EFFECTS OF LIGHTNING ON THE MIDDLE AND UPPER ATMOSPHERE: SOME NEW RESULTS

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ABSTRACT

Recent observations of the effects of lightning on the middle and upper atmosphere have revealed several new dynamical effects of sprites and yielded initial estimates of the total internal energy, including energy residing in nonradiative vibrational states. High speed images (1000 fps) of sprite development and decay show evidence of modification of the local atmosphere by sprites, which may in turn affect the form of subsequent sprites occurring in the same region. Small, relatively long lived (~100s ms) stationary "balls" are often observed within the decaying regions of some sprite tendrils. Calculations of diffusion time scales for the balls are roughly consistent with thermal diffusion, but the relatively long lifetime of the balls relative to nearby tendrils suggests that other processes, perhaps chemical in nature, are operative to extend the lifetime of the balls. Other contrasting features within sprites include an invariably spatially diffuse top and highly structured tendril bottoms. Following the suggestion of Williams [2000], we test as a possibly useful plasma parameter the number of electrons per electron-neutral collision volume for being potentially able to account for the clear separation between the highly structured tendril lower region and the diffuse upper regions of sprites. Models of spectrographic measurements of sprites obtained in 1998 suggest that substantial energy resides in nonradiating vibrational states of both molecular nitrogen and oxygen, in addition to the energy associated with the N2(1PG) optical emissions. Estimates of the internal energy of sprites are ~1 GJ for a large event.

INTRODUCTION

The transient optical excitation of the mesosphere by lightning (sprites) came as an unexpected surprise to atmospheric electricians when first reported by Franz *et al.* [1990]. Subsequent investigations from the Space Shuttle [Boeck *et al.*, 1998], from aircraft [Sentman *et al.*, 1993; Sentman *et al.*, 1995], and from the ground [Lyons *et al.*, 1994, 1996] using a variety of instruments have shown that sprites occur globally and are associated with mesoscale convective complexes (MCCs), intense large scale thunderstorm systems Observations of sprites and correlated electromagnetic measurements [Bocippio *et al.*, 1995], have revealed a causative relationship to positive cloud-to-ground lightning. Various theories have been advanced to account for this connection, including a quasi-electrostatic mechanism [Pasko *et al.*, 1996, 1997], an electromagnetic mechanism [Cho and Rycroft, 1998], and runaway electrons [Roussel-Dupre *et al.*, 1998]. Spectroscopic observations [*Hampton et al.,* 1996; *Mende et al.*, 1995; *Heavner*, 2000] show that most of the optical emissions in sprites are from molecular nitrogen, N_2(1P) leaving the nitrogen in the N_2 exited A state. Recent reviews are given by Rowland [1998] and Rodger [1999].

In this paper we present several new observations of sprites and results obtained by the University of Alaska as part of a NASA-sponsored EXL98 aircraft campaign, and the 1999 Sprites99 balloon campaign, balloon campaign, and follow-up analyses.

OBSERVATIONS

High Speed Images

Most of the spatial phenomenology of sprites has been determined using intensified television technology, with interlaced frame rates of 30/sec, or deinterlaced field rates of 60/sec (e.g., Franz *et al.* [1990], Sentman *et al.* [1993, 1995], Lyons *et al.* [1994]). These video systems are limited in their temporal resolution to 16.7 ms, but high speed photometer measurements (e.g., Armstrong *et al.*, 1998) reveal that the major features of sprites develop over time scales much shorter than this, typically a few ms. Imaging measurements have only recently achieved the required speeds to resolve sprite development at this time scale. The first high speed image sequences of sprites were obtained by Stanley et al. [1999], and showed that they start as small breakdown regions at an altitude of ~75 km and subsequently developed simultaneously upward and downward from this "ignition" point.

