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Optical Emissions Associated with Stepping Lightning Leaders in Cloud-to-Ground Lightning Flashes

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Intense and brief bursts of X-ray emissions have been detected from the ground during 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]. The measurements at the International Center for Lightning Research and Testing (ICLRT) have further revealed that discrete and intense bursts of X-rays were closely correlated with the formation of leader steps during CGs [*Dwyer et al.,* GRL, 32, L01803, 2005]. The mechanism of relativistic runaway electron avalanches (RREAs) in large-scale thunderstorm electric fields has been ruled out for this energetic phenomenon as it is not capable of explaining the observed energy spectra [*Dwyer*, GRL, 31, L12102, 2004]. On the other hand, *Celestin and Pasko* [JGR, 116, A03315, 2011] have shown theoretically how the large flux of thermal runaway electrons generated by streamers during the negative corona flash stage of stepping lightning leaders could instead be responsible for these X-ray bursts during negative CGs, and for terrestrial gamma-ray flashes (TGFs) [*Fishman et al.,* Science, 264, 1313-1316, 1994] during intra-cloud lightning flashes (IC). In addition to intense X-ray emissions, *Stolzenburg et al.* [JGR, 118, 2918-2937, 2013] have suggested that the impulsive breakdown associated with initial leaders during the initial breakdown (IB) stages of CGs and ICs can generate considerable amount of visible light. The purpose of the present work is to quantify the optical emissions resulting from the excitation of air molecules produced during the acceleration process of thermal runaway electrons in the highly inhomogeneous electric field produced around lightning leader tip region in negative CGs. For this purpose, a full energy range Monte Carlo model combined with an optical emission model is employed to simulate, from first principles, the dynamics of electrons in the energy range from sub-eV to GeV and the subsequent generation of optical emissions by the large ensemble of low- and high-energy electrons involved. We specifically investigate the geometrical and optical features of the fluorescence light produced as corresponding measurements could be used to probe the electrical properties of lightning leaders.