



## Abstract

During the 2022 New Mexico monsoon season, we deployed two X-ray scintillation detectors, coupled with a 180 MHz data acquisition system to detect X-rays from natural lightning at the Langmuir Lab mountain-top facility, located at 3.3 km above mean sea level. Data acquisition was triggered by an electric field antenna calibrated to pick up lightning within a few km of the X-ray detectors. We report the energies of over 240 individual photons, ranging between 13 keV and 3.8 MeV, as registered by the LaBr<sub>3</sub>(Ce) scintillation detector. These detections were associated with four lightning flashes. Particularly, four stepped leaders and seven dart leaders produced energetic radiation. The reported photon energies allowed us to confirm that the X-ray energy distribution of natural stepped and dart leaders follows a power-law distribution with exponent ranging between 1.09 and 1.96, with stepped leaders having a harder spectrum. Characterization of the associated leaders and return strokes was done with four different electric field sensing antennas, which can measure a wide-range of time scales, from the static storm field to the fast change associated with dart leaders.

## 1 Introduction

X-ray emissions from lightning were first discovered at Langmuir Lab by Moore et al. (2001) over twenty years ago. Moore et al. (2001) reported the discovery of X-ray photon energies up to 1.2 MeV associated with stepped lightning leaders. They also reported peak currents and electric field changes for three flashes that produced X-rays. Although the experimental setup employed by Moore et al. (2001) featured a high sampling rate of 1 MHz, they were unable to resolve energies of individual photons due to pile-up at the NaI(Th) scintillation detector. Photon pile-up refers to the situation where multiple photons arrive at the detector within a short time window (Pantuso et al., 2022). The width of this time window corresponds to the width of the voltage pulse registered in the data acquisition system, which in its turn is dictated by the decay time of the crystal and by the overall electronics of the detector. For a typical NaI(Tl) detector coupled with a photomultiplier tube (PMT), this time scale is of the order of 1  $\mu$ s or longer. This inability to resolve pile-up due to long pulse duration persisted in the subsequent studies reviewed in this Introduction. NaI(Tl) scintillation detectors were deployed at Langmuir Lab every Summer, for several years, following the Moore et al. (2001) study. The additional data collected showed that dart leaders also produce X-rays (although not all in the same flash necessarily do), and that single-photons can have (up to) gamma energies (i.e.,  $>1$  MeV as evidenced by two co-located detectors displaying a single MeV photon detected by just one of them) (Eack et al., 2006).

Substantial knowledge on the nature of X-ray emissions from lightning leaders was gained through nearly two decades of investigations at the International Center for Lightning Research and Testing (ICLRT) in Camp Blanding, FL. Dwyer et al. (2003, 2004) reported that rocket-triggered lightning also emits bursts of X-rays and that the detected energetic radiation of triggered lightning X-rays extended up to about 250 keV in discrete bursts lasting less than 1  $\mu$ s. Howard et al. (2008) confirmed the emission of X-rays from negative natural and rocket-triggered lightning strokes. Moreover, using time of arrival techniques, they were able to correlate the emission of X-rays with the stepping process. Howard et al. (2008) and Biagi et al. (2010) solidified the idea that burst of X-rays are emitted during the stepping process of negative leaders. Biagi et al. (2010) did so by using simultaneous observations with high-speed video, and measurements of current, field changes, and X-ray emissions. The work done at ICLRT showed that all types of subsequent stroke leaders (in rocket-triggered lightning) emit X-rays, including dart, dart-stepped, and “chaotic” dart leaders (Hill et al., 2012). Particularly, chaotic dart leaders (which are characterized by numerous, narrow, irregular pulses in the electric field derivative signal) seem to be more prolific X-ray emitters than the other two kinds (Hill et al., 2012).

69 Saleh et al. (2009) compared multi-station measurements of X-ray emissions made  
 70 with the Thunderstorm Energetic Radiation Array (TERA) at the ICLRT with Monte  
 71 Carlo simulations of runaway electron propagation, their collisions with air molecules,  
 72 and the subsequent Bremsstrahlung X-ray emissions. Saleh et al. (2009) reported that  
 73 the energetic electrons that emit X-rays can have a characteristic energy of about 1 MeV,  
 74 which is not consistent with the relativistic runaway electron avalanche mechanism (RREA)  
 75 (Gurevich et al., 1992), which predicts that the runaway electrons should have a char-  
 76 acteristic energy of 7.3 MeV. Schaal et al. (2012) expanded on the work of Saleh et al.  
 77 (2009) and compared measurements of spatial and energy distributions of X-ray emis-  
 78 sions made with TERA at the ICLRT with Monte Carlo simulations. Through this com-  
 79 parison Schaal et al. (2012) showed that the characteristic energy electrons responsible  
 80 for X-ray emissions in lightning leaders is less than 3 MeV. Once again in contrast to the  
 81 7.3 MeV value predicted by the RREA theory. Schaal et al. (2012) also reported that  
 82 electron luminosity increases exponentially with the return stroke current up to about  
 83 10 kA.

84 Arabshahi et al. (2015) performed measurements of the X-ray energy spectrum of  
 85 rocket-triggered lightning by developing an X-ray spectrometer. The Atmospheric Ra-  
 86 diation Imagery and Spectroscopy spectrometer (ARIS-S) is made of seven NaI(Tl) scin-  
 87 tillators coupled with PMTs. These detectors are all located next to each other and have  
 88 variable shielding around them, consisting of varying thicknesses of steel and lead, which  
 89 constrain the energy range of photons that can be stopped by a particular channel. The  
 90 combination of the multi-channel measurements with Monte Carlo simulations allowed  
 91 the authors to determine that the spectrum of X- and gamma-rays emitted by rocket-  
 92 triggered lightning follows an inverse power-law distribution  $\propto \varepsilon^{-\lambda}$ , where  $\varepsilon$  is the en-  
 93 ergy of an individual photon, and the power-law exponent  $\lambda$  varies between 2.45 and 2.92  
 94 for a particular type of leader and for the entire data set (Arabshahi et al., 2015).

95 The studies reviewed above support the idea that RREA do not play a significant  
 96 role in the production of runaway electron fluxes emitted by leader steps. In lightning  
 97 leaders, the so-called thermal (or cold) runaway mechanism seems to be a better candi-  
 98 date to explain acceleration of electrons into the runaway mode (Dwyer, 2004; Moss  
 99 et al., 2006; Celestin et al., 2015). This mechanism requires the electrical discharge to  
 100 produce electric fields in excess of 30 MV/m, ten times higher than the conventional break-  
 101 down threshold, for electrons to overcome the friction force experienced by collisions with  
 102 air molecules. d'Angelo (1987) suggested that these high fields could be present at the  
 103 streamer heads, leader tips, or even in the lower-density leader channel. Most TERA sen-  
 104 sors include detectors with NaI(Tl) scintillating crystals and suffer from pile-up issues.  
 105 However, Schaal et al.'s data set included one natural flash detected by two LaBr<sub>3</sub>(Ce)  
 106 detectors, which have a much shorter decay time. Since LaBr<sub>3</sub>(Ce) is not as subject to  
 107 photon pile-up issues, this allowed the authors to estimate the X-ray single-photon en-  
 108 ergy spectrum. Xu et al. (2017) used this data set as ground truth for their Monte Carlo  
 109 simulations, and showed that the measured X-ray spectrum of Schaal et al.'s flash is fully  
 110 consistent with the thermal runaway acceleration mechanism, for a leader with 10 MV  
 111 potential difference between its tip and the surrounding environment.

112 Mallick et al. (2012) reported X-ray emissions associated with leaders of natural  
 113 cloud-to-ground lightning and showed that, in some cases, subsequent strokes can emit  
 114 more X-rays than the leaders preceding the first return stroke in the same flash. These  
 115 authors attributed this effect to the reduced air density inside of the (warm) decaying  
 116 return stroke channel, which would allow the electric field enhancement created by the  
 117 dart leader to accelerate electrons in an environment with reduced collisional rates, i.e.,  
 118 reduced friction force (see also, Tran et al., 2019). Mallick et al. (2012) also reported that,  
 119 for strokes within 2 km of their observation facility, X-ray emissions were associated with  
 120 88% of first-stroke and 47% of subsequent-stroke leaders (see also, Kereszy, 2021, Fig-  
 121 ure 3-11).

122 The aforementioned references established that the energy spectrum of X- and gamma-  
 123 rays emitted by lightning leaders is softer than what is predicted by the RREA theory.  
 124 The RREA theory (augmented by relativistic feedback mechanisms), nonetheless, suc-  
 125 cessfully explains the spectra of Terrestrial Gamma-ray Flashes (TGFs), emitted upward  
 126 by thunderclouds and registered at satellite altitudes (Dwyer & Smith, 2005; Dwyer, 2008).  
 127 The story becomes more complicated when we consider downward TGFs, particularly  
 128 the ones timed to the downward leader propagation, which are observed at the Utah Tele-  
 129 scope Array (TA) (Abbasi et al., 2018, 2023; Belz et al., 2020). The TA downward TGFs  
 130 seem to have a harder spectrum than leader X-rays, but at the same time, weaker flu-  
 131 ence than upward TGFs. In the words of Smith et al. (2018), the existence of the TA  
 132 TGFs blurs the clear-cut distinction between leader X-rays (soft, weak) and TGFs (hard,  
 133 strong).

