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Understanding the Venusian and Terrestrial lightning due to the streamer propagation

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Abstract

The Venusian Lightning presents an opportunity to comprehend the behavior of streamers, which are essential components of electrical discharge. Streamers are the ionized columns of materials with a heightened electric field at their tips, necessary for phenomena including Lightning, sprites and spark discharge. These streamers impacted by microscopic ionization, electron drift, diffusion, photoionization and ion processes are detached, recombination and attachment produce complex tree-like structures or branched patterns in significant discharge. Although the numerical model can replicate the columnar shape of the ionization front, they often fall short of pinpointing the physical and mathematical mechanism determining the streamer radius, speed, branching and streamer discharge in atmospheric pressure using hydrodynamic approximation. We used the relation by describing the streamers with a finite set of parameters such as speed and radius head of the streamer tip. It has been seen that while the electron concentration drops with pressure, the electric field in the streamer head is barely impacted by pressure change. The expected streamer speed in the Venusian middle cloud is about 10^5 – 10^7 m/s. Furthermore, the lightning on Venus is expected to occur in the middle layer at 50-55 km altitude. By the comparative study of Venusian to Terrestrial lightning, it is possible to investigate Venus's atmospheric condition and its traits. These study advances our knowledge of streamer dynamics in various atmospheric scenarios and sheds light on the characteristics of Venusian Lightning.

1. Introduction

Venus and Earth are often considered twin planets due to their similar size, mass, internal structure, and chemical processes. However, they are more like fraternal twins, with Venus having little water, no plate tectonics, a dense atmosphere, and a lack of a significant magnetic field. Both planets have clouds and dynamic atmospheres at a 1-bar pressure level, but Venus's clouds are composed of sulfuric acid, making the sulfur cycle. Despite these differences, Venus has experienced significant volcanic activity and a similar atmospheric composition to Earth, with lightning despite the absence of water clouds. Earth and Venus have distinct atmospheres with Earth having a surface temperature of 300 K and a pressure of 1 bar and Venus having a surface temperature of 700 K and a pressure near 100 bar. Earth's atmosphere is primarily nitrogen, while Venus' is mainly carbon dioxide. Clouds on Earth are typically 1-10 km high, while on Venus they are 47-65 km high. Despite these differences, both planets have similar temperatures and pressures at cloud altitudes. Lightning is a naturally occurring electrical discharge event that can be seen on Earth and Venus, among other planetary atmospheres. On Earth, lightning is a well-studied phenomenon that mostly happens during thunderstorms.

The intricate interactions during lightning there will be ionization, charge separation, and updrafts cause it. However, because of the peculiar atmospheric conditions of Venus. Comprehending the actions of streamers, which precede complete lightning strikes, is crucial to understanding the features of lightning on both planets. This study explores the initiation and development of streamer discharges in Venusian clouds, comparing them with terrestrial lightning to understand the underlying physical processes.

2. Streamer's Dynamic in atmospheric

Streamers are regions of heightened ionization within gases or liquids, playing a crucial role in natural phenomena and industrial applications. They contribute to mesospheric discharges known as Red Sprites and are used to generate suprathermal electrons with energies exceeding 1 eV. This study focuses on streamers in air and Venusian atmosphere, examined in laboratory discharge experiments across electrode gaps ranging from a few centimeters to several meters. In large-scale laboratory discharges, streamers develop intricate branched structures, with high-frame-rate video cameras allowing for temporal observation of streamer branching in Sprites. Long-duration sparks exhibit a sequence of processes, from simpler to more complex scales, involving various physical mechanisms:- a)Electron Avalanche: This stage involves a Townsend discharge where space charges can be neglected. Electrons gain energy but transfer it weakly to molecules or atoms in inert gases, b) Streamers: As the electron avalanche extends, space charges become significant according to Meek's criterion. Electrons achieve typical energies around 3.6 eV, while the surrounding molecules remain relatively cold and c) Leaders: are akin to streamers but represent a more developed stage with increased current. Here, neutral molecules are heated, and strong ionization occurs.

Assuming the cylindrical shape, the lightning's initial channel will develop a branched structure. the distance between the axis of the cylinder and the channel expansion center is x, and the radius of the charged cylinder is R. To model the fractal growth of lightning channels, a 3D grid with spacing l is employed. If we assume that the channel grows along a direct path between the channel expansion center and the cylinder's periphery[2]. Given a constant streamer speed v_s the time t_s required for this direct growth to be completed,

$$t_s = \frac{R + x}{v_s}$$

A lightning channel may not always follow a straight path and can grow in various fractal patterns. Follow three different lightning channel paths—Path 1, Path 2, and Path 3, path 3 being the longest. The time for the channel to grow from the initiation point to the expansion center is [2],

$$\frac{l_0}{v_s} + \frac{R + x}{v_s} + \frac{l_t}{v_s} = t_{strike} .$$

The initial time $t_0 = \frac{l_0}{v_s}$ and terminal time for lightning to discharge is $t_t = \frac{l_t}{v_s}$. In the early stage of intracloud lightning, the streamer speed is relatively low, ranging from 10^4 to 10^5 m/s. Once an ionized discharge channel forms between charged regions, faster streamers, known as K-streamers, with speeds between 10^6 and 10^7 /s, transport charges more rapidly [1]. The initiation phase typically lasts 10 to 20 milliseconds, while an intracloud discharge event lasts approximately ten times longer [1].
The propagating channel is modeled as a cylindrical plasma structure with a hemispherical tip. At the tip of the streamer, four key processes take place due to the movement and diffusion of electrons and ions: i) ionization of neutral gas molecules by electron impact, ii) recombination of electrons with positive ions, iii) electron attachment, and iv) electron detachment. By solving for the steady-state concentration of plasma at the tip of the streamer, it is possible to estimate the expected streamer speeds v_s using relations derived from a detailed analysis of the one-dimensional fast ionization wave equation that aligns with the physical streamer model.

