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Streamer discharges in the atmosphere of Primordial Earth

C. Köhn[1], O. Chanrion[1], M. Bødker Enghoff[1], S. Dujko[2]

[1]Technical University of Denmark, National Space Institute (DTU Space), Elektrovej 328, 2800 Kgs Lyngby, Denmark
[2]Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia

Key Points:

- We perform simulations of electron avalanches and streamers in different gas mixtures for Primordial and Modern Earth.
- Ionization rates are higher in strongly reducing gas mixtures, such as used by Miller and Urey, than in weakly reducing mixtures.
- In the Miller and Urey gas mixture streamers incept at ≈ 114 Td; in weakly reducing atmospheres, suggested by Kasting, at 140-180 Td.

Corresponding author: Christoph Köhn, `koehn@space.dtu.dk`

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Abstract

The seminal Miller-Urey experiment suggests that lightning may have contributed to the origin of life on Earth through the formation of amino acids and carbon acids. We here focus on the early stages of lightning in the atmosphere of Primordial Earth, so-called streamer discharges. We discuss rate coefficients for electrons and study electron avalanches and avalanche-to-streamer transitions by modeling the motion of electrons with a 2.5D Particle-in-Cell Monte Carlo code in the strongly reducing atmosphere used by Miller and Urey (MU) and the weakly reducing atmospheric suggested more recently (by Kasting (1993)) for Earth 3.8 Ga ago and compare results with conditions on Modern Earth. Our simulations show that streamers incept at fields of 140-180 Td in Kasting's mixture and at fields of $\approx$ 114 Td in the MU mixture, thus their inception is more difficult in Kastings mixture. Conclusively, discharges on Primordial Earth might have been more challenging to incept.

Plain Language Summary

In the 1950s Miller and Urey performed discharge experiments in a gas mixture resembling the atmosphere of Ancient Earth and showed that a significant amount of prebiotic material was produced, possibly laying the foundation for the further synthesis of the first biomolecules. We perform numerical computer simulations of electron avalanches in the gas mixture used by Miller and Urey as well as in a mixture suggested more recently for the composition of Ancient Earth's atmosphere 3.8 Ga ago and study the conditions needed for the inception of filamentary discharges. We calculate electron and discharge properties and compare them with results for discharges on Modern Earth. We provide a table summarizing the electric fields needed for discharge inception in these different atmospheres. Our simulations show that discharges in the Miller-Urey mixture incept at lower fields than in Kasting's mixture and partly on Modern Earth which implies that discharges in the atmosphere of Ancient Earth might have been more challenging to incept than previously thought.

1 Introduction

Lightning on Earth is a complex phenomenon bridging several lengths, time, and energy scales ranging from the motion of thermal electrons in streamer discharges to the emission of MeV leptons and photons by kilometer long lightning leaders (Villanueva et al., 1994; Ebert & Sentman, 2008; Rakov, 2013). In addition to solar UV radiation (Ranjan & Sasselov, 2016; Green et al., 2021), atmospheric shock heating by meteorites (Saladino et al., 2013), powerful coronal mass ejection events from the young Sun (Airapetian et al., 2016) and cosmic rays (Globus & Blandford, 2020; Atri, 2020), lightning possibly acted as a catalyst for organic chemistry leading to the formation of life, one of the most enigmatic research questions in astrobiology (Chang et al., 1983; Miller & Cleaves, 2006).

Streamers are thin plasma channels with strong electric fields at their tips and a quasi-neutral interior driven by an ambient electric field and forming the building blocks of long lightning discharges. Whilst streamer and lightning properties are well understood for the atmosphere of Modern Earth and have also been investigated for a variety of other bodies in our solar system (Zarka & Pedersen, 1986; Gibbard et al., 1999; Vasavada & Showman, 2005; Yair et al., 2008; Dubrovin et al., 2010; Dyudina et al., 2010, 2013; Brown et al., 2018; Köhn, Dujko, et al., 2019), not much is known about streamer discharges as the precursors of lightning in the atmosphere of Primordial Earth.

In addition to the emission of energetic particles (Fishman et al., 1994; Dwyer et al., 2008; Briggs et al., 2011; Köhn & Ebert, 2015; Köhn et al., 2017), electric discharges are responsible for the plasma chemistry in our atmosphere related to the production of nitrogen oxides and other greenhouse gases (Murray, 2016). Likewise, the Miller-Urey

experiment has shown that the discharges in the atmosphere of Primordial Earth may have catalyzed the production of amino acids and carbon acids as a precursor of life on Earth (Miller, 1953, 1955; Miller & Urey, 1959; Miller & Cleaves, 2006).

Older theories suggest that life probably appeared approximately between 3.8 and 3.5 Ga ago after the Late Heavy Bombardment (LHB), as found from stromatolites and microfossils found in prehistoric sediments (Schopf, 1983; Schopf & Packer, 1987). Before the LHB, it seemed improbable for life to have had a sufficiently large chance to form, due to the large number of impactors hitting Earth repeatedly and vaporizing its ocean (Maher & Stevenson, 1988; Sleep et al., 1989). More recent theories, however, give evidence that life could have originated before 3.8 Ga ago, even dating back to ~ 4.1 Ga ago (Kitadai & Maruyama, 2018), see also (Ebisuzaki & Maruyama, 2017; Sutherland, 2017; Sasselov et al., 2020; Preiner et al., 2020).

The Miller-Urey experiment (Miller, 1953, 1955; Miller & Urey, 1959; Miller & Cleaves, 2006) demonstrated that many biologically important organic compounds, including amino acids and carbon acids, could be created by spark discharges in the strongly reducing H_2O:CH_4:NH_3:H_2 atmosphere, as originally suggested by Oparin (1924) and Haldane (1933). Whilst they found five amino acids only, a re-analysis of their experiment (see e.g. (Parker et al., 2014)) and more recent experiments in volcanic and H_2S environments (Johnson et al., 2008; Parker et al., 2011) have shown that tens of amino acids can be formed. However, it is uncertain whether methane and ammonia, as in Miller-Urey's experiment, were significantly abundant in Primordial Earth's atmosphere. Holland (1962,1984) states that Primordial Earth experienced two types of atmospheres: 4.5 Ga ago, Earth's atmosphere consisted of strongly reducing gases containing almost no oxygen, but massive amounts of volcanic gases released to the atmosphere through magma oceans covering the surface prior to crust formation. As Earth was cooling down rapidly radiating its heat into space and reaching temperatures below 100° C, water, probably transported to Earth by meteroits, chondrites, asteroids or comets (Robert, 2001; Albertsson et al., 2014; McCubbin & Barnes, 2019; Peslier, 2020), started to appear and Earth's atmosphere became weakly reducing with a significant number of oxygen-containing compounds (Holland, 1984). A more thorough overview of the condition and evolution of the atmosphere of Primordial Earth is presented in (Zahnle et al., 2010). It is thus more probable that the atmosphere during the production of prebiotic molecules was rather weakly reducing mostly consisting of N_2, CO_2 and H_2O, with just small quantities of H_2 and CO, and almost no CH_4 or NH_3, as summarized by Kasting (1990,1993). Schlesinger et al. (1983) and Miyakawa et al. (2002) performed Miller-Urey like experiments in such CO and CO_2 containing atmospheres and observed that the production of organic molecules in these atmospheres is possible, but less efficient.

