Understanding lightning leaders

J. Montanyà

***Abstract*— a lightning flash is defined by the initiation and multiple development of leaders. But lightning leaders are still poorly understood. Since most of my atmospheric electricity has been focused on lightning that means that it has been devoted to understand lightning leaders. In this work, I summarize my investigations related to different aspects of lightning leaders. That includes high-speed video observations of lightning leaders, investigations of bidirectional development of leaders by means of radio mapping systems, research on the high energy emissions produced by lightning leaders and the study of upward leader initiation from wind turbines and development. In the second part, the need of an improved lightning leader model is exposed and proposed as future work. Lightning leader models can be approached by different ways depending on the purpose but agreement between all the approaches is still not complete.**

***Index Terms*—lightning, lightning initiation, lightning leaders, bidirectional leaders, lightning mapping, high speed video, wind turbines, x-rays.**

I. Introduction

IN a lightning flash, the duration of the return stroke represents less than 1 ‰ of the total time. The rest, hot plasma channels are found at a wide range of cloud altitudes travelling very long distances in relatively low electric fields. Lightning flashes can be defined just as the initiation and development of multiple leaders in which, eventually, one leader can reach the ground. The initiation and propagation of lightning leaders are determined by the electric structure of the cloud charge regions.

After decades of research the full dynamics of a leader are still not understood. Most of the data come from the relatively recent high voltage experiments (e.g. [1-2]), high time resolution images of lightning (e.g. [3-4] and radio mapping of leader emissions (e.g. VHF time-of-arrival or interferometry [5-8]).

One of the interests of the investigation of lightning leaders is because they determine the location where a lightning will strike or initiate. In the point of view of lightning protection, it is of great importance because the extensive use of electronic and communication systems as well the power quality needs in electric power systems. But there are two particular sensitive applications: wind turbines and aircraft. Both have in common the use of composite materials, especially conductive carbon fibers reinforced plastics (CFRP).

In the physics of lightning, the understanding of leaders means the understanding of lightning. Lightning leaders are complex and very asymmetric and conditioned to the cloud electric charges (related to cloud microphysics) and the environment (space charges). In the field of atmospheric electricity, during the recent years, the intense high energy emissions named Terrestrial Gamma ray Flashes [9] are attributed to be related to the intense electric fields in negative stepped leaders (e.g [10]).

In this context most of my investigations in the field of atmospheric electricity and lightning protection are straight or indirectly related to lightning leaders. From the very beginning I investigated the electric fields produced by lightning leaders. The use of high speed video cameras allowed to have a new view of the complexity of lightning. But video images can only show what happens outside the thunderstorm cloud, the rest is obscured by the cloud. For that reason I have been investigating the properties of lightning leaders by means of VHF mapping systems. That allowed to relate the lightning activity to the cloud microphysics and investigate the occurrence of severe weather. In addition the Eagle Nest (2537 m, Alp, Girona, Spain) helps to investigate the initiation and development of upward leaders form tall objects. For the last eight years, my research has been focused on the high energy production from natural lightning leaders and high voltage laboratory sparks.

This paper is organized in two parts. In the first part some of my contributions to the physical knowledge of lightning leaders are summarized. These include the observation of the start of a bidirectional leader, the study of the bidirectional leader development of lightning, the investigation of the basic parameters of lightning (size and duration), the new data of leader development from tropical storms, the high energy emissions related to lightning leaders and the lightning interactions with wind turbines. In the second part it is discussed about the need of an improved lightning leader model. Here I am referring to lightning leader models that can represent the development of the lightning leaders in the entire lightning flash. I focus on models where leaders are initiated in the cloud and propagate within the cloud. But eventually, a leader can propagate towards the ground.

