Parallel and Simultaneous EAS events due to Gerasimova-Zatsepin effects observed by LAAS experiments

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***Abstract*. We have measured extensive air showers (EASs) originated from primary cosmic ray energies above PeV at multiple EAS observatories deployed in Japan since Sept. 1996. Each EAS array has been located at the rooftop of the buildings in the university campus, and has GPS-disciplined TCXO 10 MHz oscillator to provide UTC time stamps for each EAS event with microsecond accuracies. We have carried out to search for simultaneous and parallel EAS events at multiple EAS sites, such as Gerasimova-Zatsepin events, by comparing EAS arrival time stamps and directions between long baseline EAS arrays.**

We selected EAS pairs of which time difference and angular distance were less than 15 degree and 5 millisecond respectively and then examined the angular distances of these events from solar direction and lunar direction. We also calculated numerically the GZ probability dependence on both primary energies and arrival directions of cosmic ray nuclei. Consequently, we did not conclude that we found such excesses of these events in solar direction, as expected in the theoretical prediction of GZ effects. We found that the deficiencies of EAS pairs in the lunar direction, but its deviation is not significant.

***Keywords*: Gerasimova-Zatsepin effect, UHE cosmic ray nuclei, nuclear photodisintegration**

I. Introduction

The origin, acceleration mechanism and propagation processes of ultra-high energy cosmic rays has been a fundamental question for many decades, and it still is an unresolved mystery in the field of high energy astrophysics. Especially, above PeV energies, direct observations of primary cosmic ray have been difficult and the only way to estimate mass composition in these energies is the EAS observation derived statistical approach which is dependent on the hadronic interaction model strongly because accelerator data are not available in these ultra-high energies.

Another way to determine the mass composition of cosmic rays is as follows. The photo-disintegration process of cosmic ray nuclei with solar photons allow directly to study the mass composition of cosmic ray at energies above 10^{17}eV, if the multiple EAS events due to them, could be registered simultaneously at several EAS arrays and the energy of each EAS could be estimated. This method was suggested by Zatsepin and Gerasimova and this process is know as the Gerasimova-Zatsepin (GZ) effect [1], [2].

Several theoretical and numerical approaches [3], [4], [5], [6] have been carried out to estimate the possibilities of observations by using several types of EAS experiments according to GZ scenarios. In these calculations, the photo-disintegration cross section, fragmentation cross section and propagations of fragments in the interplanetary magnetic field along each magnetic rigidity are taken into account. They predicted the separation distance between EAS events at arriving the earth's surface. The most probable directions which GZ events will come from are also estimated as the solar direction. This implies that daytime observations are more effective for GZ events. The key observables to identify GZ events are that EAS events arrive essentially at the same time, from the same direction and at multiple EAS sites which are lying over 100km baselines. The other importance is the threshold energy of EAS arrays. While GZ effects of cosmic ray nuclei occur above 10^{17} eV, the energies of fragments should be less than 10^{16} eV. The detector spacing should be much less than 1 km at each EAS site.

The Large Area Air Shower (LAAS) experiments [7] have been established in order to study large-scale correlations in ultra high energy cosmic rays by Kitamura [8] in 1995. And the LAAS EAS arrays scattered over in Japan and located at the sea-level atmospheric depth, have been operated since 1996, and they have been synchronized each other with the accuracy of one microsecond in UT time stamp system, so that we can observe simultaneous and parallel EAS events at multiple EAS arrays. The minimum energy of cosmic rays to detect EAS in our array is around PeV. Thus, LAAS experiments are one of the most suitable experiments for investigating the GZ events by using of EAS observations.

This paper describes the LAAS experimental apparatus briefly. Then the results of data analysis for identifying the GZ candidate events are discussed with some numerical results.

II. LAAS EXPERIMENTS

The LAAS experiments [7] are the joint projects of compact arrays maintained at several institutes in Japan. These arrays are scattered over Japan from 34° N to 40° N and 134°E to 140°E, whose baselines are ranging from 0.1 km to 1000 km. The geographical location and mutual distance from LAAS arrays are listed in Table I.

The EAS arrays are located at the rooftop of buildings in university campus and institute. The array typically consists of 8 plastic scintillation detectors of which size is $50 \times 50\text{cm}^2 \times 5\text{cm}$. The detectors are deployed over an rooftop area of approximately 200m^2.