134 Measurements of X-rays emitted by natural lightning are quite important for pin-  
 135 ning down their source mechanisms and the role of runaway electrons in leader physics.  
 136 However, spectral information on the X-rays emitted by natural lightning are still scant  
 137 in the literature, since the vast majority of data acquired at the ICLRT correspond to  
 138 rocket-triggered lightning and/or it was collected with NaI(Tl) detectors. To the best  
 139 of our knowledge, there is only one (other) report of a direct measurement of the energy  
 140 spectrum of X-rays emitted by a natural lightning flash, and it is the single-stroke flash  
 141 MSE 10-01 in Schaal et al. (2012, Figure 10). By “direct”, we mean without contam-  
 142 ination of photon pile-up, and not indirectly determined via Monte Carlo simulation. The  
 143 present paper is aimed at augmenting the data available on the energy spectrum of X-  
 144 and gamma-rays emitted by natural lightning. We report on the composite spectra of  
 145 four natural flashes recorded in the Summer of 2022 at Langmuir Lab with a fast LaBr<sub>3</sub>(Ce)  
 146 detector. We confirm the spectral dependence previously reported in the literature and  
 147 show that stepped leaders have a harder spectrum than dart leaders.

## 148 2 Methods

149 Over two decades after the original discovery, Langmuir Lab’s mountain-top facil-  
 150 ity (Figure 1) remains an ideal place to perform X-ray observations of natural lightning  
 151 due to three main reasons: (i) orographic effects facilitate the formation of single-cell con-  
 152 vective thunderstorms over the lab during the yearly monsoon season, (ii) at 3.3 km above  
 153 mean sea level, the lower air density reduces photon attenuation, and (iii) Langmuir Lab  
 154 has an extensive list of co-located atmospheric electricity instruments that provide bet-  
 155 ter context on the production of runaway electrons. The main instrument — the X-ray  
 156 instrument box — was deployed atop of an underground Faraday cage room (called Kiva,  
 157 Figure 1a) located on South Baldy peak, the highest peak in the Magdalena Mountains  
 158 in central New Mexico. This is the exact same location where Moore et al.’s detectors  
 159 were located. Figure 1c shows South Baldy peak as viewed from the Langmuir Lab main  
 160 facility, which is located 1.8 km away. Below we present the instrumentation and meth-  
 161 ods used in this study.

### 162 2.1 Sensors

163 A key feature of the present investigation is the use of a fast data acquisition sys-  
 164 tem (DAS). The DAS used is similar to the one used by Akita et al. (2014) and subse-  
 165 quent lightning interferometry works (Rison et al., 2016; Jensen et al., 2021), and it op-  
 166 erated at a 180 MHz sampling rate. This DAS was housed inside of the Kiva and linked  
 167 to the same slow electric field antenna Moore et al. (2001) used to trigger their exper-  
 168 imental setup. This slow antenna has a time constant of 31 ms and triggered data ac-  
 169 quisition when the electric field change reached 2.5 kV/m. Four sensors were connected  
 170 to our DAS:

171 **LaBr** A  $2'' \times 2''$  LaBr<sub>3</sub>(Ce) scintillation detector (hereafter simply referred to as LaBr)  
 172 manufactured by Saint-Gobain was mounted in our instrument box on top of the  
 173 Kiva (Figure 1b) to detect the X-ray emissions. The LaBr crystal has a fast de-  
 174 cay time of 16 ns, which results in a narrow voltage pulse recorded in the DAS (<100  
 175 ns). The pulse has rise/decay times of 16/54 ns. The background radiation rate  
 176 during storm time for the LaBr was measured to be 1 photon per 3 ms.

177 **NaI** The X-ray instrument box also contained a  $2'' \times 2''$  NaI(Tl) scintillation detector  
 178 (hereafter NaI for short). This detector was included for the sake of presenting a  
 179 comparison between the two types of detectors used in this research area. This  
 180 particular NaI unit is connected to a pulse-shaping amplifier, making the regis-  
 181 tered voltage pulse have a duration of  $>10 \mu\text{s}$ . This is the result of a design choice  
 182 made in our group for a previous research project. This was needed to allow for  
 183 the operation of NaI detectors with 100 kHz data acquisition systems. All key re-  
 184 sults of this paper are based on the LaBr detector measurements, and the NaI data  
 185 is just shown for comparison. The background radiation rate during storm time  
 186 for the NaI detector was measured to be 1 photon every 20 ms.

187 **Fast antenna** A fast electric field change antenna (FA) with a time constant of  $100 \mu\text{s}$   
 188 and a flat bandpass (between 20 kHz and 70 MHz) was used to measure rapid field  
 189 changes from lightning leaders. The FA uses the standard “inverted salad bowl”  
 190 design and it sits on top of the Kiva, essentially co-located with the X-ray sensors  
 191 (Figure 1a).

192 **Timing** A microsecond resolution GPS unit (Figure 1b) was used to time the the record-  
 193 ings of the three instruments described above. This allowed for synchronization  
 194 of our measurements with other instruments located at Langmuir Lab and with  
 195 the Earth Networks Total Lightning Detection Network (ENTLN) data.

196 We used the following supporting instruments and data sets to characterize the flashes  
 197 analyzed in this paper:

198 **Slow antenna** As mentioned above, an insensitive slow antenna with time constant of  
 199 31 ms was used to trigger the DAS. It has the same antenna design as the one used  
 200 in Moore et al. (2001) and it was sampled at 250 kHz.

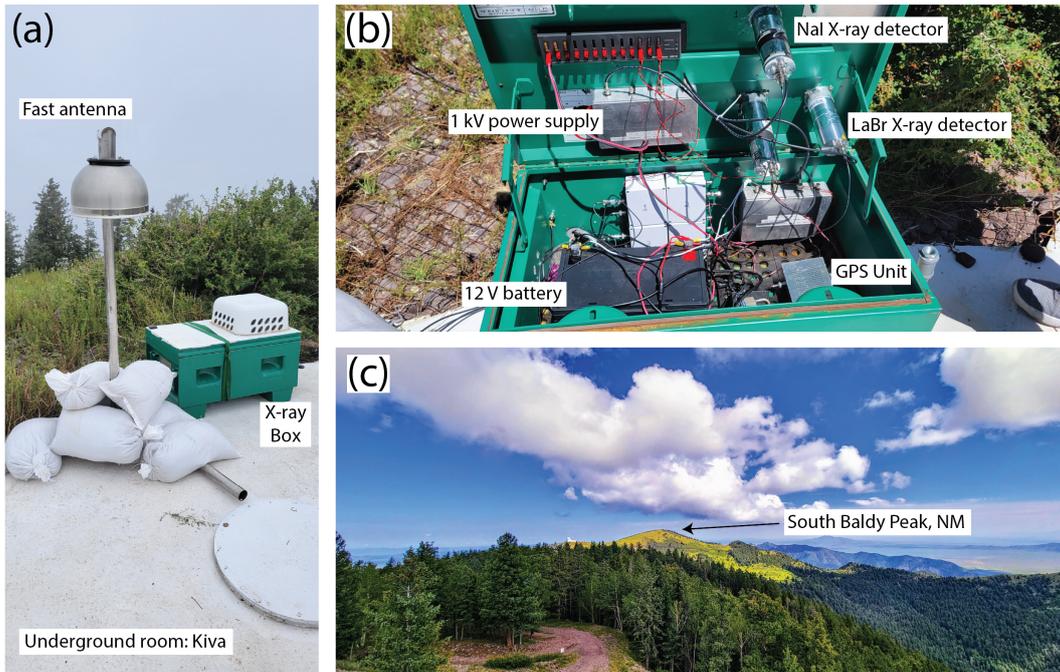
201 **LEFA** A single station from the Langmuir Lab’s Lightning Electric Field Array (LEFA)  
 202 (Lapierre et al., 2014; Contreras-Vidal et al., 2021) was used in this study. LEFA  
 203 is characterized by its ultra-slow time constant (3 s) and high dynamic range (con-  
 204 sisting of three different gain levels). LEFA provided us with additional informa-  
 205 tion to distinguish between dart and stepped leaders, particularly when the FA  
 206 saturates. LEFA recordings were digitized at 50 kHz.

207 **Field mill** A field mill recording at 10 Hz was used in this analysis. Field mills are ca-  
 208 pable of capturing the slow field changes associated with the overall storm elec-  
 209 trification and subsequent dissipation (Christian et al., 1980).

210 **THOR** One of the units of the Terrestrial High-energy Observations of Radiation (THOR)  
 211 instrument (Smith et al., 2019) was deployed at Langmuir Lab during the Sum-  
 212 mer of 2022. THOR is located at the main lab, 1.8 km away from our X-ray sen-  
 213 sor. THOR did not record energetic emissions associated with any of the flashes  
 214 analyzed in this paper. This fact is briefly used later to constrain the footprint  
 215 size of the X-ray emissions.

216 **ENTLN** We used the Earth Networks Total Lightning Detection Network (ENTLN)  
 217 data to assist us with flash classification (cloud-to-ground versus intracloud), as  
 218 well as determining stroke order. More importantly, ENTLN provided the flash  
 219 peak current and location (i.e., distance to the X-ray sensor).

