

1 **Different types of corona discharges associated with**
2 **high-altitude positive Narrow Bipolar Events nearby**
3 **cloud top**

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18 **Key Points:**

- 19 • Corona discharges are found to be associated with unusual high-altitude positive
20 narrow bipolar events nearby cloud tops.
- 21 • Corona discharges are classified into different types according to their different op-
22 tical and radio features.
- 23 • The detailed features of corona discharges and their parent thundercloud are es-
24 timated using different theoretical models.

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Abstract

Single- and multi-pulse blue corona discharges are frequently observed in thunderstorm clouds. Although we know they often correlate with Narrow Bipolar Events (NBEs) in Very Low Frequency/Low Frequency (VLF/LF) radio signals, their physics is not well understood. Here, we report a detailed analysis of different types of blue corona discharges observed by the Atmosphere-Space Interactions Monitor (ASIM) during an overpass of a thundercloud cell nearby Malaysia. Both single- and multi-pulse blue corona discharges were associated with positive NBEs at the top of the cloud, reaching about 18 km altitude. We find that the primary pulses of multi-pulse discharges have weaker current moments than the single-pulse discharges, suggesting that the multi-pulse discharges either have shorter vertical channels or have weaker currents than the single-pulse discharges. The subsequent pulse trains of the multi-pulse discharges delayed some milliseconds are likely from horizontally oriented electrical discharges, but some NBEs, correlated with both single- and multi-pulse discharges, include small-amplitude oscillations within a few microseconds inside their waveforms, which are unresolved in the optical observation and yet to be understood. Furthermore, by jointly analyzing the optical and radio observations, we estimate the photon free mean path at the cloud top to be ~ 6 m.

Plain Language Summary

Recent studies indicate that the blue corona discharges detected by the Atmosphere-Space Interactions Monitor (ASIM) onboard the international space station have close association with a special type of intracloud discharges named Narrow Bipolar Events (NBEs). In this study, we present a detailed analysis of different types of NBE-associated corona discharges detected by both optical and radio observations. All the detected corona discharges are found to be associated with unusual high-altitude positive NBEs, which located a few kilometers below the cloud top where the cloud droplets have low impact on the optical observation. This allowed us to infer the physical properties of them and their parent thundercloud by using theoretical models. The results can provide important reference to further investigate the physical mechanism of corona discharge and their role in lightning initiations.

1 Introduction

Blue Luminous Events (BLUEs) are special Transient Luminous Events (TLEs) associated with thunderclouds that radiate intense near-ultraviolet blue optical emissions dominated by 337 nm with weak or absent signals in the atomic oxygen line at 777.4 nm. They have also been termed as blue corona discharges in the recent studies (Soler et al., 2020, 2021, 2022; Li et al., 2021; Dimitriadou et al., 2022; Husbjerg et al., 2022; F. Liu, Lu, et al., 2021; F. Liu, Zhu, et al., 2021). They have similar features with different phenomena in other studies, such as blue starters/blue jets (Wescott et al., n.d., 2001; Kuo et al., 2005; Edens, 2011), Blue Luminous Events (BLEs) (Chou et al., 2011, 2018; F. Liu et al., 2018), *glimpses* (Chanrion et al., 2017) and *gnomes* (also called *Pixies*) (Lyons et al., 2003). These optical signals normally last a few to hundreds of milliseconds and appear either isolated or in groups in the active thunderstorms, especially those with overshooting cloud tops and they occurred at the global frequency about 11 s^{-1} at local midnight (Soler et al., 2021; Edens, 2011; Lyons et al., 2003; Chou et al., 2018; Li et al., 2021; Chanrion et al., 2017; Husbjerg et al., 2022; Dimitriadou et al., 2022; F. Liu, Lu, et al., 2021; F. Liu, Zhu, et al., 2021; Li, Neubert, et al., 2022).

Recently, corona discharges have attracted a lot of attention due to their close correlation with a special type of intracloud discharges named Narrow Bipolar Events (NBEs) identified from the Very Low Frequency/Low Frequency (VLF/LF) radio signals. NBEs (also called Narrow Bipolar Pulses (NBPs) or Compact Intracloud Discharges (CIDs)) (Smith et al., 1999; Nag & Rakov, 2010a,b; Leal et al., 2019) are bipolar-shaped pulses with a duration

of tens of microseconds, fast velocity $\sim 10^7$ - 10^8 m/s and strong Very High Frequency (VHF) radiation (Le Vine, 1980; Rison et al., 2016).

NBEs can be either positive or negative based on the polarity of first initial half cycle in its waveform (Willett et al., 1989). The majority of positive NBEs are located at median heights about 13 km between the main negative and upper positive charge regions (Wu et al., 2012, 2014; Smith et al., 1999, 2004; Karunarathne et al., 2015), while the negative NBEs predominantly occur at higher altitudes 14 km to 20 km between the main positive charge region and the screening negative layers (Smith et al., 1999, 2004; Wu et al., 2012, 2014; Leal et al., 2019; Ahmad et al., 2017a). However, some negative NBEs are also found to occur at lower altitudes, from 4 km to 8 km (Bandara et al., 2019), and a few cases of positive NBEs are also reported to occur at lower altitudes from 5 km to 10 km (Wu et al., 2014). Additionally, the altitudes of positive NBEs might be even higher than 16 km, when they are associated with convective surges overshooting the tropopause (Nag & Rakov, 2010a,b; Jacobson & Heavner, 2005; Jacobson et al., 2007).

NBEs can occur either individually isolated from other lightning discharges within tens of milliseconds (Le Vine, 1980; Smith et al., 1999; Rison et al., 2016; Kostinskiy et al., 2020) or as the lightning initiation event (Nag & Rakov, 2010a; Wu et al., 2011, 2014; Rison et al., 2016; Karunarathne et al., 2015; Lyu et al., 2019; López et al., 2022), or sometime localized in groups (Bandara et al., 2021). The nature of NBEs, and their relation to the formation of the lightning leader is still poorly understood; however, it may provide further insight into the most important problem in lightning physics: the initiation of lightning inside thunderstorms (Rison et al., 2016). Recent observations connected NBEs with a new type of discharge, called fast breakdown (FB), suggesting that NBEs are produced by a system of streamer coronas without a conducting channel or leader involved (Rison et al., 2016; Tilles et al., 2019; Lyu et al., 2019), which is further supported by the recent studies of the NBEs-associated BLUEs detected by ASIM (Soler et al., 2020; Li et al., 2021; Li, Luque, Lehtinen, et al., 2022; F. Liu, Lu, et al., 2021; Li, Neubert, et al., 2022).

In this study, we present a detailed analysis of the different types of corona discharges observed by ASIM during its overpass of an active thundercloud near Malaysia. The BLUEs are found to be associated with unusual high-altitude positive NBEs nearby a deep convective cloud top where the cloud droplets have low impact on the optical observations. This allows us to estimate detailed features of the corona discharges by jointly analyzing the optical and radio observations.

2 Instruments and Observations

Since April 2, 2018, the Modular Multispectral Imaging Array (MMIA) of the Atmosphere-Space Interactions Monitor (ASIM) onboard the International Space Station (ISS) has provided important insights into Earth thunderstorms from space (Chanrion et al., 2019; Neubert et al., 2019). It includes three photometers with temporal sampling rate at 10^5 samples/s including one in the UV band at 180 - 230 nm, while the other two are associated with the cameras, in the near-UV at the strongest spectral line of the second positive system of Nitrogen, N_22P (337 nm) and in the strongest lightning emission band, OI (777.4 nm), respectively. The spatial resolution of the cameras on the ground is around $400\text{ m} \times 400\text{ m}$ with 12 frames per second.

On the evening of April 30, 2020, 21 Blue Luminous Events (BLUEs) were observed by ASIM when it passed over a thundercloud cell nearby Malaysia during the time period from 17:49:55 to 17:50:55 UTC. All these BLUEs are only detected in the 337 nm photometer and camera, with no or weak signals in the 180 - 230 nm photometer nor in the 777.4 nm photometer and camera. Among them, 16 BLUEs were captured by both photometers and their corresponding cameras of MMIA, other 5 BLUEs were only captured by the photometers of MMIA without the corresponding camera images. Figure 1 shows the distribution of

125 the cloud-to-ground (CG)/intracloud (IC) lightning and 21 BLUES (16 with camera images
 126 (green square) and 5 without camera images (pink square)) superimposed on the Cloud Top
 127 Height (CTH, in *km*) provided by the Fengyun-4A (FY-4A) satellite (Yang et al., 2017) at
 128 the time 17:50:00 UTC (a) and the zoom of its black-dotted rectangular region (b), as well
 129 as the 337 nm images detected by MMIA in the zoom region (c). During the BLUE occurred
 130 time, there were a total of 20 lightning events with 11 CGs (red dots) and 9 ICs (red crosses)
 131 reported by the ground-based Vaisala GLD360 global lightning network (Said & Murphy,
 132 2016) in the zoom region of Figure 1(b). The total number of lightning events at the zoom
 133 region, shown in figure 1(d), started to increase around 15:00 UTC, then peaked at the time
 134 around 17:50 UTC when ASIM passed over. The BLUES are accompanied by the highest
 135 concentration of IC and CG lightnings. The geolocations (latitude and longitude) of the 16
 136 BLUES are based on the 337 nm images detected by MMIA. For the 5 BLUES without the
 137 corresponding camera images, we use the meta data of 337 nm camera images to find their
 138 geolocations. Note that the final geolocations of all the BLUES have been projected to the
 139 cloud top (about 18 km) with a horizontal uncertainty of less than 10 km (Husbjerg et al.,
 140 2022; Bitzer et al., 2021; Li, Neubert, et al., 2022).

141 The broadband VLF/LF magnetic field sensor operates at 400 Hz to 400 kHz located
 142 at Universiti Teknikal Malaysia Melaka (UTeM), Malacca, Malaysia (Zhang et al., 2016;
 143 Ahmad et al., 2017b) (see the yellow star in figure 1(a)). In our case, the time shift for
 144 MMIA with respect to the ground-based VLF/LF measurements is within -15 ± 0.6 ms (see
 145 Figure S1 in Supplemental Material).

146 3 Methodology

147 3.1 Light-Scattering Model

148 To simplify the modeling, we assume the corona discharges are impulsive and point-like
 149 sources inside a homogeneous isotropic cloud. We fit the 337 nm photometer signal of MMIA
 150 based on the first-hitting-time model proposed by Soler et al. (2020) to infer the depth L
 151 (relative to the cloud top). The photon flux emitting from the cloud top with the time t_0
 152 being the moment of light emission:

$$153 \quad f(t) = A \left(\frac{\tau}{t - t_0} \right)^{3/2} \exp(-\tau/(t - t_0) - \nu(t - t_0)), \quad (1)$$

154 where A is the fitting constant, ν is the collision rate, τ is the characteristic time of diffusion
 155 for the depth L between the source and the cloud top. By fitting the 337 nm photometer
 156 signal of MMIA, one can obtain the values of the parameters A , t_0 , ν and τ .

