Sprites and halos produced by positive and negative cloud-to-ground lightning over Argentina and Brazil: Overview of video images, ELF/VLF data and meteorology

J.N. Thomas\(^{(1,2)}\), M.J. Taylor\(^{(3)}\), M. Bailey\(^{(3)}\), S.A. Cummer\(^{(4)}\), N.N. Solorzano\(^{(5)}\), F. Sao Sabbas\(^{(6)}\), P.D. Pautet\(^{(6)}\), R.H. Holzworth\(^{(1)}\), N. Jaugey\(^{(4)}\), J. Li\(^{(4)}\), M.P. McCarthy\(^{(1)}\), M. Kokorowski\(^{(1)}\), O. Pinto, Jr.\(^{(6)}\), and N.J. Schuch\(^{(7)}\)

\(^{(1)}\)Dept. of Earth and Space Sciences, University of Washington, Seattle, WA
\(^{(2)}\)Geomagnetism Program, USGS Golden, CO
\(^{(3)}\)Center for Atmospheric and Space Sciences and Physics Dept., Utah State University, Logan, UT
\(^{(4)}\)Dept. of Electrical and Computer Engineering, Duke University, Durham, NC
\(^{(5)}\)Physics Dept., Digipen Institute of Technology, Redmond, WA
\(^{(6)}\)National Institute of Space Research (INPE), Sao Jose dos Campos, SP, Brazil
\(^{(7)}\)Brazilian Southern Space Observatory, Southern Regional Space Research Center (CRSPE/INPE), Santa Maria, RS, Brazil

Support: US National Science Foundation and FAPESP, Brazil
Recent lightning ULF/ELF studies indicate high TLE occurrence over South America.

Coordinated balloon and ground-based measurements of sprite energetic over South America (PI: R. Holzworth, U. of Washington).
Ground Instrumentation

Imaging (USU):
- Two intensified Xybion CCD cameras (unfiltered)
- Field mode: 16.7 ms exposure with
- GPS timing (1ms accuracy)

ELF/VLF Sensor (Duke University):
- 1 Hz to 30 kHz Electric and Magnetic Fields
- Unambiguous polarity and direction finding
- Integrated GPS for ~20µs absolute timing

World Wide Lightning Location Network (WWLLN):
- Global network of VLF sensors (3-30 kHz)
- Detects 15-20% of all CG lightning
- Spatial accuracy of ~10 km
- Timing uncertainty < 30 µs
Feb. 22-23, 2006 Mesoscale Thunderstorm

Lightning Events on 22/02/2006, 60min prior to 17:20:00 UT

SSO
Feb.23, 2006 Mesoscale Thunderstorm
(Thomas et al., EOS Feature, March 6, 2007)

- Thunderstorm system over Argentina at a range of 500-1000 km
- TLEs were imaged for over 6 hours originating from multiple regions of the storm
- 445 TLEs (sprites, halos and a few elves) recorded (the 3rd largest Spriting storm on record)

TLEs (stars) and WWLLN (black dots) 06:15 -06:45 UT
Feb. 23 03:00 UT
Feb. 23 05:00 UT
Feb. 23 06:00 UT
Feb. 23 07:00 UT

SSO
Feb. 23 07:30 UT
Cloud-top Temps and TLES
(Solorzano et al., AGU, 2006 and Sao Sabbas et al. AGU, 2007)

Feb 23, 2006 Argentine Storm

US High Plains Steps Campaign (from Lyons et al., 2006)

Argentine and US High Plains storms similar, although higher percentage of Argentine TLEs above clouds warmer than -60 C
Most TLEs occur in regions with low to moderate rainfall, i.e. the stratiform region of the storm.
• Observed TLE rate grows with storm size until data gap in IR images
• WWLLN peaks at ~04 UT and TLEs at ~05 UT

(Solorzano et al., AGU, 2006 and Sao Sabbas et al., AGU, 2007)
March 4, 01:30 UT
March 4, 02:30 UT
500 km
SSO
March 4, 03:00 UT

This image represents a satellite view of the Earth with the following annotations:

- The coordinates of the region shown are from 25° S to 35° S, and 55° W to 65° W.
- The distance marked is 500 km.
- The term "SSO" is prominently displayed, likely indicating a specific location or event.

The colors on the map likely represent different atmospheric or geophysical data, but the specific details of the data are not provided in the image.
Example Sprite-Halo Data
(Bailey et al., AGU, 2007)

- 6 hrs of observations 23 Feb. 2006
- 121 sprite-halo events over Argentina
- A total of 182 halo and sprite-halo were observed (i.e., about 40% of total TLEs).

Typical Sprite-Halo Images 17 ms apart
Halo Analysis
(Bailey et al., AGU, 2007)

Assumed center of halo is within ~5 km of the parent lightning strike (Wescott, et al., 2001).

