Streamer discharges in the atmosphere of Primordial Earth

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Introduction: Life on Primordial Earth

Miller-Urey experiments suggest that the formation of amino and carbon acids was catalyzed by electric discharges (lightning?) in the atmosphere. What about inception of discharges in the atmosphere of Primordial Earth???

Introduction: Streamer discharges

Streamers originate from electron-ion patches in an ambient electric field $E_{\text{amb}}$, and evolve by electron acceleration and the ionization of ambient gas (high fields at the tips).

Lightning originates from small discharge channels, called streamers, the building blocks of lightning/spark discharges.
Introduction: Atmospheres on Primordial Earth

- To understand streamers on Primordial Earth and associated chemistry, one needs to know composition of atmosphere

- Miller and Urey used $H_2O:CH_4:NH_3:H_2 = 37.5\%:25\%:25\%:12.5\%$ (reducing atmosphere)

  \[ N_2:CO_2:H_2O:H_2:CO = 80\%:18.89\%:1\%:0.1\%:0.01\% \] (oxidizing atmosphere)
Modelling of streamers

Ingredients:
- initial electron/ion patch \( n_{e,i}(t=0, r, z) = n_{e,0} e^{-\frac{r^2+(z-z_0)^2}{\lambda^2}} \)  
  \( (n_{e,0} = 10^{20} \text{ m}^{-3}, \lambda = 0.2 \text{ mm}, z_0 = 7 \text{ mm}) \)
- ambient field \( E_{\text{amb}} \)
- ambient gas mixture (Urey-Miller/UM, Kasting)
- gas pressure/number density of ambient gas
  (here use \( 2.5 \cdot 10^{25} \text{ m}^{-3} \) as for Modern Earth)

Modelling:
- 2.5D particle code (2D in space, 3D in velocity)
- tracing individual electrons (incl. collision with ambient gas)
- cross section sets as input data for electron scattering in individual gases
- vary mixture and ambient field \( \Rightarrow \) study inception of streamer discharges  

Breakdown fields I

- Electron avalanche/streamer evolution depends on two competing mechanisms (depending on the electric field)
  - Ionization: $A + e^- \rightarrow A^+ + 2e^-$
  - Attachment, e.g. $A + e^- \rightarrow A^-$
- Equilibrium of rates determines the breakdown (or classical) electric field $E_k \Rightarrow \alpha_{ion}(E_k) = \alpha_{att}(E_k)$
  
  ($\alpha_{ion}$: ionization rate
  $\alpha_{att}$: attachment rate
  $E_k$: classical electric field indicating (not equal to) field when avalanche-to-streamer transition occurs)
Breakdown fields II

Rates for Kasting’s mixture:

\[ E_{k,Kasting} = 90.3 \text{ Td} = 2.3 \text{ MV m}^{-1} \]

Similarly:

\[ E_{k,UM} = 113.9 \text{ Td} = 2.9 \text{ MV m}^{-1} \]

\[ E_{k,ME} = 125.6 \text{ Td} = 3.2 \text{ MV m}^{-1} \]

Reduced electric field [Td] as ratio of electric field and ambient gas density, here \( n_{amb} = 2.547 \cdot 10^{25} \text{ m}^{-3} \)

(avalanche/discharge properties scale with gas density)
Swarm parameters

Electron mobility

above breakdown: electrons more mobile in Urey-Miller mixture

Ionization rate

ionization more efficient in Urey-Miller mixture
Sources of ionization: Photoionization and background ionization

On the positive side, electrons are dragged into streamer.

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Build-up of space charge
=> enhance electric field
=> accelerate electrons further

? Source of new electrons:
- background ionization (Modern Earth air ≈10^3-10^5 cm^-3)
- photoionization

In air:
\[ \text{N}_2 + e^- \rightarrow \text{N}_2^* + e^- \]
\[ \text{N}_2^* \rightarrow \text{N}_2 + \gamma_{\text{UV}} \]
\[ \text{O}_2 + \gamma_{\text{UV}} \rightarrow \text{O}_2^+ + e^- \]

But we do not know how photoionization really works in other gas mixtures: use increased level of background ionization: 10^9 cm^-3 [A. Bourdon et al., 2010. Plasma Sources Sci. Technol., vol. 19, 034012]
**Electron densities I**

In Kasting mixture after $t=2.85$ ns for different ambient fields:

- $E_{\text{amb}} = 3.6 \text{ MV m}^{-1} = 141.3 \text{ Td}$
- $E_{\text{amb}} = 4.0 \text{ MV m}^{-1} = 157.0 \text{ Td}$
- $E_{\text{amb}} = 5.0 \text{ MV m}^{-1} = 196.3 \text{ Td}$

Electron avalanches on both fronts, positive front might turn to streamer.