220 We used 4 electric field antennas to give proper flash context and be able to “see”  
 221 field changes from fast to very slow lightning and storm processes. In order of increas-  
 222 ing time constant we had: the fast antenna, slow antenna, LEFA, and the field mill. The



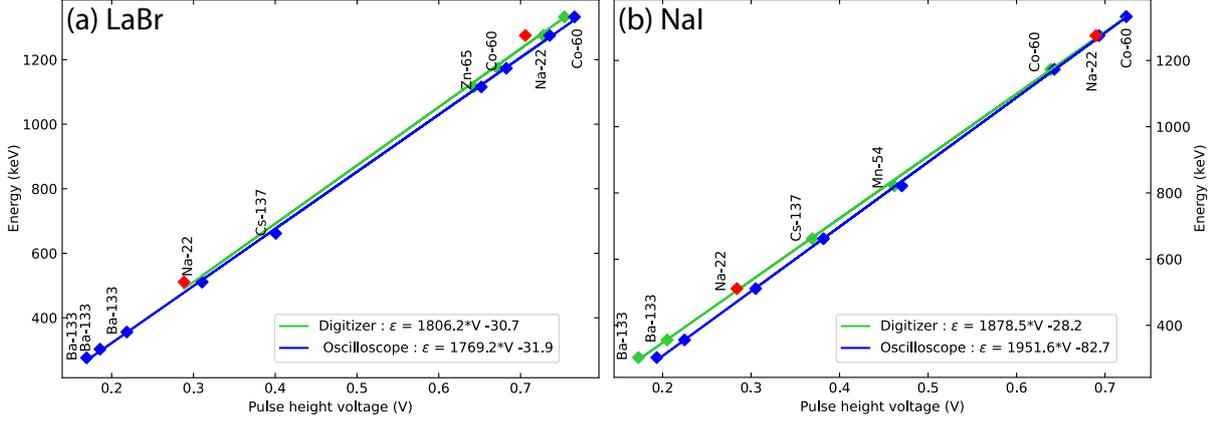
**Figure 1.** Instruments & deployment. (a) X-ray box and fast electric field antenna on top of the Kiva underground Faraday cage room (which houses the 180 MHz data acquisition system). (b) X-ray box contents: LaBr and NaI X-ray detectors, power source, and the GPS unit. (c) The Kiva sits atop South Baldy Peak in the Magdalena Mountains photographed from the Langmuir Lab main facility. Not shown are Langmuir’s slow antenna and (non-collocated) LEFA.

223 slow antenna and field mills have been used in our group for many years and have been  
 224 properly calibrated. The calibration includes determining the gain factor associated with  
 225 placing the antenna on a stand 1 m above ground level and also with deploying it in a  
 226 mountainous terrain. For this study LEFA and the FA were not directly calibrated. In  
 227 order to display them in the same plot as the slow antenna we have empirically deter-  
 228 mined the calibration factors by ensuring that they (FA and LEFA) predict the same  
 229 field changes as the slow antenna. Therefore, we only report quantitative field changes  
 230 measured by the slow antenna. For the other two antennas, qualitative field change fea-  
 231 tures are used to discern between dart and stepped leaders.

## 232 2.2 X-ray detector calibration

233 Standard radioactive sources were selected to calibrate and test the linear response  
 234 of the LaBr and NaI detectors. Figure 2a and 2b show data from the five sources used  
 235 (Ba-133, Na-22, Cs-137, Zn-65, Co-60) and the linear response of each detector. All sources  
 236 were placed 10 cm above the detector. Figures 2a & 2b show that both detectors have  
 237 a linear response in the range of interest. In a separate study, the linearity of the LaBr  
 238 detector was verified down to 20 keV (Contreras-Vidal et al., 2022).

239 The two detectors were powered with the same power supply at 1 kV, which de-  
 240 fined their gain. As a consequence, the maximum energy that each detector was able to  
 241 record was 6 and 1 MeV, for the LaBr and NaI, respectively. The PMT gain can be in-  
 242 fluenced by the external temperature. In order to check if this may introduce large er-  
 243 rors, we collected data with the Na-22 source at the field during a hot Summer day (dur-  
 244 ing deployment). Figure 2 shows that the data collected in the field (red symbols) agrees



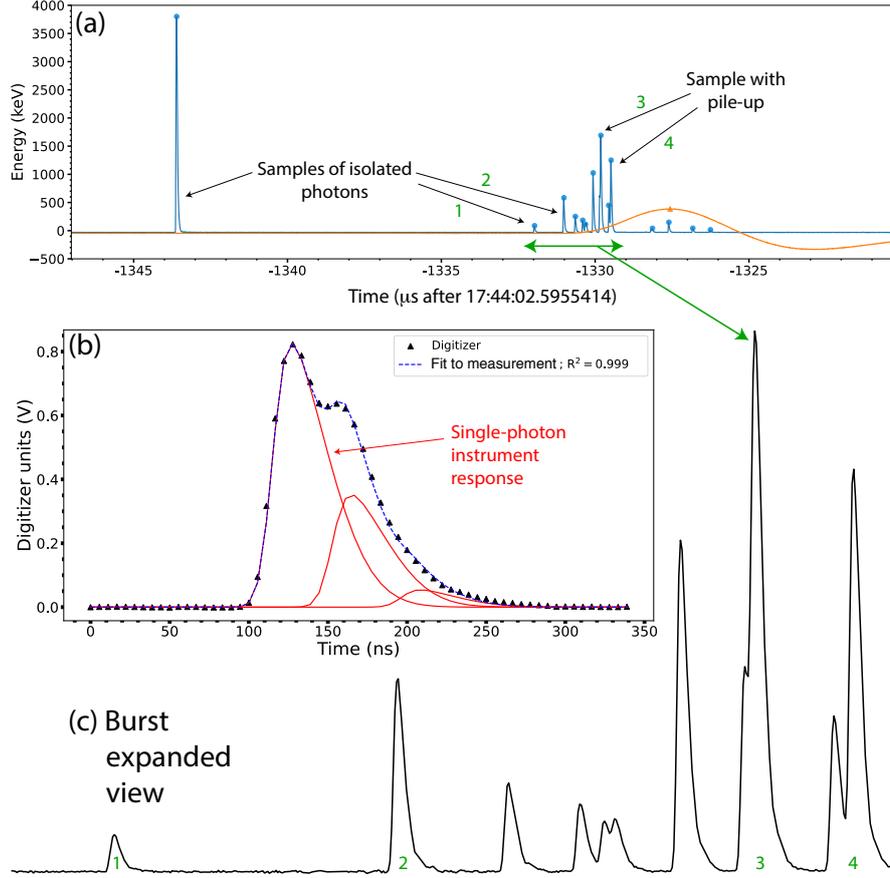
**Figure 2.** Calibration of the X-ray detectors using 5 different standard radioactive sources. Panels (a) and (b) show the linear response of the LaBr and NaI detectors, respectively. The green line corresponds to the response of the detectors using our DAS, while the blue line corresponds to the response of the detectors using a LeCroy HDO6014a oscilloscope (same as in Contreras-Vidal et al., 2022). The red symbols correspond to data collection with the DAS at the field site.

245 well with the data collected in the lab (green symbols). The figure also shows that both  
 246 also agree well with data collected using a different acquisition method (a standard os-  
 247 cilloscope, shown as blue symbols). Since the agreement has been deemed good, no cor-  
 248 rection for temperature has been added to the voltage-to-energy conversion formula (listed  
 249 in the figure legend).

### 250 2.3 Photon pile-up resolution

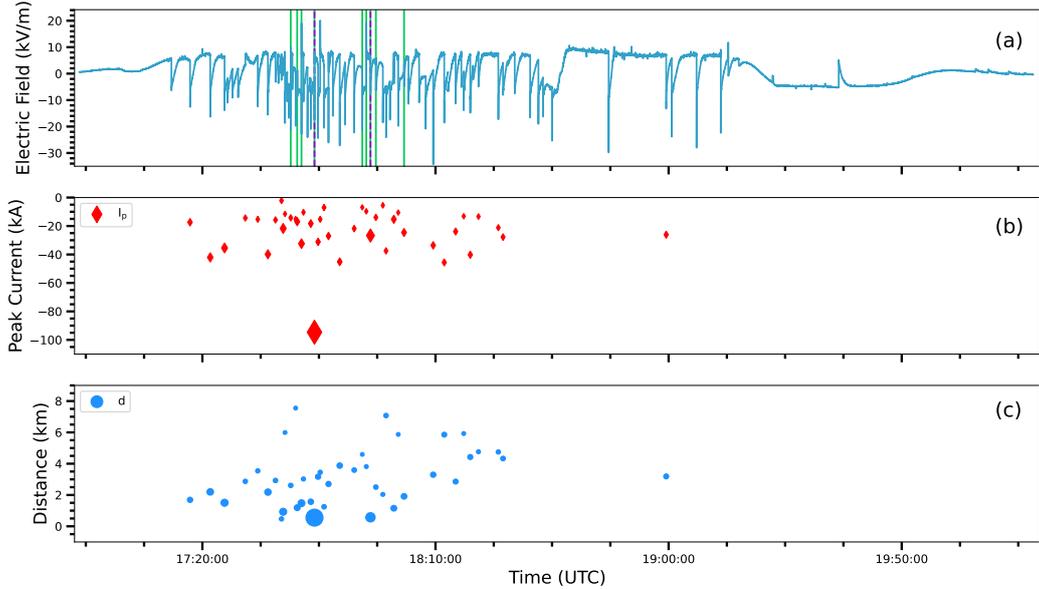
251 Figure 3a shows an X-ray burst from event A1 (discussed later). Pile-up can be seen  
 252 in the form of the characteristic X-ray pulse shapes being interrupted by incoming pho-  
 253 tons arriving within the pulse duration, less than 100 ns apart. In this work we are able  
 254 to resolve photon pile-up due to three main reasons: (i) we employ a fast scintillator, which  
 255 has a crystal with short decay time, of 16 ns, (ii) we collect data at a high-sampling rate  
 256 of 180 MHz, corresponding to 5.56 ns between samples, and (iii) the recorded flashes took  
 257 place at a typical distance of 500 m from the LaBr detector. The latter effect reduces  
 258 pile-up because Compton scattering will tend to spread the photons in a given burst spa-  
 259 tially and, as a consequence, temporarily. Photon pile-up is a major issue in the inter-  
 260 pretation of laboratory measurements due to the compactness of the spatial scales in-  
 261 volved, of the order of 10s of centimeters (Contreras-Vidal et al., 2022; da Silva et al.,  
 262 2017; Pantuso et al., 2022). This issue is also present in the measurements of rocket-triggered  
 263 lightning X-rays, where detectors are 10s of meters away from the source (Saleh et al.,  
 264 2009; Schaal et al., 2012). However, factor (iii) alone alleviates this issue substantially  
 265 as the distance between source and detector increases to 100s of meters.

