Electron acceleration above thunderclouds

This content has been downloaded from IOPscience. Please scroll down to see the full text.
2013 Environ. Res. Lett. 8 035027
(http://iopscience.iop.org/1748-9326/8/3/035027)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 138.38.54.59
This content was downloaded on 25/11/2013 at 16:42

Please note that terms and conditions apply.
Electron acceleration above thunderclouds

Martin Füllekrug1, Ivana Kolmasova2, Ondrej Santolik2,3, Thomas Farges4, József Bör5, Alec Bennett6, Michel Parrot7, William Rison8, Ferruccio Zanotti9, Enrico Arnone10, Andrew Mezentsev1, Radek Lan2, Ludek Uhlik2, Giles Harrison11, Serge Soula12, Oscar van der Velde13, Jean-Louis Pinçon7, Christiane Helling14 and Declan Diver15

1 Centre for Space and Atmospheric Science, Department of Electronic and Electrical Engineering, University of Bath, Bath, UK
2 Institute of Atmospheric Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
3 Faculty of Mathematics and Physics, Charles University in Prague, Czech Republic
4 Commissariat à l’Energie Atomique et aux Energies Alternatives, DAM-DIF, Bruyères le Châtel, France
5 Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Sopron, Hungary
6 Bristol Industrial and Research Associates Ltd, Portishead, Bristol, UK
7 Laboratoire de Physique et Chimie de l’Environnement et de l’Espace, CNRS, Orléans, France
8 New Mexico Tech, Electrical Engineering Department, NM, USA
9 Italian Meteor and TLE Network, Ferrara, Italy
10 Istituto di Scienze dell’Atmosfera e del Clima, CNR, Bologna, Italy
11 Department of Meteorology, University of Reading, Reading, UK
12 Laboratoire d’Aérologie, Université de Toulouse, CNRS, Toulouse, France
13 Department of Electrical Engineering, Technical University of Catalonia, Terrassa, Spain
14 SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, UK
15 School of Physics and Astronomy, University of Glasgow, Glasgow, UK

E-mail: eesmf@bath.ac.uk (Martin Füllekrug)

Received 12 May 2013
Accepted for publication 26 July 2013
Published 13 August 2013
Online at stacks.iop.org/ERL/8/035027

Abstract
The acceleration of electrons results in observable electromagnetic waves which can be used for remote sensing. Here, we make use of ~4 Hz–66 MHz radio waves emitted by two consecutive intense positive lightning discharges to investigate their impact on the atmosphere above a thundercloud. It is found that the first positive lightning discharge initiates a sprite where electrons are accelerated during the exponential growth and branching of the sprite streamers. This preconditioned plasma above the thundercloud is subsequently exposed to a second positive lightning discharge associated with a bouncing-wave discharge. This discharge process causes a re-brightening of the existing sprite streamers above the thundercloud and initiates a subsequent relativistic electron beam.

Keywords: atmospheric electricity, lightning, electromagnetic wave propagation, storms

1. Introduction
Transient energetic charged particle populations occur in association with thunderstorms where the lightning
electromagnetic field can release electrons from the radiation belts precipitating into the atmosphere (Voss et al. 1998, 1984). These electrons have typical kinetic energies \( \sim 100–250 \text{ keV} \) in addition to their rest mass \( \sim 511 \text{ keV} \) and occur \( \sim 0.1–1 \text{ s} \) after the causative lightning discharge (Gemelos et al. 2005). Electrons are accelerated when penetrating the neutral atmosphere and deposit their energy in \( \sim 100–2000 \text{ km} \) large ionization patches north/south of a lightning discharge in the northern/southern hemisphere (Inan et al. 2007). Electrons are accelerated to very high energies \( \sim 10–100 \text{ MeV} \) inside thunderclouds, either in lightning leader tips (Celestin and Pasko 2011) and/or in large scale thunderstorm electric fields (Dwyer and Cummer 2013, Gurevich and Karashtin 2013, Dwyer 2012, Gurevich et al. 1992). The acceleration of the electrons is accompanied by gamma rays emanating from thunderstorms (Ostgaard et al. 2013, Tavani et al. 2011, Smith et al. 2005, Fishman et al. 1994) which can be used as a diagnostic tool. When the gamma rays interact with air molecules and exceed an energy of \( \sim 1.022 \text{ MeV} \), i.e., two times the rest mass of an electron, the gamma rays can disintegrate into an electron–positron pair around \( \sim 40–60 \text{ km} \) height such that magnetized positrons and electrons are observed on board of satellites in near-Earth space (Briggs et al. 2011, Carlson et al. 2009, Dwyer et al. 2008).

