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Results of Identification of UHECR Sources

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Abstract. Arrival directions of 63 EAS at energies E≈4 10^{19}-3 10^{20} eV, including 11 showers at E≥10^{20} eV, detected at AGASA, Yakutsk, Havera Park, and Fly's Eye arrays were investigated. Astrophysical objects - x-ray pulsars (as most powerful), radiogalaxies, Seyfert galaxies, and BL Lac's objects were searched in the 3-error box around particle direction of each shower. The probabilities of objects of each type to get by chance in the 3-error box were determined. They appeared to be small, P≈3.20σ (σ is a Gaussian parameter) for Seyfert galaxies with red shifts z<0.01, i.e. located at distances within 40 Mps from us if Hubble constant is H=75 km/s Mpc, having moderate fluxes in radio and roentgen bands. The probability is also small for BL Lac's objects, P≈3.10σ. For other objects it is large: P≈(0.01-0.1)

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1 Introduction

EAS at energies E>4 10^{19} eV seems to be initiated by CR particles of extragalactic origin (Hillas, 1998). Extragalactic CR above 6 10^{19} eV should be attenuated by photomeson interactions with relic photons (Greisen, 1966; Zatsepin and Kuzmin, 1966). Heavy nuclei with similar total energy would be attenuated by photodisintegration interactions with infrared background radiation (Stecker, 1998). In consequence UHECR at energies E<10^{20} eV have linear propagation distances of only ~40 Mpc, UHECR with E≈10^{21} eV have those of 10-15 Mpc, UHECR nuclei propagate from a distance of ~100 Mpc (Stecker 1968, 1998). UHECR sources which are discussed in literature are of three types: in the first place, these are astrophysical objects, e.g. pulsars, active galactic nuclei (AGN) (Berezinsky et al., 1990), hot spots and cocoons of powerful radiogalaxies and quasars (Norman et al., 1995), interacting galaxies (Cesarsky, Ptuskin, 1993), gamma-ray bursts (Totani, 1998); secondly, topological defects which may have been produced in the earliest stages of the big bang (Sigl et al., 1994), and finally, UHECR may be produced in decays of metastable supermassive particles of cold dark matter, accumulating in galactic haloes (Kuzmin and Rubakov, 1998; Berezinsky et al. 1997). In the first case we expect that objects which are UHECR sources occur in a region around the particle arrival direction not accidentally (assuming UHECR propagation along straight lines). In the second and in the third cases any objects get into this region randomly.

In this paper we present results of identification of UHECR sources assuming that they are astrophysical objects, that UHECR propagate through the extragalactic space along straight lines and that their deflection in galactic magnetic fields is negligible. The second is true if the strength of extragalactic magnetic fields outside clusters of galaxies are B<<10^{-9} G (Gaisser et al., 1993; Uryson, 2001). Deviation in galactic magnetic fields is discussed below. We consider x-ray pulsars (as most powerful), radiogalaxies, and AGN as possible UHECR sources, and we search these objects in the 3-error box around the particle arrival direction of each shower. In particular Seyfert galaxies and BL Lac's objects were searched. (The latter were suggested as possible UHECR sources in (Kardashev, 1995).) Then we calculate probabilities of getting objects in the 3-error box by chance.

2 Experimental Data and Identifying Procedure

For identification we treated EAS at 4 10^{19}<E<3 10^{20} eV with errors in arrival directions in equatorial coordinates of (Δα, Δδ)≤3^0: 48 EAS from AGASA (Takeda et al., 1999), 4 Yakutsk EAS (Afanasiev et al., 1996; errors see in (Uryson, 1999), 1 EAS from Havera Park (Watson, 1995; errors see in (Farrar and Biermann, 1998), including 8 EAS with E≥10^{20} eV. By contrast with EAS the optical coordinates of astrophysical objects are known to within seconds. Further according to statistics (Squires, 1968), for a random distribution of the errors in the coordinates the probability

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that coordinates occur within 1 rms error is 66%. It is equals to 99.8% for 3 rms error. On these reasons we chose the search region of $(3\Delta\alpha, 3\Delta\delta)\leq 9^0$.

