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Space-time analysis of the Seismic Waves propagation and World Wide Lightning Location Network data association with the Terrestrial Gamma-ray Flashes detected by the Fermi Gamma-ray Burst Monitor

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Abstract. The natural high intensity sub-millisecond electromagnetic pulses associated with seismic waves from earthquakes can trigger +CG, –CG and IC lightning discharges, transient luminous events (TLEs) and non luminous events as TGFs. The lightning discharges with higher peak currents are more probable during the moments when seismic waves from earthquakes pass through a place of lightning. Huge charge transfer of triggered +CG, –CG and IC lightning discharges can radiate powerful electromagnetic emission. Space-time analysis of the seismic wave's propagation and WWLLN data was done together with the second Fermi GBM Terrestrial Gamma-ray Flashes (TGF) Catalog. A total number of 1203 events from the WWLLN associations table were associated with the entrance the exact seismic waves from earthquakes in the place of lightning. Only 11 events from 1214 associations were rejected. After that the full list of 1049 TGFs has been checked out. As the result the 1038 TGFs has been associated with earthquakes. Among them 42 events with time difference exceeding ±100 sec were found. As the result 996 events get inside the time interval for the space-time analysis ±100 sec, they correspond to 95% from the total number of 1049 TGFs. The probability density function for the Time difference data was calculated and more preferably can be explained by the probability density functions of Cauchy distribution. The Phases of Seismic Waves and earthquakes magnitude associated with selected 996 TGFs from WWLLN associations table were studied.

1. INTRODUCTION

The TGFs were discovered during the Burst and Transient Source Experiment (BATSE) (Fishman et al., 1994). Since that time the lightning strokes have been studded together with the very low frequency (VLF) radio signals of lightning and gamma ray observations from both BATSE (Inan et al., 1996; Cohen et al., 2006), the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) (Cummer et al., 2005; Stanley et al., 2006; Inan et al., 2006; Lay, 2008; Hazelton et al., 2009; Cohen et al., 2010; Shao et al., 2010) and the Gammaray Burst Monitor (GBM) on the Fermi Gamma-ray Space Telescope (Briggs et al., 2010; Connaughton et al., 2010).

The WorldWide Lightning Location Network (WWLLN) (Rodger et al., 2009) based on acquisition and processing the VLF radio signals, provides lightning data with localization about 20 km and an average RMS timing accuracy of 30 ms. The WWLLN data was used for finding the correlations with RHESSI TGFs (Lay, 2008; Hazelton et al., 2009). The GPS absolute timing accuracy available bough for TGFs and lightning data are within several microseconds. Perfect timing with the satellite orbital measurements provide the coordinated information on TGFs position.

The associations between Fermi GBM TGFs and WWLLN sferics, with both simultaneous and nonsimu-ltaneous cases was reported by Briggs et al. (2010).

WWLLN sferic correlations with TGFs have been reported on the distances up to 1000 km away from the satellite (Hazelton et al., 2009) and the statistical analysis (Brigs et al., 2013) demonstrate the uniform density up to 300 km, then the density decreases with increasing offset.

The research of Stanley et al. (2006), Cummer et al. (2005), Williams et al. (2006) and Shao et al. (2010) describe the TGFs association with intracloud (IC) lightning. With the help of Lightning Mapping Array the initial development of an IC lightning event (Lu et al., 2010) was associated with TGFs seen by RHESSI.

The Aragats Space Environmental Center of the Cosmic Ray Division (CRD) of the Yerevan Physics Institute provide the research on Thunderstorm Ground Enhancements (TGEs) and observation flux of electrons and gamma rays correlated with thunderstorms (Chilingarian et al., 2010; Chilingarian et al., 2011; Chilingarian and Mkrtchyan, 2012).

In our previous papers we had done the space-time analysis of the lightning triggering (Sorokin, 2007b) by the seismic waves. On the base of actual data records, the cases of Electromagnetic Pulses generation at the big angular distances by exact seismic waves from earthquakes have been described (Sorokin, 2007a). Electromagnetic Pulses related with seismic waves can provoke positive polarity lightning (Sorokin, 2005a, 2005b, 2006). All these can be associated with triggering the High-Altitude Atmospheric Discharges (Sorokin, 2002, 2006) and transient luminous events (TLEs) (Sorokin, 2009).

