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A STUDY OF PULSARS AS THE SOURCES OF ULTRA-HIGH ENERGY COSMIC RAYS

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The arrival directions of ultra-high energy cosmic rays (UHECR) are considered by using of the data of world extensive air shower (EAS) arrays. It is found that, the arrival directions of showers with energies above 10^{19}eV correlate with galactic coordinates of some kind of pulsars. The classification of showers according to their muon component has been done and in comparison with simulation work [1], showers have been divided to the three classes which some of them shows correlation with the galactic coordinates of pulsars. The problem of mass composition and origin of UHECR have been discussed.

Keywords : Ultra high energy cosmic rays, pulsar, extensive air shower, muon component, cosmic rays

1. Introduction

The origin problem of UHECR is one of the priorities in high energy astrophysics. There are two main hypotheses about the origin of UHECR. Galactic [2] and extra Galactic [3] sources. In Galactic origin model of cosmic rays (CR), more probable sources are supernova remnants, pulsars [4] and etc. Here, the data of EAS of Yakutsk and Haverah Park arrays are analyzed to find any correlation between arrival directions of EAS with different sort of pulsars. (Such as binary, millisecond, gamma ray and etc.) To know more details about possible correlated showers with pulsars, we have also considered the muon component of EAS of Yakutsk data whichit is a sensitive parameter to know the mass composition of primary particles. (i.e. photon) V. Kolosov et al. [1] studied without Muon component EAS initiated by UHECR and found that some clusters of showers in the Galaxy have correlation with pulsars, and indicated that pulsars are the most likely sources of cosmic rays in the energy rang of 5×10^{18}eV to 5×10^{19}eV. A. Mccann et al. [5] also concluded that pulsars, especially the millisecond ones, are the origin of UHECR, where charged particles are accelerated to relativistic energies within the pulsar correlating magnetosphere and emit non thermal radiation from radio waves through gamma rays.

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P. Kaaret [6] has also performed Lorentz Invariance (LI) tests with regard to very high energy emission from pulsars and concluded that pulsars are the site and can be used as a third method (after gamma ray bursts, GRB, and active galactic nucleus, AGN) to search for LI violation effects.

Also, Quantum gravity (QG) may lead to an energy dependence in the speed of light (EDSL). The study of high energy radiation from pulsars can be used to put limits on such effects. There are several QG models [7] that lead to predictions of Lorentz Invariance Violation (LIV) or EDSL. Although a quantitative prediction of energy dependency of the speed of light does not exist. At present, the most sensitive test of LIV come from gamma ray burst, flaring AGN and also pulsars [8] which first was given by P.Kaaret [6]. The method is consideration of the time of the peak positions in the pulse profile and search for an energy dependent shift of the peak positions. In this studding, two photons with different energy E1 and E2 that are emitted simultaneously from a pulsar at distance d will arrive the earth at slightly different times, Δt. For linear dependency of energy we have E_{LIV}= (d/c) (E2-E1/ Δt), where E_{LIV} is the energy scale at which LIV effects become evident and c is the speed of light. If we calculate E_{LIV} for the crab pulsar which lie at distance of 2.2 kpc, for emitted photons with median energy of 2.93 GeV and 83.8 TeV and the measured Δt = 0.35 ms [8], for linear term we will get the limit $E_{LIV} > 2\times10^{18}$Gev. This amount is in the order of magnitude of some prediction (i.e. string theory) and is compatible with the limit derived by MAGIC collaboration [9] and one order of magnitude below HESS [10]. By attention to all obtained results, further studies will be needed in the future to give more robust results and to be able to definitively reject or validate proposed models.

2. Pulsars and EAS

Here, we searched to find out any correlation between pulsars and EAS. For this purpose, we used different sort of pulsars from the catalogue [11] (such as binary, millisecond, visible or glitches,gammaray, radio emitting X ray and alsothe nearest pulsars), where their properties and Galactic coordinates have been given. Also, we studied the EAS world data [12] with different energy range from 10^{19}eV to larger than 4×10^{19}eV and tried to find their arrival direction correlation with the coordinates of pulsars and checked up to what energies this correlation is appropriate.