Similarly, it was proposed that the lightning electromagnetic field can accelerate electrons above thunderclouds from the cosmic ray layer upwards to produce avalanching relativistic electron beams (Roussel-Dupré et al. 1998, Roussel-Dupré and Gurevich 1996). Experimental evidence for such electron beams was reported by remote sensing with low frequency radio waves (Füllekrug et al. 2011b, 2010). The lightning electromagnetic field also causes Joule heating above thunderclouds which results in electrical breakdown of air such that sprite streamers develop (Pasko 2010). The exponential growth and splitting of streamers results in an electron multiplication associated with the acceleration of electrons to a few eV. The accelerated electrons radiate a small amount of electromagnetic energy and the incoherent superposition of many streamers causes low frequency radio noise (Füllekrug et al. 2013a, Qin et al. 2012a). As a result, the remote sensing with radio waves can be used to investigate the acceleration of electrons above a thundercloud during a sprite followed by a consecutive electron beam which is the aim of this contribution.

### 2. Observations

Unstable air masses near the north-eastern coast of Spain developed into a thunderstorm in the evening of 29 August 2012. The storm propagated eastward along the Mediterranean coast of southern France and produced numerous lightning discharges in the early morning hours of August 30. The accumulated leader steps of one particular \( \sim 1.7 \text{ s} \) long lightning discharge were recorded with a lightning mapping array in 80 \( \mu \text{s} \) long time intervals as part of the HyMeX campaign (figure 1). Shortly after the beginning of the discharge process, one particularly intense positive lightning discharge (44.0°N, 5.6°E) with a peak current of \(+124 \text{ kA} \) occurred at 03:33:46.680 UTC and caused a subsequent sprite. The sprite was recorded with an astronomical color video camera in Ferrara (44.8°N, 11.6°E) as part of the Italian Meteor and TLE network. The sprite producing lightning discharge was associated with a charge moment change as large as \( \sim 1300 \text{ C km} \). The charge moment was calculated from an exponentially decreasing lightning current inferred from electric field measurements in the frequency range \( \sim 5–30 \text{ Hz} \) (figure 2, left, upper panel) near Nagycenk observatory (47.6°N, 16.7°E) in Hungary (Sátory et al. 2013, and references therein). This large charge moment change exceeded the charge moment change \( \sim 600 \text{ C km} \) which is typically required for sprite initiation (Qin et al. 2012b, Cummer et al. 2005). The lightning discharge was also intense enough to be picked up by a quasi-static current sensor operated in the frequency range of \( \sim 1–50 \text{ Hz} \) near Portishead (51.5°N, 2.8°W) in south-west England. Similar unusual quasi-static current signatures (figure 2, left, middle panel) have previously been used to successfully detect sprites with \( \sim 30–50\% \) detection efficiency because the detected sprites are almost certainly associated with halos (Bennett and Harrison 2013). Finally, the sprite streamers produced low frequency radio noise from \( \sim 400 \text{ kHz} \) (Füllekrug et al. 2013a, Qin et al. 2012a) lasting for \( \sim 20 \text{ ms} \) which was measured here with two independently recording radio receivers near Orléans (47.8°N, 1.9°E) in central France and
Figure 2. Left. Upper panel. Electric field measurements from \(\sim 5\)–\(30\) Hz at Nagycenk (NCK) are used to infer the charge moment change of the two consecutive lightning discharges (black dotted lines). The charge moment of the first positive lightning discharge exceeds the limit for sprite initiation. The second positive lightning discharge exhibits a much smaller charge moment. Middle panel. The recordings of the quasi-static current from \(\sim 1\)–\(50\) Hz near Portishead (PTH) indicate that the first lightning discharge initiated a sprite. Lower panel. The low frequency radio noise from \(\sim 4\)–\(400\) kHz near Orléans (ORL) and Bath (UOB) indicates radio emissions from sprite streamers (red dotted line) initiated by the first lightning discharge and a re-brightening of the remaining sprite streamers during the second lightning discharge. Right. Upper panel. The second lightning discharge exhibits the typical \(\sim 0.1\)–\(1\) ms long \(\sim 5\)–\(15\) kHz (VLF) electric field enhancement which is larger in LeQuartier (LQT) when compared to Bath as a result of the proximity to the lightning discharge. Lower panel. About \(\sim 8\)–\(9\) ms after the second lightning discharge, a \(\sim 1\) ms long \(\sim 270\)–\(400\) kHz (LF/MF) radio pulse indicates the acceleration of electrons associated with an electron beam which is recorded by both radio receivers. Note that the leader steps recorded with the lightning mapping array from \(\sim 60\)–\(66\) MHz (crosses in the lower panel) do not seem to be related to the VLF or LF/MF recordings.

