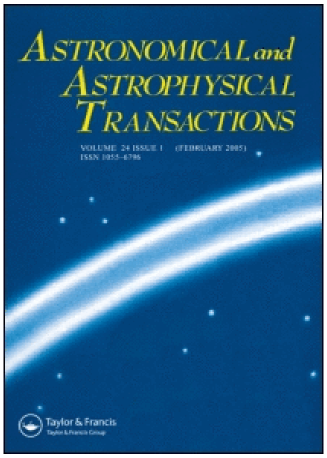

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IDENTIFICATION OF NEARBY ACTIVE GALAXIES AS SOURCES OF COSMIC RAYS ABOVE 4×10^{19} eV

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Arrival directions of 63 extensive air showers with energies 4×10^{19} eV $< E \leq 3 \times 10^{20}$ eV detected by the AGASA, Yakutsk and Haverah Park arrays are analysed in order to identify possible sources of cosmic rays with these energies. We searched for active galactic nuclei within error boxes around the shower-arrival directions and calculated the probabilities that objects are in the error boxes by chance. Our previous result obtained in 1996–2001 is confirmed: the probabilities are small, $P > 3\sigma$ (σ is the parameter of the Gaussian distribution) for Seyfert galaxies with red shifts $z < 0.01$. The Seyfert galaxies are characterized by moderate luminosities ($L < 10^{46}$ erg s^{-1}) and weak radio and X-ray emission.

Keywords: Cosmic rays; Active galaxies

1 INTRODUCTION

Particles initiating extensive air showers with energies $E > 4 \times 10^{19}$ eV are likely to have an extragalactic origin (see for example Hayashida *et al.* (1996) and Hillas (1998)). In this case, the spectrum of extragalactic cosmic rays may abruptly steepen near 10^{20} eV owing to their interaction with the microwave background radiation (Greisen, 1966; Zatsepin and Kuz'min, 1966). The ultrahigh-energy cosmic-ray (UHECR) data do not show the Greisen–Zatsepin–Kuzmin (GZK) cut-off (Sakaki *et al.*, 2001). This GZK cut-off should not be observed if sources of UHECRs are relatively near objects; the mean free path of particles with energies $E < 10^{20}$ eV in the background radiation field is about 40–50 Mpc, and particles with energies up to $E \approx 10^{21}$ eV should traverse distances of about 10–15 Mpc (Stecker, 1968, 1998) essentially unattenuated.

UHECR sources considered in the literature can be divided into three categories. The first includes astrophysical objects, such as pulsars, active galactic nuclei, the hot spots and cocoons of powerful radio galaxies and quasars, γ-ray bursts and interacting galaxies (see Bhattacharjee and Sigl (2000) and references therein). The second category of proposed UHECR sources is cosmic topological defects (Hill *et al.*, 1987; Berezinsky and Vilenkin, 1997), and the third is the decay of supermassive metastable particles of cold dark matter that have accumulated in galactic halos (Berezinsky *et al.*, 1997; Kuzmin and Rubakov, 1998). Direct identification of

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astrophysical objects is possible only in the first case. In other cases, any objects falling within error boxes centred on particle arrival directions should be chance coincidences.

In our previous papers (Uryson, 1996, 1999, 2001a, b, c) we searched for possible sources within error boxes centred on the arrival directions of showers and calculated the probabilities that objects are in the error boxes by chance. We found this probability to be rather small, $P > 3\sigma$ for Seyfert galaxies with red shifts $z < 0.01$, that is located within 40 Mpc ($H = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). We found earlier (Uryson, 2001a, b, c) that P is also small for Blue Lacertae (BL Lac) objects. For pulsars and radio galaxies the probability P is about 0.1. The result that BL Lac's objects are probable sources of UHECRs was also obtained by Tinyakov and Tkachev (2001) and by Gorbunov *et al.* (2002). Other results on UHECR sources identification are as follows. Farrar and Biermann (1998) found quasars to be UHECR sources. However, this result was discussed by Hoffman (1999) and by Sigl *et al.* (2001). Sigl *et al.* (2001) showed that neither compact radio sources nor γ-ray-emitting blazars seemed to be sources of UHECRs.

