Lightning Physics

P. Lalande

ONERA, Chatillon, France

Lightning development is split in two main phases. The first one is associated with the leader propagation, the second to the high pulse current. The physic of the leader is described in regard with the laboratory long spark. Negative and positive leaders have a propagation very different due to the physic involved. Plasma modelling shows that a long spark can propagate inside electric field of few kV/m as soon as its leader reaches the temperature of thermalization. For high pulse current, the channel evolution is driven by magneto hydrodynamic equation. The radiative process is the main mechanism to quickly transfer heat from the channel core to the periphery leading to the expansion of the radius channel.

The development of atmospheric lightning is initiated by the formation in virgin air of bi directional leader, following few tenths of millisecond later by the ignition of high current pulses when, for instance, one of the leaders reaches the ground.

The lightning leader physics have been extensively investigated from laboratory long sparks which are very similar. In laboratory, two types of leader can be defined as a function of the electrode voltage polarity. When a positive pulse voltage is applied to the electrode, a positive discharge initiates and propagates continuously (Figure 1a) in the direction of the electric field Eg (Figure 1b). It is composed of a leader, a conductive channel, at the tip of which there is a diffused corona (filaments of streamer) region (Figure 1b). In this region, the ionization processes occur which supply the current necessary to sustain the leader propagation. Conversely, the advancement of the conductive channel into the air gap keeps the electric field at the corona front high enough to sustain the ionization processes. This coupled propagation continues until the corona reaches the ground and the electric breakdown occurs. The temperature of the positive leader is from 1500°K to 5000°K. In the channel, the electrons from negative ions are completely released. The channel internal electric field is approximately 100 kV/m. On contrary, the temperature of the corona region is low around 300°K and the electrons become attached to oxygen. Then, the conductivity is low corresponding to an internal field of 500 kV/m. At the tip of the corona, the ionization processes occur.

When a negative impulse voltage is applied to an electrode, a negative discharge starts and propagates in a non-continuous phenomenon (Figure 2a) in the opposite direction of the electric field Eg (Figure 2b). It progresses through regular and discrete steps separated by time period of 10 to 20µs. Complex phenomena occur during two steps. Inside this period, the negative discharge is composed of a negative leader (conductive channel), a space leader (a conductive channel) and a negative corona linked themselves by high resistive plasma column. The step occurs when there is a junction between the space leader and the negative leader. The negative leader quickly expands to the pilot with the formation at its tip of a large negative corona. After the step, the inter step mechanism restarts up to the next step. The internal field of the negative leader is around 100 kV/m.

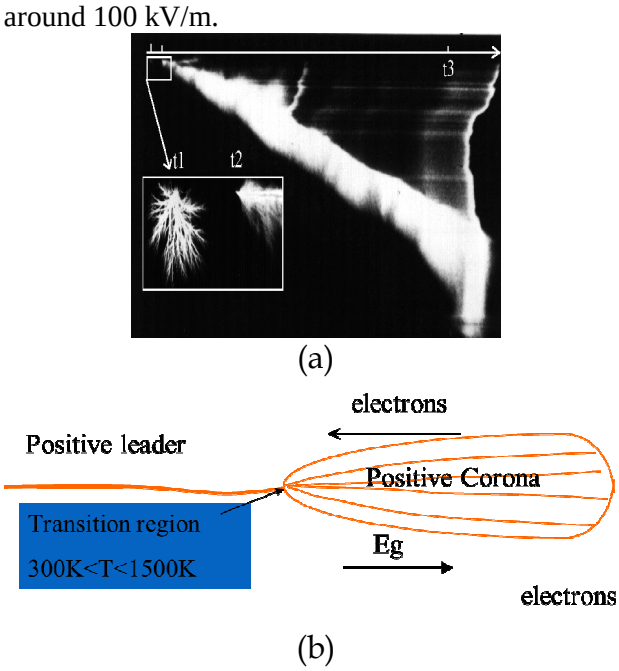


Figure 1 : (a) streak photograph of a laboratory positive discharge (10 meter gap, tm=500µs, Vmax = 2.5 MV) from the Group des Renardières journal. (b) Positive discharge structure