II. Most Important Knowledge

Unconsciousness most of my investigations have been orbited around different lightning leader properties. In this section I summarize the most important results of my investigations:

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A. *The start of lightning*

Lightning inception is typically hidden from sight of camera because the initiation inside thunderstorms. Lightning flashes initiate in regions of strong electric fields between regions of positively and negatively charged precipitation particles. In [11] we reported a serendipitous high speed video recording of bidirectional lightning initiation in virgin air under the cloud base at ~11,000 images per second (Fig. 1). With this case we proved the existence of the bidirectional lightning leaders where both ends propagate at the time without a preconditioned path as in recoil leaders (e.g. [12]).

The event is described as follows. Both ends of the bidirectional leader began simultaneously (Fig 1c) within the 90-180 μs frame exposure. The positive and negative leader ends of the bidirectional areas the negative leader end exhibited multiple branches. The single positive leader channel was continuously visible and was brighter than the multiple negative leader branches. At both leader ends, the leader tips were brighter but their luminosity decreased as the bidirectional leader expanded. The average speed of the negative leader was a factor of two higher than the positive leader end.

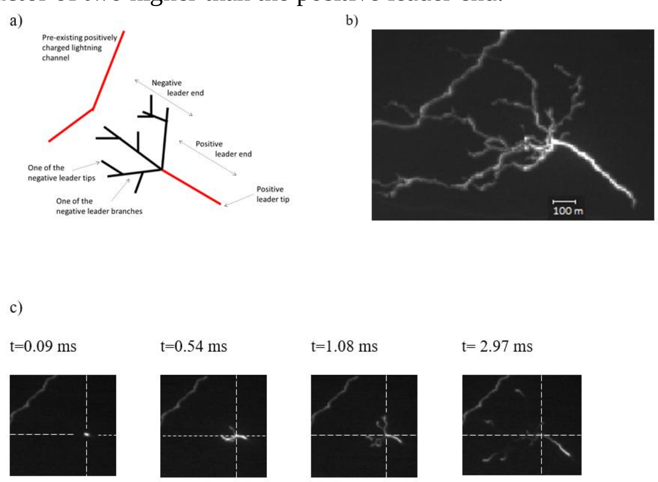

Figure. 1 a) Description of the morphology of the bidirectional leader event; b) integrated images of the video; c) four selected video images at different times showing the initial part of the event. Image adapted from [11].

Both ends of the bidirectional leader exhibited their highest speeds during the first millisecond. After the first millisecond, the speed of the positive leader end decreased faster than the negative leader end.

The simultaneous propagation of the leaders was interrupted when one of the negative branches attached to a preexisting lightning channel. That attachment, produced the re-illumination of a negative leader branch up to the bidirectional leader origin. That allowed us to assume that the neutral point of the bidirectional leader remained fixed. The immobility of the neutral point implies that the charge density deposited at the positive leader tip be higher than the charge at the negative leader tips in order to compensate the speeds of the leader.

This case reveals natural lightning initiation, propagation and a return stroke as in negative cloud-to-ground flashes, upon connection to another lightning channel – without any masking by cloud.

B. *Bidirectional development of lightning leaders*

The previous observation was optically observed but the fact that lightning starts inside the cloud limits the number of observations. In 2011 our research group (UPC Lightning Research Group) installed the first Lightning Mapping Array (LMA) network in Europe as ground support for the future ASIM ESA's mission [13]. The ELMA (Ebro LMA) maps radio emissions of lightning channels in three dimensions by the time-of-arrival method in the very high frequency range (e.g. [7]). Each station samples the maximum radio power amplitude and its GPS-derived precise time over 80 μs intervals. Typically few thousand of sources per second are located during lightning flashes. Power in dBW is available for every located source. The located ELMA sources are predominantly coming from negative leaders moving through locations of positively charged cloud particles. However, weaker sources from positive leader traces inside the negative charge locations are often detected as well. These emissions are caused by negative recoil leaders (e.g. [12]). So, effectively the LMA detects negative breakdown at both negative and positive leader sections.

In [8, 14-15] we presented and discussed the bidirectional leader development by means of ELMA data. A time vs. distance graph was designed. This graph plots each leader detection using the flash origin or a cloud-to-ground stroke as reference. This graph allows to follow the horizontal development of positive and negative leaders over time.

