Upward bipolar lightning flashes originated from interaction with intracloud lightning

Ivan Toucedo Cruz[1], Marcelo Magalhães Fares Saba[2], Carina Schumann[3], and Tom A. Warner[4]

[1]National Institute for Space Research, INPE
[2]INPE - National Institute for Space Research
[3]University of the Witwatersrand
[4]South Dakota School of Mines and Technology

November 22, 2022

Abstract

The present work shows high-speed videos of two upward flashes that started with positive upward leaders and, instead of being followed by negative subsequent return strokes, they were followed by positive subsequent return strokes. In both cases, after the positive leaders developed, recoil leaders appeared in their decayed branches as would be usual in negative upward lightning flashes. However, in these flashes the negative end of a recoil leader connected to a positive leader of an intracloud flash nearby. The connection initiated a downward positive leader that re-ionized the decayed channel of the upward flash all the way to the tower giving origin to a positive subsequent return stroke. This work shows that recoil leaders do play an important role in the occurrence of bipolar upward flashes and their interaction with intracloud flashes can provide explanations for all types of bipolar upward flashes initiated by upward positive leaders.

Upward bipolar lightning flashes originated from interaction with intracloud lightning

Enter authors here: Ivan T. Cruz[1], Marcelo M. F. Saba[1], Carina Schumann[2], Tom A. Warner[3]

[1]National Institute for Space Research, INPE, São José dos Campos, Brazil.

[2]Johannesburg Lightning Research Laboratory, University of the Witwatersrand, South Africa.

[3]South Dakota School of Mines and Technology, Rapid City, USA.

Corresponding author: Marcelo M F Saba (marcelo.saba@inpe.br)

Key Points:

- High-speed cameras observation of upward bipolar lightning flashes originated from intracloud lightning.
- Connection of recoil leaders with intracloud lightning.
- Positive subsequent return stroke using the same channel of the upward positive leader.

Abstract

The present work shows high-speed videos of two upward flashes that started with positive upward leaders and, instead of being followed by negative subsequent return strokes, they were followed by positive subsequent return strokes. In both cases, after the positive leaders developed, recoil leaders appeared in their decayed branches as would be usual in negative upward lightning flashes. However, in these flashes the negative end of a recoil leader connected to a positive leader of an intracloud flash nearby. The connection initiated a downward positive leader that re-ionized the decayed channel of the upward flash all the way to the tower giving origin to a positive subsequent return stroke. This work shows that recoil leaders do play an important role in the occurrence of bipolar upward flashes and their interaction with intracloud flashes can provide explanations for all types of bipolar upward flashes initiated by upward positive leaders.

Plain Language Summary

The increasing number of tall buildings and towers, and the rapid expansion of wind power generation, has also increased the concerns about damages caused by upward flashes. Although upward flashes are not the most common type of flashes in nature, they can pose a serious threat to tall structures. They are usually initiated by a positive upward leader that starts at the tip of the structure. After reaching cloud base, the discharge ends or is followed by a negative downward leader that strikes the tower and produces an intense negative discharge known as a return stroke. This common type of upward flash is named negative upward flash. The present work presents high-speed videos of a rare type of upward flash, the bipolar upward flash. In this flash, after the propagation of the positive upward leader, another positive leader retraces the same path traveled by the original upward leader, but in a downward manner resulting in a positive return stroke. The increased threat of damage caused by this rare flash is due to the intense positive return stroke and long duration current that frequently follows. This work explains how this, and other types of bipolar flashes are possible.

1 Introduction

Negative upward lightning originates at the tip of tall structures when the electric field exceeds a critical level (Schumann, 2016). A positive upward leader initiates from these structures and propagates towards the base of the thundercloud (Warner et al., 2013; Heidler et al., 2015; Saba et al., 2015; Saba et al., 2016; Warner et al., 2016; Schumann et al., 2019). After a while their branches decay, producing recoil leaders (Mazur & Ruhnke, 1993; Mazur & Ruhnke, 2011; Mazur et al., 2013; Mazur, 2016). Some of these recoil leaders (RL) develop towards the lightning initiation point as dart leaders (Lu et al., 2008; Mazur & Ruhnke, 2011; Saba et al., 2016). When they reach the ground, the electric potential is transferred to the cloud causing a fast wave of luminosity moving upward, phenomenon called subsequent return stroke. In the literature is usually observed records of negative leaders (negative end of RL) touching the ground at the same point of initiation of the positive upward leader. That is, positive upward leaders from ground structures are frequently followed by negative subsequent return strokes striking these structures. In this work, we show two cases of upward positive leaders that were followed by positive subsequent return strokes. Here we show that this is possible due to the interaction of RL with intracloud (IC) lightning.

It is known that the polarity of lightning is defined according to the net charge transferred to the ground. Negative upward lightning transfer negative net charge to ground. In the two cases observed by this work, the upward positive leader (negative charge transfer to ground) was followed by positive subsequent return strokes (positive charge transfer to ground), that is, there was a transfer of negative and positive charge during these events, characterizing the flashes as upward bipolar lightning flashes (Wang & Takagi, 2008; Zhou et al., 2011; Romero et al., 2012; Azadifar et al., 2016; Shi et al., 2018; Sunjerga et al., 2019). There are three types of bipolar lightning: Type 1 – lightning that had a polarity change during the initial continuing current (ICC), representing 76.9% of the upward bipolar lightning flashes. Type 2 – lightning with a given ICC followed by a subsequent return stroke of different polarity, corresponding to 15.4% and Type 3 – lightning with subsequent return strokes of different polarities during the same event, corresponding to 7.7% of upward bipolar lightning flashes (Rakov & Uman, 2003; Azadifar et al., 2016).