In this paper an attempt to associate the entrance the exact seismic waves from earthquakes in the place of lightning with the occurrence of the non luminous events as TGFs were done.

2. TERRESTRIAL GAMMA-RAY FLASHES (TGF) DETECTED BY THE FERMI GAMMA-RAY BURST MONITOR (GBM)

The Fermi Gamma-ray Space Telescope was launched from Kennedy Space Center on 11, 2008 and supports two instruments: the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The observed data are available from GBM Terrestrial Gamma-ray Flashes (TGF) Catalog (G. Fitzpatrick et al., in preparation) Website. The relevant information about the Fermi GBM TGF catalog is available by Briggs et al. (2013). This catalog contains 3356 TGFs, detected from GBM trigger enabled on 2008 July 11 through 2015 June 23 and 579 brighter TGFs are included in the Trigger Table. The correlation of the GBM and WWLLN signals was described in Connaughton et al. (2010, 2013) and these events were included in the WWLLN Associations Table. The WWLLN Associations Table contains accurate localizations of the 1049 TGFs with the 1214 WWLLN radio signals.

3. THE COMPUTATIONAL METHOD

The standard procedure of seismic wave definition is based on computational methods.

All evaluations for the definition of seismic wave possible phases (Pup, P, Pdiff, PKPab, PKPbc, PKPdf, PKiKP, pP, pPKPab, pPKPbc, pPKPdf, pPKiKP, sP, sPKPab, sPKPbc, sPKPdf, sPKiKP, PcP, ScP, SKPab, SKPbc, SKPdf, SKiKP, PKKPab, PKKPbc, PKKPdf, SKKPab, SKKPbc, SKKPdf, PP, P'P', Sup, S, Sdiff, SKSac, SKSdf, pS, pSKSac, pSKSdf, sS, sSKSac, sSKSdf, ScS, PcS, PKSab, PKSbc, PKSdf, PKKSab, PKKSbc, PKKSdf, SKKSac, SKKSdf, SS, S'S' SP, PS, PnS) and evaluations of their travel times were conducted with the use of model AK135 based IASPEI-91 (Kennett, 1991a, 1991b), (Buland and Chapman, 1983).

The AK135 model calculates the travel times for 57 possible phases of seismic waves. The travel times found from AK135 can be estimated with an accuracy of ±10 seconds. The AK135 use an averaged crust model, and do not differ the oceanic and continental parts of the crust. This can be very important for the coastline areas and the travel times found from AK135 can be significantly different for the direction to the highlands area or to the ocean. Taking in an account the elliptical error for the Earth radius one can improve the accuracy on 3-4 sec. One more source for the more accurate travel time's calculation is the use of the local model of the Earth crust and this can be done in future research.

The range of Fermi Gamma-ray Burst Monitor (GBM) is about 1000 km (Hazelton et al., 2009). This means that the seismic waves propagating in the Earth crust can cover this distance within several minutes. From the other side the scale of the weather front or atmospheric cyclone can be the same dimension as the range of Fermi GBM. The lightning activity can also affect the accuracy. The positive polarity lightning (+CG) can propagate on huge distance up to 100-200 km. The negative polarity lightning (–CG) can force the delayed lightning discharge (+CG) or upward lightning on the huge distance from the first one. Taking in account all information we consider the time interval for the space-time analysis ±100 sec (Sorokin, 2009).

Seismic waves scattering around the globe, propagating through the Earth's mantle, core and reflecting from the back of crust can trigger, with high efficiency, lightning (Sorokin, 2007b), including positive polarity lightning (Sorokin, 2005b, 2006), High-Altitude Atmospheric Discharges (Sorokin, 2002, 2006) and TLEs (Sorokin, 2009).

Using the U.S. Geological Survey Search Earthquake Catalog data (time UTC, geographical coordinates Latitude and Longitude, depth, magnitude) together with the WWLLN data (date and time UTC, geographical coordinates Latitude and Longitude) it is possible to establish the space-time coupling between exact seismic waves from the earthquake with WWLLN lightning's associated with TGFs. For this purpose we will calculate for the observed TGFs the Event Time in the coordinates of the earthquake (the difference between the WWLLN time stamp and earthquake occurrence time) and the computational Travel Time for exact seismic waves from this earthquake.

In the case if the exact seismic wave from the earthquake passing the place of lightning in the same time with the WWLLN detection we will have a “Zero” Time difference.

