



Observed emission rates in sprite streamer heads

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Received 2 March 2007; revised 9 April 2007; accepted 1 May 2007; published 6 June 2007.

[1] Sprite observations at 10,000 fps have shown tendrils and branches to be formed by bright streamer heads moving at $\sim 10^7$ m/s. The streamer heads typically brighten as they move up or down, often saturating the detector. We present here inferred emission rates. The streamer heads are presumably smaller than our 140 m spatial resolution and, therefore, they have to be treated as point sources. The optical emissions are assumed to be dominated by the N₂ 1P band and comparing with stars in the images we find total emission rates in individual streamer heads ranging from $4 \cdot 10^{21}$ to $3 \cdot 10^{24}$ photons/s. For a 25 m streamer head the range of average brightness would be $9 \cdot 10^8$ – $5 \cdot 10^{11}$ R. Alternatively, using a volume emission rate of $8 \cdot 10^{11}$ photons/cm³/s the size range would be 10 to 100 m. **Citation:** Stenbaek-Nielsen, H. C., M. G. McHarg, T. Kanmae, and D. D. Sentman (2007), Observed emission rates in sprite streamer heads, *Geophys. Res. Lett.*, 34, L11105, doi:10.1029/2007GL029881.

1. Introduction

[2] Sprites are short-lived optical events occurring in the mesosphere and lower ionosphere above electrically very active thunderstorms. Initially researchers did not truly appreciate their short duration and thus their true brightness. For example, *Sentman et al.* [1995] estimated a brightness around 600 kR from 30 ms video images. Subsequent observations with ms resolution, first by *Stanley et al.* [1999] and later by *Stenbaek-Nielsen et al.* [2000], demonstrated their short duration, and *Stenbaek-Nielsen et al.* [2000] estimated a maximum brightness of about 12 MR. The ms resolution images showed a temporal development only hinted at in the video; however, it was also clear that still higher time resolution was needed to fully time resolve their development and their true brightness.

[3] In 2005 *Cummer et al.* [2000] and *McHarg et al.* [2007] separately fielded new, faster intensified cameras. A critical equipment feature is the intensifier phosphor. The intensifier used by *McHarg et al.* [2007] has a 1 μ s (P24) phosphor so, even at 10,000 frames per second (fps), there would be no persistence between successive frames. Only with the short phosphor persistence was the true nature of the tendril and branches revealed. Rather than being long luminous structures, as might be inferred from lower time resolution images, tendrils and branches are formed by very bright, spatially compact, and fast moving streamer heads.

[4] The streamer heads recorded at 10,000 fps often saturate the imager and must be considerably brighter than our previous estimate of 12 MR. So the question immediately comes up: What is their brightness? The answer is important for theoretical and modeling work, and we give here an estimate based on our 2005 observations.

2. Data

[5] Sprite images were recorded in July 2005 from the Langmuir Observatory (latitude 33.975°N, longitude 107.181°W, altitude 3.13 km) near Socorro, New Mexico. The camera used was a Phantom-7 intensified CMOS camera. The Gen III intensifier has a 1 μ s (P24) phosphor. The recordings were made at 10,000 fps and the intensifier was gated at 50 microseconds, i.e., the exposure time of each image would be equivalent to 20,000 fps. The images are 6.12×6.12 degree field of view with 256×256 pixels and an image depth of 12 bits (4096 gray levels). The observations were made unfiltered, so the images represent the luminosity integrated across the intensifier wavelength range, 400 to 900 nm. Maximum sensitivity is near 800 nm. The camera was mounted on an equatorial mount, which aligns the images with the celestial equator rather than the local horizon. For analysis and presentation we rotated the images so that rows would be horizontal.

[6] For the presentation here we show the analysis of a streamer head from a sprite with many well-defined downward propagating streamer heads. It occurred at 04:38:00 UT on July 9, 2005. We will assume a range of 335 km, the distance to the associated lightning discharge identified by NLDN. A frame from near the start of the event is shown in Figure 1, and an enhanced, false color animation is available in the auxiliary material.¹ About 20 streamer heads, the nearly circular luminous features, are visible in the image. Some have intensities barely above the limit of detection and some clearly saturate the imager. They emerge from a featureless background at altitudes between 96 and 81 km and brighten as they move down. The velocities range from $1 \cdot 10^7$ to $6 \cdot 10^7$ m/s. There was a very faint elve at the start of the event, but no obvious sprite halo.