In a recent paper, Longo et al. (2021) review the state-of-the-art of prebiotic chemistry including electron-molecule reactions and energey exchanges between molecules in various electric fields. In this paper, we present the ionization and attachment rate coefficients, breakdown electric fields, avalanche-to-streamer transition as well as streamer velocities, which are needed to understand the plasma induced chemistry processes for the production of organic molecules in the atmosphere of Primordial Earth. We therefore employ a 2.5D partice-in-cell Monte Carlo code to study the formation of electron avalanches and eventually of streamer discharges as precursors of lightning both for the weakly reducing atmosphere suggested by Kasting as well as for the strongly reducing atmosphere used by Urey and Miller and compare results with streamer discharges for Modern Earth.

We briefly recall the model including the rate coefficients for electrons in section 2 and present the results in section 3. We finally conclude on which conditions favoured the inception of streamers and therefore of lightning in section 4.

2 Modelling

2.1 Gas mixtures and the critical electric field for Primordial and Modern Earth

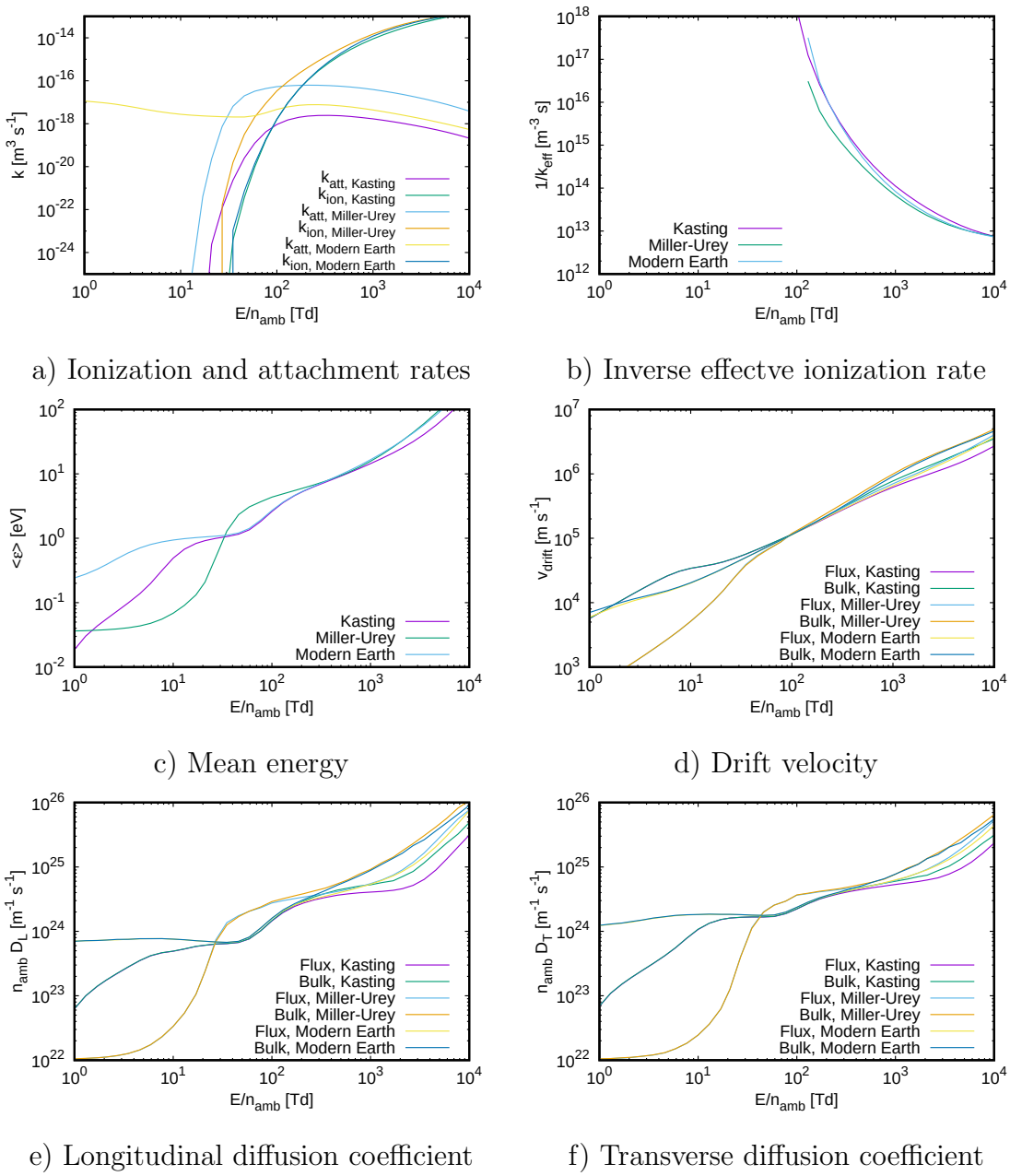
We here trace electrons in three different gas mixtures: i) in the weakly reducing atmosphere N_2:CO_2:H_2O:H_2:CO = 80% : 18.89% : 1% : 0.1% : 0.01% (Kasting, 1990, 1993), which we refer to as Kasting's mixture, ii) in the strongly reducing mixture used by Miller and Urey (MU) and for comparison iii) in the mixture N_2:O_2=80% : 20% of Modern Earth (ME). The apparatus used by Miller and Urey was filled with 20 cm pressure of methane, 20 cm of ammonia and 10 cm of hydrogen at a temperature of about 80°C with a water vapour pressure of 30 cm, thus a total pressure of approximately 80 cm (Miller, 1953, 1955). Therefore, the gas mixture yields H_2O:CH_4:NH_3:H_2=37.5%:25%:25%:12.5%.

Figure 1 displays the variation of the ionization and attachment rate coefficients, inverse effective ionization rate, mean energy, drift velocity, longitudinal diffusion coefficients, and transverse diffusion coefficient with E/n_{amb} for electrons in gas mixtures that mimic the atmosphere of Primordial and Modern Earth. The swarm conditions were assumed to apply and the calculations were performed using the multi-term numerical solutions of the Boltzmann equation. Panel a) shows that amongst these three gas mixtures, attachment is less significant in Kasting's mixture and becomes more significant in the mixture used by Urey and Miller for fields above approximately 20 Td (where 1 Td = 10^{-21} V m^2). For E/n_{amb} above $\sim$ 100 Td, the attachment rates follow the same trend for all gas mixtures slightly decreasing up to fields of 104 Td. For Modern Earth, the attachment rate does not decrease for low electric fields because of three body attachment where an electron attaches to molecular oxygen in the presence of another oxygen or nitrogen molecule; such a process is negligible for the other two gas mixtures. Moreover, the ionization rates in Kasting's mixture and on Modern Earth are similar for all considered cases and are smaller than the ionization rate in the Miller-Urey gas mixture which becomes comparable to the rates in the other two mixtures for fields above approximately 100 Td.

