Searching for cosmic ray nuclei above the KNEE energies through the Gerasimova-Zatsepin effect with the LAAS experiments

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Abstract: Multiple and parallel cosmic rays originated from primary cosmic ray nuclei with energies above $10^{18}$eV such as due to Gerasimova-Zatsepin (GZ) effect have been searched at multiple extensive air shower (EAS) observatories scattered in Japan since 1996. Each EAS array has a GPS-disciplined 10 MHz oscillator to provide the UTC time synchronization for each EAS event within a few μs accuracies. In data analysis, EAS pairs whose time differences were less than 5 ms were selected and their angular distances from the solar direction were examined in term of local solar time. The data were compared with numerical GZ probability as a function of arrival directions of cosmic ray nuclei.

Keywords: EAS, ultra-high energy cosmic ray nuclei, Gerasimova-Zatsepin effects, Photo-disintegration process

1 Introduction

Direct measurements of cosmic ray primary energy and identifications of cosmic ray nuclei have become impossible above the KNEE(several×$10^{18}$eV).

One of the approaches to estimate the mass composition of cosmic ray nuclei is as follows. The photo-disintegration process of cosmic ray nuclei with solar photons ~ 1eV, allows directly exploring the elemental composition of cosmic ray nuclei above $10^{18}$eV, if the multiple and parallel EAS events due to fragment particles can be registered simultaneously at several EAS arrays and the energy of each EAS can be estimated. A long time ago, this idea was suggested by Zatsepin and Gerasimova and this process is known as the Gerasimova-Zatsepin (GZ) effect [1, 2].

Several simulation studies [3, 4, 5, 6] have been carried out in order to study the observation possibilities of GZ events by using huge surface arrays at the earth. In this scenario, the photo-disintegration cross section, fragmentation process and propagations of fragments in the interplanetary magnetic field according to their magnetic rigidity were taken into account. The separation distances between EAS events at arriving the earth’s surface and the flux of GZ events have been reported.

Lafèbre et al. [6] discussed the absolute GZ spectrum and the fraction of the integral primary cosmic ray spectrum above $10^{18}$eV. They concluded the maximum GZ probability ~ $10^{-4}$ near $1.5 \times 10^{18}$eV at the earth. The separation distance distributions of GZ events arriving at the earth’s surface had already been reported in Ref. [5, 6]. The separation distances for cosmic ray iron nuclei at $10^{18}$eV were expected as 1000 km. Lafèbre et al. well described the average separation distance $\langle \delta \rangle$ as a function of primary cosmic ray nuclei energies $E$ in Ref. [6],

$$\langle \delta \rangle = 4A \left| \frac{Z_1}{A_1} - \frac{Z_2}{A_2} \right| \left( \frac{10^{19} \text{eV}}{E} \right) \text{km} \quad (1)$$

where $Z_1$ and $Z_2$ represent the charge of fragments, and $A_1$ and $A_2$ do their mass number, respectively. $A$ is the mass number of primary cosmic ray nuclei.

The significant feature of GZ events is that the observation possibility of GZ events strongly depends on the arrival directions. When cosmic ray nuclei came from the solar direction or the anti-solar direction, which means daytime or nighttime observations respectively, the GZ probabilities are enhanced because of head-on collisions of nuclei with the solar photons. Our numerical predictions were shown in Fig. 1. These probabilities enhanced around the solar di-
Figure 1: The GZ probabilities as a function of the angular distance of cosmic ray iron nuclei from the solar direction. The symbols (+), (x), (*) and (□) represent the primary energies: $10^{17}$, $10^{18}$, $10^{19}$ and $10^{20}$ eV respectively.

Figure 2: The geographical location of EAS arrays in Japan. The symbols (●) represent the location of EAS arrays and the institution names are also shown.

rection and anti-solar direction. On the other hand, Lafèbre et al. [6] predicted that due to the strong turbulent nature of the solar magnetic field in the very vicinity of the Sun, the fragment trajectories would deviate very largely.

From the experimental view point, the most important key observables are the coincidence of the EAS arrival timing and the parallelity of EASs at multiple and distant EAS sites separated by more than one hundred km. The other important observable is the threshold energy of each EAS array. While the photo-disintegration process of cosmic ray nuclei with solar photon could occur above their energies of $10^{18}$ eV, the energies of fragments should be less than several $\times 10^{17}$ eV. This energy threshold required that 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. The LAAS EAS arrays are scattered over in Japan shown in Fig. 2. Those mutual baselines are ranging from 0.1 km to about 1000 km. The geographical location and mutual distances from the specified EAS arrays are listed in Table 1. Their mutual distances are shown in the fifth column to the seventh column of Table 1, which are measured from HU, KU and OUS sites respectively. In each institute, the EAS arrays are located in university campus. The array typically consists of eight plastic scintillation detectors whose size is $50 \times 50$ cm$^2 \times 5$ cm and typical area is approximately 200m$^2$.

