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Burst of high energy radiation from lightning discharge, observed by Telescope Array

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***Abstract*—The Telescope Array (TA) Surface particle Detector (TASD) has observed short time bursts of air-shower like events. We checked the correlation for time and position between these burst events and lightning data, and found evident correlation. Some features of the burst events are similar to the normal cosmic ray air-shower, and some are not. We report on the observed bursts of air-shower like events and their correlation with lightning.**

Keywords—Air Shower, High Energy Radiation, TGF, NLDN

I. INTRODUCTION

There are some reports about the observation of energetic radiation from thunderclouds. Some of these reports discuss bursts of energetic radiation observed from space, known as Terrestrial Gamma-ray Flashes [Fishman et al., 1994][Briggs et al., 2010]. Their mechanism is still unknown, but they are believed to be associated with upward lightning flashes at the top of thunderclouds. Other reports discuss the increase of arrival rates of single radiation along with thundercloud at ground. Finally, observations of energetic radiation have been associated with particular lightning processes in the flash.

The natural lightning flash consists of several processes, known as the stepped leader, return stroke, dart leader and subsequent return stroke. The leader direction may be up or down and of positive or negative polarity, hence there are four types of lightning. However, except for lightning strikes on tall objects, most lightning starts with negative charges moving downward. Moore, et al. [2001] reported the observation of energetic radiation from stepped leaders, using NaI as a radiation detector. Dwyer, et al. [2003] reported the observation of energetic radiation from dart leader also using NaI as a radiation detector, for rocket triggered lightings. Dwyer, et al. [2005] reported the observation of energetic radiation from stepped leaders, and Dwyer, et al. [2012] reported radiation associated with the return stroke, for natural cloud-to-ground lightning. The electric fields present in a typical thunderstorm are not sufficient to start the stepped leader process, the beginning of lightning. Therefore, it has been hypothesized that the atmospheric ionization caused by cosmic ray air-showers plays a role in triggering lightning. From this side, there are some reports about energetic radiation with lightning. Gurevich, et al. [2009] reported the coincidence of air-showers with lightning, using NaI and gas-counter as radiation detectors.

The detectors used in these prior observations were mainly NaI, and sometimes gas-counters. TASD uses plastic scintillator of 3 m^2 area, which is approximately 300 times the area of the NaI detectors but cannot measure the energy of individual particles. TASD responds 10 times faster than NaI detectors. Prior particle detectors were deployed over several square kilometers. TASD coverage is about 300 times larger, although it is inefficient for small air-showers due to the lower number density of the detectors.

II. OBSERVED BURST EVENTS

The Telescope Array (TA) experiment, located in Midwest Utah, USA, consists of two types of detector (Figure 1). Both detection methods observe the high energy phenomena known as "air-showers", which are generated by ultra-high energy cosmic rays. One type of TA instrument is the atmospheric fluorescence telescope, and the other is an array of ground surface particle detectors. In contrast to the atmospheric fluorescence which is observable only on moonless nights, the TA Surface Detector (TASD) runs 24 hours per day, throughout the year. TASD consists of 507 individual particle detectors. The particle-sensitive part of a TASD detector element is shown in Figure 1. The TASD elements are deployed on a 1.2 km square grid, covering a total of 680 km^2. When three adjacent elements detect a signal corresponding to three or more particles within an 8 μs window, waveforms of all detectors within ±32 μs are recorded [AbuZayyad et al., 2012]. TASD is designed to detect all air showers from cosmic rays with energy greater than 10 EeV (= 10^{19} eV). TASD data used for this report was collected between May 11, 2008 and May 4, 2013.

