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Mesosphere-troposphere coupling due to sprites

Victor P. Pasko

CSSL Laboratory, Penn State University, University Park, Pennsylvania

Umran S. Inan, and Timothy F. Bell

STAR Laboratory, Stanford University, Stanford, California

Abstract. Results from a new three-dimensional fractal model of sprites as well as recent experimental data on thundercloud charge moment changes associated with sprites indicate that ionized regions in sprites can sometimes reach thundercloud tops, creating favorable conditions for establishing a highly conducting link between the Earth's surface and the lower ionosphere.

Introduction

Sprites are transient luminous events which appear in clear air above thunderstorms following intense lightning discharges [e.g., *Sentman et al.,* 1995]. Sprites are morphologically complex phenomena showing a lot of variability in their temporal and spatial appearance. Sprites often exhibit an amorphous non structured glow at their tops, the so-called sprite "halo" [e.g., *Barrington-Leigh et al.,* 2001], which converts to highly (predominantly vertical) structured breakdown regions at lower altitudes [e.g., *Stanley et al.,*1999; *Gerken et al.,*2000]. This vertical structure in sprites is also apparent in recent high speed video images of *Stenbaek-Nielson et al.*[2000], and is consistent with the scaling laws controlling electrical breakdown in different altitude ranges above thunderstorms proposed by *Pasko et al.*[1998].

A recent electrodynamic model of the upper "halo" region of sprites has produced results in very close agreement with high-speed video observations [*Barrington-Leigh et al.,* 2001]. Such direct modeling of the lower, highly structured sprite regions poses insurmountable computational difficulties due to the dramatic differences between the scale of individual ionized channels (i.e., streamers) constituting sprites (of order several meters [*Gerken et al.,* 2000]) and the overall spatial extent of sprites (of order 10 to 100 km). To overcome this difficulty, a two-dimensional fractal model has recently been proposed [*Pasko et al.,* 2000, hereafter denoted I], which allows the reproduction of the observed large scale volumetric shapes of sprites.

The question about possible attachment of sprites to the cloud tops can be readily addressed with the fractal type of model put forth in [I]. This question is of fundamental importance for understanding the role of sprites in the global atmospheric electric circuit, since it directly relates to the possibility of establishing a highly conducting link between the Earth's surface and the lower ionosphere.

The experimental evidence of the possible attachment of sprites to the cloud tops has been presented recently by *Siefring et al.* [1999] in the context of the observations performed during EXL98 Sprites Campaign. Other similar evidence includes reports by *Lyons et al.* [2000] of well defined "trolls", or jet-like features propagating upwards from near cloud tops to 40-50 km at 150 km/s along the preceding sprite's tendrils, and reports of the high thundercloud charge moment changes [*Stanley et al.,* 2000; *Cummer and Fullekrug,* 2001], which as discussed later in this paper create favorable conditions for propagation of sprite tendrils down to thundercloud altitudes. *Stanley et al.* [2000] reported daytime sprite ELF signatures with associated thundercloud charge moment changes of ~3900-6100 C·km. *Cummer and Fullekrug* [2001] reported sprite associated thundercloud charge moment changes of ~2100-5950 C·km.

The purpose of this paper is to analyze the question about possible attachment of sprites to the cloud tops by means of numerical experiments using a newly developed three-dimensional (3-D) fractal model of sprites.

Model

We use a new 3-D fractal model of sprites, which represents a straightforward extension of the previously reported 2-D version [I] to three spatial dimensions. The model simulates the propagation of a streamer corona associated with sprites as a three dimensional growth of fractal trees composed of a large number of line channels, and allows realistic three dimensional modeling of upward, downward and quasi-horizontal propagation and branching of sprite ionization. The fractal model is based on a phenomenological probabilistic approach, which was proposed in [*Niemeyer et al.,* 1989] for modeling of a streamer corona and uses experimentally and theoretically documented properties of positive and negative streamers in air for a realistic determination of the propagation of multiple breakdown branches in a self-consistent electric field. The fractal model follows the dynamics of highly branched electrical breakdown in large volumes of space without actually resolving internal physics of individual streamer channels [I], but rather relying on demonstrated collective characteristics of streamers in air. The fractal model uses E^+_{cr}=4.4 kV/cm and E^-_{cr}=12.5 kV/cm as minimum electric field magnitudes required for propagation of positive and negative streamers in air at ground pressure, respectively [I and references therein]. The critical fields E^+_{cr} and E^-_{cr} scale with altitude proportionally to the atmospheric neutral density as shown in Fig.1b.

