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The electrodynamics of sprites

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[1] A balloon campaign was conducted in summer, 1999, to measure the stratospheric electromagnetic fields associated with sprites. The balloon payloads were instrumented with electric field detectors, magnetometers, an upward looking photometer, and other instruments. Ground observations for detection of sprites included low light level TV (LLTV) observations from three sites, Jelm Mt., Wyoming, Bear Mt., South Dakota, and Yucca Ridge, Colorado. Flight 3 of the campaign flew from Ottumwa, Iowa at 00:39:32 UTC to 11:12:00 UTC on 08/21/99. A sprite at 0955:36.980 UTC produced a vertical electric field perturbation of ~0.275 V/m that was similar in time profile to the light emission. There was also a positive azimuthal magnetic pulse of ~3 nT. *INDEX TERMS:* 0342 Atmospheric Composition and Structure: Middle atmosphere—energy deposition; 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning

1. Introduction

[2] Interest in "sprites" (D. Sentman, as quoted by [*Lyons*, 1994]) was stimulated by a report of video observations of what appeared to be cloud to stratosphere electrical discharges above active thunderstorms [*Franz et al.*, 1990]. The phenomena are now thought to be a common manifestation of large storm systems. In fact, multiple transient luminous event (TLE) phenomena above thunderstorms have been observed.

[3] The term sprite refers to a type of visible light emission occurring in the mesosphere and ionosphere above thunderstorms [*Sentman et al.*, 1995]. Sprites occur in the 40–90 km altitude range, with maximum altitudes of 88 ± 5 km and maximum brightness at 66 km [*Wescott et al.*, 2001]. The upper portion is red, with wispy, faint blue tendrils extending to 40 km or lower. Sprites have a horizontal size of tens of km. Sprite appearances range from simple columnar forms to intertwined dendritic structures. Sprites exist for several ms, with the brightest part usually occurring within 1 video field (17 ms). Evidence suggests that sprites are produced in association with large positive cloud-to-ground (CG) lightning strokes typically found within the trailing stratiform region of mesoscale convective systems [*Boccippio et al.*, 1995].

[4] The exact details of the sprite excitation mechanism remain controversial [*Rowland*, 1998]. Several models have been proposed to explain the optical emissions of sprites. Heating of ambient electrons [*Taranenko et al.*, 1992], quasi-electrostatic breakdown discharges [*Pasko et al.*, 1998], and runaway electron acceleration [*Bell et al.*, 1995] have been considered. The electromagnetic (EM) field signatures produced by quasi-electrostatic models are quite different from those of EMP models. It is difficult to choose among the competing models using ground observations owing to the boundary conditions imposed on the EM field by the conducting earth. High altitude balloon measurements of sprite EM fields are not similarly constrained. This paper reports the first such data.

2. Balloon Payload

[5] The balloon payload measured the vector electric field, the vector magnetic field, X-ray counting rate, light emissions, vertical current density, conductivity, temperature and balloon location [*Bering et al.*, 2001]. Most data were transmitted using a 1 kHz sample rate 16 bit pulse code modulated (PCM) telemetry link. An event trigger captured 160 ms bursts of 50 kHz sampling rate in on-board "burst" memory.

[6] This paper uses 3 axis double probe electric field PCM and burst memory data with a dynamic range of ±2 V/m and a bandwidth of 0 Hz – 10 kHz. Data from channels with a range of ±100 V/m and similar bandwidth were available but not required. The magnetic field was sensed by a 3 axis search coil magnetometer that had three output channels per receiver, with different gains and bandwidths. The search coils used 10 turn, 0.4 m^2 air core antennae. The PCM channels had a range of ±20 nT and a bandwidth of 10 Hz – 300 Hz. The burst memory channels had a range of ±480 nT and a bandwidth of 10 Hz – 20 kHz. The all sky photometer was a Hamamatsu R374, 28 mm diameter phototube with hemispherical lens, no filter and a 2π sr field of view. The gas bag was occulted by a conical mirror that blocked reflections of tropospheric flashes and increased light collection from distant sprites. Balloon location was provided by on-board GPS receivers, which also provide 1 ms accurate timing for the data recorders.

