Ground Level observation of Gamma-ray Showers in Coincidence With Downward Lightning Leaders

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Terrestrial gamma-ray flashes (TGFs) are bursts of gamma-rays initiated in the Earth's atmosphere. TGFs were serendipitously first observed over twenty years ago by the BATSE gamma ray satellite experiment. Since then, several satellite experiments have shown that TGFs are produced in the upward negative breakdown stage at the beginning of intracloud lightning discharges. In this proceeding, we present the ground-based first observation that TGFs are also produced by the downward negative breakdown occurring at the beginning of negative cloud-to-ground flashes.

The TASD detector is a 700 km^2 detector in the southwestern desert of Utah, an area hundreds of times larger than other ground-based detectors of lightning-associated events, making it the largest such detector to date. It is comprised of 507 (3 m^2) plastic scintillator detectors on a 1.2 km square grid. The LMA stations are colocated within and around the array, and the slow electric field antenna is located close to the center of the TASD detector. The data discussed in this work was collected by this suite of instruments between 2014 and 2016. Gamma ray showers were observed in the first 1-2 ms of downward negative breakdown prior to cloud-to-ground lightning strikes. The shower sources were observed by the LMA detector at an altitude of a few kilometers or less above ground level. The detected energetic burst showers have a footprint on the ground typically $\sim$ 3–5 km in diameter. The duration of the bursts are of the order of several hundred microseconds. GEANT simulation studies indicate that the showers are consistent with a forward-beamed primary gamma rays of $10^{12} - 10^{14}$ primary photons. This result may provide a new insight into the understanding of the TGF phenomenon.

I. INTRODUCTION

Terrestrial gamma-ray flashes (TGFs) are bursts of gamma-rays initiated in the Earth's atmosphere. The first detection of TGFs was reported in 1994 by the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory satellite [1, 2]. Since then, several observations have shown that satellite-detected TGFs are associated with lightning flashes. In a normal polarity thunderstorm, a high-level intra-cloud lightning flash begins with a negative leader propagating upward from the mid-level negative charge region towards the upper positive charge region [3–7]. If upward-propagating negative leaders produce TGFs beamed upward to satellite detectors, then a downward-propagating negative leaders might also produce TGFs which are beamed downward.

Several bursts were observed by the Telescope Array (TA), an Ultra High Energy Cosmic Rays (UHECRs) detector, between 2008 and 2013 [8]. The bursts triggered the detector with a rate much higher than that expected by an accidental coincidence of UHECRs. These bursts were found to correlate with local lightning activity. A Lightning Mapping Array (LMA) and Slow electric field Antenna (SA) were installed at the TA site in order to study the effect.

In this proceeding, we report on the first joint observations with the TA/LMA instruments. Ten downward propagating gamma-ray particle showers were observed. Each of the gamma-ray events was detected during the downward initial negative breakdown at the beginning of low-altitude intracloud flashes. In each case the parent flash was a –CG discharge and the burst occurred within the first or second millisecond of the flash. Such breakdown maybe the downward analog the TGF phenomenon observed by satellite borne experiments.

II. LIGHTNING DETECTION AT TA

The TA detector is the largest UHECRs in the northern hemisphere. It is located in Millard County, Utah and is composed of 507 scintillator detectors on a 1.2 km square grid covering 700 km^2 Surface Detector (SD) array [9]. The Telescope Array Surface Detector (TASD), has an approximately 100% duty cycle, and provides shower footprint information including core location, lateral density profile, and timing.

Each SD unit consists of upper and lower scintillator planes, each plane is 3 m^2 in area by 1 cm thick. The upper and lower planes are separated by a 1 mm thick steel plate, and are read out by individual photomultiplier tubes (PMTs) which are coupled to the scintillator via an array of wavelength-shifting fibers. The scintillator, fibers and photomultipliers are contained in a light-tight and electrically grounded stainless steel box (1.5 mm thick on top and 1.2 mm thick on the bottom) under an additional 1.2 mm iron roof providing protection from extreme temperature variations [9].