A study published by Shi et al. (2018) showed three upward bipolar lightning flashes of Type 2 (same type as the ones presented in this paper), which occurred in winter storms in Japan. The authors, in an attempt to explain the phenomenon, proposed a scenario. They state that a bipolar floating channel would originate in a decayed branch of the upward lightning and its negative end, being close to a center of positive charges, would begin to propagate towards it while the positive end would develop towards the ground generating a positive subsequent return stroke. The proposed scenario for the physical processes involved in Type 2 events analyzed by Shi et al. (2018) differs from what was observed in this work. Shi et al. (2018) could not observe the role of RL in the formation of bipolar upward flashes but recommend that further studies could try to find it. In this work the analysis of high-speed videos of two upward flashes shows, as in a previous study about bipolar cloud-to-ground flashes (Saba et al., 2013), that RL do play an important role in the occurrence of bipolar upward flashes. Furthermore, in bipolar upward flashes, IC flashes are also involved and this interaction provides explanations not only for Type 2 bipolar upward flashes but also for Type 1 and 3.

2 Instrumentation

2.1 High-speed camera

The first upward lightning flash (UP 44) was filmed on February 1, 2013, at 19:58:41 UTC (Universal Time Coordinated), by a Phantom v310 high-speed camera (acquisition rate of 10,000 fps, exposure time of 100 µs, and image spatial resolution of 640x480 pixels). The second lightning flash (UP 76) occurred on January 16, 2014, 17:05:28 UTC, filmed by a Phantom v711 high-speed camera, which was configured to acquire 20,000 fps, with an exposure time of 50 µs, and a spatial resolution of 720x400 pixels. Both cameras (equipped with a 6.5 mm lens) were located at a distance of 5 km from the upward flashes initiated from two towers located on Jaragua peak, Sao Paulo, Brazil. For more details on high-speed cameras, on the location and heights of the towers and on characteristics of upward flashes from these towers see Saba et al. (2006), Warner et al. (2013), Saba et al. (2016) and Schumann et al. (2019).

2.2 Lightning location systems

Data from a lightning localization system (Earth Networks Lightning – ENL) was used in this work to confirm the polarity and peak current of the subsequent return stroke of the analyzed lightning flash. For more information about the network see Liu & Heckman (2012), Marchand et al. (2019) and Zhu et al. (2022).

3 Data

3.1 Upward lightning flashes (UP 44 and UP 76)

The occurrence of positive cloud-to-ground lightning flashes (+CG) near the Jaragua Peak triggered upward positive leaders that initiated the upward lightning flashes UP 44 and UP 76. The +CGs that triggered UP 44 and UP 76 were at a distance from the tower of 21 and 31 km; and had an estimated peak current of 43 and 85 kA, respectively.
UP 44 was triggered by a negatively charged leader propagating during the continuing current that followed the return stroke of the +CG. UP 76 was triggered right after a +CG that transferred negative charge to the cloud base over the tower.
These are the most common triggering modes of upward leaders for the Jaragua Peak region according to a previous study of 72 cases of upward lightning (see Table 2 in Schumann et al., 2019). All upward leaders occurring from the towers in the region and reported in previous works had also positive polarity (see also Saba et al., 2016).
The positive upward leaders had almost no branches but presented many RL during their propagation as is usually reported for positive leaders (see for example the works of Mazur 2002, Heidler et al. 2015 and Saba et al. 2008).

In both upward flashes the connection of RL (present in the upward leader) with IC discharges resulted in positive subsequent return strokes striking the towers. These IC discharges appear in the video only 130 ms (UP 44) and 48 ms (UP 76) after the occurrence of the +CG flashes. Despite these large time intervals, the IC discharges may be linked to the previous triggering +CG flashes as positive discharges to ground often involve long, horizontal channels, up to several tens of kilometers in length (Saba et al., 2008 and 2009; Fuquay, 1982; Kong et al., 2008).

The upward lightning flash UP 44 (Figure 1a) was initiated at the highest telecommunication tower of the Jaragua peak (T_1). It produced an ICC with duration longer than 142 ms (the initiation of the positive upward leader was not recorded due to late video triggering; therefore, the duration of the ICC is an underestimate). The positive upward leader developed towards the cloud base and after a while the lightning channel decayed, and several RL started to occur.

The upward flash UP 76 initiated with two positive upward leaders from towers T_1 and T_2 of the Jaragua peak. The leader from T_1 originated first, and after 1.7 ms the positive leader from T_2 emerged. After an ICC that lasted 157 ms, several RL appeared on the decayed positive upward leaders. The RL that will be analyzed in the following section was originated in the channel of upward leader initiated on T_2.