High speed images of sprites were subsequently obtained by the University of Alaska [Stenbaek-Nielsen *et al.*, 2000] using a digital, low-light-level, 1000 frame per second intensified CCD imager developed by the Geophysical Institute and operated at the University of Wyoming Infrared Observatory (WIRO) at Jelm Mountain south of Laramie, Wyoming, during August 1999. The observatory is at an altitude of 9650 feet and has unobstructed views ranging from the Canadian border area to the north, the Mississippi river to the East, and into Texas and New Mexico to the South. Over a three week period in August 1999 several hundred sprites were observed from this location and at a second location at Bear Mt., SD. On the night of August 18, 1999 a very active thunderstorm over Nebraska-Kansas (Figure 1) provided an opportunity to capture numerous sprites with excellent spatial resolution.

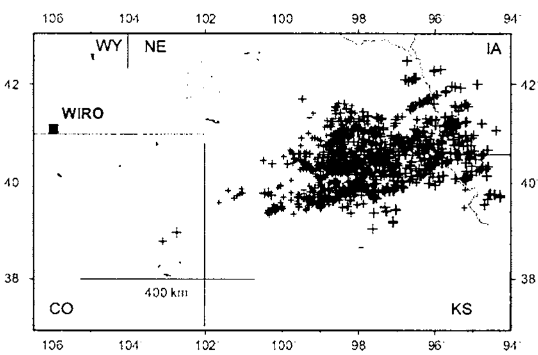

Figure 1. Geographic distribution of lightning strikes, 4-7 UT, August 18, 1999, as recorded by the National Lightning Detection Network (NLDN). Observations presented here were made at WIRO.

Sample image sequences from the high speed camera at WIRO are presented in Figures 2 and 3. The digital images are 256x256 pixels at 8 bit (256 gray levels) and the field of view is 6.4 x 6.4 deg. The instrument wavelength pass band is 500-900 nm with maximum sensitivity at 700 nm. All observations were made unfiltered and at 1000 frames per second. At this data rate the imager saturates at 3.0 MR (at 700 nm). Since most, if not all, sprite events substantially saturated the imager at onset, the maximum brightness is considerably above 3 MR.

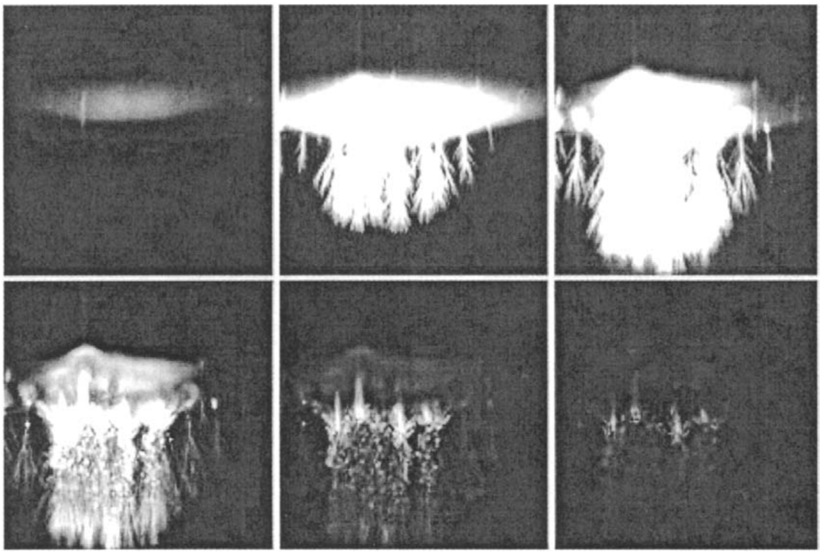

Figure 2. Six consecutive high-speed images, each 1 ms apart, of a large sprite 06:15:07.67 UT on 18 August 1999. The example illustrates some of the typical sprite features: The large horizontal, fairly featureless structure prominent in the two first images is the sprite halo. It often precedes the sprite event. The sprite then develops from an altitude near that of the halo with tendrils going down and branches going up. In this example most of the activity is in the tendrils.