Figure 3. The high frequency magnetic field measurements from \(\sim 5\) kHz–\(40\) MHz near Rustrel (RST) show that the second positive lightning discharge (upper panel) exhibits resonant type oscillations with a period of \(\sim 3.8\) \(\mu\)s (\(\sim 260\) kHz) lasting for \(\sim 9\) cycles over \(\sim 34.2\) \(\mu\)s (lower panel) attributed to a bouncing-wave discharge. Type oscillations is followed \(\sim 8\)–\(9\) ms later by a characteristic \(\sim 1\) ms long \(\sim 270\)–\(400\) kHz radio pulse recorded by the radio receivers near Bath and LeQuartier (figure 2, right, lower panel). This radio pulse has a relatively featureless flat spectrum extending from \(\sim 40\)–\(300\) kHz when compared to the spectrum of ordinary lightning discharges (Füllekrug et al. 2011b) which typically exhibit larger amplitudes at lower frequencies with a relative maximum near \(\sim 10\) kHz (figure 2, right, upper panel). A more detailed analysis of the electric field recordings in LeQuartier shows that the spectrum of the radio pulse extends up to \(\sim 400\)–\(500\) kHz,
but the presence of medium wave radio transmitters from \(~500–1600\) kHz and the local electromagnetic environment inhibit an unambiguous assertion on the extent of the spectrum towards higher frequencies.

3. Interpretation

The first intense positive lightning discharge causes a sprite as evidenced by the optical observations and the radio recordings. The lightning discharge is followed \(~528\) ms later by a second positive lightning discharge which exhibits \(~34.2\) \(\mu\)s long resonance type oscillations at \(~260\) kHz. This second lightning discharge is followed \(~8–9\) ms later by a \(~1\) ms long \(~270–400\) kHz radio pulse.

This pulsed discharge event was initially discovered by high frequency magnetic field recordings with a ground based doublet of a high frequency receiver (Kolmasova and Santolik 2013) which is being developed for the TARANIS spacecraft (Blanc et al 2007). It was the only high frequency event recorded during the passage of the thunderstorm. The high frequency recordings of the second lightning discharge exhibit resonance type oscillations with a period of \(~3.8\) \(\mu\)s lasting for about \(~34.2\) \(\mu\)s. These oscillations are superimposed on the radio signal from the lightning discharge. To the best of our knowledge, these type of oscillations have been observed and reported only in connection with compact intracloud discharges (Nag and Rakov 2009). However, in our case the observed lightning discharge lacks some typical features of compact intracloud discharges. The bouncing wave can be explained by a traveling current pulse which is injected at one end of a conducting channel and reflected multiple times at both ends of the channel until the instability is attenuated and absorbed (Nag and Rakov 2009). The modeling results for the current propagation and reflection show that the pulse travels at a speed between \(~10^8\) m s\(^{-1}\) and the speed of light (Nag et al 2010). In this case, the length of the lightning channel would be \(~1\) km resulting in the lower charge moment which is still consistent with a large peak current of the lightning discharge.