266 Data from the LaBr detector calibration provided a wealth of characteristic X-ray  
 267 pulse shapes. An analytical expression was obtained for the X-ray pulse shape by nor-  
 268 malizing a synthesis of fifty X-ray pulses from calibration data and fitting them with a  
 269 closed-form function. This is the impulse response of the LaBr to a single photon, and  
 270 it was best fit by a skewed Gaussian function. These fits lined up with our character-  
 271 istic X-ray pulse on the order of  $R^2 \geq 0.999$ . Once this analytical fit was obtained, only  
 272 the height and location of the pulse needed to be adjusted to match the recorded traces.



**Figure 3.** (a) A 20- $\mu\text{s}$  X-ray burst from event A1. The recorded voltage traces for the LaBr and NaI detectors are shown in blue and orange, respectively. (b) An example of photon pile-up occurrence and our strategy to resolve it. This particular pulse did not occur during the burst shown in panel (a). Panel (b) shows that photon pile-up can be resolved if photons arrive more than 16-ns apart by fitting the recorded waveform with several single-photon impulse responses (with different arrival times and amplitudes). (c) Expanded view of the LaBr X-ray burst with sample photons labelled.

273 Occurrences of photon pile-up were manually isolated by locating irregular X-ray  
 274 pulse shapes in the LaBr detector channel. X-ray pulses derived from our analytic fit were  
 275 then placed nearby the pileup event, at which point their locations and magnitudes would  
 276 be adjusted until their collective sum fitted the piled-up event with a coefficient of deter-  
 277 mination no less than 0.97. A plot of one such pile-up resolution process is shown in  
 278 Figure 3b. The solid red curves correspond to the single-photon impulse response, with  
 279 the digitizer data shown as black triangular markers. The dashed, blue line is the sum  
 280 of all red pulses, fitting the digitizer data with  $R^2 = 0.999$ . After analyzing all data re-  
 281 ported in this paper, which consists of hundreds of X-ray pulses correlated to lightning  
 282 activity, we found that pile-up occurred in only 12% of all recordings. The remaining  
 283 88% are perfectly fit by the single-photon impulse response. Tests with the fitting pro-  
 284 cedure shown in Figure 3b revealed that if two photons arrive within the decay time of  
 285 the crystal ( $=16$  ns or four samples), the system is not able to resolve the two photons.

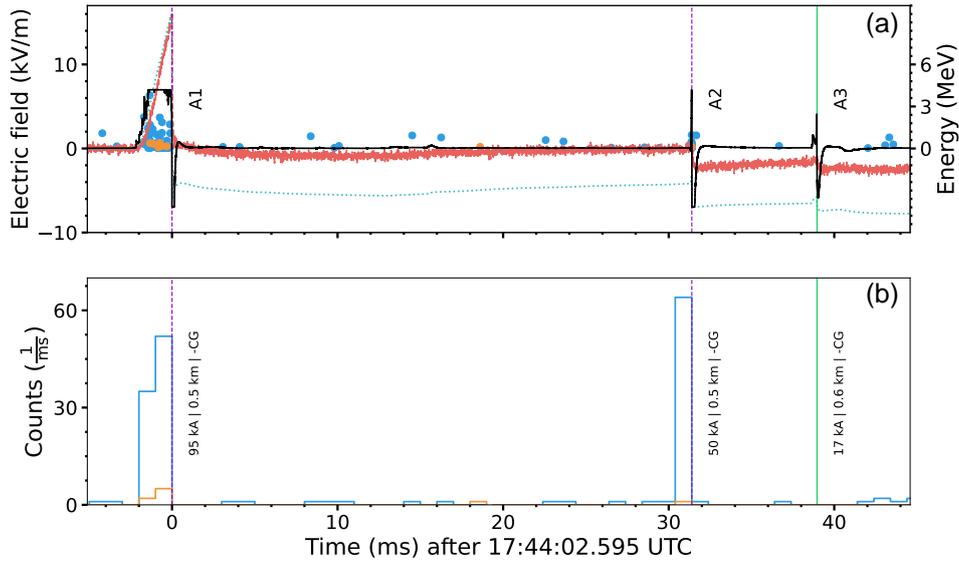


**Figure 4.** An overview of the observed thunderstorm on August 9, 2022, lasting from approximately 17:00 to 20:00 UTC. (a) Information from Langmuir’s electric field mill spanning the whole storm. Vertical lines indicate lightning flash that triggered our system, with purple lines indicating triggers with X-ray observations. (b) A display of peak return stroke current for individual  $-CG$  flashes within 10 km of South Baldy peak. (c) Flash distance to the X-ray detectors, as reported by ENTLN. In panels (b) and (c) markers are sized according to the ratio of peak current to distance, which makes the two events with X-ray detections stand out.

### 286 3 Results

287 Our most interesting recordings took place during a midday thunderstorm on Au-  
 288 gust 9, 2022. This storm lasted approximately three hours between 17:00 and 20:00 UTC  
 289 (11 AM to 2 PM local time), as shown in Figure 4. Figure 4a shows the measured elec-  
 290 tric field through the storm as seen by an electric field mill. The storm’s main stage has  
 291 a positive electric field (i.e., directed upward) due to the dominant effect of negative charge  
 292 overhead. This is indicative of a normally-electrified storm. The numerous negative def-  
 293 lections (or dips) in the field mill record are negative cloud-to-ground lightning flashes  
 294 ( $-CG$ s). At the end of the record we can see a characteristic end-of-storm oscillation in  
 295 the electric field (Moore & Vonnegut, 1977).

296 The nine vertical lines indicate flashes that triggered the DAS, with the two pur-  
 297 ple lines indicating triggers containing X-ray detections. These flashes were correlated  
 298 with ENTLN data to obtain their peak current, classification, and distance from the Kiva  
 299 for each individual stroke in a flash (Zhu et al., 2017). Figure 4b shows the peak cur-  
 300 rent for all  $-CG$  flashes within 10 km of the X-ray detectors. Figure 4c shows the ac-  
 301 tual distance between these lightning flashes and the X-ray detectors. As discussed by  
 302 Mallick et al. (2012), the probability of detecting X-rays from lightning increases with  
 303 peak current ( $I_p$ ) and decreases with distance ( $d$ ). Therefore, we can speculate that the  
 304 probability of detecting X-rays should increase with the following ratio:  $I_p/d$ . The size of  
 305 markers in Figures 4b–4c are scaled according to the  $I_p/d$  ratio, and we can clearly  
 306 see that the two flashes containing X-ray emissions stand out, particularly the first one.  
 307 The ratio  $I_p/d$  is proportional to the measured field change, which is also a proxy for the



**Figure 5.** The first three return strokes in flash A on a scale of tens of milliseconds. (a) Data from electric field antennas and X-ray detectors. The three traces correspond to the slow antenna (red), LEFA (dotted teal curve), and fast antenna (black). X-ray energy pulse peak locations are shown as blue (LaBr detector) and orange (NaI) dots. (b) Histogram showing photon counts in a one-millisecond window by the LaBr (blue) and NaI (orange) detectors. For return strokes with associated X-ray observations, all photons were detected during the preceding leader phase.

308 probability of detecting X-rays. We note that the  $1/d$  scaling is not the precise trend for  
 309 deposited X-ray energy versus distance. According to Saleh et al. (2009), this trend is  
 310 actually  $\propto \exp(-d/120 \text{ m})/d$ , with the additional decaying exponential term arising from  
 311 X-ray absorption and scattering in air.

312 Figure 5 shows a zoom on the order of tens of milliseconds of the first lightning flash  
 313 containing X-rays and its individual return strokes. This flash took place at 17:44:02.6  
 314 UTC and it is referred hereafter as flash “A”. Each individual return stroke reported by  
 315 ENTLN, including the one that triggered the system, are represented as vertical lines.  
 316 In a similar fashion as Figure 4a, return strokes of leaders with X-ray observations are  
 317 marked by dashed, purple lines, with all other strokes marked with solid, green lines. In-  
 318 cluded with each return stroke are reported ENTLN data, such as classification (IC vs. CG),  
 319 peak current, and distance to the X-ray detectors. This lightning flash was composed  
 320 of five return strokes (events A1 to A5). Only the leaders associated with the first (event  
 321 A1, a stepped leader) and second (event A2, a dart leader) strokes produced detectable  
 322 X-rays. Both events A1 and A2 lead to return strokes with high peak currents of 95 and  
 323 50 kA, respectively. As shown previously in Figure 4, flash A clearly stands out as hav-  
 324 ing the highest peak current of the entire storm and by taking place very close to our  
 325 detectors.