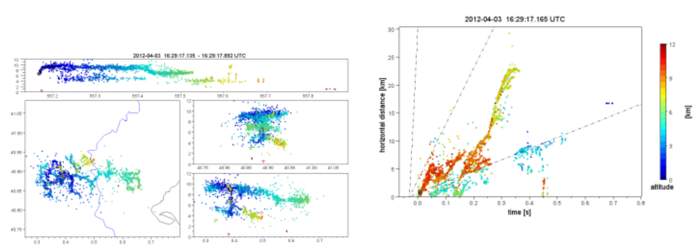

Figure 2. a) conventional time-altitude, lat-lon and side views plot. b) time-distance plot, altitude (0-12 km) is colored. The reference was the flash origin. Three dashed lines are reference slopes corresponding to 10^6 m s^{-1}, 10^5 m s^{-1}, and $2\cdot10^4$ m s^{-1}.

The observations confirm that negative and positive leaders propagate at characteristic horizontal speeds of 10^5 and $2\cdot10^4$ m s^{-1}. The low apparent speed of positive leaders corresponds to the stages when recoil processes are active. Very fast negative leaders (up to $8\cdot10^5$m s^{-1}) are detected in positive cloud-to-ground strokes. Negative leaders redevelop repeatedly from the origin or as a retrograde negative leader at the positive leader branch. Commonly, positive leaders remain propagating throughout the flash or until reaching ground. Assuming the bidirectional leader model [16], the velocity difference would shift the potential of the leader, increasing the potential gradient with the cloud charge at the positive leader end while decreasing it at the negative leader end. The effect of retrograde negative leaders (recoil leaders) would contribute to lowering the leader potential. The reduction of the leader potential would eventually emit a new negative leader into the upper positive 'potential well'.

C. Size, duration of lightning flashes derived from leader development

After five years of operation of the ELMA data from a large number of thunderstorms is currently available. This data comprises different type of storms: ordinary single cell storms, multicell storms, mesoscale convective systems occurring at different time of the year. In [17-18] and currently (unpublished work by J. López and N. Pineda) basic lightning parameters such as flash size and duration are investigated. For the analysis, the complex geometry of a lightning flash is simplified by a confidence ellipse fitting most of the detected sources. The flash length is represented by the major axis of the ellipse. The analysis of more of 38000 flashes in a set of different type of thunderstorms results in a median flash length of ~15 km with a median duration of ~0.4 s.

These even basic results provide valuable information in order to update the classical conception of a lightning flash (e.g. see AMS definition of lightning) and to the stroke grouping criteria in lightning location systems.

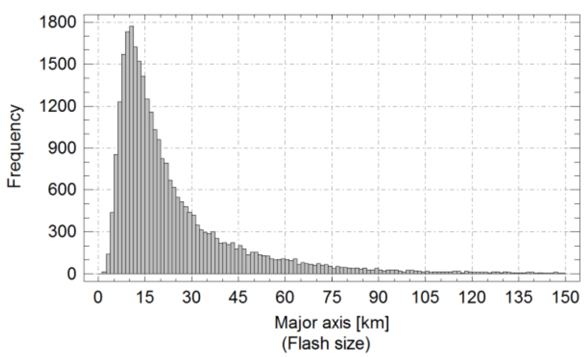

Figure 3. Histogram of the flash size. The flash size is computed by the major axis by means of ellipse fitting of the LMA sources [17-18].