The new 3-D model uses the same parameter values and numerical algorithms as documented in [I], and has been validated using a series of numerical experiments with different spatial resolutions similar to those reported in [I] for the 2-D case. Specifically, the validation runs involved place-

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ment of a spherical charge inside a small metallic box (cubic, with side length 2 cm) filled with air at ground pressure and investigation of the resultant fractal trees (in terms of Hausdorff fractal dimension D [e.g., I and references therein]) and macroscopic electric fields as a function of the spatial discretization of the system. Result of one of the runs obtained using a simulation box with spatial resolution of $n = 50$ grid points per 2 cm (i.e., with total 50×50×50 grid points) is shown in Fig.1a and is similar to that shown in Fig.2a of [I] for the 2-D case. Runs were repeated 10 times for each spatial resolution studied (n=30, 40, and 50 points per 2 cm). Consistent with the previously reported 2-D case, results were found to be independent of the spatial resolution. In particular, results demonstrated quasi-constant electric fields inside of the streamer corona (not shown, but similar to those reported in Fig.2b of [I]). Results also demonstrated similar fractal dimensions D: D=1.26±0.15; 1.46±0.14 and 1.34±0.10 for n=30, 40 and 50, respectively.

Although results of the 3-D model appeared to be intrinsically consistent and independent of the spatial resolution, some slight differences between results obtained with the 2-D and 3-D models were observed. Specifically, the electric field magnitude inside the streamer corona was found to be ~20% higher in 3-D case. This and some other geometrical differences between 2-D and 3-D models when applied to sprites will be discussed in the next section.

For the 3-D sprite simulations reported in this paper we chose the simulation box to have cartesian (i.e., x,y,z) dimensions of 200×200×95 km, with 95 km being the effective distance between the ground and the ionosphere (same as in [I]). We report results for two sets of runs. For the first set the source charge Q is centered at altitude z=h_Q=10 km (at the point with cartesian coordinates x=100 km, y=100 km, z=10 km, see Fig.2) and is assumed to have a Gaussian spatial distribution with the vertical dimension a=3 km and the horizontal dimension b=$3(Q/100)^{0.675}$ km. The parametric dependence of b on Q was chosen so that the electric field magnitude inside the thundercloud does not exceed ~50 kV/m for the model charge values in the range 100-600 C, where 50 kV/m is the reference field typically measured on balloons inside thunderclouds [e.g., *Marshall et al.,* 1996; 2001]. For the second set of runs we place the charge at lower altitude h_Q=7 km and increase its horizontal dimension so that $b = 6(Q/143)^{0.511}$ km. The model electric field distributions for three different values of thundercloud

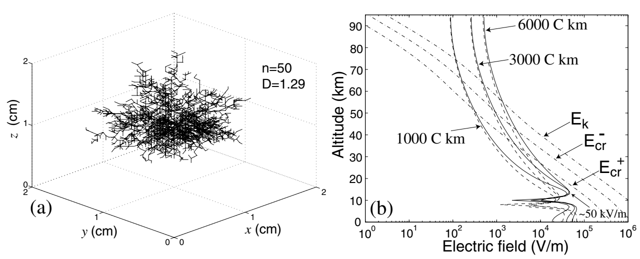

Figure 1. (a) An example of the model generated 3-D positive streamer corona; (b) Altitude scans of the electrostatic field corresponding to different charge moments (1000 C·km, 3000 C·km and 6000 C·km) and different spatial charge distributions discussed in the text. The conventional breakdown field E_k, and the minimum fields required for the propagation of positive (E_{cr}^{+}) and negative (E_{cr}^{-}) streamers (see [I] for further details) are also shown for reference by the dashdot lines.