Figure 2 shows a typical large sprite obtained on the night of 18 Aug 1999 using the high-speed imager. The duration of the event shown in Figure 2 is only 6 ms, compared to more typical durations of 10-30 ms. Sprites are often immediately preceded by the appearance of a diffuse "sprite halo" at an altitude of 70-80 km [*Barrington-Leigh et al.*, 2000; *Wescott et al.*, 2000], and this behavior is evident in Figure 2. The sprite develops tendrils branching both upwards and downwards from the onset region near the altitude of the sprite halos. A columniform sprite (C-sprite) [*Wescott et al.*, 1998] is evident in the first frame. In the event shown in Figure 2, as well as in other events, most of the spatial structure is in the tendrils on the bottom side of the sprite. The sprite is fully developed within 2 ms of onset and then begins to fade. In our high-speed imager recordings the tendrils typically reach more than 90% of their full downward extent in less than 1 ms, i.e., essentially the full sprite appears within one video frame, demonstrating that the characteristic time scale for development is less than 1 ms.

Lightning information from the National Lightning Detection Network (NLDN) provided the position of the associated cloud to ground strike at 40.422N, -98.817E, which is 620 km from WIRO. The direction to this point is in the center of the observed sprite. Using the 620 km distance we derived the altitude of the center of the sprite to lie at 84 km, and its full horizontal width is about 75 km. The top of the optical emissions is at 94 km, and the bottom at 38 km.

A second example, observed at 05:24:22 UT and shown in Figure 3, exhibits a more complex development and decay sequence. Here we show two sequences of 1 ms images, separated by 98 ms. Initially, a large sprite occurs in the middle of the imager field of view (top row). The main sprite fades rapidly, but very faint activity continues in the region of the sprite itself. After almost 100 ms low-level activity picks up in the area to the left of the sprite with some filamentary structure visible in the images. Eventually, additional sprite structures appear near the left edge of the high-speed imager field of view (start of the

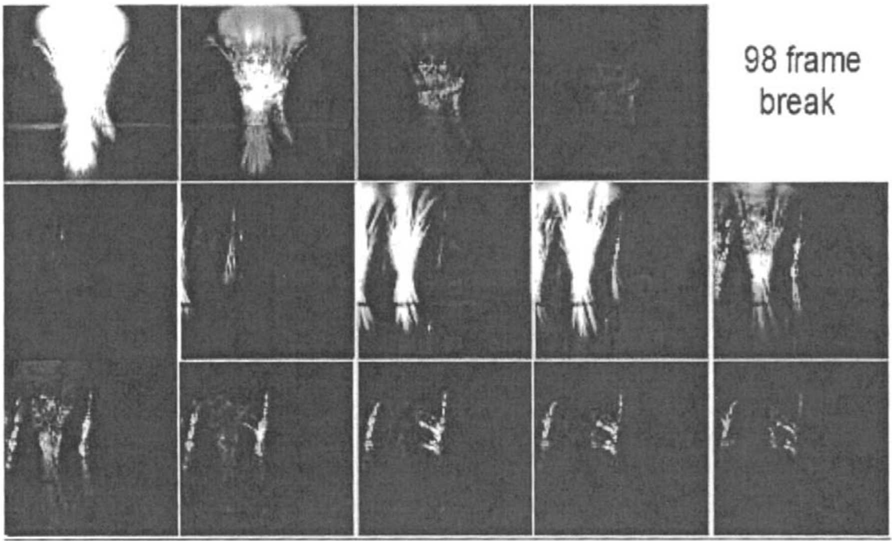

Figure 4. Two sequences from a sprite event at 05:24:22.829 UT, 18 August 1999. The images in each sequence are 1 ms apart, and the sequences are separated by 99 ms. Note the branches going up, in contrast to the tendrils going down in Figure 2, but directed towards the sprite just left of center.

second sequence of images). A filamentary structure in the center of the field of view gradually brightens and after 5 ms (first image bottom row), develops branches towards the sprite to the left, which at this time is rapidly fading. Again, the branches appear to start from small, localized ball-like features at or near the surface of the volume occupied by the sprite. The branches also appear to terminate at the surface of the other, older sprite.