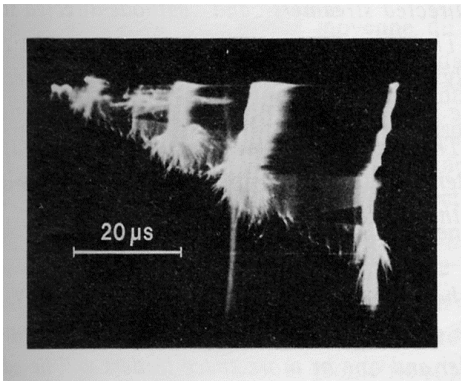
Both laboratory positive and negative leaders have an internal field of 100 kV/m which is very high in regards with the ambient electric field inside the cloud. With a such internal field, the lightning

leader propagation will stop as soon as the leaders exit the cloud region where the field is higher than 100 kV/m. A plasma model has been used to understand what kind of mechanisms enable the internal field to highly fall down for lightning leaders. In laboratory, the internal field is driven by the field inside the channel for temperature lower than 4000 °K. It means that an electron is accelerated by the electric field. Its interaction with an atom produces another electron (Eq. 1). It is a feedback process which leads to maintain the internal field to 100 kV/m.

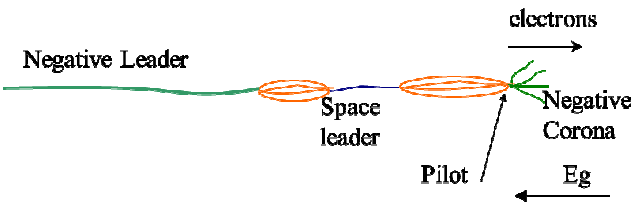
$$e^- + M \rightarrow M^+ + 2e^- \qquad \text{Eq. 1}$$

When the temperature exceeds 4000°K, the electron production is driven by thermic ionization. The thermal agitation is high enough to produce electron when atoms interact. Plasma simulation shows that the internal field falls down to 0.1 kV/m which enables the lightning to propagate in very low ambient field.

$$M + N \rightarrow M^+ + N + e^- \qquad \text{Eq. 2}$$



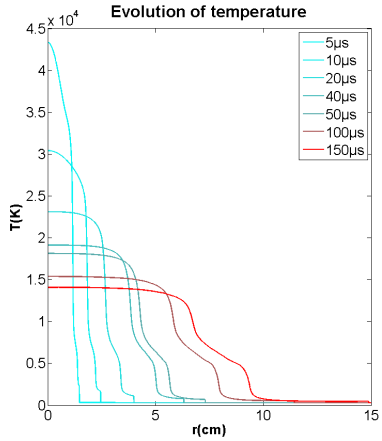
(a)



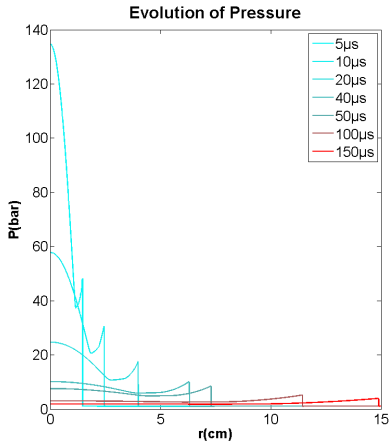
(b)

Figure 2 : (a) streak photograph of a laboratory negative discharge (7 meter gap, tm=6µs, Vmax = -2.8 MV) from the Group des Renardières journal. (b) Negative discharge structure

As soon as a lightning leader reaches the ground, a high intense pulse current (return stroke) goes up through the channels of the leader producing a luminous flash and the thunder. The modelling of the lightning channel during this phase is based on the resolution of magneto hydrodynamic equations. The plasma is assumed as a homogenous fluid at local thermodynamic equilibrium. To the fluid equations, the Laplace force and the joule heating are added. The time evolution of the channel expansion (Figure 3) shows that the main mechanism which drives the channel expansion is the radiative process. It quickly transfers the heat from the core to the periphery, increasing the conductive channel radius of the lightning.



(a)



(b)

Figure 3 : (a) Time evolution the temperature profile inside the lightning channel; (b) Time evolution the pressure profile inside the lightning channel for a pulse current of 100 kA (Waveform A/2).