The formation of electron avalanches and eventually streamers depends on the ambient electric field and thus on the rate of electron multiplication. While electrons are accelerated in a sufficiently high electric field, they keep gaining energy becoming sufficiently energetic to ionize the ambient gas. On the contrary, electrons also collide with the gas molecules inelastically losing their energy; hence, if fields are too low, attachment dominates over ionization and the evolution of an electron avalanche is damped. The critical (or breakdown) electric field E_k is then defined as the electic field where the ionization rate equals the attachment rate. For the mixtures considered here, the critical fields amount to $E_{k,Kasting}$ = 90.3 Td= 2.3 MV m^{-1}, $E_{k,MU}$ = 113.9 Td= 2.9 MV m^{-1} and $E_{k,ME}$ = 125.6 Td= 3.2 MV $^{-1}$ for a number density n_{amb} of the ambient gas equal to $2.547 \cdot 10^{25}$ m^{-3}. Note that discharge phenomena depend on the electric field and the density of ambient gas and thus on the reduced electric field E/n_{amb}; therefore, since we do not know exactly the magnitude of n_{amb} for Primordial Earth, we will present results as a function of the reduced electric field E/n_{amb} [Td] or of the normalized electric field E/E_k being independent of n_{amb}.

2.2 Set up of the model

In all performed simulations, we use a 2.5D Particle-in-Cell Monte Carlo collision (PIC-MCC) code with two spatial and three velocity coordinates (Chanrion & Neubert, 2008; Köhn et al., 2017) which traces individual electrons in a cylindrical domain of $L_r \times L_z$ = 1.25 mm ×14 mm. As in other work (Arrayás et al., 2002; Liu & Pasko, 2004), we start tracing electrons from a Gaussian $n_{e,i}(t=0,r,z) = n_{e,0} \exp\left(-\left(r^2 + (z-z_0)^2\right)/\lambda^2\right)$ where the initial patch is located at the center of the simulation domain, i.e. $z_0 = L_z/2$. This is common practice in streamer modelling as the Gaussian is a solution of the dif-



a) Ionization and attachment rates

b) Inverse effectve ionization rate

c) Mean energy

d) Drift velocity

e) Longitudinal diffusion coefficient

f) Transverse diffusion coefficient

Figure 1. Variation of the ionization and attachment rate coefficients (a), the inverse effective ionization rate (b), mean energy (c) drift velocity (d) and diffusion coefficients (e,f) with the applied reduced electric field. The calculations for Modern Earth are performed assuming 1 bar pressure and a temperature of 293 K.

fusion equation if the initial condition for the distribution of electrons and ions is a delta function. The size of the initial patch is related to the Raether-Meek criterion (Raether, 1939; Meek, 1940) with

$$\lambda \approx 2 \cdot \sqrt{\frac{20D}{(\alpha_{ion} - \alpha_{att})\, v_{drift}}} \tag{1}$$

where the diffusion coefficient D and the electron drift velocity v_{drift} are shown in Fig. 1 and the ionization rates α_{ion} as well as the attachment rates α_{att} are derived from the rates k_{ion} and k_{att}. For the considered cases, the initial size λ varies between 0.02 mm and 0.4 mm. In order to have the same initial condition for all simulations, we here use $\lambda \approx 0.2$ mm as a compromise; this does not affect our simulation results significantly as previous simulations have shown that changing the initial radius within a factor of $5-10$ affects the time for the electric field evolution only by a few percent (Köhn, Chanrion, & Neubert, 2019). Yet, we have also run simulations for $\lambda = 0.02$ mm and $\lambda = 1$ mm (results not shown here) and indeed seen that the size of the initial Gaussian patch does not influence our results which is in alignment with results by Luque et al. (2008).

We take into account the self-consistent electric field created by the charge separation of the slow ions and the fast electrons. Therefore, we solve the Poisson equation $\Delta\Phi = e_0\,(n_e - n_i)\,/\epsilon_0$ on a grid with 150 discrete points in r- and 1200 points in z-direction. At the boundaries ($z = 0, L_z$), we use Dirichlet boundary conditions $\Phi(r, 0) = 0$ and $\Phi(r, L_z) = E_{amb} \cdot L_z$ whilst we use the Neumann condition $\partial\Phi/\partial r = 0$ for $r = 0, L_r$. More details on how the Poisson equation is solved, can be found in (Chanrion & Neubert, 2008).

When electrons are accelerated by the superposed ambient and self-consistent electric field, they are decelerated by the collisions with the relatively large and heavy molecules of the ambient gas. For all considered cases, we have implemented elastic collisions, rotational, vibrational and electronic excitations, electron impact ionization as well as electron attachment. Note that detachment and associative ionization occur on timescales of micro- to milliseconds and are thus negligible within the simulated time scales. In these kind of MCC simulations, air molecules are placed as an implicit background where the probability P for an electron-gas molecule collision within a time step Δt is

$$P = 1 - \exp\left(-n_{amb}\sigma v \Delta t\right) \tag{2}$$

with v being the electron velocity and σ the cross section of the collision process. Cross sections for electron scattering in N_2 and O_2 are well-documented in literature (Gurevich, 1961; Phelps & Pitchford, 1985; Moss et al., 2006; Chanrion & Neubert, 2008; Dujko et al., 2011; Köhn & Ebert, 2014). For electron scattering in CH_4, we use a set of cross sections, which was initially developed by Hayashi (1987) and further improved by Šašić (2004) et al. The cross sections for electron scattering in H_2O was taken from Kawaguchi and coworkers (2016), while the set of cross sections for electron scattering in CO was retrieved from the MAGBOLTZ code ("https://magboltz.web.cern.ch/magboltz/", n.d.). For electron scattering in NH_3, we employ a set of cross sections developed by Hayashi, which is available in the LxCat database ("Phelps database, www.lxcat.net", n.d.). The initial set of cross sections for electron scattering in CO_2 was developed by Phelps ("Phelps database, www.lxcat.net", n.d.). For the purposes of this work and using the standard swarm analysis, the cross sections were slightly modified, in order to achieve a better agreement between experimentally measured transport coefficients by Yousfi and coworkers (2009) and theoretically calculated data. Finally, the set of cross sections for electron scattering in H_2, is largely based on data developed by Phelps ("Phelps database, www.lxcat.net", n.d.). The cross sections for rotational excitations of H_2 are taken from England and coworkers (1988). Although differential cross sections are well known for N_2 and O_2, there is a lack of data for the other considered molecular species. Therefore, we assume isotropic scattering for all relevant scattering processes for the low-energy electrons of electron avalanches

and streamer discharges since numerous elastic collisions randomize the electron motion and should thus not falsify the results of this paper. Details of the implementation for electron scattering in the mixtures of N_2 and O_2, and N_2:CH_4 can be found in (Chanrion & Neubert, 2008; Köhn et al., 2017; Köhn, Dujko, et al., 2019).

