Sprites and the influence of the atmospheric density on their initiation mechanism

Fernanda T. São Sabbas[1]*, Davis D. Sentman[2], Antonious Otto[2], 1 – Instituto Nacional de Pesquisas Espaciais, 2 – University of Alaska Fairbanks

This paper was prepared for presentation at the 9th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, 11-14 September 2005.

Abstract

Sprites are transient optical signatures of mesospheric electrical breakdown in response to lightning discharges. Multiple sprites are often observed to occur simultaneously, laterally displaced from the underlying causative cloud-to-ground (CG) lightning discharge. The causes of this lateral displacement are presently not understood. We investigated the role of neutral density perturbations in determining the locations of sprite initiation by performing Computer simulations of the temporal-spatial evolution of lightning-induced electric fields in a turbulent upper atmosphere were performed. The modeled turbulence in the simulations spanned the amplitude range 10% to 40% of the ambient background neutral density, with characteristic scale sizes of 2 km and 5 km, respectively. The results indicate that neutral density spatial structure, similar to observed turbulence in the mesosphere, facilitates electrical breakdown in isolated regions of density depletions at sprite initiation altitudes. These spatially distributed breakdown regions provide the seed electrons necessary for sprite generation, and may account for the observed sprite offsets.

Introduction

The mechanisms by which energy and momentum originating in solar processes are transferred downwards into and distributed within the Earth's Mesosphere-Thermosphere-Ionosphere (MTI) region, have been the subjects of studies over many decades and are relatively well understood. Beginning in the early 1980s, sources involving upward transfer and dissipation of mechanical energy from the neutral lower atmosphere into the MTI region were identified, in the form of atmospheric gravity waves. This form of energy input into the MTI region signaled that understanding the properties of near-earth space requires taking into account inputs from both above and below.

In 1989 *Franz et al*. [1990] discovered a new form of energy input into the Mesosphere-Thermosphere-Ionosphere (MTI) region in the form of lightning induced transient optical emissions. After it was determined that this new electrical component extend to the ionosphere [*Sentman et al.*, 1995], they acquired the mechanism-neutral name of "sprites". This marked the beginning of a new research area that investigates the electrodynamical coupling of the various atmospheric layers, including the ionized region. The field has the main characteristic of being interdisciplinary, since the phenomena present electrodynamical, electrical, optical, and meteorological components, studied by different research areas, e.g. Atmospheric Electricity and Chemistry, Plasma and Ionospheric Physics, Airglow, and Meteorology.

Sprites are one of several optical observable components of electrical energy deposition in the middle/upper atmosphere by lightning. They are observed as short lived (ms – 100s ms), low-light level (100 kR – 10 MR), predominantly red (N_2 1PG bands [*Hampton at al.*, 1996]) optical emissions. They are primarily associated with positive cloud-to-ground (+CG) lightning and the larger events have a distinctive ELF-VLF radio signature [*Inan et al*., 1995]. Sprites can extend from the top of the clouds [*Pasko et al*., 2002] to 90 km altitude and possess lateral dimensions from ~10s m, for the column sprites, to ~40 km for fully developed events.

Observations of sprites provide possible opportunities to indirectly determine the associated electrical energy transferred from thunderstorms into the mesosphere. The total energy deposited in the mesosphere by a large sprite was estimated in 1-10 MJ [*Sentman et al*., 2003]. Photometric measurements have determined that less than 1% of the total energy goes into producing optical emissions (<50 kJ [*Heavner*, 2000]). Gas discharge physics developed since the 1930s and subsequent kinetic models show that a substantial amount of energy is also deposited in excited electronic or nonradiating rotational and vibrational states of N_2 and O_2 [e.g., *Raizer*, 1991]. Vibrationally and electronically activated molecular states may launch reaction chains or catalytic cycles by interaction with minor species that would not otherwise occur in the quiescent nighttime mesosphere.

Following the *Franz et al.* [1990] discovery, other investigations quickly revealed that sprites are only one of a diverse set of lightning driven optical transients above thunderstorms. Other types of optical transients that exhibit different structural properties and dynamical behavior include Blue Jets and Blue Starters [*Wescott et al*., 1995a, 1996, 1998a], Elves, which are sub-ms optical enhancements of the ionosphere at an altitude of ~100 km [*Inan et al*., 1997], Halos, which are disk shaped optical emission believed to be produced by the same physical process that generates sprites [*Barrington-Leigh,* 2000; *Wescott et al*., 2001], and various subspecies of these genres. In their totality, these events, which are collectively called Trasient Luminous Events, TLEs, span the full vertical extent of the atmosphere from the tropopause (~18 km) to the base of the ionosphere (~100 km).

