Title: OPTICAL, RADIO AND X-RAY RADIATION OF RED SPRITES PRODUCED BY RUNAWAY AIR BREAKDOWN

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Optical, radio and X-ray radiation of Red Sprites produced by runaway air breakdown

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1. Introduction

We use the runaway air breakdown model of upward discharges to calculate optical, radio, and X-ray radiation generated by red sprites. Red sprites are high altitude (up to 90 km) lightning discharges. Aircraft based observations [1] show that sprites are predominantly red in color at altitudes above ~ 55 km with faint blue tendrils, which extend downward to an altitude of 40 km; the duration of a single sprite is less than 17 ms, their maximum brightness is about 600 kR, and estimated total optical energy is about 1-5 kJ per event. The ground based observations show similar results, and provide some additional information on spatial and temporal structure of sprites [2], and on sprite locations [3]. One difference between aircraft and ground-based observations is that blue tendrils are rarely observed from the ground. Sprites usually occur above the anvils of large mesoscale convective systems and correlate with strong positive cloud to ground discharge [4]. Upward discharges are the most probable source of X-ray emission observed above large thunderstorm complexes by the Compton Gamma-ray Observatory [5]. To escape the atmosphere these γ-rays must originate above 25 km altitude. Red sprites are usually observed at altitudes higher than 50 km, and are therefore a likely source of this x-ray emission.

2. Theoretical results

We compute optical, radio and gamma-ray emissions caused by electrical discharges propagating upward in upper atmosphere. The results of the kinetic theory for runaway air breakdown [6] are used in our numerical calculations. We use the air fluorescence efficiencies measured by Davidson and O'Neil [7], and Mitchell [8] to calculate optical emissions. The spatial and temporal distribution of the number density and velocity of charged particles, from computer simulations, allow us to reproduce the corresponding distribution of optical emissions in space and time. We use extinction coefficients measured by Guttman [9] to calculate the atmospheric attenuation of optical emissions. The maximum intensity of optical emission calculated over 17 ms (corresponding to one camera frame) is 647 kR. Red emission of 1P N_2 predominates at altitudes higher than 55 km. At altitudes lower than 55 km blue emission of 2P N_2 and 1N N_2+ predominates. We also calculate the radio emissions caused by the upward propagating discharge by using the distribution of electrical current density and charged particle number density in space and time, taken from the numerical simulations of runaway air breakdown.
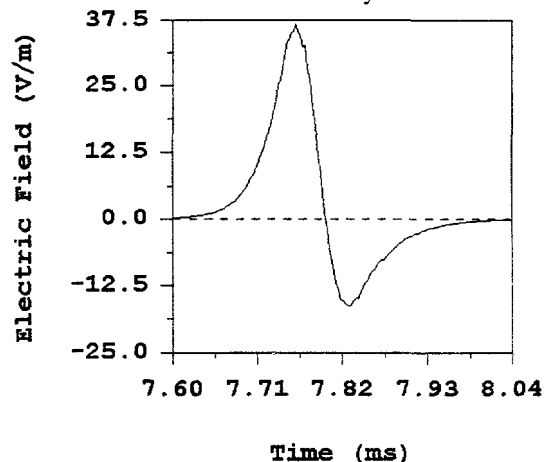

Fig. 1

The electric field of electromagnetic radiation as a function of time for an observer at altitude 80 km and 50 km from the center of the discharge is shown in Fig. 1. The maximum electric field amplitude is 37 V/m. Our results show that the radio emission of upward discharges is comparable with the radio emission of regular lightning. Therefore it is reasonable to conclude that ionospheric phenomena usually associated with radio emission of regular lightning such as ionospheric heating and glowing, lower-hybrid wave generation, explosive spread F and others can be caused by the radio emissions of upward discharges as well. Given the distribution of velocity and number density of relativistic

electrons in space and time we compute the spatial and temporal distribution of gamma-ray flux caused by the upward propagating discharge. In our calculations we use the emissivities calculated by Roussel-Dupré et al., [6] based on the Bethe-Heitler doubly differential cross section for bremsstrahlung emission by a relativistic electron. We take into account gamma-ray photons with energy E > 30 keV.
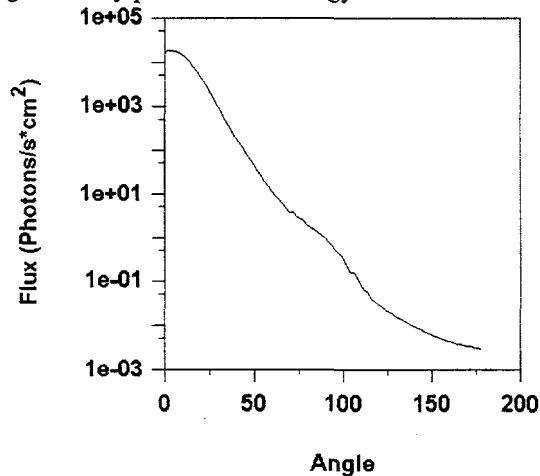

Fig. 2

The gamma-ray flux angular distribution at 1000 km from the discharge center is shown in Fig. 2.

3. Discussion and conclusion

We have compared our theoretical results for optical emissions with observations [1,2,3]. The computed intensity is in excellent agreement with the results of observations [1] measured from aircraft. The peak value measured by Sentman et al. [1], is about 600 kR, which is close to our computed peak value: 647 kR. Our calculations show the presence of visible blue emission at the bottom of the red sprite (blue tendril), which extends downward as low as 40 km. In this case, the blue tendril is visible only from high-altitude platforms (h ~ 11 km), and becomes invisible from low-altitude because of Rayleigh scattering and scattering from aerosols. This result is in agreement with ground-based observations of red sprites which show no blue tendril for distant sprites.

The computed values of the gamma-ray flux are in agreement with observational results reported by Fishman et al., [5]. As one can see in Fig. 2, the gamma-ray flux depends significantly on the angle of observation. For an observation angle of 90° the computed flux value is about 0.8

photons/s×cm^2, for an angle near 0° the flux exceeds 10^4 photons/s×cm^2. The measured gamma ray flux [5] is about 100 photons/s×cm^2. We have calculated the gamma-ray flux without taking into account scattering by air. The scattering will lead to increasing the duration of the pulse and simultaneously decreasing the peak flux value. Our simulation shows that an upward discharge has a tendency to produce several short (with duration about 0.1-0.5 ms) gamma-ray pulses with time separation about 0.1-1 ms. These pulses could appear to an observer as one gamma-ray burst with duration 1-3 ms as a result of gamma-ray scattering. Indeed, such fine structure of the gamma-ray burst was observed by [5], and gamma-ray pulses with duration between 1-3 ms usually had multiple peaks.

In conclusion we note that the runaway air breakdown theory explains γ-ray emissions above thunderstorms and the blue tendrils of sprites; two phenomena that can not be explained by any other model of upward discharges.

4. References

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