2.3 Photoionization and background ionization

In an oxygen-rich mixture, photoionization is the main propagation mechanism of positive streamers and facilitates the evolution of negative streamers (Zhelezniak et al., 1982; Liu & Pasko, 2004; Nijdam et al., 2010; Wormeester et al., 2010). In air, electrons excite molecular nitrogen which in turn emits a UV photon ionizing molecular oxygen whilst in the case of absent oxygen, simulations have shown that Bremsstrahlung photons can ionize molecular nitrogen and oxygen (Köhn et al., 2017). In mixtures other than air, positive streamers have been observed in laboratory experiments in mixtures of CO_2:N_2= 96.5%:3.5% and H_2:He=89.8%:10.2% mimicking the atmospheres of Venus or Jupiter (Dubrovin et al., 2010). Whilst it is unclear how photoionization works in CO_2:N_2 mixtures, the emission of photons from excited helium is sufficiently energetic to ionize molecular hydrogen. However, there is little understanding of how photoionization would work in the mixtures suggested by Kasting and used by Miller and Urey. Therefore, we use a constant level of background ionization as a substitute for photoionization allowing for positive streamers to propagate in these gas mixtures.

On Earth, typical levels of natural background ionization, created by cosmic rays, lie between 10^3 cm^{-3} and 10^5 cm^{-3} (Marsh & Svensmark, 2000) where the ion production through cosmic rays is most efficient between approx. 10 and 15 km altitude, typical for thunderstorm. However, we here use a level of 10^9 cm^{-3} between $z = 3$ mm and $z = 13$ mm not only to account for the natural level of background ionization, but also to mimic the effect of photoionization. Previous simulations of positive streamers in air (Bourdon et al., 2010; Wormeester et al., 2010) have indeed shown that a background ionization level of 10^9 cm^{-3} mimics the effect of photoionization.

3 Results

3.1 Temporal evolution of electron avalanches and streamers

Figure 2 shows the electron density for the mixtures of Kasting (first row) as well as of Miller and Urey (second row) for different ambient electric fields. The applied electric fields are chosen such that we can thoroughly discuss the avalanche-to-streamer transition for the negative and positive streamer front; as the electric fields and the subsequent effective ionization rate (see Fig. 1 b) vary for each gas mixture, we show the electron densities at different time steps for different gas mixtures. The first row shows that in Kasting's mixture, positive streamers start to incept at approx. 141 Td whilst the negative front only shows the propagation of an electron avalanche with a moderate electron multitplication only. Only for higher fields of approx. 196 Td is the electron multiplication large enough to turn the electron avalanche into a negative streamer. The second row shows that the electron density grows more significantly and faster in the mixture used by Miller and Urey. Additionally, we observe that streamers incept at electric field strengths of $\approx$ 113.9 Td which is substantially smaller than the fields needed for streamer inception in Kasting's mixture. This results from the different ionization rates; as Figure 1 a) shows, the ionization rate above E_k in the Miller-Urey mixture is larger than in the Kasting mixture, thus leading to a higher electon multiplication and thus to easier streamer inception. For comparison, the last row shows electron avalanches and streamers for Modern Earth after 7 ns. It shows that for 117.8 Td, we observe the slow inception of a positive streamer whilst negative streamers propagate for a field of 149.2 Td which lie in-between the inception fields for Kasting's and Miller-Urey's mixture.

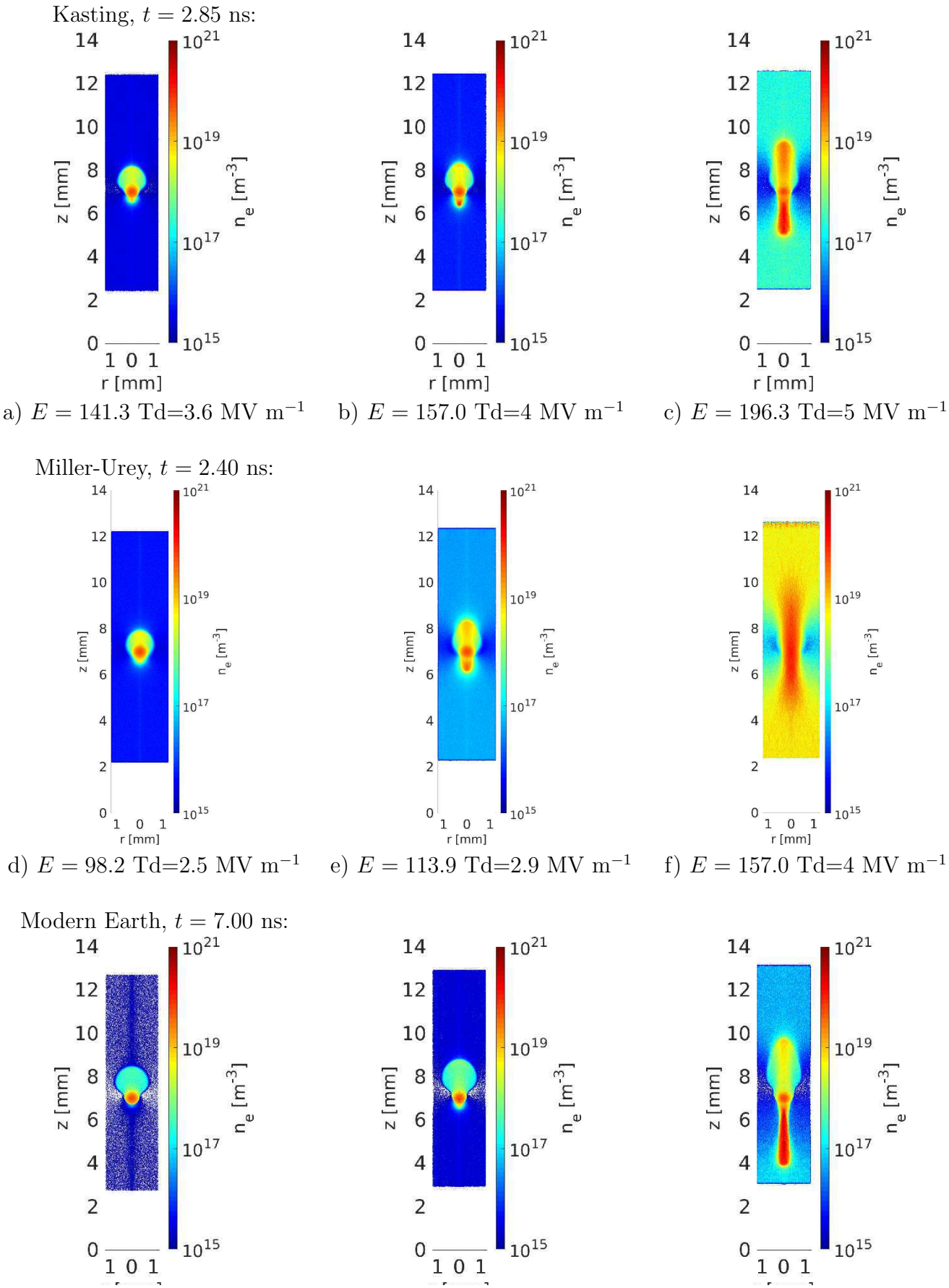


Figure 2. The electron density of electron avalanches in different gas mixtures for different ambient electric fields.