The bouncing-wave discharge is followed \(~8–9\) ms later by a \(~1\) ms long \(~270–400\) kHz radio pulse without corresponding radio emissions near \(~10\) kHz which are typical for ordinary lightning discharges (figure 2, right, upper panel). The radio pulse is also not associated with radio emissions near \(~60–66\) MHz from intracloud lightning discharges (figure 2, right lower panel). The absence of \(~10\) kHz radio emissions during the radio pulse also excludes an interpretation of the radio pulse as a pulsing impulsive radio noise emanating from sprite streamers which exhibit a spectrum with amplitudes which increase towards lower frequencies (Füllekrug et al 2013a). On the other hand, the radio pulse was clearly observed by two entirely independent radio recordings, i.e., with the dipole antenna in LeQuartier and the flat plate antenna in Bath. Radio signatures with the observed characteristics have been predicted by numerical simulations of relativistic runaway breakdown above thunderclouds (Roussel-Dupré et al 1998, Roussel-Dupré and Gurevich 1996). These theoretical predictions have recently been confirmed by experimental measurements (Füllekrug et al 2011b, 2010). It is shown here for the first time that such experimental observations cannot easily be explained by currently known lightning discharge processes and that corresponding measurements can be obtained by another radio receiver with a sufficient sensitivity. As a result, the observed radio pulse is attributed to a relativistic electron beam following a sprite producing lightning discharge as predicted by numerical model simulations.

It is interesting to note that a recent detailed comparison of ground based optical sprite observations in southern France with electric field recordings on board the DEMETER satellite on 17 November 2006 (Parrot et al 2013), revealed low frequency radio signals up to \(~130\) kHz associated with the sprite and/or the causative lightning discharge which have never been observed before in association with ordinary lightning discharges (figure 4). Given that the ionosphere attenuates \(~100\) kHz radio signals by \(~2\) orders of magnitude (Füllekrug et al 2011a), the signal intensity of the lightning and/or sprite was undoubtedly exceptionally large. This observation shows that powerful low frequency radio signals associated with sprite producing lightning, as reported here, can be observed in space with unprecedented temporal and spectral resolution which is the aim of the French TARANIS satellite due to be launched in 2015 (Blanc et al 2007).

4. Discussion

In plasma physics it is known that pulsed discharges can accelerate and beam electrons efficiently in the presence of a specific electrostatic field configuration defined by a hollow cathode (Becker et al 2006, Slevin and Harrison 1975). It is speculated that a similar physical mechanism might occur above thunderclouds in the presence of aerosols (Füllekrug et al 2013b, pp 8–9). In this picture, the first lightning discharge produces free electrons which attach to the aerosols and cause a quasi-static electric field. This electric field defines the geometric shape and the physical properties of any consecutive discharge process. For example, the leader
Figure 5. The thunderstorm cloud top height reaches up to $\sim 12–13$ km as inferred from lidar measurements on board the CALIPSO spacecraft. Above the maximum cloud top height, an ensemble of stratospheric ice particles occurs at $\sim 13–14$ km around the tropopause as inferred from temperature measurements during a preceding radiosonde ascent (inset figure). The mixed phase region of the thundercloud is found at $\sim 6–7$ km height where ice and water coexist. The convective storm might have entrained dust which is confined to a layer from the ground up to $\sim 5–6$ km.

The mechanism proposed here requires knowledge on the presence of charged aerosols above thunderclouds. The recent discovery of sporadic stratospheric aerosol layers (Renard et al. 2010) which are possibly charged (Renard et al. 2013) suggests that the presence of small quantities of stratospheric aerosols could assist the occasional formation of relativistic electron beams above thunderclouds caused by consecutive lightning discharges. In the absence of in situ measurements of charged aerosols above the thunderclouds investigated here, it is interesting to put the electromagnetic observations in the context of the surrounding atmospheric environment.

Air masses from a Saharan dust storm reached France around 17 August 2012, which might have helped to entrain silt into convective storms. The size of silt particles ranges from $\sim 2–4$ $\mu$m to $\sim 62–64$ $\mu$m and they tend to be larger than clay and smaller than sand. Silt can be carried over long distances in air, whereas sand particles settle down more quickly as a result of gravitational forces and clay particles attach more quickly to any larger particles. Interestingly, Saharan dust storms can be electrified (Nicoll et al. 2011) such that dust particles are aligned by the electric field (Ulanowski et al. 2007). In addition, smoke particles from ongoing forest fires in Spain might have been transported by the westerly trade winds towards air masses in France during the month of August and an unusual large number of sprites was observed in the second half of August 2012 as reported by numerous observers on the Eurosprite mailing list. It was previously speculated that the presence of smoke particles can increase the occurrence rate of positive lightning discharges inside thunderstorms and thereby increase the occurrence rate of sprites above thunderstorms (Lyons et al. 1998).