[7] Upward propagating streamer heads start later than the downward propagating streamers, as has also been noted by *Stanley et al.* [1999] and *Cummer et al.* [2000], and they start from a lower altitude, as well as being initiated from pre-existing luminous sprite structures [*McHarg et al.*, 2007]. Our analysis indicates the velocity and brightness of the upward streamer heads are similar to those of the downward propagating structures, and the velocity generally increases as the streamer head propagates. The highest

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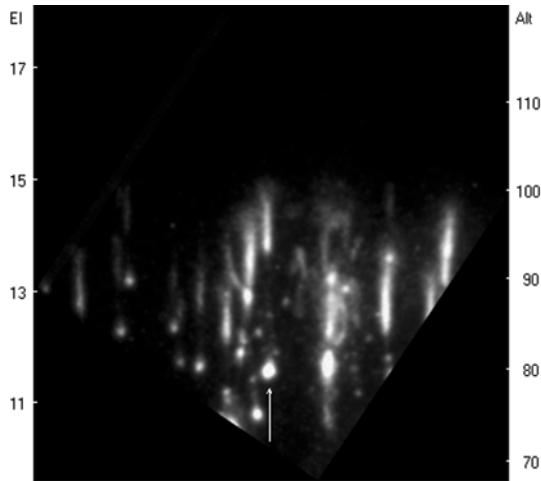


Figure 1. Frame from near the start of the event 9 July, 2005 at 04:38:00 UT. Most of the beadlike structures are streamer heads moving rapidly downwards. The 256×256 pixel image is rotated so that the vertical is up-down. Arrow points to the streamer head analyzed (Figures 2 and 3). The altitude is based on an assumed range of 335 km. An enhanced, false color animation is available in the auxiliary material.

velocity and brightness found so far is in an upward moving streamer head.

3. Streamer Head Analysis

[8] The streamer heads are slightly elongated in the direction of propagation. With $50 \mu\text{s}$ gating the streamer heads would move 2–3 pixels during the exposure time. Thus the elongation appears to be an artifact of velocity. The streamer heads are brightest in the center and a Gaussian profile fits the observed horizontal intensity profiles very well. In the case where streamer heads saturate the imager the wings of the profiles fit a Gaussian. Many streamer heads can be followed as they brighten into saturation, and a Gaussian profile can be used to extrapolate and obtain the maximum brightness. A sequence of images showing the streamer head pointed to in Figure 1 is shown in Figure 2. The images have been enhanced to show low intensity features. The streamer head was first detected at an altitude of 96 km, brightened as it descended, and went out of our field of view at an altitude of 73 km. Below the image slices are shown three horizontal intensity profiles through the centers and the fitted Gaussian profiles. The streamer head goes from non-saturation to severe saturation as it brightens. The rightmost Gaussian fit indicates a maximum brightness of 2.2 times saturation.

[9] Brightness analysis was performed on isolated and well-defined streamer heads, such as shown in Figure 2, to provide unambiguous fitting with a Gaussian profile. The fit was made separately for each row covering the streamer head. The base of the Gaussian was set at the background level. The row signal was then calculated by integrating the Gaussian and the total signal in the streamer head by summing over the rows. We did attempt a 2-D Gaussian fit, as is often used for stars in astronomical applications,

but that did not work well because of effects from nearby luminous sprite structures. Also movement of the streamer head creates asymmetries between front and back (top and bottom) of the streamer head. The analysis of upward streamers (not presented here) is significantly more challenging as they propagate against a background of luminous sprite structures.

[10] Figure 3 shows the total counts for the downward very bright streamer head shown in Figure 2. The maximum pixel count is about 600,000. The streamer heads in the left of center in Figure 1, more typical of the larger data set, have maximum counts near 100,000. The pronounced dimming in frame 13 is not entirely real. At this time the streamer head splits into two and it was difficult to separate the two parts, but it does appear that there is a real dimming associated with the splitting. A splitting is also seen at the end of the sequence. We note that when streamer heads split they do so without any significant pause or interruption to otherwise smoothly advancing propagation.

