

On the association of terrestrial gamma-ray bursts with lightning and implications for sprites

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Abstract. Measurements of ELF/VLF radio spherics at Palmer Station, Antarctica, provide evidence of active thunderstorms near the inferred source regions of two different gamma-ray bursts of terrestrial origin [Fishman *et al.*, 1994]. In one case, a relatively intense spheric occurring within ± 1.5 ms of the time of the gamma-ray burst provides the first indication of a direct association of this burst with a lightning discharge. This spheric and many others launched by positive cloud-to-ground (CG) discharges and observed at Palmer during the periods studied exhibit 'slow tail' waveforms, indicative of continuing currents in the causative lightning discharges. The slow tails of these spherics are similar to those of spherics originating in positive CG discharges that are associated with sprites.

Introduction

Luminous glows above thunderclouds (termed sprites), observed from aircraft [Sentman *et al.*, 1995], from the ground [Lyons, 1994], and from the space shuttle [Boeck *et al.*, 1995]; and gamma-ray bursts of terrestrial origin [Fishman *et al.*, 1994] are new upper atmospheric phenomena uncovered in recent observations. The Burst and Transient Source Experiment (BATSE) detector on the Compton Gamma Ray Observatory (CGRO), observed relatively few gamma-ray events (~ 50 in four years) [Fishman *et al.*, 1994]. Sprites are associated with positive CG lightning [Bocippio *et al.*, 1995], but no direct evidence has yet been available of electrical activity associated with the gamma-ray events.

Spherics observed at Palmer indicate that the CGRO footprint passed near active thunderstorm centers with large, positive CGs. In one case, a lightning flash occurred within ± 1.5 ms of the terrestrial gamma-ray burst. Many other more intense spherics may have produced gamma-ray bursts, which would not have been detected due to the post-trigger 10-minute dead-time of the BATSE detector. The 'slow-tails' of these spherics, characterized by unusually high energy content below 500 Hz, are similar to those originating in large positive CGs which occur in association with sprites.

Description of Experimental Data

ELF/VLF (~ 300 Hz to 20 kHz) recordings at Palmer Station, Antarctica ($64^{\circ}46'S$, $64^{\circ}03'W$) are typically made for 6 to 9 hours per day. Simultaneous recordings of the outputs from two orthogonal [labeled North-South (N/S) and

East-West (E/W)] antennas allow the reconstruction of the arrival azimuth direction of the signals with 180° ambiguity, using wideband ELF/VLF direction finding [Burgess, 1993].

Spherics are impulsive electromagnetic signals launched into the earth-ionosphere waveguide by lightning discharges [Budden, 1961; pp. 5, 69], which can propagate with little attenuation, typically ~ 1 dB/Mm at large distances from the source [e.g., Davies, 1990; p. 389], and are thus observable at large distances (>12 Mm) from the source.

The BATSE detector on the CGRO is described elsewhere ([Fishman *et al.*, 1994] and references therein). The instrument is triggered by the detection of gamma-ray bursts of intensity above a preset threshold, and accumulates high temporal resolution data for about 10 minutes, during which time it cannot re-trigger [Fishman *et al.*, 1994]. During the subsequent read-out time (~ 90 min) the instrument can only re-trigger on a more intense event. The source direction of the bursts can be estimated (rather imprecisely due to the penetrating nature of the photons) by comparing the responses of the eight BATSE detectors.

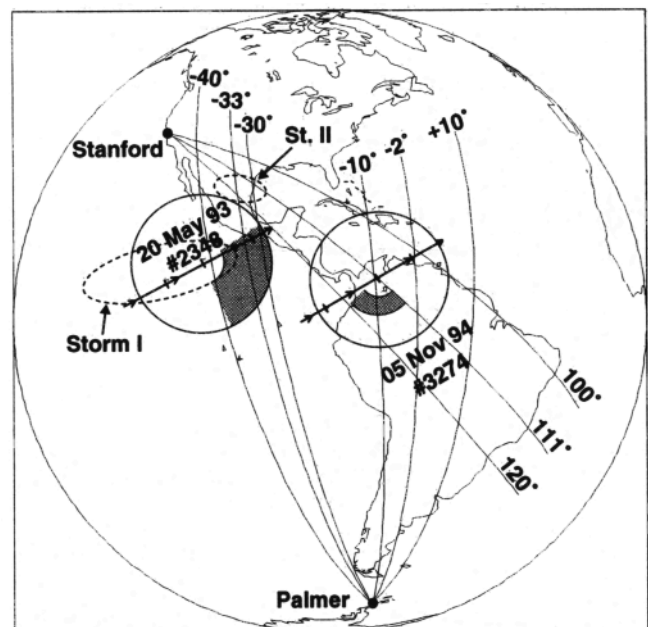


Figure 1. The orbital track and the horizon circle of the CGRO during Bursts 2348 and 3274. The shaded regions are the inferred (based on BATSE data) source locations. The dotted ovals show the locations of two separate storms on 20 May 93 (Figure 3). The lines originating at Palmer (and at Stanford for 3274) are the arrival azimuth bearings, with the central lines indicating the azimuth of the peak activity (Figure 3).