D. The new Colombia Lightning Mapping Array: High altitude lightning occurrence in the tropics

Terrestrial Gamma ray Fleshes (TGF) seem to occur more in the tropics [19-20] probably because lightning leaders can reach higher altitude [21]. In 2015 we installed a LMA network in Colombia (COLMA). The COLMA is located at the Santa Marta region at the north of the country. At the tropics the higher tropopause allows to thunderstorms to reach higher altitudes. That would contribute to allow lightning leaders to reach higher altitudes than mid latitude thunderstorms. In order to verify this well-established assumption we setup the COLMA in order to investigate high altitude (> 12 km) leader development.

a)

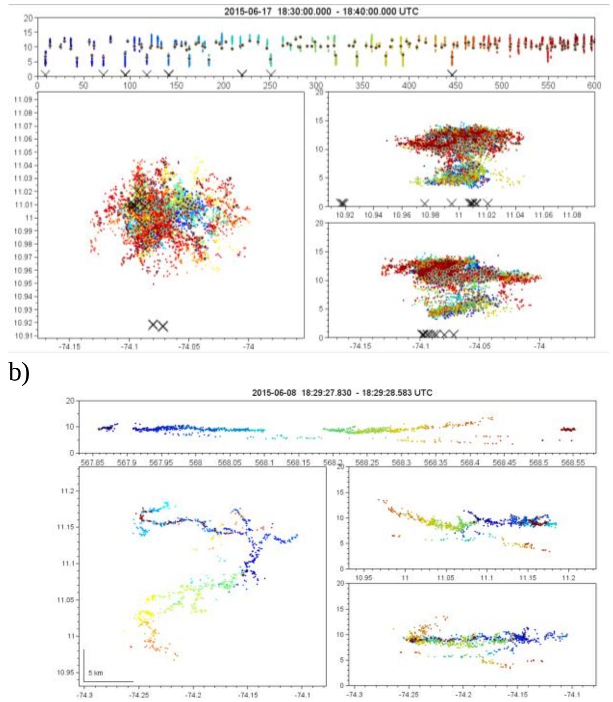

Figure 4. a) Ten minutes of lightning activity recorded by the COLMA. b) Example of a single flash.

E. X-rays from lightning leaders

Not long ago, in [22] and later by others (e.g. [8, 23-24]), it was discovered that lightning leaders to ground can be accompanied by high-energy radiation (e.g. x-rays). This implies that some process in the leader development allows to electrons to runaway and produce x-rays. The observations have shown that these emissions are related to negative stepped leaders to ground and negative polarity dart leaders. In [24] we also showed measurements of upward leaders emerging from an instrumented tower. In none of the twelve negative cloud-to-ground upward flashes (upward positive leaders) were x-rays observed. Also no energetic radiation was found in one negative upward leader at close range (20 m). We detected x-rays in a negative cloud-to-ground flashes.

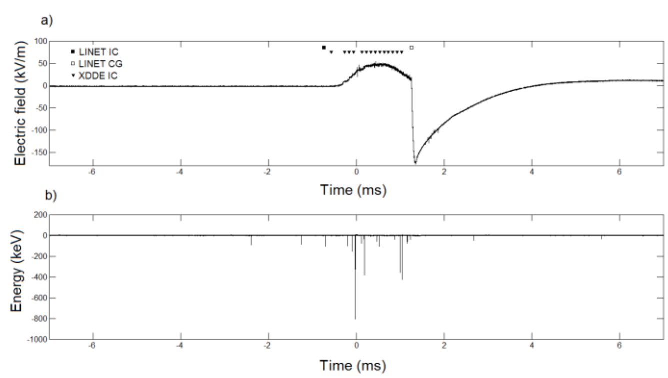

Figure 5. a) Electric field and VHF (XDDE) detections and (VLF/LF) detections. b) X-ray pulses occurring before the return stroke. Adopted from [24].

X-rays were detected during the last ~1.75 ms of the leader before connecting to ground. During the time of energetic radiation, an intense burst of IC VHF sources was located by the interferometers. The x-ray production was attributed to the high-electric-field runaway electron mechanism during leader stepping [22-24]. In one case, a flash struck closer than the previous one, no x-rays were detected during that flash. The absence of energetic radiation is attributed to occur 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. It seems plausible that the electric fields that allow electrons to runaway might be not present all the time in lightning leaders. The analysis of high speed video of downward negative leaders (Fig. 6) at the time when x-rays are commonly detected on the ground (the last 2 ms) revealed the increase of speed and luminosity of the leader probably because the intensification of the electric field due to the close presence of the ground (or leader image).