3. Ground-Based Optical Observations

[7] Low-light-level video (LLTV) observations of TLE's were made from three sites located on the eastern edge of the Rocky Mountains. Multiple sites allowed triangulation of the location and size of some events: the Wyoming Infrared Observatory (WIRO) atop Jelm Mt., Wyoming (2943 m, 41.098N, 105.997W), Bear Mt., South Dakota, (2185 m, 43.875N, 103.750W) [*Wescott et al.*, 2001], and Yucca Ridge Field Station, Ft. Collins, Colorado (1655 m, 40.669N, 104.939W) [*Lyons*, 1994]. WIRO also had a high speed (1000 Hz frame rate) low-light imager (HSI) [*Stenbaek-Nielsen et al.*, 2000].

4. Flight Operations and Weather Conditions

[8] The 1999 Sprite balloons were launched at sunset, floated at 32 km altitude and drifted westward at ~55 km/hr. Flight 3 was

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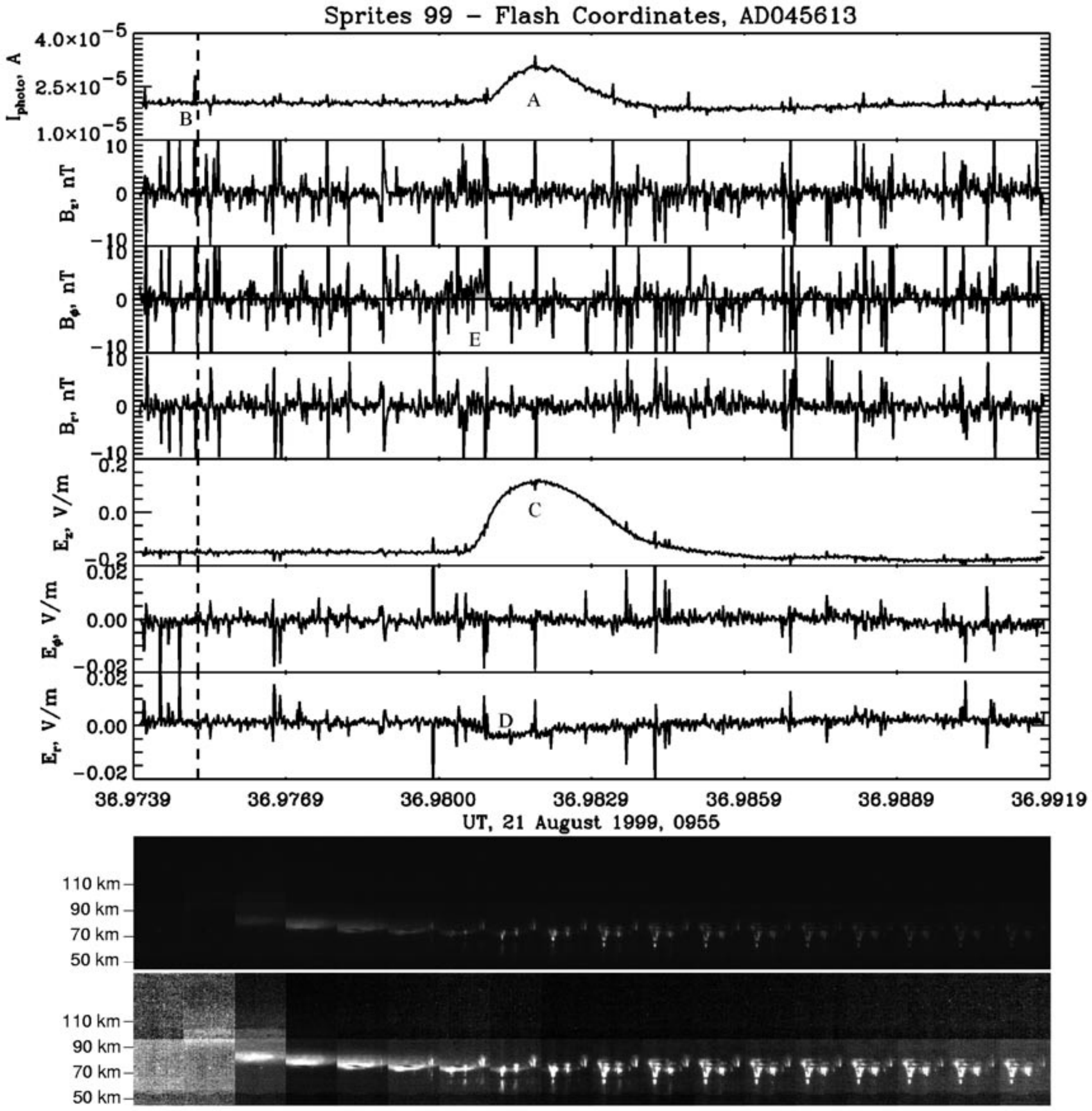