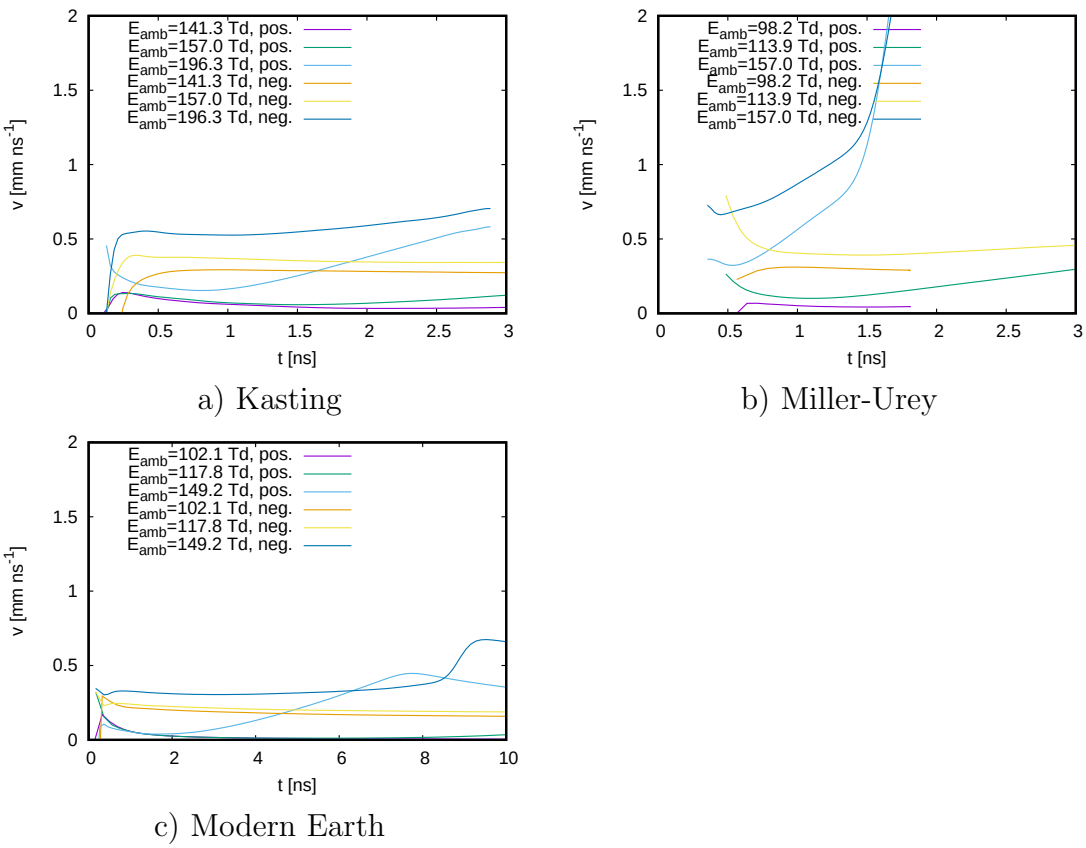


Figure 3. The velocity of electron avalanches and streamer velocities as a function of time in a) Kasting's, b) Miller-Urey's mixture and c) in air for the same electric fields as in Fig. 2.

Gas mixture	$E_{inc,pos}$ [MV m^{-1}]/[Td]/E_k	$E_{inc,neg}$ [MV m^{-1}]/[Td]/E_k
Kasting	3.6/141.3/1.6	4.6/180.6/2.0
MU	2.9/113.9/1.0	2.9/113.9/1.0
ME	2.3/90.3/0.7	3.6/141.4/1.1

Table 1. The inception electric field for positive and negative streamers in Kasting's (N_2:CO_2:H_2O:H_2:CO= 80% : 18.89% : 1% : 0.1% : 0.01%) and Miller-Urey's (H_2O:CH_4:NH_3:H_2=37.5%:25%:25%:12.5%) mixture as well as in air on Modern Earth (N_2:O_2=80%:20%). The inception field is given in units of MV m^{-1} and of Td as well as a ratio to the critical field E_k.

In addition, Figure 3 shows the avalanche and streamer velocities for the different gas mixtures. It shows that avalanches and streamers in Kasting's mixture move with velocities $\lesssim 0.5$ mm ns^{-1}=5·10^5 m s^{-1}; in the Miller-Urey mixture fronts move faster than in Kasting's mixture because of the larger electron drift velocity in fields above E_k, see Fig. 1 d). For comparison, panel c) shows that electron avalanches on Modern Earth in preionized air with a level of 10^9 cm^{-3} move with velocities of approx. 0.5-1 mm ns^{-1}.

3.2 Streamer inception in different gas mixtures

As Fig. 2 illustrates, there is a significant difference on whether electron avalanches turn into streamers. Table 1 summarizes the electric fields needed for a successful streamer inception: In Kasting's mixture, one requires a field of approx 141.3 Td to incept a positive streamer and a field of ≈ 180.6 Td for the inception of a negative streamer. Note that, as in air, positive streamers incept more easily than negative streamers in Kasting's mixture since electrons move into the positive fronts, accumulate charge and increase the local electric field. Since electrons energize more easily and the ionization rate at fields in the order of the critical field is higher in the mixture used by Miller and Urey, streamers already incept at fields of 113.9 Td which is smaller than in Kasting's mixture.

Although the critical field is higher in the gas mixture used by Miller and Urey than in Kasting's mixture, streamers incept at lower electric field strengths. This might seem contradictory since the critical field separates the two regimes where electron impact ionization or electron attachment are dominant. However, the critical field alone does not give a criterium on whether a streamer incepts since the field also controls the electron energies. Fig. 4 shows the electron energies for the three considered gas mixtures for the same time steps and ambient fields as in Fig. 2. Panel a) shows that in fields of 141.3 Td and 157.0 Td in Kasting's mixture the maximum electron energy varies between 20 and 30 eV which is only slightly higher than the ionization energies of 15.58 eV for N_2 and of 13.78 eV for CO_2, the most abundant species in this mixture. Hence, the electron energies are significantly low limiting the ionization rate and therefore prohibiting the avalanche-to-streamer transition on the negative front. On the positive front, however, the avalanche-to-streamer transition is facilitated through the motion of background electrons into the positive field tip. For a field of 196.3 Td, the maximum electron energy is approx. 50 eV, which is significantly high to ensure substantial ionization forming the streamer inception on both sides. In the Miller-Urey mixture, the electron energies are comparable to the ones in the Kasting mixture. However, note that the mobility in Miller-Urey's mixture is higher than in Kasting's mixture and that the ionization energies of H_2O, CH_4, and NH_3 are 12.65 eV, 12.61 eV, and 10.02 eV which are smaller than those of N_2 and CO_2, thus driving the streamer inception more easily. For comparison, panel c) shows the electron energy distribution for Modern Earth. For fields of 102.1 Td and 117.8 Td, the maximum electron energy lies around 20 eV which is only