- Negative front: electron avalanche, but no streamer positive front: avalanche-to-streamer transition
- Full evolution of positive and negative streamer
Electron densities II

In Urey-Miller mixture after $t=1.81$ ns for different ambient fields:

- $E_{\text{amb}} = 2.5$ MV m$^{-1}$ = 98.2 Td
- $E_{\text{amb}} = 2.9$ MV m$^{-1}$ = 113.9 Td
- $E_{\text{amb}} = 4.0$ MV m$^{-1}$ = 157.0 Td

Full evolution of positive and negative streamer avalanche-to-streamer transition for both polarities.

electron avalanches on both fronts

avalanche-to-streamer transition for both polarities

full evolution of positive and negative streamer
Front velocities

- in Kasting mixture: $v < 0.6 \text{ mm ns}^{-1}$
- velocities in Urey-Miller (in average) larger (although smaller electric fields)
- for comparison: $v_{\text{Modern Earth}} \approx 1-10 \text{ mm ns}^{-1}$
Electron energies

Kasting, $t=2.85 \text{ ns}$

- for $141.3 \text{ Td}$ and $157.0 \text{ Td}$ $E_{\text{max}} < 30 \text{ eV}$
- for $196.3 \text{ Td}$ $E_{\text{max}} \approx 40 \text{ eV}$

$E_{\text{amb}} = 141.3 \text{ Td} = 3.6 \text{ MV/m}$
$E_{\text{amb}} = 157.0 \text{ Td} = 4.0 \text{ MV/m}$
$E_{\text{amb}} = 196.3 \text{ Td} = 5.0 \text{ MV/m}$

Urey-Miller, $t=1.81 \text{ ns}$

- for all considered cases $E_{\text{max}} < 30 \text{ eV}$

$E_{\text{amb}} = 98.2 \text{ Td} = 2.5 \text{ MV/m}$
$E_{\text{amb}} = 113.9 \text{ Td} = 2.9 \text{ MV/m}$
$E_{\text{amb}} = 157.0 \text{ Td} = 4.0 \text{ MV/m}$

$\Rightarrow$ similar electron energies

$\Rightarrow$ mean ionization energy in Kasting mixture larger than in Urey-Miller mixture

$\Rightarrow$ discharge inception/evolution less efficient in Kasting mixture
Inception fields
(field when avalanche-to-streamer transition occurs)

<table>
<thead>
<tr>
<th>Gas mixture</th>
<th>$E_{\text{inc,pos}}$ [MV m$^{-1}$]/[Td]</th>
<th>$E_{\text{inc,neg}}$ [MV m$^{-1}$]/[Td]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kasting $\text{N}_2 : \text{CO}_2 : \text{H}_2 \text{O} : \text{H}_2 : \text{CO}$</td>
<td>3.7/145.3</td>
<td>4.6/180.6</td>
</tr>
<tr>
<td>Urey-Miller $\text{H}_2 \text{O} : \text{CH}_4 : \text{NH}_3 : \text{H}_2$</td>
<td>2.7/106.0</td>
<td>2.7/106.0</td>
</tr>
</tbody>
</table>

(for comparison, on Modern Earth: ≈ 3.2/125.6)
Conclusions and outlook

- Streamer discharge inception in Kasting mixture requires higher fields than in Urey-Miller mixture
- Front velocities in Kasting mixtures smaller than in Urey-Miller mixture
- Comparable energies (<40 eV)

=> Discharges (lightning) inception might be more difficult in the oxidizing Kasting mixture
   (does not say anything about local reducing environments)

- Future project: include plasma chemistry of Primordial Earth into streamer code