4. SPACE-TIME ANALYSIS OF THE EARTHQUAKE – TGF RELATION

The Trigger Table contains information for 579 brighter TGFs. We do not focus on the Trigger events, due to most of them are included in the WWLLN associations table.

The WWLLN associations table has data on the 1049 TGFs for which a close association between a GBM Terrestrial Gamma-ray Flashes (TGF) and WWLLN radio signal was found in the window of ±3.5 ms (Connaughton et al., 2010). This table contains 1214 associations, including 1019 simultaneous ones.

A total number of 1203 events from the WWLLN associations table were associated with the entrance the exact seismic waves from earthquakes in the place of lightning. Only 11 events from 1214 associations were rejected. After that the full list of 1049 TGFs has been checked out. As the result the 1038 TGFs has been associated with earthquakes. Among them 42 events with time difference exceeding ±100 sec were found. As the result 996 events get inside the time interval for the space-time analysis ±100 sec, they correspond to 95% from the total number of 1049 TGFs.

The WWLLN associations table from the second Fermi GBM TGF Catalog is not homogeneous and can be divided into two periods. The first part from 1 October 2008 to 17 February 2013 consist 41 events with Time difference exceeding ±100 sec and only one event can be seen in the second part of the catalog from 18 February 2013 to 23 June 2015. It looks like that in these two periods the different algorithms can be applied. We can use the second part of the catalog or skip 42 events with Time difference exceeding ±100 sec for the whole WWLLN associations table with the same result.

The computational Travel Time for exact seismic waves it is possible to compare (Figure 1) with the Event Time in the coordinates of the earthquake.

The Event Time can be calculated as the difference between the WWLLN time stamp and earthquake occurrence time:

$$Event\ Time = T_{(WWLLN)} - T_{(Earthquake)}.$$

We can feet the linear regression (Event number=996, R^2=0.99906) for the dependence of calculated Event Times from the computational Travel Times (Figure 1).

The exact seismic wave from the Earthquake entering the place of lightning in the time ($T_{(Seismic\ Wave)}$) equal to the sum of earthquake occurrence time and the computational Travel Time:

$$T_{(Seismic\ Wave)} = (T_{(Earthquake)} + Travel\ Time).$$

Time difference between the WWLLN time stamp and entering of exact seismic wave from the earthquake to the place of lightning, can be calculated as:

$$t = Time\ difference = T_{(WWLLN)} - (T_{(Earthquake)} + Travel\ Time).$$

A small number of the events (42) are situated beyond the linear regression function (±100 sec) and looks like random component ($-100\ sec < Time\ difference < +100\ sec$). For the selected 996 events the mean value of the Time difference distribution is –0.173 sec and the variance is 498 sec with the standard deviation 22.32 sec. We can plot the probability density function (amplification factor (N=3522.89) of the normal distribution for the estimated parameters (Figure 2). From the Figure 2 we can see that the probability density function of the normal distribution do not feet the probability density function of the Time difference between the WWLLN time stamp and entering of exact seismic wave from the Earthquake to the place of lightning.

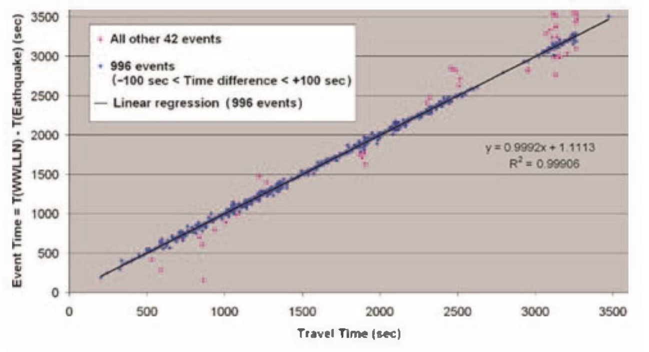

Figure 1. The comparison of calculated Event Times and computational Travel Times for 1038 TGFs associated with earthquakes
Data sources: GBM Terrestrial Gamma-ray Flashes (TGF) Catalog; Search Earthquake Catalog U.S. Geological Survey; WorldWide Lightning Location Network (WWLLN).