157 The mean free path Λ with a uniform population of droplets is approximated according
 158 to the equation 7 in Thomson & Krider (1982):

$$159 \quad \Lambda \approx \frac{1}{2\pi r^2 N_d}, \quad (2)$$

160 where $r = 20 \mu\text{m}$ is the particle radius and $N_d = 1 \times 10^8 \text{ m}^{-3}$ is the particle number density
 161 (Soler et al., 2020; Luque et al., 2020).

162 The depth L can be estimated as:

$$163 \quad L \approx \sqrt{4\Lambda c\tau / (3(1 - g))} \quad (3)$$

164 where $g = 0.87$ is the scattering asymmetry parameter and c is the speed of light.

165 3.2 Electromagnetic Radiation Model

166 In the simulation, we assume the source of corona discharge as a vertical dipole located
 167 at an altitude of H away from observer at a distance of R . The ground is assumed to be

168 perfectly conducting since the corona discharges in our case occurred above the ocean. The
 169 magnetic field dB_ϕ for a dipole source is proposed by Uman et al. (1975) and given by:

$$170 \quad d\vec{B}_\phi(\vec{R}, t) = \frac{\mu_0 dz'}{4\pi} \sin \theta \left[\frac{i(z', t - R/c)}{R^2} + \frac{1}{cR} \frac{\partial i(z', t - R/c)}{\partial t} \right] \vec{a}_\phi \quad (4)$$

171 where dz' is the size of the dipole source, c is the speed of light, μ_0 is the magnetic
 172 permeability of free space, \vec{R} is the observation vector between dz' and the observer. θ is
 173 the angle between dz' and the vector \vec{R} , $\sin \theta = H/\sqrt{H^2 + R^2}$. \vec{a}_ϕ is the unit vector in ϕ
 174 direction. The current $i(t)$ is assumed to be the bi-Gaussian function:

$$175 \quad i(t) = i_0(e^{-t^2/\tau_1^2} - e^{-t^2/\tau_2^2}), \quad (5)$$

176 where i_0 is the amplitude, τ_1 and τ_2 is the rise time and the fall time, respectively.

177 The length-integrated current or current moment $M_i(t) = \int i(t)dl$, where l is the length
 178 of the lightning current, can be inferred by solving the inverse convolution problem (Cummer
 179 & Inan, 2000; Cummer, 2003):

$$180 \quad B(t) = \int_{-\infty}^{\infty} M_i(\tau)h(t - \tau)d\tau, \quad (6)$$

181 where $B(t)$ is the measured magnetic field waveform and $h(t)$ is the propagation response
 182 evaluated from the modeling results of equation (4).

183 4 Results

184 In this study, we first classify the corona discharges into two groups based on their
 185 optical features: Single-pulse BLUEs (Soler et al., 2020; Li et al., 2021) and multi-pulse
 186 BLUEs (Soler et al., 2020; Li, Luque, Lehtinen, et al., 2022). Both single- and multi-
 187 pulse BLUEs are statistically significant with their 337 nm signals above $\mu \pm 5\sigma$ level of the
 188 background noise, with absent or negligible signals in both the 180-230 nm photometer and
 189 the 777.4 nm photometer (see Appendix A for more details). For the multi-pulse BLUEs,
 190 we calculate the binned average of 15 data points (about 150 μ s) of their 337 nm photometer
 191 signals (see Appendix B for further details). Figure B1 shows that the secondary optical
 192 peaks of all the multi-pulse BLUEs are statistically significant above the standard deviation
 193 of preceding signals.

194 Both single- and multi-pulse BLUEs are associated with positive NBEs (+NBE), then
 195 by considering their corresponding radio features, we further classify the BLUEs into four
 196 different types, namely (1) single-pulse BLUEs associated with NBEs ($BLUE^S$), (2) single-
 197 pulse BLUEs associated with NBEs including secondary peaks and oscillations ($BLUE_{OSC}^S$),
 198 (3) multi-pulse BLUEs associated with NBEs and their subsequent pulse trains ($BLUE^M$)
 199 and (4) multi-pulse BLUEs associated with oscillated NBEs and their subsequent pulse
 200 trains ($BLUE_{OSC}^M$). For the cases of NBEs with and without oscillations, we estimate the
 201 existence of oscillations when the amplitudes of the subsequent radio pulses with the same
 202 polarity of the ground wave are above the 3σ level of the background noise (see Appendix C
 203 for further details). The small-amplitude oscillations within a few microseconds inside NBE
 204 waveforms are marked as ‘‘OSC’’ in the corresponding cases of both single- and multiple-
 205 pulse BLUEs in Figure C1 and C2, respectively.

206 Table 1 shows the detailed feature of the four different types of BLUEs. Among
 207 them, there are 10 single-pulse BLUEs and 11 multi-pulse BLUEs, including 4 $BLUE^S$,
 208 6 $BLUE_{OSC}^S$, 8 $BLUE^M$, and 3 $BLUE_{OSC}^M$. All the BLUEs are found to be isolated from
 209 other lightning discharges with no 777.4 nm emission identified by MMIA and no IC or CG
 210 lightning event detected by GLD360 within at least 100 ms. The rise times of the BLUEs
 211 change from 40 μ s to 300 μ s with the total time duration ranging from 900 μ s to 3500 μ s

212 for the single-pulse BLUES and to 6900 μs for the multi-pulse BLUES. There is no obvious
213 difference for the peak irradiance between the single-pulse and multi-pulse BLUES.

214 Further details for all the cases can be found in figure S2-S22 in the Supplemental
215 Materials with two examples for both single- and multi-pulse BLUES shown in figures 2
216 and 3, respectively. As shown in figure 2, both $BLUE^S$ and $BLUE_{OSC}^S$ are found to be
217 associated with +NBEs. The waveforms of NBEs in figure 2(c,d) include the ground wave
218 followed by a 1-hop sky waves, first reflected from the surface of the earth and then from
219 the ionosphere. The NBE pulses for $BLUE_{OSC}^S$ include secondary peaks and oscillations
220 inside the waveform, marked as “OSC” in the figure 2(d).

221 For the $BLUE^M$ in figure 3, the primary BLUE is found to be associated with a +NBE
222 pulse, but its subsequent optical pulse is found to be associated with several subsequent
223 pulse trains within 3.1 ms. The $BLUE_{OSC}^M$ is found to be similar to $BLUE^M$ with NBE
224 pulse and two subsequent optical pulses within 1.4 ms and 4.4 ms, respectively, but with
225 secondary peaks and oscillations inside the NBE waveform. The subsequent optical pulses
226 of multi-pulse BLUES, which followed the primary corona discharges a few milliseconds later,
227 have comparable optical emissions but their associated radio signals are either accompanied
228 by weaker radio emissions or buried in the background noise (see S5, S8, S10, S12 and S19
229 in the Supplemental Materials). Li, Luque, Lehtinen, et al. (2022) discussed the multi-
230 pulse corona discharges related to this study and noted that the subsequent pulse trains
231 of the multi-pulse corona discharges include the electromagnetic pulse pairs that resemble
232 1-hop sky waves without the ground wave (the red dashed circle outlines the subsequent
233 pulse trains in figure 3(e,f)), which might emanate from the horizontally oriented corona
234 discharges.

235 As shown in Table 1, the altitude H of the NBEs are evaluated based on the ground-
236 based VLF/LF radio signals by using the simplified ray-theory method (Smith et al., 1999,
237 2004) with an uncertainty about ± 1 km compared to the full-wave method (Li et al., 2020).
238 Previous studies indicate that the majority of +NBEs are located at a median height around
239 13 km, between the main negative and upper positive charge regions (Smith et al., 2004;
240 Wu et al., 2014; F. Liu, Zhu, et al., 2021). However, note that the +NBEs in our study
241 are found to be located at relatively high altitudes, ranging from 15.5 km to 18 km near the
242 cloud top heights obtained from the Fengyun-4A (FY-4A) satellite (see Table 1).

243 To further understand the features of the BLUES, we estimate the depths L (relative
244 to the cloud top) and the current moments M_i based on the light-scattering model and the
245 electromagnetic radiation model in section 3. In the fitting process, we only fit the BLUES
246 with clear impulsive pulses and considered as good fitting condition when the coefficient of
247 determination $R^2 > 0.6$ (see green lines in Figure 2 (a,b) and 3 (a)). The modeling light
248 curves agree well with the 337 nm photometer signals of MMIA, indicating the evaluated
249 depths L for the BLUES are from 1 km to 3 km below the cloud top (see figure S2-S22 in
250 Supplemental Materials). Among them, 3 cases with ID 27206, ID 27243 and ID 27245 are
251 too noisy to be fitted, as well as 3 cases with ID 27224, ID 27231 and ID 27236 contain
252 a small pulse on the rising edge of light-curve that distorted the fitting process (see the
253 footnote in Table 1 for further details).

254 Figure 4 further shows the correlation between different parameters associated with the
255 BLUES. There are two special cases marked in green dots with ID 27236 and ID 27238,
256 whose subsequent pulse trains seem to be “NBE-like” events, which might two NBE events
257 that occurred closely in time (see figure S15 and S17 in Supplemental Materials), however,
258 it is too noisy to identify it through the radio signals.

259 As shown in figure 4(a), the rise times of MMIA photometer signals have an obvious
260 correlation with the altitudes H of NBEs. This might be due to the high-altitude +NBEs
261 in our study are located only a few kilometers below the cloud top where the cloud droplets
262 have relatively low impact on the MMIA measurements. Figure 4(b) shows a linear corre-

lation between the radio-signal inferred altitude H and the parameter $\eta = \sqrt{4c\tau/(3(1-g))}$ evaluated from the MMIA photometer signals. According to equation (3), the photon mean free path at the cloud top can be obtained by using $\Lambda = 1/(0.4)^2 \approx 6$ m, where $0.4 \text{ m}^{1/2}$ is the slope of the fitting line in figure 4(b). This is consistent with the photon mean free path $\Lambda \approx 4$ m assumed in the previous studies by considering the particle radius $r = 20 \mu\text{m}$ and the number density $N_d = 1 \times 10^8 \text{ m}^{-3}$ (Soler et al., 2020; Luque et al., 2020; Li et al., 2021).

