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HIGH ALTITUDE ATMOSPHERIC DISCHARGES ACCORDING TO THE RUNAWAY AIR BREAKDOWN MECHANISM

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High Altitude Atmospheric Discharges According to the Runaway Air Breakdown Mechanism

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1. Introduction

High altitude optical transients (see e.g. [1]) - red sprites, blue jets, and elves - are modeled in the context of the relativistic electron runaway air breakdown mechanism. These emissions are usually associated with large mesoscale convective systems (hereafter MCS). In thunderstorms cloud electrification proceeds over a time scale long enough to permit the conducting atmosphere above the cloud to polarize and short out the thunderstorm electric field. When a lightning strike rapidly neutralizes a cloud charge layer runaway driving fields can develop in the stratosphere and mesosphere. According to our simulations of the full runaway process the variety of observed optical emissions are due to the nature of the normal lightning event in the MCS that kick starts the runaway avalanche. In this paper we describe some details of the model, present the results of the evolution of the primary electron population, and summarize the initial conditions necessary for different types of discharges. Two companion papers present (a) the predicted optical, gamma ray, and radio emissions caused by these electrical discharges, and (b) the time evolution of the secondary electron population and its implications in terms of observables.

2. Theoretical results

In our simulations a quasi-electrostatic, multifluid approach similar to that of Taranenko and Roussel-Dupré [2] is used to model the relativistic (primary) electrons, secondary electrons and the positive and negative ions. The work includes, for the first time, the full time evolution of the runaway discharge. This evolution starts by resolving the initiating cloud-to-ground or intracloud discharge and continues to late times when the discharge itself or the background conductivity eliminates the driving electric fields. The present formulation, contrary to [2], includes the contributions of the positive and negative ions, produced as a result of ionization and attachment, to the total electrical current density and hence the evolution of the self-consistent fields. Because of their large densities at low altitude, the ion contribution to the net current is significant for slow discharges and in particular blue jet simulations. The electrostatic equations are solved in a different way, providing significant savings in computational time.

Polynomials are fit to the numerical results from detailed kinetic calculations [3] to obtain the primary electron energy, velocity, and production rate as a function of the total electric field (E) and the atmospheric pressure (p). At an altitude of about 55 km, the mean free path of the primary electrons becomes large. A simple prescription is used, for the first time, to allow the primary electrons to smoothly transition between the collision dominated regime and the free streaming limit.

The secondary (low energy) electrons produced in the avalanche process are collision dominated and establish equilibrium distributions in time scales much shorter than the time for runaway breakdown. Their mean properties are also defined by E and p and are derived from the standard swarm parameters [4,5].

3. Discussion and conclusion

We have been able to find reasonable parameters for intracloud and positive cloud-to-ground lightning strokes that produce the observables for red sprites, blue jets, and elves. Since we have just begun to explore the morphology of the observable emissions we do not claim that the cases we describe next are the only possible scenarios. The MCS, and the annihilation of charge by discharges in the MCS are modeled by the creation of charge of opposite polarity in free air. The highly complex thunderstorm complex is thereby eliminated, and we can only look at atmospheric evolution well above the discharge location. The charge is allowed to build with an exponential time scale or with a constant current source (i.e. a linear time scale).

Four simulations that produced red sprites were initiated by a positive cloud to ground stroke. They discharged 200 C at an altitude of 11 km with an exponential time scale of 3, 5, 7, and 10 ms respectively. The computational grid extended from 20 to 80 km in altitude and 50 km in radius. The peak primary electron concentrations were 1.1, 0.75, 0.5, and 0.15 per cc respectively. In each case there were two large scale and very bright atmospheric discharges. However, when observed with a video camera and thereby integrated over 17 ms, to the observer there would only be one flash. For example, in the 7 ms case, the first discharge occurred between 6.7 and 8.0 ms after the start of the positive cloud-to-ground stroke. The second discharge occurred between 12 and 14 ms. The kinetic energy of the primary electron population in each discharge reached 100 kJ. The peak current to the ionosphere reached 6 kA.

In each of these four red sprite simulations, the electric field first broke threshold, for the runaway mechanism to start, at high altitude and the location for breaking threshold moved downward in time. By the time the threshold was broken at 30 km there were enough avalanche lengths traversed by the upward propagating electron beam to produce large concentrations responsible for the first discharge. This also had the effect of quickly shorting out the field in the region of the discharge. However, the external driving field was still growing around the high conductivity region eventually resulting in the second discharge. The external driving field was complete by this time and the runaway process was ended. The fastest case produced the highest peak primary electron concentrations and also the highest electric radiation fields - reaching nearly 40 V/m in the lower ionosphere. As a result this case also provides the electromagnetic environment required for elves.

For discharges that occur at lower altitudes within the MCS, more charge would have too be annihilated and conversely less charge for higher altitude discharges. The fact that the runaway mechanism produces red sprites with a wide range of time scales is a notable result. Red sprites are now observed quite routinely which suggests a mechanism that is not too sensitive to normal lightning discharge parameters.

A blue jet was modeled with a constant current intracloud discharge of reverse polarity. Computationally this is simulated by the creation of a dipole. The location of the dipole was at 17 and 14 km. A current of 1 kA for 200 ms (or a total charge of 200 C) produced a blue jet that moved from the bottom of the grid (19 km) to 35 km with an average speed of about 70 km/s. In this case the electric field first breaks threshold near the cloud top and moves upward in time. The reverse polarity of the discharge means the primary electron beam is moving down. When the primary electron beam reaches 40 km in altitude the ambient electrical conductivity has had enough time to eliminate the driving electric field. Obviously the termination altitude is quite sensitive to the ambient conductivity profile. We have chosen a nighttime profile from [6]. The blue jet simulations are computationally more intensive because of their long time duration and because the avalanche process must still be resolved in space and with the same time resolution. Also, the peak electric fields during the evolution are less than a factor of two over the threshold value. Therefore the simulation is strongly dependent on the runaway process parameters near threshold electric field values.

We are continuing to explore the parameter space of the initiating lightning strokes and are also beginning to look at aspects of normal lightning in the context of the runaway mechanism.

4. References

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