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MULTISCALE INVESTIGATION OF LIGHTNING AND ASSOCIATED PHENOMENA

Komise pro obhajoby doktorských disertací v oboru geofyzikálních věd

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ABSTRACT

This Thesis presents the summary of twelve years of research into lightning and related phenomena, spanning ten orders of magnitude in both temporal and spatial scales. The work is structured around three core research areas: (1) Small-scale lightning processes, (2) Large-scale lightning processes, and (3) Jovian lightning. The findings are based on selected 22 peer-reviewed publications in international journals, including *Nature Astronomy* and *Nature Communications*. A central methodology throughout this work is the analysis of electromagnetic waves emitted by lightning over a broad frequency spectrum. Our research has significantly advanced the understanding of lightning initiation, revealing, for example, the rapid evolution of intense winter lightning and identifying reasons why initiation processes are often underreported in standard narrow-band datasets. We successfully characterized intracloud processes, such as dart-stepped leaders and attempted leaders, and demonstrated how large-scale climatic phenomena can disrupt typical lightning weather patterns. These findings also highlight the potential of lightning research in the context of climate change. A particularly notable achievement was the first detection of transient luminous events known as "elves" and their causative, extremely powerful lightning discharges within a small-scale continental thunderstorm. Among the most valuable contributions are several discoveries related to lightning on Jupiter. These include the identification of rapid whistlers generated by Jovian lightning, the presence of low-density regions—“holes”—in Jupiter’s ionosphere, and the observation that Jovian lightning develops in a step-like fashion, analogous to terrestrial lightning. Furthermore, we demonstrated that lightning rates on Jupiter can reach up to four strokes per second, comparable to those in Earth's thunderstorms. This research underscores the fundamental importance of lightning as a natural laboratory for studying atmospheric physics and electromagnetic wave propagation. The discoveries made throughout this work not only enhanced our understanding of lightning on Earth and Jupiter, but also open further avenues for interdisciplinary research across atmospheric science, space physics, and planetary exploration.

List of publications included in the dissertation

A. Small-scale lightning processes (10 papers)

1) **Kolmašová, I.** & O. Santolík (2013). Properties of unipolar magnetic field pulse trains generated by lightning discharges, *Geophysical Research Letters, 40*, 1637–1641. Doi:10.1002/grl.50366.
2) **Kolmašová, I.**, O. Santolík, T. Farges, W. Rison, R. Lán, & L. Uhlíř (2014). Properties of the unusually short pulse sequences occurring prior to the first strokes of negative cloud-to-ground lightning flashes, *Geophysical Research Letters, 41*, 5316–5324. Doi:10.1002/2014GL060913.
3) **Kolmašová, I.**, O. Santolík, T. Farges, S. A. Cummer, R. Lán, & L. Uhlíř (2016). Sub-ionospheric propagation and peak currents of preliminary breakdown pulses before negative cloud-to-ground lightning discharges, *Geophysical Research Letter, 43,* 1382–1391. Doi:10.1002/2015GL067364.
4) **Kolmašová, I.**, O. Santolik, E. Defer, W. Rison, S. Coquillat, S. Pédeboy, R. Lán, L. Uhlír, D. Lambert, J.-P. Pinty, S. Prieur & V. Pont (2018). Lightning initiation: Strong pulses of VHF radiation accompany preliminary breakdown. *Scientific Reports* 8, 3650. Doi:10.1038/s41598-018-21972-z.
5) **Kolmašová, I.**, Marshall, T., Bandara, S., Karunarathne, S., Stolzenburg, M., Karunarathne, N., & Siedlecki, R. (2019). Initial breakdown pulses accompanied by VHF pulses during negative cloud-to-ground lightning flashes. *Geophysical Research Letters*, 46. Doi:10.1029/2019GL082488.
6) **Kolmašová, I**., Santolík, O., Defer, E., Kašpar, P., Kolínská, A., Pédeboy, S., & Coquillat, S. (2020). Two propagation scenarios of isolated breakdown lightning processes in failed negative cloud-to-ground flashes, *Geophysical Research Letters*, 47, e2020GL090593. Doi:10.1029/2020GL090593.
7) **Kolmašová, I.**, Soula, S., Santolík, O., Farges, T., Bousquet, O., Diendorfer, G., Lán, R., & Uhlíř, L. (2022). A frontal thunderstorm with several multi-cell lines found to produce energetic preliminary breakdown. *Journal of Geophysical Research: Atmospheres*, 127, 4. Doi:10.1029/2021JD035780.
8) **Kolmašová, I.**, O. Scholten, O. Santolík, B. M. Hare, P. Zacharov, R. Lán et al. (2023). A strong pulsing nature of negative intracloud dart leaders accompanied by

regular trains of microsecond-scale pulses. *Geophysical Research Letters*, 50. Doi:10.1029/2023GL103864.

9) **Kolmašová, I.**, Santolík, O., Kolínská, A. et al. (2025). Rapid evolution of energetic lightning strokes in Mediterranean winter storms. *npj Climate and Atmospheric Science* 8, 71. Doi:10.1038/s41612-025-00965-6.

10) Kolínská, A., **Kolmašová, I.**, Defer, E., Santolík, O., & Pédeboy, S. (2025). Post-return stroke VHF electromagnetic activity in north-western Mediterranean cloud-to-ground lightning flashes, *Atmospheric Chemistry and Physics*, 25, 1791–1803. Doi:10.5194/acp-25-1791-2025.

B. Large-scale lightning processes (6 papers)

11) Santolík, O. & **Kolmašová, I.** (2017). Unusual Electromagnetic Signatures of European North Atlantic Winter Thunderstorms, *Scientific Reports*, 7, 1, 13948. Doi:10.1038/s41598-017-13849-4.
12) Santolík, O., **Kolmašová, I.**, Pickett, J. S., & Gurnett, D. A. (2021a). Multipoint observation of hiss emerging from lightning whistlers. *Journal of Geophysical Research: Space Physics*, 126, e2021JA029524. Doi:10.1029/2021JA029524.
13) Santolík, O., Miyoshi, Y., **Kolmašová, I.**, Matsuda, S., Hospodarsky, G. B., Hartley, D. P., et al. (2021b). Inter-calibrated measurements of intense whistlers by Arase and Van Allen Probes. *Journal of Geophysical Research: Space Physics*, 126(9), e2021JA029700. Doi:10.1029/2021JA029700.
14) **Kolmašová, I.**, Santolík, O., Kašpar, P., Popek, M., Pizzuti, A., Spurný, P. et al. (2021). First observations of elves and their causative very strong lightning discharges in an unusual small-scale continental spring-time thunderstorm. *Journal of Geophysical Research: Atmospheres*, 126(1). Doi:10.1029/2020JD032825.
15) **Kolmašová, I.**, Santolík, & O., Rosická, K. (2022). Lightning activity in northern Europe during a stormy winter: disruptions of weather patterns originating in global climate phenomena, *Atmospheric Chemistry and Physics*, 22, 5, 3379-3389. Doi:10.1038/s41598-017-13849-4.
16) **Kolmašová, I.**, Santolík, O. & Manninen, J. (2024), Whistler echo trains triggered by energetic winter lightning. *Nature Communications,* 15, 7166. Doi:10.1038/s41467-024-51684-0.

C. Jovian lightning (6 papers)

17) **Kolmašová, I.**, Imai, M., Santolík, O., Kurth, W. S., Hospodarsky, G. B., Gurnett, D. A., et al. (2018). Discovery of rapid whistlers close to Jupiter implying similar lightning rates to those on Earth. *Nature Astronomy*, 2, 544– 548. Doi:10.1038/s41550-018-0442-z.
18) Brown, S., Janssen, M., Adumitroaie, V. … **Kolmašová. I**. …et al. (2018). Prevalent lightning sferics at 600 megahertz near Jupiter's poles. *Nature* 558, 87–90. Doi:10.1038/s41586-018-0156-5.
19) Imai, M., Santolík, O., Brown, S. T., **Kolmašová, I.**, Kurth, W. S., Janssen, M. A., Hospodarsky, G. B., Gurnett, D. A., Bolton, S. J., & Levin, S. M. (2018). Jupiter lightning-induced whistler and sferic events with Waves and MWR during Juno perijoves, *Geophysical Research Letters*, 45, 15, 7268-7276. Doi:10.1029/2018GL078864.
20) Imai, M., **Kolmašová, I.**, Kurth, W. S., Santolík, O., Hospodarsky, G. B., Gurnett, D. A., Brown, S. T., Bolton, S.J., Connerney, J. E. P., & Levin, S. M. (2019). Evidence for low density holes in Jupiter's ionosphere, *Nature Communications*, 10, 2751. Doi: 10.1038/s41467-019-10708-w.
21) Imai, M., Wong, M. H., **Kolmašová, I.**, Brown, S. T., Santolík, O., Kurth, W. S., Hospodarsky, G. B., Bolton, S.J., & Levin, S. M. (2020). High-Spatiotemporal Resolution Observations of Jupiter Lightning-Induced Radio Pulses Associated With Sferics and Thunderstorms, *Geophysical Research Letters*, 47. Doi:10.1029/2020GL088397.
22) **Kolmašová, I.**, Santolík, O., Imai, M., Kurth, W. S., Hospodarsky, G. B., Connerney, J. E. P., Bolton, S.J., & Lán, R. (2023). Lightning at Jupiter pulsates with a similar rhythm as in-cloud lightning at Earth, *Nature Communications,* 14, 2707. Doi: 10.1038/s41467-023-38351-6.