Moreover, as expected, the amplitude of the azimuthal magnetic field component B_ϕ and the estimated current moment M_i show a tight linear relationship in figure 4(c). Despite one special case, the current moments and magnetic fields of the NBEs corresponding to the multi-pulse BLUES (red dots) are found to be weaker than those related to the single-pulse BLUES (blue dots). It suggests that the multi-pulse BLUES either have shorter vertical channels or have weaker currents than the single-pulse BLUES.

5 Discussion and Summary

In this study, we first classify 21 BLUES near the cloud top of a localized thunderstorm into two groups based on their optical features: Single-pulse BLUES (10) and multi-pulse BLUES (11). Then by considering their corresponding radio features, we further classify them into four different types including (1) the single-pulse BLUES associated with NBEs ($BLUE^S$), (2) the single-pulse BLUES associated with NBEs including secondary peaks and oscillations ($BLUE_{OSC}^S$), (3) the multi-pulse BLUES associated with NBEs and their subsequent pulse trains ($BLUE^M$) and (4) the multi-pulse BLUES associated with oscillated NBEs and their subsequent pulse trains ($BLUE_{OSC}^M$).

Both single- and multi-pulse BLUES are found to be associated with unusual high-altitude +NBEs nearby the cloud top. Both the CTH image (see Figure 1) and the ring structures in the 337 nm camera image indicated that there is an overshooting convective cloud top associated with the corona discharges (see figures S10 and S11 in the Supplemental Materials). In our case, the high-altitude +NBEs might occur between the positive charge lifted to relatively high altitude by the strong updraft and the negative screening charge layer near the overshooting cloud top (Li, Luque, Lehtinen, et al., 2022; MacGorman et al., 2017).

The subsequent pulse trains of the multi-pulse BLUES, which followed the NBEs a few milliseconds later, are either accompanied by weaker radio emissions or buried in the background noise. As discussed in (Li, Luque, Lehtinen, et al., 2022), they might emanate from the horizontally oriented corona discharges. The results indicate that the NBEs associated with the multi-pulse BLUES might have similar features with the initiation-type NBEs (INBEs) (Wu et al., 2014), but interestingly, all the NBEs in our study are so-called isolated NBEs which does not trigger full-edged lightning.

Some NBEs, correlated with both single- and multi-pulse BLUES, included small-amplitude oscillations within a few microseconds inside their waveforms. Recent studies indicate that the fast breakdowns of NBEs sometimes contain secondary fast breakdowns along the previous path (Attanasio et al., 2021; Rison et al., 2016; Tilles et al., 2019; Li, Luque, Gordillo-Vázquez, et al., 2022). Most recent observations from the LOw Frequency ARray (LOFAR) also indicate that multiple, spatially distributed corona bursts can occur in lightning processes with a timescale of $10 \mu\text{s}$ (N. Liu et al., 2022). The feature of secondary peaks and oscillations might be a fundamental property in NBE radio waveforms (Leal et al., 2019). However, the optical signals in our case are affected by the scattering effect and the temporal sampling rate of MMIA corresponding to a time resolution of $10 \mu\text{s}$, which is not high enough to show this feature. Therefore, it is yet to be understood.

The current moments of the multi-pulse BLUES are found to be weaker than those related to the single-pulse BLUES. Since the current moments are evaluated by assuming

the sources to be vertical dipoles, it suggests that the multi-pulse BLUEs either have shorter vertical channels or have weaker currents than the single-pulse BLUEs. However, the results of our study are based on a localized thundercloud cell nearby Malaysia, additional studies are required in order to determine whether the features are general or particular.

The estimated altitudes of the +NBEs range from 15.5 km to 18 km, near the cloud top where the cloud droplets have relatively low impact on the MMIA measurements. Nevertheless, by fitting the correlation between the radio-signal inferred altitude H and the parameter $\eta = \sqrt{4c\tau/(3(1-g))}$ evaluated from the optical signals, we estimate the photon mean free path at the cloud top $\Lambda \approx 6$ m, which is consistent with the findings of a recent study (Li, Neubert, et al., 2022). In their study, Li, Neubert, et al. (2022) showed that most of the corona discharges are located close to high ice water content with a photon mean free path $\Lambda \approx 3$ m measured by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). However, note that both particle radius and the number density can be strongly affected by the deep convection inside the thunderstorm (Li, Neubert, et al., 2022; Brunner & Bitzer, 2020). To further investigate the cloud microphysics and its effect on the corona discharges, a more detailed light-scattering model including a parameterization of cloud microphysics is required in future studies.

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Open Research

The Modular Multispectral Imaging Array (MMIA) level 1 data and Global Lightning Detection Network GLD360 data were obtained from <https://asdc.space.dtu.dk/>. ASIM data is proprietary and not currently available for public release. Interested parties should direct their data request to the ASIM Science Data Centre (asdc@space.dtu.dk). The Fengyun-4A (FY-4A) satellite data is public to the registered user and supplied by the Fengyun satellite data center (<http://satellite.nsmc.org.cn/PortalSite/Data/Satellite.aspx?currentculture=en-US>). The VLF/LF radio data that support the findings of this study are openly available at (<https://doi.org/10.5281/zenodo.7096902>).

References

- Ahmad, M. R., Periannan, D., Sabri, M. H. M., Aziz, M. Z. A. A., Lu, G., Zhang, H., ... Cooray, V. (2017a). Emission heights of narrow bipolar events in a tropical storm over the Malacca Strait. In *2017 international conference on electrical engineering and computer science (icecos)* (p. 305-309). doi: 10.1109/ICECOS.2017.8167155
- Ahmad, M. R., Periannan, D., Sabri, M. H. M., Aziz, M. Z. A. A., Lu, G., Zhang, H., ...

- 361 Cooray, V. (2017b). Emission heights of narrow bipolar events in a tropical storm over the
 362 Malacca Strait. In *2017 international conference on electrical engineering and computer*
 363 *science (icecos)* (p. 305-309). doi: <https://doi.org/10.1109/ICECOS.2017.8167155>
- 364 Attanasio, A., da Silva, C., & Krehbiel, P. (2021). Electrostatic Conditions That Pro-
 365 duce Fast Breakdown in Thunderstorms. *Journal of Geophysical Research: Atmospheres*,
 366 *126*(19), e2021JD034829. (e2021JD034829 2021JD034829) doi: [https://doi.org/10.1029/](https://doi.org/10.1029/2021JD034829)
 367 [2021JD034829](https://doi.org/10.1029/2021JD034829)
- 368 Bandara, S., Marshall, T., Karunarathne, S., Karunarathne, N., Siedlecki, R., & Stolzen-
 369 burg, M. (2019). Characterizing three types of negative narrow bipolar events in
 370 thunderstorms. *Atmospheric Research*, *227*, 263-279. doi: [https://doi.org/10.1016/](https://doi.org/10.1016/j.atmosres.2019.05.013)
 371 [j.atmosres.2019.05.013](https://doi.org/10.1016/j.atmosres.2019.05.013)
- 372 Bandara, S., Marshall, T., Karunarathne, S., & Stolzenburg, M. (2021). Groups of narrow
 373 bipolar events within thunderstorms. *Atmospheric Research*, *252*, 105450. doi: [https://](https://doi.org/10.1016/j.atmosres.2021.105450)
 374 doi.org/10.1016/j.atmosres.2021.105450
- 375 Bitzer, P. M., Walker, T. D., Lang, T. J., Gatlin, P. N., Chanrion, O., Neubert, T., ...
 376 Victor, R. (2021). Multifrequency optical observations of lightning with iss-lis and asim.
 377 In *Agu fall meeting 2021*.
- 378 Brunner, K. N., & Bitzer, P. M. (2020). A first look at cloud inhomogeneity and its effect
 379 on lightning optical emission. *Geophysical Research Letters*, *47*(10), e2020GL087094.
 380 (e2020GL087094 10.1029/2020GL087094) doi: <https://doi.org/10.1029/2020GL087094>
- 381 Chanrion, O., Neubert, T., Mogensen, A., Yair, Y., Stendel, M., Singh, R., & Siingh, D.
 382 (2017). Profuse activity of blue electrical discharges at the tops of thunderstorms. *Geo-*
 383 *physical Research Letters*, *44*(1), 496-503. doi: <https://doi.org/10.1002/2016GL071311>
- 384 Chanrion, O., Neubert, T., Rasmussen, I. L., Stoltze, C., Tcherniak, D., Jessen, N. C.,
 385 ... others (2019). The Modular Multispectral Imaging Array (MMIA) of the ASIM
 386 payload on the international space station. *Space Science Reviews*, *215*(4), 1-25. doi:
 387 <https://doi.org/10.1007/s11214-019-0593-y>
- 388 Chou, J. K., Hsu, R.-R., Su, H.-T., Chen, A. B.-C., Kuo, C.-L., Huang, S.-M., ... Wu,
 389 Y.-J. (2018). ISUAL-observed blue luminous events: The associated sferics. *Journal of*
 390 *Geophysical Research: Space Physics*, *123*(4), 3063-3077. doi: [https://doi.org/10.1002/](https://doi.org/10.1002/2017JA024793)
 391 [2017JA024793](https://doi.org/10.1002/2017JA024793)
- 392 Chou, J. K., Tsai, L. Y., Kuo, C. L., Lee, Y. J., Chen, C. M., Chen, A. B., ... Lee, L. C.
 393 (2011). Optical emissions and behaviors of the blue starters, blue jets, and gigantic jets
 394 observed in the Taiwan transient luminous event ground campaign. *Journal of Geophysical*
 395 *Research: Space Physics*, *116*(A7).
- 396 Cummer, S. A. (2003). Current moment in sprite-producing lightning. *Journal of Atmo-*
 397 *spheric and Solar-Terrestrial Physics*, *65*(5), 499-508. (Sprites, Elves and their Global
 398 Activities) doi: [https://doi.org/10.1016/S1364-6826\(02\)00318-8](https://doi.org/10.1016/S1364-6826(02)00318-8)
- 399 Cummer, S. A., & Inan, U. S. (2000). Modeling ELF radio atmospheric propagation and
 400 extracting lightning currents from ELF observations. *Radio Science*, *35*(2), 385-394. doi:
 401 <https://doi.org/10.1029/1999RS002184>
- 402 Dimitriadou, K., Chanrion, O., Neubert, T., Protat, A., Louf, V., Heumesser, M., ...
 403 Reglero, V. (2022). Analysis of Blue Corona Discharges at the Top of Tropical Thun-
 404 derstorm Clouds in Different Phases of Convection. *Geophysical Research Letters*, *49*(6),
 405 e2021GL095879. doi: <https://doi.org/10.1029/2021GL095879>
- 406 Edens, H. E. (2011). Photographic and lightning mapping observations of a blue starter
 407 over a New Mexico thunderstorm. *Geophysical Research Letters*, *38*(17). doi: [https://](https://doi.org/10.1029/2011GL048543)
 408 doi.org/10.1029/2011GL048543
- 409 Husbjerg, L. S., Neubert, T., Chanrion, O., Dimitriadou, K., Li, D., Stendel, M., ... Reglero,
 410 V. (2022). Observations of Blue Corona Discharges in Thunderclouds. *Geophysical*
 411 *Research Letters*, *49*(12), e2022GL099064. doi: <https://doi.org/10.1029/2022GL099064>
- 412 Jacobson, A. R., Boeck, W., & Jeffery, C. (2007). Comparison of Narrow Bipolar Events
 413 with ordinary lightning as proxies for the microwave-radiometry ice-scattering signature.
 414 *Monthly weather review*, *135*(4), 1354-1363.