Figure 1. From top to bottom, high speed data plots show photometer current, magnetic and electric field in stroke centered cylindrical coordinates, and time aligned HSI images, unnormalized and normalized. The dashed line shows the retarded time of the NLDN stroke. The normalized images are adjusted to equalize the brightest pixels.

launched from Ottumwa, Iowa at 00:39:32 UTC and was terminated over Nebraska at 11:12:00 UTC on 08/21/99. There were two storms that produced TLE's, one in South Dakota and one in Kansas. The South Dakota storm was active early in the night, producing about half of the TLE's, including all triangulatable events. Bear Mt. and YRFS clouded over about 0830 UTC. From 0830 UTC, all activity was in southern Kansas, with only WIRO observing. There were 26 sprites recorded by at least one station, 23 of which were recorded by the balloon. Fifteen of these events could be associated with NLDN CG strokes, while 11 were not associated with NLDN reported CG strokes.

5. Results

[9] This paper presents the only sprite recorded in burst memory during flight 3. This event included an elve, a halo, a carrot sprite and two columnar sprites (c-sprites). Descriptions of the characteristics of these TLE's can be found in the literature [*Lyons*, 1994; *Rowland*, 1998; *Wescott et al.*, 2001]. This event was observed from WIRO in a 17 ms narrow field video frame at 0955:36.987 ± .017 and in ten 1 ms frames in the HSI. Maximum light intensity was observed on the balloon at 0955:36.982 (Labeled A in Figure 1). NLDN observed a 99 kA + CG stroke at 0955:36.974, 379 km due south of the balloon. The coordinates used are earth-fixed, stroke centered right-handed (r, ϕ, z) cylindrical coordinates. A 50 km horizontal displacement of the sprite from the +CG would produce a 7.5° error in the coordinate transformation, which has no effect on the conclusions of this paper. Dashed lines show the retarded time of the NLDN stroke at the balloon. Since a 1 ms GPS time format was used, relative timing may be uncertain by $\leq$1.5 ms and was adjusted by 1 ms to optimize alignment. The dip in the photometer trace after the sprite results from the response of the gain control to the sprite pulse. The VLF spheric of the CG pulse can be seen in all field components in Figure 1 as the burst of pulses labeled B. It begins with several monopolar pulses, ~-20 nT B_ϕ, and $\sim$20 mV/m E_z, followed by fewer pulses of opposite polarity and larger amplitude, +80 nT and -50 m/V. Since inductive coupling that produces crosstalk is frequency dependent, large fast spikes produce a few percent of crosstalk in the highspeed digitizer, as the photometer trace shows