We searched for bursts of air-shower events. The criteria used in this burst search was more than three events within 1 ms. 10 such bursts were found. The expectation for such bursts due to chance coincidence of single shower events is less than 10^{-4} for a five-year observation period. In addition, although bursts were not selected by position, the shower cores of each burst are found to be localized within a 1 km radius. Considering the event which could not generate shower trigger but are found in waveforms, the time gaps of events in a burst are distributed from several to a hundred microseconds. Five of the ten bursts contained air-showers which are reconstructible by minor modification to the cosmic ray air-shower reconstruction programs, in which unreconstructible early waveforms are artificially removed. In this reconstruction, the air-shower front is modeled as a sphere expanding at the speed of light from a single point in the sky, and the altitude of this point is a parameter of a fit to the shower. The reconstructed air-shower front curvature is much greater for the burst events than for usual cosmic ray air-showers. Therefore, the altitudes of the reconstructed shower origin for the burst events are at an atmospheric depth much deeper than those of usual cosmic ray air-showers. In addition, the reconstructed air-shower directions for each burst tend to point small region at low sky. The waveforms captured in the nearest shower core scintillator detectors do not have a sharp rising edge for many of the burst events, and in this aspects the waveforms are in contrast to those of normal cosmic ray air-showers. However, time-integrated energy deposit in the TASD scintillators is similar to that of cosmic ray air showers.

III. CORRELATION WITH LIGHTNING

We checked these bursts for correlation with the Vaisala lightning database. This database comes from the U.S. National Lightning Detection Network (NLDN). The NLDN detects lightning by multi-position very low-frequency antennas, and derives lightning information by radio arrival timing and waveform [Cummins and Murphy, 2009][Nag et al., 2011]. This lightning data list contains time, position, peak current and a C/G flag indicating whether the lightning is intracloud or cloud-to-ground lightning. NLDN is somewhat inefficient for intracloud lightning.

The lightning list used in this report was selected by position within 15 miles from the center of the TA site which covers the whole TASD area, and also by time between May 2008 and April 2013. 79% of the listed lightning is flagged as cloud-to-ground lightning. 85% of the listed lightning has negative peak current. The location and peak current distribution of lightning on the list is shown in Figure 2.

We checked the correlation between the five reconstructed bursts and lightning by timing. We categorize this search by two types of correlation, which we call “synchronized” and “related”. The result is shown in Table 1.

The criteria distinguishing those events which are “synchronized” with lightning is that the time difference between burst and lightning is less than 1 ms. Four of the five reconstructed bursts have synchronized lightning. Although no requirement is placed on position, all synchronized lightning is located in the vicinity of burst air-shower events. All synchronized lightning is flagged by NLDN as intracloud lightning having negative peak current. Considering the intracloud lightning detection efficiency of the NLDN, the observed air-shower bursts and lightning are well-synchronized. The criteria distinguishing events which are “related” to lightning is that the time difference between burst and lightning is less than 200 ms, excluding synchronized events. Three bursts in the four above have related lightning. There is no selection by position, but all related lightning is in the vicinity of burst air-shower events. All related lightning is flagged by NLDN as cloud-to-ground lightning and negative peak current. These related lightning strikes are subsequent components of the synchronized lightning events.

Our check of correlation between shower bursts and lightning shows that the observed bursts are clearly synchronized with negative intracloud lightning. The absolute peak current of the synchronized lightning is extremely high compared with other NLDN activity in the vicinity of the TASD. Therefore, these bursts are very rare phenomena.

Of the five bursts which are not reconstructible, two are correlated in time and position with lightning. One of the five reconstructed bursts and three of the five unreconstructible bursts are not correlated with lightning by the above definitions. However, there are multiple lightning strikes near the times of the observed bursts, therefore all ten bursts observed in five years occur during thunderstorms.

For precedent observation, TASD burst events have similar features. Dwyer, et al. [2005] reported high energy radiation on the ground from each step of the stepped leader process. The steps time intervals of the stepped leader is roughly from 10 microsecond to 100 microsecond. TASD burst events time interval is same as this region. Several satellites observed high energy radiation burst correlated with lightning. Cummer, et al. [2005] reported high energy radiation at satellite, which is correlated with positive lightning. In contrast, TASD burst events on the ground are correlated with negative lightning. In both situations, the electric field direction works to accelerate electrons toward detector. Briggs, et al [2010] reported high energy radiation at satellite, which show roughly two types of burst waveform. One is Gaussian like and the other is Log-Normal like. TASD burst events also have roughly two type of waveforms. Although the signal shapes of TASD burst events and terrestrial gamma ray flashes detected by satellite are similar, the signal timescale of SD events is about 2 order of magnitude shorter. This can be due to the difference of the size of accelerating region and/or the distance between the radiating point and the detector.