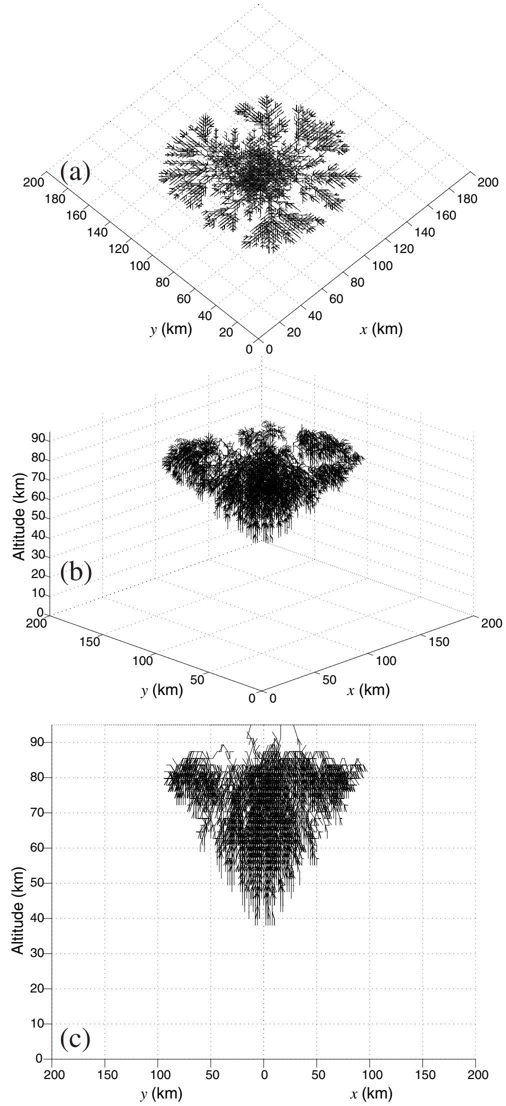

Figure 2. Results from the 3-D fractal model. The sprite is produced by 100 C of charge removed from 10 km altitude. Panels (a),(b),(c) show different views (top, perspective and side) of the same model sprite.

charge moments (i.e., $Q \times h_Q$) are shown in Fig.1b as a function of altitude (i.e., z) in the center of the simulation box, i.e., at x=100 km and y=100 km (the cases corresponding to h_Q=10 km are shown by solid lines and those to h_Q=7 km by dashed lines).

Results

Fig.2 shows results of the 3-D model for a case Q=100 C and h_Q=10 km. A large "jelly fish" sprite is formed. The azimuthal symmetry of sprites which was necessarily present in the 2-D model [I] is obviously lost in the 3-D case. Otherwise, the results appear to be quite similar to those obtained previously with the 2-D model in terms of the general volumetric shape of sprites and their lateral and vertical extent. Detailed analysis of results indicated that sprites in our 3-D model propagate to slightly (~2 km) lower altitudes than in 2-D cases, for identical driving thundercloud charge moments. This aspect will be further discussed below.

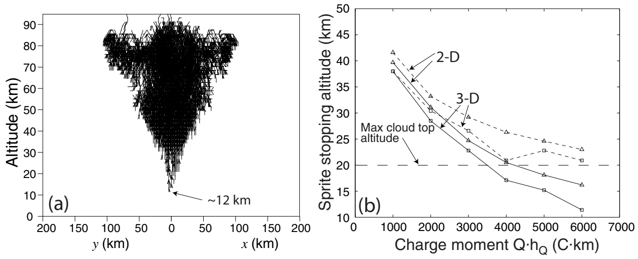

Figure 3. (a) A side view of a model sprite produced by the removal of 600 C of charge from 10 km altitude; (b) A sprite lower stopping altitude is shown as a function of the thundercloud charge moment for different model cases discussed in the text.