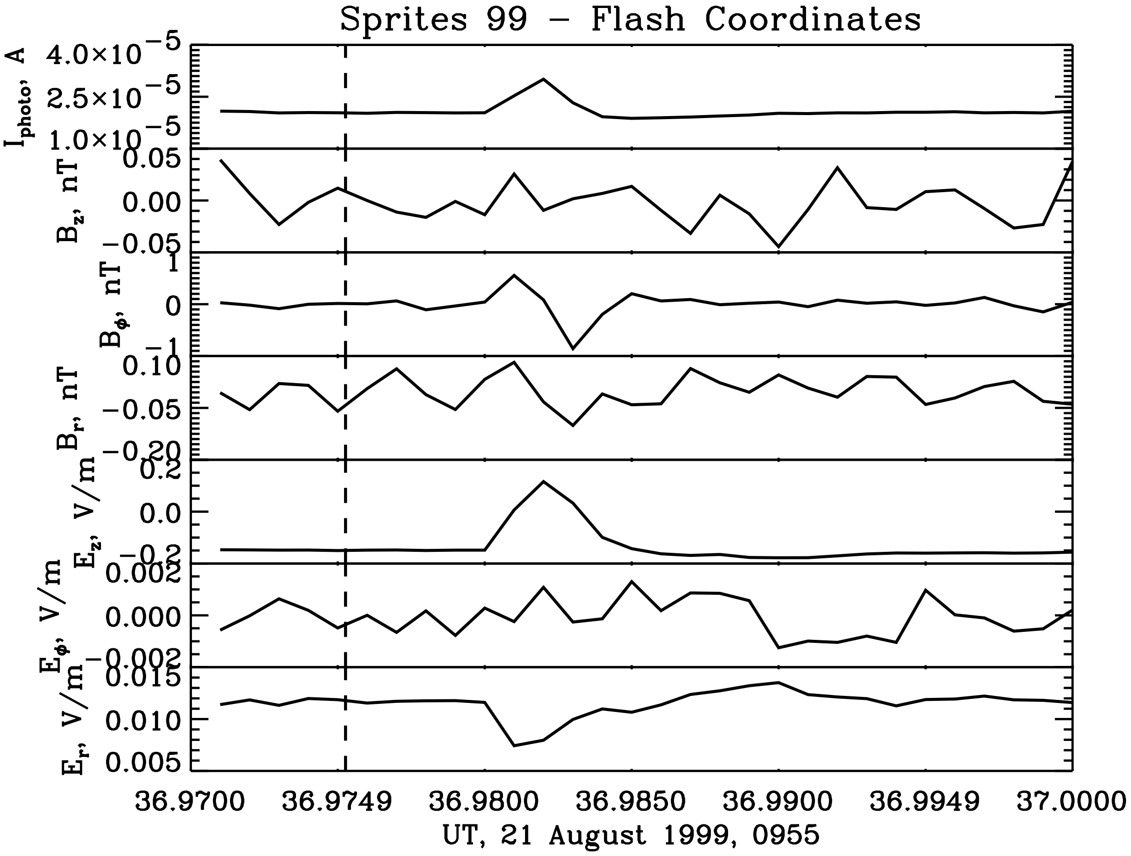

Figure 2. The 1 kHz PCM data plots show the same sprite as in Figure 1. The panels show the same data as the top seven panels of Figure 1.

during this burst. This problem does not affect any of these results. This event included an elve (bottom panel, 2nd subpanel from left). The balloon photometer data (top panel) shows a small fast spike (B) followed by the emission from the brightest interval of the sprite, also shown in the unnormalized HSI data. There was a 275 mV/m pulse in E_z (C) and a −4 mV/m pulse in E_r (D) that began about 300 μs before the main light signal was seen at the balloon and that lasted ~4 ms. The −100 mV/m DC level in E_z is a typical fair-weather signal and part of the evidence that the instruments were working normally. There was also a 1.5 ms 3 nT triangular pulse in B_ϕ (E, shaded), beginning prior to the E_z pulse.

[10] The B_ϕ pulses of interest can be seen better in the 1 kHz sample rate PCM data shown in Figure 2. The PCM magnetometer channels had a 4-pole 300 Hz low pass filter that was not used on the other channels. This filter attenuates and adds 1 ms delay to ΔB_ϕ. The other apparent differences between Figures 1 and 2 are artifacts of the differences in digitization rate. Thus, the −0.9 nT peak in ΔB_ϕ in Figure 2 was actually coincident with the peak in E_z, giving an outward Poynting flux. We only present one event here because the PCM data from the other 22 events look like this one.

