leader front [*Chen et al*., 1999; *Lalande et al*., 1998]. It is remarkable that the time when the luminosity rapidly increases is the time when commonly X-rays are observed and VHF pulses detected. It is clear that a threshold electric field is necessary for the production of runaway electrons [e.g., *Gurevich et al*., 2007] and that the electric field profile just in front of the leader tip would allow thermal runaway to escape [*Kunhardt and Byszewski*, 1980]. The charge pile up and the enhancement of the current would increase the leader conductivity, thereby reducing the voltage drop along the leader channel. All these effects occurring during the final stages would provide the most favorable conditions for runaway electrons at the leader front. This is consistent with the observation by *Saleh et al*. [2009] where the increase of luminosity (in terms of energetic electrons and X-rays per second) as the dart leader approached to ground was suggested to be produced by the image charge effect on the electric field.

4. Background Radiation

When the high-energy instrument is in operation, the background radiation is measured continuously by one of the NaI(Tl) detectors. A spectrum is acquired in intervals of 1 min and the total counts over certain energy are computed for the same period. On 5 July 2012, three storms passed over the site. Figure 6a shows 24 h of count rate history for the NaI(Tl) detector. The three count enhancements are related to the storms that

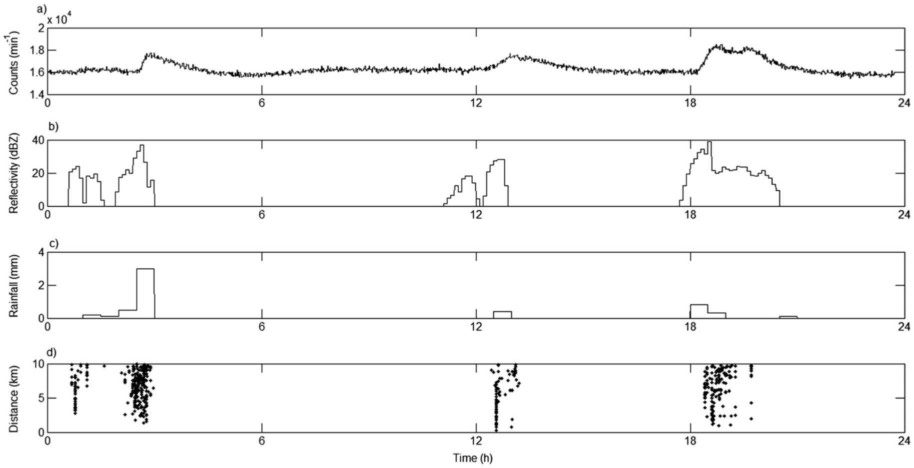

Figure 6. Diurnal evolution of the 5 July 2012 (a) X-ray count rates; (b) maximum radar reflectivity at the tower; (c) rainfall at the closest weather station; and (d) distance to the tower of the XDDE VHF sources.