326 In Figure 5a, the recorded electric field changes are shown alongside the X-ray sen-  
 327 sors. The slow antenna is shown as a red dashed line, LEFA as a teal-  
 328 dotted line, while the fast antenna is overlaid as a solid, black curve. During this cam-  
 329 paign, the FA was designed to provide accurate electric field readings up to 7 kV/m be-  
 330 fore saturation. This figure is given in scaled units, as discussed in Section 2.1. Saturat-

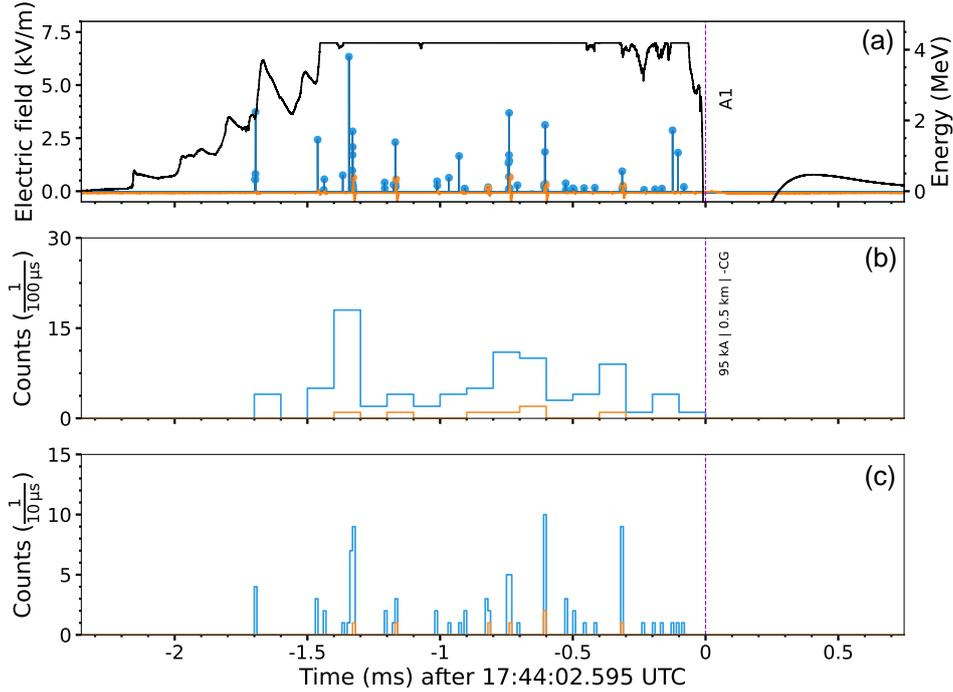
tion in the fast antenna can be seen in events A1 and A2 in Figure 5a, but not A3. In conditions where the fast antenna saturates we rely on the additional information provided by the other two antennas. Looking at the electric field records it is often pretty easy to tell stepped and dart leaders apart. Stepped leaders display this characteristic ramp in the electric field change prior to the return stroke dip, which lasts on the order of milliseconds, and is associated with the downward motion of the stepped-leader network (see event A1).

The dots in Figure 5a show the energy of detected X- and gamma-ray photons, with the LaBr (blue) and NaI (orange) detectors. The ordinate of each dot represents its energy with values indicated on the right-hand side vertical axis. The histogram in Figure 5b correspond to the number of photons observed by each detector in a one-millisecond time window, using the same color scheme as in Figure 5a. It is clear that events A1 and A2 had photon counts much higher than the background rate of the LaBr detector (1 photon every 3 ms). Event A1 had 87 photons associated with it, detected during the stepped leader descent. The average energy of the detected photons was 416 keV and the maximum energy was 3.8 MeV (well into the gamma range). Event A2 had 64 photons detected during the dart leader descent, with an average energy of 138 keV and a maximum of 969 keV.

Figure 6 has a similar format to Figure 5 with the key difference being that we display a zoom, of the order of milliseconds, into event A1 to show the X-ray detections in greater detail. Figure 6a includes again electric field information from the fast antenna, but omits data from the other two antennas for the sake of clarity. X-ray peak locations are included, as well as the full trace of each X-ray detector channel. Figures 6b and 6c show histograms of photon counts by each detector binned in 100- and 10- $\mu$ s windows, respectively. A brief glance at Figure 6b would indicate that the X-ray emissions are continuous and last for 1.5 ms. The higher temporal resolution of Figure 6c reveals that X-ray photons come in bursts. Our interpretation of these results is that, in alignment with previously-published work, these bursts are associated with leader steps. Nonetheless, attempts to align the bursts in Figure 6c with features in the LEFA recording (which did not saturate) did not yield a straightforward correlation. This is likely due to the fact that there must be a multitude of leader tips stepping towards the ground at any given time (see e.g., Urbani et al., 2021). The photon burst highlighted in Figures 3a and 3c is an excerpt of this event and took place 1.33 ms before the return stroke. A comparison between the NaI and LaBr data reveals that the fewer NaI detections correlate with stronger bursts seen in the LaBr detector (Figures 6b–6c). This lends further credence to the conclusion that the X-rays from stepped leaders come in bursts. Hereafter, we shall focus the discussion on the LaBr data, and the NaI detections will be shown simply for the sake of completeness. Figure 6 makes the obvious case that the LaBr detector can reveal so much more details about the source.

Figure 7 shows a zoom on the order of tens of microseconds into event A2, a dart leader followed by a subsequent return stroke. An immediate noteworthy observation of this event is that all the X-ray emissions of this event occurred on a comparable time scale of one single burst of event A1. The stepped leader produce 87 (detectable) photons in 1.7 ms, while the dart leader produced 64 photons in under 25  $\mu$ s. It seems that the dart leader X-ray emission process behaved as a single, very-intense stepped leader step. Figure 7a shows that the field change associated with a descending dart leader also ramps up from zero prior the return stroke. But the key difference is that this process is much faster than in a stepped leader, of the order of tens of microseconds.

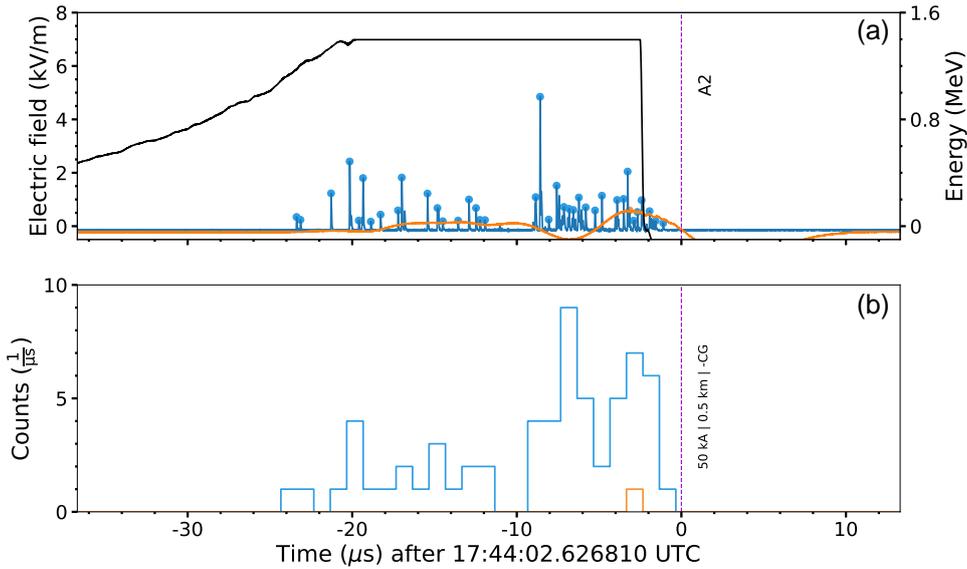
We zoom even further into the X-ray pulses and catalog the energies of all individual photons that were recorded in the LaBr detector. As discussed in Section 2.3, we are able to distinguish individual photons to a 16-ns temporal resolution. The same process was repeated for other 3 flashes of the 2022 monsoon season where X-rays were observed. They are referred to as flashes B, C, and D in the Appendices. The LaBr detector reg-



**Figure 6.** A zoom into event A1, the first return stroke and preceding stepped leader from Figure 5, on a scale of a few ms. (a) Electric field measured with the fast antenna (on the left-hand side axis), plotted alongside the X-ray detections (full trace and peaks with values displayed on the right axis). (b-c) Histogram showing photon counts in 100- and 10- $\mu$ s windows. Across the three panels, data for the LaBr and NaI detectors are displayed in blue and orange colors, respectively.

384 istered a total of 127 and 120 photons associated with stepped and dart leaders, respec-  
 385 tively, across these four flashes. The median energy of photons emitted by stepped lead-  
 386 ers is 115 keV, while their maximum value is 3.8 MeV. Meanwhile, photons emitted by  
 387 dart leaders had a median energy of 65 keV and a maximum of 1.16 MeV. A summary  
 388 of each event’s number of photons, maximum energies, peak electric fields, and ENTLN  
 389 stroke information is provided in Table A1 in Appendix A.

390 Figure 8 shows the measured X- and gamma-ray spectrum. The top row shows data  
 391 for flash A discussed in detailed in this Results section, while the bottom row shows com-  
 392 posite spectra for the four flashes recorded in the Summer of 2022. The spectra shown  
 393 in the four panels follows a power-law distribution,  $\propto \varepsilon^{-\lambda}$ , in agreement with Arabshahi  
 394 et al. (2015), with varying values of the exponent  $\lambda$ . The power-law index was determined  
 395 in the four plots by fitting the closed-form dependence to the data, yielding fits with  $R^2 > 0.88$ .  
 396 The inferred  $\lambda$  values are listed in the figure legends. A comparison between the spec-  
 397 tra of stepped (Figures 8a,8c) and dart (8b,8d) leaders reveals that, although both spec-  
 398 tra are similar, dart leaders have a softer spectrum with a much lower population of  $>1$   
 399 MeV photons. The power-law index for stepped leaders is  $\lambda = 1.21$ , while for dart lead-  
 400 ers it is  $\lambda = 1.96$ . Note that a smaller value of  $\lambda$  corresponds to a distribution with a longer  
 401 tail. For different types of dart leaders in rocket-triggered lightning, Arabshahi et al. (2015)  
 402 reported  $\lambda = 2.45\text{--}2.53$ , which is 25–29% larger than the value reported here. This means