The data acquisition system of each array is triggered when each of more than 3 detectors is hit coincidently by the equivalent of more than 0.8 charged particles within 45 ns. The relative arrival times of EAS front particles is digitized with a CAMAC TDC (Kaizuworks Model 3780) with the resolution of 40 ps. The local density of EAS particles is digitized with a CAMAC ADC (Lecroy Model 2249W), of which dynamic range is limited to about 10 particles. The typical trigger frequency is about 0.1 to 0.5 Hz. The time stamp of EAS events is derived from a CAMAC GPS timing module (Kaizuworks Model 3850A), which maintains GPS-disciplined TCXO of 10MHz frequency. The accuracy of UT time stamping is 1μs in the entire EAS arrays.

The EAS arrival direction was determined by fitting a plane of EAS front for TDC values. It is unlikely that the EAS core location and size could be obtained, because of the limitation of EAS area and ADC dynamic ranges. Thus, the arrival direction angle and UT time stamp of each EAS event are analyzed in the following physics analysis.

III. DATA ANALYSIS AND NUMERICAL APPROACH

A. Data Analysis

To search for simultaneous and parallel EAS events at multiple EAS arrays, we have applied the following event selection criteria:(1) the number of coincidece counters was larger than 5 corresponding to the threshold energy of 5 PeV, (2)the baseline lengths were limited longer than 100 km, (3) the time difference of EAS events were smaller than 5 ms, taking into account of array geographical locations, and (4)the angular distances of EAS events were less than 15 degree, because the angular accuracy of EAS arrays is about 7 degree. The data period analyzed is from Sept. 1996 to Dec. 2006, and total number of events is about 65M and the accumulated exposure time is 11k days.

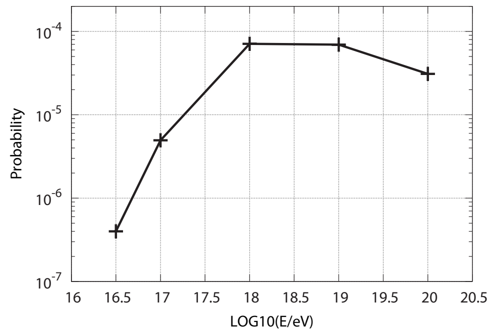

Fig. 1: The probability distribution of GZ effects for cosmic ray iron nuclei as a function of primary energies. Each symbol represents numerical result at each energies.

B. Numerical Approach

We calculated GZ probabilities and their dependence on the arrival angle respect to the solar direction, in order to estimate the possibilities of GZ events at multiple EAS arrays. We used the formulation defined in Epele *et al.* [4] for calculating the photodisintegration processes of cosmic ray nuclei with solar photons, described in Fujiwara *et al.* [5]. The GZ probability of iron nuclei with energies ranging from $10^{16.5}$ to 10^{20} eV before arriving the earth were shown in Fig. 1. This probability becomes a maximum at around several 10^{18} eV, but that value is still under 10^{-4}. This result is consistent with other numerical predictions such as Lafebre *et al.* [6]. The fragment nuclei including proton and neutron have the same velocity of parent iron nucleus, because the photointegration process is a kind of electromagnetic processes. Therefore, the fragment energies are almost smaller by more than one order of magnitude than that of parent iron nucleus. Then the EAS energies of GZ fragments, are expected as energies of several 10 PeV, so that the energy threshold for detecting EAS is one of important issues. Recent huge EAS arrays would be not suitable for detecting GZ fragments because of their much higer energy threshold. On the other hand, in LAAS experiments, the typical energy threshold is lying around 5 PeV.

We also simulated the GZ probability dependence on the angular distance of primary nuclei's arrival direction from solar directions. This issue is another important aspect to detect GZ fragments whether the efficient event

TABLE I: The geographical location and mutual distance between arrays

Institute	Abbreviation	Latitude(N)	Longitude(E)	Distance[km]		
Hirosaki University	HU	°40 35’	°140 29’	-	787	872
Kinki University^{+}	KU	°34 39’	°135 36’	787	-	152
Nara University of Industry	NUI	°34 35’	°135 41’	788	11	161
Okyama University*	OU	°34 41’	°133 55’	873	153	1
Okyama University of Science	OUS	°34 42’	°133 56’	872	152	-

+:moved to NUI and * :moved to OUS in 2008.