IV. CONCLUSION AND DISCUSSION

We have detected bursts of high energy events using the TASD, which seem to come from negative high-current intracloud lightning as judged by correlation of time and position. There is no evidence that the bursts come from cloud-to-ground lightning.

What generates the individual events within a burst? We do not have a clear answer. If these are interpreted as arising from cosmic rays, the trigger rate in a burst is inconsistent with the observed energies. We summarize the features of the bursts as follows:

- This burst phenomenon does not arise from thunderstorms at random, but rather comes from negative high current intracloud lightning.
- The reconstructed shower directions for events in a burst, within reconstruction accuracy, indicate that they arise from a very small region at low altitude.
- The showers seem to start their development low in the atmosphere compared to cosmic rays, as determined by the shower front curvature.
- The waveforms exhibit time gaps in the detected radiation which is consistent to that expected by the stepped leader process (several tens of microseconds).
- The leading edge of the waveforms at the shower core are less-sharply rising than those of typical cosmic ray air-showers, for many events.

To prior observations of energetic radiation associated with lightning, we add somewhat unique information especially such as spatial distribution, derived from air-shower reconstruction using a faster waveform from a larger detector for higher current intracloud lightning.

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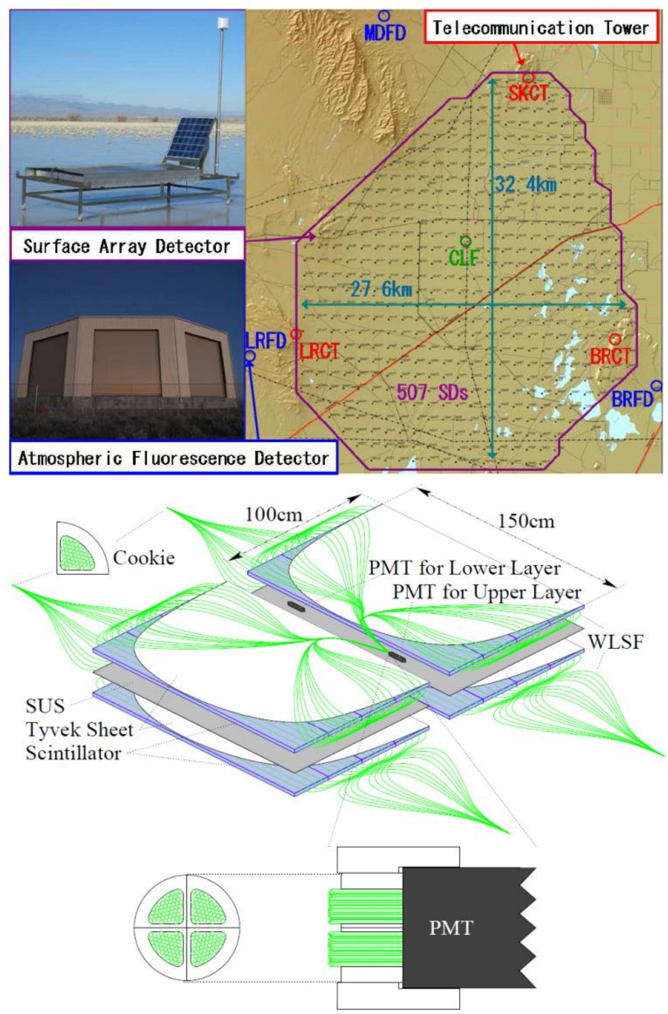

Figure 1: Telescope Array Experiment. Top: 507 ground surface particle detectors (tiny dots above) are surrounded by 3 atmospheric fluorescence telescope stations. Bottom: Particle detecting part of TASD consists of 2 layers of plastic scintillators. Each scintillation layer has 1.2 cm thickness and provides information respectively via wavelength-shifting fibers.