occurred at the Eagle Nest during that day. For the first storm the count rate surpassed the background by 8.2% with a rise time of 15 min. In the second storm the count rate overpassed 7.6% with a slower rise time of 52 min. Finally, the third storm produced a count rate 13% higher than the background with a rise time of 33 min. Figures 6b and 6c plot the maximum radar reflectivity at the site and the rainfall at the closest automatic weather station (<5 km), respectively. The graph in Figure 6d corresponds to the distance of the VHF sources detected by the XDDE. Inspecting Figures 5a and 5c, a relation between rain and count increase can be noted. For that day, rainfalls were light but as shown in Figure 6, there is no straight relation between the intensity of precipitation and overshooting of radiation counts. Some relation can be noted between the precipitation and the rise times of the counting rate peaks. However, looking at the maximum vertical reflectivity of the radar at the location, there is good agreement between the maximum reflectivity and the maximum count rate. The less pronounced count increase (7.6%) of the day was during ~13 h UT which corresponds with a reflectivity of 28 dBZ. The maximum reflectivity of the day was observed at the storm of the afternoon where the reflectivity peaked at 39 dBZ. For the three storms the count rate increased after peaking in the radar reflectivity over ~30 dBZ. Contrary, the closest located VHF lightning sources were detected during the ~13:00 h storm but the maximum count rate of that storm was the smallest. At 00:45 h some lightning activity and rainfall were located <3 km, but no noticeable increase of the count rate was observed. The flash in which X-rays were detected (section 3.1) occurred during the 18:36 h storm that produced the maximum count rate. Interestingly, in that storm the count rate remained high for long time after the peak of maximum radar reflectivity and without collected precipitation. During this time the reflectivity did not disappear and remained to about 20 dBZ. But none of the observations supports that these increases of counts are associated to the storm electrification or lightning. As result the counting increases are attributed to radon daughter-ion precipitation. Radon (^{222}Rn) is produced in the ground and migrates to the atmosphere where it alpha decays into a daughter-ion sequence. In the atmosphere, the daughter ions (positive) can attach to aerosols which form nucleation sites for water droplets. Those are bringing back the daughter ions to the ground by rainfall and deposited just on the detector. For a comprehensive analysis, see *Suszcynsky et al.* [1996]. As calculated by *Bhandari and Rama* [1963], the 50% reduction in the collective activity of all precipitated daughter ions should occur after about 50 min of daughter-ion decay from initial equilibrium values. This was also experienced by *Suszcynsky et al.* [1996] and is consistent with the present work. Similarly, *Mallick et al.* [2012] attributed the increase of the average counts per second to precipitation during thunderstorms.

In some previous works [e.g., *Torii et al.*, 2009; *Gurevich et al.*, 2013] radiation was measured at altitudes of more than 3000 m that would explain the lack of long lasting bursts (especially gamma ray) associated with lightning or longer gradual variations associated with thunderstorms. In *Torii et al.* [2008], the authors pointed out that the increase of gamma-ray dose measured at sea level has only been observed during winter storms and never during summer storms. In a winter event measured at lower altitude, *Torii et al.* [2011] estimated the radiation source as a downward hemispherical surface with a radius of 700 m centered at 1000 m altitude.

In the case presented here (Figure 6), the altitude of the midlevel negative charge region was estimated to be at 5.6 km according to the -10°C isotherm which means 3 km above the instrument. At such distance, radiation from the thunderstorm is not expected to be measured. But in *Tsuchiya et al.* [2009], the authors found simultaneous detections of gamma radiation extending to 10 MeV and electrons lasting for 90 s measured at a mountain observatory located 2770 m above sea level during a thunderstorms on September. They estimated the source to be located 60–130 m.

5. Conclusions

We presented data of high-energy radiation associated with lightning and with thunderstorms. Three types of natural leaders in natural lightning events and their radiation have been presented and discussed. The observed X-ray emissions from natural negative CG lightning will join the list of few existing reports. Only radiation of negative leaders seems to be possible since the flux of the electrons is in the forward direction of the leader. We discussed the importance of being close to the striking location but also being the leader toward the field of view of the detector. At the source, the photon angular distribution is narrow as energy increases, but the divergence of the electric field lines at the leader front, Coulomb, and Compton scattering would broaden X-ray flux as it propagates. Future Monte Carlo simulations are needed in order to evaluate the X-ray flux in the presented events. The high-field runaway electron mechanism seems to be a good candidate to explain the observations of X-rays by lightning and laboratory sparks [e.g., *Gurevich et al*., 2007; *Dwyer*, 2008]. Since this mechanism requires very high electric fields at the leader tip and the leader is assumed to bring the cloud potential to ground, the last stages of the leader approaching to ground would produce the conditions for RE. The observed increase of luminosity of the lower part of the leader, and especially at its tip, suggests that the current at the leader increases indicating charge pile up and higher electric fields between the leader tip and the ground. The leader current increase can be related with the detected IC VHF sources in the case when X-rays were detected. Assuming that current at the leader tip is composed of two components [*Chen et al*., 1999], the one of continuing current would contribute to an increase of the electrostatic field component, whereas the second component is a fast pulse that would allow the "overvoltage" in the close vicinity of the leader front. As result, the very favorable conditions would arise during the last part of the leader to ground being consistent with the reported observations and others resumed recently by *Dwyer and Uman* [2013]. However, the distances and the energies in which X-rays have been detected do not close the door to be arriving from some local coronas near the detector.