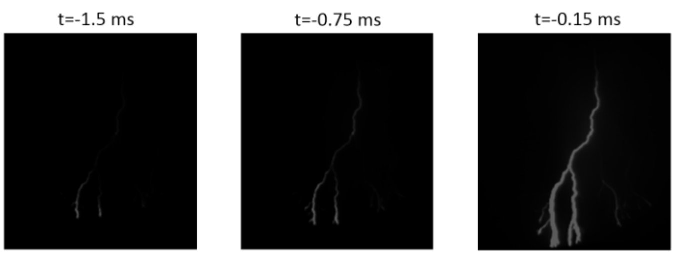

Figure 6. Example of the increase in luminosity of a negative lightning leader before connecting to the ground. Adopted from [24].

F. *Upward wind turbines*

In the previous subsections I related some of the investigated physical properties of lightning leaders. I would like to finalize the summary of my contributions with the investigation of lightning interactions with wind turbines and aircraft.

Thanks to the ELMA we have been able to characterize lightning flashes where wind turbines are involved. In [25] we shown an upward initiated flash from a wind turbine that ended with to cloud-to-ground strokes (Fig. 7).

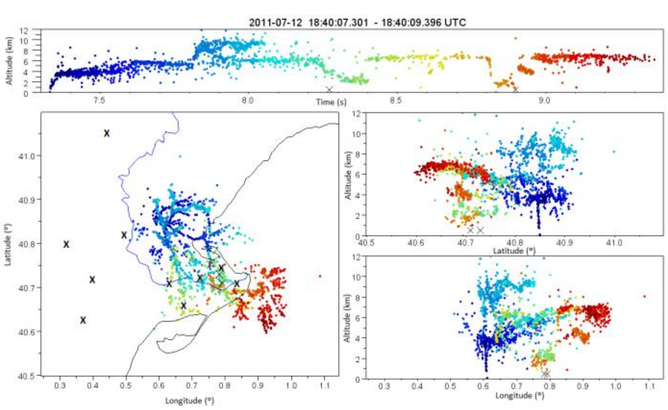

Figure 7. ELMA plot of an upward lightning intiated by a wind turbine on 20110712. Adopted from [25].

But surprisingly we discovered that some rotating wind turbines produced repetitive corona (or perhaps leaders) during long periods of time (Fig. 8). These emissions are similar to those produced by aircraft when they are close enough to electrified clouds (see the strait path at 6 km in Fig. 8).

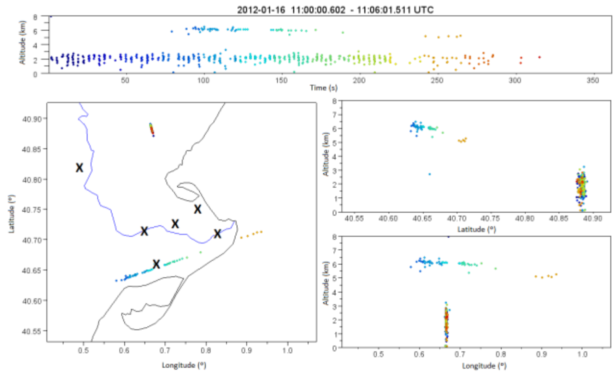

Figure 8. Periodic electric discharges produced by wind turbines. At higher altitude (~6 km) corona emissions from a passing aircraft are shown. Adopted from [25].

III. The Need of a Unified Lightning Leader Definition

Many leader models have been developed and used for different purposes. In some models, a leader to ground is modelled as an electric charged line with some defined charge distribution (e.g. [26-30]). These models are useful for evaluation of lightning protection and even they can reproduce the electric field measured at ground (e.g. [31]).