- 415 Jacobson, A. R., & Heavner, M. J. (2005). Comparison of narrow bipolar events with
 416 ordinary lightning as proxies for severe convection. *Monthly Weather Review*, *133*(5),
 417 1144–1154. doi: 10.1175/MWR2915.1
- 418 Karunarathne, S., Marshall, T. C., Stolzenburg, M., & Karunarathna, N. (2015). Observa-
 419 tions of positive narrow bipolar pulses. *Journal of Geophysical Research: Atmospheres*,
 420 *120*(14), 7128–7143. doi: <https://doi.org/10.1002/2015JD023150>
- 421 Kostinskiy, A. Y., Marshall, T. C., & Stolzenburg, M. (2020). The mechanism of the
 422 origin and development of lightning from initiating event to initial breakdown pulses
 423 (v.2). *Journal of Geophysical Research: Atmospheres*, *125*(22), e2020JD033191. doi:
 424 <https://doi.org/10.1029/2020JD033191>
- 425 Kuo, C.-L., Hsu, R. R., Chen, A. B., Su, H. T., Lee, L. C., Mende, S. B., . . . Takahashi,
 426 Y. (2005). Electric fields and electron energies inferred from the ISUAL recorded sprites.
 427 *Geophysical Research Letters*, *32*(19). doi: <https://doi.org/10.1029/2005GL023389>
- 428 Leal, A. F., Rakov, V. A., & Rocha, B. R. (2019). Compact intracloud discharges: New
 429 classification of field waveforms and identification by lightning locating systems. *Electric*
 430 *Power Systems Research*, *173*, 251–262. doi: <https://doi.org/10.1016/j.epsr.2019.04.016>
- 431 Le Vine, D. M. (1980). Sources of the strongest RF radiation from lightning. *Journal of*
 432 *Geophysical Research: Oceans*, *85*(C7), 4091–4095. doi: 10.1029/JC085iC07p04091
- 433 Li, D., Liu, F., Pérez-Invernón, F. J., Lu, G., Qin, Z., Zhu, B., & Luque, A. (2020). On
 434 the Accuracy of Ray-Theory Methods to Determine the Altitudes of Intracloud Electric
 435 Discharges and Ionospheric Reflections: Application to Narrow Bipolar Events. *Journal*
 436 *of Geophysical Research: Atmospheres*, *125*(9), e2019JD032099. doi: [https://doi.org/](https://doi.org/10.1029/2019JD032099)
 437 [10.1029/2019JD032099](https://doi.org/10.1029/2019JD032099)
- 438 Li, D., Luque, A., Gordillo-Vázquez, F. J., Liu, F., Lu, G., Neubert, T., . . . Reglero, V.
 439 (2021). Blue Flashes as Counterparts to Narrow Bipolar Events: The Optical Signal of
 440 Shallow In-Cloud Discharges. *Journal of Geophysical Research: Atmospheres*, *126*(13),
 441 e2021JD035013. doi: 10.1029/2021JD035013
- 442 Li, D., Luque, A., Gordillo-Vázquez, F. J., Silva, C. d., Krehbiel, P. R., Rachidi, F., &
 443 Rubinstein, M. (2022). Secondary Fast Breakdown in Narrow Bipolar Events. *Geophysical*
 444 *Research Letters*, *49*(7), e2021GL097452. (e2021GL097452 2021GL097452) doi: [https://](https://doi.org/10.1029/2021GL097452)
 445 doi.org/10.1029/2021GL097452
- 446 Li, D., Luque, A., Lehtinen, N. G., Gordillo-Vázquez, F. J., Neubert, T., Lu, G., . . . Reglero,
 447 V. (2022). Multi-pulse corona discharges in thunderclouds observed in optical and radio
 448 bands. *Geophysical Research Letters*, e2022GL098938. doi: [https://doi.org/10.1029/](https://doi.org/10.1029/2022GL098938)
 449 [2022GL098938](https://doi.org/10.1029/2022GL098938)
- 450 Li, D., Neubert, T., Husbjerg, L., Zhu, Y., Chanrion, O., Lapierre, J., . . . et al. (2022).
 451 Observation of corona discharges and cloud microphysics at the top of thunderstorm cells
 452 in cyclone fani. *Earth and Space Science Open Archive*, *15*. doi: 10.1002/essoar.10512239
 453 .1
- 454 Liu, F., Lu, G., Neubert, T., Lei, J., Chanrion, O., Østgaard, N., . . . Zhu, B. (2021). Optical
 455 emissions associated with narrow bipolar events from thunderstorm clouds penetrating
 456 into the stratosphere. *Nature Communications*, *12*(6631). doi: [https://doi.org/10.1038/](https://doi.org/10.1038/s41467-021-26914-4)
 457 [s41467-021-26914-4](https://doi.org/10.1038/s41467-021-26914-4)
- 458 Liu, F., Zhu, B., Lu, G., Lei, J., Shao, J., Chen, Y., . . . Zhou, H. (2021). Meteorological and
 459 Electrical Conditions of Two Mid-latitude Thunderstorms Producing Blue Discharges.
 460 *Journal of Geophysical Research: Atmospheres*, *126*(8), e2020JD033648. doi: [https://](https://doi.org/10.1029/2020JD033648)
 461 doi.org/10.1029/2020JD033648
- 462 Liu, F., Zhu, B., Lu, G., Qin, Z., Lei, J., Peng, K.-M., . . . Zhou, H. (2018). Observations
 463 of Blue Discharges Associated With Negative Narrow Bipolar Events in Active Deep
 464 Convection. *Geophysical Research Letters*, *45*(6), 2842–2851. doi: [https://doi.org/10](https://doi.org/10.1002/2017GL076207)
 465 [.1002/2017GL076207](https://doi.org/10.1002/2017GL076207)
- 466 Liu, N., Scholten, O., Dwyer, J. R., Hare, B. M., Sterpka, C. F., Tilles, J. N., & Lind, F. D.
 467 (2022). Implications of multiple corona bursts in lightning processes for radio frequency
 468 interferometer observations. *Geophysical Research Letters*, *49*(7), e2021GL097367. doi:

- 469 <https://doi.org/10.1029/2021GL097367>
- 470 Luque, A., Gordillo-Vázquez, F. J., Li, D., Malagón-Romero, A., Pérez-Invernón, F. J.,
471 Schmalzried, A., ... Østgaard, N. (2020). Modeling lightning observations from space-
472 based platforms (CloudScat.jl 1.0). *Geoscientific Model Development*, *13*(11), 5549–5566.
473 doi: <https://doi.org/10.5194/gmd-13-5549-2020>
- 474 Lyons, W. A., Nelson, T. E., Armstrong, R. A., Pasko, V. P., & Stanley, M. A. (2003).
475 Upward electrical discharges from thunderstorm tops. *Bulletin of the American Meteorolo-*
476 *gical Society*, *84*(4), 445–454.
- 477 Lyu, F., Cummer, S. A., Qin, Z., & Chen, M. (2019). Lightning Initiation Processes Imaged
478 With Very High Frequency Broadband Interferometry. *Journal of Geophysical Research:*
479 *Atmospheres*, *124*(6), 2994–3004. doi: <https://doi.org/10.1029/2018JD029817>
- 480 López, J. A., Montanyà, J., van der Velde, O., Romero, D., Gordillo-Vázquez, F. J., Pérez-
481 Invernón, F. J., ... Reglero, V. (2022). Initiation of lightning flashes simultaneously
482 observed from space and the ground: Narrow bipolar events. *Atmospheric Research*, *268*,
483 105981. doi: <https://doi.org/10.1016/j.atmosres.2021.105981>
- 484 MacGorman, D. R., Elliott, M. S., & DiGangi, E. (2017). Electrical discharges in the over-
485 shooting tops of thunderstorms. *Journal of Geophysical Research: Atmospheres*, *122*(5),
486 2929–2957. doi: <https://doi.org/10.1002/2016JD025933>
- 487 Nag, A., & Rakov, V. A. (2010a). Compact intracloud lightning discharges: 1. Mechanism of
488 electromagnetic radiation and modeling. *Journal of Geophysical Research: Atmospheres*,
489 *115*(D20). doi: 10.1029/2010JD014235
- 490 Nag, A., & Rakov, V. A. (2010b). Compact intracloud lightning discharges: 2. Estimation
491 of electrical parameters. *Journal of Geophysical Research: Atmospheres*, *115*(D20). doi:
492 10.1029/2010JD014237
- 493 Neubert, T., Østgaard, N., Reglero, V., Blanc, E., Chanrion, O., Oxborrow, C. A., ...
494 Bhandari, D. D. (2019). The ASIM mission on the international space station. *Space*
495 *Science Reviews*, *215*(2), 1–17. doi: <https://doi.org/10.1007/s11214-019-0592-z>
- 496 Rison, W., Krehbiel, P. R., Stock, M. G., Edens, H. E., Shao, X.-M., Thomas, R. J.,
497 ... Zhang, Y. (2016). Observations of narrow bipolar events reveal how lightning is
498 initiated in thunderstorms. *Nature communications*, *7*, 10721. doi: [https://doi.org/10.1038/ncomms10721\(2016\)](https://doi.org/10.1038/ncomms10721(2016))
- 499 Said, R., & Murphy, M. (2016). GLD360 upgrade: Performance analysis and applications.
500 In *24th international lightning detection conference*.
- 501 Smith, D. A., Heavner, M. J., Jacobson, A. R., Shao, X. M., Massey, R. S., Sheldon,
502 R. J., & Wiens, K. C. (2004). A method for determining intracloud lightning and
503 ionospheric heights from VLF/LF electric field records. *Radio Science*, *39*(1), RS1010.
504 doi: <https://doi.org/10.1029/2002RS002790>
- 505 Smith, D. A., Shao, X. M., Holden, D. N., Rhodes, C. T., Brook, M., Krehbiel, P. R.,
506 ... Thomas, R. J. (1999). A distinct class of isolated intracloud lightning discharges
507 and their associated radio emissions. *Journal of Geophysical Research: Atmospheres*,
508 *104*(D4), 4189–4212. doi: <https://doi.org/10.1029/1998JD200045>
- 509 Soler, S., Gordillo-Vázquez, F. J., Pérez-Invernón, F. J., Luque, A., Li, D., Neubert, T.,
510 ... Østgaard, N. (2021). Global Frequency and Geographical Distribution of Nighttime
511 Streamer Corona Discharges (BLUES) in Thunderclouds. *Geophysical Research Letters*,
512 *48*(18), e2021GL094657. doi: <https://doi.org/10.1029/2021GL094657>
- 513 Soler, S., Gordillo-Vázquez, F. J., Pérez-Invernón, F. J., Luque, A., Li, D., Neubert, T., ...
514 Østgaard, N. (2022). Global distribution of key features of streamer corona discharges
515 (BLUES) in thunderclouds. *Earth and Space Science Open Archive*.
- 516 Soler, S., Pérez-Invernón, F. J., Gordillo-Vázquez, F. J., Luque, A., Li, D., Malagón-Romero,
517 A., ... Østgaard, N. (2020). Blue Optical Observations of Narrow Bipolar Events by ASIM
518 Suggest Corona Streamer Activity in Thunderstorms. *Journal of Geophysical Research:*
519 *Atmospheres*, *125*(16), e2020JD032708. doi: 10.1029/2020JD032708
- 520 Thomson, L. W., & Krider, E. P. (1982, September). The Effects of Clouds on the Light
521 Produced by Lightning. *Journal of Atmospheric Sciences*, *39*(9), 2051–2065. doi: 10.1175/
522