The sprite presented in Figure 3 is an example of an event in which a decayed sprite appears to be "reactivated" by subsequent nearby sprites. This suggests that sprites can modify the local electrical properties of the atmosphere to lower the threshold for subsequent sprite development, and that the changes last substantially longer than the optical sprite events themselves. We also frequently observed new, off-vertical or even horizontal tendrils, such as are evident in the third row of Figure 3. These oblique structures seem to originate from the surface of the volume occupied by the first sprite. These off-vertical tendrils presumably follow the local electric field, and could be evidence of either a local modification by the previous sprite of the electrical conductivity that distorts an external field, or the presence of residual electrical charge generating an additional local field.

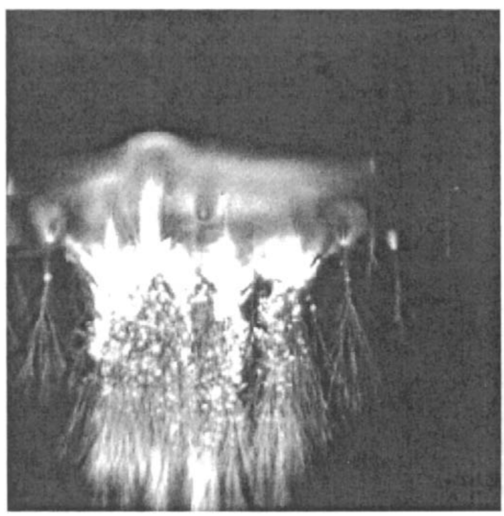

Figure 3. A single frame from the sequence of images in Figure 2, showing the presence of long-lived balls at the juncture of tendril forks.

Long Lived Stationary "Balls" Within Sprite Tendrils

The downward propagating tendrils often lead to the formation of secondary small ball-like structures [*Sentman et al.*, 1996], as noted in Figure 2. One of the frames showing this clearly is shown in Figure 4, where the small isolated balls are visible at the left and right, and numerous others are distributed throughout the volume occupied by the tendrils. The filamentary tendril structures, once developed, seem to remain spatially stationary. The balls do not develop during the tendril development phase, but appear several ms after the tendril onset. They decay in brightness much slower than the main sprite structures, often remaining visible for more than 100 ms. This is longer than the duration of both the causative low-altitude lightning stroke and the mesospheric electrical relaxation time, as well as nearby or adjacent tendril structures. This in turn suggests that the main sprite event initiates secondary localized processes within the balls that are different from processes within the tendrils, and perhaps chemical in nature [Stenbaek-Nielsen *et al.*, 2000]. The presence of such optically emitting balls at the juncture of branch structures of sprite tendrils implies the existence of a local energy enhancement of some kind at these locations. In the absence of an ongoing electrical process to replenish their energy source, these features might otherwise be expected to die with the parent sprite.

We estimate the expected characteristic transport times for thermal diffusion and electron cooling by elastic collisions with neutrals. The electron thermal diffusion coefficient is given by $D_{en} = \lambda_{en}^2 / \tau_{en}$, where λ_{en} is the electron-neutral mean free path and τ_{en} is the electron-neutral collision time. The diffusion coefficient permits estimating the escape time τ_{esc} from a region of characteristic size L as $D_{en} = L^2 / \tau_{esc}$. The electron-neutral mean free path is given by $\lambda_{en} = 1/N_n\sigma_{en}$, where N_n is the neutral number density and σ_{en} is the electron-neutral collision cross section. The electron-neutral collision time is given by $\tau_{en} = \lambda_{en} / a_{th}$, where a_{th} is the electron thermal speed. Combining these, we obtain the approximate electron diffusion escape time from a region of size as $\tau_{esc} = \tau_{en}L^2/\lambda_{en}^2 = L^2/\lambda_{en}a_{th}$. An upper limit for the electron cooling time by interaction with neutrals is estimated to be $\tau_{cool} \sim \tau_{en}m_n/m_e$, where m_n and m_e are the mean neutral mass and electron mass, respectively, where we consider only elastic collisions. Including effects of inelastic collisions would result in a shorter cooling time.