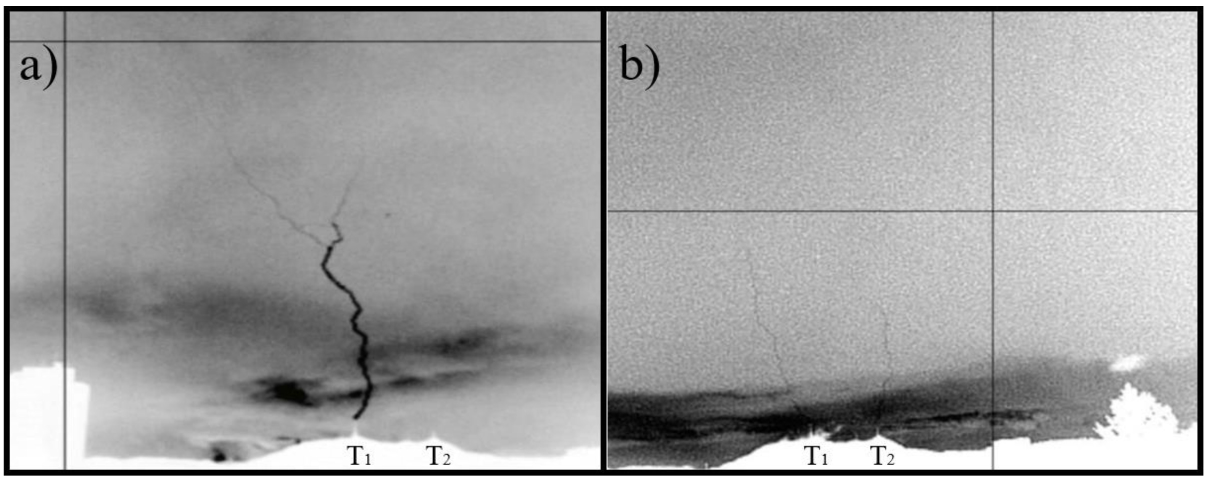

Figure 1. a) upward lightning UP 44; b) upward lightning UP 76. The intersection of the horizontal and vertical lines indicates the origin of the analyzed RL; the image was inverted and contrast enhanced to facilitate viewing.

3.2 Positive subsequent return stroke observed in upward lightning flash UP 44

Figure 2a shows a RL that starts along the decayed channel formed by the positive upward leader. In the upper right corner of this video image, the development of a positive leader of an IC can also be observed. The negative end of the RL (blue arrow) propagates along the previously formed channel and then up along the right branch to connect to the IC positive leader (red-border arrow – Figure 2b). In 2c, after connection, the positive leader re-ionizes the main channel of upward lightning flash and strikes the tower, producing a positive subsequent return stroke (Figure 2d). The peak current estimated by ENL was 83.9 kA. This subsequent return stroke was accompanied by a long continuing current, lasting 406 ms. Note that this combination of high peak current return stroke followed by a very long continuing current is very rare (see for example Figure 7 in Saba et al., 2010). The tower facility had power failure for several hours and some equipment damaged by this discharge.

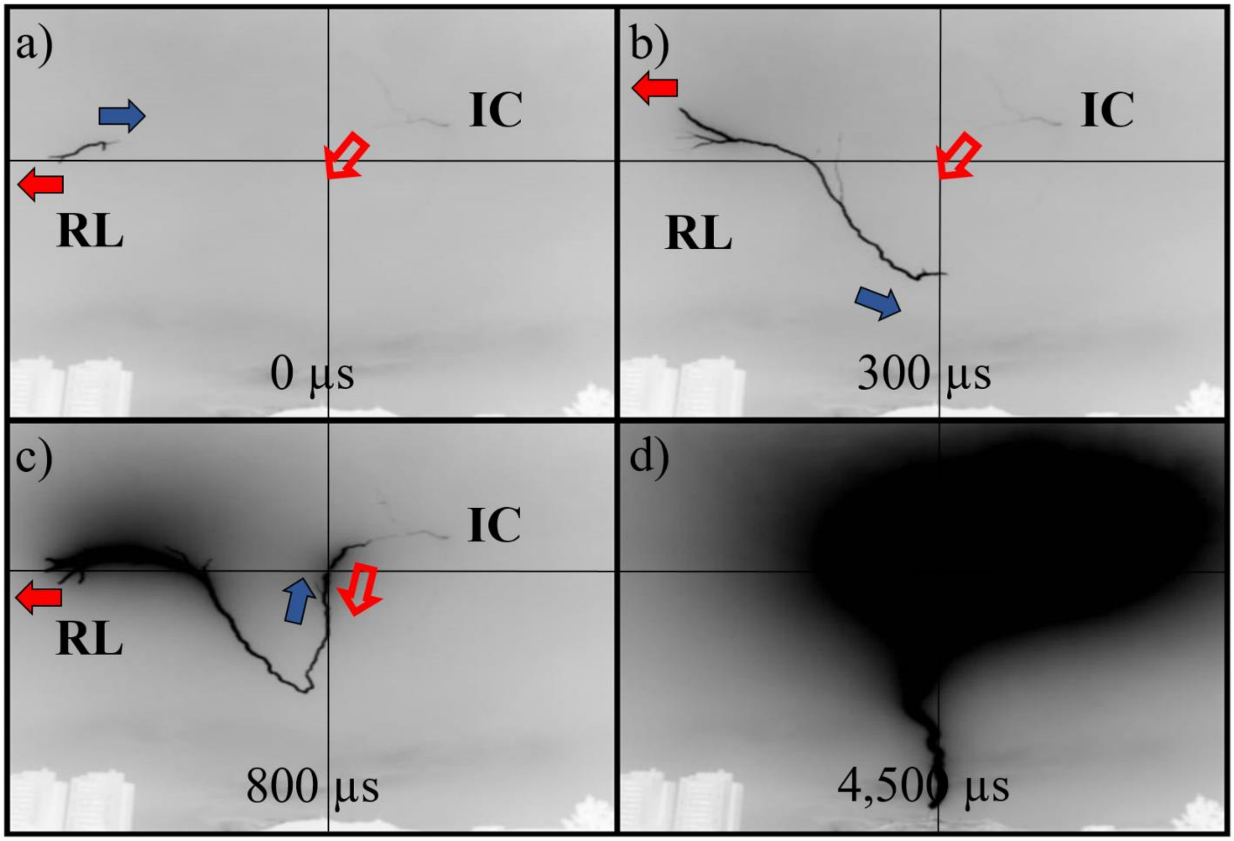

Fig. 2. Propagation of a RL towards an IC discharge (a, b, c), and the resulting positive subsequent return stroke. The intersection between the horizontal and vertical lines shows the connection region. The red-border arrow shows the development of the IC positive leader, the blue and red arrows represent the negative and positive end of the RL respectively.

3.3 Positive subsequent return stroke observed in upward lightning flash UP 76

The upward lightning flash UP 76 had two upward leaders originated on towers T_1 and T_2 (Figure 1b). The positive subsequent return stroke took place along the path traced by the upward leader that started on T_2. It also began with the interaction of a RL with an IC flash (Figure 3).