• Using star field to calibrate image data and obtain azimuth and elevation of halo event.
• Full account taken of refraction at low elevations.
• Map outline of each halo for various altitudes to determine best coincidence with WWLLN lightning location.
• 84 WWLLN halo events yielding a good estimate of their central altitudes and their diameters.
Halo Results
(Bailey et al., AGU, 2007)

- 84 events correlated with WWLLN located lightning:
  - mean altitude = 82.7 km (range: 78 – 91 km)
  - mean diameter = 58 km (range 31 – 93 km)
- Similar to US High Plains:
  - 4 events: height ~78 km, diameter 66 km, (Wescott et al., 2001)
  - 34 events: height ~80 km, diameter 86 km, (Miyasato et al., 2002)
Sprite-Halo/Halo Impulsive Charge Moment Changes
(Bailey et al., AGU, 2007)

• Mean impulsive (2 ms) charge moment change ~255 C-km

• Threshold appears lower than US High Plains (Cummer and Lyons, 2005) – more analysis needed
Sprite-Halo Driven by -CG
(Bailey et al., AGU, 2007)
Comparison of –CG and +CG Sprite-Halos
(Bailey et al., AGU, 2007)

-CG Frame 1

-CG Frame 2

+CG

Black line is horizon at ~60 km altitude
Events within +/- 30 min. of –CG Sprite-Halo

(Bailey et al., AGU, 2007)

Events from 05 – 06 UT

**Star**: -CG Sprite-Halo

**Open circles**: TLEs with corresponding WWLLN

**Solid circles**: TLE without corresponding WWLLN

<table>
<thead>
<tr>
<th>Time (UT)</th>
<th>TLE Type</th>
<th>Azimuth (°N)</th>
<th>Range (km)</th>
<th>Polarity</th>
<th>Impulse Charge Moment Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>05:21:59.198</td>
<td>Sprite</td>
<td>262.0</td>
<td>899</td>
<td>+ve</td>
<td>32 C. km</td>
</tr>
<tr>
<td>05:23:42.963</td>
<td>Sprite *</td>
<td>255.8</td>
<td>963</td>
<td>+ve</td>
<td>95 C. km</td>
</tr>
<tr>
<td>05:27:29.459</td>
<td>Sprite</td>
<td>258.7</td>
<td>957</td>
<td>+ve</td>
<td>-</td>
</tr>
<tr>
<td>05:28:59.969</td>
<td>Sprite-halo *</td>
<td>262.2</td>
<td>900</td>
<td>+ve</td>
<td>311 C. km</td>
</tr>
<tr>
<td>05:29:33.522</td>
<td>Sprite-halo *</td>
<td>257.9</td>
<td>944</td>
<td>-ve</td>
<td>-503 C. km</td>
</tr>
<tr>
<td>05:34:08.291</td>
<td>Sprite</td>
<td>262.7</td>
<td>882</td>
<td>+ve</td>
<td>151 C. km</td>
</tr>
<tr>
<td>05:34:08.625</td>
<td>Sprite-halo</td>
<td>260.5</td>
<td>862</td>
<td>+ve</td>
<td>383 C. km</td>
</tr>
</tbody>
</table>
ELF/VLF Waveforms

(Bailey et al., AGU, 2007)
-CG and Sprite Models

• Quasi-Static Electric Field after –CG directed upwards

• Runaway break-down model requires downward Electric Fields

From Fig. 7 Roussel-Dupre and Gurevich, JGR, 1996
-CG and Sprite Models

![Diagram showing models of lightning and sprite propagation.](image-url)
-CG and Sprite Models

![Graph showing the relationship between altitude and vertical electric field magnitude for different streamer propagation models.](image-url)
-CG and Sprite Models

![Diagram showing the relationship between altitude (km) and vertical electric field magnitude (V/m). The diagram includes curves for Conventional Breakdown, Negative Streamer Propagation (-CG downwards), Positive Streamer Propagation (+CG downwards), and $E_z$ after 500 C-km stroke. The x-axis represents the vertical electric field magnitude (V/m) ranging from $10^0$ to $10^4$, and the y-axis represents the altitude (km) ranging from 30 to 90.]

- CG streamers
- +CG streamers
-CG and Sprite Models

From Pasko et al. GRL, 2000
Conclusions

Feb. 23 MCS Storm:
- 3rd most active sprite storm reported
- Most sprites in stratiform region and above clouds warmer than -60 C

March 4 MCC Storm:
- Most sprites over clouds colder than -70 C

Sprite-Halos and Halos
- Halo altitude and diameter similar to US High Plains
- Impulsive charge moment changes appear lower than U.S. High Plains – more analysis needed
- Rare -CG sprite-halo observed, only 3rd confirmed, first time over land-based mesoscale storm