

## Interaction of Streamer Discharges in Air and Other Oxygen-Nitrogen Mixtures

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The interaction of streamers in nitrogen-oxygen mixtures such as air is studied. First, an efficient method for fully three-dimensional streamer simulations in multiprocessor machines is introduced. With its help, we find two competing mechanisms how two adjacent streamers can interact: through electrostatic repulsion and through attraction due to nonlocal photoionization. The nonintuitive effects of pressure and of the nitrogen-oxygen ratio are discussed. As photoionization is experimentally difficult to access, we finally suggest to measure it indirectly through streamer interactions.

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Streamer discharges are fundamental building blocks of sparks and lightning in any ionizable matter; they are thin plasma channels that penetrate nonconducting media suddenly exposed to an intense electric field. They propagate by enhancing the electric field at their tip to a level that facilitates an ionization reaction by electron impact [1,2]. Streamers are also the mechanism underlying sprites [3–5]; these are large atmospheric discharges above thunderclouds that, despite being tens of kilometers wide and intensely luminous, were not reported until 1990 [6]. Although the investigation of streamers concentrates mainly in gaseous media, they have also been studied in dense matter, such as semiconductors [7] and oil [8]. Streamers have also received attention in the context of Laplacian-driven growth dynamics [9] and a strong analogy with viscous fingering, in particular, Hele-Shaw flows [10,11], has been established.

Both in laboratory [12] and in nature [13], streamers appear frequently in trees or bundles. As their heads carry a substantial net electrical charge of equal polarity that creates the local field enhancement, they clearly must repel each other electrostatically which probably causes the “carrotlike” conical shape of sprites. On the other hand, recent sprite observations [14] as well as streamer experiments ([15], Fig. 7, [12], Fig. 6) also show the opposite: streamers attract each other and coalesce.

Up to now, streamer interactions have not been studied much theoretically, and streamer attraction has not been predicted at all. In coarse-grained phenomenological models for a streamer tree as a whole [16], the repulsive electrostatic interaction between streamers is taken into account. In a more microscopic, but still largely simplified model, Naidis [17] studied the corrections to the streamer velocity due to electrostatic interaction with neighboring streamers. In [11], a microscopic “fluid” model for a periodic array of negative streamers in two spatial dimensions is studied, showing that shape, velocity and electro-dynamics of an array of streamers substantially differs from those of single streamers due to their electrostatic

interaction, but attraction or repulsion were excluded by the approach. Because of the difficulty to represent this multiscale process [2] in a numerically efficient manner, only recently it has become possible to simulate streamers in full 3D [18,19]. We present a numerical method to handle this problem, and we apply it to the interaction of streamers in complex gases like air where a nonlocal photon mediated ionization reaction has to be included. We find that when varying gas composition and pressure, streamers can either repel or attract each other. The transition occurs in an unexpected manner, and is not simply determined by an ionization length.

The photon mediated ionization reaction in air and other nitrogen-oxygen mixtures is experimentally not easily ac-

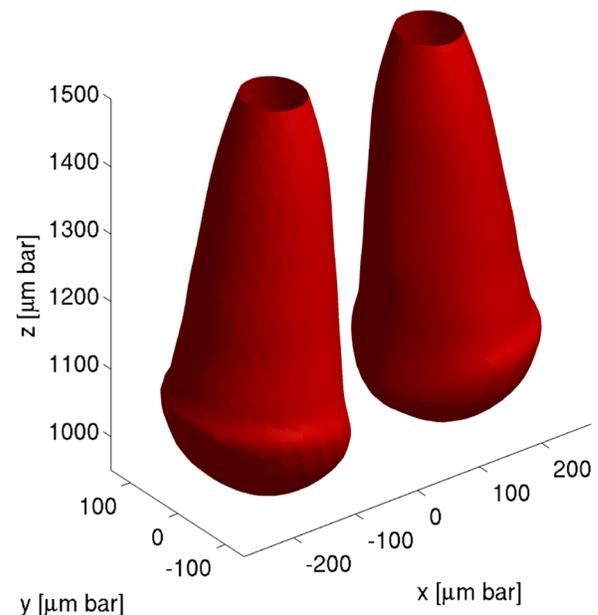


FIG. 1 (color online). Two negative streamers in nitrogen at atmospheric pressure advancing downwards and repelling each other; shown are surfaces of constant electron density in an advanced state of evolution within a constant background field.

cessible, but forms a basic ingredient of the theory of streamers in air [19–23] which relies on the single experimental measurement of Penney and Hummert in 1970 [24]. Our theoretical results suggest that this reaction could be deduced from experiments on coalescence or repulsion of adjacent streamers as a function of pressure and gas composition.