Figure 3a and 3b show the development of RL that happens along a decayed branch of the upward lightning flash. The negative end (blue arrow) of the RL connects with the IC discharge and positive charges (red-border arrow) begin to flow through the channel created by the connection (Figure 3c). The positive leader strikes T_2 generating a positive subsequent return stroke with estimated peak current of 24.2 kA (Figure 3d). After the positive subsequent return stroke, a long continuing current flow for about 227 ms.

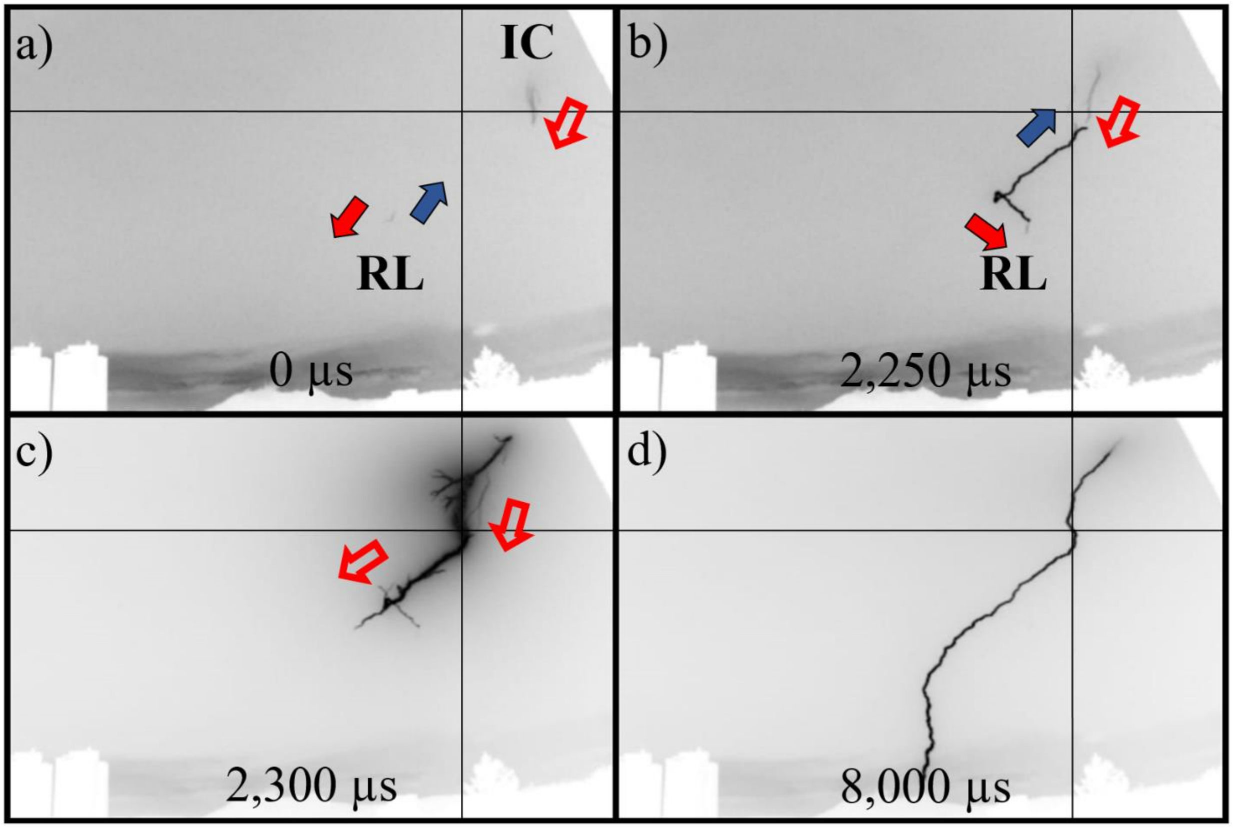

Fig. 3. Propagation of a RL initiated on a decayed branch of the positive upward leader towards an IC discharge. They connect and start a positive subsequent return stroke that hits T_2. The intersection of the horizontal and vertical lines in the images shows the connection location. The red-border arrow in the image represents the positive leader of the IC discharge. The negative and positive ends of the RL are indicated by blue and red arrows respectively.

4 Discussion and conclusion

In both upward flashes, the negative end of RL originated in the decayed branches of the positive upward leader connected to the positive leader of an IC discharge. After the connection of the negative end of the RL, positive charges flow towards the origin of the upward flashes, starting positive subsequent return strokes with long continuing currents (Figure 2 and 3).

These two flashes are Type 2 upward bipolar lightning flashes, that is, ICC followed by subsequent return stroke of opposite polarity. Figure 4 shows a schematic representation of how these discharges originate. In Figure 4a, it is possible to observe the positive leader of the upward lightning and the IC discharge. After a while, the current from the channel of the upward flash decays and cutoff occurs (Figure 4b). Then, in the Figure 4c, a RL appears in the decayed channel and the negative end (blue trace) of the RL propagates towards the positive leader of the IC flash. In Figure 4d, the negative end of the RL connects with the IC and positive charges flow towards ground giving origin to a positive subsequent return stroke (+SRS).