1. INTRODUCTION

Lightning – a powerful natural electrical discharge occurring in a mature stage of thunderstorms more than fifty times per second worldwide – is an impressive commonly known geophysical phenomenon. Research of lightning, thunderclouds (Fig.1) and thunderstorms has made a significant progress during last 30 years thanks to new observational and computational techniques. Now we have a relatively complete picture of the lightning phenomenology, but a detailed understanding of many lightning characteristics and effects is still missing; even the basic question of lightning initiation has not been satisfactorily answered yet. Difficulties in the lightning research are also connected with the unpredictability and randomness in their occurrence in time and space.

The scales of lightning processes in time or frequency domains vary by ten orders of magnitude. The rising edges of individual electromagnetic pulses generated by in-cloud currents last only a few tens of nanoseconds, the entire flash might last up to almost a second [*Dwyer & Uman,* 2014]. The lifetime of magnetospherically reflecting lightning whistlers in the inner magnetosphere reaches up to several tens of seconds [*Bortnik et al.*, 2003]. The recovery of lightning-induced ionospheric disturbances in the D-region, which have typical lateral extents of a few hundreds of kilometres, can last up to 20 minutes [*Cotts & Inan*, 2007; *Kotovsky et al.*, 2017; ***Tomičič et al.*, 2023**].

***Fig. 1** Thundercloud (author's archive).*

Lightning processes generate electromagnetic signal over a very wide range of frequencies. The small-scale in-cloud processes radiate at tens to hundreds of MHz and are used for the 3D mapping of lightning propagation inside thunderclouds [*Rison et al.*, 1999; *Hare et al.*, 2018, 2023; ***Kolmašová et al.*, 2018, 2019, 2023**; ***Scholten et al.*, 2021a,b,c, 2022**]. The lightning generated electromagnetic waves at specific frequencies (~2-20 kHz) are capable to penetrate the ionosphere and are routinely detected by spacecraft orbiting in the magnetosphere [*Zheng et al.*, 2016; *Wold et al.*, 2024]. Interference between lightning-induced waves at frequencies of several hertz results in the Earth-ionosphere cavity standing waves known as Schumann resonances [*Polk,* 1982]. Schumann resonances are being used to monitor the variability of lightning activity at global scales [*Rycroft et al.*, 2000]. Extreme events as a giant local lighting activity produced by the eruption of the Hunga Tonga-Hunga Haapai underwater volcano caused global disturbances not only in Schumann resonances but also in the geomagnetic field [*Gavrilov et al.,* 2022]. This event surprisingly also resulted in a significant suppression of the lightning detection rate of global lightning detection networks [*Mezentsev et al.,* 2023]. Lightning can even generate infrasonic waves at frequencies as low as a fraction of hertz [*Farges & Blanc*, 2010; *Applebaum et al.*, 2020; *Farges et al.*, 2021].

As concerns spatial dimensions of lightning processes, we can start at millimetre scales linked to electrification of hydrometeors (Fig. 2), which are directly involved in the lightning initiation [*Weinheimer et al.*, 1991; *Schmidt et al.,* 2012; *Gurevich and Karashtin*, 2013; *Babich et al.*, 2017, *Takahashi et al.*, 2019].

The main lightning channel is usually several kilometres long. The transient luminous events, atmospheric phenomena occurring between the thundercloud tops and the bottom of ionosphere, which result from the electrical activity in underlying thunderstorms, reach up to tens of kilometres in length [*Pasko*, 2010; *Surkov & Hayakawa*, 2020]. We can also investigate large-scale effects of lightning-generated signals, which may propagate for thousands of kilometres in the Earth-ionosphere waveguide, penetrate the ionosphere, get dispersed by propagation in the magnetosphere [*Platino et al., 2005;* ***Santolík et al.****, 2009;* ***2021a,b***], and reach several Earth radii in a form of lightning whistlers [*Zheng et al.*, 2016; *Wold et al.*, 2024].

The extremely interesting and still not quite well understood lightning phenomena are in-cloud processes leading to lightning initiation. These processes are not simply accessible by in-situ or optical measurements. As in-cloud currents emit electromagnetic radiation, they can be safely and very efficiently investigated using analysis of their electromagnetic signatures. The initiation of both cloud-to-ground (CG) and intracloud lightning (IC) flashes is usually signalized by the presence of sequences of pulses in the electromagnetic records.

A sequence of these predominantly bipolar preliminary breakdown pulses (also known as initial breakdown pulses) usually lasts from a few milliseconds to several tens of milliseconds, occurring probably prior to all first return strokes (RS) of negative CG flashes [*Marshall et al.*, 2014]. Properties of preliminary breakdown pulses have been intensively studied [*Stolzenburg et al.*, 2013; *Karunarathne et al.*, 2013, 2020; *Wu et al.,* 2013; ***Kolmašová et al.*, 2014, 2018, 2022, 2025**; ***Marshall et al.*, 2019;** *Sekehravani, et* *al.*, 2025] and modeled [*Karunarathne et al.,* 2014; *da Silva and Pasko*, 2015; ***Kašpar et al.*, 2016, 2017**] during the past decade. The origin of the short duration in-cloud currents causing the preliminary breakdown pulses and their role in the initiation of lightning discharges is still under intense investigation of many groups of scientists.

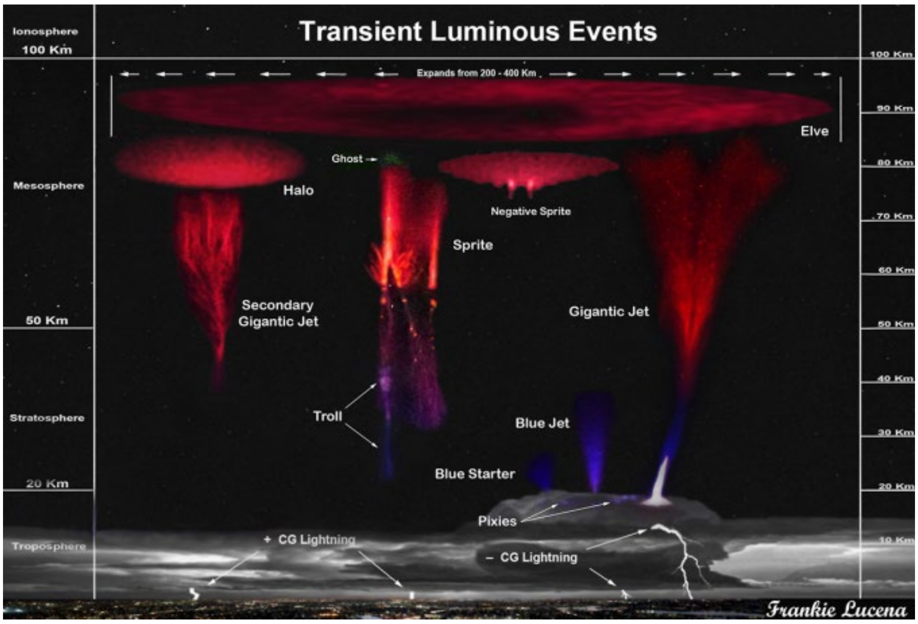

Fig. 2 *Overview of Transient luminous events (https://spaceweatherarchive.com)*

There are also other interesting in-cloud phenomena as sequences of unipolar pulses which occur during K-changes [*Rakov et al.,* 1996; ***Kolmašová & Santolík*, 2013**; ***Kolmašová et al.*, 2023**] or incloud activity following the positive CG return strokes [***Kolínská et al.*, 2025**]. Compact intracloud discharges producing Narrow Bipolar Events (NBEs) strongly radiate in the MHz frequency band [*Smith et al*., 1999; *Nag & Rakov*, 2010; *Karunarathne et al.* 2015; *Li et al*., 2022; *Chen et al*., 2024], and energetic intracloud pulses are generated by in-cloud currents higher than 200 kA [*Lyu et al*., 2015; *Antunes et al*., 2021; *Stolzenburg et al*., 2022]. A very strong Very High Frequency (VHF) radiation from narrow bipolar events, can even penetrate the ionosphere and be recorded on low-orbiting satellites [*Willet et al*., 1989; *Jacobson et al.*, 2011] in a form of trans-ionospheric pulse pairs [*Jacobson et al*., 2002; *Light*, 2020; *Li et al*., 2024]. Radiation emitted by in-cloud processes is strong enough to be detected far from their source thundercloud [***Kolmašová et al.,* 2016, 2024**; *Kotovsky et al*., 2016], and they are capable to initiate Terrestrial Gamma ray Flashes (TGFs) [*Marshall et al.,* 2013; *Cummer et al,* 2014; *Wada et al*., 2022; *Abbasi et al*., 2024].

From the large-scale point of view, the recently discovered and not fully understood optical events occurring at stratospheric and mesospheric/lower ionospheric altitudes (TLEs – Transient Luminous Events, *Neubert*, 2003; *Pasko*, 2010) attract interest of many groups of researchers (Fig. 2). The first image of one of these events was captured in 1989 during a test of an auroral imaging camera [*Franz et al*., 1990]. Since then, several different types of TLEs above thunderstorms have been documented and classified. "Sprites" develop at the bottom of the ionosphere and move rapidly downward at speeds up to 10,000 km/s [*Lu et al*., 2013; *Stenbaek-Nielsen et al*., 2020; *Huang et al*., 2025]. "Elves" are emissions of light and very low frequency perturbations, which rapidly spread over 300 km laterally and are invoked by electromagnetic pulses generated by underlying high-peak current return strokes [*Fukunishi et al*., 1996; *Barrington-Leigh & Inan*, 1999; *Blaes et al*., 2016; ***Kolmašová et al*., 2021**; *Mussa et al*., 2022]. Other types of TLEs are "halos," brief slowly downward descending glows with a lateral extent of 40–70 km [*Yashunin et al.,* 2007*; Williams et al*., 2012], which are usually observed to accompany or precede sprites. "Blue jets" are TLEs characterized by their distinct blue color. They originate from the tops of thunderclouds at altitudes of 17–18 km and travel upward into the atmosphere [*Edens et al*., 2011; *Chanrion et al.,* 2017; *Surkov & Hayakawa*, 2020].