We study the minimal streamer model [25] extended by the nonlocal photoionization reaction characteristic for nitrogen-oxygen mixtures like air. It consists of continuity equations for electron and ion densities  $n_{e,+}$  coupled to the electrical field  $\mathbf{E}$  that is determined by the potential on the outer boundaries and space-charge effects:

$$\partial_t n_e = \nabla \cdot (n_e \mu_e \mathbf{E}) + D_e \nabla^2 n_e + S_i + S_{\text{ph}}, \quad (1)$$

$$\partial_t n_+ = S_i + S_{\text{ph}}, \quad (2)$$

$$\epsilon_0 \nabla \cdot \mathbf{E} = e(n_+ - n_-), \quad \mathbf{E} = -\nabla \phi. \quad (3)$$

Here  $\mu_e$  is the electron mobility,  $D_e$  is the electron diffusion coefficient and  $e$  is the elementary charge. Ion mobility, much smaller than electron mobility, is neglected. To fully focus on the influence of photoionization, electron attachment on oxygen is here neglected as well, and we use transport parameters for pure nitrogen as in previous work [2,26]. The source terms for additional electron-ion pairs are the local impact ionization  $S_i$  in Townsend approximation,  $S_i = n_e \mu_e |\mathbf{E}| \alpha(|\mathbf{E}|) = n_e \mu_e |\mathbf{E}| \alpha_0 e^{-E_0/|\mathbf{E}|}$ , where  $\alpha_0$  is the ionization cross section and  $E_0$  is the threshold field, and the nonlocal photoionization according to the model for oxygen-nitrogen mixtures developed by Zheleznyak *et al.* [27]

$$S_{\text{ph}}(\mathbf{r}) = \frac{\xi A(p)}{4\pi} \int \frac{h(p|\mathbf{r} - \mathbf{r}'|) S_i(\mathbf{r}') d^3(p\mathbf{r}')}{|\mathbf{p}\mathbf{r} - \mathbf{p}\mathbf{r}'|^2}, \quad (4)$$

with  $A(p) = p_q/(p + p_q)$ . Here it is assumed that accelerated electrons excite certain states of nitrogen by impact with a rate  $\xi S_i$  where  $S_i$  is the local impact ionization rate and  $\xi$  a proportionality factor. These nitrogen states can deexcite under emission of a photon in the wavelength range 980–1025 Å that can ionize oxygen molecules [24,27]. The absorption length of these photons by oxygen is inversely proportional to the oxygen partial pressure  $p_{\text{O}_2}$ . Introducing the oxygen concentration in the gas as  $\eta = p_{\text{O}_2}/p$ , the absorption function of photoionizing radiation  $h(pr)$  is characterized by the two length scales  $pr_{\text{min}} \approx 380 \mu\text{m bar}/\eta$  and  $pr_{\text{max}} \approx 6.6 \mu\text{m bar}/\eta$ . Above a critical gas pressure that we take as  $p_q = 80 \text{ m bar}$  [22], the excited nitrogen states can be quenched by collisions with neutrals, hence suppressing photoemission by a factor  $A(p)$ .

A major difficulty in the theoretical study of streamer-streamer interactions is the development of an efficient numerical code for streamer simulations with their inner

multiscale structure in 3D. Here we present a locally adaptive and parallelizable approach to this problem. Our method has in common with the one described in [18] that cylindrical coordinates and a uniform grid in the angular dimension are used, but in the  $r, z$  projection we apply the grid refinement scheme of [26] to resolve better the thin, pancakelike shape of the space-charge layer. Furthermore, to allow the parallel solution of the Poisson equation in multiprocessor machines we perform a Fourier transformation in the angular coordinate  $\theta$ ,  $\tilde{\phi}_k(r, z) = \sum_{n=0}^{N-1} \phi(r, z, \theta_n) e^{-ik\theta_n}$ , where  $N$  is the number of grid cells in the  $\theta$  direction and  $\theta_n = 2\pi n/N$ . For each separate mode  $k$  we solve a two-dimensional Helmholtz equation:

$$\nabla_{rz}^2 \tilde{\phi}_k + \frac{|w_k|^2}{r^2} \tilde{\phi}_k = -\frac{e}{\epsilon_0} (\tilde{n}_{+k} - \tilde{n}_{ek}), \quad (5)$$

where a tilde represents the Fourier transform of a quantity and  $|w_k|^2 = \frac{2}{\Delta\theta^2} (1 - \cos k\Delta\theta)$ . For each Fourier mode, we apply the refinement algorithm described in [28], which is trivially generalized to solve the Helmholtz equation. The advantage of solving the electrostatic part of the problem in the Fourier domain is that each of the Fourier modes is decoupled from the rest and hence it can be solved in parallel. Once the electric field is calculated in Fourier space, the field in real space is derived through an inverse Fast Fourier Transform; and the convection-diffusion-reaction system (1) and (2) is integrated as detailed in [26]. The photoionization term is computed in a Helmholtz PDE approach as described in [22], and in the angular direction with a scheme of Fourier transformations and parallel solving that is completely equivalent to the one applied to the Poisson equation.

We now use our model and numerical algorithm to study the interaction between two streamers. We focus on the influence of (i) the pressure in air and of (ii) the oxygen-nitrogen ratio at standard pressure; standard temperature is always assumed. (i) The comparison of streamers at different pressures  $p$  relies on scaling lengths, times, etc., with appropriate powers of  $p$ . These similarity laws are strictly valid in the minimal streamer model [2,26] but broken by photoionization (4) when the pressure reaches the quenching pressure  $p_q$ ; for  $p \geq p_q$ , photoionization at unchanged gas composition is increasingly suppressed like  $A(p)$  [20]. Similarity or Townsend scaling is further discussed in Sect. 1.2 of [29]. (ii) The  $\text{O}_2 : \text{N}_2$  ratio changes the local photoionization rate which is proportional to it, while the absorption lengths are inversely proportional to it.

First, negative streamers are investigated, because they propagate even in the absence of photoionization. Then it is shown that positive streamers behave similarly. In all simulations, we use two identical Gaussian seeds of reduced width (according to Townsend scaling)  $pw = 73.6 \mu\text{m bar}$  and amplitude  $p^{-2} n_{e,\text{max}} = 1.4 \times 10^{-2} \mu\text{m}^{-3} \text{bar}^{-2}$  separated by a reduced distance of  $pd = 230 \mu\text{m bar}$  as an initial condition. They are ex-

posed to a homogeneous and constant background electric field  $E_b/p = 80$  kV/(cm bar) in the positive  $z$  direction. The streamers on reduced length, time and density scales are similar if photoionization is neglected.

The simulations were performed with an angular resolution of  $\Delta\theta = 2\pi/64$  ( $N = 64$ ), but we also checked that the results are stable when we double the number of angular grid cells. Figure 1 shows a surface of equal electron density for the discharge in nitrogen at normal pressure and temperature at time  $t = 1.56$  ns. Figures 2–4 show the space-charge layers at the streamer heads (more precisely, the half maximum line at the respective time) in the plane intersecting the two streamer axes in time steps of 0.12 ns bar; the first snapshot is at time 0.84 ns bar.

Figure 2 demonstrates the effect of pressure change for similar streamers in artificial air, i.e., in an oxygen-nitrogen mixture of ratio 20:80, corresponding to  $\eta = 0.2$ . The panels show (a) air at a pressure of 0.07 m bar, which is the atmospheric pressure at approximately 70 km height,

