Modeling of X-ray Images and Energy Spectra Produced by Stepping Lightning Leaders

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Both natural cloud-to-ground (CG) [*Moore et al.,* GRL, 28, 2141-2144, 2001] and rocket-triggered lightning flashes [*Dwyer et al.,* Science, 299, 694-697, 2003] are associated with intense bursts of X-ray emissions, with a typical duration as short as a fraction of a microsecond and a characteristic energy spectra extending up to a few MeV [*Dwyer et al.*, Space Sci. Rev., 173, 133-196, 2012]. Observations by the Thunderstorm Energetic Radiation Array (TERA) have revealed that measurements of X-ray bursts can be explained by an electron source with a characteristic energy less than 3 MeV and a maximum production rate of 10^{17} electrons/s [*Schaal et al.,* JGR, 117, D15201, 2012]. In addition, X-ray images captured by the pinhole-type high-speed X-ray Camera (XCAM) have provided a novel perspective on the temporal and spatial evolution of X-ray production [e.g., *Dwyer et al.,* JGR, 116, D20208, 2011; *Schaal et al.,* JGR, 119, 982-1002, 2014]. In spite of extensive measurements, the mechanism of X-ray production is still uncertain. The mechanism of relativistic runaway electron avalanches (RREA) has been clearly demonstrated to be incapable of explaining the measured energy spectra [*Dwyer*, GRL, 31, L12102, 2004]. Alternatively, *Celestin and Pasko* [JGR, 116, A03315, 2011] have shown theoretically how these X-ray bursts can originate from the bremsstrahlung radiation of thermal runaway electrons produced during the negative corona flash stage of stepping lightning leaders.

In this work, based on previous modeling study of *Xu et al.* [GRL, 41, 7406-7412, 2014], we calculate the energy spectra of X-rays that would be detected by TERA using Monte Carlo simulations and the response matrix of unshielded detectors in TERA. Modeling results of X-ray energy spectra and energy deposition show good agreements with TERA measurements during a negative CG ($-$CG) lightning discharge (MSE 10-01). Moreover, the X-ray images produced during the leader stepping process of natural $-$CG discharges, including both the evolution and morphological features, are theoretically quantified.