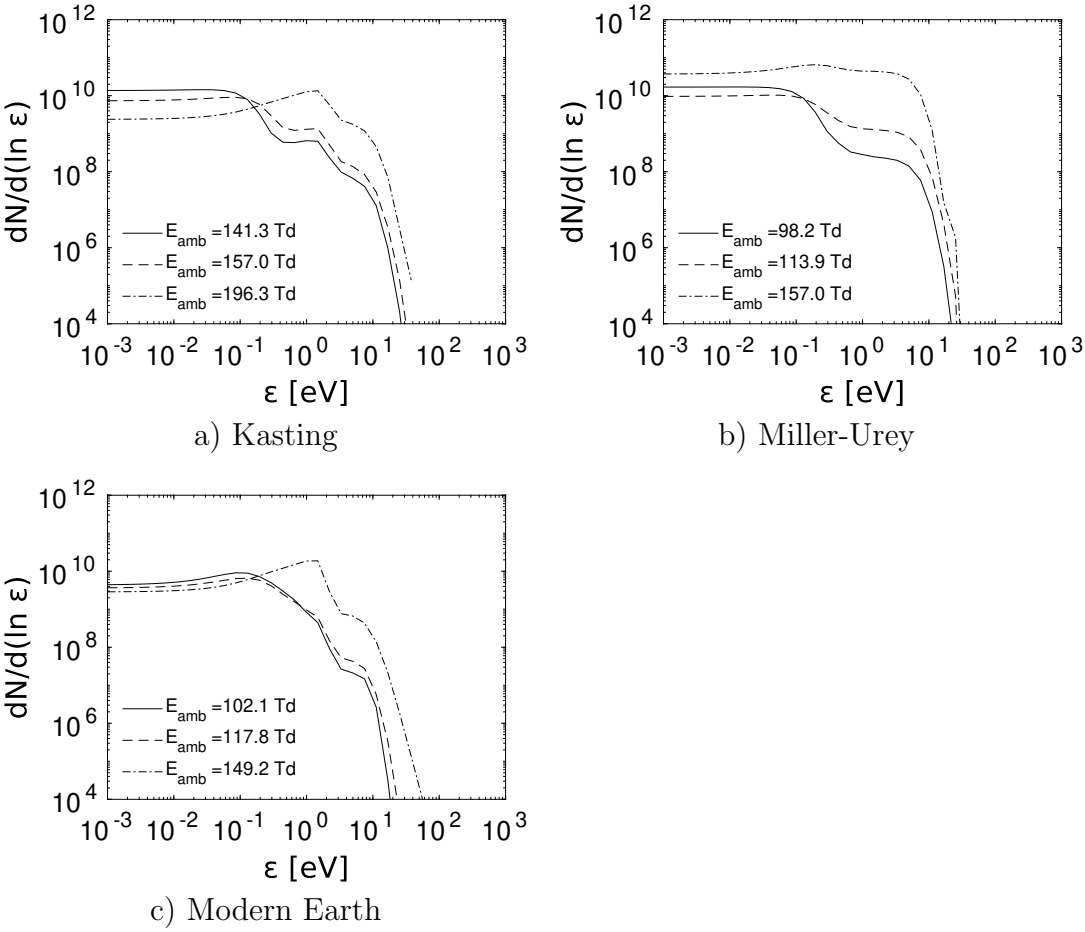


Figure 4. The electron energy distributions in Kasting's mixture (a) after 2.85 ns, in Urey's and Miller's mixture after 2.40 ns (b) and in air after 7.00 ns (c) for the same electric fields as in Fig. 2.

slighly higher than the 15.6 eV ionization energy of nitrogen, the most abundant species in air. As in the two other mixtures, this explains why there is no avalanche-to-streamer transition on the negative side whilst there is the slow inception of a positive streamer. On the contrary, for 149.2 Td, the maximum electron energy is approximately 60 eV allowing for the avalanche-to-streamer transition on the positive and negative side.

4 Conclusion and outlook

We have simulated the formation of electron avalanches and the possible inception of streamer discharges in different electric fields and in the gas mixtures N_2:CO_2:H_2O:H_2:CO suggested for Primordial Earth by Kasting (1993) and in H_2O:CH_4:NH_3:H_2 used by Miller and Urey (1953,1955,1959) and compared results with streamers on Modern Earth. In all simulations we used a uniform background ionization of 10^9 cm^{-3} in order to mimic the effect of photoionization on Primordial Earth and in order to have comparable conditions when comparing with air. We have presented the electron density along with avalanche and streamer properties such as electron energy distributions, and the front velocities.

We have seen that for electric fields around the critical field E_k, avalanches in the Miller-Urey mixture propagate with velocities of up to 2 mm ns^{-1} which is slightly faster than in the mixture suggested by Kasting and in air on Modern Earth for a constant level of preionization of 10^9 cm^{-3}. Table 1 summarizes the electric fields needed for the avalanche-to-streamer transition for all simulated gas mixtures. In the Miller-Urey gas mixture streamers incept at fields of approx. 114 Td which is lower than in air (negative streamers, $\approx$ 140 Td) and in the weakly reducing mixture N_2:CO_2:H_2O:CO suggested by Kasting ($\approx$ 140$-$180 Td). Only for positive streamers in air, the inception field in air is lower than in the Miller-Urey mixture.

For fields in the order of the critical field, energies in Kasting's mixture and Miller-Urey's mixture reach maximum energies of approximately 50 eV which is comparable to the maximum energy in air. Despite comparable energies, the ionization rates in the Miller-Urey mixture are higher than in Kasting's mixture for fields above the critical field, leading to a higher yield of electrons and thus facilitating the avalanche-to-streamer transition.

Since it is known for Modern Earth that the large-scale electric fields in thunderstorms are in the order of $0.1E_k$, hence seemingly too low for streamers and subsequently for lightning to occur, it is still an enigma how lightning can occur on Modern Earth (Gurevich & Karashtin, 2013; Dubinova et al., 2015). Thus, although the difference in the streamer inception electric field is rather small, it could potentialy make a big difference on how efficiently streamers incept. Nonetheless, it is more difficult to incept streamers as precursors of lightning in the weakly reducing Kasting mixture than in the mixture used by Miller and Urey or in modern day air. On the contrary, in local environments, with a significant contribution of methane and ammonia, it might be easier to incept streamers, to observe discharges and maybe even create prebiotic molecules.

As the Miller-Urey experiment has shown, discharges might be capable of producing amino acids and carbon acids as a precursor for the further synthesis of biotic material. Similarly, sprite streamers in the mesosphere of Modern Earth contain a rich chemistry of nitrogen, oxygen, and carbon (Sentman, 2008). At this moment, we have a simulation tool at hand to simulate streamer discharges in the atmosphere of Primordial Earth. In the future, we thus plan to add the plasmachemistry of producing amino acids and carbon acids to our streamer model to self-consistently simulate the production of these prebiotic molecules from streamer discharges.