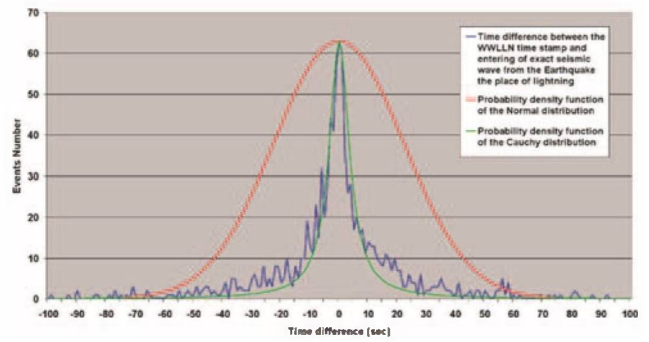

Figure 2. The probability density function for the calculated Time difference data in comparison with probability density functions of normal distribution and Cauchy distribution
Data sources: GBM Terrestrial Gamma-ray Flashes (TGF) Catalog; Search Earthquake Catalog U.S. Geological Survey; WorldWide Lightning Location Network (WWLLN).

We can check the Cauchy distribution conformity for the calculated Time difference data.

The Cauchy distribution is a continuous probability distribution and it is also known as Lorentz distribution or Cauchy-Lorentz distribution.

The Cauchy distribution has the probability density function (Feller, 1971):

$$f(t, t_0, \gamma) = \frac{1}{\pi\gamma}\left[\frac{\gamma^2}{(t-t_0)^2+\gamma^2}\right],$$

were t_0 is the location parameter, specifying the location of the peak of the distribution, t is the Time difference and γ is the scale parameter which specifies the half width at half maximum (HWHM), alternatively 2γ is full width at half maximum (FWHM).

The maximum value of the Cauchy probability density function is $\frac{1}{\pi\gamma}$, located at $t = t_0$. Applying the method of least squares we can find the scale parameter ($\gamma = HWHM = 4.2$) and amplification factor (C=831.26) to feet the probability density function of the Cauchy distribution (green line, Figure 2) to the observed data (blue line, Figure 2). In terms of interval estimation FWHM=8.4 sec for the observed data the probability will be 0.3651 (383 TGFs from the total number 1049) see Table 1.

We can see that the Cauchy distribution more preferably to the calculated Time difference between the WWLLN time stamp and entering of exact seismic wave from the Earthquake to the place of lightning.

Table 1. Interval estimation of the calculated Time difference for observed 1049 TGFs from WWLLN associations table

Time interval	TGFs observed in this Time interval	Probability
±4 sec	383	0.365
±5 sec	420	0.40
±10 sec	592	0.564
±25 sec	819	0.78
±30 sec	858	0.818
±50 sec	942	0.898
±100 sec	996	0.95

It is very difficult to compare the normal distribution (red line, Figure .2) with Cauchy distribution (green line, Figure 2) due to the fact that Cauchy distribution does not have a mean value and a variance is infinite value, so the rule of 3-sigma we could not apply. But we can compare them with in terms of HWHM and FWHM. The probability density function of the Cauchy distribution (HWHM=4.2) is the 6.25 times more narrow then for the normal distribution (HWHM=26.28).

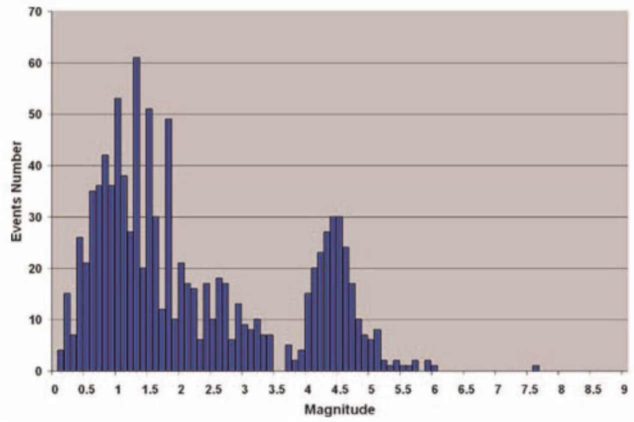

Figure 3. The earthquakes magnitude for selected 996 TGFs from WWLLN associations table
Data sources: GBM Terrestrial Gamma-ray Flashes (TGF) Catalog; Search Earthquake Catalog U.S. Geological Survey; WorldWide Lightning Location Network (WWLLN).

The Figure 3 contain the histogram of the 996 TGFs (Time difference inside the time interval ±100 sec) associated with earthquakes. From Figure 3 we can see two parts of the distribution separated by magnitude M=3.5.