It was discovered recently, that the optical effects of blue jets result from NBEs, followed by the excitation of N_2 molecules through the electron impact [*Li et al*., 2021; 2023]. The largest TLEs are "gigantic jets" emerging from thundercloud tops. They travel through the stratosphere and mesosphere, reaching a terminal altitude of approximately 85–90 km, where they establish an electrical connection between the tops of thunderclouds and the conductive D- and E-layers of the ionosphere [*da Silva & Pasko,* 2013; *van Velde et al*., 2019; *Surkov & Hayakawa*, 2020; *Soula et al*., 2023]. The newest type of TLE was named "ghost" (Green emissions from excited Oxygen in Sprite Tops). The ghosts appear due to the high electric fields at the sprite tops, which are capable to excite atomic oxygen [*Huang et al*., 2024]. The spectroscopic measurements revealed also traces of atomic iron and nickel, molecular nitrogen and ionic molecular oxygen, which might be responsible for a slow decay of the ghost luminescence [*Passas-Varo et al.,* 2023].

Electromagnetic signals generated by lightning return strokes can travel thousands of kilometers in the Earth- ionosphere waveguide in a form of sferics or tweeks. The tweek atmospherics are very important lightning induced signals because of their characteristic frequency dispersion, which is being used for the study of the properties of the ionospheric D-region [*Ohya et al.*, 2012; *Maurya et al.*, 2012; ***Santolík*** **&** ***Kolmašová*****, 2017;** ***Maslej-Kresnaková et al.*****, 2021**; *Tiwari et al.*, 2025].

The sferics or tweeks can also penetrate the ionosphere and in a form of whistlers, they can significantly contribute to the overall wave intensity in the inner magnetosphere [*Němec et al.*, 2010; ***Záhlava*** **et** ***al*****, 2018a, b, 2019**; *Wold et al.*, 2024]. They also influence populations of energetic particles in the Van Allen radiation belts due to lighting induced precipitation [*Lauben et al.*, 2001; *Bortnik et al.*, 2006a, b; *Kang & Bortnik*, 2022, *Feinland et al.*, 2024; ***Linzmayer et al.*****, 2024, 2025**]. Lightning induced whistler waves are believed to be one of the sources of plasmaspheric hiss [e.g. *Green et al.*, 2005, *Santolik & Chum*, 2009; ***Santolík et al.*****, 2021a**], which most probably causes the occurrence of the slot region with decreased radiation between the inner and outer Van Allen radiation belts of the Earth.

Final insight into large-scale lightning processes is derived through the study of lightning at other planets in our Solar System. The lightning discharges are direct evidence of electrification of planetary atmospheres driven by the convection. This is why the investigation of lightning properties can provide valuable insights into the atmospheric dynamics, cloud structure, and atmospheric chemistry of planets within our Solar System [*Aplin & Fischer*, 2017]. Planetary lightning discharges – similarly as on the Earth – produce broadband radio emissions, which originate from the current channels acting as antennas. At very low frequencies, the electromagnetic waves generated by lightning exhibit a characteristic time–frequency dispersion when propagating through the planetary plasma environment [*Storey*, 1953]. Lightning outside Earth was for the first time detected at Jupiter by the Voyager 1 spacecraft in 1979 through detection of lightning related radio signals [*Gurnett at al.*, 1979]. Besides Jupiter [*Kurth et al.*, 1985] there is direct evidence for lightning on Saturn [*Akalin et al.*, 2006; *Fischer et al.,* 2008, 2019]. Measurements in the vicinity of Uranus [*Zarka & Pedersen*, 1986] and Neptune [*Gurnett et al.,* 1990] have also yielded possible signals of lightning discharges.

New insights into Jovian lightning were obtained thanks to high-resolution electromagnetic measurements onboard the Juno spacecraft [*Bolton et al.*, 2017], which has been orbiting Jupiter since 2016. Thanks to the unique orbit of Juno, two new types of electromagnetic signals induced by Jovian lightning were unveiled in the measurements of the Waves instrument [*Kurth et al.,* 2017]: extremely low dispersion 'rapid' whistlers [***Kolmašová et al.*, 2018**] and discrete dispersed pulses [***Imai et al.,* 2019**]. The accumulated dispersion of the individual rapid whistlers is very low varying from several milliseconds to a few tens of milliseconds. The dispersion of discrete dispersed pulses is even lower, indicating the presence of regions with very low ionospheric density. The microwave radiometer onboard Juno detected for the first time lightning related signals in GHz range [***Brown et al***., 2018]

The latest lightning-related discovery [***Kolmašová et al.,*** 2023] involves the identification of radio pulses with typical time separations of one millisecond, suggesting step-like extensions of lightning channels. This indicates that the initiation processes of Jovian lightning are similar to those of intracloud lightning on Earth, even though the two planets are fundamentally different—Earth being small and rocky, and Jupiter large and gaseous.

In this thesis, I provide an overview of the various lightning processes occurring across different temporal and spatial scales. I present the research I conducted at the Institute of Atmospheric Physics of the Czech Academy of Sciences and at the Faculty of Mathematics and Physics of Charles University, in close collaboration with my colleagues. I summarize our findings, emphasizing their contribution to the understanding of this fascinating and powerful natural phenomenon. The collection of published scientific works is complemented by a commentary and a summary. The results are organized into three groups: 1) Small-scale lightning processes, 2) Large-scale lightning processes, and 3) Jovian lightning.

2. SELECTED RESULTS

2.1 Small-scale lightning processes

Electromagnetic measurements provide valuable insight into thundercloud activity by detecting signals emitted by evolving lightning discharges. They help reveal charge structures, leader development, and storm dynamics that are otherwise hidden from our view.

2.1.1. Lightning initiation

We significantly contributed to the understanding of lighting initiation processes using the analysis of their electromagnetic manifestations. In a case study [*Kolmašová et al.*, 2014, paper **Nr. 2**] we presented an unusually short duration of the pre-stroke activity of 1-7 ms reported for the first time during a summer thunderstorm from 2012 with a low height of initiation estimated to 3-4 km only. Very fast pre-stroke processes are indicative of strong negative charge sources, when lower positive charge is either entirely or partly consumed by the initial negative in-cloud leader [*Nag & Rakov*, 2009] and is incapable to slow the propagation down by one order of magnitude to the typical stepped leader speeds.

In the follow-up study [*Kolmašová et al.*, 2016, paper **Nr. 3**] we completed the 2012 dataset with two other electric field measurements located at 321 and 577 km from Rustrel. We showed that similar pulse patterns were recognizable in all measured waveforms, up to a distance of 600 km from the source lightning.

The case studies on the initiation phase of lightning are completed by a statistical study [*Kolmašová et al.*, 2025, paper **Nr. 8**] devoted to the rapid evolution of extremely strong negative winter lightning with peak currents exceeding 100 kA occurring in the Mediterranean region. There are only a few specific regions in the world where winter lightning tends to occur. In Europe, only the Mediterranean region is rich in winter lightning, and surprisingly, the electromagnetic signatures of this intriguing and dangerous phenomenon have not yet been studied in detail there. We investigate the initial stage of energetic negative CG Mediterranean winter lightning flashes using broadband magnetic-field measurements (5 kHz-90 MHz) recorded in winter 2014/2015, which was unusually rich in global lightning activity. The dataset consists of of 193 PB pulse trains followed by typical RS pulses (Fig. 3a). 62 % of the strokes appeared above the water. We found that the pre-stroke processes of winter lightning leading to high peak current discharges lasted, on average, only 1.7 milliseconds—and in one case, as little as 220 microseconds (Fig. 3b). Such rapid lightning evolution would only be possible if the leaders propagated vertically at the highest documented average speed of about $2 \cdot 10^6$ m/s from charge centers in the thundercloud at the low average height of 3.2 km. In extreme cases, the initiation height may be as low as 500 meters above ground level. Given the size of our dataset, our results provide valuable input for modeling this hazardous winter phenomenon.