4. Imager Response Calibration

[11] The intensity response of the imager was calibrated using a rich star field in the general area of the observations. The area was centered on $22^{\text{h}}:48^{\text{m}}$ right ascension and 43° declination (in the constellation Lacerta). The recordings were made at 100 fps. At this frame rate the stars were well defined without saturating the detector. To improve signal to noise we made a 600 frame average, which also eliminated twinkling effects. The image format was the same as the image shown in Figure 1. The signal above background from 70 stars, covering a magnitude range of 3.5 to 8.5, was extracted and the star magnitudes and spectral types were obtained from the Smithsonian Astronomical Observatory (SAO) star catalog.

[12] The star signal recorded is affected by atmospheric transmission and intensifier response, both of which are

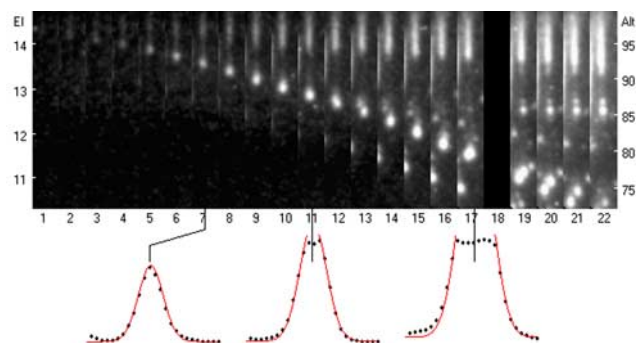


Figure 2. Strips extracted from successive images showing the downward streamer head movement. Bottom shows Gaussian profiles fitted to a row across the streamer head center at 3 points in the series. The dots are the row pixel values. The streamer head does not saturate in the left profile, just saturates in the middle profile, and in the right profile the peak brightness is 2.2 times saturation. In the right profile the background is higher as luminosity from a nearby structure extends into the left wing of the streamer head. A black strip is inserted where a frame was dropped by the camera.

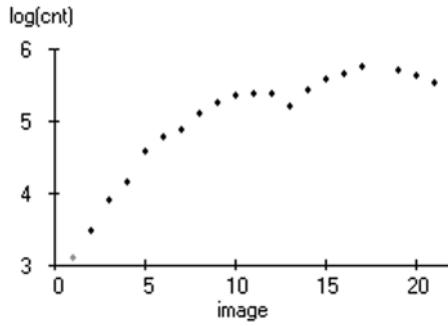


Figure 3. Total streamer head signal count. The data points cover the series shown in Figure 2.

wavelength dependent. Let the luminous stellar flux above the atmosphere be $P(\lambda)$, the atmospheric transmission $T(\lambda)$, and the photocathode response $R(\lambda)$, then the image signal count may be expressed as

$$\text{Count} = C G \Delta t \int P(\lambda) T(\lambda) R(\lambda) d\lambda \quad (1)$$

The integration is over the intensifier wavelength response range, Δt is the exposure time, and G is the intensifier gain which is controlled externally by the user. The calibration constant C can then be determined through analysis of the star field. C reflects optical and electronic gains, which we assume to be wavelength independent.

[13] The star spectra $P(\lambda)$ were derived from the “Thirteen-Color Photometry of 1380 Bright Stars” catalog by *Johnson and Mitchell* [1975]. Only one of the stars in the catalog is in the calibration star field. For the remaining 69 stars we averaged catalog entries for similar spectral type stars scaled to the magnitude provided by the SAO catalog.

[14] The atmospheric transmission $T(\lambda)$ was calculated using the U.S. Air Force Research Laboratory “Moderate Spectral Atmospheric Radiance and Transmittance” (MOSART) model [*Cornette et al.*, 1995]. The model allows the user to specify atmosphere and aerosol/haze profiles in four altitude regions. Since we did not have any specific aerosol/haze information, we used the model “Rural Aerosol” for the boundary layer and the troposphere, “Background” for the stratosphere, and “Normal” for the upper atmosphere. No local time effects were included. Figure 4 shows the atmospheric transmission with 2 nm resolution. The star field was recorded at an elevation angle of 35° while the streamer head observations (Figures 1 and 2) were at elevation angles 15° – 11° . The Gen III intensifier spectral sensitivity $R(\lambda)$ and the gain function G were provided by the manufacturer.