- 523 1520-0469(1982)039\textless{}2051:TEOCOT\textgreater{}2.0.CO;2
524 Tilles, J. N., Liu, N., Stanley, M. A., Krehbiel, P. R., Rison, W., Stock, M. G., ... Wilson,
525 J. (2019). Fast negative breakdown in thunderstorms. *Nature communications*, *10*(1),
526 1–12.
- 527 Uman, M. A., McLain, D. K., & Krider, E. P. (1975). The electromagnetic radiation from
528 a finite antenna. *American Journal of Physics*, *43*(1), 33-38. doi: 10.1119/1.10027
- 529 Wescott, E. M., Sentman, D. D., Heavner, M. J., Hampton, D. L., Osborne, D. L., &
530 Vaughan Jr., O. H. (n.d.). Blue starters Brief upward discharges from an intense Arkansas
531 thunderstorm.
- 532 Wescott, E. M., Sentman, D. D., Stenbaek-Nielsen, H. C., Huet, P., Heavner, M. J., &
533 Moudry, D. R. (2001). New evidence for the brightness and ionization of blue starters
534 and blue jets. *Journal of Geophysical Research: Space Physics*, *106*(A10), 21549-21554.
535 doi: <https://doi.org/10.1029/2000JA000429>
- 536 Willett, J. C., Bailey, J. C., & Krider, E. P. (1989). A class of unusual lightning electric field
537 waveforms with very strong high-frequency radiation. *Journal of Geophysical Research:*
538 *Atmospheres*, *94*(D13), 16255-16267. doi: 10.1029/JD094iD13p16255
- 539 Wu, T., Dong, W., Zhang, Y., Funaki, T., Yoshida, S., Morimoto, T., ... Kawasaki, Z.
540 (2012). Discharge height of lightning narrow bipolar events. *Journal of Geophysical*
541 *Research: Atmospheres*, *117*(D5). doi: <https://doi.org/10.1029/2011JD017054>
- 542 Wu, T., Dong, W., Zhang, Y., & Wang, T. (2011). Comparison of positive and negative
543 compact intracloud discharges. *Journal of Geophysical Research: Atmospheres*, *116*(D3).
544 doi: <https://doi.org/10.1029/2010JD015233>
- 545 Wu, T., Yoshida, S., Ushio, T., Kawasaki, Z., & Wang, D. (2014). Lightning-initiator type of
546 narrow bipolar events and their subsequent pulse trains. *Journal of Geophysical Research:*
547 *Atmospheres*, *119*(12), 7425-7438. doi: <https://doi.org/10.1002/2014JD021842>
- 548 Yang, J., Zhang, Z., Wei, C., Lu, F., & Guo, Q. (2017). Introducing the new genera-
549 tion of Chinese geostationary weather satellites, Fengyun-4. *Bulletin of the American*
550 *Meteorological Society*, *98*(8), 1637–1658.
- 551 Zhang, H., Lu, G., Qie, X., Jiang, R., Fan, Y., Tian, Y., ... Feng, G. (2016). Locating
552 narrow bipolar events with single-station measurement of low-frequency magnetic fields.
553 *Journal of Atmospheric and Solar-Terrestrial Physics*, *143-144*, 88-101. doi: <https://doi.org/10.1016/j.jastp.2016.03.009>
554

Table list**Table 1.** The detailed feature of all the BLUEs occurred at the time period from 17:49:55 to 17:50:55 UTC.

ID	Flux (μ W/m ²)	B _φ (nT)	Rise time ^a (ms)	Time duration ^b (ms)	M _i ^c (kA · km)	H (km)	Optical L ^d (km)	CTH (km)	Type
27206	2.00	10.84	-	-	24.24	17.23	-	18.46	<i>S</i> with oscillations
27210	6.6	2.19	0.08	2.05	7.48	17.06	1.83	18.60	<i>S</i>
27211	4.54	1.36	0.07	1.56	2.64	17.68	1.61	18.65	<i>M</i>
27213	5.57	2.08	0.12	2.02	5.50	16.67	2.34	18.55	<i>M</i>
27214	10.81	2.75	0.04	0.96	10.08	17.11	1.31	18.55	<i>S</i> with oscillations
27215	13.50	2.58	0.11	2.49	14.89	16.30	2.09	18.67	<i>S</i> with oscillations
27218	5.56	0.69	-	-	1.67	16.69	-	18.60	<i>M</i>
27222	12.42	1.94	0.08	2.73	4.21	17.03	1.82	18.27	<i>M</i> with oscillations
27224	10.28	1.75	-	-	6.23	15.55	-	18.21	<i>M</i>
27225	14.05	3.42	0.19	3.54	7.66	16.65	2.84	18.21	<i>S</i> with oscillations
27231	4.54	1.39	-	-	2.91	15.55	-	17.77	<i>M</i>
27234	6.60	4.49	0.13	2.85	9.18	16.32	2.34	17.50	<i>S</i>
27235	12.96	12.78	0.04	1.01	26.61	17.28	1.34	17.34	<i>S</i>
27236*	8.69	1.38	-	-	3.69	15.87	-	17.47	<i>M</i>
27237	24.77	15.85	0.04	0.99	37.07	17.98	1.27	17.88	<i>S</i>
27238*	10.81	11.15	0.04	0.97	22.62	17.95	1.26	17.04	<i>M</i>
27239	5.56	0.71	0.14	6.91	5.02	16.34	2.42	17.09	<i>M</i> with oscillations
27241	4.54	0.29	0.18	5.69	-	16.54	3.05	17.09	<i>M</i>
27243	3.52	0.60	-	-	-	16.78	-	17.23	<i>S</i> with oscillations
27244	7.12	9.69	0.05	1.26	32.73	17.78	1.48	17.03	<i>S</i> with oscillations
27245	3.01	0.60	-	-	3.59	17.33	-	16.73	<i>M</i> with oscillations

Note that the current moments (M_i) are inferred by solving the inverse convolution problem (Cummer & Inan, 2000; Cummer, 2003) based on the Uman's equation (Uman et al., 1975). The altitudes (H) are estimated using the simplified ray-theory method proposed by Smith et al. (1999, 2004) based on the ground-based VLF/LF sferics. The depths (L) relative to the cloud tops are evaluated by using the first-hitting-time model proposed by Soler et al. (2020) based on the 337 nm photometer signals of MMIA. The Cloud Top Heights (CTH) are obtained from FY-4A satellite products.

* Special multi-pulse cases (See Figure S15 and S17 in Supplemental Material for details).

^a Rise time is the time taken for the amplitude of a fitted photometer signal to rise from 10% to 90% of the peak.

^b Time duration is the time interval for the amplitude of a fitted photometer signal to rise from 10 % and fall to 10% of the peak.

^c The current moment M_i for ID 27241 and ID 27243 cannot be estimated due to their complex radio signals (See Figure S19 and S20 in Supplemental Material for details).

^d For ID 27224, ID 27231 and ID 27236, there is a small pulse on the rising edge of light-curve that distorted the fit process (See Figure S10, S12 and S15 in Supplemental Material for details). The photometer signal is too noisy to be fitted for ID 27206, ID 27243 and ID 27245 (See Figure S2, S20 and S22 in Supplemental Material for details).