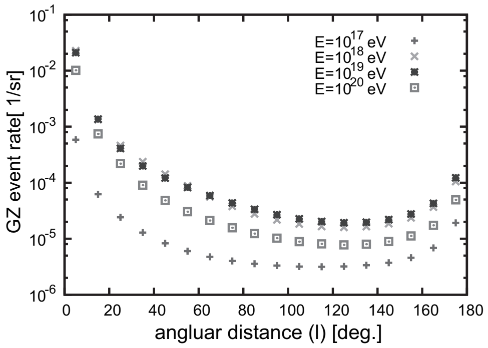

Fig. 2: The GZ event rate dependence on the angular distance of cosmic ray iron nuclei from the solar direction. The symbols of plus,cross,asterisk and dotted rectangle represent the primary energies: $10^{17}, 10^{18}, 10^{19} and 10^{20}$ eV respectively.

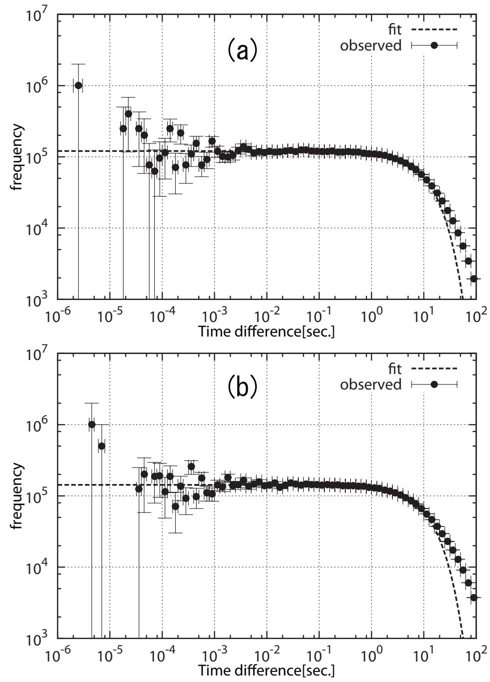

Fig. 3: Time difference distributions. (a)Very long baseline case (870 km). (b)midrange baseline case (160 km). Dashed lines represent fitted chance coincidence distributions.

rate can be expected in either daytime or nighttime. The GZ probability distribution are plotted as a function of angular distance in Fig. 2. The solar direction, daytime, corresponds to angular distance $l = 0\,\mathrm{deg}$, and the anti-solar direction, nighttime, does to $l = 180\,\mathrm{deg}$. This GZ probability increases around the solar and anti-solar directions, because the Lorentz boost of solar photon depends on the collision angle between photons and cosmic ray nuclei. The daytime observation seems to be more effective than the nighttime one in our calculations. Lafebre *et al.* [6] suggested that both the strength and the complexity of magnetic filed in the very vicinity of the solar system separate disintegrated fragments each other very effectively, and that the separate distance arriving at the earth would be maximized and be not suitable for over thousand km^2 (less than 100km $\times$100km) exposure experiments. It is the most effective that LAAS arrays are scattered over from 100km to about 1000km baseline length.

IV. Results

To obtain realistic candidates of GZ events, the arrival time difference were examined. In case of long baselines such as 870 km between Okayama array and Hirosaki array and 160 km between Okayama array and Kinki array, time difference distributions are presented in Fig. 3. In these figures, fitted lines are shown, which came from chance coincidences. Data points were fluctuated below millisecond time differences statistically and there are some discrepancies above 10 s due to the array maintenance periods. The limitation of angular resolution causes some ambiguity on time differences which came from the geographical arrangement of EAS arrays. Thus, we selected events in the time difference ranging up to 5 ms.

After applying the criteria described above, we obtained the distributions of the angular distance and time difference between EAS pairs, which are shown in Fig. 4. The value of the reduced χ^2 value for uniform angular distance distribution is $\chi^2_\nu = 1.9$ for DOF$= 14$. In case of the time difference distribution (Fig. 4(b)) the reduced χ^2 value and DOF are also 0.6 and 14 respectively. Both distributions are quite uniform, because the probabilities of GZ events are less than 10^{-5}.