The CALIPSO spacecraft (Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation) passed over the investigated thunderstorm around $\sim 01:53$ UTC and determined a thunderstorm cloud top height of $\sim 12–13$ km (figure 5). These large heights are required for compact intracloud discharges to occur. In addition, CALIPSO reported the presence of a dust layer from the ground up to $\sim 5–6$ km height (figure 5). It is very likely that this dust was entrained into the convective storm and transported upwards to the tropopause by convective updrafts. The tropopause was located around $\sim 13–14$ km height as inferred from the radiosonde ascent from Nimes-Courbessac ($43.9^\circ$N, $4.4^\circ$E) at 00:00 UTC (figure 5, inset). Finally, CALIPSO detected a disconnected ensemble of ice particles at $\sim 13–14$ km height which might have been injected into the lower stratosphere by an overshooting cloud top where dust and smoke particles assisted ice nucleation. In any case, the unusual accumulation of ice particles above the thundercloud top might have helped to define a particular electrostatic charge configuration leading to the bouncing-wave discharge and/or the subsequent electron beam.

5. Summary

The impact of two consecutive positive lightning discharges on the area above a thundercloud is investigated in detail. It is found that the first positive lightning discharge initiates sprite streamers which discharge the lightning electromagnetic field above the thundercloud. The exponential growth and
splitting of the streamers results in an electron multiplication associated with the acceleration of electrons to a few eV. A consecutive positive lightning discharge occurs \( \sim 528 \text{ ms} \) later and is associated with a bouncing-wave discharge. About \( \sim 8–9 \text{ ms} \) after the bouncing-wave discharge an electron beam occurs associated with the acceleration of electrons to a few MeV. This is the first simultaneous detection of radio signatures from electrons accelerated to thermal and relativistic energies above thunderclouds. The environmental conditions leading to the bouncing-wave discharge and the subsequent electron beam remain to be investigated in more detailed future studies.

Acknowledgments

The work of MF and AM is supported by the Natural Environment Research Council (NERC) under grant NE/H024921/1. IK, OS, RL, and LU are supported by the international cooperation program of the ASCR grant M10042120 and by the GACR project 205-09-1253. JB is supported by the Earth-system project TAMOP-4.2.2.C-11/1/KONV-2012-0015 sponsored by the EU and European Social Foundation. OV is supported by the Spanish Ministry of Science and Innovation under project AYA2011-29936-C05-04. ChH acknowledges an ERC starting grant from the European Union. The authors wish to thank the team of the Laboratoire Souterrain à Bas Bruit for hosting the radio receivers. Special thanks to Julien Poupeney, Christophe Sudre, Alain Cavaillou, Daniel Boyer, and Stéphane Gaffet, whose assistance and hospitality were invaluable to conduct the experiments in south-eastern France. MF acknowledges enlightening discussions with Thorwald Stein and Robin Hogan. The CALIPSO data were made available by NASA through www-calipso.larc.nasa.gov. The communication between collaborators was facilitated by the scientific programmes EPHRAT/French Embassy, TEA-IS/European Science Foundation, HYMEX/European Commission, and IMTN/Eurosprite mailing list.