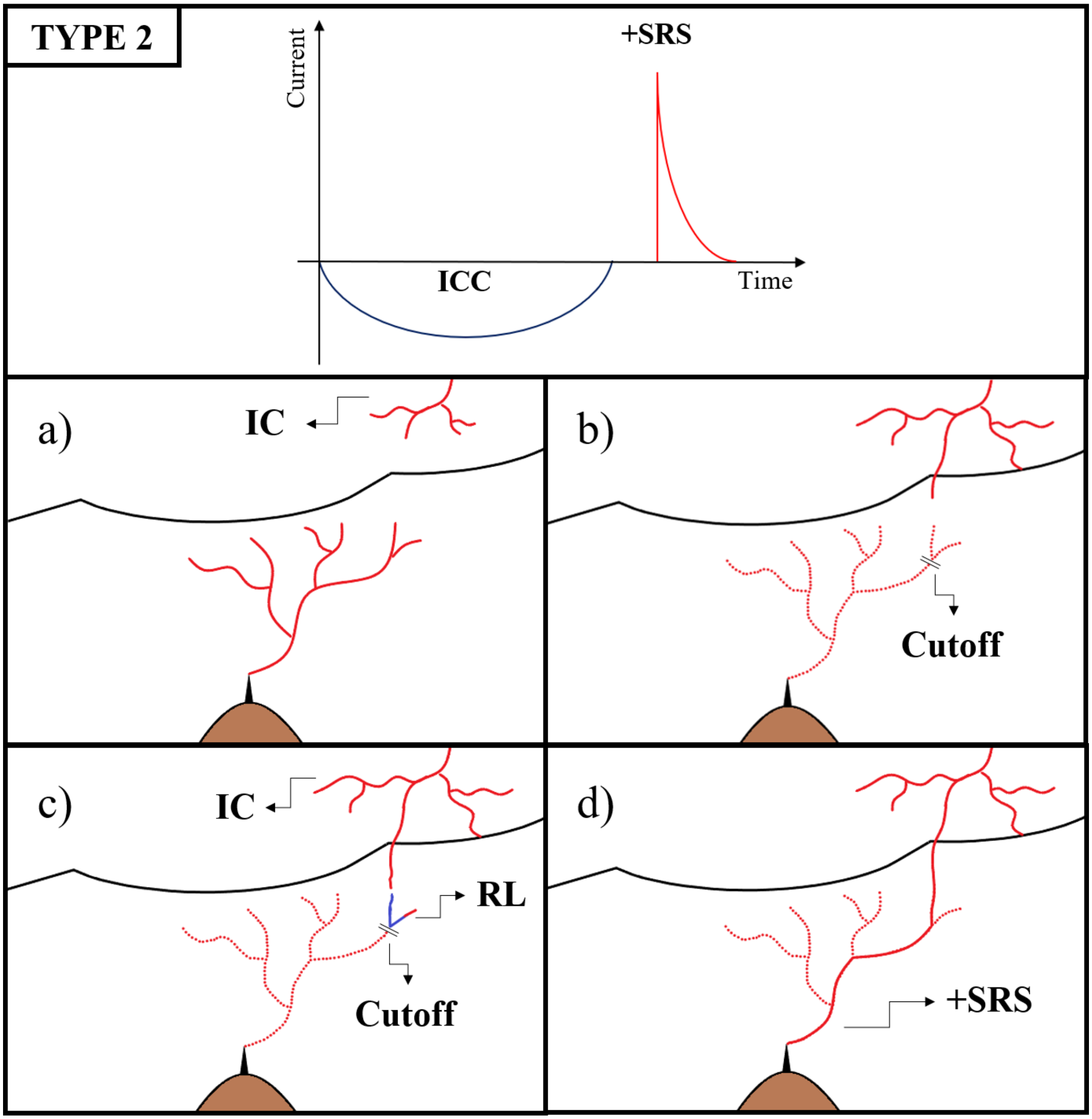

Fig. 4. Schematic representation of the origin of Type 2 bipolar upward flashes caused by the interaction of RL with IC discharges.

Based on what was observed in UP 44 and UP 76 by the high-speed videos, possible scenarios are presented in Figures 5 and 6 showing how the interaction of RL with IC discharges could explain the origin of Type 1 and 3 upward bipolar lightning flashes.

Figure 5 shows a possible scenario for Type 1 bipolar upward lightning flashes (polarity change during the ICC). In Figure 5a, it is possible to observe the positive leader of the upward lightning and the IC discharge. After a while (Figure 5b) there is a current cutoff in one of the branches of the upward flash. In Figure 5c, a RL appears in the decayed channel of the disconnected branch and the negative end of the RL propagates towards the IC discharge. In Figure 5d, the negative end of the RL connects with the positive leader of the IC discharge and positive charges flow towards the ground originating a brief ICC pulse of opposite polarity. If the positive upward leaders (show in Figure 5a) continue to propagate, the ICC current returns to the original polarity (negative net charge transfer to the ground) as is depicted on the current plot on top of Figure 5.