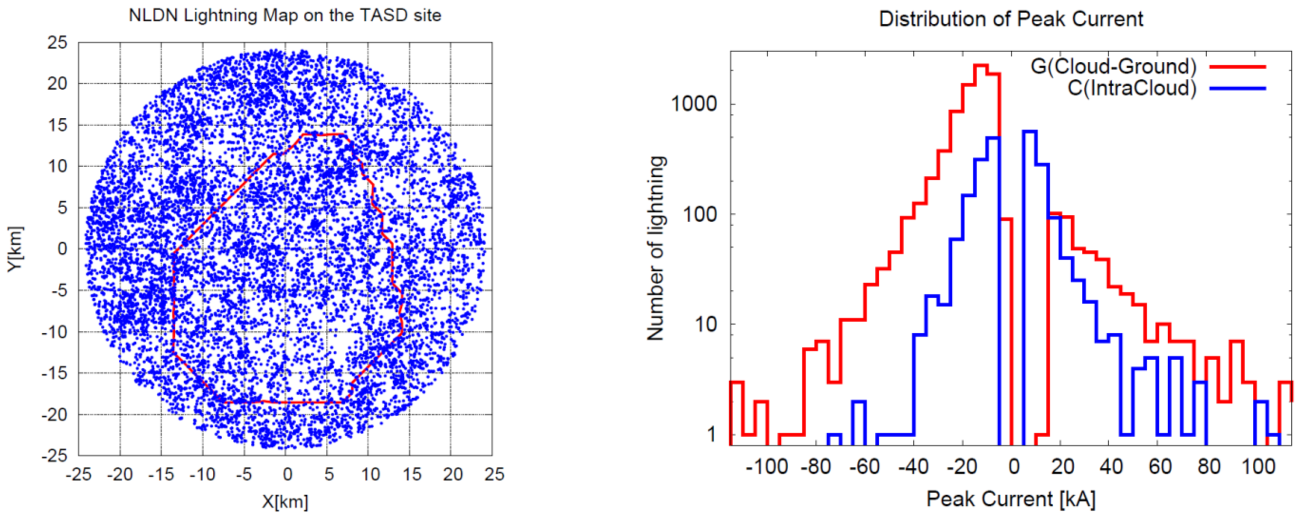

Figure 2: NLDN data distribution. Left: Lightning map on the TA site. Blue points show individual strokes. Red line shows the area of TASD. Right: Peak current distribution for 2 categories of a C/G flag which indicates intracloud or cloud-ground lightning.

Table 1: Reconstructed event list with NLDN lighting information. AS means air shower event observed by TASD, and LG means lightning event measured by NLDN. These X and Y are from the center of the TA site. The last column has altitude parameter for air shower front curvature and peak current[kA] & C/G flag for lightning. The synchronized lightning is categorized to blue. The related lightning is categorized to red.

Event	Date yymmdd	Time HHMMSS	μ sec [μ s]	X [m]	Y [m]	AS[m] LG[kA C/G]
AS	101004	165842	930565	11356	−7425	3963
AS	101004	165842	930612	10478	−7368	4400
AS	101004	165842	930835	11142	−8159	3270
LG	101004	165842	930608	12480	−5068	−63.5 C
LG	101004	165842	934058	10619	−8069	−35.8 G
AS	110727	080615	124319	3447	1952	4070
AS	110727	080615	124543	2897	2232	3070
LG	110727	080615	124303	3653	2285	−35.6 C
LG	110727	080615	130887	3084	1996	−28.0 G
AS	110916	194056	567481	−3210	−9285	3253
AS	110916	194056	567566	−3524	−9413	3134
AS	120706	014911	184219	9847	−10702	3770
AS	120706	014911	184307	7635	−9674	3361
LG	120706	014911	184122	8997	−9670	−36.3 C
AS	120907	015545	380684	−8636	1254	4446
AS	120907	015545	380755	−9857	−337	4805
AS	120907	015545	380881	−9450	−961	3361
LG	120907	015545	380675	−8942	668	−53.9 C
LG	120907	015545	390411	−9635	−1952	−20.1 G
LG	120907	015545	409370	−8608	−1653	−12.2 G