The results are shown in table 1. As seen, none of pulsars shows any significant correlation with UHECR in the energy range of above 4×10^{19}eV. The most sensible correlations is shown for millisecond and binary pulsars up to energy 4×10^{19}eV. It is probable that glitches and radio emitting X ray pulsars could also be the probable sources of UHECR. Then special and important characteristics of correlated pulsars were checked up where for example we found that more than 60% of all binary pulsars are correlated with EAS. By a statistical method, correlation percent of pulsars and EAS is defined as the relative correlation percent of one of them (pulsars or EAS) which are located in a Galactic coordinates of a circle of radius less than a certain degree to the second object. For these correlated pulsars, we found the lowest rotation period (0.0013-162.07 sec) or highest orbital speed [7]. Radio pulsars emitting X ray, those having lowest X ray flux, show also correlation with EAS (i.e. log f(mw/m^2) is from -8.92 to -15.09) where correlated pulsars flux is in the range of -13.39 to -15.09 [7] which it is showing an anti correlation between this kind of pulsars and their X ray flux. About glitches; 50 % of correlated ones show the lowest times between two glitches T (time of travel). It is between 267 to 4815 days [7], where the correlated ones are in the range of the lowest T or 267 to 835.5 days. The correlated millisecond pulsars show an anti correlation with their radio luminosities. Also, as we know, the millisecond pulsars have the highest rotation speeds around their own spin axes. Therefore, among all kind of pulsars, they are the most energetic pulsars and also have the lowest reduced rate in their rotation periods. It is concluded that pulsars are the most probable sources of UHECR which is also suggested by Brezhko et al. [4].

3. Statistical method

At this session, the point estimation was performed that the used formulas are as follow:

$$\hat{p}=\frac{x}{n} \tag{1}$$

$$\hat{p}\pm Z_{\left(1-\frac{\alpha}{2}\right)}\sqrt{\frac{\hat{p}\,\hat{q}}{n}}\ ;\ \sigma=\sqrt{\frac{\hat{p}\,\hat{q}}{n}}\ ;\ \hat{q}=1-\hat{p} \tag{2}$$

in which $\hat{p}$ is sample ratio, x is successful sample and n is total sample. The amount of error was considered as 0.05 ($\alpha=0.05$). To this end, distance estimation was done. According to the amount of error, a confidence interval was considered as 95%. By using of these formulas (1 and 2), the mentioned distance was obtained.

For example, correlation percent between glitch pulsars and showers in energy range of $1\times10^{19}\,eV$ and $1.25\times10^{19}\,eV$ has obtained at the range of 32% to 55% which the total number of showers was 75 and the number of correlated showers was 33.

Table 1.

Correlation percent of different pulsars with high, normal and low muon content showers

Type of pulsar	High muon showers	Normal muon showers	Low muon showers
Binary	53 % – 79 %	31 % - 35 %	30 % - 44 %
Gamma ray	0%	20 % - 24 %	50 % - 74 %
Millisecond	40 % - 60 %	7 % - 15 %	0%
Near	25 % - 41 %	53 % - 71 %	70 % - 80 %
Glitch	28 % - 38 %	29 % - 37 %	54 % - 70 %
Radio	15 % - 17 %	30 % - 36 %	45 - 55 %

4. Pulsars and Muon component of EAS

The muon shower size is related to the EAS primary energy and also to the mass composition of primary particle where the kind of primary particles (i.e. photon) depends on the number of muons. In other word, the relative number of muons in a fixed EAS primary energy is proportional to the mass composition. An Fe primary develops faster than lighter mass (which have less nucleon) in the atmosphere so it produce much more muons. In reverse, photon primary is poor in produced muons. In this work, according to number of muons, EAS are divided into 3 classes that called low, normal and high Muon showers. This is done by using the simulation work of Kolosov et al. [1] that the corresponding parameter for division is the ratio of muon to electron densities at 600 meters from the EAS core.($\frac{\rho_\mu(600)}{\rho_e(600)}=A$)

The ratio of A for low, normal and high Muon showers correspondingly is chosen as less than 0.05, 0.05 to 0.27 and greater than 0.27 [1]. The muon information is from the Yakutsk data [12] where the density of muons is given in various distances from the shower cores, r, and the primary energy is greater than 10^{19}eV. To calculate the ratio of muon to electron density at 600 meters from the core, the following formulas (1 and 2) were used correspondingly:

$$\rho_{\mu}(N_e, r) = 18\left(\frac{N_e}{10^6}\right)^{\frac{3}{4}} r^{\frac{-3}{4}} \left(1+\frac{r}{320}\right)^{-2.5} \tag{3}$$

$$\rho_e(N_e, r) = \frac{N_e}{2\pi r_0^2} \frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)} \left(\frac{r}{r_0}\right)^{s-2} \left(1+\frac{r}{r_0}\right)^{s-4.5} \tag{4}$$

in which ρ_{μ} and ρ_e are Muon and electron density respectively at detector surface, N_e is the number of electrons in detector surface, s is the age parameter (related to longitudinal development of shower), r_0 is the Moliere unit and r is the distance from the core of shower.