On the other hand, the seminal idea by Kasemir [16] provided another method to represent a lightning leader. Leaders are modeled as perfect conductor lines where the induced charge results by virtue of electrostatic induction due to the difference between the leader potential and the ambient (cloud) potential. These models assume that lightning leaders are actually bidirectional leaders that keep the zero net charge. Advanced versions of bidirectional leader models have been used in order to simulate 3D lightning flashes in numerical storms (e.g. [32]). However, still leader models are far to include full dynamics and dispersion in the concept and parameters are found in literature.

In this section, I expose the need of an improvement of lightning leader models that can represent the development of lightning leaders in entire lightning flashes. In addition, the call for agreement in some aspects is claimed. I focus on models where leaders are initiated in the cloud and propagate within the cloud. Eventually, a leader can propagate towards the ground.

In my discussion, I systematically use the references [33-34] because provide a more physical view. From high voltage laboratory experiments three parts of leader are distinguished: the channel, the tip or head, and the streamer zone. A fourth important part, but not visible with cameras, is the charge cover around the channel.

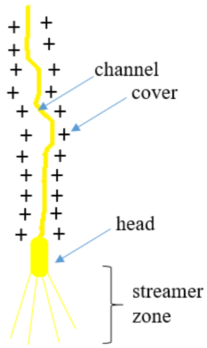

Figure 9. Concept of a positive leader in air.

The leader head is the brightest part, whereas the streamer zone is more diffuse. Behind the head, there is the channel, which is connected to the cloud potential in case of lightning leaders or to a high voltage electrode in case of laboratory sparks. The charge cover around the channel is due to the streamer zone. When the leader advances, the charges of the streamers at the tip are accumulated at the channel cover. The cover radius is close to that the streamer zone. The ionization rate is much larger at the leader head than along the lateral channel. The leader current is composed by the contribution of the head and the contribution of the lateral of the channel [33-34].

The propagation of a leader is determined by the fields around the head and in the front of the streamer zone. The charge at the head only provides a small portion of the potential since the electric field at the head is limited by the streamer zone to about ~30 kV/cm. The potential drop at the streamer zone is about half of the potential of the leader. The field at the surface of the leader is believed to be ~50 kV/cm and cannot be much higher otherwise streamer flux would be too high [34].

The total current of the streamers supplies with energy the leader channel and heats it up. The streamer zone acts as a kind of current source. The leader cover holds most of the charge and this charge is neutralized when the leader contacts to ground.

Channel properties depend on the current flowing. In the channel, thanks to the high gas temperature, electron loss through attachment is compensated by detachment. Recombination also slows down. Then the contraction of the current and the attenuation of the radial fields are very important for the leader survive. The capacitance of the leader includes the cover and the channel. Since the cover radius is much larger than the channel it contributes more to the leader capacitance.

According to [33-34] polarity asymmetry in leader speed can be due because the same voltage drop at the streamer zone creates streamer zones of difference size ($E_{CR+}\approx$4.5 kV/cm and $E_{CR-}\approx$12.5 kV/cm) [35]. The current at the channel ends can also be different.

In my point of view, the following questions would need to be investigated or clarified:

1. The nature of the leader current is well approached by simply electrostatic induction? How much is the contribution of the tip?
2. Effect on the observed asymmetries due to leader speed and branching?
3. The relation of optical emissions and current in order to infer leader currents are possible?
4. How large is the cover? Is the cover radius changing along the leader?
5. Some models consider the leader channel radius as the radius of the leader.
6. Channel conductivity shall be considered (e.g. the negative differential resistance [36]).
7. Why retrograde leaders appear only in negative leaders.

Of course other processes in the leaders like the inception including the streamer to leader transition, high energy emissions from lightning leaders, the dynamics of the negative step process, etc, need very particular attention.