The TASD event trigger is recorded when three adjacent SDs observe a time-integrated signal greater than 3 Vertical Equivalent Muon (VEM) within 8 μs. When a trigger occurs, the signals from all the SDs within $\pm$ 32 μs detecting an integrated amplitude greater than 0.3 VEM are also recorded. The VEM is a unit of energy deposit, equivalent to the energy deposited in a single TASD scintillator plane by a vertical relativistic muon. In more conventional units a VEM is about 2 MeV per scintillator plane, roughly 30 ADC counts above background. The abundance of penetrating cosmic-ray induced muons in the Earth's atmosphere makes the VEM a convenient standard for scintillation detectors.

In 2013 the Lightning Mapping Array (LMA) was deployed and running at the Telescope Array site. LMA was developed at the Langmuir Laboratory for Atmospheric Research [10, 11]. LMA is an ideal instrument for studying electrical discharges in the Earth's atmosphere. Nine LMA detectors were deployed throughout the TA detector. The Langmuir LMA utilizes low-VHF (60-66 MHz) radio emissions in order to create 3-dimensional reconstruction of a lightning flash. It is most sensitive when deployed in radio-quiet, rural areas like the southwestern desert of the State of Utah. Each LMA detector records time and amplitude of impulses above trigger threshold. A fit is performed on the GPS-timed arrival of these impulses in order to determine the position and time of each unique LMA source. Six or more detectors are required to determine the location and time of the source events.

In 2014, a slow antenna [12] was also deployed at the Telescope Array site in order to measure changes in the ambient electric field. The slow antenna is located in the center of the TASD. It consists of a flat metal plate centered in a grounded metal bowl and records voltage proportional to the electric field at the surface of the plate. The slow antenna has a low-frequency time constant of 10 seconds, and an upper frequency response of 25 kHz. The nominal sensitivity of the sensors allows us to accurately measure field changes in the range of 10 mV/m to 10 kV/m.

The TASD covers an area hundreds of times larger than other ground-based detectors of lightning-associated events, making it the largest such detector to date. The addition of an LMA network and ΔE observations to the TASD provides us with a unique suite of instruments for studying the TGF phenomena from the ground.

III. OBSERVATIONS

Following Okuda *et. al.* [8]. In this study we searched for candidate lightning events in the TASD dataset by identifying instances in which "bursts" of consecutive TASD triggers were recorded in 1 ms time intervals. Since the TASD mean trigger rate is less than 0.01 Hz, it is extremely unlikely that such a burst could be caused by accidental coincidence of high-energy cosmic rays. We report here on ten such bursts. Three bursts were found to be correlated with LMA while seven were found to be correlated with the slow antenna detector.

A typical trigger burst event waveform recorded by a SD together with the corresponding TASD footprint ($\sim$ 3–5 km in diameter) is shown in Figure 1. Each circle in the TASD footprint is a triggered SD with a color related to its relative arrival time. The size of the circle is proportional to the logarithm of the energy deposited in the SD. The number on each circle is the integrated area under the photomultiplier waveform VEM (one VEM corresponds to ≈ 2 MeV). The LMA and the the Vaisala National Lightning Detector Network (NLDN) source events are indicated by stars and diamonds respectively.

Typically the bursts occurred during the first 1–2 ms of the discharges and have overall durations between 87 and 551 μsec. With the high-resolution timing of the TASD, the bursts are found to consist of several (2–5) individual components, each of which are a few microseconds in duration, separated in time by $\simeq$10-250 μs between events.

A. LMA-Correlated TASD Bursts

The three flashes observed in correlation with LMA are shown in Figure 2. Figure 2 shows the TASD and the NLDN trigger time relative to the LMA source heights versus time. In each case the TASD triggers (dashed red lines) occurred within the first 1-2 ms of the flash, as the initial negative breakdown descended toward and into the lower positive charge region.

Flashes FL1 and FL2 occurred in different storms on 15 Sept 2015. In both cases, the LMA observations show that the heights of the TASD trigger events can be estimated quantitatively by averaging the altitudes of the the LMA events leading up to the triggers. The average initial activity was at 4.4 km and 3.0 km Above Ground Level (AGL) for the first and the second flash consecutively. After the first ms of the first LMA source observation the TASD was triggered, the flashes spent 200 and 300 ms discharging the large regions of lower positive charge before producing negative strokes to ground.