The form factor of the first part of the distribution with the magnitude from 0 to 3.5 (Events number=755) can be explained by the multiplication of two functions: increasing a number of the earthquakes with lower magnitude and in the same time the lower probability to influence the atmosphere by them. This mechanism can be effective for the local seismicity. The next part of the distribution (Events number=241) can be the result of global seismicity due to the fact that the earthquakes with magnitude higher then 3.5 can emit the seismic waves traveling all over the glob within one hour. In bough cases the seismic waves from the earthquakes can affect on the electric field of the atmosphere and trigger the lightings (Sorokin, 2002, 2007b) and TLEs (Sorokin, 2006, 2009).

The propagation of the exact seismic waves through the earths crust causes the significant changes in the atmosphere electric field protuberances and a different probabilities to trigger the +CG, –CG and IC lightings. On the Figure 4 we can see that not all seismic waves can trigger the lightingsassociated with 996 TGFs, some of them have a "Zero" probability, but others are extremely effective.

In the case if all seismic waves can trigger the lightings it will look like a random distribution. But 12 seismic waves do not produce TGFs at all or the probabilities are too low. Other seismic waves demonstrate that the probability to produce TGFs can depend from wave trajectory, angular distance and the seismic wave energy.

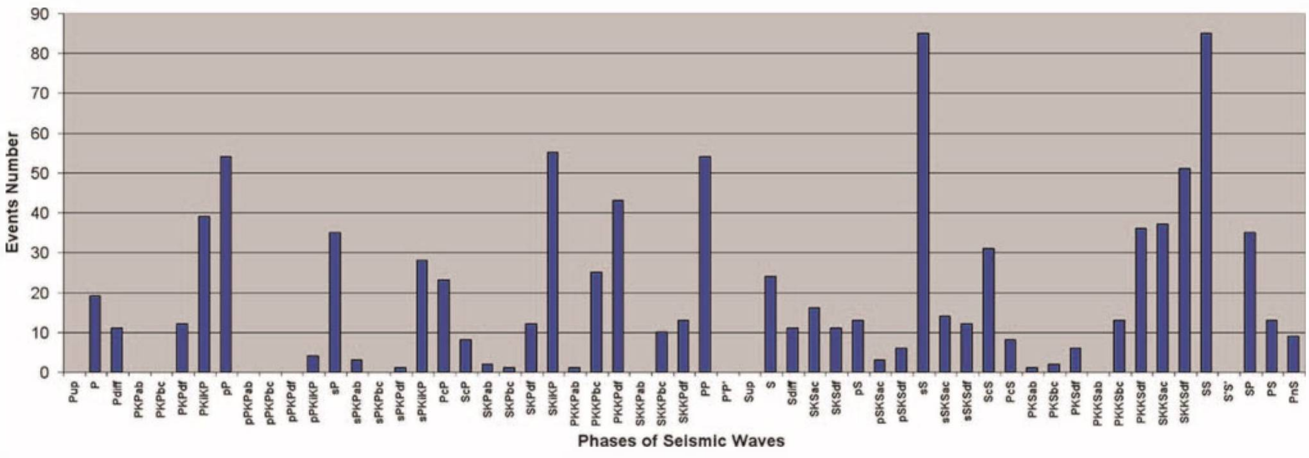

Figure 4. The Phases of Seismic Waves associated with selected 996 TGFs from WWLLN associations table
Data sources: GBM Terrestrial Gamma-ray Flashes (TGF) Catalog; Search Earthquake Catalog U.S. Geological Survey; WorldWide Lightning Location Network (WWLLN)

CONCLUSION

The 1049 TGFs from WWLLN associations table (second Fermi GBM TGF Catalog) split in two different statistical arrays. The first has strong space-time relation with seismic waves passing through the place of WWLLN lightning's detection associated with selected 996 TGFs. The second one looks like a random component and consist from 42 and 11 events. To investigate the 42 events with Time difference exceeding ±100 sec we need go in the manual mode and provide an analyses of all lightning's detected during these cases.