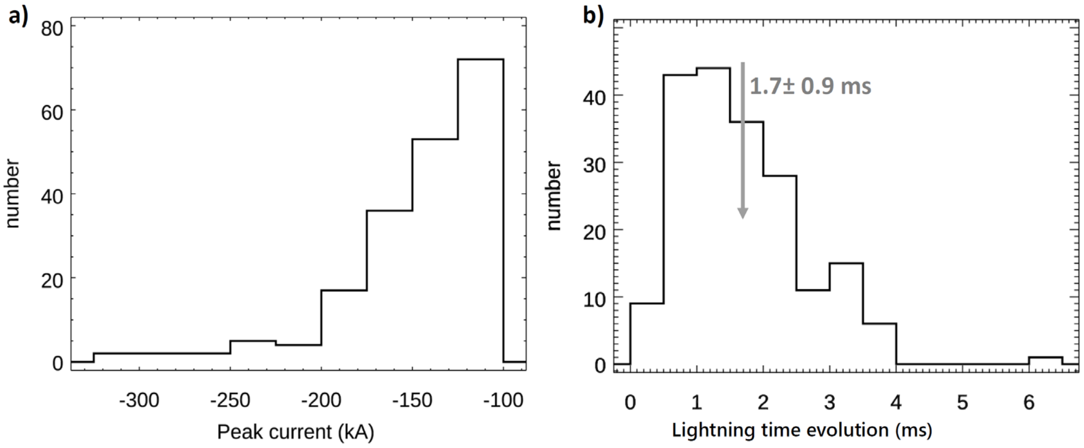

Fig. 3 a) Distribution of peak currents of 193 lighting discharges included in our study. b) Distribution of the lightning time evolution (from the first PB pulse to RS). (Fig. 1b and from Kolmašová et al., 2025).

The studies *Kolmašová et al.* [2018, paper **Nr. 4**], *Kolmašová et al.* [2019, paper **Nr. 5**], and *Kolmašová et al.* [2020, paper **Nr. 6**] were dedicated to the comparison of PB pulses identifies in the broadband records and in the narrow band VHF records. We analyzed magnetic field waveforms of PB pulses observed at time scales of a few tens of microseconds by a broadband receiver and compared these pulses with sources of narrow-band VHF radiation at 60-66 MHz recorded by two separate LMA systems [*Kolmašová et al.*, 2018, paper **Nr. 4**]. We find that almost none of the observed PB pulses correspond to geo-located VHF radiation sources (Fig. 4a), in agreement with previous results and with the hypothesis that processes generating VHF radiation and PB pulses are only weakly related [*Wilkes et al.*, 2016; *Stolzenburg et al.*, 2013]. However, our detailed analysis discovered that individual peaks of strong VHF radiation seen by separate LMA stations correspond surprisingly well to the PB pulses (Fig. 4b,c). This result shows that electromagnetic radiation generated during fast stepwise extension of developing lightning channels is spread over a large interval of frequencies. We also show that intense VHF radiation abruptly starts with the first PB pulse and that it is then continuously present during the entire PB phase of developing discharges. Similar results were obtained for attempted leaders [*Kolmašová et al.,* 2020, paper **Nr. 6**]. These interesting lightning phenomena are characterized by radio wave pulses similar to signatures of PB phase before negative cloud-to-ground flashes, but a strong positive charge layer at the bottom of the thundercloud prevents them from evolving into a return stroke that would move the negative charge from the cloud to the ground.

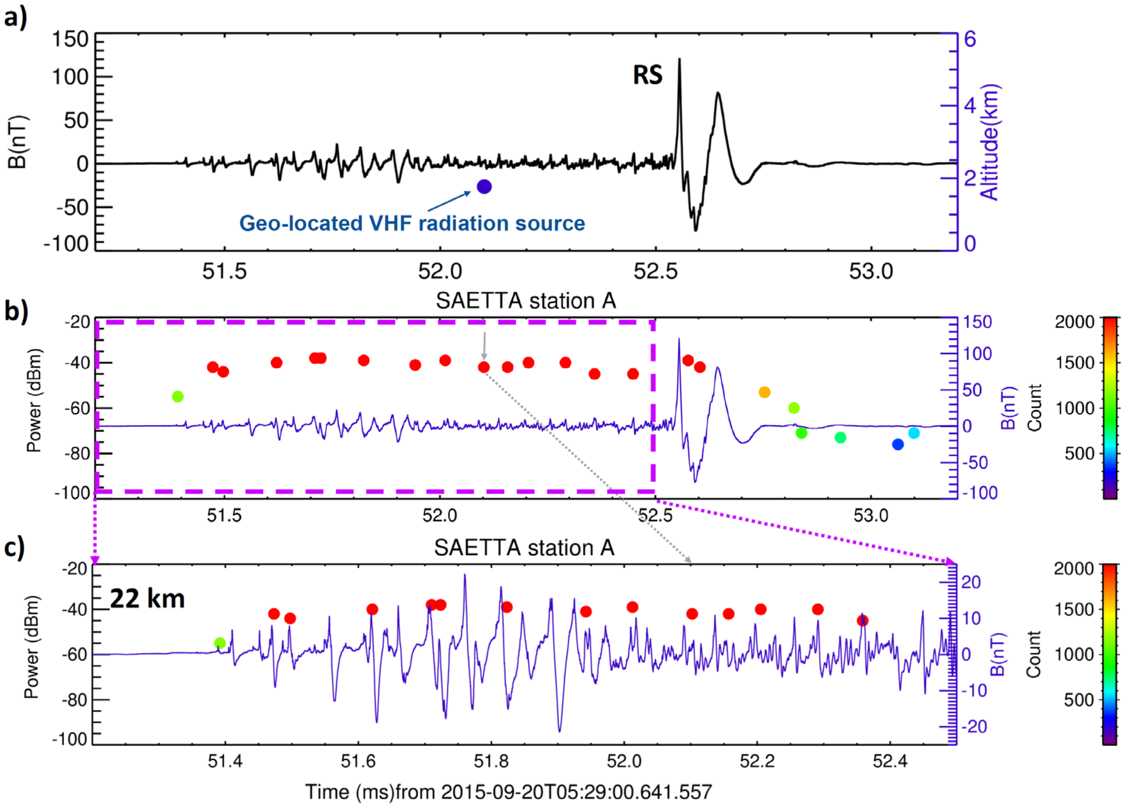

Fig. 4 *A broadband waveform showing a sequence of PB pulses and the corresponding return stroke pulse (20 September 2015, 05:29:00.7 UTC, 9.45°E, 42.80°N) with a) geo-located VHF radiation sources including their occurrence altitudes from LMA (blue dots) and b, peaks of radiated VHF power recorded at the closest station B. The dots representing the occurrence of strongest VHF peaks are color-coded by the number of intense VHF samples recorded in the corresponding 80 μs LMA windows. The power of the strongest peak of radiated VHF power in the corresponding windows is shown on the left-hand vertical axis. c) A 2-ms long detail the same PB pulse sequence with the peaks of radiated VHF power detected at station the station A. Gray arrows and lines identify the geo-located VHF radiation source occurring within the pre-stroke period of the observed discharge and peaks of radiated VHF power recorded at individual stations. (Fig. 3a,b,c from Kolmašová et al., 2018).*

We were able to verify our hypothesis, that classical IB pulses are systematically accompanied by VHF radiation, in the follow-up study [*Kolmašová et al.*, 2019, paper **Nr. 5**]. We analyzed the simultaneously sampled broadband antenna and narrowband LogRF waveforms obtained by the array of sensors, which was deployed at seven sensor sites within 45 km of Oxford, Mississippi, USA. We found that most larger-amplitude PB pulses were systematically accompanied by VHF radiation (Fig. 5).

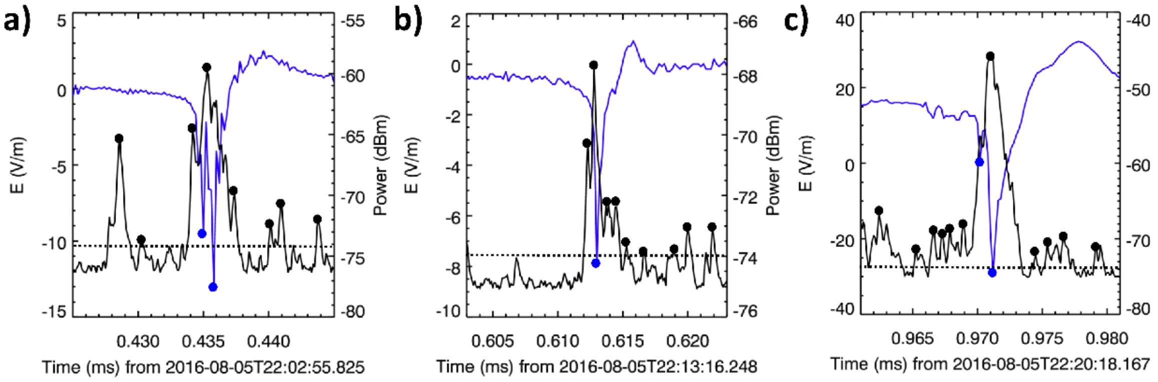

***Fig. 5** Examples of detailed view of broadband antenna and LogRF data recorded on 5 August 2016. Black curves represent the calibrated waveforms measured by the LogRF receiver, and blue curves represent the calibrated waveforms recorded by the broadband receiver. Blue and black dots identify pulse peaks chosen for the correlation analysis. Dashed horizontal lines identify the estimates of a triple the impulsive background noise in the LogRF records (Fig. 2a,b,c from Kolmašová et al., 2019).*

The meteorological context was successfully incorporated into the analysis of lightning initiation associated with energetic preliminary breakdown, helping to explain the thundercloud properties that led to the observed phenomena [*Kolmašová et al.*, 2022, paper **Nr. 7**]. The peak currents responsible for generating these strong PB pulses reached –36 kA. The initial polarity of all observed energetic PB pulses confirmed the downward movement of negative charge, consistent with PB pulses that precede negative CG discharges. Notably, the PB pulses were detected in regions with little to no lightning activity. Most were found within small, short-lived, fast-moving convective storm cells, characterized by low radar reflectivity (generally < 40 dBZ), limited vertical development, and low flash density (Fig. 6).