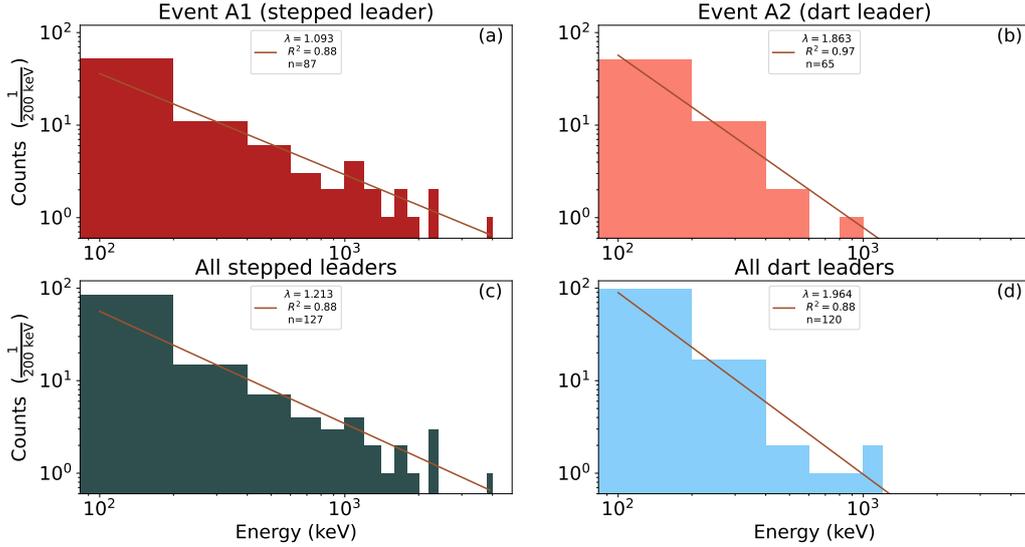


**Figure 7.** A zoom into event A2 from Figure 5, a dart leader followed by a subsequent return stroke, on a scale of tens of microseconds. The figure format is the same as in Figure 6, with the only difference that the histogram in panel (b) is binned in  $1\text{-}\mu\text{s}$  windows.

403 that, contrasting these two particular data sets, we can say that the energy spectra of  
 404 (natural) dart leaders recorded at Langmuir Lab is (somewhat) harder than in rocket-  
 405 triggered lightning at ICLRT. It should be noted that the composite spectra (Figures  
 406 8c–8d) are dominated by events A1 and A2 (8a–8b). These events contributed to over  
 407 60% of the detected photons. Nonetheless, there is a measurable difference in the power-  
 408 law index between flash A versus the entire data set, with the latter producing 5–10%  
 409 larger  $\lambda$  values.

410 Mallick et al. (2012) reported that in some cases a dart leader (leading to a sub-  
 411 sequent stroke) in a flash can produce more X-rays than the first-stroke (stepped) leader.  
 412 These authors argue that the reduced air density in the (pre) dart-leader channel may  
 413 facilitate runaway electron acceleration. Our observations reveal that the picture may  
 414 be far more complex than that, i.e., that the X-ray emission process is profoundly dif-  
 415 ferent between stepped and dart leaders. We make this statement based on the vastly  
 416 different temporal patterns reported in Figures 6 and 7, as well as, on the different spec-  
 417 tral hardness in Figures 8a and 8b. The stepped leader emits X-rays over a long time  
 418 period, of  $\gtrsim 1$  ms, while the dart leader X-rays come within  $\sim 25$   $\mu\text{s}$ . Despite the distinctly  
 419 different durations, the amount of X-ray photons detected is similar. The stepped leader  
 420 produced more photons, but just 36% more. In just one of the four flashes reported in  
 421 this paper (in the Appendices), the X-ray count in a dart leader superseded the stepped  
 422 leader.

423 We interpret our findings as indicative of two key differences between stepped- and  
 424 dart-leader X-ray emissions. First, the stepped leader photon spectra is harder because  
 425 it is able to accelerate electrons to higher energies. This likely happens because the elec-  
 426 tric fields at the tips of advancing stepped leaders are higher than in dart leaders, since  
 427 the former needs to break down virgin air to propagate. Perhaps even the impulsive nature  
 428 of the stepping process facilitates acceleration. Second, dart leaders are somewhat



**Figure 8.** Energy spectra of X- and gamma-ray photons emitted by natural lightning, for flash A only (a-b), and for the entire data set (c-d). The left- and right-hand side panels show data for stepped and dart leaders, respectively. Across the four panels, experimentally-determined spectra, binned in 200 keV bins, is compared to power-law distribution fits.

429 more efficient X-ray producers. They are able to emit a comparable amount of X-rays  
 430 in a substantially-shorter time window. A significant portion of the asymmetry in the  
 431 emission’s temporal profile can be explained from the fact that dart leaders are roughly  
 432 ten times faster than stepped leaders (da Silva et al., 2023; Jensen et al., 2021).

433 The photon energy spectra of stepped leaders extends well into the gamma range.  
 434 This helps fuel the idea that there may not be a clear cut distinction between leader X-  
 435 rays and downward TGFs (particularly the downward TGFs that take place during leader  
 436 propagation, such as the ones observed at the Utah Telescope Array). It may be that  
 437 if the potential drop between leader tip and environment is just large enough to accel-  
 438 erate runaway electrons (e.g., a few MV), the X-ray emissions display a soft power-law  
 439 spectrum. This is the case of our dart-leader detections. If we increase the potential drop,  
 440 we start measuring a harder power-law spectrum, such as we see in the stepped-leader  
 441 recordings. If the potential becomes becomes very large (in the 100s of MV), the field  
 442 around the leader tip may be able to sustain avalanching, and the photon spectra will  
 443 have the characteristic RREA shape (Celestin et al., 2015).

444 We conclude the discussion by noting that the footprint of the X-ray emissions detected  
 445 at Langmuir Lab is no larger than 2 km wide (or 1 km radius). We have reached  
 446 this conclusion based on two facts. First, no detections were made for lightning flashes  
 447 that happened more than 0.6 km away from the sensors. The August 9 storm contained  
 448 additional triggers, all marked as vertical lines in Figure 4. Triggers corresponding to  
 449 flashes that took place more than 1.2 km away from the sensor did not contain X-ray  
 450 emissions. Flash-to-sensor distance was estimated using ENTLN data, which reported  
 451 semi-major ellipse errors of 100–200 m. Second, the UCSC THOR instrument was lo-  
 452 cated 1.8 km (roughly) South of our X-ray sensors. THOR did not register any concur-  
 453 rent surges in X-ray emissions associated with the four lightning flashes presented in this  
 454 paper. The estimated size of the X-ray emission footprint lays in between the ICLRT  
 455 triggered dart-leader X-rays (of <1 km in diameter in Schaal et al., 2012) and the Utah  
 456 TA downward TGFs (of <5 km in diameter in Abbasi et al., 2018).

## 4 Summary and conclusions

In this article, we described in detail a natural lightning flash and its X- and gamma-ray emissions. This flash was detected by two X-ray instruments, including a fast LaBr scintillator connected to a 180 MHz digitizer, as well as four electric field-sensing antennas. These four antennas can probe a multitude of time scales, revealing contextual details of the storm, its flashes, and their individual leaders. In this flash, the X-ray emission associated with the first-stroke, stepped leader lasted 1.7 ms and came in multiple bursts, meanwhile the X-ray emissions associated with the subsequent stroke leader (a dart leader) lasted only 25  $\mu$ s. Despite the shorter duration, the dart leader managed to produce a comparable amount of X-rays. This is in alignment with the findings of Mallick et al. (2012), who found that in some flashes a subsequent stroke leader may produce more X-rays than the first-stroke one. We have one case, presented in the Appendices, that behaved in a similar manner.

Furthermore, we reported the composite energy spectra of four lightning flashes recorded in the Summer of 2022 at Langmuir Lab, and discriminated them according to the type of leader: stepped (4 cases) versus dart (7 cases). Our results show that X-ray emissions associated with both stepped and dart leaders follow an inverse power-law distribution, and contain no significant evidence of RREA contribution. This in agreement with previous work by Arabshahi et al. (2015) and Xu et al. (2017). We also determined that the energy spectra of stepped leaders seem to be harder than dart leaders, i.e., containing more gamma ( $>1$  MeV) photons, and displaying a longer tail. We interpret these findings as a consequence of the fact that electric fields at the tips of stepped leaders must be stronger than in dart leaders, since the former needs to break down virgin air to propagate. One may speculate that if a particular stepped leader has a very high potential drop with respect to the environment, RREA may take place around the leader tip, and bring the fluence to the high levels associated with TGFs.

Since our conclusions regarding the spectral characteristics of leader X-rays are based on just 4 flashes, we must deem these results preliminary, and must plan to continue with the experimental campaigns to collect more data. Future work may include correlating X-ray emissions with three-dimensional flash structure, as revealed by the Lightning Mapping Array (da Silva et al., 2023), or by broadband interferometry (Jensen et al., 2021; Urbani et al., 2021). We determined that the footprint of the X-ray emission has roughly 1 km radius, and we estimate (in the Appendices) that we should be able to record  $\sim 10$ – $20$  strikes per year within this distance of our instrument.

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## 665 Appendix A Data log

666 Table A1 contains a list of flashes that triggered our data acquisition system (DAS).  
 667 The top section shows all flashes that triggered the DAS during the August 9, 2022 thun-  
 668 derstorm, while the bottom section contains two additional flashes with X-ray emissions  
 669 recorded during different days that Summer. The system triggered on 9 flashes during  
 670 the August 9 storm, but only two produced detectable X-rays (all are marked with ver-  
 671 tical lines in Figure 4). In Table A1, for flashes that did not produce X-rays, we only dis-  
 672 play basic information pertinent to the entire flash, such as mean distance to sensors,  
 673 largest peak current, and peak field change. Meanwhile, for flashes that produced X-rays,  
 674 we show this information for the actual strikes that produced X-rays, as well as infor-  
 675 mation on the properties of the X-rays detected with the LaBr scintillator. There are  
 676 11 strikes with associated X-ray data. Four of them were preceded by stepped leaders  
 677 (A1, B2, C1, and D1), while the other 7 were preceded by dart leaders. The peak field  
 678 change reported on Table A1 was measured with the calibrated slow antenna.