The experience with the background radiation during thunderstorms denoted that the increases in the count rates are attributed to radon daughter-ion precipitation rather than storm electrification. Even though the instrument has been installed at two mountain peaks, the attenuation path of gamma rays of few MeV would require to be much closer to the charged regions of the storm. But this can be achieved during winter thunderstorms as shown in data from Japan but no similar observations have been obtained yet here. The observations showed good agreement between count rate increases and high radar reflectivity (~30 dBZ) and not straightforward relation with the total lightning activity.

Acknowledgments
The authors thank the helpful comments of the anonymous reviewers that have led to improvements of the paper. This study was supported by research grants from the Spanish Ministry of Economy and Competitiveness (MINECO) AYA2009-14027-C05-05 and AYA2011-29936-C05-04.

References

Babich, L. P., and T. V. Loiko (2010), Peculiarities of detecting pulses of runaway electrons and X-rays generated by high-voltage nanosecond discharges in open atmosphere, *Plasma Phys. Rep.*, *36*(3), 263–270.

Babich, L. P., I. M. Kutsyk, E. N. Donskoĭ, and J. R. Dwyer (2013), Analysis of the experiment on registration of X-rays from the stepped leader of a cloud-to-ground lightning discharge, *J. Geophys. Res. Space Physics*, *118*, 2573–2582, doi:10.1002/jgra.50236.

Bazelyan, E. M. (1995), Waves of ionization in lightning discharge, *Plasma Phys. Rep.*, *21*, 470–478.

Bazelyan, E. M., and Y. P. Raizer (2000), *Lightning Physics and Lightning Protection*, IOP Publ, Philadelphia, Pa.

Berger, K. (1967), Novel observations on lightning discharges: Results of research Mont San Salvatore, *J. Franklin Inst.*, *283*, 478–525.

Bethe, H. A., and W. Heitler (1934), On the stopping of fast particles and on the creation of positive electrons, *Proc. Phys. Soc. London*, *146*, 83–112.

Betz, H.-D., K. Schmidt, P. Oettinger, and M. Wirz (2004), Lightning detection with 3-D discrimination of intracloud and cloud-to-ground discharges, *Geophys. Res. Lett.*, *31*, L11108, doi:10.1029/2004GL019821.

Betz, H.-D., T. C. Marshall, M. Stolzenburg, K. Schmidt, W. P. Oettinger, E. Defer, J. Konarski, P. Laroche, and F. Dombai (2008), Detection of in-cloud lightning with VLF/LF and VHF networks for studies of the initial discharge phase, *Geophys. Res. Lett.*, *35*, L23802, doi:10.1029/2008GL035820.

Bhandari, N., and Rama (1963), Study of atmospheric washout processes by means of radon decay products, *J. Geophys. Res.*, *68*, 3823–3826.

Campos, L. Z. S., M. M. F. Saba, T. A. Warner, O. Pinto Jr., E. P. Krider, and R. E. Orville (2013), High-speed video observations of natural cloud-to-ground lightning leaders—A statistical analysis, *Atmos. Res.*, doi:10.1016/j.atmosres.2012.12.011.

Celestin, S., and V. P. Pasko (2011), Energy and fluxes of thermal runaway electrons produced by exponential growth of streamers during the stepping of lightning leaders and in transient luminous events, *J. Geophys. Res.*, *116*, A03315, doi:10.1029/2010JA016260.