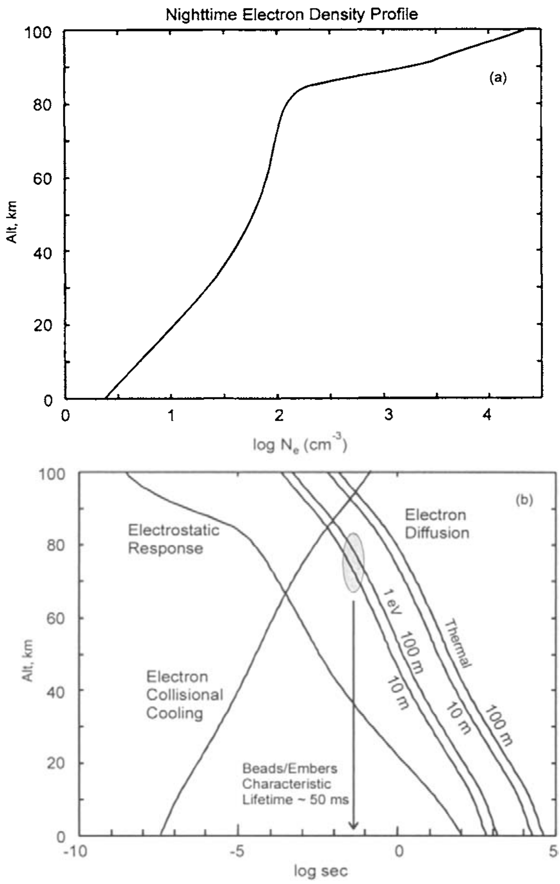

Figure 5. Ambient nighttime electron density profile used in calculation models. (b) Electrostatic relaxation (response) time, electron collisional cooling time, and electron diffusion times. The diffusion times are computed assuming two temperatures and two diffusion distances.

Figure 5 summarizes several characteristic time scales associated with electrical and transport processes within the atmosphere as functions of altitude. We have used a standard model for the neutral atmosphere number densities and temperatures and the nighttime electron density profile shown in Figure 5(a), and assumed a constant electron-neutral collision cross section of 10^{-15} cm^2. [We note in passing that with this model the fractional electron density is only 10^{-12}-10^{-14}, so the ambient nighttime medium is extremely weakly ionized. However, with roughly 10^4-10^5 electrons in a Debye sphere within the ambient mesosphere region of sprite occurrence, a microphysical plasma description of collective behavior using the Boltzmann equation (not provided here) is in principle feasible.] In Figure 5(b) are shown cooling and diffusion time scales derived for this model. From the basic atmospheric and electron density parameters the ambient electrical conductivity and the associated electrostatic relaxation (response) time are computed. Four electron thermal diffusion time profiles are computed, assuming ambient thermal electron temperature and 1 eV electron energy, and diffusion scale distances of 10 m and 100 m, respectively. Also shown is the electron elastic collisional cooling time. The altitude-duration regime (70-80 km, 10-100 ms) occupied by the balls is indicated by the oval in Figure 5b. The profile most nearly matching the observed altitude-duration regime of beads is electron-neutral collisional diffusion. From these results we conclude that the lifetime of the balls is broadly consistent with electron thermal diffusion. Their long lifetime relative to nearby tendrils may be a reflection of differences in electron energy in the respective structures, i.e., the balls have longer lifetime because the characteristic electron energy of the balls is lower than that of tendrils.

A Plasma Parameter Delineating Regions of Discrete Tendrils and Diffuse Hair

A persistent feature in virtually all well defined sprites, such as in Figure 4, is the diffuse "hair" in the topmost 5-10 km of the structures between 85-95 km, often separated from the highly structured tendril regions at lower altitudes by a dark band of depressed optical intensity [Sentman *et al.*, 1997]. Until recently, no theories have been advanced to account for the underlying physical mechanism behind the difference between the diffuse top region of a sprite and the structured tendril region.