We used catalogue of AGN (Veron, 1998), the one of x-ray pulsars (Popov, 2000), and catalogues of radiogalaxies (Kuhr et al., 1981; Spinrad et al., 1985) for search of objects. Catalogues include more or less entries depending on galactic latitude b of the celestial sphere, as galactic gas and dust impede observations at relatively low b. (Parts of sky with low values of b are well known "zones of avoidance" of galaxies.) The higher is b more objects are seen on the sky. Because of this the showers were divided into groups depending on galactic latitude of arrival directions. In each group we counted up the number K of showers and the number N of those having at least 1 object of the given type in the 3-error box. Next we calculated the probability that objects of the given type got by chance in the search region. We considered artificial showers with arrival directons in the region α=(0-24)h, $\delta=(-10\text{-}90)^0$ simulated by Monte-Carlo technique with the random number code (Forsythe, 1977). Artificial and experimental groups contained the same number K of showers. Denoting the number of artificial showers which have at least 1 object of the given type in their search regions by N_{sim}, the probability that objects get accidentally in search regions of N_{sim} showers in a group of K showers is equal to $P=\Sigma(N_{sim})_i/M$, i ranges from 1 to M, $M=10^5$ is the number of tests performed for each group. (In each artificial group the range of N_{sim} is $0\leq N_{sim} \leq K$.)

3 Results

We get following results for Seyfert galaxies.

As a rule there are more than 1 Seyfert nuclei in the search field of each shower. In each field we searched galaxies with red shift $z\leq 0.0092$, i.e. located within 40 Mpc from us if Hubble constant is H=75 km/s Mpc. Probabilities of accidental occurance of these galaxies in search fields are: $|b|>11^0$, K=48, N=27, $P\approx 2.84\ 10^{-3}$; $|b|>21^0$, K=33, N=22, $P\approx 1.85\ 10^{-3}$; $|b|>31^0$, K=26, N=22, $P\approx 1.40\ 10^{-3}\approx 3.20\sigma$; $|b|>41^0$, K=23, N=21, $P\approx 5.98\ 10^{-3}$; irrespectively of b, K=53, N=27, $P\approx 2.25\ 10^{-3}$.

One can see that farther showers are from "zones of avoidance" less is the probability of Seyfert nuclei to get accidentally in search fields. (At latitudes $|b|>41^0$ the value of P increases due to the poor statistics of showers.) In addition probabilities increase with z increasing, e.g. for $|b|>31^0$ and $z\leq 0.025$, 0.017 they are $P\approx 1.27\ 10^{-1}$, $3.15\ 10^{-2}$ respectively. According to the law of probability it is unlikely that at $|b|>31^0$ Seyfert galaxies with $z\leq 0.0092$ get by chance in search fields. They seem to be possible UHECR sources. All these Seyfert nuclei are of moderate luminocities and emit weak fluxes in radio and x-ray bands.

For BL Lac's values of the probability are: $|b|>11^0$, K=48, N=39, $P\approx 2.56\ 10^{-2}$; $|b|>21^0$, K=33, N=28, $P\approx 2.93\ 10^{-2}$; $|b|>31^0$, K=N=26, $P\approx 1.71\ 10^{-3}\approx 3.20\sigma$; $|b|>41^0$, K=N=23, $P\approx 1.56\ 10^{-2}$; irrespectively of b, K=53, N=41, $P\approx 4.28\ 10^{-3}$. Following to the law of probability BL Lac's at $|b|>31^0$ occur in search fields not accidentally. They seem to be possible UHECR sources together with nearby moderate Seyfert galaxies. At what distances are BL Lac's located? Red shifts of most of them are unknown (Veron, 1998). However it is difficult to determine z when there is no absorbing matter on the line of sight. This occurs often when objects are located within ~100 Mpc from us. Therefore BL Lac's with unknown z are located most likely at these distances (Kardashev, 2000).

For radiogalaxies with different z and for those irrespectively of z probabilities are within the range $P\approx(0.01\text{-}0.1)$ for each group of showers. For x-ray pulsars probablities are above 0.1. It follows from the law of probability that both radiogalaxies and x-ray pulsars get by chance into search fields.