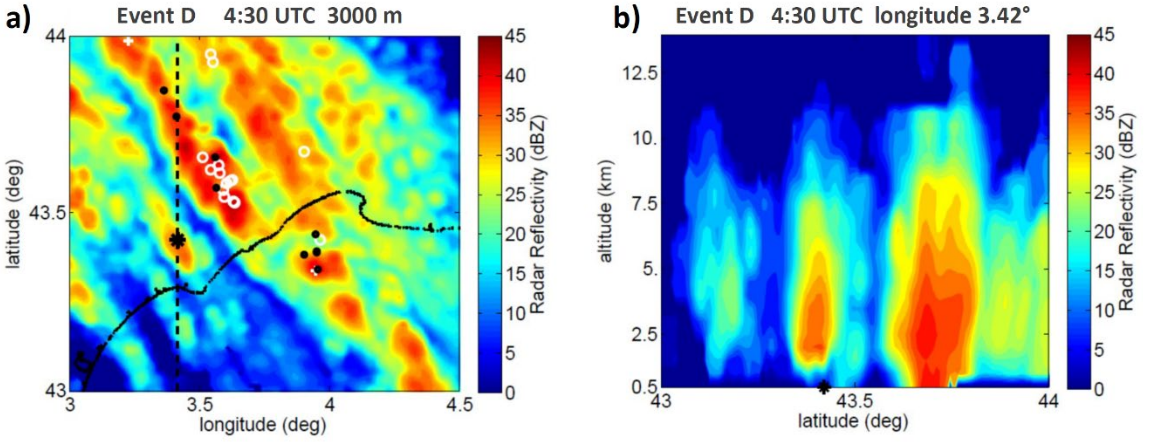

Fig. 6 *a) Horizontal cross section of radar reflectivity in dBZ at 3000 m of altitude (from several scans made over 10 minutes before the time indicated); b) vertical cross section of radar reflectivity along the dashed lines in (a). The black stars indicate the PB pulses location. The strokes (pulses) detected by EUCLID over 10 minutes (04:20 - 04:30 UTC) are displayed by white circles for CGs, and black dots for IC (Fig. 5e,f from Kolmašová et al., 2022).*

Our findings suggest that these thunderstorms possessed an atypical charge configuration composed of a temporarily strongly negative charge pockets situated above a low-level region of strong positive charge.

3.2.2 Inter-stroke and post-stroke incloud processes

A systematic analysis of the properties of unexpectedly regular microsecond-scale electromagnetic pulse sequences [*Kolmašová & Santolík*, 2013, Paper **No. 1**] drew renewed attention to this underexplored phenomenon, following a long gap since the last publication on the topic [*Rakov et al.*, 1996]. We found that the observed trains contained several tens of pulses and the time interval between neighboring pulses typically varied between 1 and 10 microseconds. The inter-pulse interval was usually increasing (on average by 4.1 μs during a train) and the pulse amplitude is decreasing (on average by 15% of the maximum value within a given train). The pulses were believed to originate inside the cloud being emitted by processes occurring between the strokes in CG or IC flashes. We tentatively explained the sequential decrease of the amplitude of the pulses by the decrease of the speed of the leader propagation.

Thanks to the simultaneous measurements of the SLAVIA sensors and the radio telescope LOFAR, we were able to reveal the origin of processes producing microsecond scale pulses [*Kolmašová et al.*, 2023, paper **Nr. 9**]. Four investigated pulse trains occurred during complicated intracloud flashes on 18 June 2021, when heavy thunderstorms hit the Netherlands. By precisely aligning the timestamps of the two simultaneously operating observational systems, we found that the regular broadband pulses corresponded exactly with localized, isolated bursts of energetic VHF radiation detected by LOFAR (Fig. 7).

The 3D mapping of these radio sources enabled us to place the observed events within the context of the parent intracloud lightning flash. The results revealed negative intracloud dart stepped leaders propagating at a lower speed than usual dart leaders along preconditioned channels originally formed by earlier positive or negative intracloud leaders occurring within the same flash several tens of milliseconds before the reported observations. We propose that this atypical stepping may require a favorable combination of the conductivity of the preexisting lightning channels and the strength of the ambient electric field within the thundercloud.

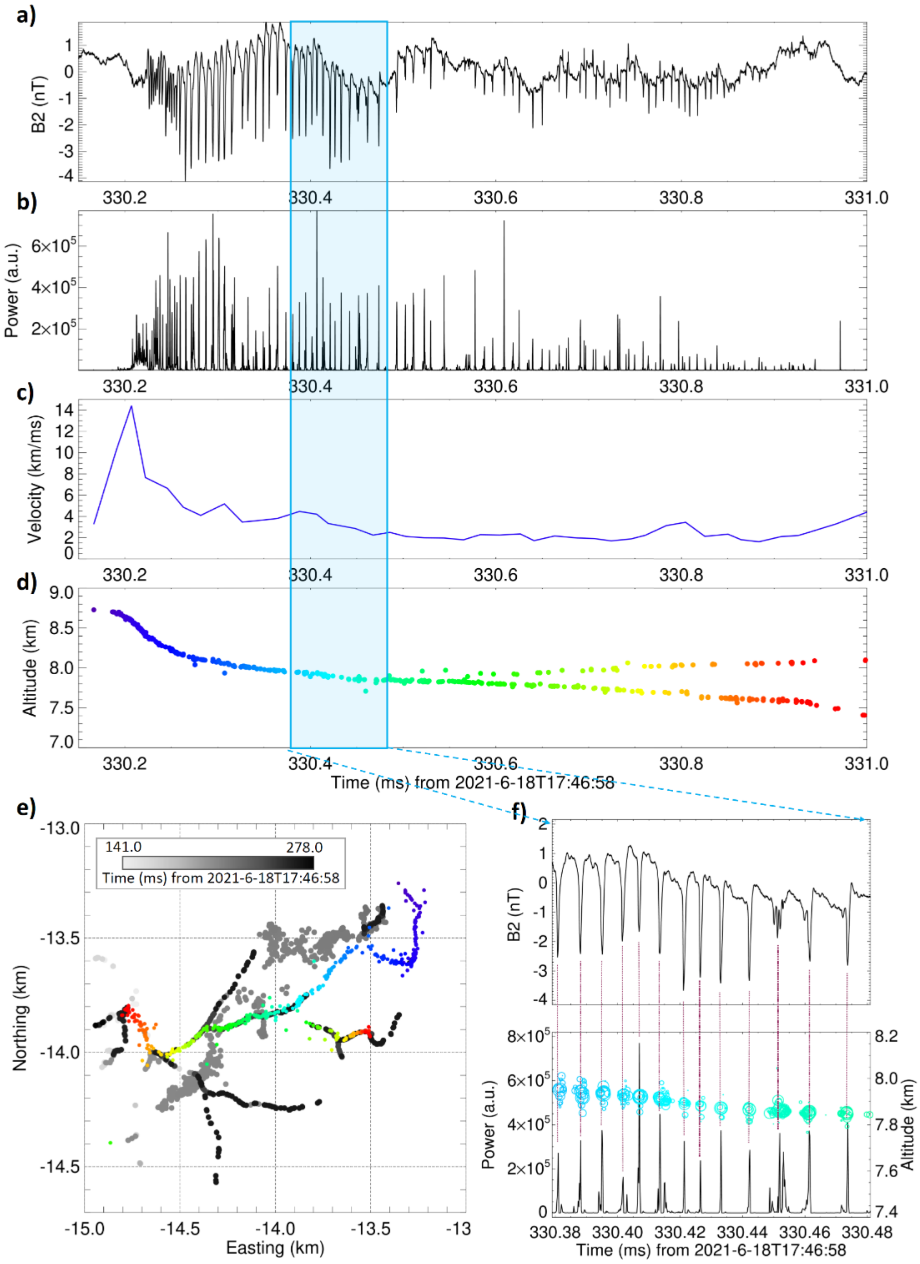

***Fig.** 7 a) Magnetic field pulse train measured by the SLAVIA 2 antenna on 18 June 2021. b) VHF power detected at the same time by the LOFAR antenna CS002. c) Average* *velocity of the leader movement. d) Sources of VHF radiation located by the LOFAR impulsive imager. e) A map showing a development of the flash before the pulse train was observed (in grey scale) and the leader propagation during the pulse train (color scale). f) Detail of the magnetic field waveform together with VHF power peaks and VHF sources imaged by the LOFAR TRI-D imager. The detail is marked in panel a) by a blue rectangle. (Fig. 1 from Kolmašová et al., 2023).*

2.2 Large-scale lightning processes

Large-scale lightning processes offer a window into the dynamic coupling between the Earth's atmosphere, weather, and space environment. Global climatic events drive changes in lightning patterns, which are reflected in shifts in storm locations and changes in their intensities. Transient luminous events such as sprites and elves, occurring above thunderstorms, and lightning-generated whistlers, propagating through the ionosphere into the magnetosphere, demonstrate the influence of lightning on the upper atmosphere

2.2.1 Lightning reflecting the climatic phenomena

Lightning activity reflects broader climatic trends, often increasing with warmer temperatures and higher humidity. A significant increase of polar lightning is expected due to global warming [*Holzworth et al*., 2021].