Flash FL3 occurred on 10 May 2016. It was unusual in that its initial leader went directly to ground at a high speed, reaching ground 2.6 ms after flash initiation. Assuming the leader was initiated at 3.5 km AGL altitude, its average 1-D propagation speed to ground was 1.4×10^6 m/s. The first TASD trigger occurred 2.1 ms after the flash initiation. The return stroke happened 26 μs after the last TASD trigger (with a peak current of -94 kA). From this, we can deduce that the first TASD trigger occurred when the leader was $\simeq$640 m AGL.

Note that while FL3 leader source was closer than FL1 and FL2, the TASD trigger has similar-size footprints on the ground and similar time duration to the first two flashes.

B. SA-Correlated TASD Bursts

The seven flashes observed in correlation with the slow antenna occurred in three different days in the 2014 storm season. As seen for flashes FL1 and FL2 of the LMA correlations, the TASD trigger bursts occurred in

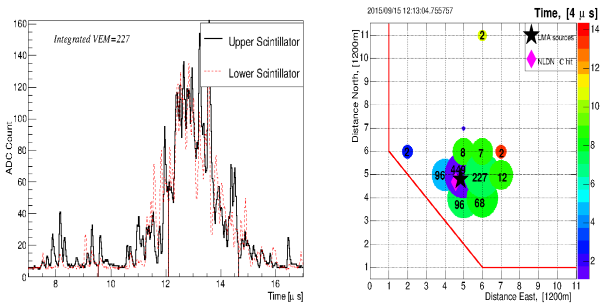

FIG. 1. *Left:* Upper and lower scintillator waveforms in a single surface detector unit, for the second trigger in the LMA-correlated TASD burst observed at 12:13:04 on 15 Sept. 2015. *Right:* Footprint of TASD hits for all detectors units involved in the second trigger of the burst, with the numbers indicating the Vertical Equivalent Muon (VEM) counts, and the color indicating the relative arrival times. Initial LMA and NLDN events are indicated by stars and diamonds respectively. The red line indicates the southwestern boundary of the TASD array.

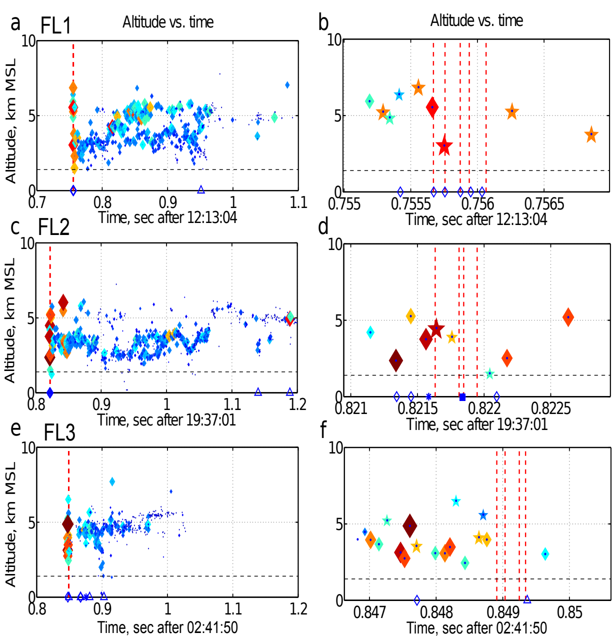

FIG. 2. Observations of the LMA-correlated TASD bursts, showing altitude versus time plots of the LMA sources (colored diamonds) and the TASD trigger times (red dashed lines). The left panels show the complete flashes and the right panels show zoomed-in views during the first 2–3 ms of each flash. The LMA sources are colored and sized by the log of their radiated power randing from –20 dBW (10 mW; blue colors) up to +25 dBW (320 W; red colors). NLDN events are shown in the blue empty symbols on the abscissa. The mean altitude of the Telescope Array was ∼1.4 km above Mean Sea Level (MSL) (horizontal dashed line).

the first millisecond of the flash for each of the seven events. Although the SA observations do not locate the flashes, the cores of the energetic showers were directly below the NLDN sources. In addition, the SA leader field changes are the same polarity as the ensuing return strokes, namely negative, consistent with downward negative leader breakdown for flashes beyond the reversal distance. Moreover, even though there is no direct altitude data. The SA-correlated TASD bursts were found to be consistent with those observed in correlation with LMA in terms of timing, duration, and footprint size. It is therefore reasonable to assume that the SA-observed TGF events have similar source altitudes as for the flashes observed with the LMA.