[15] A fit of the observed to the calculated star signal determines the calibration constant C . The fit is largely determined by the brighter stars. The dimmer stars are affected by low signal to noise and this clearly shows in larger scatter. Additionally, the dimmer stars covered a number of pixels indicating that the camera focus was not optimum. Based on the star calibration, saturation at $50 \mu\text{s}$ exposure would occur for a brightness of 57 MR at 800 nm. The streamer head observations were made at 1.77 times

higher gain resulting in a correspondingly lower saturation level, 35 MR.

5. Streamer Head Emission Rates

[16] The spatial resolution in the images, assuming a range of 335 km, is 140 m. High resolution sprite observations by *Gerken et al.* [2000] show the transverse width of tendrils to be ~ 10 s–100 s of m. These observations were made at video rates and, assuming that the tendrils recorded are the optical signatures of compact, fast moving streamer heads, their width would reflect the size of the streamer head. A scale size of a few 10 s of meters agrees with theoretical considerations [*Pasko et al.*, 1998], and the streamer head model of *Liu and Pasko* [2004, 2005] has a scale size of ~ 25 m at an altitude of 70 km. Thus, streamer heads may not fill the pixel field of view and, consequently, we will treat them as point sources. We further note that Gaussian profiles, which fit our streamer head observations well, also fit stars [*Keyes*, 1971] and are used for that purpose in many astronomical software packages. To obtain brightness the total emission from the streamer head will be derived, and then, assuming a size, its brightness. We use equation (1) again, but now we solve for the flux, $P(\lambda)$.

[17] The images are “white light” and spectral information must come from other sources. Sprite spectra obtained with a large aperture slit spectrograph [*Kanmae et al.*, 2007] are dominated by the neutral nitrogen 1P band system. The relative strength of individual bands within the system is similar to those given by *Vallance Jones* [1974] for the aurora, and we will use those to describe the spectrum. Model work by *Liu and Pasko* [2004] indicate additional emissions from the N_2 2P and the N_2^+ 1N band systems, but these emissions are primarily in the blue and combined with the camera spectral response would contribute less than 1% to the signal in the images.

[18] Let n be the total number of photons/cm² in the N_2 1P band system and $f(\lambda)$ the fraction in each band within the system, then $P(\lambda) = n f(\lambda)$ and we have:

$$\text{Count} = C G \Delta t n \sum (f(\lambda) T(\lambda) R(\lambda)) \quad (2)$$

[19] The sum can be evaluated independently since the 3 elements in the sum do not depend on scene brightness.

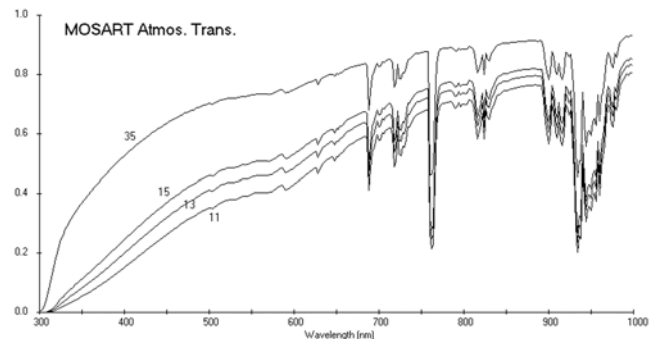


Figure 4. Atmospheric transmission calculated with MOSART for elevation angles 35° (star calibration) and 15° , 13° , and 11° (streamer head observations).

The terms in front are the calibration constant C from the star calibration, the intensifier gain G , and the exposure time Δt .

[20] The streamer head shown in Figure 2 appeared at 14° elevation angle, descended and went out of the field of view at 10° elevation angle. Over these elevation angles the atmospheric transmission varies considerably as was shown in Figure 4. For a path at 13° elevation angle we find for the N_2 1P photon flux above the atmosphere as function of counts in the image:

$$n = 3.1 \cdot 10^2 \text{ Count } [\#/ \text{ cm}^2/\text{s}] \quad (3)$$

We estimate an uncertainty of 20% coming primarily from the star intensity calibration.