Celestin, S., and V. P. Pasko (2012), Compton scattering effects on the duration of terrestrial gamma-ray flashes, *Geophys. Res. Lett.*, *39* L02802, doi:10.1029/2011GL050342.

Chen, M., N. Takagi, T. Watanabe, D. Wang, Z.-. I. Kawasaki, and X. Liu (1999), Spatial and temporal properties of optical radiation produced by stepped leaders, *J. Geophys. Res.*, *104*, 27,573–27,584, doi:10.1029/1999JD900846.

Chilingarian, A., K. Daryan, A. Arakelyan, B. Hovhannisyan, L. Mailyan, G. Melkumyan, S. Hovsepyan, A. Reymers Chilingaryan, and L. Vanyan (2010), Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons, *Phys. Rev. D*, *82*, 043009, doi:10.1103/PhysRevD.82.043009.

Cooray, V., M. Becerra, and V. Rakov (2009), On the electric field at the tip of dart leaders in lightning flashes, *J. Atmos. Sol. Terr. Phys.*, *71*(12), 1397–1404, doi:10.1016/j.jastp.2009.06.002.

Cooray, V., J. R. Dwyer, V. Rakov, and M. Rahman (2010), On the mechanism of X-ray production by dart leaders of lightning flashes, *J. Atmos. Sol. Terr. Phys.*, *72*(11–12), 848–855, doi:10.1016/j.jastp.2010.04.006.

Dreicer, H. (1959), Electron and ion runaway in a fully ionized gas. I, *Phys. Rev.*, *115*, 238–249.

Dwyer, J. R. (2003), A fundamental limit on electric fields in air, *Geophys. Res. Lett.*, *30*(20), 2055, doi:10.1029/2003GL017781.

Dwyer, J. R. (2004), Implications of x-ray emission from lightning, *Geophys. Res. Lett.*, *31*, L12102, doi:10.1029/2004GL019795.

Dwyer, J. R. (2008), Source mechanisms of terrestrial gamma-ray flashes, *J. Geophys. Res.*, *113*, D10103, doi:10.1029/2007JD009248.

Dwyer, J. R., and M. A. Uman (2013), The physics of lightning, *Physics Reports*, doi:10.1016/j.physrep.2013.09.004.

Dwyer, J. R., et al. (2003), Energetic radiation produced during rocket triggered lightning, *Science*, *299*, 694–697.

Dwyer, J. R., et al. (2005a), X-ray bursts associated with leader steps in cloud-to-ground lightning, *Geophys. Res. Lett.*, *32*, L01803, doi:10.1029/2004GL021782.

Dwyer, J. R., H. K. Rassoul, Z. Saleh, M. A. Uman, J. Jerauld, and J. A. Plumer (2005b), X-ray bursts produced by laboratory sparks in air, *Geophys. Res. Lett.*, *32*, L20809, doi:10.1029/2005GL024027.

Dwyer, J. R., Z. Saleh, H. K. Rassoul, D. Concha, M. Rahman, V. Cooray, J. Jerauld, M. A. Uman, and V. A. Rakov (2008), A study of X-ray emission from laboratory sparks in air at atmospheric pressure, *J. Geophys. Res.*, *113*, D23207, doi:10.1029/2008JD010315.

Dwyer, J. R., D. M. Smith, M. A. Uman, Z. Saleh, B. Grefenstette, B. Hazelton, and H. K. Rassoul (2010), Estimation of the fluence of high-energy electron bursts produced by thunderclouds and the resulting radiation doses received in aircraft, *J. Geophys. Res.*, *115*, D09206, doi:10.1029/2009JD012039.

Fishman, G. J., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, *264*, 1313–1316.

Gurevich, A. V., and G. M. Milikh (1999), Generation of X-rays due to multiple runaway breakdown inside thunderclouds, *Phys. Lett. A*, *262*, 457–463.

Gurevich, A. V., G. M. Milikh, and R. Roussel-Dupré (1992), Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, *Phys. Lett. A*, *165*, 463–468.