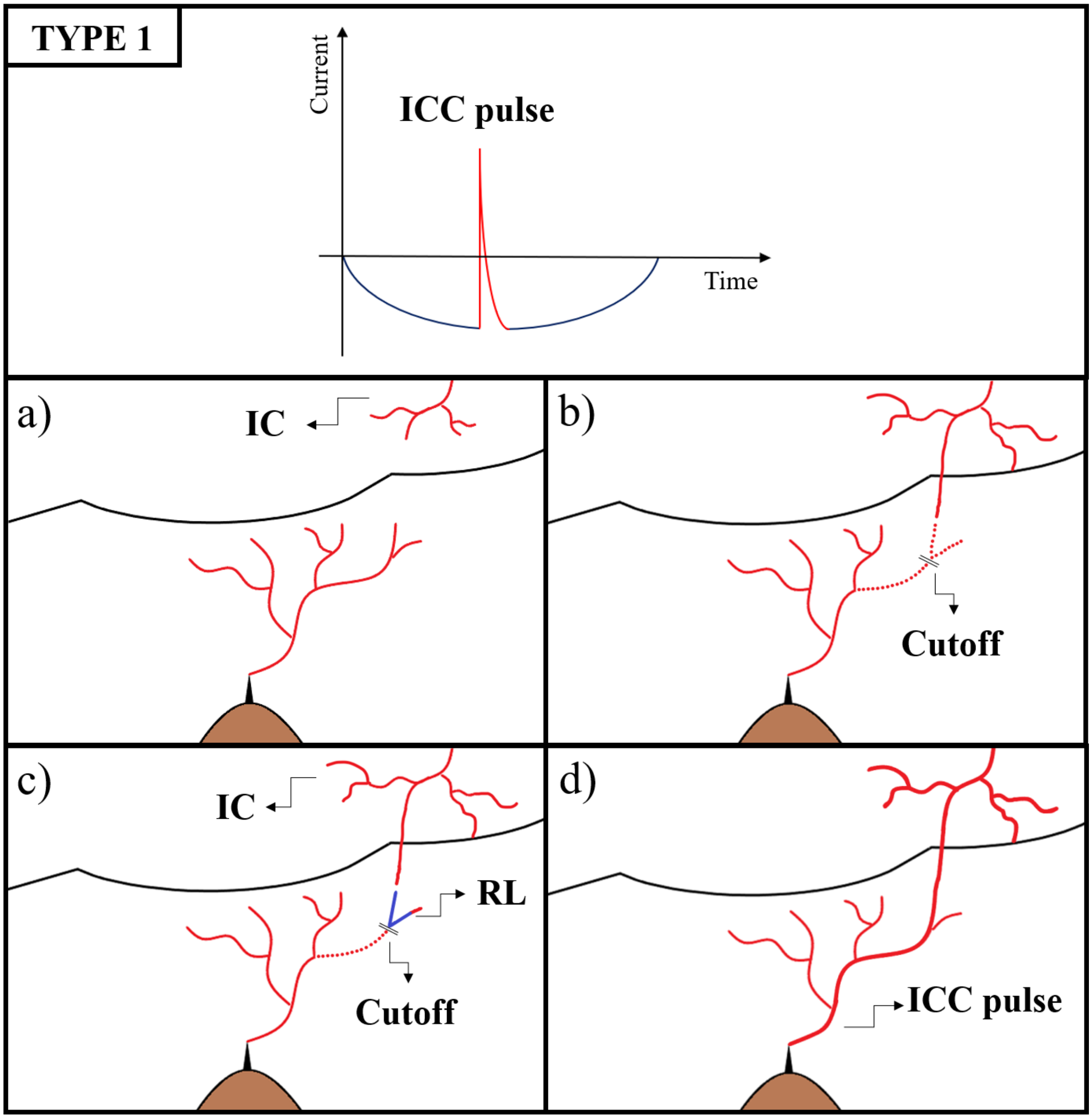

Fig. 5. Schematic representation of the origin of bipolar upward lightning flashes of Type 1 caused by the interaction of RL with IC discharge.

Finally, Figure 6 shows the schematic representation of how a Type 3 bipolar upward lightning flash (subsequent return stroke of different polarities during the same event) could happen. Figure

6a shows the positive leader of the upward lightning and the IC discharge. Figure 6b shows the cutoff of the current and the RL that connects with the IC discharge (Figure 6c). After connection, positive charges flow giving origin to a +SRS. This sequence is equal to the one followed by Type 2 upward bipolar flash described before (Figure 4). After the +SRS, if a RL happens along another upward positive leader branch a –SRS may occur as in a common negative upward lightning flash (Figure 6d).