Brazil is located in the second most active thunderstorm region of the planet: South America. Local development of this new multidisciplinary research area is strategic to identify the local and global contributions of lightning energy deposition to energy budget of the Earth's atmospheric system.

Theoretical Background

The principal energy transfer mechanism within sprites is believed to be the local acceleration of ambient electrons by large transient electric and electromagnetic fields associated with CGs. The most well accepted theory is quasi-electrostatic (QE) heating of the neutral atmosphere [*Pasko et al*., 1997]. More recent models [*Pasko et al.*, 1998; *Raizer et al*., 1998] have incorporated mesospheric streamers (thin filamentary plasma channels) as a key element in the generation of sprites. The streamer model accounts for many sprite properties, including the elementary columnar form of the simplest structures termed "c-sprite" , sprite ignition at ~75 km, the estimated magnitude of the current (~20 A) flowing within the streamer [*Cummer and Inan*, 1997], inferred channel electron densities of 10^5 cm^{-3} [*Dowden et al*., 1996], and several others.

Most sprite models using a laminar atmospheric pressure and conductivity profile predict that sprites will occur directly above the lightning discharge, where the electric field is strongest. In contrast to the predictions of these models, most sprites are observed to be laterally displaced from the underlying lightning source by several tens km [*Wescott et al*., 2001; *São Sabbas et al.*, 2003]. Several alternative mechanisms have been previously proposed to account for the observed offset of sprites relative to the underlying lightning. The mechanisms suggested may be classified as being of two different types: (1) Perturbations in the dielectric due to effects in gas dynamical parameters, such as local neutral, ion and electron density perturbations, as well as temperature perturbations, with consequent focusing and enhancement of the electric field in the inhomogeneous conductivity background [*Valdivia et al*., 1997; *Rowland et al*., 1996; *Pasko et al.*, 1997]. (2) Effects of particulates such as micro-meteors, and dust or ice particles in general, where corona sites on microspires may provide seed electrons to initiate sprites [*Symbalisty et al*., 2000; *Wescott et al*., 2001; *Zabotin and Wright* 2001]. In principle, both types of effects might occur. It is presently unknown which of these two classes of effects is the more important.

In this paper we investigated the role played by neutral density and conductivity inhomogeneities in the mesosphere/lower ionosphere in determining specific locations where electric breakdown, which may lead to sprite ignition, occurs. We simulated the spatial-temporal evolution of the lightning induced quasi-electrostatic field in the mesosphere up to breakdown. The work was motivated by results from two previous studies where the space-time relationships between sprites and lightning [*São Sabbas et al*., 2003] and their relationship with the infrared cloudtop temperatures of the generating storm [*São Sabbas and Sentman*, 2003] were investigated. Of relevance for this work the first paper showed that the offset of the sprites observed on the night of July 22, 1996, relative to the underlying lightning, followed a distribution with a mean of ~40 km [*São Sabbas et al*., 2003]. Likewise, the second paper [*São Sabbas and Sentman*, 2003] revealed that the maximum sprite and –CG production of the thunderstorm were simultaneously reached at the time of maximum contiguous cloud cover of the coldest region, corresponding to the period of greatest convective activity of the system. This kind of convective activity is a potential source of neutral density perturbations in the mesosphere/lower ionosphere such as gravity waves and turbulence.

Model Description

We adopted a QE description of lightning induced electric field based on the model of *Pasko et al*. [1997]. In the QE approximation the electric field is written solely in terms of a scalar potential **E** = $-\nabla\varphi$. Ohm's law, **J** = σ**E**, with a scalar conductivity, is applied. The simulations involved solving Gauss Law and the Continuity Equation for the charge:

$$\nabla^2\phi = -\frac{\rho_{tot}}{\varepsilon_0}$$

$$\frac{\partial\rho_{tot}}{\partial t} = \nabla\sigma\cdot\nabla\phi - \frac{\sigma\rho_{tot}}{\varepsilon_0}.$$

The time evolution of the electric field and conductivity were calculated in a self-consistent manner by taking into account the effects of the electric field on the conductivity through changes in the mobility μ_e due to heating and changes in the electron density n_e due to ionization and attachment, similarly to the model of *Pasko et al*. [1997]. The problem was solved in using 2-D cylindrical geometry (*r*, *z*) with axial symmetry. The computation domain was a square region of 90 km with grid elements, *dr* and *dz* of 1 km, and the boundary conditions were set such that the field was vertical at all boundaries. The thunderstorm charge centers were modeled as Gaussians having the total charge, center altitude, and 1/e widths as free parameters. The charge centers were placed along the *z*-axis.