In the next step of analysis, the Galactic position of low, normal and high Muon showers are compared with different kind of pulsars to find the kind of CR primary particles of correlated showers. All mentioned pulsars are again considered. This comparison is shown in table 2.

Table 2

Correlation percent of types of pulsars with EAS in the different energy ranges

Type of pulsar	10^{19}<E<$1.25.10^{19}$	$1.25.\ 10^{19}$<E<$2.\ 10^{19}$	$2.\ 10^{19}$<E<$4.\ 10^{19}$	$4.\ 10^{19}$<E
Binary	45% - 68%	50% - 69%	38% - 67%	9% - 38%
Gamma ray	27% - 48%	30% - 49.5%	18% - 45%	9% - 26%
Millisecond	39% - 60%	33% - 52%	46% - 73%	-
Glitch	32% - 55%	34% - 51%	27% - 52%	13% - 32%
Radio with X ray emission	34% - 53.5%	40% - 59%	33% - 60%	26% - 36%
Radio	3% - 15%	1% - 12%	1% -12%	5% - 15%
Near	17% - 36%	22% - 39%	7% - 28%	26% - 49%

As shown, there is again some correlation among many pulsars and showers especially as seen from table 1 for low Muon showers in the energy range of 10^{19}eV to 4×10^{19}eV. It confirms the Galactic origin of CRs up to energies about $4{\times}10^{19}$eV which has also suggested by Eitchler et al. [13]. About the nearest pulsars, we also studied their correlation with the low muon showers (as also suggested by Kolosov et al. [1] which concluded that these kinds of correlated showers are initiated by photons.) By attention to table 2, some probable correlation is also shown for gamma ray pulsars. Mikhailov et al. [14] have also claimed a high correlation between the nearest pulsars (< 2.3 Kpc)and low Muon showers which is in accordance with our correlated low Muon events, where percent of correlation of pulsars with low, normal and high Muon showers is 75 %, 62% and 33%. As seen from the same table, there is also correlation between millisecond and binary pulsars with high Muon showers. So, this issue is again supported that these two sort of pulsars could be the sources of UHECR with energies less than 4×10^{19}eV (up to about GZK cutoff energy).

Therefore, it is in accordance with our previous paper, doostmohammadi et al. [15] that we concluded CRs at energies lower than 4×10^{19}eV tends to low or normal and at higher energies tends to heavy mass composition.We also looked at the mass composition of UHECR using all showers having muon densities. For these showers, the parameter A were calculated and compared with the A values given by the simulation work of Kolosov et al. [1]. Our calculated A is up to the number of 0.55 which indicate the existing of primary elements in CRs higher than iron.Our comparisons of experimental A with simulations show that the mass composition of UHECR will be 21.8% photons, 53.1% proton and 28% iron and higher mass. (See fig.1) The percent of primary photon is in accordance with our previous works [15] and also capdeville et al. [16] and Shinozaki et al. [17] where the percent of gamma primary are given about 20%.In this range of energy, the percent of photons is an important clue to distinguish one of the two absolutely different astrophysical source models of CRs.

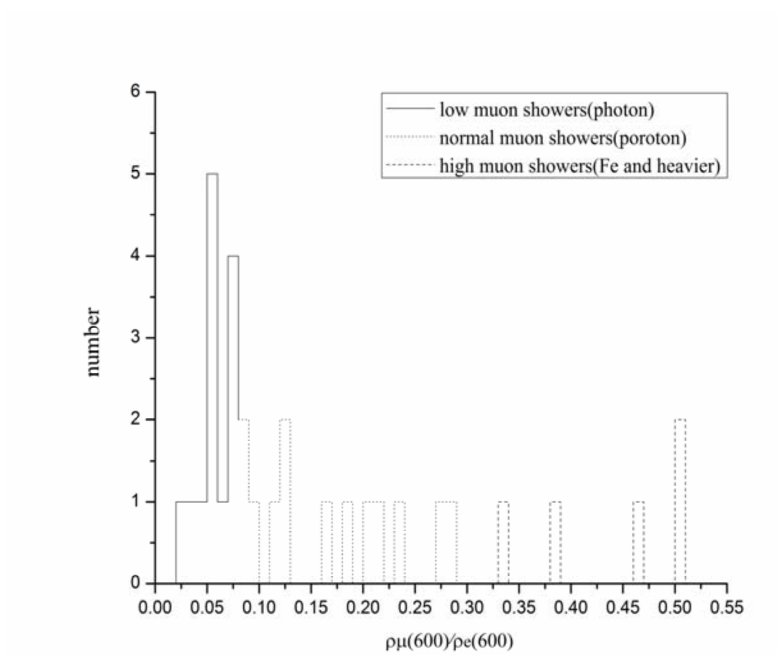

Fig. 1.The number of events vs. the ratio of muon to electron density for three classes of EAS.