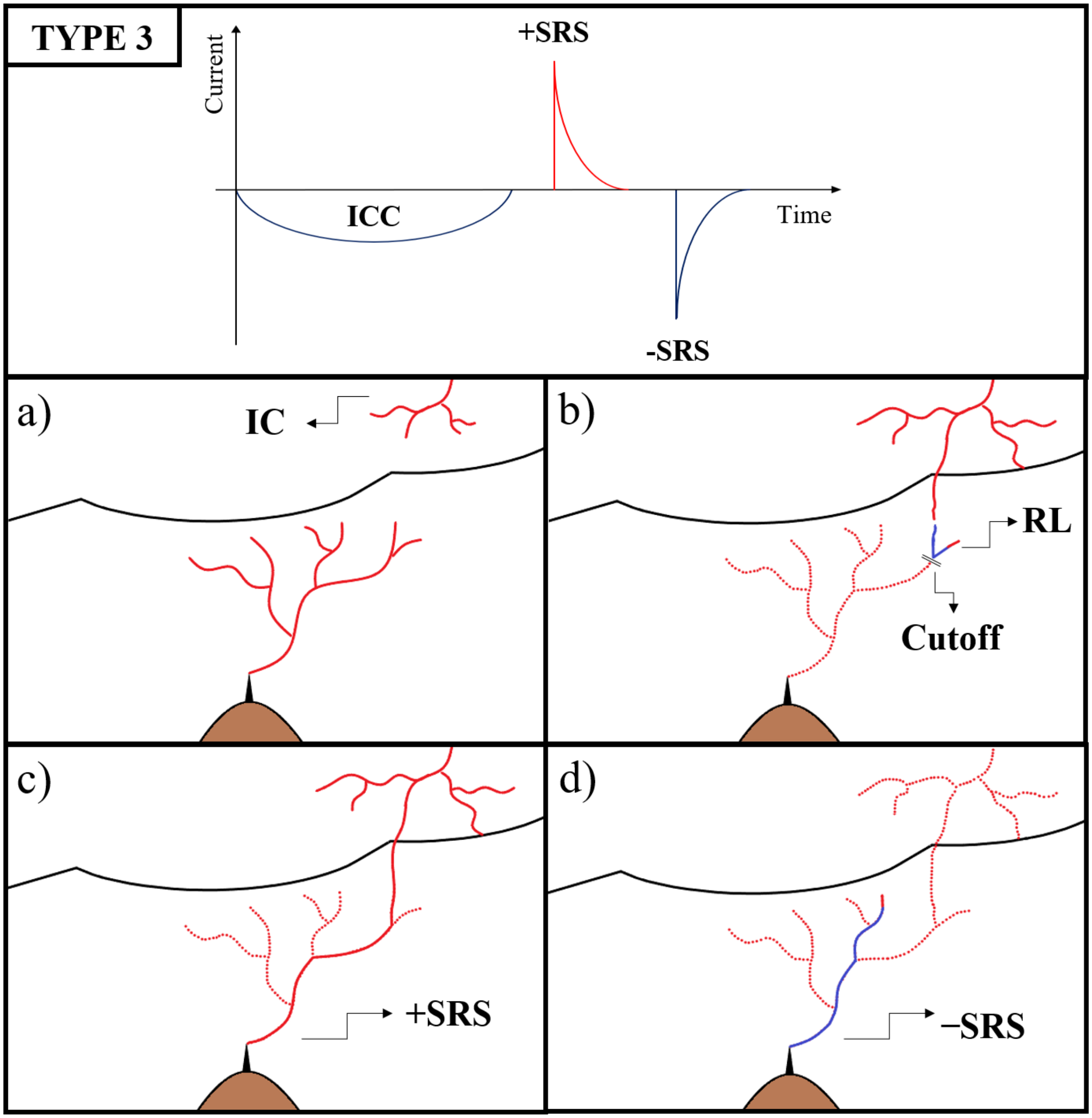

Fig. 6. Schematic representation of the origin of bipolar upward lightning flashes of Type 3 caused by the interaction of RL with IC discharges.

In summary, this work reports two Type 2 bipolar upward flashes observed by high-speed cameras. Through the above analysis it is shown that the connection of RL with IC positive leaders results in positive subsequent return strokes striking the towers. The increased threat of damage caused by this rare flash is due to the intense positive return stroke and long duration current that frequently follows. Based on the observed interactions between RL and IC flashes we suggested two possible scenarios that could also explain bipolar upward lightning flashes of Type 1 and 3.

Acknowledgments

This research has been supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) through projects 88887.676681/2022-00 (CAPES), 130928/2020-8 (CNPq) and 2012/15375-7, 2013/05784-0 (FAPESP). The authors would like to give sincere thanks to Lie Liong Lee (Benny), Raphael Guedes and Guilherme Aminger, for their assistance in obtaining the high-speed camera data used for this research. Finally, would like to thank Jeff Lapierre for sharing lightning localization system data (courtesy from ENL).

Data Availability Statement

The high-speed videos (UP 44 and UP 76) analyzed in this work are available at: http://urlib.net/ibi/8JMKD3MGP3W34T/47GTSCE.

References

Azadifar, M., Rachidi, F., Rubinstein, M., Rakov, V. A., Paolone, M., & Pavanello, D. (2016). Bipolar lightning flashes observed at the Säntis tower: Do we need to modify the traditional classification? *Journal of Geophysical Research*, *121*(23), 14,117-14,126. https://doi.org/10.1002/2016JD025461

Fuquay, D. M. (1982). Positive cloud-to-ground lightning in summer thunderstorms. *Journal of Geophysical Research*, *87*(C9), 7131–7140. https://doi.org/10.1029/JC087iC09p07131

Heidler, F. H., Manhardt, M., & Stimper, K. (2015). Characteristics of upward positive lightning initiated from the Peissenberg Tower, Germany. *IEEE Transactions on Electromagnetic Compatibility*, *57*(1), 102–111. https://doi.org/10.1109/TEMC.2014.2359584

Kong, X., Qie, X., & Zhao, Y. (2008). Characteristics of downward leader in a positive cloud-to-ground lightning flash observed by high-speed video camera and electric field changes. *Geophysical Research Letters*, *35*(5). https://doi.org/10.1029/2007GL032764

Liu, C., & Heckman, S. (2012). Total lightning detection and real-time severe storm prediction. *TECO-2010—WMO Tech. Conf. on Meteorological and Environmental Instruments and Methods of Observation*, Helsinki, Finland, World Meteorological Organization, P2(7), 1–24.

Lu, W., Zhang, Y., Li, J., Zheng, D., Dong, W., Chen, S., & Wang, F. (2008). Optical observations on propagation characteristics of leaders in cloud-to-ground lightning flashes. *Acta Meteorologica Sinica*, *22*(1), 66–77.

Marchand, M., Hilburn, K., & Miller, S. D. (2019). Geostationary Lightning Mapper and Earth Networks Lightning detection over the contiguous United States and dependence on flash characteristics. *Journal of Geophysical Research: Atmospheres*, *124*(21), 11552–11567. https://doi.org/10.1029/2019JD031039

Mazur, V. (2002). Physical processes during development of lightning flashes. *Comptes Rendus Physique, 3*(10), 1393–1409. https://doi.org/10.1016/S1631-0705(02)01412-3

Mazur, V. (2016). The physical concept of recoil leader formation. *Journal of Electrostatics*, *82*, 79–87. https://doi.org/10.1016/j.elstat.2016.05.005

Mazur, V., & Ruhnke, L. H. (1993). Common physical processes in natural and artificially triggered lightning. *Journal of Geophysical Research*, *98*(D7), 12913– 12930. https://doi.org/10.1029/93jd00626

Mazur, V., & Ruhnke, L. H. (2011). Physical processes during development of upward leaders from tall structures. *Journal of Electrostatics*, *69*(2), 97–110. https://doi.org/10.1016/j.elstat.2011.01.003

Mazur, V., Ruhnke, L. H., Warner, T. A., & Orville, R. E. (2013). Recoil leader formation and development. *Journal of Electrostatics*, *71*(4), 763–768. https://doi.org/10.1016/j.elstat.2013.05.001

Rakov, V. A., & Uman, M. A. (2003). *Lightning physics and effects* (Cambridge University Press).