The laminar neutral density profile was obtained from the MSIS-E-90 model for 22 July, 1996, latitude 37.5^o N, longitude 99.0^o W, and 6 UT as input parameters. This configuration approximately corresponds to the location of the sprite producing region of the thunderstorm studied in *São Sabbas et al*. [2003] and *São Sabbas and Sentman* [2003], during the period of high lightning and sprite activity. The laminar conductivity profile was calculated as a sum of the ion and electron components. The ion component was adapted from *Holzworth et al*., [1985] and the electron component was calculated as a function of the electron density and mobility. The electron density profile of the bottom of the nighttime ionospheric D/E region used in the calculation of the electron component of the conductivity was modeled after Chapman's theory.

A simple isotropic model characterized by a Gaussian amplitude probability distribution generated by a spatially low pass filtered random number field was adopted to create smooth perturbation patterns. The random pattern was centered at 80 km altitude with characteristic layer thickness of 10 km. This perturbation model is sufficiently flexible to permit investigation of the effects of turbulence on sprite initiation over a wide variety of turbulent conditions.

Results and Conclusions

The first step in the simulations was to calculate the electric field and induced charge in the laminar atmosphere due to the presence of the thunderstorm, before the lightning discharge, i.e., the pre-lightning configuration. Since the time scale of thunderstorm development, of the order of hours, is much larger than the electric relaxation time over all altitudes, in the pre-lightning configuration the atmosphere would have relaxed over all altitudes. The relaxation time decreases with altitude, therefore the top of the system relaxes first and the relaxation level moves downwards with time, i.e., the so called "moving capacitor model" of *Greifinger and Greifinger* [1976]. In these simulations, due to computational limitations, the atmosphere was allowed to relax only down to 50 km altitude. The simulations are therefore valid for altitudes above 50 km.

Several parameter regimes were selected to provide a variety of atmospheric conditions under which sprites may occur. Two laminar conductivity profiles, the control conductivity and a variation of that with reduced electron density were used. For each conductivity profile, three charge configurations ($Q_{\pm} = \pm 50$ C, $Q_{\pm} = \pm 100$ C and $Q_{\pm} = \pm 200$ C) were used to model thunderstorm charge centers. In order to consistently compare results due to different thunderstorm charges, the location of the charge centers (z_{+} = 10 km, z_{-} = 5 km) and their relative sizes (3 km) were kept constant; only the total charge amount was varied.

The results from the simulations of a laminar atmosphere, which agree with results previously obtained by Pasko et al. [1997], elucidated the non-linear self-consistent relationship between the electric field and conductivity. The electric field applied to the mesosphere due to thundercloud charge removal heats the free electrons above 60 km, increasing the electron-neutral collision frequency, which decreases their mobility. Consequently, the conductivity, which is directly proportional to the mobility, is reduced; this reduction can be as much as a factor of fifty. The effects due to changes in the electron density, which are completely dominated by the effects due to electron heating, also contribute to the reduction of conductivity, since attachment dominates before the field reaches the breakdown threshold. This reduction of the conductivity leads to a faster growth of lightning induced electric field in the mesosphere than if the self-consistent effects are not taken into account.

The simulation of a negative lightning discharge also produced breakdown in a perturbed atmosphere. The breakdown occurred at the same location as for the first breakdown point produced by a positive discharge using the same perturbation pattern. The removal of a larger amount of charge was necessary for breakdown with a negative discharge than for the positive charge, consistent with observations that negative sprites are less frequent events than positive sprites on account of the lower overall charge moments associated with negative lightning.

The perturbed, or inhomogeneous, pre-lightning configurations were generated by superimposing six different perturbation patterns of varying amplitude and scale size onto the neutral density profile. Since the atmosphere has relaxed down to 50 km in the pre-lightning scenario, the electric field is almost totally excluded above that altitude and $E/E_k \sim 0$, were E_k is the breakdown electric field. Therefore, superimposing the perturbation patterns on the already calculated laminar pre-lightning configuration produces the same perturbed pre-lightning configurations as if they were initially calculated with the perturbation patterns.