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Observations

Of the ~ 50 terrestrial gamma-ray bursts observed on the CGRO, Palmer ELF/VLF data were available for four bursts identified as 1915, 2340, 2348, and 3274. In two cases (1915 and 2340), data were inconclusive as to the detection of thunderstorm activity because the paths from the CGRO footprints to Palmer cross the polar cap, with consequent high losses due to the ice-sheet and intense electron precipitation in the auroral regions [e.g., *Westerlund and Reder, 1973*]. The sferics data for the two bursts 2348 and 3274 (Figure 1), with closer source locations (~ 8700 km and ~ 7700 km), are presented below as cases A and B.

Case A: Gamma-Ray Burst 2348

Dynamic spectra of sferics observed at Palmer during a 2-sec period centered at the time of Burst 2348 are shown in Figure 2, indicating many sferics arriving from the northwest, consistent with the azimuth bearing from Palmer of the CGRO (see Figure 1). The onset of sferic AE (Figure 5) was observed at $0202:17.680 \pm 0.001$ UT, while Burst 2348 was recorded by BATSE at $0202:17.655$ UT. Assuming the sferic source to be at point P in Figure 4, a propagation delay to Palmer of 29.2 ms places the causative lightning of sferic AE to be $0202:17.6508 \pm 0.001$ UT. Assuming Burst 2348 to be generated at 50 km altitude, the 2.8 ms speed-of-light delay from point P to CGRO (at 500-km altitude) indicates that the peak of Burst 2348 occurred 1.4 ± 1 ms after the onset of sferic AE. Considering that sferics of intensity greater than or equal to that of AE occurred at a rate of $\sim 4 \text{ min}^{-1}$ during this period (see Table 1 and the bottom panel of Figure 3),

the probability of chance occurrence of such a sferic in any given 1 ms interval is 10^{-5} , suggesting that Burst 2348 was generated by the energy released in the lightning discharge that launched sferic AE.

The occurrence peak in Figure 3 between -40° and -30° (cf. Figure 1) shows the extent of thunderstorm activity near the footprint of CGRO. Based on the GOES-7 infrared image shown in Figure 3a of *Fishman et al. [1994]*, this arrival azimuth range is consistent with the coldest cloud tops measured above Storm I in the CGRO region as well as Storm II over the western shore of the Gulf of Mexico, both of which might have produced sferics.

The magnitude axis in Figure 3 represents the time-average intensity of sferics over a 10-ms duration, starting 1 ms before the onset (see Figure 5). Characteristics of the 10 strongest sferics between 0150 and 0220 UT and the three sferics nearest the gamma-ray burst time are in Table 1. Nine of these sferics (A1, A3, A4, A5, A7, A9, AE-2, AE-1 and AE) have azimuths in the range -39° to -36° , placing them clearly in the CGRO storm (I) instead of the Gulf storm (II). Sferics A1 and AE are marked in Figure 2. A1, which occurs 145 ms after Burst 2348, is by far the strongest sferic measured during this 30-min period, while AE ranks between 80th and 85th (see Figure 3, bottom panel).

Since the sferic due to a CG discharge is an electromagnetic pulse radiated by the return stroke current, the onset of its waveform at a distant receiver either initially increases or decreases depending on the polarity of the return stroke current. With the system polarity unambiguously resolved via comparison with National Lightning Detection Network (NLDN) data, most of the sferics in Table 1 were determined to be produced by *positive* discharges; this determi-