IV. EVENT SIMULATION

The principal question is whether the observed showers are indeed comprised substantially of gamma-rays — usually defined as having energies greater than 100 keV — or whether the predominant source of energy deposit in the TASD is due to lower-energy x-rays.

A simple argument can be made on the basis of the effects of attenuation and scattering in the atmosphere above the TASD. The absorption length of photons in the atmosphere plateaus above 100 keV to about 100 m at TA altitudes [13]. Because the leaders associated with the TASD occur at up to 4 km above ground level and leave footprints on the ground of a few kilometers in size, we can expect that substantial attenuation of lower-energy photons will occur in the atmospheric above the detector.

In order to be more quantitative, we performed a GEANT4 simulation [14] incorporating a model of the atmosphere as well as the TASD [15]. We varied the energy and altitude of the primary photons, and recorded the total energy deposited in the TASD.

The results of this simulation are summarized in Figure 3, showing the mean TASD energy deposit versus altitude for various primary photon energies. The effect of decreasing photon attenuation in the x-ray to gamma-ray transition range is significant: At an altitude of 1 km AGL, the mean energy deposited by a 1 MeV photon is a factor of five orders of magnitude greater than that of a 100 keV photon. For reasonable energy spectra [16] the corresponding decrease in flux is far less, only one or two orders of magnitude. Thus from the GEANT4 simulation the TASD signal is due to primary photons with energy of order 1 MeV or greater.

The sources number of primary photons were also estimated. The number of primary photons are highly dependent on the simulation variables such as the productions altitude and the openning angle of the cone. With the TASD we have the unique opportunity to use for the first time the full footprint size of the shower (∼ 3–5 km in diameter) information in the simulation. This together with knowing the sources heights and the fact that the LMA and the NLDN sources were also found to be directly above the TASD bursts, we conclude that the observed showers are forward beamed within a cone of approximately half-angle 16°. The angular distribution of particles is assumed to be isotropic within that cone. Showers are simulated using GEANT4 simulation following the RREA spectrum [17, 18] and are then tracked through the atmosphere and the TASD detector model. The observations were found to be consistent with fluence of $\simeq 10^{12}$-10^{14} photons.

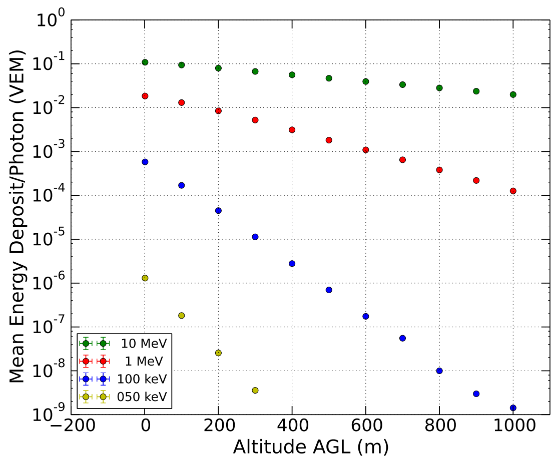

FIG. 3. Mean energy deposit (average of two TASD planes) per primary photon, versus altitude AGL for various photon energies.

V. SUMMARY

Over a two-year period between 2014 and 2016, a total of ten TGF bursts were identified for which 3-D LMA or ΔE lightning measurements were available. In each case:

- The parent flash was a –CG discharge and the burst occurred within the first or second millisecond of a downward negative leader activity.
- The burst durations were found to be with several hundred microseconds, with sub showers of few to few tens of microseconds.
- The sources altitude were typically of a few kms or less above ground level.
- The showers were forward beamed with footprints of 3-5 kms in diameter.

From simulation, we conclude that the observed TASD bursts are due to primary gamma-ray showers. Moreover, the observed energy deposit of the shower found to be consistent with fluence of $\simeq 10^{12}$-10^{14} photons.

The observed bursts are consistent with TGFs produced by the initial burst of negative downward lightning leaders. This is the downward analog of the satellite-born observed TGFs found to be produced by upward negative breakdown at the beginning of intracloud discharges.

Currently, both the LMA network and slow antenna electric field change instrument remain deployed at the Telescope Array site. An expansion by a factor of four in the coverage area of TASD is planned within the next several years. A plan is also in place to deploy additional slow as well as fast electric field sensors. This will enable us to study the relation between SD observations and the development of negative breakdown in greater detail.

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