The 3-D model also was used to model sprites produced by negative cloud-to-ground lightning discharges. Results (not shown) are similar to those reported for the 2-D case: the lowest altitude extents of such "negative" sprites were ~10 km higher than those of "positive" ones for the same absolute values of the driving thundercloud charge moment. In addition, negative sprites exhibited numerous attachment points to the lower ionosphere and grew wider in lateral dimension than positive ones. For relatively low driving thundercloud charge moments negative sprites required higher values of the driving moments for their initiation (for further discussion of this issue please see [I]).

Both the new 3-D and previously reported 2-D models were used with different thundercloud charge moments to investigate the question of possible attachment of sprites to thundercloud tops. Fig.3b shows the lower stopping altitude of sprites obtained with the 2-D and 3-D models as a function of the driving thundercloud charge (points corresponding to h_Q=10 km cases are connected by solid lines and those to h_Q=7 km by dashed lines).

For the 2-D case the model was run 10 times for each charge moment and charge altitude combination studied (1000, 2000, 3000, 4000, 5000, 6000 C·km, and h_Q=10 and 7 km) with the open triangles in Fig.3b showing average value of the ten runs. Due to very substantial computational time required (~40 hours per run on a desktop 500 MHz G4 Macintosh computer) the 3-D model was run only once for each of these combinations with results shown in Fig.3b as open squares. Fig.3a shows a 3-D model sprite extended down to ~12 km altitude, a result obtained for the case Q=600 C and h_Q=10 km. Assuming that the maximum altitude of the thundercloud top is located at ~20 km, consistent with triangulated altitudes reported by *Wescott et al.* [1995, 1996 and references therein] for sprite and jet producing storms, we see from Fig.3b that sprites can reach thundercloud tops with thundercloud charge moments which are below maximum values observed experimentally [e.g., *Stanley et al.,* 2000; *Cummer and Fullekrug,* 2001].

Fig.3b also illustrates the difference between 2-D and 3-D models, namely that with all other parameters being equal, in the 3-D case modeled sprites are able to propagate to slightly (typically several km) lower altitudes. We suggest that observed differences between results of two models in terms of the macroscopic electric fields discussed in the previous section and the lower extent of sprites illustrated in Fig.3b can be explained by purely geometrical factors associated with representation of fractal trees as true line channels in the 3-D case and as azimuthally symmetric surfaces of rotation in the 2-D case. In the 2-D model, for example, a line channel can only exist when it coincides with the center of the system (i.e., z axis). In the 3-D model the streamer coronas are modeled by line channels at any location in the simulation space. Since the line channels are associated with a higher degree of focusing of the electric field the 3-D model is generally expected to have a higher probability to propagate fractal trees to the lower altitudes or to exhibit a higher macroscopic electric fields due to tips of channels inside of streamer coronas.

Discussion

The results reported in Fig.3 indicate that sprites can sometimes reach thundercloud tops for experimentally measured thundercloud charge moment changes. However, we note that several assumptions were adopted in our formulation which may influence the quantitative results. In this section, we provide a discussion of the various input parameters in our model which may affect the results in Fig.3b.

The Fig.3b demonstrates that the model results are sensitive to the concentration of the thundercloud charge (parameters a and b) and the charge altitude (parameter h_Q), which significantly affect the resultant electric field magnitudes in the vicinity of the thundercloud (Fig.1b). Very little is known at present about actual altitudes of positive charge removal by sprite producing cloud to ground lightning. *Stanley* [2000, pp. 52, 58, 66, 73] reported the altitudes in the range 6-10 km, with the average values between 7 and 8 km. The measurements of *Marshall et al.* [2001] indicate altitudes either 5.3 or 6.6 km. The electric fields ~50 kV/m, which we used to put upper bound on charge concentration in our model, are commonly observed in thunderclouds [e.g., *Winn et al.,* 1974; *Marshall et al.,* 1996; 2001]. We note, however, that due to screening effects of charges with different polarities a point measurements of quasi-DC fields set up by slow separation of charge inside the cloud may be a poor reference for spatial extents and concentrations of charges removed by lightning, and our model parameters a and b may be inacurate (i.e., underestimated or overestimated). For the same thundercloud charge moment, lower values of a and b and higher values of h_Q would lead to higher electric fields near thunderclouds and resultant propagation of sprites to lower altitudes, thus indicating that sprites may reach cloud top altitudes even for lower total charge moment than is used for cases shown in Fig.3b.