Figure list

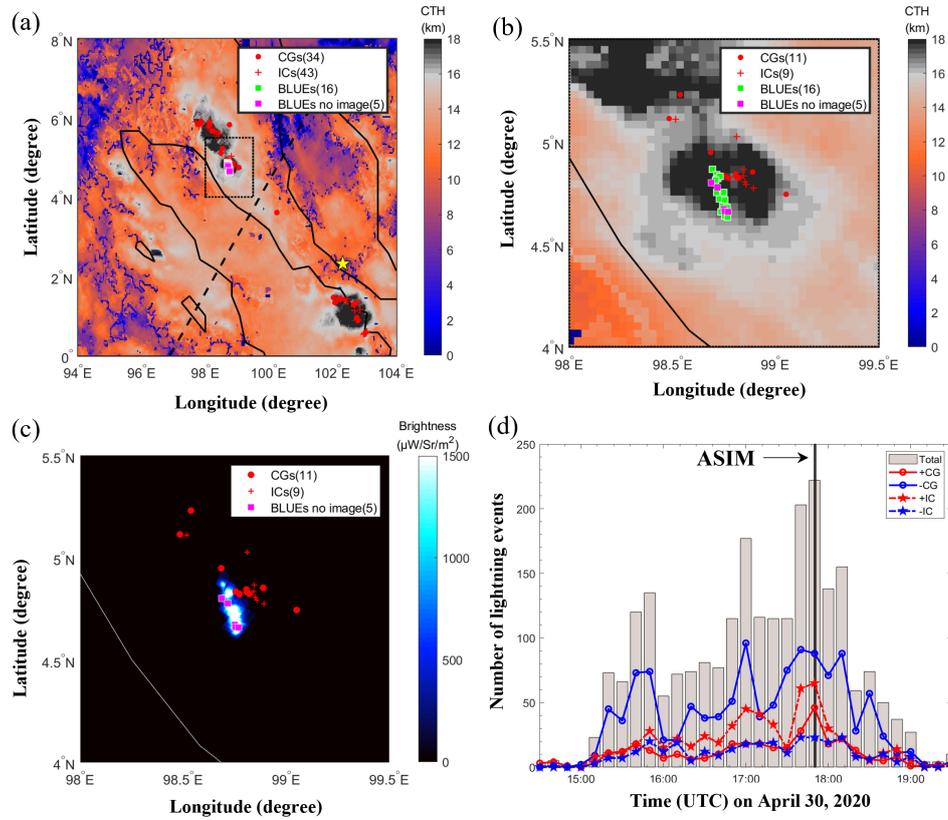


Figure 1. The distribution of 21 BLUEs (16 with camera images (green square) and 5 without MMIA camera images (pink square)) along with the CG (red dots)/IC (red crosses) lightning on the Cloud Top Height (CTH) at 17:50:00 UTC (a), the zoom of its black-dotted rectangular region (b) and the projected images measured by the 337 nm camera of MMIA in the zoom region (c). In (a), the ground-based VLF/LF sensor at Malaysia is shown as yellow star. The footprints of ASIM are shown in black dashed line. Numbers of lightning events from 15:00 UTC to 19:00 UTC in the zoom region are shown in (d): positive CGs (+CGs), negative CGs (-CGs), positive ICs (+ICs) and negative ICs (-ICs). The ASIM overpass time is marked in black line.

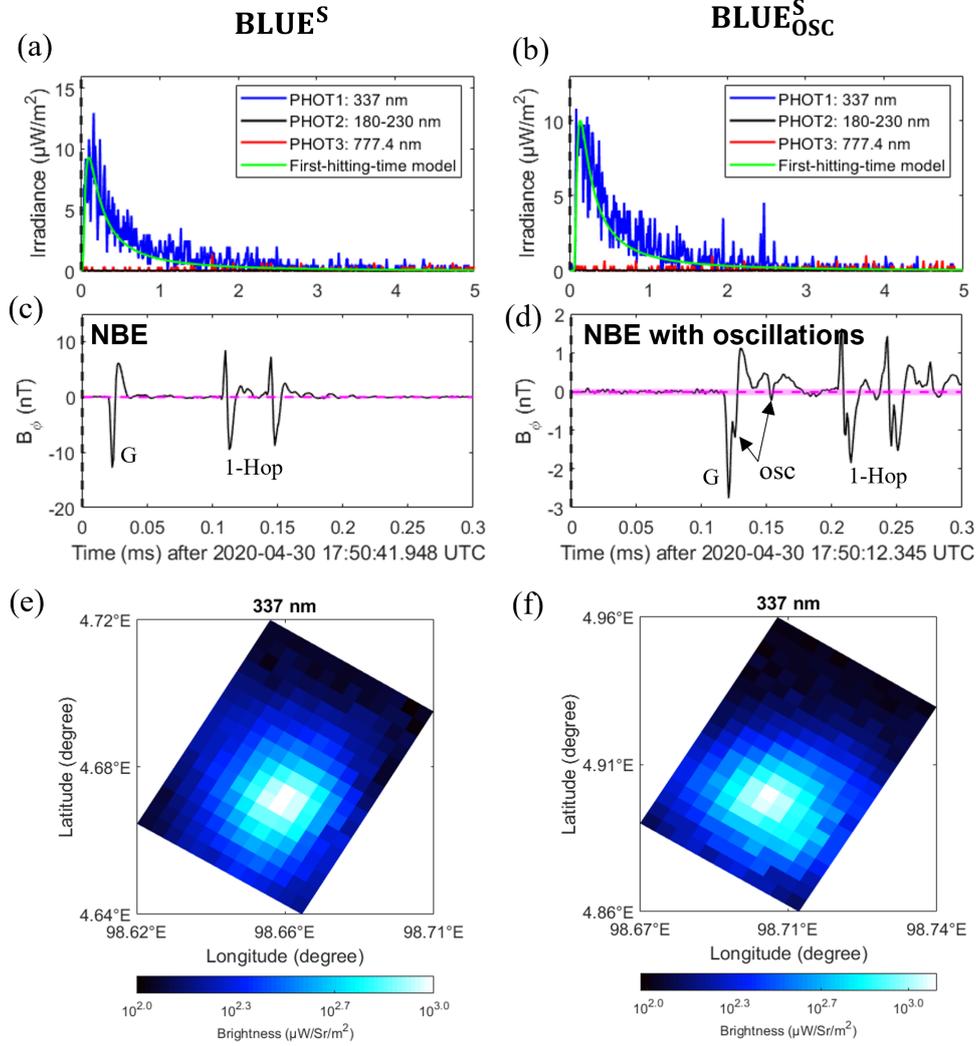


Figure 2. Examples of the single-pulse BLUEs associated with NBEs ($BLUE^S$) for ID 27235 (a,c) and NBEs including secondary peaks and oscillations ($BLUE^S_{osc}$) for ID 27214 (b,d). MMIA photometer irradiance (blue: 337 nm, black: 180-230 nm, red: 777.4 nm and green: modeling result of the first-hitting-time model) (a,b) and its corresponding radio signal detected from the ground-based VLF/LF sensor nearby Malaysia (c,d). The 337 nm images of MMIA are shown in the (e) and (f). The pink horizontal dashed line is the mean of the background noises with the pink shaded band $\mu \pm 3\sigma$ in (c,d). The oscillations are marked as *OSC* in (d). The ground wave and the ionospheric 1-hop sky waves are marked as *G* and *1-Hop* in (c,d), respectively.

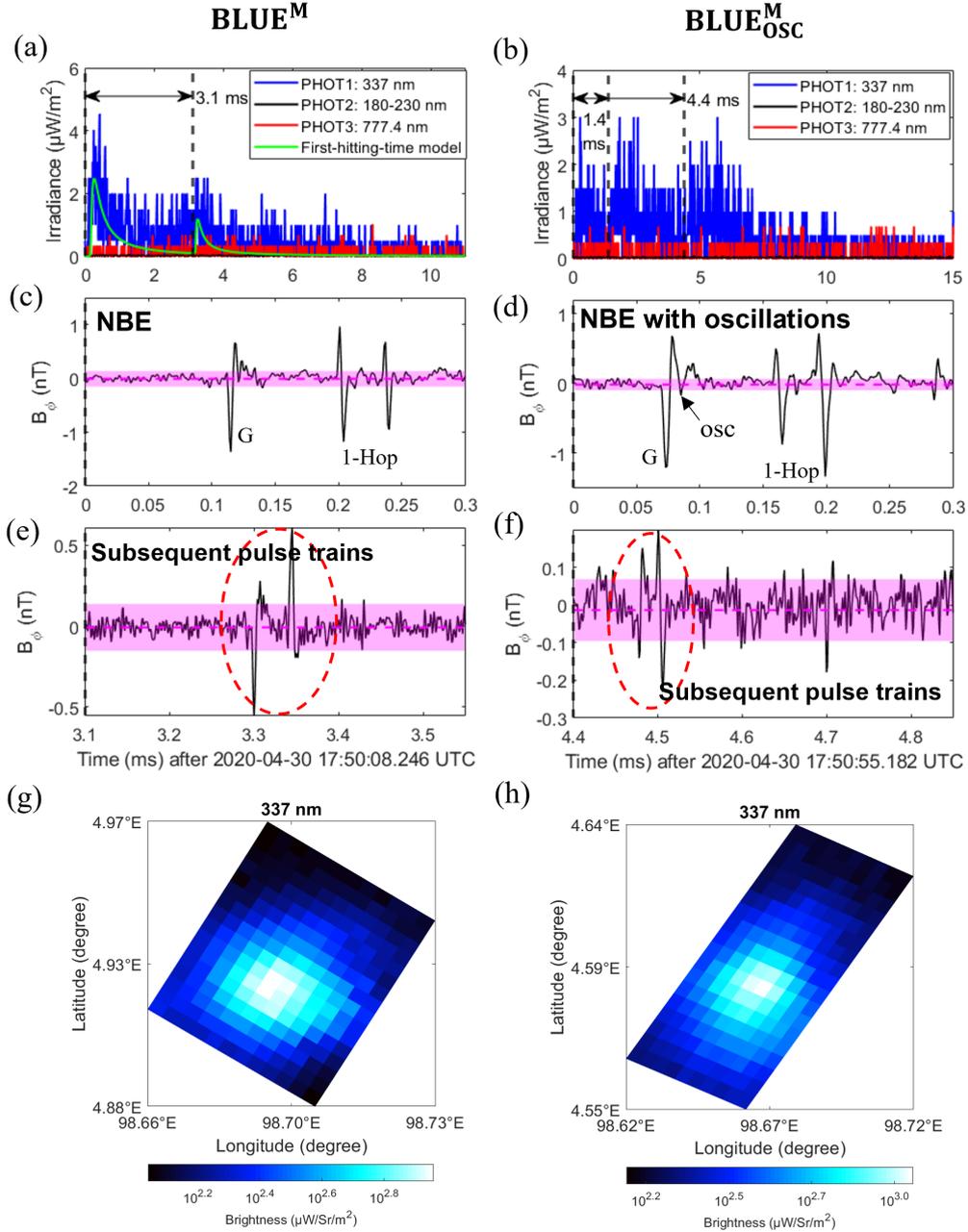


Figure 3. Similar to Figure 2, but for the multi-pulse BLUEs associated with NBEs and their subsequent pulse trains (marked in the red dashed circle region) ($BLUE_{OSC}^S$) for ID 27211 (a,c,e,g) and the multi-pulse BLUEs associated with oscillated NBEs and their subsequent pulse trains (marked in the red dashed circle region) ($BLUE_{OSC}^S$) for ID 27245 (b,d,f,h). Note that (f) only shows the subsequent pulse trains after 4.4 ms since the radio signals after 1.4 ms are not obvious and might overlap with the multiple-hop ionospheric reflections of NBEs (see Figure S22 in Supplemental Material). The pink horizontal dashed line is the mean of the background noises with the pink shaded band $\mu \pm 3\sigma$ in (c,d,e,f). The oscillations are marked as *OSC* in (d). The ground wave and the ionospheric 1-hop sky waves are marked as *G* and *1-Hop* in (c,d), respectively.

