Sprite discharges on Venus, Jupiter and Saturn: a Laboratory Investigation in Planetary Gas Mixtures

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ABSTRACT: Lightning was detected on several planets in the solar system, where it could also produce sprites in the upper layers of these atmospheres. Large sprite discharges at mesospheric altitudes on Earth have been found to be physically similar to streamer discharges in air at sea level density. Based on this understanding, we investigate possible sprite discharges on the Gas Giant planets and on Venus through laboratory experiments on streamers in H_2-He and CO_2-N_2 mixtures. Streamer diameters, velocities, radiance and overall morphology are investigated for sprites on Jupiter, Saturn and Venus, by means of a fast ICCD camera. The spectra of the streamer discharges are measured; they are dominated by the minority species N_2 on Venus, and by radiative dissociative continuum radiation of H_2 in the Gas Giants. The spectrum of a fully developed spark on Venus and Saturn is also measured.

1. INTRODUCTION

1.1 Planetary lightning

Lightning had been detected on several planets in the Solar system, via direct optical imaging on Earth, Jupiter and Saturn, and by electromagnetic remote sensing on Earth, Venus, Jupiter, Saturn, Neptune and Uranus (see a recent review by Yair et al. [2008]). Terrestrial lightning is often accompanied by dielectric breakdown in the mesosphere known as sprites, which occur when the quasi-electrostatic field induced by the parent lightning exceeds the local breakdown threshold. Based on this mechanism Yair et al. [2009] investigated the possibility of sprite occurrence in various planetary atmospheres, and the basic conditions for electric breakdown were shown to be possible under reasonable assumptions on the parent lightning, leading to the conclusion that sprites and similar discharges can potentially exist in the atmospheres of Venus, Jupiter and Saturn.

1.2 Modelling sprites in the laboratory

It is by now well understood that the large sprite discharges at low air density are essentially up-scaled versions of small streamer discharges at high air density that dominate the initial breakdown of large gas volumes in a sufficiently strong electric field. Streamers and sprites are related through scaling laws. The scaling of electric fields with gas density in discharges goes back to Townsend at the beginning of the 20th century; other scaling relations were developed later, and some particular relations are valid for streamers. They were recently reviewed by Ebert et al. [2010]. In the propagating heads of streamer discharges scaling laws hold

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particularly well because these fast processes are dominated by collisions of single electrons with neutral molecules, while density dependent two-step processes and three-particle processes are negligible. This implies that the basic length scale of the streamer discharge is the mean free path of the electron, which is inversely proportional to the density *n* of the gaseous medium. Scaling between different densities implies that the streamer velocity, as well as velocity and energy distributions of individual electrons are independent of gas density, while streamer length and time scale as *1/n*, electric field as *n*, and densities of charged particles as n^2. The similarity of the overall morphology including diameters and velocities of streamers and sprites in terrestrial air of varying density were confirmed experimentally by Briels et al. [2008] and later by Nijdam et al. [2010]. Since the scaling relations hold in any gas mixture, this naturally opens the possibility to simulate planetary sprites through laboratory experiments using the proper gas mixtures.

The scaling of length can be tested by examining the minimal diameter of streamers. Streamers approach this diameter when they hardly can exist, either because the applied voltage is marginal, or because they are approaching their maximal length, typically after branching several times. Briels et al., [2008] show that the product of density and minimal diameter does not depend on the gas density.

More information on streamers and scaling relations can be found in the recent review by Ebert et al., [2010] and references within.

2. EXPERIMENTAL SETUP

We create positive streamers in a point-plane 16 cm gap contained within a large cylindrical stainless steel vacuum vessel, specifically designed to maintain the purity of the gases in use. The vessel is filled with a gas mixture of our choice, and the pressure is controlled in the range of 25 to 1000 mbar. For the work described here the vessel was filled with gas mixtures specifically chosen to represent the atmospheres of the planets of interest, namely: Venus (CO_2:N_2 – 96.5:3.5), Jupiter (H_2:He – 89.8:10.2), Saturn (H_2:He:CH_4 – 92.2:7.4:0.4) and Earth (N_2:O_2 – 80:20). Short positive voltage pulses with a repetition rate of 1 to 14 Hz are applied to the anode tip, causing the initiation of positive streamers near the tip. The streamers are imaged using a fast intensified CCD camera, with exposure times as short as 1 nsec. The imaging setup is sensitive in the range 300 to 800 nm. Three small spectrometers are used to study the spectrum in the range 230 to 940 nm. Detailed description of the setup can be found in [Dubrovin et al., 2010; Nijdam et al., 2010].