Gurevich, A. V., K. P. Zybin, and Y. V. Medvedev (2007), Runaway breakdown in strong electric field as a source of terrestrial gamma flashes and gamma bursts in lightning leader steps, *Phys. Lett. A*, *361*(1–2), 119–125.

Gurevich, A.V., et al. (2013), Cosmic rays and thunderstorms at the Tien-Shan mountain station, *J. Phys. Conf. Ser.*, *409*, 012234, doi:10.1088/1742-6596/409/1/012234.

Howard, J., M. A. Uman, J. R. Dwyer, D. Hill, C. Biagi, Z. Saleh, J. Jerauld, and H. K. Rassoul (2008), Co-location of lightning leader x-ray and electric field change sources, *Geophys. Res. Lett.*, *35*, L13817, doi:10.1029/2008GL034134.

Howard, J., M. A. Uman, C. Biagi, D. Hill, J. Jerauld, V. A. Rakov, J. R. Dwyer, Z. H. Saleh, and H. K. Rassoul (2010), RF and X-ray source locations during the lightning attachment process, *J. Geophys. Res.*, *115*, D06204, doi:10.1029/2009JD012055.

Hubbell, J. H., and S. M. Seltzer (2004), Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients (version 1.4), National Institute of Standards and Technology, Gaithersburg, MD. [Available at http://physics.nist.gov/xaamdi.]

Kochkin, P. O., C. V. Nguyen, A. P. J. van Deursen, and U. Ebert (2012), Experimental study of hard X-rays emitted from metre-scale positive discharges in air, *J. Phys. D Appl. Phys.*, *45*, 425202, doi:10.1088/0022-3727/45/42/425202.

Köhn, C., and U. Ebert (2013), Angular distribution of bremsstrahlung photons and of positrons for calculations of terrestrial gamma-ray flashes and positron beams, *Atmos. Res.*, doi:10.1016/j.atmosres.2013.03.01.

Kostyrya, I. D., V. F. Tarasenko, A. N. Tkachev, and S. I. Yakovlenko (2006), X-ray radiation due to nanosecond volume discharges in air under atmospheric pressure, *Tech. Phys.*, *51*, 356–361.

Krider, E. P., and G. J. Radda (1975), Radiation field wave forms produced by lightning stepped leaders, *J. Geophys. Res.*, *80*(18), 2653–2657.

Kunhardt, E. E., and W. W. Byszewski (1980), Development of overvoltage breakdown at high gas pressure, *Phys. Rev. A*, *21*, 2069–2077.

Lalande, P., A. Bondiou-Clergerie, P. Laroche, A. Eybert-Berard, J.-P. Berlandis, B. Bador, A. Bonamy, M. A. Uman, and V. A. Rakov (1998), Leader properties determined with triggered lightning techniques, *J. Geophys. Res.*, *103*, 14,109–14,115.

Lehtinen, N. G., T. F. Bell, and U. S. Inan (1999), Monte Carlo simulation of runaway MeV electron breakdown with application to red sprites and terrestrial gamma ray flashes, *J. Geophys. Res.*, *104*, 24,699–24,712, doi:10.1029/1999JA900335.

Lojou, J. Y., and K. L. Cummins (2006), Total lightning mapping using both VHF interferometry and time-of-arrival techniques, 19th International Lightning Detection Conference, Tucson (AZ), USA.

Mallick, S., V. A. Rakov, and J. R. Dwyer (2012), A study of X-ray emissions from thunderstorms with emphasis on subsequent strokes in natural lightning, *J. Geophys. Res.*, *117*, D16107, doi:10.1029/2012JD017555.

March, V., and J. Montanyà (2010), Influence of the voltage-time derivative in X-ray emission from laboratory sparks, *Geophys. Res. Lett.*, *37*, L19801, doi:10.1029/2010GL044543.