5. Conclusion

Pulsars, especially the kind of binary and millisecond one's, can be the source of CR in the energy range of 10^{19}eV to 4×10^{19}eV. So, at least, CRs with energies up to 4×10^{19}eV could be from Galactic origin. CRs from the nearest pulsars show correlation with the lowest Muon class of EAS which is in agreement with previous works. For all classes of Muon showers, their calculated mass composition shows a mixed one's where the most particles are protons and the rest consistent with photons, iron and heavier primaries.

R E F E R E N C E S

[1] *V. Kolosov, A. Mikhailov, I. Makarov , A. Saburov,* Extensive air shower of ultrahigh energy without muon component: 2009; Proceeding of the 31st ICRC Lodz

[2]*A.A. Mikhailov,* Estimate of the mass composition of cosmic rays above 4×10^19eV: Pisma v zhetf., 2004; (79): 1175 – 177.

[3] *V.S. Berezinsky, A. Gazizov, S. Grigoreva,*On astrophysical solution to ultrahigh energy cosmic rays: Phys.Review, 2006; (74): 43005-4325

[4] *E.G. Berezhko, L.T. Ksenofontov, V.S. Ptuskin,V.N. Zirakashvili, H.J. Völk,* Cosmic ray production in supernova remnants including reacceleration: the secondary to primary ratio: Astronomy & Astrophysics, 2003; (410): 189 – 198.

[5] *A. McCann,* Detection of the crab pulsar with VERITAS above 100Gev, 32nd ICRC, Beijing 2011.

[6] *P. Kaaret,* Pulsars radiation and Quantum Gravity: Astronomy and Astrophysics 2008; (5): 145 – 147.

[7] *N.E. Mavromatos,* String Quantum Gravity, Lorentz Invariance Violation and Gamma Ray astronomy. International Journal of modern physics A. 2010; 25, 5409 or at arXiv 1010.5354,

[8] *A. NepomukOtte,* Prospects of performing Lorentz invariance tests with VHE emission from pulsars. 2011; 32nd ICRC Conference, Beijing, 3, 230.

[9] *J. Albert, E. Aliu, H. Anderhub, L.A. Antonelli, P. Antoranz, M. Backes, et al.* (MAGIC collaboration) Probing quantum gravity using photons from a flare of the active galactic nucleus Markarian 501 observed by the MAGIC telescope: Phys, Lett. B, 2008; **668**, 253

[10] *F. Aharonian, A.G. Akhperjanian, A.R. Bazer-Bachi, B. Behera, M. Beilickeet al.,*(H.E.S.S. Collaboration) AnExceptionalVeryHighEnergyGamma-RayFlareofPKS2155-304: APJL. 2007; 664, l71

[11] http://Vizier.u_strasbg.fr/

[12] *N.N. Efimov, T.A. Egorov, D. Krasilnikov, M.I.D.Pravdin, I. Sleptsov,*Ye.: 1988, world data center of Yakutsk arrays.

[13] *D. Eitchler, D. Guetta, and phol.* M. 2010. Apj, 722. 543.

[14] *A.A. Mikhailov, N.N. Efremov, E.S. Nikiforova,* Classification of Ultrahigh-Energy Extensive Air Showers in terms of the Muon content, JETP Letters. 2006; 83(7):265-267

[15] *S. Doostmohammadi, S.J. Fatemi,* an investigation of mass composition of ultra-high energy cosmic rays via the study of extensive air shower: Serb. Astron. J. 2012; 184: 87 – 92

[16] *J.N. Capdevielle, C. Le Gall, Kh.N. Sanosyan,*Aspt.Phys. 2000; B (4): P 259-275
[17] *K. Shinozaki, M. Chikawa, M. Fukushima, N. Hayashida, K. Honda, N. Inoue, et al.,* 2005; 29th ICRC, 00, 101-104.