3. RESULTS

3.1 Study of morphology and confirmation of scaling laws

The morphology of the discharges we observed depends on the gas composition to some extent; however the general picture shows thick streamers emerging from the tip and branching several times. The observed morphological differences are described below (Figure 1).

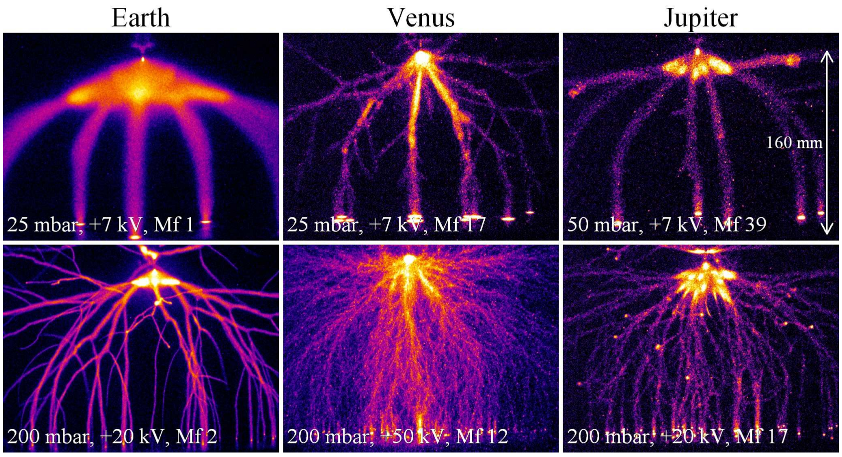

Figure 1: Fully developed streamer discharges in planetary gas mixtures. Gas pressure and applied voltage are indicated in the images. The magnifying factor (Mf) is a measure of the degree by which the image is enhanced. Higher Mf values correspond to originally dimmer images. The images in the Saturn mixture are similar to those in the Jupiter mixture (far right).

Streamers in air are the brightest. They form relatively smooth traces in the image and branch less than in the other gas mixtures. Streamers in the mixture representing Venus are dimmer by one order of magnitude, within the imaging setup sensitivity range of 300 to 800 nm. They branch more often and form traces with uneven boundaries. Higher inception voltages are required to create the discharge. On the other hand, our measurements indicate that the reduced minimal diameter of the Venusian streamers are quite similar to those of the streamers in air and in pure nitrogen, with $p \cdot d_{min} = 0.09 \pm 0.03\ mm \cdot bar$ at room temperature. Similarly to Venus, streamers in the Jupiter and Saturn mixtures are dimmer by one order of magnitude than in air in the observed wavelength range, though in this case most of the radiation comes from continuum radiation in the near UV, outside the range of our imaging equipment, as discussed in the next section. The traces of these streamers are quite straight with a reduced minimal diameter almost three times as wide as in the mixtures containing nitrogen, namely $p \cdot d_{min} = 0.26 \pm 0.03\ mm \cdot bar$ at room temperature. More information can be found in [Dubrovin et al., 2010].

3.2 Spectrum

We measured the emission spectrum of pulsed glow discharge in the four gas mixtures (repetition rate 10 to 14 Hz). In air (Figure 2) it is dominated by nitrogen lines: predominantly the second positive group (N_2-2P, UV) in the near UV and blue and the first positive group emissions (N_2-1P, red) in the red, and a atomic oxygen line is observed at 777 nm. This spectrum corresponds well with the available sprite spectra, mainly in the red [Hampton et al., 1996].