679 On the seventh column in Table A1 we report the number of X-ray photons detected  
 680 in association with each stroke. We estimate that all of these photons are due to the de-  
 681 scending lightning leaders, and none of them are from background emissions. Recall that  
 682 the background emission rate observed with the LaBr detector is 1 photon every 3 ms.  
 683 The probability that  $k$  photons (out of the total) correspond to background emissions  
 684 in a given time interval  $\Delta t$  can be calculated using the Poisson distribution:  $P(k, \Delta t) =$   
 685  $(\lambda \Delta t)^k e^{-\lambda \Delta t} / k!$  (e.g., Urbani et al., 2021). Thus, as an example, for event A2, the prob-  
 686 ability that one or more photons correspond to background is  $P(k \geq 1, 30 \mu s) \leq 1\%$ . Mean-  
 687 while for all events in the table, this probability is given by  $P(k \geq 1, 1.5 \text{ ms}) \leq 30\%$ . If  
 688 we repeat these calculations for the probability that 2 or more photons arise from back-  
 689 ground emissions, these percentages are further reduced to 0.005% and 8%, respectively.

690 Figure A1 shows the distribution of lightning strikes around South Baldy peak dur-  
 691 ing the Summer of 2022. The distribution is plotted as a function of distance ( $d$ ) to the  
 692 detectors and peak current ( $I_p$ ). The figure also marks the bins that contain the strikes  
 693 from Table A1 that produced X-rays. Based on this figure, and also on a similar anal-  
 694 ysis done by Kereszy (2021, Figure 3-11), we conclude that high probability of X-ray de-  
 695 tection exists for strikes with  $d < 1$  km and  $I_p > 20$  kA. We have managed to collect data  
 696 on 8 of the 20 strikes within this range (plus 3 other strikes with lower peak current).  
 697 To guide future campaigns at the same site, we will use the 10-20 strikes per year fig-  
 698 ure to estimate how much X-ray data may be collected in a season. Referring back to  
 699 the August 9 storm, we can see that the other DAS triggers that did not contain X-rays  
 700 correspond to flashes that took place more than 1.2 km away from South Baldy peak.

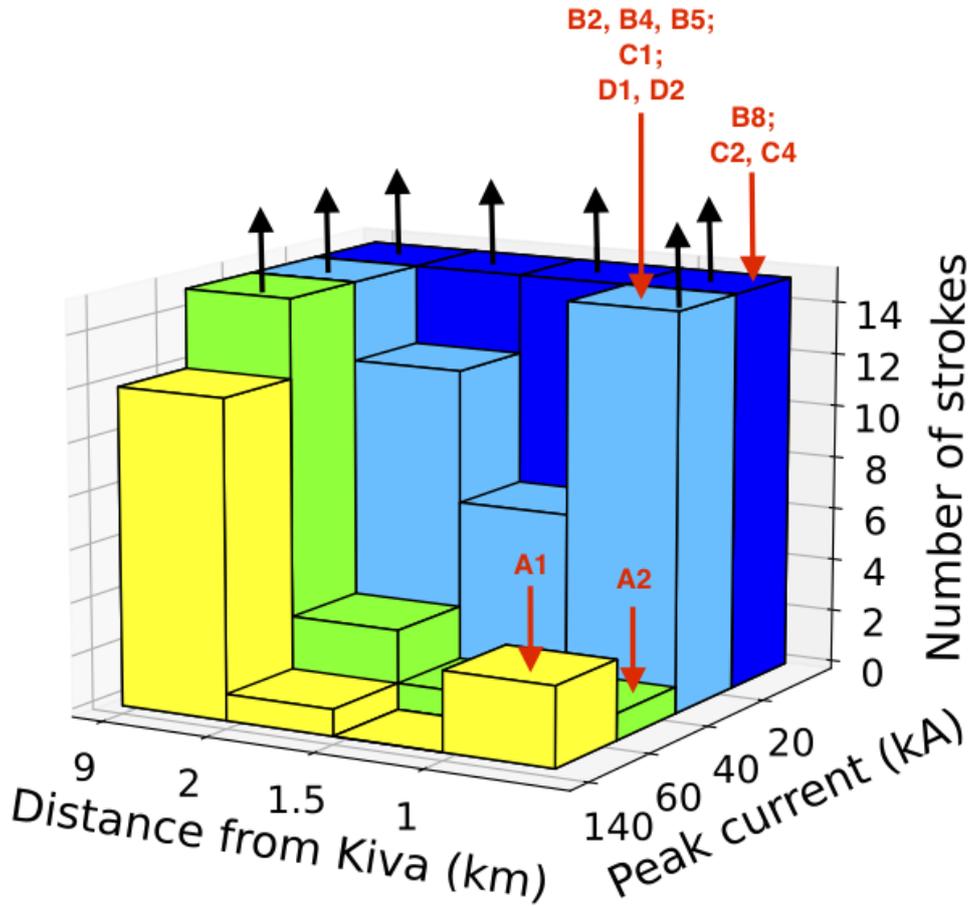
## 701 Appendix B Flash B

702 A second flash was detected during the August 9, 2022 storm, which had X-ray emis-  
 703 sions. Three stepped leaders (events B1, B2, and B3) and subsequent dart leaders (events  
 704 B4 to B9) can be distinguished in Figure B1a. An analysis of the location of the strikes  
 705 allowed us to group events B1 and B3 to B9 to nearby striking points, i.e., subsequent  
 706 strokes B4 to B9 reuse the channels created by either the B1 or B3 stepped leaders, which  
 707 touch the ground very close to each other, within the uncertainty of ENTLN. Meanwhile,  
 708 event B2 corresponds to a stepped leader that made ground contact at a separate loca-  
 709 tion ( $> 1$  km away from the rest). The maximum photon energy was 744 keV and cor-  
 710 responded to event B4, a dart leader. Photon count was similar between the stepped and  
 711 two of the dart leaders, as reported in Table A1.

712 A zoom into event B2 (Figure B2) shows a complex temporal structure. Thirteen  
 713 out of the 14 photons detected (in the LaBr scintillator) prior to the return stroke were  
 714 counted as being emitted by the descending leaders, since they were highly correlated

Event	Date	Time (UTC)	ENTLN		Slow antenna	X-rays photons recorded in the LaBr detector		
			Distance (km)	Peak current (kA)		Peak E-field (kV/m)	Number of photons detected	Avg. energy (keV)
August 9 storm								
	08-09-22	17:38:56	2.8	-14	15.6	-	-	-
	08-09-22	17:40:20	1.2	-17	9.4	-	-	-
	08-09-22	17:41:51	1.5	-32	13.2	-	-	-
A1 (stepped)	08-09-22	17:44:02	0.5	-95	15.9	87	416	3801
A2 (dart)	08-09-22	17:44:02	0.5	-50	2.8	64	138	969
	08-09-22	17:54:18	4.6	7	-4.7	-	-	-
	08-09-22	17:55:09	3.8	-10	5.3	-	-	-
B2 (stepped)	08-09-22	17:56:03	0.4	-25	12.3	13	88	212
B4 (dart)	08-09-22	17:56:03	0.5	-20	2.9	12	125	744
B5 (dart)	08-09-22	17:56:03	0.5	-20	2.2	12	101	359
B8 (dart)	08-09-22	17:56:03	0.5	-10	2.2	4	31	44
	08-09-22	17:57:12	2.5	-14	2.5	-	-	-
	08-09-22	18:03:15	1.9	-25	6.7	-	-	-
Other triggers								
C1 (stepped)	07-11-22	17:53:52	0.5	-34	20	6	629	2224
C2 (dart)	07-11-22	17:53:52	0.2	-10	7	6	67	211
C4 (dart)	07-11-22	17:53:52	0.6	-6	3.5	5	38	47
D1 (stepped)	07-31-22	23:38:25	0.4	-27	12	9	125	411
D2 (dart)	07-31-22	23:38:25	0.2	-21	12.5	16	249	1158

**Table A1.** Summary of flashes recorded with our X-ray detection system. Events labelled on the first column are the ones with associated X-ray emissions, and are scrutinized per stroke/leader type. All other events from the August 9, 2022 storm did not produce detectable X-rays. The last 3 columns display the X-ray data, including, from left-to-right, the number of X-ray photons detected, the average, and the maximum photon energies.

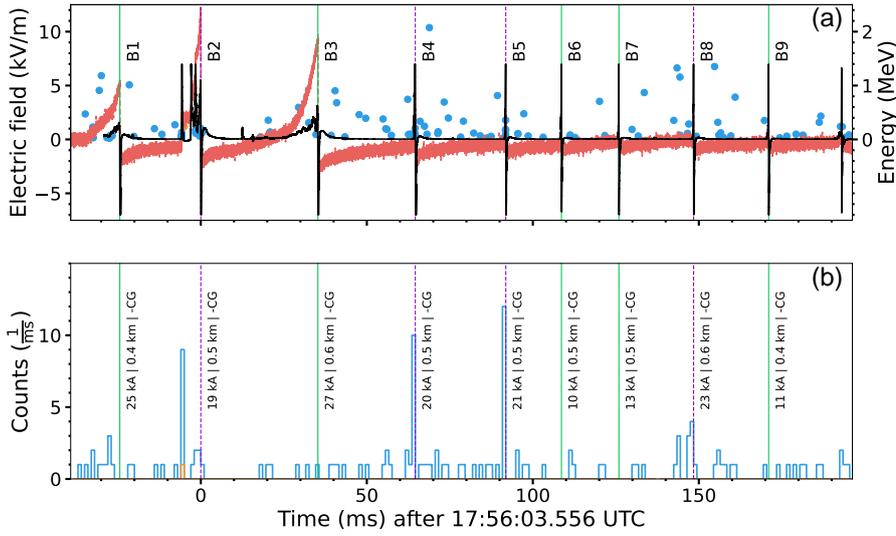


**Figure A1.** Distribution of lightning strikes that took place within a 9-km radius of South Baldy peak during the Summer of 2022, based on ENTLN data. The black upward arrows mark cropped bins with more than 14 strikes. The red downward arrows mark the locations in the histogram of the events in Table A1 with X-ray detections. The format is similar to Kereszy (2021, Figure 3-11).