In our present model we assume that sprites reaching thundercloud tops are formed from positive streamer coronas the dynamics of which are governed by the minimum field required for the propagation of positive streamers in air E_{cr}^{+} (see Fig.1b and [I]). It is expected, however, that at lower altitudes (<50 km) the heating of the neutral gas in streamer channels would become more and more pronounced as sprite approaches the thundercloud top (see related discussion in [*Pasko et al.,* 1998]), leading eventually to transition from streamer coronas to a leader process dominated by thermal ionization of the neutral gas, which is well known to be the process by which lightning propagates through virgin air at thundercloud altitudes. The detailed modeling of this transition process is beyond the scope of this paper. For the purposes of this paper it is important to note that the experimentally documented minimum field required for leader propagation in long gaps >30 m at ground pressure is ~1 kV/cm [*Raizer*, 1991, p. 362] and is generally a factor of four lower than E_{cr}^{+}=4.4 kV/cm [I, and references therein], thus providing an additional factor which would ease the attachment of sprites to the cloud tops (i.e., a shift of curves shown in Fig.3b to the left).

We model the post-discharge electric fields producing sprites as fields of a single monopole negative charge deposited at 10 km or 7 km altitude. Since removal of a positive charge from the thundercloud by a positive cloud-to-ground lightning discharge is equivalent to the deposition of a negative charge of the same magnitude at the same location, the resultant fields at high altitudes above the thundercloud do not depend on complexity of the initial charge configuration in the thundercloud and only depend on the effective charge moment (the charge times the altitude) of the removed charge. This approach provides a valid representation of post-discharge electric fields at the lower ionospheric and mesospheric altitudes as was previously discussed in detail in [*Pasko et al.*, 1997]. We note however, that as the sprite approaches the thundercloud top the situation becomes more complicated. Specifically, the effective boundary which defines the altitude above which the monopole model gives a valid representation of the post-discharge electric fields is highly dependent on the charge separation time scale inside the thundercloud prior to the lightning discharge and the ambient atmospheric conductivity profile [*Pasko et al.,* 1997]. If charges accumulate for a long time period comparable to or larger than the dielectric relaxation time scale near the thundercloud top (∼100 sec [e.g., *Pasko et al.,* 1997]), the resultant post-discharge electric field is accurately represented by the monopole electric fields used in our model and shown in Fig.1b. However, if charges accumulate faster than the dielectric relaxation time scale near the thundercloud top we would expect that the field magnitudes near cloud top would be lower than those used in our model (see [*Pasko et al.,* 1997] for the related discussion), requiring larger charge moments for sprites to reach to thundercloud tops.

The conical narrowing of sprite toward the thunderloud top shown in Fig.3a resembles the geometrical shape of the recently reported "trolls" [*Lyons et al.,* 2000]. Trolls are jet like structures propagating upwards from near the thundercloud tops along the preceding sprite's tendrils [*Lyons et al.,* 2000]. Our modeling therefore supports the suggestion of *Lyons et al.* [2000] that trolls may be analogs of conventional return strokes developing upwards after sprites reach thundercloud tops. A secondary breakdown process which started near the horizon and propagated upward toward the renmants of a sprite was reported on several occasions during EXL98 sprites campaign [*Siefring et al.,* 1999] and may be the result of a similar scenario, however, we note that no experimental reports exists at present time which conclusively document the attachment of sprites to the cloud tops. We also note that the real connection between the ionosphere and the ground is subject to sprite ionization reaching the parent discharge. Although it is a realistic possibility for sprites reaching thundercloud tops, the connection may be realized only for a small fraction of these sprites.

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References

Barrington-Leigh, C.P., U.S.Inan, M.Stanley, Identification of sprites and elves with intensified video and broadband array photometry, *J. Geophys. Res., 106,* 1741, 2001.