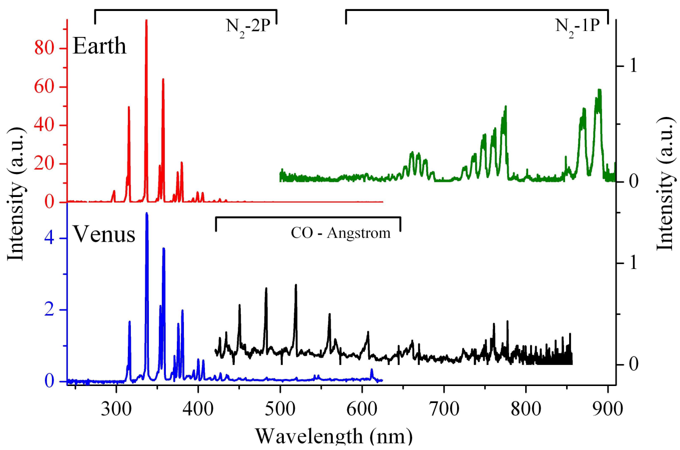

Figure 2: The integrated spectra of pulsed glow discharges in artificial air (top) and the Venus mixture (bottom).

The spectrum of pulsed glow in the mixture representing Venus is dominated by strong N_2-2P emissions in the near UV and blue. In the visible we find the CO Angstrom band, about one order of magnitude weaker than the blue group. The N_2-1P is practically absent except for several weak lines between 700 and 800 nm barely visible above the noise level.

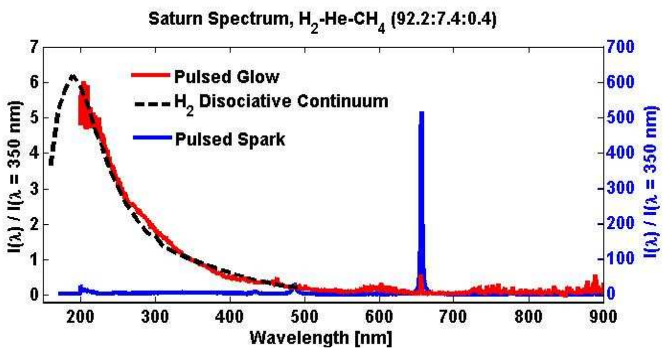

Figure 3: Integrated spectra of pulsed glow discharges in the Saturn mixture (red), compared with H_2 dissociative continuum (black, [Lavrov et al. 1999]). Integrated spectrum of pulsed spark in the Saturn mixture is shown in blue.

The spectrum of pulsed glow in the mixtures representing Saturn and Jupiter are dominated by a continuum in the UV, from 230 nm, the lowest edge of our sensitivity, up to ~500 nm. The shape of the continuum corresponds well with the H_2 radiative dissociative continuum modelled analytically by Lavrov et al. [1999]. According to Lavrov et al., the continuum reaches a maximum at 170 nm, beyond the range of our equipment. The Balmer alpha line at 656 nm is also present, but it is weak compared to the intense UV continuum. In the pressure range of 25 to 100 mbar and voltage range of 20 to 50 kV the continuum line shape is not affected, however the Balmer line is relatively less intense at the higher pressures. Sparks in these gases emit mainly in the Balmer series wavelengths, and the continuum is absent. Therefore the emissions caused by sprites could be easily differentiated from emissions caused by lightning during observations of those planets. More information can be found in [Nijdam, 2011] and in [Dubrovin et al., 2010].

4. CONCLUSIONS

We observed streamers in a previously unexplored set of gas mixtures simulating the atmospheres of Venus, Jupiter and Saturn in controlled laboratory settings. We demonstrated that streamer discharges are possible in these gases, which gives firmer ground to the possibility of observing sprites on these planets by orbiting spacecrafts. Streamers in the different gases are rather similar in their appearance, albeit differences in branching, intensity and the propagation path morphology. In particular the streamer reduced minimal diameter in the mixture representing Venus is the same as in terrestrial air and in pure nitrogen, and in the helium-hydrogen mixtures of Jupiter and Saturn it is three times as wide. We report the expected spectral emissions of the streamer discharges in the planetary gases, which can be instrumental in planning for remote sensing.

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