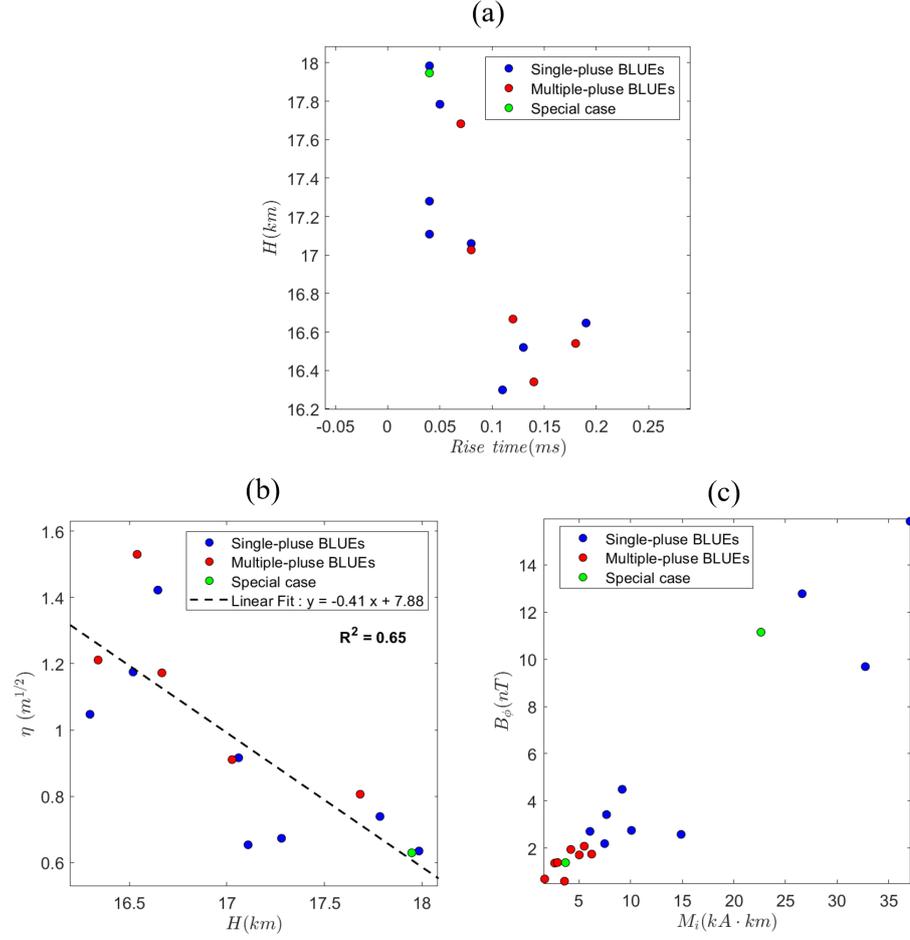


Figure 4. The correlation of (a) the rise time of 337 nm photometer signal and the altitude of NBEs (H), (b) the altitude of NBEs (H) and the parameter $\eta = \sqrt{4c\tau/(3(1-g))}$ and (c) the current moment (M_i) and the magnetic field strength (B_ϕ). The single- and multi-pulse BLUEs are shown in blue and red dots, respectively. The 2 special multi-pulse cases for ID 27236 and ID 27238 are marked as green dots.

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Appendix

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Appendix A The statistical significance of photometer signals detected by MMIA

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In this appendix, we estimate the statistical significance of the three photometer signals detected by MMIA. The mean μ and standard deviation σ for the background signal are calculated by using 1000 data points (10 ms) before the first primary BLUE begins. In our case, both single-pulse and multi-pulse BLUES are statistically significant with their 337 nm signals above $\mu \pm 5\sigma$ level of the background noise, with absent or negligible signals in both the 180-230 nm photometer and the 777.4 nm photometer. Figure A1 and A2 give examples of the statistical significance of the photometer signals of a single-pulse BLUE with ID 27214 (corresponding to Figure 2(a)) and a multi-pulse BLUE with ID 27211 (corresponding to Figure 3(a)), respectively.

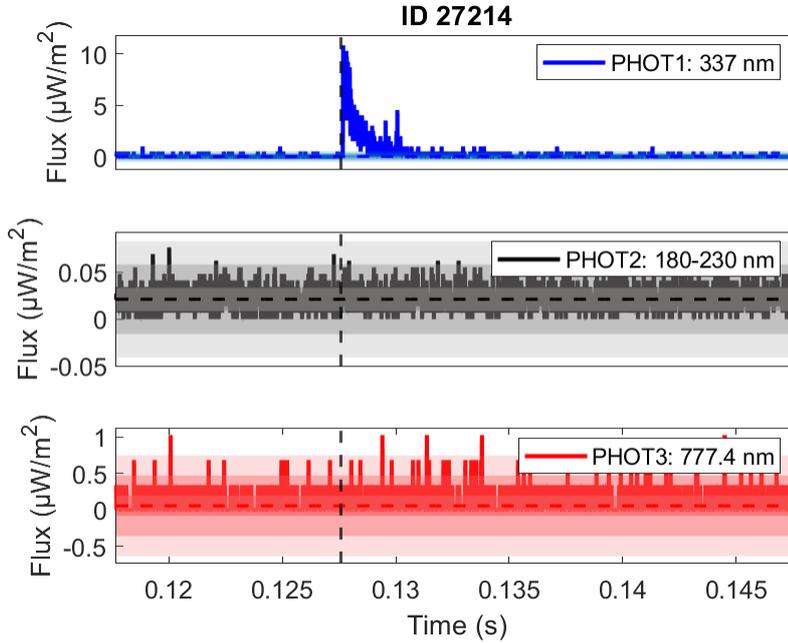


Figure A1. The statistical significance of the photometer signals of a single-pulse BLUE with ID 27214 (corresponding to Figure 2(a)) (Blue: 337 nm, Black: 180-230 nm and Red: 777.4 nm). The black vertical dashed line marked the start time for the BLUE pulse. The horizontal dashed line is the mean of the background noises with the shaded bands indicating $\mu \pm \sigma$, $\mu \pm 3\sigma$ and $\mu \pm 5\sigma$.

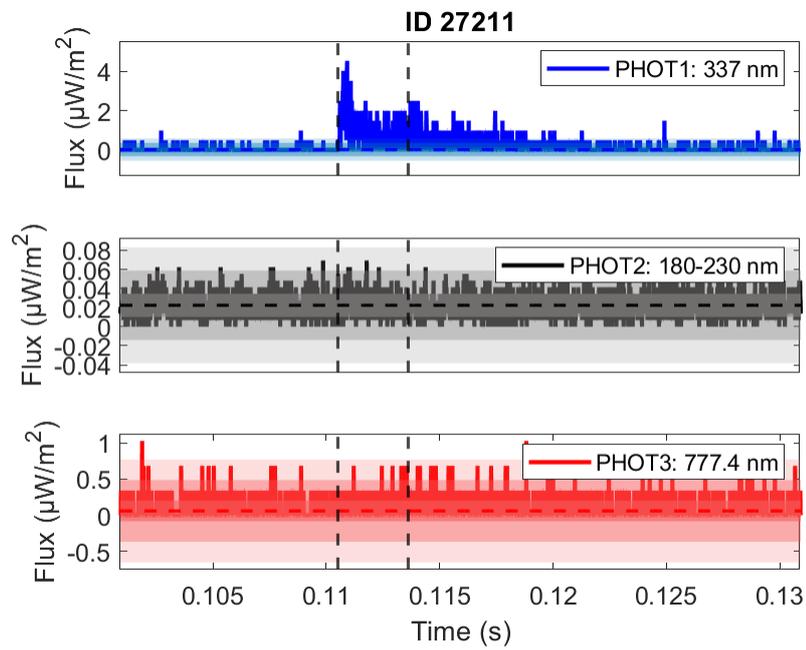


Figure A2. Similar to Figure A1, but for a multi-pulse BLUE case with ID 27211 (corresponding to Figure 3(a)). The black vertical dashed lines marked the start time for the primary and secondary BLUE pulses.

569 Appendix B The statistical significance of multi-pulse corona discharges

570 In this appendix, we calculate the binned average of 15 data points (corresponding
571 to 150 μ s) of the 337 nm photometer signal to estimate the statistical significance of all
572 the multi-pulse BLUEs. For each bin we compute the standard deviation of the samples
573 within the bin and plot the estimated standard deviation of the mean (standard deviation
574 of the samples inside the bin divided by the square root of the number of samples). In
575 most of cases, the secondary peaks of multi-pulse BLUEs are statistically significant. The
576 event with ID 27236, where the two pulses overlap but are identifiable nevertheless, is
577 corresponding to one special case where the subsequent pulse trains look very much like a
578 negative NBE, however, it is too noisy to identify it through the radio signals (see Figure
579 S15 in Supplemental Material).