A total of eight different perturbation cases were evaluated, in which the relative average amplitude of the perturbation was varied from 0.1 to 0.4 in steps of 0.1, and the average characteristic spatial scale was either 2km or 5km. In all the perturbed cases breakdown occurred in locations laterally displaced from the underling lightning, agreeing with sprite observations and with the distribution presented by *São Sabbas et al*. [2003]. Furthermore, breakdown occurred at multiple regions, simultaneously or within time scales less than 1 ms. Sprites initiated at these points would appear to be "simultaneous" for observations at a rate of 1000/s or less, e.g. *Stenbaek-Nielsen et al*. [2000] 1000 fps observations of sprites, showing multiple sprite initiation regions that breakdown points simulated by this model could trigger.

Breakdown first occurred inside "pocket" regions of unrealistically large density depletions ($\geq$ 70%). As the charge moment increased, breakdown progressively occurred in regions of lower, realistic, density depletions ($\leq$ 25%). Around the termination of the lightning breakdown was produced in regions with depletions $\leq$ 10%, which are often observed in airglow imagery as been produced by gravity waves and/or turbulence (c.f. *Taylor et al.* [1991]). In these pocket regions the breakdown electric field was lowered. This effect summed with the self-consistent reduction of the conductivity, caused by the reduction of the electron mobility, due to heating, and the reduction of the electron density before breakdown, due to attachment, "facilitated" the breakdown process.

In all cases, the conductivity is enhanced in the regions of depleted density, which tends to inhibit breakdown. A focusing of the electric field is expected to occur at the external surface of the pocket of enhanced conductivity, however this effect is only minor. Conductivity effects, however, are dominated by the lowering of the breakdown threshold due to the depleted density and the overall effect is breakdown facilitation, as already mentioned.

In the perturbed cases, breakdown occurred in isolated pockets of neutral density depletions. In no case was breakdown observed in regions of increased density. The physical reason for this behavior is that inside pockets of lower density, the electron-neutral mean free path is increased, which lowers the characteristic electric breakdown field. In the absence of an electric field such density depletions induce local conductivity enhancements due to reduced collision frequency and increased mobility. At the onset of the cloud-to-ground lightning discharge, the enhanced conductivity initially leads to a lower electric field inside the depletions. However, when the field grows enough to heat the local free electrons (E ~ 0.0005 E_k), their mobility decreases, leading to a reduction of the local conductivity and larger electric fields. Even though by the moment of breakdown the conductivity can be a factor of 50 lower than the initial value, it is still a local maximum. Focusing of the electric field occurs at the external surface of those pocket regions, but this effect is only minor compared to the effect of conductivity enhancement. Consequently, the resulting effect of the conductivity is to inhibit breakdown at the pockets of density depletions. Conductivity effects, however, are dominated by the lowering of the breakdown threshold purely due to the depleted density, with the end result that breakdown is locally "facilitated" inside pockets of neutral density depletions. Sprites will initiate at these locations if the local mesospheric conditions are conducive to the subsequent development of streamer channels.

Acknowledgments

I would like to thank CNPq, INPE, the U.S. Air Force, NASA, and the Geophysical Institute of Univeristy of Alaska for their support.

References

Barrington-Leigh, C.P., C.P., Fast Photometric Imaging of High Altitude Optical Flashes Above Thunderstorms, Ph.D. Dissertation, Dept. of Electrical Engineering, Stanford University, Stanford, 2000.

Cummer, S.A., and U.S. Inan, Measurements of charge transfer in Sprite-producing lightning using ELF radio atmospherics, *Geophys. Res., Lett*., 24, 1731-1734, 1997.

Franz, R.C., R.J. Nemzek, and J.R. Winckler, Television image of a large upward electrical discharge above a thunderstorm system, *Science*, 249, 48-51, 1990.

Greifinger, C., and P. Greifinger, Transient ULF electric and magnetic fields following a lightning discharge, *J. Geophys. Res*., 81, 2237, 1976.

Hampton, D. L., M. J. Heavner, E. M. Wescott, and D. D. Sentman, Optical spectral characteristics of sprites, *Geophys. Res. Lett*., 23, 89-92, 1996.

Heavner, M.J., *Optical Spectroscopic Observations of Sprites, Blue Jets, and Elves: Inferred Microphysical Processes and Their Macrophysical Implications*, Ph.D. Dissertation, Department of Physics, University of Alaska, 2000.