The data acquisition system is triggered when each of more than 3 detectors are hit within 100 ns time window. The relative arrival times of EAS front particles are 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 less than 10 particles. The typical trigger frequency is about 0.1 to 0.5 Hz at each array. The EAS arrival time is registered by using a CAMAC GPS timing module (Kaizuworks Model 3850A), which maintains GPS-disciplined 10 MHz oscillator and provides $1 \mu$s UTC accuracies.

The EAS arrival direction is determined by fitting a plane to EAS particle arrival times calculated from TDC values. In this analysis the UTC time stamp of each EAS event are only analyzed in the following physics analysis.

This paper describes the LAAS experimental apparatus. The results of data analysis up to Mar. 2011 are discussed with some numerical results.

2 LAAS experiments

2.1 Array setup

The LAAS experiments [7] maintained EAS arrays at several institutes in Japan. These arrays are scattered over Japan shown in Fig. 2. Those mutual baselines are rang-
Table 1: The geographical location and mutual distances between LAAS EAS arrays

<table>
<thead>
<tr>
<th>Institute</th>
<th>Abbreviation</th>
<th>Latitude(N)</th>
<th>Longitude(E)</th>
<th>Distance[km] from</th>
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<td>‘140 29’</td>
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<td>‘133 56’</td>
<td>872</td>
</tr>
</tbody>
</table>

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

vations and adopting event selection criteria predicted by numerical approaches, it will enable to identify simultaneous EAS events at long baseline EAS sites. Therefore, we have applied the following event selection criteria for our observation data: (1) the number of coincidence counters was larger than 5 corresponding to the threshold energy of 5 PeV, (2) the baseline lengths were limited to more than hundred km, (3) the time difference of EAS events were smaller than 5 ms which came from the mutual geographical locations of EAS sites. The data period is from Sept. 1996 to Nov. 2010.

4 Results

To obtain the candidates of GZ events, the condition described in Sec. 3 are set for data analysis. The obtained time difference distributions are presented in Fig. 3. These exponential decreasing is expected from the randomness of EAS arrival time distributions. While statistical fluctuations are seen in the time range below several ms time differences, the small enhancement of EAS pairs are observed even in the large baseline cases.

In this analysis, we selected 1120 EAS pairs as GZ candidate events within the time difference window of 5ms from the combination of EAS arrays between HU and KU/NUI/OU/OUS.

According to simulation studies, the possibilities of GZ event depends on the solar angle when EAS pairs arrived at the earth, and they could maximize at the solar direction. We examined the selected GZ candidate’s arrival time as a function of local solar time shown in Fig. 4-(a). The frequency of GZ candidate events distributed uniformly instead of expected maximizations at the solar direction (UTC=3 corresponds to JST=12 o’clock) and the anti-solar direction (UTC=15 does to 24 o’clock). Some double peak structures are also seen at noon(UTC=3, 24) and midnight(UTC=13, 18). Although these structures are not significant statistically, they are located around expected enhancements of GZ effects shown in Fig. 1. To compare the non-solar variation, we calculated the event rate as a function of local sidereal time shown in Fig. 4-(b). The GZ event rate also seems to be uniform as a function of local sidereal time.

5 Conclusion

The joint EAS observatories in LAAS have carried out GZ candidate EAS searches by using GPS synchronized arrays. By using the array in Okayama area, we have demonstrated the potential of GPS time stamp system, when applying the time difference analysis for EAS pairs. The extension of EAS array combinations to long baseline EAS sites allows searching simultaneous EAS events. Using LAAS’s one decade observation data, we have selected EAS pairs like Gerasimova-Zatsepin effects under the limitation of time differences of EAS pairs.

We compare obtained angular distance distributions around the solar position as a function of local solar time. The significant excesses in solar direction and anti-solar direction were not found, and the distribution seems to be uniform. However, some spike structure can be seen around local noon and midnight in local solar time analysis. On the other hand, the GZ pair distribution as a function of local sidereal time seems to be more uniform.

In this analysis, we were not able to use the arrival direction information of each EAS event so far. Continuous observations and detail analyses using arrival direction of EAS could open the gate of GZ scenario. Furthermore, we have developed the EAS energy determination method for compact EAS arrays by using Linsley’s EAS time structure method [9]. This will provide to the energy information for LAAS compact arrays, and we can estimate primary cosmic ray nuclei mass number according to the equation (1).

References

Figure 3: Time difference distributions. (a) OUS-OUS combinations (less than one km). (b) OUS-OUS combination (nearly one km), (c) 150 km baseline such as KU/NUI-OU/OUS, (d) long baseline combination (nearly one thousand km). Dashed lines represent fitted exponential functions due to randomness of EAS arrival time distributions.

Figure 4: Arrival time distributions of selected GZ events as a function of UTC. Japan standard time (JST) is 9 hours ahead of UTC.