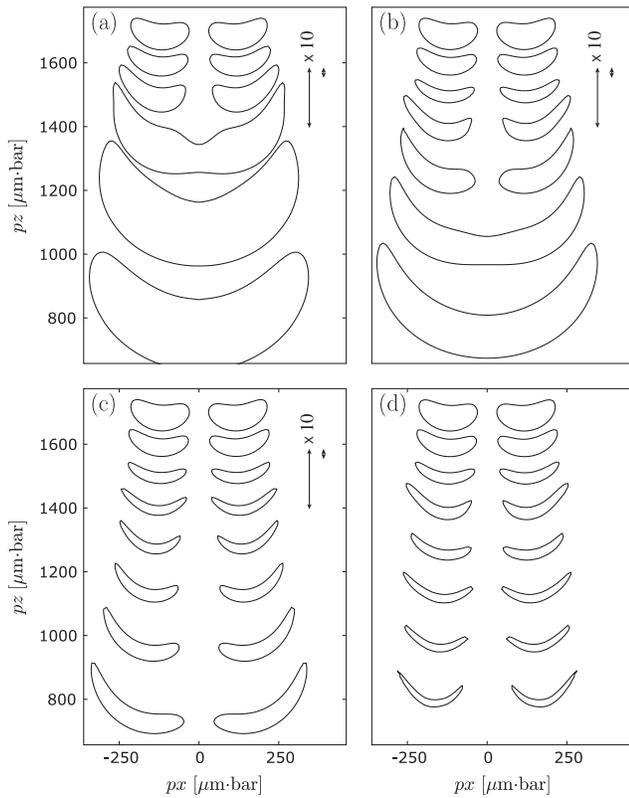


FIG. 2. Evolution of the space-charge layers of two adjacent negative streamers at different pressures in air. (a)  $p = 0.07$  m bar, (b)  $p = 1$  bar, (c)  $p = 50$  bar, (d)  $p \rightarrow \infty$ . (a) corresponds to  $A(p) \approx 1$  and (d) to  $A(p) = 0$ , which is equivalent to pure nitrogen since there is no photoionization (even though in pure nitrogen the length scales formally diverge). The axes show reduced lengths  $px$ ,  $pz$  to exhibit similarities. In the upper right corners, the two photoionization lengths are inserted as vertical bars. A multiplicative factor is used where the lengths are too long to fit into the figure.

where sprites are frequently observed, (b) air at 1 bar, (c) air at 50 bar, and (d) pure nitrogen which in our model is equivalent to air at infinite pressure.

The first observation is that two streamers do not always repel each other. Rather there are two qualitatively different regimes: at a pressure of 50 bar and above, when the fast collisional quenching of  $N_2$  molecules suppresses photoionization, the streamers repel each other electrostatically due to the net negative charge in their heads. However, at atmospheric pressure and below, the streamers attract each other: a cloud of electrons is created between the two streamers which eventually makes them coalesce into a single, wider one. As it has been suggested that the photoionization length could determine length scales in the streamer head [30], the two reduced photoionization lengths are indicated by the vertical bars in the upper right corners, they are the same in all panels. Obviously, there is no simple relation between these lengths and the observed repulsion or attraction; the interaction is rather governed by the quenching prefactor  $A(p)$ .

Figure 3 demonstrates the effect of the oxygen concentration. For fixed atmospheric pressure, the relative oxygen concentration  $\eta = p_{O_2}/p$  is reduced to  $10^{-1}$ ,  $10^{-2}$ ,  $10^{-3}$ , and  $10^{-4}$ . As the photoionization lengths scale inversely