March, V., and J. Montanyà (2011), X-rays from laboratory sparks in air: The role of the cathode in the production of runaway electrons, *Geophys. Res. Lett.*, *38*, L04803, doi:10.1029/2010GL046540.

Mazur, V. (2002), Physical processes during development of lightning flashes, *C. R. Physique*, *3*(10), 1393–1409.

Mazur, V., and L. H. Ruhnke (1993), Common physical processes in natural and artificially triggered lightning, *J. Geophys. Res.*, *98*, 12,913–12,930, doi:10.1029/93JD00626.

Mazur, V., X. Shao, and P. R. Krehbiel (1998), "Spider" lightning in intracloud and positive cloud-to-ground flashes, *J. Geophys. Res.*, *103*(D16), 19,811–19,822, doi:10.1029/98JD02003.

Montanyà, J., S. Soula, and N. Pineda (2007), A study of the total lightning activity in two hailstorms, *J. Geophys. Res.*, *112*, D13118, doi:10.1029/2006JD007203.

Montanyà, J., O. A. van der Velde, V. March, D. Romero, G. Solà, and N. Pineda (2012), High-speed video of lightning and X-ray pulses during the 2009–2010 observation campaigns in northeastern Spain, *Atmos. Res.*, *117*, 91–98.

Moore, C. B., K. B. Eack, G. D. Aulich, and W. Rison (2001), Energetic radiation associated with lightning stepped-leaders, *Geophys. Res. Lett.*, *28*, 2141–2144.

Moss, G. D., V. P. Pasko, N. Liu, and G. Veronis (2006), Monte Carlo model for analysis of thermal runaway electrons in streamer tips in transient luminous events and streamer zones of lightning leaders, *J. Geophys. Res.*, *111*, A02307, doi:10.1029/2005JA011350.

Nguyen, C. V., A. P. J. van Deursen, and Ute Ebert (2008), Multiple X-ray bursts from long discharges in air, *J. Phys. D: Appl. Phys.*, *41*, 234012, doi:10.1088/0022-3727/41/23/234012.

Nguyen, C. V., A. P. J. van Deursen, E. J. M. van Heesch, and G. J. J. Winands (2010), X-ray emission in streamer-corona plasma, *J. Phys. D: Appl. Phys.*, *43*, 025202, doi:10.1088/0022-3727/43/2/025202.

Oreshkin, E., S. Chaikovsky, A. Oginov, and K. Shpakov (2012), Bremsstrahlung radiation of fast Electrons in long air gaps, *Int. J. Energ. Power Eng.*, *6*, 906–911.

Proctor, D., R. Uytenbogaardt, and B. Meredith (1988), VHF radio pictures of lightning flashes to ground, *J. Geophys. Res.*, *93*(D10), 12,683–12,727, doi:10.1029/JD093iD10p12683.

Rahman, M., V. Cooray, N. A. Ahmad, J. Nyberg, V. A. Rakov, and S. Sharma (2008), X-rays from 80 cm long sparks in air, *Geophys. Res. Lett.*, *35*, L06805, doi:10.1029/2007GL032678.

Raizer, Y. P. (1991), *Gas Discharge Physics*, Springer, New York.

Rakov, V. A., and M. A. Uman (2007), *Lightning: Physics and Effects*, Cambridge Univ. Press, Cambridge, U. K.

Rep'ev, A. G., and P. B. Repin (2008), Spatiotemporal parameters of the X-ray radiation from a diffuse atmospheric-pressure discharge, *Tech. Phys.*, *53*, 73–80.

Saleh, Z., J. Dwyer, J. Howard, M. Uman, M. Bakhtiari, D. Concha, M. Stapleton, D. Hill, C. Biagi, and H. Rassoul (2009), Properties of the X-ray emission from rocket-triggered lightning as measured by the Thunderstorm Energetic Radiation Array (TERA), *J. Geophys. Res.*, *114*, D17210, doi:10.1029/2008JD011618.