[21] The streamer head signal (Figure 3) ranges from ~ 1000 to more than 600,000 counts corresponding to photon fluxes from $3 \cdot 10^5$ to more than $2 \cdot 10^8$ photons/ cm^2/s . Assuming that the sprite is 335 km away (the distance to the associated lightning strike) and assuming isotropic emissions, the total N_2 1P emission rate from the streamer head would range from $4 \cdot 10^{21}$ to $3 \cdot 10^{24}$ photons/s.

6. Discussion

[22] The streamer heads are bright. At $50 \mu\text{s}$ exposure a 600,000 count signal is equivalent to a star of magnitude -6 . The streamer heads are compact and typically brighten as their speed increase. This is clearly illustrated in Figure 2. The dynamical properties observed fits well with the theoretical framework for streamer development by *Liu and Pasko* [2004] (see also review of models by *Pasko* [2007]). The increase in brightness should also be associated with an increase in size, but we cannot confirm this observationally because of insufficient spatial resolution. *Liu and Pasko* [2004] assumed an external electric field greater than the local electrostatic break-down field (overvoltage condition), but streamers can also propagate in sub-break-down fields (undervoltage condition) [*Liu and Pasko*, 2005]. In the latter case the optical emissions are more spatially restricted to the streamer head in agreement with our observations. We should note that the model by *Liu and Pasko* [2004] predicts simultaneous up and down propagating streamers, which we do not observe.

[23] The streamer heads are smaller than or comparable to our spatial resolution and hence, to derive their brightness requires a physical size. The average brightness, in Rayleigh, is the total emission rate divided by the streamer head cross section area (1 R is 10^6 photons/s from a 1 cm^2 -column), which for a 25 m diameter streamer head would give a range of $9 \cdot 10^8$ to $5 \cdot 10^{11}$ R. The *Liu and Pasko* model for that size at 70 km altitude has an average brightness of $\sim 5 \cdot 10^8$ R for the strong field case [*Liu and Pasko*, 2004] and $\sim 10^7$ R for the weak field case [*Liu and Pasko*, 2005], but these values are highly dependent on the assumed background reduced electric field and stage of streamer development. Conversely, if we know the volume emission rate we can obtain the scale size. The N_2 1P band emission calculated by D. D. Sentman et al. (Plasma chemistry of sprite streamers, submitted to Journal of Geophysical Research, 2007) peaks at 10^{13} photons/ cm^3/s with a value of $8 \cdot 10^{11}$ averaged over the image $50 \mu\text{s}$ exposure time corresponding to streamer head scale size from ~ 10 m to

~ 100 m for the 1000 to 600,000 count range. This range agrees with the telescopic observations of *Gerken et al.* [2000]. The 600,000 maximum count is for one of the brightest streamer heads in our analysis. Most streamer heads are less bright, typically peaking at image count rates around 100,000.

[24] There were a total of 22 downward propagating streamer heads analyzed in this sprite event. With a distance of 335 km, given by the associated NLDN strike location, start altitudes would range from 96 to 85 km. This altitude appears to be high. *Pasko et al.* [1998] argue the onset altitude to be near 75 km; the streamer head model by *Liu and Pasko* [2004, 2005] assumes 70 km; and *Cummer et al.* [2000] found the onset of streamer heads in the lower edge of an associated halo at altitude 72 km. Sprites may be offset laterally from the causal lightning strike, e.g., *Lyons* [1996] finds an average of ~ 50 km. If the streamer heads were 65 km closer, i.e. at a distance of 270 km, the 96 km altitude would decrease to 75 km. If this range is used instead, the total emissions range calculated above would decrease by a factor of 1.5 to $3 \cdot 10^{21}$ to $2 \cdot 10^{24}$ photons/s and the brightness range for a 25 m streamer head to $4 \cdot 10^8$ – $3 \cdot 10^{11}$ R. On the other hand, the higher altitude onset may also be linked to the absence of an obvious halo. *Mende et al.* [2005] report ionization associated with an initial elve, and this higher altitude ionization could provide the seed for streamer initiation. A similar suggestion was made by *Stanley et al.* [1999] describing their observations. An analysis of all streamer events in our 2005 data set is underway and will be reported on later.

[25] **Acknowledgments.** We thank Dr. Bill Winn, Langmuir Laboratory, Socorro, New Mexico, and his staff for their generous help and hospitality. This research was supported by NSF grants 0334795 to UAF and 0334521 to USAFA.

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