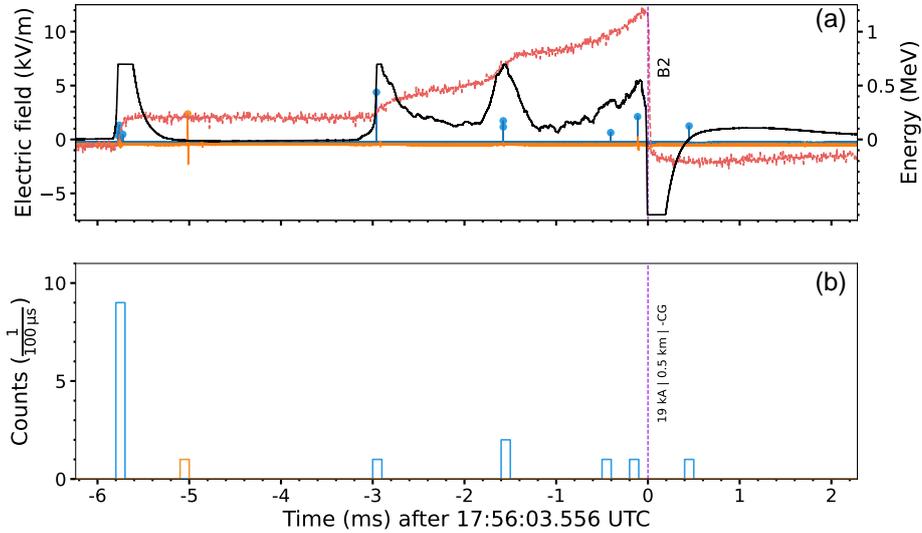
715 to fast antenna field changes. We estimate that 1 photon (or perhaps 2 at the most) dur-  
 716 ing that period is (are) associated with background emissions. Figure B2 and the remain-  
 717 ing figures in the Appendices have the same format as Figures 5–7 in the main text. They  
 718 show the electric field in the top panel (a) with the slow antenna in red, and fast antenna  
 719 in black (if data is available). LEFA was down during the three flashes reported in the  
 720 Appendices. The top panels also show the X-ray energies and time of arrival of individ-  
 721 ual photons, with the LaBr detector shown in blue, while the NaI detector data in or-  
 722 ange. The bottom panels (b) display a histogram of the X-ray count rate, using the same  
 723 color scheme as above to distinguish the two detectors.

## 724 Appendix C Flashes C and D

725 Figures C1 and C2 show flashes C and D, which occurred on July 11 and 31, re-  
 726 spectively. Thus, they are not related to the storm discussed in detail in this manuscript.  
 727 In terms of detectability, flash C is a marginal case with just 5–6 photons per strike. Nonethe-  
 728 less, we can see a similar pattern between its stepped leader (C1) and the one from the



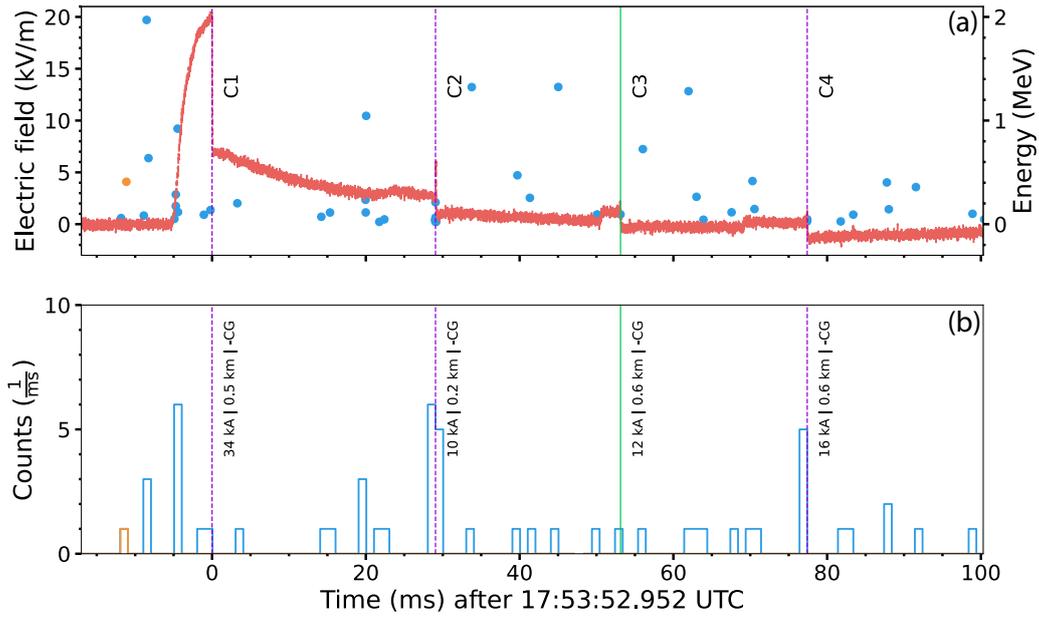
**Figure B1.** Electric field and X-ray data for flash B. (a) Data from (fast and slow) electric field antennas, as well as both X-ray detectors. (b) Photon count rate histogrammed in 1-ms bins. The figure uses the same color scheme for different instruments as Figures 5–7 in the main text.



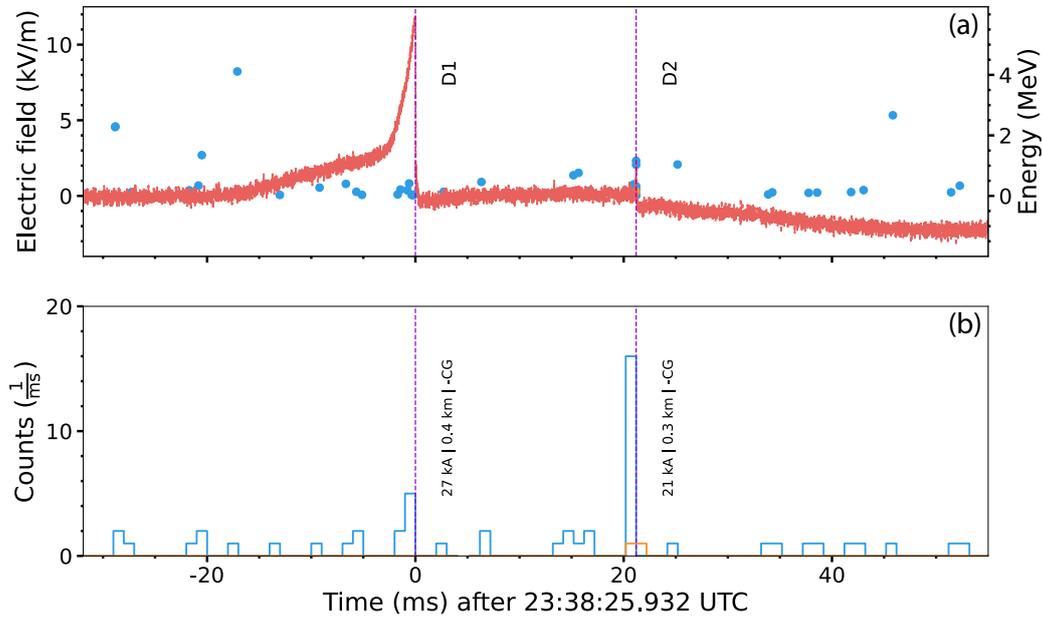
**Figure B2.** A zoom into event into event B2. An X-ray burst is observed early in the stepped leader phase at  $t = -5.8$  ms. The average photon energy of this burst is 88 keV, while the maximum is 212 keV. The figure has the same format and color scheme as Figures 5–7 in the main text.

729  
730

previous flash (B2). Both display a clear X-ray burst (above background levels) at the very beginning of the stepped leader field change, a few ms before the return stroke.



**Figure C1.** Electric field and X-ray data for flash C, which took place on July 11, 2022. The figure has the same format and color scheme as Figures 5–7 in the main text. Figures C1 and C2 do not display the fast antenna and LEFA records because the antennas were down during these particular triggers.



**Figure C2.** Electric field and X-ray data for flash D, which took place on July 31, 2022. The figure has the same format and color scheme as Figures 5–7.

731 The maximum photon energy detected for flashes C and D was 2.2 and 1.2 MeV,  
 732 respectively. In both cases the photons with highest energies were produced by their re-

733 spectively stepped leaders. Flash D (in Figure C2) is the only clear case in our data set  
734 where a subsequent-stroke leader was a more-prolific X-ray emitter than the first-stroke  
735 leader. In all flash overview figures (Figs. 5, B1, C1, and C2), the background count rate  
736 of 1 photon every 3 ms can be easily observed in between strikes. For all return strokes  
737 with associated X-ray observations, all photons were detected during the preceding leader  
738 phase (within the level of uncertainty of relative timing across our data sets). In all fig-  
739 ures where non-colocated instruments are lined up, a correction for the speed of light ( $c$ )  
740 travel between source and instrument is added to the data. We use the frame of refer-  
741 ence of the X-ray instrument in all plots. Thus, before overlaying the ENTLN strike data  
742 to the plots, we delay its arrival by an amount  $d/c$ . For flashes located around  $d = 1$  km  
743 from South Baldy peak, this delay has a 10–20% uncertainty ( $< 1 \mu\text{s}$ , arising from loca-  
744 tion uncertainty).