High Speed Sprite Imaging

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Sprites, or TLEs, are brief and very dynamic optical features in the mesosphere caused by tropospheric lightning activity. Some of these features, such as streamers, can be very small, a few tens of meters, and they can move at very high velocities, up to about half the speed of light. Thus to investigate these features we need imagers with high spatial and temporal resolution. Our group has over the last decade made sprite observations at up to 16,000 frames per second and down to 20 m spatial resolution. The presentation will focus on what we have learned and can learn from such observations, as well as the technical limitations imposed by current imaging capabilities. High speed imaging can verify theory and modelling efforts as well as provide observational details to be addressed by theory and modelling.

1. Background

Sprites are spectacular optical emissions in the mesosphere caused by transient electric fields originating from cloud to ground lightning strikes. They typically occur in the altitude range 55 to 90 km, although sprites have been observed reaching all the way down to near cloud tops at ~25km altitude and up to about 100 km altitude. They last from a few ms to more than 100 ms [1].

Typically sprite events are a combination of three optical features: Elve, halo, and sprite (streamers and glow). The three features may vary considerably in brightness and all may not be detected, or may not be present, in individual events. The elve is well understood; it is caused by the electromagnetic pulse radiated from the lightning strike exiting airglow emissions at an altitude near 95 km [2,3]. The halo and sprite follow the elve. They are triggered by the quasi-static mesospheric electric field resulting from the redistribution of electric charges due to the lightning strike [4]. The halo is a large, diffuse, pancake-like luminous feature [*3*], while the streamers and glow are the result of an electrical break-down in the local atmosphere [5]. The onset altitude of the sprite streamer is somewhere in the 65 to 85 km range [6]. Streamers occurring immediately after the causal lightning strike, prompt sprites, tend to have their onset at higher altitude than delayed sprites, and the delay time is likely related to effects of the lightning associated continuous current [7].

The sprites are surprisingly bright often outshining Jupiter and Venus [8]. An example is shown in figure 1. In this recording we used slitless spectroscopy to investigate the optical emissions from sprites [9]. The emissions are primarily from the 1P molecular nitrogen band emitting in the in the 600-900 nm wavelength range. The very bright emissions make high speed imaging possible without very large aperture optics.

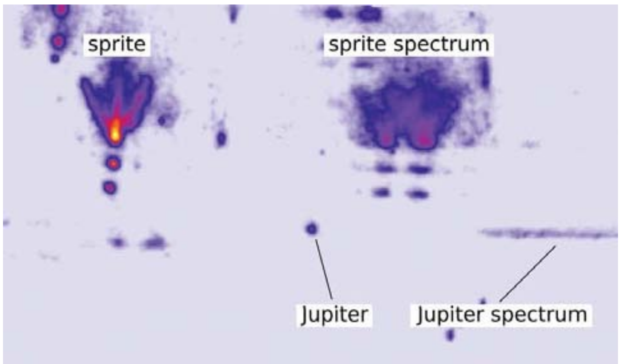

Figure 1. Sprite recorded with a slitless spectrograph. Zero order image to the left and first order spectrum to the right. Sprite clearly brighter than planet Jupiter (visual magnitude -2.4)

Sprite streamers are phenomenologically similar to electrical discharges observed in laboratory experiments (reviews [10,11]) and they have been modeled by several groups [5,12-14]. Common for most of these simulations is that the streamer is initiated by an artificially introduced small electron density enhancement that serves as a seed for the streamer development. Recently *Luque and Ebert* [13] and *Qin et al.* [5] have presented modeling efforts placing streamer formation as part of the larger response of the mesosphere to an electric pulse caused by a cloud to ground lightning strike. *Luque and Ebert* [13] suggest that the sprite streamer is formed out of an ionization wave associated with the sprite halo, but *Qin et al.* [5] argue that other processes must also be involved.

The most dynamic features requiring high speed imaging are the sprite streamers, and they will be the primary focus of this presentation.

2. Imagers used

The sprite data to be presented are from thunderstorms over the Mid-West of the USA. The data were primarily obtained with two intensified high-speed digital CMOS cameras, a Vision Research Phantom v7.1 and v7.3, respectively. Both have 800x600 pixel detectors. The Phantom v7.1 has 12 bit images (4096 grayscales) recording into 2 gigabyte camera memory, while the Phantom v7.3 has 14 bit images (16384 grayscales) recording into 4 gigabyte camera memory.