We contributed to these efforts [*Kolmašová et al.*, 2022, paper **Nr. 15**] by uncovering an enormous amount of lightning that hit Northern Europe in winter 2014/2015. For this study, we used the database of the global network WWLLN [*Hutchins et al*., 2012a,b]. The number of lightning strokes was about four times larger than the long-term median calculated over the last decade. Lightning was concentrated above the ocean close to the western coastal areas (Fig. 8a). We showed for the first time that winter superbolts [*Holzworth et al.*, 2019] with radiated electromagnetic energies above one mega joule appeared at night and in the morning hours, while the diurnal distribution of all detected lightning was nearly uniform (Fig. 8b). This is very different from usual summer thunderstorms, where most lighting occurs in the local afternoon. We figured out that a combination of the significant positive phase of North Atlantic Oscillation (NAO) and the transition from cold to warm phase of El Niño, two global climate events occurring throughout the analyzed period, was probably responsible for an increase of the sea surface temperature and for significantly stronger updraft velocities. A resultant very effective thundercloud charging then lead to observed enormously intense and energetic winter lightning activity.

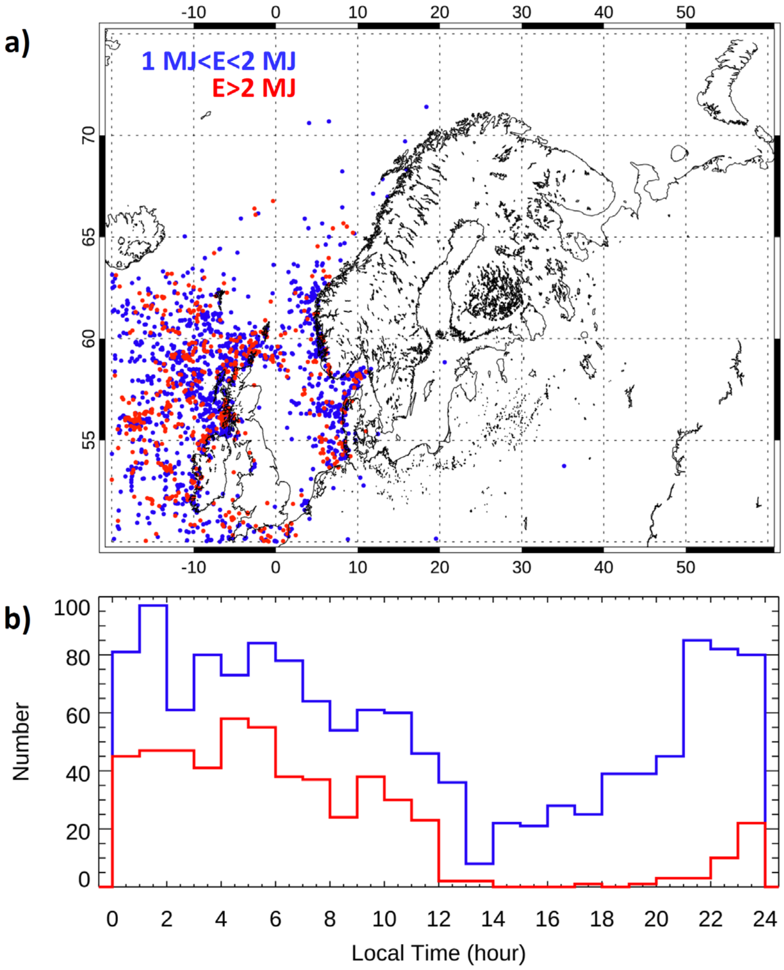

Fig. 8 *a) Spatial distribution of superbolts (strokes with energies between 1and 2 MJ and above 2 MJ are respectively represented by blue and red color). b) Temporal distribution of superbolts as a function of the local time (Figs. 4a,b from Kolmašová et al., 2022).*

2.2.2 Transient luminous events

Investigating the source lightning of transient luminous events through their electromagnetic signatures is key to understanding how these high-altitude phenomena are initiated. By analyzing the timing, polarity, and intensity of lightning generated radio waves—particularly in the VLF and ELF ranges—the specific strokes responsible for triggering TLEs can be identified and analyzed. This enables precise characterization of the parent lightning and reveals the conditions and mechanisms behind the formation of sprites, elves, and jets, highlighting the electrical connection between thunderstorms and the upper atmosphere

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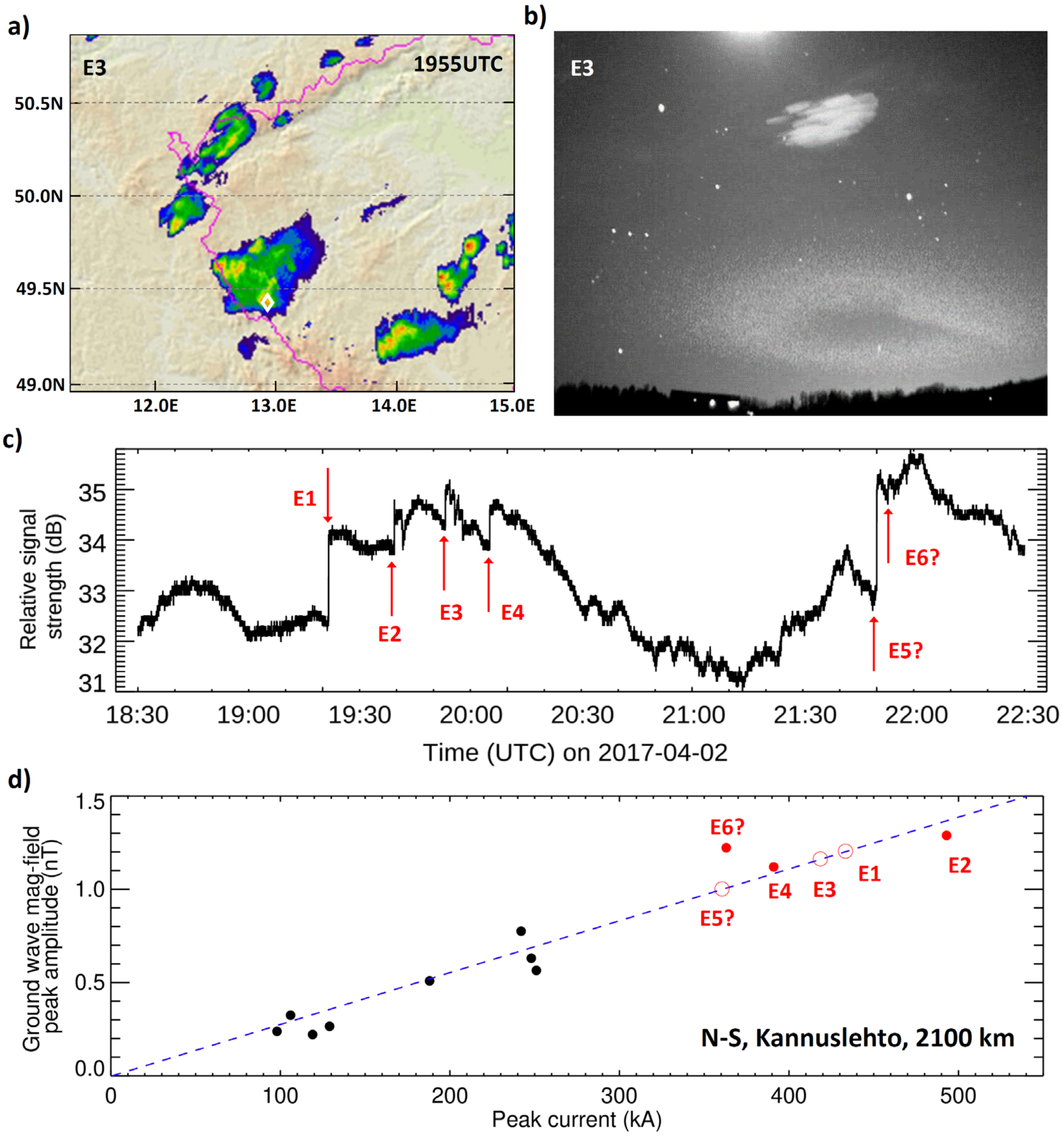

Fig. 9 a) *Weather radar plots from 2 April 2017 19:55 UTC provided by the CZRAD network operated by the Czech Hydrometeorological Institute. A white diamonds corresponds to the location of the causative stroke for elves E3. b) Picture of elves E3 by the Watec 910HX camera in Nýdek (Czechia) at a distance of 430 km from the thunderstorm. c) The intensity of the DHO38 transmitter signal recorded by the narrowband VLF receiver in Bojnice (Slovakia). The abrupt drops in the signal intensity correspond to elves E1-E4 and optically missed elves E5 and E6. d) Ground wave peak amplitudes of all positive return strokes (Ip >100 kA) measured at Kannuleshto station in Finland as a function of the peak currents provided by EUCLID. The blue dashed line represents a linear regression line without elves producing strokes. The red open circles marked E1, E3 and E6 show current estimates for known magnetic* *field peak amplitudes. Red bullets show the strokes for which both the peak currents and VLF waveforms were available (from Figs. 2c, 3c, 4b, and 5c from Kolmašová et al., 2021).*

The multi-instrument observation [*Kolmašová et al.*, 2021, paper **Nr. 14**] revealed that elves (Emissions of Light and Very low frequency perturbations due to Electromagnetic pulse Sources) can be produced also by a small-scale thunderstorm (Fig. 9a). An unusual small-scale continental thunderstorm—the first of 2017 in Czechia—occurred in spring with a Convective Available Potential Energy (CAPE) of 375 kJ/kg, over three times the typical April value. Accompanied by above-average afternoon temperatures and winter-like cloud tops reaching 9.5 km, the storm produced an exceptionally high proportion (55%) of positive cloud-to-ground return strokes with a mean peak current of 64 kA. The peak currents of return strokes associated with elves (Fig. 9b) exceeded ~300 kA. All electromagnetic observations including the changes of the intensity of the military VLF transmitter DHO38 (Fig. 9c) aligned with four optically detected elves and strongly suggested the occurrence of two additional elves during the storm's decaying phase. Interestingly, the same measurements showed that other strong lightning strokes did not produce any elves. Our finding contradicted the generally accepted peak current threshold of approximately 90 kA required for elves generation [*Blaes et al.*, 2016].