References

Becker K, Schoenbach K and Eden J 2006 J. Phys. D: Appl. Phys. 39 R55–70
Bennett A and Harrison R 2013 Phys. Rev. Lett. 111 045003
Blanc E, Lefeuvre F, Roussel-Dupré R and Sauvaud J 2007 Adv. Space Res. 40 1268–75
Briggs M et al 2011 Geophys. Res. Lett. 38 L02808
Carlson B, Lehtinen N and Inan U 2009 Coupling of Thunderstorms and Lightning Discharges to Near-Earth Space ed N Crosby, T Huang and M Ry croft (Melville, NY: American Institute of Physics) pp 84–91
Celestin S and Pasko V 2011 J. Geophys. Res. 116 A03315
Cummer S, Zhai Y, Hu W, Smith D, Lopez L and Stanley M 2005 Geophys. Res. Lett. 32 L08811
Dwyer J 2012 J. Geophys. Res. 117 A02308
Dwyer J and Cummer S 2013 J. Geophys. Res. 118 3769–90
Dwyer J, Grefenstette B and Smith D 2008 Geophys. Res. Lett. 35 L02815
Fishman G et al 1994 Science 264 1313–6
Füllkreug M, Hanuise C and Parrot M 2011a Atmos. Chem. Phys. 11 667–73
Füllkreug M, Mezentsev A, Soula S, van der Velde O and Farges T 2013a Geophys. Res. Lett. 40 2395–9
Füllkreug M, Roussel-Dupré R, Symbalisty M, Chaninon O, Odzimek A, van der Velde O and Neubert T 2010 J. Geophys. Res. 115 A00E09
Füllkreug M et al 2011b Atmos. Chem. Phys. 11 7747–54
Füllkreug M et al 2013b Surv. Geophys. 34 1–41
Gemelos E, Inan U, Walt M, Parrot M and Sauvaud J 2009 Geophys. Res. Lett. 36 L21107
Gurevich A and Karashin A 2013 Phys. Rev. Lett. 110 185005
Gurevich A, Milikh G and Roussel-Dupré R 1992 Phys. Lett. A 165 463–8
Inan U, Piddyachiy D, Peter W, Sauvaud J and Parrot M 2007 Geophys. Res. Lett. 34 L07103
Kolmasova I and Santolik O 2013 Geophys. Res. Lett. 40 1637–41
Lyons W, Nelson T, Williams E, Cramer J and Turner T 1998 Science 282 777
Nag A and Rakov V 2009 IEEE Trans. Electromagn. Compat. 51 466–70
Nag A, Rakov V, Tsalikis D and Cramer J 2010 J. Geophys. Res. 115 D14115
Neubert T, Chaninon O, Armone E, Zanotti F, Cummer S, Füllkreug M, Soula S and van der Velde O 2011 J. Geophys. Res. 116 A12329
Nicolli K, Harrison R and Ulanowski Z 2011 Environ. Res. Lett. 6 014001
Østgaard N, Gjesteland T, Carlson B, Collier A, Cummer S, Gurevich A and Christian H 2013 Geophys. Res. Lett. 40 2423–6
Parrot M, Sauvaud J, Soula S, Pincon J and van der Velde O 2013 J. Geophys. Res. at press
Pasko V 2010 J. Geophys. Res. 115 A00E09
Qin J, Celestin S and Pasko V 2012a Geophys. Res. Lett. 39 L22803
Qin J, Celestin S and Pasko V 2012b Geophys. Res. Lett. 39 L22801
Renard J, Berthet G, Salazar V, Catoire V, Tagger M, Gaubicher B and Claude R 2010 Geophys. Res. Lett. 37 L20803
Renard J, Tripathi S, Michael M, Rawal A, Berthet G, Füllkreug M, Harrison R, Robert C, Tagger M and Gaubicher B 2013 Atmos. Chem. Phys. Discuss. 13 7061–79
Roussel-Dupré R and Gurevich A 1996 J. Geophys. Res. 101 2297–311
Roussel-Dupré R, Symbalisty E, Taranenko Y and Yu khimuk V 1998 J. Atmos. Sol.-Terr. Phys. 60 917–40
Sátori G, Ry croft M, Benicz P, Márcz F, Bór J, Bartu V, Nagy T and Kovács K 2013 Surv. Geophys. 34 255–92
Slevin P and Harrison W 1975 Appl. Spectrosc. Rev. 10 201–55
Smith D, Lopez L, Lin R and Barrington-Leigh C 2005 Science 307 1085–8
Tavani M et al 2011 Phys. Rev. Lett. 106 018501
Ulanowski Z, Bailey J, Lucas P, Hough J and Hirst E 2007 Atmos. Chem. Phys. 7 6161–73
Voss H, Walt M, Imhof W, Mobilia J and Inan U 1984 Nature 312 740–2
Voss H, Walt M, Imhof W, Mobilia J and Inan U 1998 J. Geophys. Res. 103 11725–44

Environ. Res. Lett. 8 (2013) 035027