The intensifier units are VideoScope VS4-1845HS. Both intensifiers have 1 μs phosphors (P-24) so there is no signal carried into subsequent images due to phosphor persistence. (Long phosphor persistence is typical of most 'night-vision' devices and is responsible for the luminous trails often present in TV news reports filmed at night). The intensifier spectral responses are slightly different, but the differences are not important to this presentation.

Bore-sighted with the high speed imagers is a Watec low light level video camera to provide overall scene awareness as well as event detection. Operationally, the Phantoms are using the memory as a circular buffer, and when an event is seen, the operator stops the camera and download the images to computer disk. Because the recordings rely on a human to detect the event the recording time that can be accommodated by the finite camera buffer size must be more than the human reaction time which we have found to be in the 0.5 to 1 s range. This poses severe limitations on the recording speed. To maximize the recording time we typically use a smaller than 800x600 pixel image size.

3. Specific observational issues to be discussed

To observe the temporal development in sprites requires a frame rate of at least 5,000 fps. Spectacular images were obtained in 1999 at 1000 fps, but it was clear then that higher frame rates are required. We have used up to 16,000 fps with 20 microsecond exposures. This will adequately resolve streamer formation and propagation, but streamers split on even smaller time scales. (See poster at this meeting by McHarg et al.). To resolve the splitting we estimate that a frame rate of 50,000 fps is needed. Fortunately, streamers are typically bright enough to make such observations.

Sprite streamer heads are fairly small; modeling suggests a few 10s of meters. Most of our observations have had a pixel resolution (evaluated at the distance of the sprites) of more than 100 m so the streamer heads are not resolved. We have used a 500 mm focal length lens providing a 20 m pixel resolution, but the field of view is then very small, about 1°. The streamers are observed to move up and down at velocities near 10^7 m/s, which with such a small field of view means that they pass through in a few frames. Another issue to consider is 'smearing' due to the high streamer velocities. During a 20 μs exposure a 10^7 m/s streamer would move about 200 m, which is significantly larger than the size of the streamer head. To resolve the streamer head requires very short exposures combined with high spatial resolution.

Our high speed sprite observations show that streamer activity always starts with one or more downward propagating streamer. Based on triangulations the onset altitude is between 65 and 85 km altitude, a surprisingly large range. Higher altitude onsets are for sprites forming immediately after the causal lightning strike. In some sprites we also observe upward propagating streamers. When they are observed, their onset is later and from a lower altitude than the initial downward streamer. This is illustrated in Figure 2 where the initial downward streamer starts at 82 km and the upward streamer, about 2.5 ms later, at 73 km.

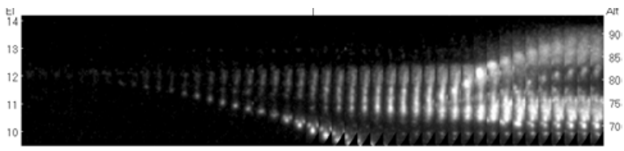

Figure 2. Image time series shows the initial downward streamer and a later upward streamer. Time series covers 4.5 ms. Recording speed is 10,000 fps. The image strips cover the altitude range 65 to 95 km. The maximum downward and upward streamer head velocities are 1.3 10^7 m/s and 2.3 10^7 m/s respectively. (Figure adapted from [1]).

Modelling has suggested that streamer onset has symmetric upward and downward streamers, but this has never been observed. The reason for the initial downward only streamer may be associated with onset near the steep increase in electron density at the bottom of the ionosphere. A screening charge will set up there effectively preventing the upward streamer propagation.

Video recordings indicate that sprites typically fall into two types: Carrot sprites and columnar sprites (C-sprites). High speed observations show that the two types are related to the presence of upward propagating streamers. If there are many upward streamers the sprite will appear as a carrot. However, it must be noted that sprites have a highly varying number of upward streamers and hence, the classification can be highly subjective.

At times the initial streamer comes out of the halo, but we also see examples where the streamers do not appear before the halo has faded, and there are events with streamers appearing without any obvious halo. The observations place constraints on the causal mechanism, and may possibly indicate that more than one process is involved.

The similarity with laboratory observations is intriguing suggesting that sprite streamers and laboratory discharger might obey various scaling laws. However, the relative importance of several processes involved differs with altitude (pressure). For example, photoionization in front of the advancing streamer is significantly more effective at sprite altitudes (low pressure), and conversely, three body processes are more important in the laboratory environment (high pressure). Recent observations indicate that the minimum size of sprite streamers is considerably larger than expected from the scaling of laboratory streamers.

4. References

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