Our modeling showed that elves formation is influenced not only by the peak current of the causative strokes but also by factors such as lightning channel conductivity, the velocity of current wave fronts, and the sharpness of the ionospheric boundary. We hypothesize that the absence of elves associated with peak currents below 300 kA may be due to less conductive return stroke channels and/or slower current waves in the investigated thunderstorm. Moreover, our study demonstrated that distant VLF measurements (Fig. 9d) could be highly useful for estimating peak currents in cases where commercial lightning location networks fail.

3.2.3 Lightning generated whistlers

Lightning-generated whistlers are electromagnetic waves in the VLF range produced by lightning strokes. These waves are not only key indicators of lightning activity but also serve as valuable diagnostic tools for studying the ionosphere and magnetosphere. By analyzing their propagation characteristics, we can infer the details about electron density, the presence of field-aligned density structures (ducts), and the dynamics of wave-particle interactions. In this field, we combined the thesis author's background in atmospheric electricity with O. Santolík's expertise in satellite-based measurements of plasma waves. This collaboration resulted in two publications [*Santolík et al.*, 2021a, b, papers **Nr. 12** and **Nr. 13**].

In the study by *Santolík et al.* [2021a, paper **Nr. 12**] we assisted in the exploration of the role of lightning whistlers in generation of plasmaspheric hiss known as a shaping agent for the Earth radiation belts. In our case study, we aimed at finding sources of hiss observed close to the geomagnetic equator in the outer plasmasphere on the dayside using the measurements of the fleet of Cluster spacecraft. We found hiss to be triggered by whistlers of different spectral properties (Fig. 10). Positions of causative lightning discharges were identified through time coincidences with data from WWLLN within three active thunderstorm regions in Europe. Our analysis showed that subionospheric propagation of lightning atmospherics is needed to explain the observations and that geographic locations of the ionospheric exit point then determine spectral properties of resulting unducted whistlers and triggered hiss. This well-documented chain of events, from a lightning discharge in the atmosphere to magnetospherically reflected whistlers, supports the conclusion that such processes are among the possible sources of plasmaspheric hiss.

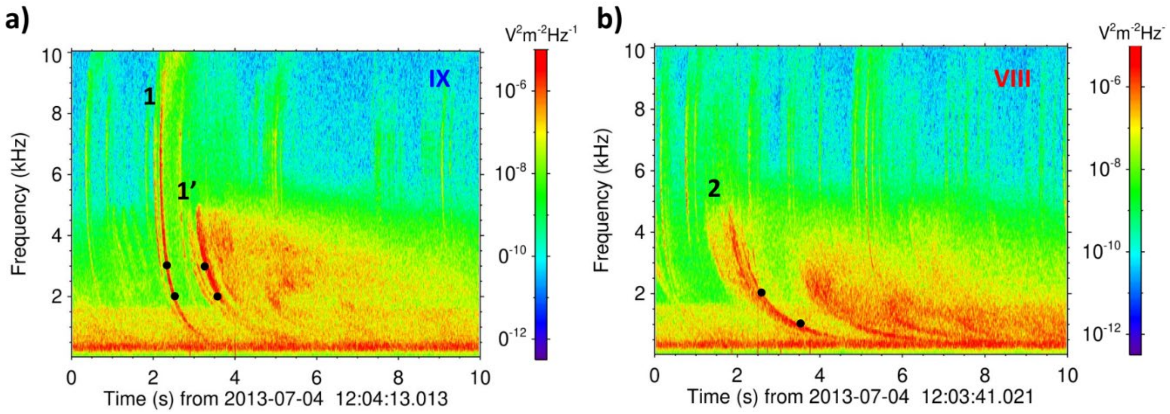

***Fig. 10** Examples of two whistlers with different spectral properties shown in 10 s intervals of the electric field power spectral density obtained from spectral analysis of waveform data recorded by Cluster 3. Black dots show time delays and frequencies that we use to calculate whistler dispersions for three types of traces: 1, 1' and 2 (Figs 2b,c from Santolík et al., 2021a).*

Electromagnetic signals emitted by lightning discharges in the form of whistlers are also an ideal tool for validating the performance of satellite radio receivers. Specifically, knowing the time, location, and energy of the source lightning for an observed whistler allows us to cross-calibrate measurements from instruments on different spacecraft, assuming they detected the same whistler (*Santolík et al*., 2021b, paper **Nr. 13**).

In rare cases, the whistlers travel within a density tube (also known as a duct) that surrounds a magnetic field line connecting both hemispheres. In such a duct, the signal from the lightning discharge travels between the hemispheres, repeatedly reflecting from the top of the ionosphere, with part of its energy potentially passing back through the ionosphere to the Earth's surface. If a receiving station is located near the entrance of the density tube, the station’s recordings will show a series of whistlers with progressively lower and lower tones [*Laaspere et al*., 1965].

On January 3, 2017, two key conditions—intense lightning activity and the presence of a magnetospheric plasma duct—enabled the observation of numerous whistler echo trains (Fig. 11) at the high-latitude station in Kannuslehto, Finland [*Kolmašová et al*., 2024, paper **Nr. 16**] for nearly eight hours. In this study, we focused on the characterization of lightning strokes, which were responsible for observed whistler echoes.

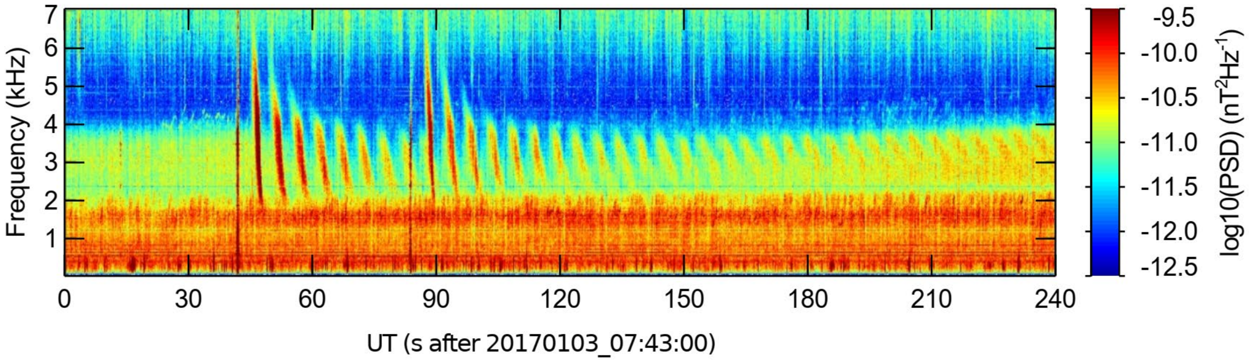

Fig. 11 *Frequency-time spectrograms showing two overlapping whistler echo trains recorded on January 3, 2017. The color represents the logarithm of the Power Spectral Density (PSD) in* nT^2Hz^{-1}*. The dark red vertical lines, spanning over the entire frequency band and initiating each group of dispersed signals, are attributed to sferics emitted by lightning return strokes, which triggered the echo trains. Weaker broadband impulsive signals extending from the top of the spectrograms correspond to sferics emitted by distant lightning (Fig. 1c from Kolmašová et al., 2024).*

We identified three distinct winter thunderstorms as sources of the causative lightning sferics: a compact storm along the Norwegian coast, which generated energetic discharges capable of triggering echo trains in 50% of cases, and two unexpectedly distant storms located in the Mediterranean region. These findings demonstrate that intense thunderstorms can repeatedly inject electromagnetic energy into a magnetospheric duct, producing whistler echo trains after subionospheric propagation over distances of up to 4000 km.

Our analysis suggests that it is crucial to study winter storms and focus on lightning discharges occurring at higher latitudes, as they can generate whistler echo trains and are therefore ideal tools for exploring density ducts.

3.3 Jovian lightning

Lightning on Jupiter is a significant phenomenon. Atmospheric convection, driven by the planet's internal heat, generates storms that produce electrical discharges, which in turn radiate electromagnetic energy into space. Analyzing these signals improves our understanding of the atmosphere-ionosphere-magnetosphere coupling, and tells us how electromagnetic waves propagate through the Jovian plasma environment. In a broader context, the research of Jovian lightning allows us to compare lightning processes across planets in our Solar system.

Since NASA's Voyager 1 spacecraft flew past Jupiter in March of 1979 [*Gurnett et al.*, 1979; *Kurth et al.,* 1985], scientists have wondered if the radio-signature bandwidth for Jupiter's lightning was much narrower than that of lightning found on the Earth. It changed by the arrival of the NASA Juno probe to Jupiter in 2016, when Microwave Radiometer (MWR) instrument surprisingly recorded lightning related emissions from the giant gas in the hundreds of MHz frequency range [*Brown et al.*, 2018, paper **Nr.19**].