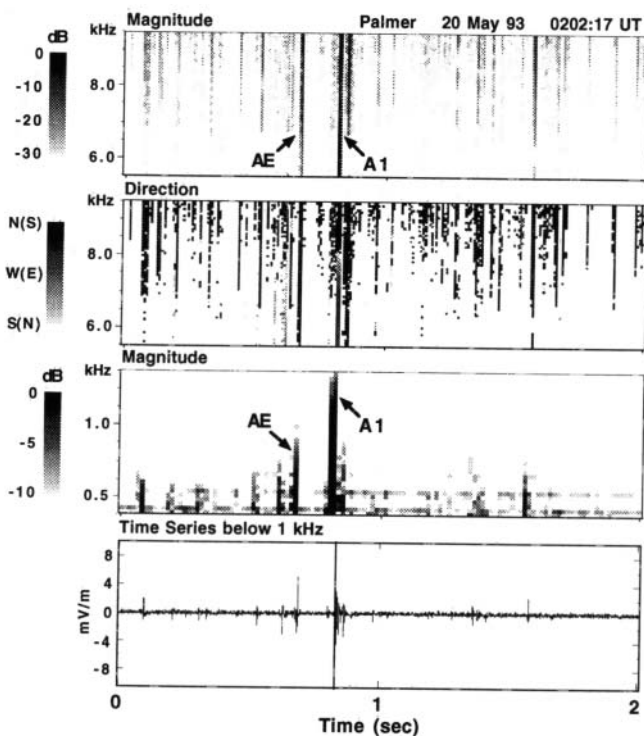


Figure 2. The first and third panels show frequency-time spectrograms, of VLF and ELF bands respectively, of sferics observed at Palmer. Two sferics marked AE and A1 are discussed in the text. AE is the 'event' sferic, launched by the lightning discharge which led to Burst 2348. The second panel indicates the arrival azimuth of the sferics. The bottom panel shows the time-series waveform of the lowpass filtered (<1 kHz) data.

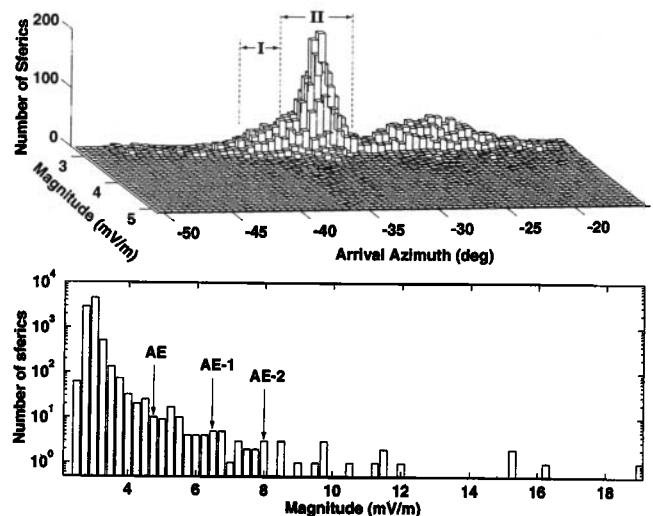


Figure 3. Intensity and arrival azimuth distribution of sferics observed at Palmer in the arrival azimuth range from -50° to -15° during the 30-minute period 0150-0220 UT on 20 May 1993. Arrival azimuth is in degrees clockwise from north, with west denoted as -90° and east as $+90^\circ$. The sferics were detected (as having peak intensity above a set threshold) and their arrival bearings were measured on the basis of their energy in the 5.5 to 9.5 kHz range. The sferic magnitudes are the time-average intensities as defined in the text. The dashed lines denote the azimuth ranges of the coldest cloud tops of the storm in the CGRO region (I) and of the Gulf coast storm (II) (dotted ovals in Figures 1 and 4), derived from the GOES-7 infrared image for the same time period (shown in Figure 3a of *Fishman et al. [1994]*). The bottom panel shows a magnitude histogram.

Table 1. Characteristics of Selected Sferics

Label	Time (UT)	Magnitude (mV/m)	Azimuth (deg)	Polarity
A1	0202:17.825	26.78	-35.7	positive
A2	0219:51.110	22.32	-14.8	positive
A3	0201:05.366	19.26	-36	positive
A4	0211:41.708	15.26	-38.8	positive
A5	0152:10.865	15.10	-35.8	positive
A6	0159:59.365	13.51	-54.9	positive
A7	0158:53.965	12.97	-35.8	negative
A8	0219:51.383	11.11	-16.3	positive
A9	0200:54.702	11.07	-35.8	positive
A10	0217:21.283	11.07	-28.3	positive
AE-2	0201:43.779	7.97	-35.8	positive
AE-1	0201:46.973	6.44	-39.7	uncertain
AE	0202:17.680	4.72	-35.7	positive

nation presumes CG lightning discharges, consistent with large continuing currents [Brook et al., 1982].