Cummer, S. A., and M. Fullekrug, Unusually intense continuing current in lightning produces delayed mesospheric breakdown, *Geophys. Res. Lett., 28,* 495, 2001.

Gerken,E.A., U.S.Inan, and C.P.Barrington-Leigh, Telescopic imaging of sprites, *Geophys.Res.Lett.,27*,2637,2000.

Lyons,W.A.,M.Stanley,T.E.Nelson,M.Taylor,Sprites,elves, halos, trolls, and blue starters above the STEPS domain, *Eos Trans. AGU, 81 (48)*, Fall Meet.Suppl.,F131,2000.

Marshall, T. C., M. Stolzenburg, and W. D. Rust, Electric field measurements above mesoscale convective systems, *J. Geophys. Res., 101*, 6979, 1996.

Marshall,T.C.,M.Stolzenburg,W.D.Rust,E.R.Williams,and R.Boldi,Positive charge in the stratiform cloud of a meso- scale convective system, *J. Geophys. Res., 106*, 1157,2001.

Niemeyer, L., L. Ullrich, and N. Wiegart, The mechanism of leader breakdown in electronegative gases, *IEEE Trans. Electr. Insul., 24,* 309, 1989.

Pasko,V.P.,U.S.Inan,T.F. Bell, and Y.N. Taranenko, Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere, *J.Geophys.Res., 102,*4529,1997.

Pasko, V. P., U. S. Inan, and T. F. Bell, Spatial structure of sprites, *Geophys. Res. Lett., 25*, 2123,1998.

Pasko, V. P., U. S. Inan, and T. F. Bell, Fractal structure of sprites, *Geophys. Res. Lett., 27,* 497, 2000.

Raizer, Y. P., *Gas discharge physics,* Springer-Verlag Berlin Heiddelberg, 1991.

Sentman, D.D., E.M. Wescott, D.L. Osborne, D.L. Hampton, M.J. Heavner, Preliminary results from the Sprites94 campaign: Red Sprites,*Geophys. Res. Lett., 22*,1205,1995.

Siefring, C. L., J. S. Morrill, D. D. Sentman, D. R. Maudry, E. M. Wescott, M. J. Heavner, D. L. Osborne, and, E. J. Bucsela, Do sprites sometimes connect to the cloud tops? *Eos Trans. AGU, 80 (46)*, Fall Meet. Suppl., F225, 1999.

Stanley, M., P. Krehbiel, M. Brook, C. Moore, and W. Rison, High speed video of initial sprite development, *Geophys. Res. Lett., 26*,3201,1999.

Stanley, M., M. Brook, P. Krehbiel, and S. A. Cummer, Detection of daytime sprites via a unique sprite ELF signature, *Geophys. Res. Lett., 27*, 871, 2000.

Stanley, M., Sprites and their parent discharges, Ph.D. dissertation, New Mexico Tech, New Mexico, May 2000.

Stenbaek-Nielsen, H. C., D. R. Moudry, E. M. Wescott, D. D. Sentman, and F. T. Sao Sabbas, Sprites and possible mesospheric effects, *Geophys. Res. Lett., 27*, 3827, 2000.

Wescott,E.M.,D.Sentman,D.Osborne,D.Hampton,and M. Heavner,Preliminary results from the sprites 94 aircraft campaign: 2.Blue jets, *Geophys.Res.Lett.,22*,1209,1995.

Wescott, E. M., D. D. Sentman, M. J. Heavner, D. L. Hampton, D. L. Osborne, and O. H. Vaughan Jr., Blue starters: brief upward discharges from an intense Arkansas thunderstorm, *Geophys. Res. Lett., 23*, 2153, 1996.

Winn,W.P.,G.W.Schwede,C.B.Moore, Measurements of electric field in thunderclouds, *J.Geophys.Res., 79,* 1761,1974.

V. P. Pasko, 211 B EE East, CSSL Laboratory, The Pennsylvania State University, University Park, PA 16802-2706 (e-mail: vpasko@psu.edu)

U. S. Inan, and T. F. Bell, Packard 350, STAR Laboratory, Stanford University, Stanford, CA 94305-9515.

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