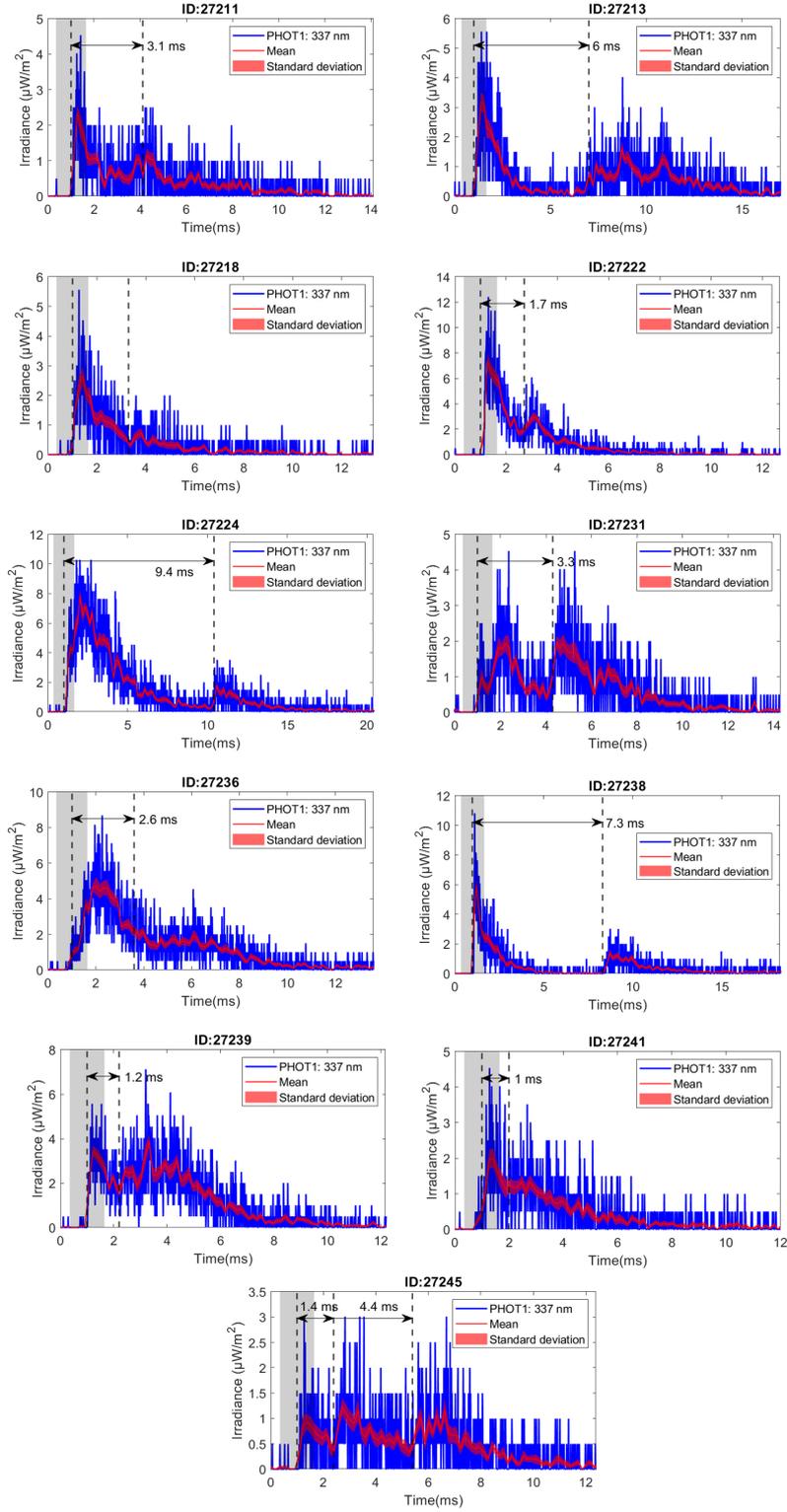


Figure B1. The binned average of 15 data points (corresponding to $150\ \mu\text{s}$) of the 337 nm photometer signals for multi-pulse BLUEs. The mean and standard deviation of the sample mean are marked in the red solid line and its shaded band. The start time (refer to source) for NBE and its subsequent pulse is marked in dashed black line with ± 0.65 ms uncertainty (gray shadowed region).

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Appendix C The statistical significance of the oscillation features in radio signals

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In this appendix, we analyze the statistical significance of the NBE radio pulses for both single- and multi-pulse BLUEs. The mean μ and standard deviation σ for the background signal are calculated by using radio signals within 10 ms before the NBE event begins. We estimate the existence of oscillations when the amplitudes of the subsequent radio pulses in the same polarity of the ground wave are outside $\mu \pm 3\sigma$ level of the background noise. The NBE radio signals with and without oscillation features for single- and multi-pulse BLUEs are shown in Figure C1 and C2, respectively.

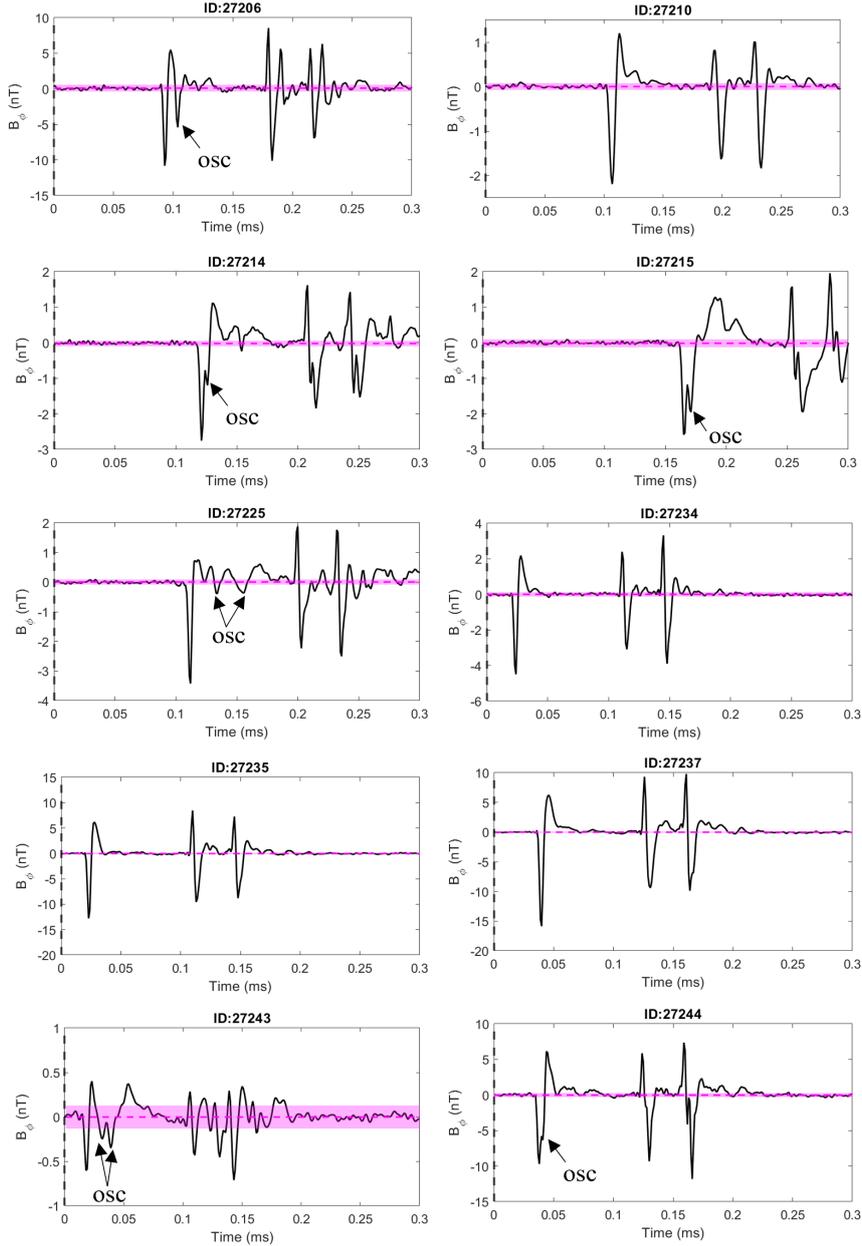


Figure C1. The statistical significance of the oscillation of the NBE radio pulses for all the single-pulse BLUEs. The pink horizontal dashed line is the mean of the background noises with the pink shaded band $\mu \pm 3\sigma$. The oscillations are marked as *OSC* in the corresponding cases.

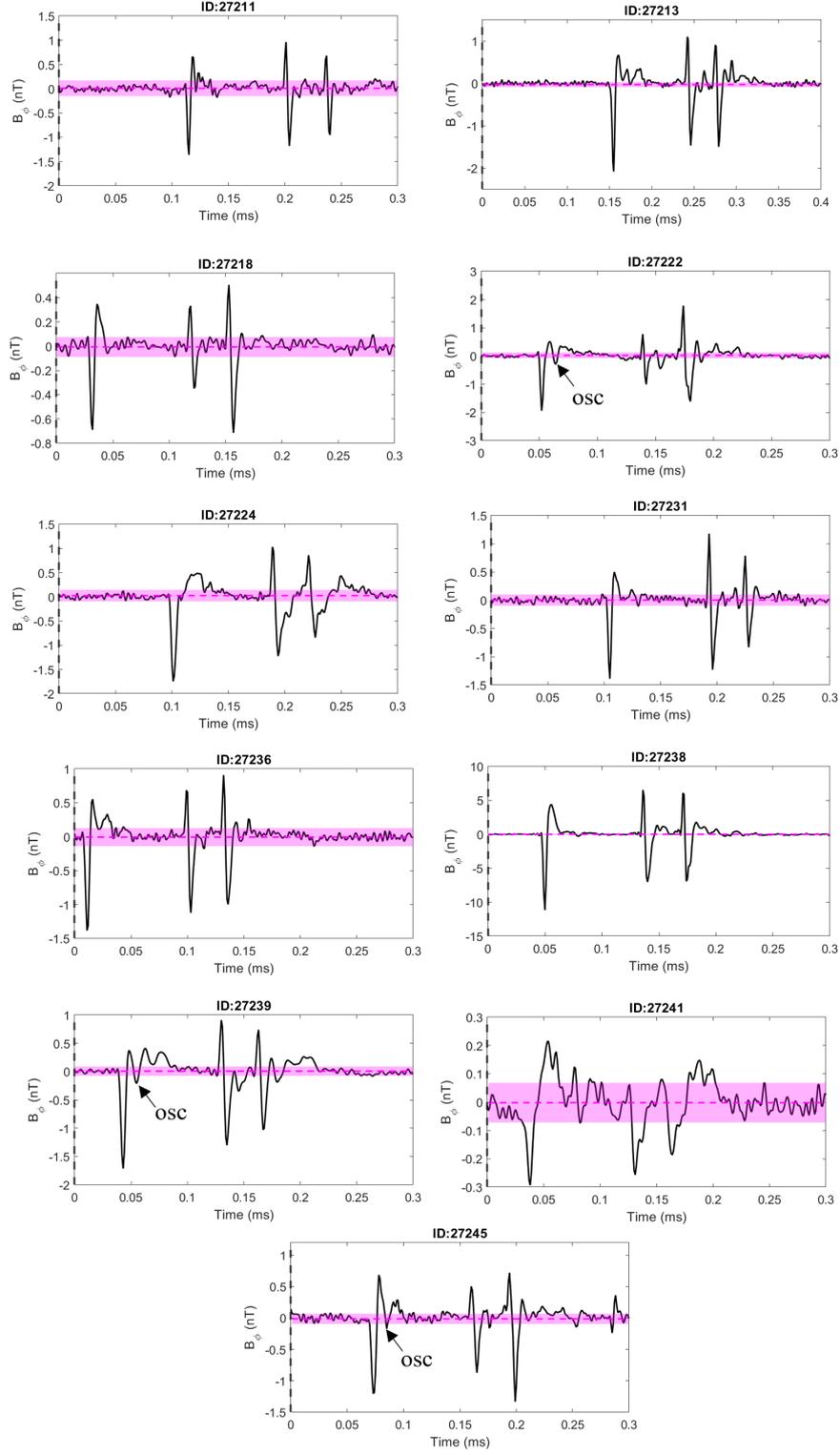


Figure C2. Similar to C1, but for the NBE radio pulses of all the multi-pulse BLUEs. The horizontal dashed line is the mean of the background noises with the pink shaded band $\mu \pm 3\sigma$. The oscillations are marked as *OSC* in the corresponding cases.