Romero, C., Rubinstein, M., Rachidi, F., Paolone, M., Rakov, V. A., & Pavanello, D. (2012). Some characteristics of positive and bipolar lightning flashes recorded on the Säntis tower in 2010 and 2011. *31st International Conference on Lightning Protection (ICLP),* Vienna, Austria, September 3–7, 2012. https://doi.org/10.1109/ICLP.2012.6344271

Saba, M. M. F., Campos, L. Z. S., Krider, E. P., & Pinto, O. (2009). High-speed video observations of positive ground flashes produced by intracloud lightning. *Geophysical Research Letters*, *36*(12), 1–5. https://doi.org/10.1029/2009GL038791

Saba, M. M. F., Cummins, K. L., Warner, T. A., Krider, E. P., Campos, L. Z. S., Ballarotti, M. G., Pinto, O., & Fleenor, S. A. (2008). Positive leader characteristics from high-speed video observations. *Geophysical Research Letters*, *35*(7), 1–5. https://doi.org/10.1029/2007GL033000

Saba, M. M. F., Pinto, J., & Ballarotti, M. G. (2006). Relation between lightning return stroke peak current and following continuing current. *Geophysical Research Letters*, *33*(23), 7–10. https://doi.org/10.1029/2006GL027455

Saba, M. M. F., Schulz, W., Warner, T. A., Campos, L. Z. S., Schumann, C., Krider, E. P., Cummins, K. L., & Orville, R. E. (2010). High-speed video observations of positive lightning flashes to ground. *Journal of Geophysical Research Atmospheres*, *115*(24). https://doi.org/10.1029/2010JD014330

Saba, M. M. F., Schumann, C., Warner, T. A., Ferro, M. A. S., Paiva, A. R., Helsdon, J. Jr., & Orville, R. E. (2016). Upward lightning flashes characteristics from high-speed videos. *Journal of Geophysical Research: Atmospheres*, *121*, 8493–8505. https://doi.org/10.1002/2016JD025137

Saba, M. M. F., Schumann, C., Warner, T. A., Helsdon, J. H., & Orville, R. E. (2015). High-speed video and electric field observation of a negative upward leader connecting a downward positive leader in a positive cloud-to-ground flash. *Electric Power Systems Research*, *118*, 89–92. https://doi.org/10.1016/j.epsr.2014.06.002

Saba, M. M. F., Schumann, C., Warner, T. A., Helsdon, J. H., Schulz, W., & Orville, R. E. (2013). Bipolar cloud-to-ground lightning flash observations. *Journal of Geophysical Research Atmospheres*, *118*(19), 98–106. https://doi.org/10.1002/jgrd.50804

Schumann, C. (2016). *Estudo dos raios ascendentes a partir de observações de câmeras de alta resolução temporal e de medidas de campo elétrico* [Upward lightning flash characterization from high-speed camera videos and electric field measurements], (Doctoral thesis). Retrieved from Digital Library of Scientific Memory of INPE. (sid.inpe.br/mtc-m21b/2016/05.04.19.06-TDI). Sao Jose dos Campos, SP: National Institute for Space Research.

Schumann, C., Saba, M. M. F., da Silva, R. B. G., & Schulz, W. (2013). Electric fields changes produced by positives cloud-to-ground lightning flashes. *Journal of Atmospheric and Solar-Terrestrial Physics*, *92*, 37–42. https://doi.org/10.1016/j.jastp.2012.09.008

Schumann, C., Saba, M. M. F., Warner, T. A., Ferro, M. A. S., Helsdon, J. H., Thomas, R., & Orville, R. E. (2019). On the triggering mechanisms of upward lightning. *Scientific Reports*, *9*(1), 1–9. https://doi.org/10.1038/s41598-019-46122-x

Shi, D., Wang, D., Wu, T., Thomas, R. J., Edens, H. E., Rison, W., Takagi, N., & Krehbiel, P. R. (2018). Leader polarity-reversal feature and charge structure of three upward bipolar lightning flashes. *Journal of Geophysical Research: Atmospheres*, *123*(17), 9430–9442. https://doi.org/10.1029/2018JD028637

Sunjerga, A., Rubinstein, M., Mostajabi, A., Azadifar, M., Pineda, N., Romero, D., Van der Velde, O., Montanya, J., Diendorfer, G., Ventura, J. F., Besic, N., Grazioli, J., Hering, A., Germann, U., & Rachild, F. (2019). LMA Observation of upward bipolar lightning flash at the Säntis tower. *International Symposium on Lightning Protection (XV SIPDA*), Brazil, October, 1–6, 2019.

Wang, D., & Takagi, N. (2008). Characteristics of upward bipolar lightning derived from simultaneous recording of electric current and electric field change. *XXIX General Assembly, International Union of Radio Science*, Chicago, 2–5.

Warner, T. A., Helsdon, J. H., Bunkers, M. J., Saba, M. M. F., & Orville, R. E. (2013). Uplights: Upward lightning triggering study. *Bulletin of the American Meteorological Society*, *94*(5), 631–635. https://doi.org/10.1175/BAMS-D-11-00252.1

Warner, T. A., Saba, M. M. F., Schumann, C., Helsdon, J. H., & Orville, R. E. (2016). Observations of bidirectional lightning leader initiation and development near positive leader channels. *Geophysical Research Atmospheres*, *121*, 9251–9260. https://doi.org/10.1038/175238c0

Zhou, H., Diendorfer, G., Thottappillil, R., Pichler, H., & Mair, M. (2011). Characteristics of upward bipolar lightning flashes observed at the Gaisberg Tower. *Journal of Geophysical Research Atmospheres*, *116*(13), 1–13. https://doi.org/10.1029/2011JD015634

Zhu, Y., Stock, M., Lapierre, J., & Digangi, E. (2022). Upgrades of the Earth Networks Total Lightning Network in 2021. In *Remote Sensing* (Vol. 14, Issue 9). MDPI. https://doi.org/10.3390/rs1409220