Figure 4 shows the passage of the CGRO over this storm. Sferics A1 and A3 are the two sferics of the top ten (Table 1) nearest in time to Burst 2348, whereas AE-2 and AE-1 are the only two of greater intensity than the event sferic (AE) which occur between A3 and AE. The arrival bearings in Figures 1, 2 and 4 show consistency with the inferred source location of Burst 2348 (i.e., the shaded region). As the CGRO approached the 'source' region, sferic A3 occurred at 0201:05.366 UT within $\pm 2^\circ$ of the corresponding azimuth line in Figure 4. Although this sferic was very intense, no gamma rays were detected on CGRO, possibly because the source was beyond the horizon circle. It is also possible that the particular lightning flash that led to A3 did not produce a gamma-ray burst, or that the gamma rays were beamed. The same circumstance was probably in effect for the weaker sferics AE-2 and AE-1. Once BATSE was triggered by Burst 2348 associated with sferic AE, it

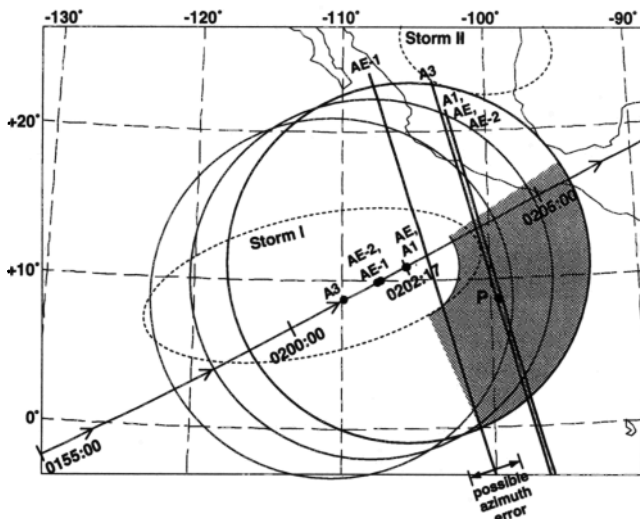


Figure 4. The encounter of CGRO with the thunderstorm center on 20 May 1993 (Case A). The solid circles on the CGRO track indicate the time of occurrence of indicated sferics, while the arrival bearings of these sferics are indicated as lines emerging from Palmer (see Figure 1). The horizon circles of CGRO, ~ 2500 km in diameter, at the time of occurrence of the sferics are also indicated. The shaded region and the dotted ovals are the same as those shown in Figure 1.

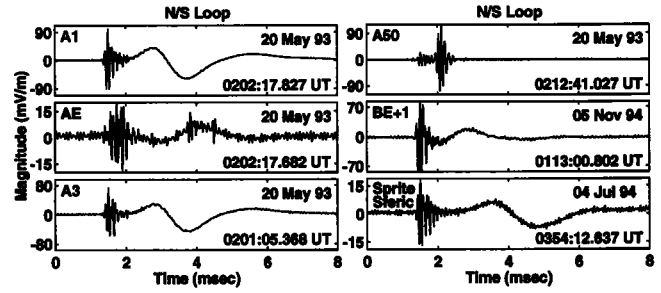


Figure 5. The waveforms of selected sferics observed at Palmer on 20 May 1993 (Case A) and on 5 November 1994 (Case B). The bottom right panel shows a sferic observed at Palmer on 4 July 1994, launched by an intense positive CG lightning discharge which occurred in the midwestern United States, and which was associated with a sprite [Sentman et al., 1995].

could not detect any gamma-ray burst associated with the 'most intense' sferic A1, occurring 145 ms later.

The waveforms of the 'event' sferic AE and sferics A1 and A3 (Figure 5) exhibit a so-called 'slow tail', consisting of an ELF asymmetric bipolar pulse, following the initial oscillating VLF portion [Hepburn, 1957; Sukhorukov 1992, and references therein]. The slow tail is a manifestation of the relatively small attenuation for the zeroth-order waveguide mode, and theoretical calculations show that it is excited at significant levels by source lightning discharges with a slowly varying and lingering continuing-current component [Wait, 1960]. Therefore, the lightning discharge which generated the sferic AE may have had a continuing-current component contributing to the triggering of Burst 2348. Some other intense sferics from the same storm also had slow tails, and may have led to other gamma-ray bursts. Many other sferics with high peak intensity but with no detectable slow tail (e.g., sferic A50 in Figure 5) were observed with arrival bearings consistent with storm I in Figure 3. Note that the time-average intensity measure used here is well suited to the assessment of the slow tail intensity; therefore most of the 80-90 sferics more intense than AE (Figure 3 bottom panel) are likely to have had slow tails.