The probability of GZ event depends on the angle between the directions of propagation of cosmic ray nuclei and of the solar photons, which increases around both solar and anti-solar directions. According to the GZ scenario, we calculated the angular distance of selected EAS pairs from the solar direction. The obtained angular distributions are shown in Fig. 5(a). The GZ standard scenario predicted the probability maximum in the solar directions, but our results show the uniform distribution

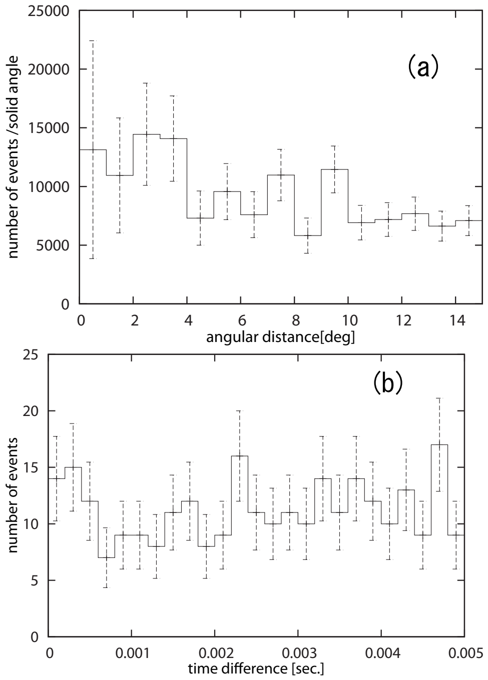

Fig. 4: -(a)The angular distance distribution and (b) the time difference distribution between the selected EAS events.

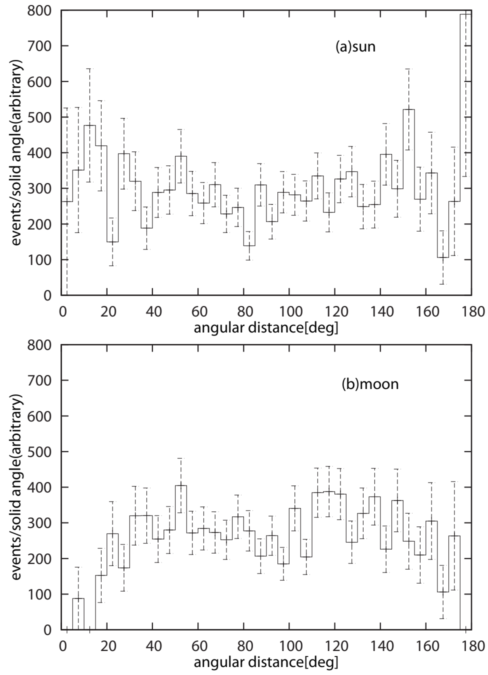

Fig. 5: The angular distance distribution between each direction of the selected EAS events and (a)solar and (b)lunar directions.

rather than the excesses in the solar direction as well as in the anti-solar direction. The GZ candidate event distribution seems to be very flat compared with Fig. 2. We had no GZ signal statistically so far.

Another apparent obstacle of very high energy cosmic ray stream is the moon reported in Tibet, L3 and some other experiments. The distribution of angular distances from the lunar direction is shown in Fig. 5(b). The present result suggests the existence of some deficiencies from the uniform distribution around the lunar direction. The significance level, however, is still one sigma, so that we can not conclude any more for this phenomena.

V. Conclusion

Using LAAS's one decade observation data, we have selected EAS events like Gerasimova-Zatsepin effects under the limitation of angular and time differences, with primary energies above PeV. And numerical calculations of GZ probabilities were also performed and we obtained their maximum value is about 10^{-4} at around serval 10^{18} eV. Therefore energies of disintegrated fragments expected to be several tens PeV.

We compare obtained angular distance distributions from solar direction with numerical one. The apparent excess in solar direction and anti-solar direction was not found, and the distribution seems to be uniform. On the other hand, the correlation between GZ like events and lunar direction indicates somewhat deficiencies in small angular distances, but its deviation is not significant. The present result does not require the existence of GZ events so far.

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