An updated basic leader model is found in Fig. 10. According to our observations [8, 14] that would be valid only for the first stage before the positive leader produce branches followed to the occurrence of retrograde leaders. The model would include the asymmetries in leader speeds considering $v^- \approx 2\, v^+$ and branching. The difference in speeds does not necessarily mean that the charge inversion of polarity shifts. That shift would be more related to any change of potential of the leader or the cloud. The need of zero net charge results in lower charge densities in the individual branches of the negative leader end. The branched leaders increase capacitance then the potential should decrease. The streamer zone needs to be considered in all leader ends. The streamer zones are also asymmetrical in size $R_{sz}^{\pm} = \frac{U_L}{2\, E_S^{\pm}}$. The cover size at the leader head shall be related to the size of the streamer zone $\sim R_{sz}^{\pm}$. If the charge along the leader channel is related to the size of the cover, R_C shall be different at any leader position. Then R_C must be evaluated at any z. The electric field at the leader E_t tip must be limited due to the streamer zone. In Fig. 10 the limit of E_t in the positive end is shown (typically $1.5E_k$). That is of interest for runaway electron production (e.g. [10]) because the step at the negative end allows very high electric fields at the leader tip for very short periods (due to negative corona flash [34]).

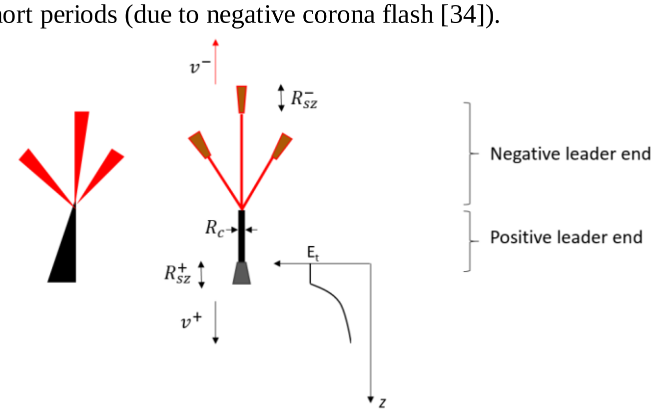

Figure 10. Sketch of the leader model including some of the observed asymmetries.

IV. Conclusions

In the attempt to understand lightning, we need to understand leaders first. In this article, I have described my investigations related to lightning leaders. The used methods range from optical observations, remote VHF radio mapping, high energy detection and electric field measurements. The findings show how asymmetric are lightning leaders. Negative leaders tend to move faster, present more branches and produce high-energy emissions. In the counterpart, positive leaders have slower progression and commonly showing less branches. Retrograde leaders are observed to occur in positive leaders. The progression of lightning leaders is linked with the cloud charge structure that in turn is related to the storm microphysics.

High-speed video images showed how a bidirectional leader started in virgin air. By means of the Ebro Valley Lightning Laboratory Mapping Array data (ELMA), we investigated the bidirectional development of lightning leaders. ELMA data has been also use to track leaders and compute the total size and duration of lightning flashes. Currently we are investigating tropical storms by means of the recent LMA network installed in Colombia. In addition, the investigation of high energy radiation from lightning leaders showed that the detected emissions are related with downward negative leaders and the increase of the electric fields in front of the leader during the last milliseconds before contacting ground can be the responsible of these emissions.

In the second part of the paper, I summarized some of the physical leader properties and discussed the need of improvement of the models. In the near future leader models will be improved. One of the reasons is that currently efforts to explain the intense TGF emissions pass through understand how leader develops.

Acknowledgment

The contents of this work were supported by research grants from the Spanish Ministry of Economy and Competitiveness (MINECO) and EU ERDF: ESP2007-66542-C04-02, AYA2009-14027-C05-05, AYA2011-29936-C05-04, ESP2013- 48032-C5-3-R. The contributions to the UPC Lightning Research Group members: O. van der Velde, D. Romero, F. Fabró, N. Pindea, J. López, G. Solà, V. March, O. Argemí.

I thank to Prof. Horacio Torres and the committee members for the organization of the innovative World Meeting on Lightning (WOMEL) event.

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