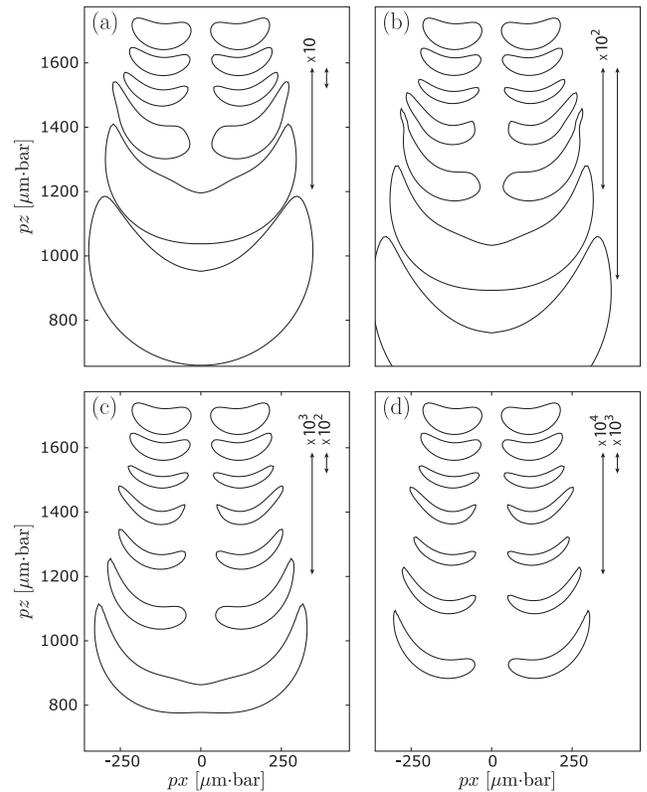


FIG. 3. Evolution of the space-charge layers of two adjacent streamers at atmospheric pressure, but different concentrations of  $O_2$ :  $\eta = p_{O_2}/p = 10^{-1}$ ,  $10^{-2}$ ,  $10^{-3}$ , and  $10^{-4}$  in panels (a)–(d).

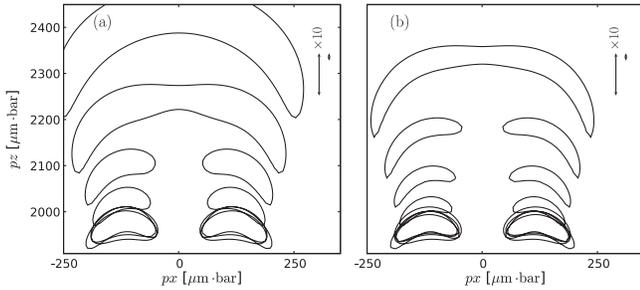


FIG. 4. Evolution of the space-charge layers of two adjacent positive streamers in air at 1 bar (a) and 50 bar (b).

with  $\eta$ , these lengths increase by factors 10 from one panel to the next while  $A(p)$  decreases by  $10^{-1}$ . The attraction between the streamers decreases with decreasing oxygen concentration until it is not visible anymore for  $\eta = 10^{-4}$ .

Figure 4 shows that the interaction between two positive streamers is qualitatively similar to that of negative streamers, since the same two competing phenomena are present. Initial and boundary conditions are the same, and we show positive streamers in air at 1 bar and at 50 bar. The positive streamers take longer to start but after a relatively short time they merge.

Because of the nonlinear and nonlocal nature of streamer interactions and to the many dimensions of our parameter space, it is difficult to develop a simple prediction for streamer merging. Nevertheless, the following remarks can be made. First, to produce enough ionization between the streamers, at least one of the absorption lengths of photoionization must be larger than or comparable to the streamer distance. Second, this photoionization is only amplified to a level comparable to that on the streamer head if the field is enhanced between the streamers; hence the streamer distance should not be much larger than the streamer radius. Finally, an approximation for the relative photoionization level can be extracted from (4) as the maximum of the instantaneous rate of photoionization on the middle axis produced per impact ionization event in the tip of a given streamer, namely,  $\beta = \xi A(p)h(pd/2)/\pi p^2 d^2$ . Preliminary results show that this parameter influences the electron densities in the axis at early stages of the evolution. We have not found a deterministic law but coalescence is favored for large  $\beta$  and occurs always if  $\beta \gtrsim 10^{-11} \mu\text{m}^{-3} \text{bar}^{-3}$ .

We have developed a code to study the interaction of streamers in full 3D space, and we have studied the basic processes that govern the interaction of two adjacent streamers. To focus on the underlying physics of photoionization we have neglected electron attachment and non-trivial electrode geometries. Further steps are needed to successfully predict the outcome of experiments and observations; we mention needle electrodes and the nonalign-

ment of the streamer heads. But our results show that for a given pressure  $p$ , electric field  $E_0$ , oxygen-nitrogen ratio  $\eta$  and initial seeds, there is a threshold distance  $d^*$  below which two streamers coalesce. This distance, which is experimentally accessible, would be an indirect measure of the frequency of photoionizing events. Hence we believe that fully three-dimensional calculations of streamer dynamics will provide a suitable test case for streamer models as they predict easily observable behavior like attraction, repulsion, or branching.

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