Schaal, M. M., J. R. Dwyer, Z. H. Saleh, H. K. Rassoul, J. D. Hill, D. M. Jordan, and M. A. Uman (2012), Spatial and energy distributions of X-ray emissions from leaders in natural and rocket triggered lightning, *J. Geophys. Res.*, *117*, D15201, doi:10.1029/2012JD017897.

Schonland, B. F. J., D. J. Malan, and H. Collens (1935), Progressive lightning, part 2, *Proc. R. Soc. London, Ser. A*, *152*, 595–625.

Shao, X., and P. Krehbiel (1996), The spatial and temporal development of intracloud lightning, *J. Geophys. Res.*, *101*(D21), 26,641–26,668, doi:10.1029/96JD01803.

Shao, T., C. Zhang, Z. Niu, P. Yan, V. F. Tarasenko, E. K. Baksht, A. G. Burahenko, and Y. B. Shut'ko (2011), Diffuse discharge, runaway electron, and X-ray in atmospheric pressure air in a inhomogeneous electrical field in repetitive pulsed modes, *Appl. Phys. Lett.*, *98*, 021503, doi:10.1063/1.3540504.

Stankevich, Y. L., and V. G. Kalinin (1967), Fast electrons and X-ray radiation during the initial stage of growth of a pulsed spark discharge in air, *Sov. Phys. Dokl.*, *12*, 1042–1043.

Suszcynsky, D. M., R. Roussel-Dupré, and G. Shaw (1996), Ground-based search for X-rays generated by thunderstorms and lightning, *J. Geophys. Res.*, *101*, 23,505–23,516.

Torii, T., T. Sugita, and Y. Muraki (2008), Observation of the gradual increases and bursts of energetic radiation in association with winter thunderstorm activity, in *Proceedings of the 30th International Cosmic Ray Conference*, vol. 1, edited by R. Caballero et al., pp. 677–680, Univ. Nac. Auton. de Mex., Mexico City.

Torii, T., T. Sugita, S. Tanabe, Y. Kimura, M. Kamogawa, K. Yajima, and H. Yasuda (2009), Gradual increase of energetic radiation associated with thunderstorm activity at the top of Mt. Fuji, *Geophys. Res. Lett.*, *36*, L13804, doi:10.1029/2008GL037105.

Torii, T., T. Sugita, M. Kamogawa, Y. Watanabe, and K. Kusunoki (2011), Migrating source of energetic radiation generated by thunderstorm activity, *Geophys. Res. Lett.*, *38*, L24801, doi:10.1029/2011GL049731.

Tsuchiya, H., et al. (2009), Observation of an energetic radiation burst from mountain-top thunderclouds, *Phys. Rev. Letters*, *102*, 255003, doi:10.1103/PhysRevLett.102.255003.

van der Velde, O. A., and J. Montanyà (2013), Asymmetries in bidirectional leader development of lightning flashes, *J. Geophys. Res. Atmospheres*, *118*, 1–16, doi:10.1002/2013JD020257.

Williams, E., et al. (2006), Lightning flashes conducive to the production and escape of gamma radiation to space, *J. Geophys. Res.*, *111*, D16209, doi:10.1029/2005JD006447.

Yoshida, S., C. J. Biagi, V. A. Rakov, J. D. Hill, M. V. Stapleton, D. M. Jordan, M. A. Uman, T. Morimoto, T. Ushio, and Z.-I. Kawasaki (2010), Three-dimensional imaging of upward positive leaders in triggered lightning using VHF broadband digital interferometers, *Geophys. Res. Lett.*, *37*, L05805, doi:10.1029/2009GL042065.

Yoshida, S., T. Morimoto, T. Ushio, Z.-I. Kawasaki, T. Torii, D. Wang, N. Takagi, and T. Watanabe (2008), High energy photon and electron bursts associated with upward lightning strokes, *Geophys. Res. Lett.*, *35*, L10804, doi:10.1029/2007GL032438.