Holzworth, R.H., M.C. Kelley, C.L. Siefring, L.C. Hale and J.D. Mitchell, Electrical measurements in the atmosphere and the ionosphere over an active thunderstorm. 2. Direct current electric fields and conductivity, *J. Geophys. Res*., 90(A10), 9824-9830, 1985.

Inan, U.S., C. Barrington-Leigh, S. Hansen, V.S. Glukhov, T.F. Bell, and R. Rairden, Rapid lateral expansion of optical luminosity in lightning-induced ionospheric flashes referred to as "elves", *Geophys. Res. Lett.,* 24, 583-586, 1997.

Pasko, V.P., U.S. Inan, and T.F. Bell, Sprites as evidence of vertical gravity wave structures above mesoscale thunderstorms, *Geophys. Res. Lett., 24*, 1735-1738, 1997.

Pasko, V.P., M.A. Stanley, J.D. Mathews, U.S. Inan, and T.G. Wood, Electrical discharge from a thundercloud top to the lower ionosphere, *Nature*, 416, 152, 14 March, 2002.

Raizer, Yu.P., *Gas Discharge Physics*, Springer, Berlin, 1991.

Raizer, Yu.P., G.M. Milikh, M.N. Shneider, and S.V. Novakovski, Long streamers in the upper atmosphere above a thundercloud, *J. Phys. D: Appl. Phys.*, 31, 3255-3264, 1998.

Rowland, H.L., R.F. Fernsler, and P.A. Bernhardt, Breakdown of the neutral atmosphere in the D-region due to lightning driven electromagnetic pulses, *J. Geophys. Res.*, 101, 7935, 1996.

São Sabbas, F. T., D.D. Sentman, E.M. Wescott, O. Pinto Júnior, O. Mendes Júnior and M. J. Taylor, Statistical analysis of space-time relationships between sprites and lightning, *J. Atmos. Solar-Terr. Phys.*, 65(5), 523-533, 2003.

São Sabbas, F. T., and D.D. Sentman, Dynamical relationship of infrared cloudtop temperatures with occurrence rates of cloud-to-ground lightning and sprites, *Geophys. Res. Lett*., 30(5), 40-1 to 40-4, 2003.

Sentman, D. D.; Wescott, E. M.; Osborne, D. L.; Hampton, D. L. and Heavner, M. J. Preliminary results from the Sprites94 aircraft campaign: 1. Red sprites. *Geophys. Res. Lett.*, 22, 1205-1208, 1995.

Sentman, D.D., E.M. Wescott, R.H. Picard, J.R. Winick, H.C. Stenbaek-Nielsen, E.M. Dewan, D.R. Moudry, F.T. São Sabbas, M.J. Heavner, and J. Morrill, Simultaneous observations of mesospheric gravity waves and sprites generated by a midwestern thunderstorm, *J. Atmos. Solar-Terr. Phys*., (in press), 2003.

Stenbaek-Nielsen, H.C., D.R. Moudry, E.M. Wescott, D.D. Sentman, and F.T. São Sabbas, Sprites and possible mesospheric effects, *Geophys. Res. Lett*., 27(23), 3829-3932, 2000.

Symbalisty, E.M.D., R.A. Roussel-Dupré, D.O. ReVelle, D.M. Syszcynsky, and V. Yukhimuk, Meteor trails and columniform sprites, *Icarus*, 148(1), 65, 2000.

Taylor, M.J., D.N. Turnbull, and R.P. Lowe, Coincident imaging and spectrometric observations of zenith OH nightglow structure, *Geophys. Res. Lett.*, 18, 1349–1352, 1991.

Valdivia, J., G. Milikh, and K. Papadopoulos, Red sprites: Lightning as a fractal antenna, *Geophys. Res. Lett*., 24(24), 3169-3172, 1997.

Wescott, E.M., D. Sentman, D. Hampton, M. Heavner, D. Osborne, and O. Vaughan, Blue starters and lightning discharges from an intense thunderstorm over Arkansas, July 1, 1994, *Geophys. Res. Lett*., 23, 2153-2156, 1996.

Wescott, E.M., H.C. Stenbaek-Nielsen, D.D. Sentman, M.J. Heavner, D.R. Moudry, and F.T. São Sabbas, Triangulation of sprites, associated halos and their possible relation to causative lightning and micro-meteors, *J. Geophys. Res*., 106(A6), 10,467-10,477, 2001.

Zabotin, N.A., and J.W. Wright, Role of meteoric dust in sprite formation, *Geophys. Res. Lett.*, 28(13),2593-2596, 2001.