Acknowledgments

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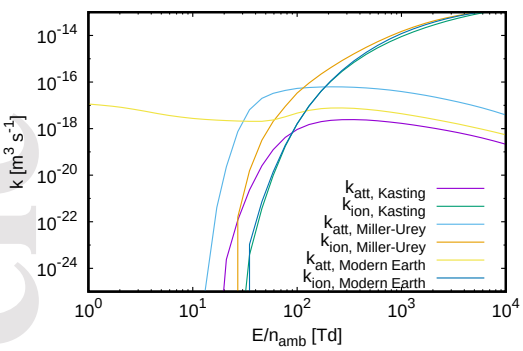
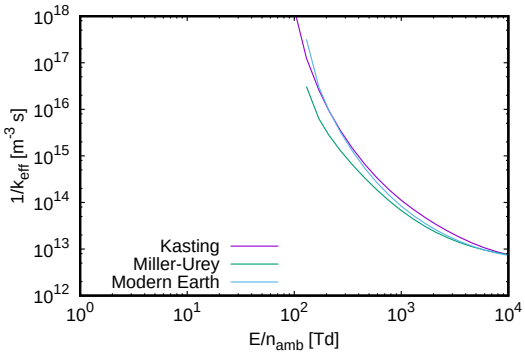
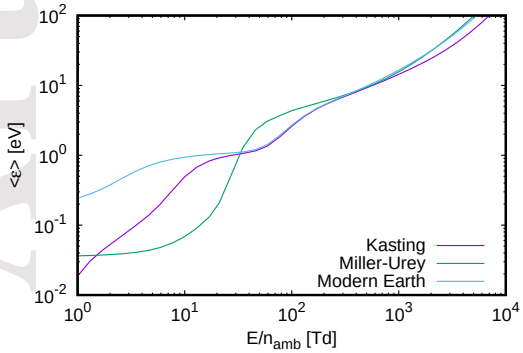


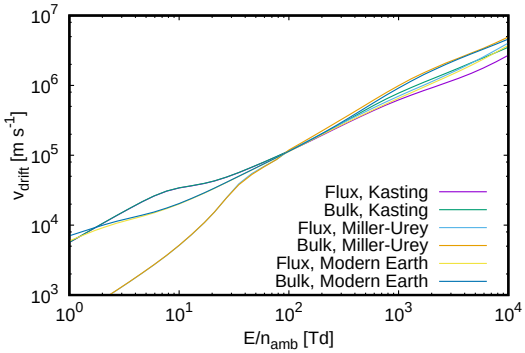
a) Ionization and attachment rates



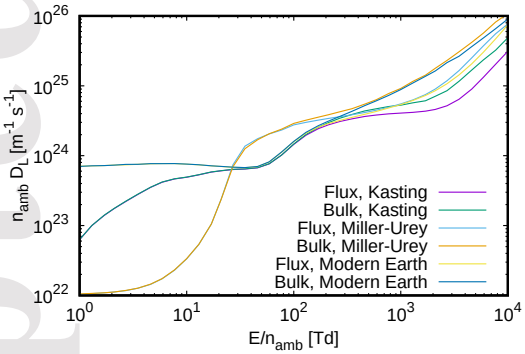
b) Inverse effectve ionization rate



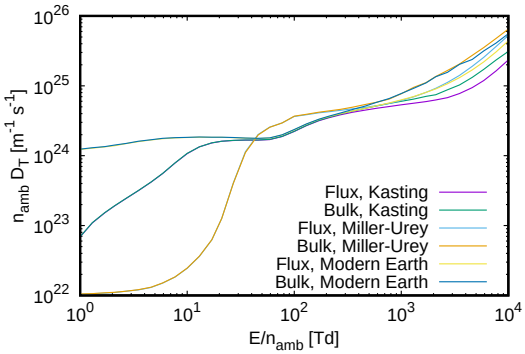
c) Mean energy



d) Drift velocity

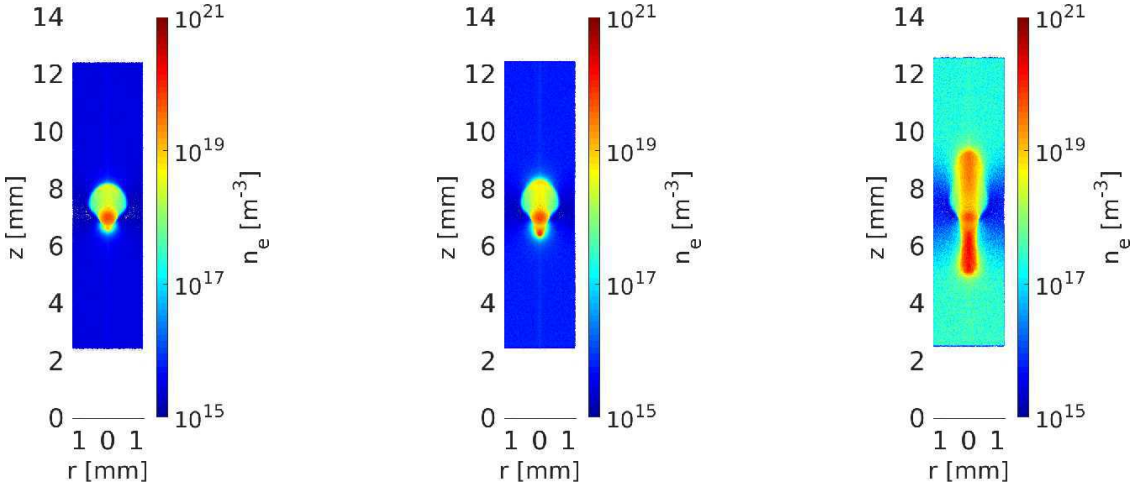


e) Longitudinal diffusion coefficient



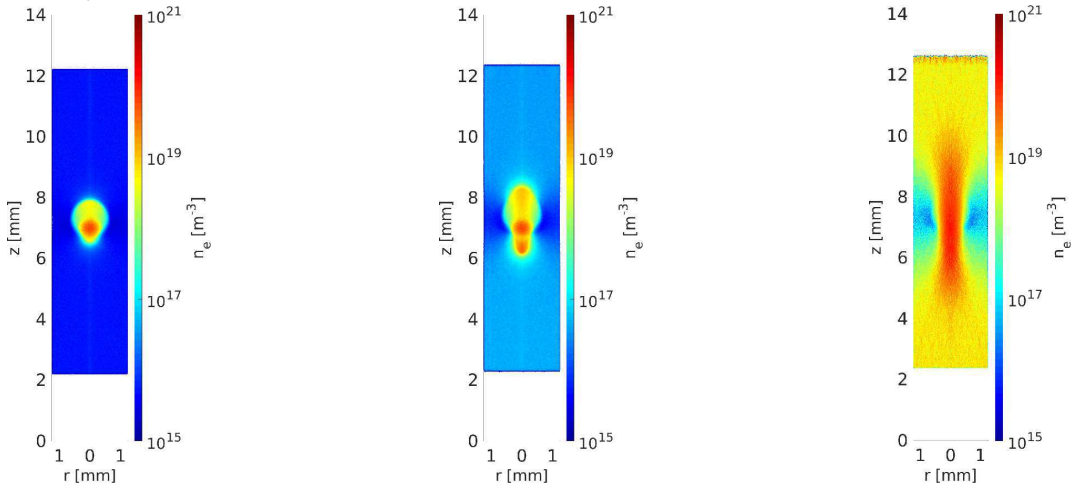
f) Transverse diffusion coefficient

Kasting, $t = 2.85$ ns:



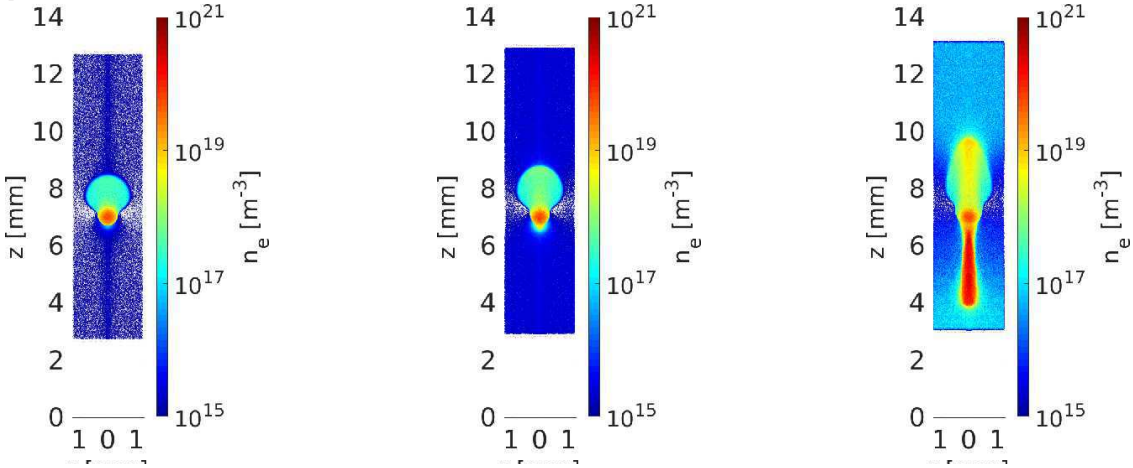
a) $E = 141.3$ Td=3.6 MV m^{-1} b) $E = 157.0$ Td=4 MV m^{-1} c) $E = 196.3$ Td=5 MV m^{-1}

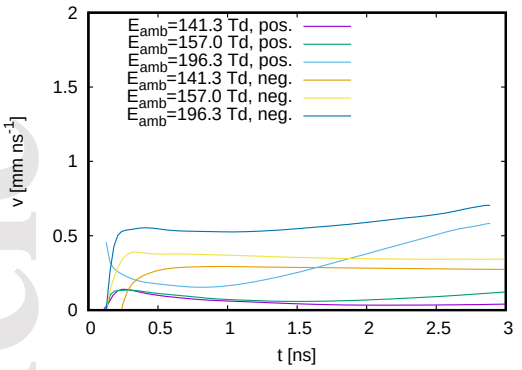
Miller-Urey, $t = 2.40$ ns:



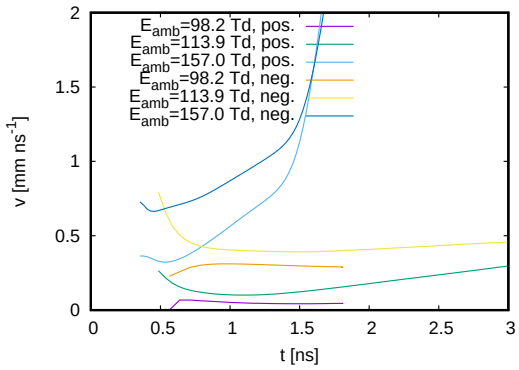
d) $E = 98.2$ Td=2.5 MV m^{-1} e) $E = 113.9$ Td=2.9 MV m^{-1} f) $E = 157.0$ Td=4 MV m^{-1}

Modern Earth, $t = 7.00$ ns:

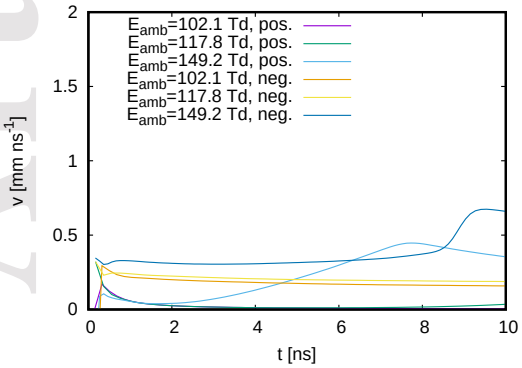




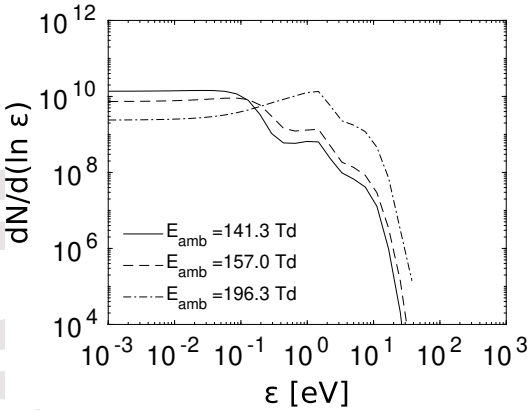
a) Kasting



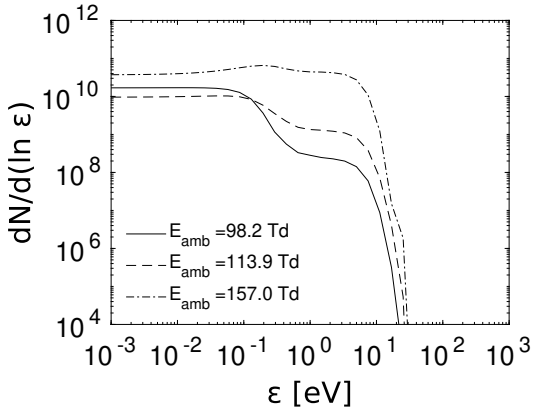
b) Miller-Urey



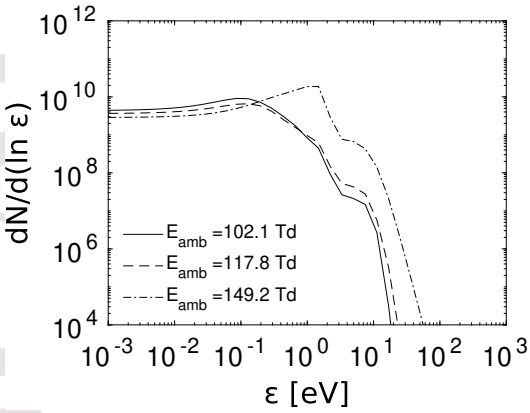
c) Modern Earth



a) Kasting



b) Miller-Urey



c) Modern Earth