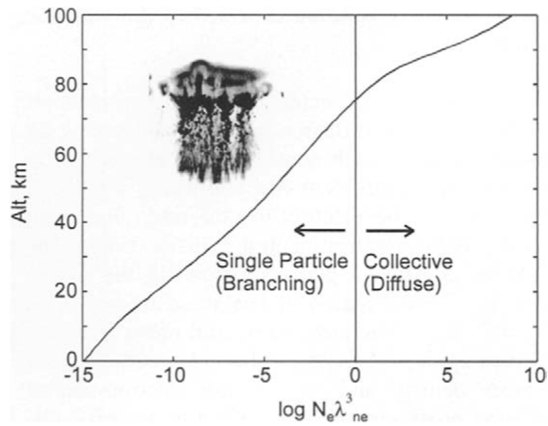

Figure 6. Number of electrons in a collision sphere vs. altitude.

Williams [2000] has proposed that the plasma parameter consisting of the number of electrons per thermal electron-neutral collision volume may be an important determinant separating the diffuse and structured regions. The underlying concept is that at low altitudes electron avalanches originating from single thermal seed electrons are widely separated, by many mean free paths, from other avalanches that may similarly develop, so the avalanches will tend to develop as discrete structures, such as observed in the tendrils. By way of contrast, at high altitudes where there are many electrons within a collision volume avalanches initiated by any single electron would immediately be joined within a single collision time by electrons within the collision volume, thus producing a homogenized glow, such as is observed in the diffuse "hair" of the sprite, instead of a discrete structures.

In Figure 6 is plotted the number of electrons in a collision sphere vs. altitude, with the sprite of Figure 4 included at scale. Although the heuristic concept remains to be developed quantitatively, it is intriguing to note that the Williams [2000] parameter behaves as suggested., steeply increasing from sub-unity values at altitudes below 75-80 km, below which sprites are highly structured, to large values above this height, where the emissions are diffuse.

Nonradiative Energy in Sprites

Based on spectral measurements and optical intensities obtained from aircraft during the EXL98 sprite campaign, Heavner *et al.* [2000] concluded that the total energy stored in N_2 electronically excited states in a typical sprite is ~26 MJ. This figure is obtained from the total intensity of a sprite as observed in white light, combined with spectral observations that show that most of the optical emissions arise from the $N_2(1P)$ group of transitions from the electronically excited B state to the lower energy A state. These transitions occur primarily at red and near infrared wavelengths (hence the name "red sprite"). There is only a very weak ionized component, although the earliest stages of sprite development undoubtedly involve ionization of neutrals. The total internal energy of the excited neutrals includes in addition to the electronic excitation energies a much larger amount of energy stored in nonradiative vibrational states within the ground electronic states of both N_2 and O_2. Using an assumed value of 0.3 eV for the vibrational energy of the ground electronic state associated with sprite emissions, the ratio of total internal energy (vibrational + electronic excitation) to the energy emitted optically is ~20. For a sprite with an optical emission energy of 50 kJ [Sentman *et al.*, 1995], this corresponds to approximately 1 GJ [Heavner *et al.*, 2000]. Uncertainties in the various parameters entering into this calculation are estimated to produce a corresponding multiplicative uncertainty in the energy on the order of 2-5. Hence, the total internal energy of a "typical" sprite is 200 MJ – 5 GJ.

SUMMARY

We have presented several examples of recent observations of sprites imaged a 1 ms time resolution and discrete "balls" of persistent (~100 ms) of luminous emissions that often occur in sprite tendril structures. The images show several new features, including evidence for local modification of the mesosphere by sprites. The relatively long lifetime of the luminous balls is broadly consistent with thermal diffusion lifetimes. However, the fact that the lifetimes are longer than adjacent tendrils suggests that either the internal energy density of the two structures is different, or perhaps balls possess an internal energy source for optical emissions not present in, or distinct from, those in the tendrils, such as from chemical processes. The potential for chemical processes within sprites has been recognized from almost the earliest reports [Sentman *et al.*, 1993, 1995]. Based on spectral and optical measurements, estimates of the total internal energy of a "typical" sprite yield values of ~1 GJ, with generous error estimates ranging between factors of 2-5 above and below this.

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