We proved that the Cauchy distribution more suitable to the calculated Time difference between the WWLLN time stamp and entering of exact seismic wave from the Earthquake to the place of lightning. The scale parameter which specifies the half width at half maximum (HWHM=4.2) for the Cauchy distribution, according to this FWHM=8.4 sec is 2.38 times more narrow then the estimated accuracy of ±10 seconds for the computational travel times found from AK135. In terms of interval estimation FWHM=8.4 sec for the Cauchy distribution correspond to the probability of 0.3651 (Tab. 1) and the probability for the observed TGFs data to be in the time interval of ±10 seconds is the 0.564 (Tab. 1). The selected 996 TGFs associated with the earthquakes (from the WWLLN associations table) observed in the time interval of ±100 seconds corresponds to the event probability of 0.95 (Tab. 1). So the observed 996 TGFs from WWLLN associations table (second Fermi GBM TGF Catalog) can be associated with earthquakes and exact seismic waves passing through the place of WWLLN lightnings.

It is very important to find the sensitivity of triggered lightning's associated with TGFs with the magnitude of earthquakes. This is not a simple threshold, but this function will depend from exact seismic wave trajectory, angular distance and the seismic wave energy. That is why the lightning's associated with TGFs can be triggered in the wide range of magnitudes and we do not separate them in this research.

In the previous research it was shown that the natural high intensity sub-millisecond electromagnetic pulses associated with seismic waves from earthquakes (Sorokin, 2007a) can trigger +CG lightning discharges and transient luminous events. The +CG, –CG and IC lightning discharges with higher peak currents are more probable during the moments when seismic waves from earthquakes pass through a place of lightning. Huge charge transfer of triggered +CG, –CG and IC lightning discharges can radiate powerful electromagnetic emission (Sorokin, 2007b). In the case of triggering intracloud lightning the huge volume of the cloud can be involved and a bigger electric charge for the shorter time can be transferred, so the powerful electromagnetic emission can be observed. This electromagnetic emission can be so huge that the WWLLN can detect them even from IC lightning.

We can face a problem of the WWLLN low probability (15%) detection of IC lightning (Connaughton et al., 2010) that can be a source of the difficulties during the TGFs identification also.

The stage of the initial development of an IC lightning (Stanley et al., 2006; Cummer et al., 2005; Williams et al., 2006; Shao et al., 2010; Lu et al., 2010) accompanied with the burst mode (Krider et al., 1975; Rakov et al., 1996) can be necessary but not sufficient requirement for the TGF formation. We can see that a small part of IC lightning can be associated with TGFs.

The additional necessary requirements can be closely connected with physical conditions of the initiation and development of the intracloud lightning. The unipolar magnetic field submicrosecond pulses with repetition period 2-10 μs generated by lightning discharges were described by Kolmašová1 and Santolík (2012). This observation can be very important for the lightning physics and for intracloud lightning in general.

For the intracloud lightning the repetition rate can go up to some hundreds within hundreds of microseconds, so the pinch effect can be common for them and can be the source of high-energy radiation (Sorokin, 2012). The conditions for the pinch effect can be only in the case when the next lightning discharge goes in the same channel during the continuous current stage. It is possible to explain this phenomenon by pinch effect or hot plasma instability with the plasma focus conditions in the compact area of plasma channel (Sorokin, 2012).

The CG lightning usually goes with lower rate of some events per second and choosing the new channel for the next stroke. But it can happen that CG lightning goes in the same channel within some ms twice. So for the CG lightning the probability of pinch effect is very low then for intracloud lightning. This fact can explain that a few CG lightning can produce X-rays and gamma-rays with neutrons and for the intracloud lightning the high energy photons and neutrons are common.

The production of high energy neutrons and protons in the D–T, D–D and D–^{3}He fusion reaction together with proton capture reactions of type (p, γ), (p, α) and neutron capture reactions of type (n, n), (n, γ), (n, p), (n, α), (n, $2n$) can explain the production of the radioactive materials, gamma-ray radiation and the air ionization during the lightning discharges (Sorokin, 2012). The X-ray and gamma-ray signatures from lightning can be explained due to the Compton scattering effect (Sorokin, 2012). The observation of the long period gamma-ray radiation during the thunderstorm can be due to the decay of isotopes.

So for the TGFs associations describe above relations can be very important: high intensity sub-millisecond electromagnetic pulses associated with seismic waves from earthquakes; triggered +CG, –CG and IC lightning discharges; powerful electromagnetic emission from triggered lightning; intracloud lightning repetition rate; pinch effect or hot plasma instability; the nuclear fusion reaction together with proton capture reactions and neutron capture reactions and Compton scattering effect.

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