The slow tail of sferic AE may also be evidence of a possible connection between gamma-ray bursts and sprites. Sferic waveforms of positive CGs associated with sprites ex-

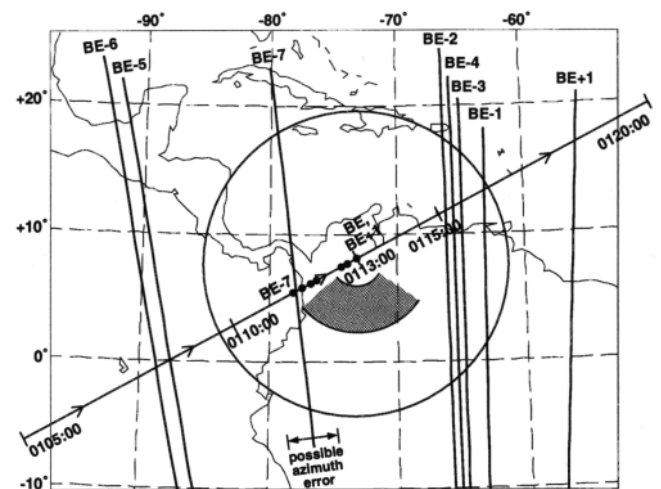


Figure 6. The encounter of CGRO with the thunderstorm activity on 5 November 1994. The format is identical to that of Figure 4.

hibit unusually intense slow-tail components [Reising et al., 1995]. An example is shown in Figure 5; the 133-kA positive CG lightning which produced this sferic was associated with sprites (Figure 1 of Sentman et al. [1995]).

Case B: Gamma-Ray Burst 3274

On 5 November 1994 ELF/VLF data were recorded at Stanford and at Palmer (Figure 1). The relatively noisy Stanford data was not useful for measurements at low frequencies (<5 kHz), and were used only on a statistical basis. Both sferics data and infrared cloud-top image data indicate a distributed set of storms at this time, which were either more active or closer in distance to Palmer than the storm near the CGRO footprint. Many sferics observed at Palmer near the time of Burst 3274 originated in other storms.

The occurrence time and arrival azimuth of some sferics more intense than AE are illustrated in Figure 6, including one (marked BE+1 and also shown in Figure 5) which occurred ~60 ms after Burst 3274, accounting for travel times as in Case A. A sferic (BE) too weak for azimuth determination did occur within ± 1 ms of Burst 3274. However, the rate of occurrence of such weak sferics was ~20 per second. The references to various sferics in Figure 6 as BE-2, BE-1, etc. are based on their occurrence time with respect to BE.

If the production of gamma-ray bursts preferentially occurs in the identified source region of Burst 3274 (shaded region in Figure 6), due for example to particular thundercloud charge distributions, the fact that BATSE did not trigger on most of these earlier sferics (BE-7, -6, ..., -1) is consistent with their arrival bearings, placing them outside this source region. The arrival azimuth of BE-7 is closer to the source region; however, even if BE-7 led to gamma ray production, the lightning discharge could have been north or south of the region or the satellite may have been outside the gamma-ray 'beam'. It is possible that the gamma-ray burst was produced prior to a lightning discharge (e.g., the one which launched BE+1 ~60 ms later); another energetic upper atmospheric phenomenon, the so-called Blue Jets, is believed to occur without associated lightning discharges [Wescott et al., 1995; Pasko et al., 1996].

Summary and Discussion

We have presented evidence, in two different cases, of the association of terrestrial gamma-ray bursts with electrically active thunderstorms. Both of the thunderstorms produced many intense, positive CG discharges, one of which, observed on 20 May 1993, was clearly associated with Burst 2348, providing the first direct evidence that at least some of the terrestrial gamma-ray bursts are associated with lightning. The occurrence of this sferic 1.4 ± 1 ms earlier than the peak of Burst 2348 is consistent with the process of runaway acceleration of energetic electrons by intense quasi-electrostatic fields which immediately follow lightning discharges [Gurevich et al., 1992; Bell et al., 1995].

Many of the positive CG lightning discharges surrounding the gamma-ray events exhibited intense slow tails, consistent with continuing currents that follow the initial impulsive charge transfers in the corresponding lightning discharges. The slow-tail waveforms of these sferics were similar to those of sferics associated with sprites. This connection provides the first evidence that sprites and terrestrial gamma-ray bursts may be different manifestations of the same physical process, most likely involving the runaway acceleration of energetic electrons [Bell et al., 1995].

Burst 3274 was not accompanied by a strong CG lightning discharge, since the sferic from any significant discharge would have been detected at Palmer. This experimental fact may indicate that terrestrial gamma-ray bursts may occur prior to lightning discharges, consistent with the fact that the runaway breakdown thresholds can be exceeded during the thundercloud charge accumulation phase, as may be the case for Blue Jets [Pasko et al., 1996].

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