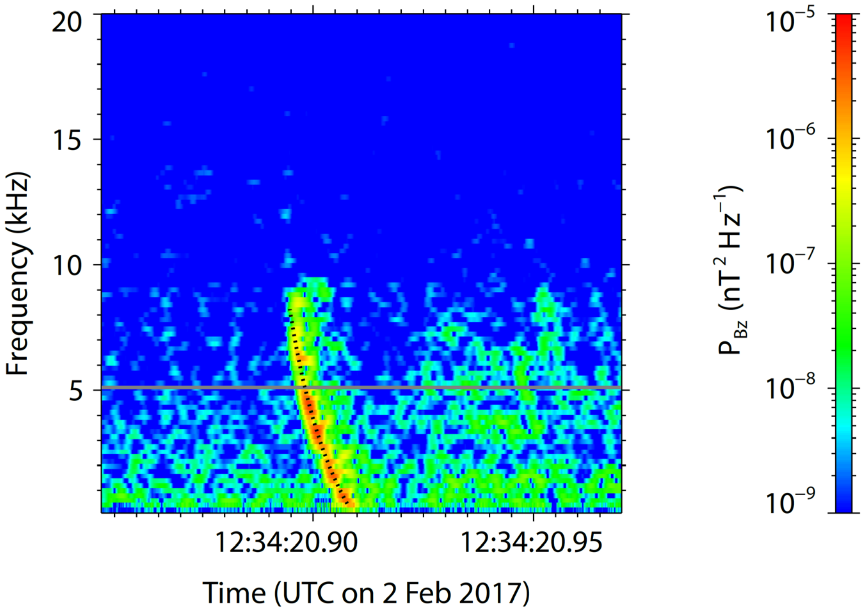

Fig. 12 *Frequency–time power spectrogram of the magnetic field fluctuations showing the rapid whistler measured on 2 February 2017 after 12:34:20 UTC at an altitude of 25,100 km above the 1 bar level. The horizontal grey lines show the local proton cyclotron frequency calculated from measurements of the vector magnetometer instrument (Connerney et al., 2017). The black dotted lines were calculated from a field-aligned propagation model of electromagnetic waves in a cold plasma. (Fig. 1a from Kolmašová et al., 2018).*

A simultaneously conducted and published study [*Kolmašová et al.*, 2018, paper **Nr. 18**] presented the largest database of lightning-generated whistlers from Jupiter to date. This data set of more than 1,600 signals, collected by Juno's Waves instrument, was almost ten times the number recorded by Voyager 1. These whistlers exhibited about 100 times smaller frequency dispersion than the whistlers detected by Voyager 1. Because of this extremely short dispersion, we named this newly discovered phenomenon "rapid whistlers" (Fig. 12). Peak rates of four lightning strikes per second were detected, which is similar to the rates observed in thunderstorms on Earth, and six times higher than the peak values detected by Voyager 1. Both studies confirmed the absence of lightning in the equatorial region and significant lightning activity in the mid-latitudes or near Jupiter's poles. This lightning distribution follows the planet's internal heat source, which is very different from Earth, where thunderstorms are driven by the Sun and thus peak in the tropics. We were unable to explain a visible prevalence of lightning in the Northern hemisphere.

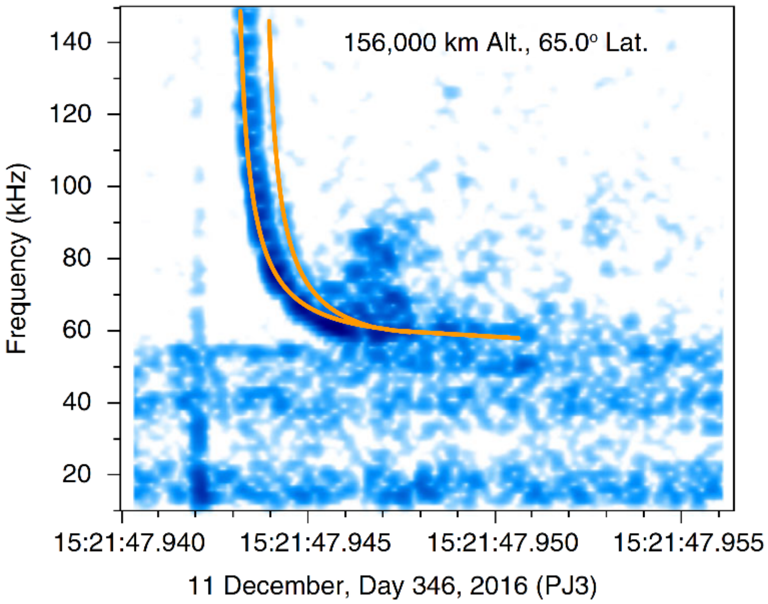

Fig. 13 *Frequency–time power spectrogram of the electric field fluctuations showing an example of a Jupiter dispersed pulse examples of Jupiter dispersed pulse). The orange curve is fitted assuming the ordinary mode wave propagation (Fig. 1a from Imai et al., 2019).*

We also reported another discovery associated with Jovian lightning, revealed thanks to the Juno planetary probe measurements close to the planet. Millisecond-scale dispersed electric field pulses (Fig. 13) were detected by the Juno Waves instrument during its polar perijove passes [*Imai et al.*, 2019, paper **Nr. 20**]. We named these signals Jupiter Dispersed Pulses (JDPs). Their presence provided direct evidence of low-density

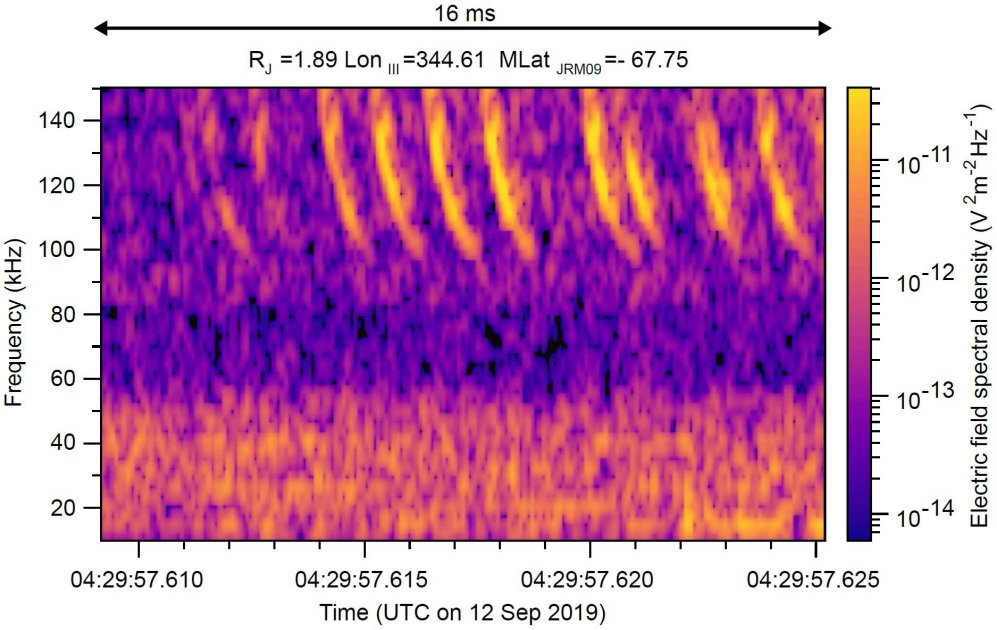

Fig. 14 *Frequency–time power spectrograms of the electric field fluctuations showing a snapshot recorded on 12 September 2017 after 04:29:57 UTC. The Juno probe was located above Jupiter's southern hemisphere at a distance of just under 64,000 kilometers above its surface (Fig. 1a from Kolmašová et al., 2023).*

regions—'holes'—in Jupiter's nightside ionosphere, with electron densities ≤ 250 cm^{-3}, assuming the maximum delay occurs near the free-space ordinary mode cutoff frequency.

Using the unprecedentedly high temporal resolution provided by the Waves receiver, we were able, for the first time, to investigate the fine structure of lightning processes on Jupiter at sub-millisecond timescales [*Kolmašová et al.*, 2023, paper **Nr. 22**]. We identified Jovian radio pulses typically separated by about one millisecond (Fig. 14). This pattern suggests step-like extensions of lightning channels, with steps ranging from several hundred to a few thousand meters, indicating a similarity between the initiation processes of Jovian lightning and terrestrial intracloud lightning.

SUMMARY

Our work has made significant contributions to the understanding of lightning processes across multiple scales. These results were achieved through comprehensive analysis of electromagnetic data from a variety of sources, including both ground-based and satellite observations. By combining broadband and narrowband electromagnetic data with complementary measurements (optical, meteorological, and particle-based), we constructed a detailed and integrated picture of the studied phenomena.

Using our methods, we explored the regions inside, below, and above thunderclouds, and investigated how lightning patterns change in response to climatic events. Furthermore, we examined the coupling between the atmosphere, ionosphere, and magnetosphere—both on Earth and on Jupiter.

The most important results include:

- The discovery of rapid whistlers generated by lightning in Jupiter's atmosphere
- The discovery of low-density holes in Jupiter's ionosphere
- The discovery of step-like evolution of Jovian lightning
- A substantial contribution to the investigation of lightning initiation through analysis of electromagnetic waves
- The first detection of elves and their causative, extremely powerful lightning discharges in a small-scale continental thunderstorm
- Observations of disruptions in lightning weather patterns due to large-scale climatic effects

A selected set of 22 papers published in refereed journals highlights the vitality of our research and clearly demonstrates both the potential and the challenges for future investigations in all three of the explored research domains.

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