6. Discussion

[11] The biggest puzzle is the magnitude and dynamics of the lightning sferic fields. The previously reported ELF pulse during the sprite (Figure 1) [*Cummer et al.*, 1998] was clearly seen in E_z. The observed E/B ratio in this pulse was ~*c*, indicating that the instruments were working, for $f < 1$ kHz. The E/B ratio of the sferic was 3 orders of magnitude smaller. Even if the electric field instrument had a bandwidth of 1 kHz, the E_z ELF pulse from the sferic should have been 2.5 V/m [*Pasko*, private communication, 2001]. It is not understood why the observed pulse was many times smaller. Furthermore, none of the 15 sprites observed in association with CG's reported by NLDN during flight 3 show any sign of a continuing current ELF signature in the PCM data during the several ms time interval between the CG stroke and the light emission. None of the spriteless halo events do either. This absence is consistent with the low sferic amplitude. The instruments were obviously working below 1 kHz and the sprite E/B ratio was apparently unattenuated, suggesting a flaw in our understanding of the physics of the upward propagation of the sferic through the conducting atmosphere.

[12] The time profiles of the photometer signal and E_z (Figure 1) imply that this pulse originated in the sprite in the mesosphere [*Cummer et al.*, 1998; *Pasko et al.*, 1998]. The E-field leads the light by about 300 μs and recovers in 2 ms. The *Pasko et al.* [1998] model has been used to interpret this event [*Pasko*, private communication, 2001]. The inputs were a 100 kA lightning current, with a linear rise time 10 μs, an exponential fall time of 10 ms and no continuing current, which removed 45 C of charge from 10 km altitude. The sprite was modeled as a cylinder having radius 50 km, lower boundary at 40 km altitude, and conductivity $3. \times 10^{-8}$ S/m, starting 4 ms after the lightning and building up to full conductivity in 4 ms. This model gives a sprite E_z pulse profile that matches Figure 1 almost exactly. The time trace of the model B_ϕ sprite pulse looks very similar to the E_z pulse, but of opposite sign. The only positive B_ϕ pulse in the model appears at the end of the sferic, 4 ms earlier than the data. The model E_r pulse must be low pass filtered with 1.5 kHz cutoff to remove the causative sferic. The resultant signature is very similar to Figure 1. In the model the charge accumulated at the bottom of the sprite was +11.25 C [see Figure 1a of *Pasko et al.*, 1998]. This charge was transferred from the ionosphere at about 90 km by a downward current of 2.8 kA with a current moment of 140 kA km. In contrast, a physically unrealistic free-space Hertzian

dipole with both radiation and near field terms requires $\sim$+8.1 C of charge at 50 km and ~ -8.1 C at 90 km to match the pulse.

[13] The ΔB_ϕ pulse in the low gain data was near the noise limit of that channel. However, the high gain PCM data pulse stands out clearly above the noise, and is seen in 20 of the observed sprite events, indicating that the event was not noise. Ampere's law suggests that the 3 nT ΔB_ϕ implies a net 5.7 kA upward current in the sprite with a vertical extent of 10's of km [*Cummer et al.*, 1998]. The delay of the start of ΔE_z relative to ΔB_ϕ implies opposite signs of the radiation (negative) and near-field contributions (positive) during the start of the pulse. This observation is hard to understand since an upward current such as this is impossible to produce in any reasonable model.

[14] The disagreements between the model above and these data are: the magnitude and time dynamics of the lightning sferic do not agree for any field components, the time dynamics of the sprite sferic do not agree for E_r and B_ϕ, the absence of a continuing current signal in E_z at 32 km altitude, the fact that ΔE_z leads the light by about 300 μs. The agreements between the model and these data are: The sprite induced E_z pulse is reproduced in terms of polarity, magnitude and time profile and the low pass filtered E_r pulse is similar to the data in these terms.

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