It is interesting to perform the identification of sources separately for UHECR at $E\geq 10^{20}$ eV. We treated 11 AGASA showers (Takeda et al., 1999), 2 EAS from Havera Park (Watson, 1995), 1 Yakutsk EAS (Afanasiev et al., 1996), and 1 EAS from Fly's Eye (Bird et al., 1995). Unfortunately some of them have too large errors in arrival directions and their statistics is poor for carring out probability evaluations. However we checked up if there are moderate Seyfert galaxies with z<0.01 and BL Lac's in search fields of showers. 2 EAS (1 Yakutsk EAS and 1 EAS from AGASA) have no these objects in their search fields. However these EAS arrived from the "zone of avoidance" of galaxies, as their galactic latitudes are $b=3\pm 2^0$ and -4.8^0 respectively. Residual 7 EAS have moderate Seyfert nuclei at $z\leq 0.0092$ in their 3-error boxes, 2 EAS have those at z=0.016 and 0.018, i.e. located at distances ~72 Mpc. The latter two redshifts agree with results (Stecker, 1998), if heavy nuclei initiated these showers. 7 EAS have also BL Lac's in their search fields.

4 Discussion

Errors in EAS arrival directons are most important for the analysis suggested. Larger are error-boxes, more objects occur in the search field and more is the probability that it is accidental. At $|b|>31^0$ the probabilities for Seyfert galaxies with $z\leq 0.0092$ to occur in 3-error-boxes of $(3\Delta\alpha, 3\Delta\delta)=12,\ 15,\ 18^0$ are $P\approx 3.65\ 10^{-3}$, $9.80\ 10^{-2}$, $2.84\ 10^{-1}$ respectively. The probabilities for BL Lac's at $|b|>31^0$ are $P\approx 5.52\ 10^{-2}$, $2.40\ 10^{-1}$, $5.14\ 10^{-1}$ respectively. Because of this showers with errors in arrival directions of $(\Delta\alpha, \Delta\delta)<4^0$ may be used for identification if EAS statistics is ~tens.

Identifying UHECR sources we search objects in disks with angular dimensions of 9^0 around EAS axes. This means that particles deviate at angles below 9^0 in extragalactic magnetic fields. It is valid if the field strength is $B_{eg} < 10^{-9}$G, propagation distances being $R\leq 70$ Mpc (Uryson, 2001). Assuming UHECR sources are components of galactic clusters, magnetic fields inside clusters can be much more: $B_{eg} \sim 10^{-6}\text{-}10^{-7}$ G at distances ~0.5 Mpc from the centre of a cluster (Kronberg, 1994).

Angular dimensions of clusters located at R≈40 Mpc are $1.4\text{-}10^0$ (Zasov, 1999). (If a cluster is farther, its angular dimension is smaller.) Then a cluster containing an UHECR source lies completely in the search region and the field strength inside clusters has no effect on results presented.

The galactic magnetic field is $B_G \sim 10^{-6}$ G. In the disk it lies in the plane of the Galaxy and follows the spiral arms, in the halo the ordered field is perpendicular to the disk. There is also a disordered field of $\delta B \sim 10^{-6}$ G with a coherence length of $\delta L \sim 100$ pc both in the disk and in the halo (Kronberg, 1994). Charge particles deviations in the ordered field depend on arrival directions and can be small. One estimates deviations in the disordered field from (Cronin, 1996)

$\psi \approx 0.03(d/30\ \mathrm{Mpc})^{1/2}(\delta L/1\ \mathrm{Mpc})^{1/2}(\delta B/10^{-9}\mathrm{G})(E/10^{20}\mathrm{eV})^{-1}Z$.

Assuming the typical scale height of the field in the halo is d≈2 kpc one has $\psi \approx 0.014^0(E/10^{20}\mathrm{eV})^{-1}Z$.

It follows from this that particles with Z≤26 and $E \approx 10^{21}$ eV deviate at angles of $\psi < 0.4^0$, particles with Z≤10 and $E \approx 10^{20}$ eV deviate at angles of $\psi < 1^0$. These deviations are small and have no effect on identification.

Thus results presented are valid if for the first place extragalactic magnetic fields outside galactic clusters are of $B < 10^{-9}$ G, secondly if particles arrive Earth in directions where deviations in the ordered galactic field are small, and thirdly if particles at energies $E \le 10^{20}$ eV have Z<10.

5 Conclusion

The probability analysis demonstrates that moderate Seyfert nuclei with z<0.01 and BL Lac's seems to be UHECR sources. The probability of accidental location of them in 3-error boxes around EAS arrival directions are P≈3.20σ and 3.10σ respectively. Radiogalaxies and pulsars seem to occur in 3-error boxes of EAS arrivals randomly, as for them the probability is P≈(0.01-0.1). Acceleration of particles to $E \ge 10^{21}$ eV in BL Lac's was suggested in (Kardashev 1995). Acceleration of UHECR in moderate Seyfert nuclei is considered in (Uryson; this conference).

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