3. Streamer parametric model

In this section, we examine the approach of using parametric modeling to understand streamer dynamics. By specifying parameters such as the electric field in Fig. (1), ionization rates in Fig. (2a), and diffusion coefficients in Fig. (2b) [4]. Here, is a detailed model that simulates streamer behavior under various conditions. This modeling technique is particularly useful for predicting how streamers will behave in different atmospheric environments, such as the middle clouds of Venus. The following sections will explore the key processes involved in streamer formation and propagation, and how these can be represented using a parametric framework. The following sections will delve into the fundamental processes involved in streamer formation and propagation.

The parametric equation for streamers is a hydrodynamic approximation in eq (1). The term in eq (1) of n represents the number of densities of electrons, positive ion and negative ion. The ϑ represents the ionization co-efficient v_i, attachment v_a and detachment v_d. The recombination of electron-ion and ion-ion recombination is defined as a term of β and β_- [3]. The streamer speed in Venusian and Terrestrial atmosphere consists of an E electric field at the tip of streamer propagation, ϑ_m is the average number of ionization, $r_m$is the radius of the propagating streamers in eq. (2) [2].

4. Equations

The parametric model equation for streamers is,

$$\begin{aligned}\frac{\partial n}{\partial t} &= -\nabla\,(\mathrm{vn}) + \nabla\,(D\nabla n) \\ &\qquad + (v_i - v_a)n_- \\ &\qquad + v_d n - \beta n\, n_+; \\ \frac{\partial n_+}{\partial t} &= v_i n - (\beta n + \beta_- n_-)n_+; \\ \frac{\partial n_-}{\partial t} &= v_a n - v_d n - (\beta_- n_+ n_-)\,; \\ \nabla E &= \frac{e}{\varepsilon_0}(n_+ - n - n_-).\end{aligned} \quad (1).$$

The streamer speeds for Venusian and Terrestrial atmospheres are[2],

$$v_s = \frac{\vartheta_m(E) r_m}{(2k-1)\ln\left(\frac{nm}{no}\right)} \quad (2)$$

5. Figures and Tables

5.1 Figures

5.2 Tables

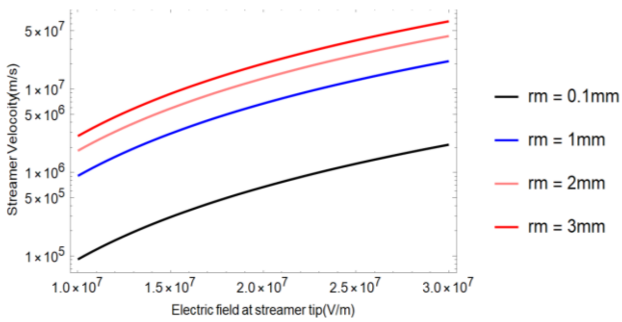

Figure1. The velocity of the streamer is affected by the electric field at the streamer tip, with different radii at the tip of the streamers**.**

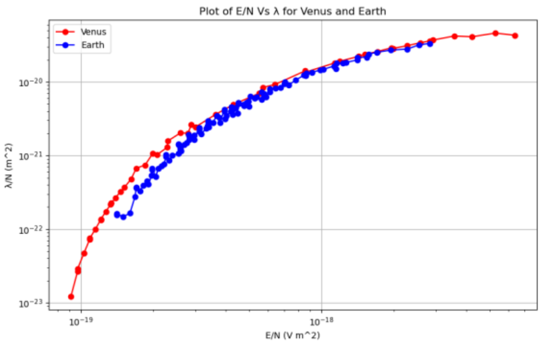

Figure 2a. The ionization coefficient with reduced electric field behaves similarly for Venusian and terrestrial.

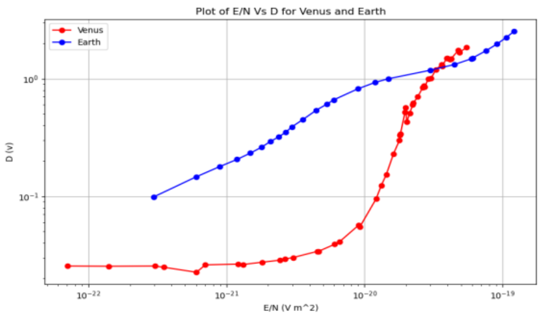

Figure 2b. The diffusion of electrons and ions with reduced electric field in the streamers.

6. Acknowledgements

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7. References

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