In this report we identified Seyfert galaxies as UHECR sources with larger statistics of showers and with the catalogue by Veron-Cetty and Veron (2001) to search for the sources.

2 THE IDENTIFICATION PROCEDURE

We used showers whose arrival directions were published together with their errors. For the identification procedure, we selected showers with errors in arrival directions $(\Delta\alpha, \Delta\delta) \leq 3^\circ$ in equatorial coordinates: 58 events with $E > 4 \times 10^{19}$ eV (Hayashida *et al.*, 2000), four Yakutsk showers with $E > 4 \times 10^{19}$ eV (Afanasiev *et al.*, 1996) (their errors were computed in our previous paper (Uryson, 1999)) and one Haverah Park showers with $E \geq 10^{20}$ eV (Watson, 1995), (its error was computed by Farrar and Biermann (1998)).

Different objects occur around the particle arrivals. We use the following procedure to obtain the probability of a chance occurence of objects near shower arrivals. The showers were subdivided into several groups depending on the Galactic latitude b of arrival directions, and in each error box we looked for objects of the given type. We counted the number K of showers in each group and the number N of showers which have at least one object of the given type within the error box. The showers were subdivided in Galactic latitude b in order to exclude events clearly lying in the galaxy 'avoidance zone'. We calculated the probabilities that objects of the given type would fall in the fields of search of N of the total of K showers by chance as follows. Showers with randomly distributed arrival coordinates were simulated. The coordinates of the simulated showers were determined by a random-number generator (Forsythe *et al.*, 1977) within a survey band $\alpha = 0$–24 h and $\delta = -10$–90°. We subdivided simulated showers into groups in the same way as real showers. Each simulated group contains the number K of showers equal to those observed. We then counted in each simulated group the number N_{sim} of showers having at least one object of the given type located in the error box (N_{sim} can take values in the interval $N_{\mathrm{sim}} \leq K \leq N$). In a group of K showers, the probability P of a chance occurrence of galaxies in the field of search of a given number N_{sim} of showers was determined as $P = \sum_{i=1}^{M} (N_{\mathrm{sim}})_i / M$, where $M = 10^5$ is the number of trials performed for each group. By the law of probability the coincidence is by chance if the probability P is $P < 3\sigma$, where σ is the parameter of the Gaussian distribution.

What is the size of the region of search? Statistics and the law of probability give the following data (Hudson, 1964; Squires, 1968): the probability that the particle coordinates are within the one-mean-square error (1-error) box is 68%, the probability for the two-mean-square error (2-error) box is 95%, and for the three-mean-square error (3-error) box it is 99.8%. This means that more than 30% of the objects are excluded from the analysis *a priori* using the 1-error box, only 5% of objects are lost with the 2-error box, and essentially all objects are considered with the 3-error box. Using the 2-error box is less strict than using the 3-error box, and it is more accurate compared with using the 1-error box. We believe that using the 1-error box region would reduce the chance coincidence against the 2- and 3-error boxes.

In the papers by Farrar and Biermann (1998), Sigl *et al.* (2001), Tinyakov and Tkachev (2001) and Gorbunov *et al.* (2002) the 1-error box was used. Here we use all the 1-, 2- and 3-error boxes in the identification procedure.

The optical coordinates of the galaxies and pulsars are accurate to several arcseconds, so that the fields of search were determined solely by the errors in the shower coordinates.

3 RESULTS

3.1 Nearby Active Galaxies

The catalogue by Veron-Cetty and Veron (2001) contains both Seyfert galaxies with detailed classification and objects which are probably or possibly Seyfert galaxies, because of a lack of available data. We found the probabilities of chance coincidence in two cases: for all Seyfert galaxies and for Seyfert galaxies with detailed classification having $z < 0.01$.

For all nearby Seyfert galaxies the probabilities of chance coincidence using the 1-, 2- and 3-error boxes, $P_1(N)$, $P_2(N)$ and $P_3(N)$ respectively, are the following (N is the number of showers having at least one nearby galaxy within the error box; if some showers in a group had galaxies in regions smaller than the 3-error box but larger than the 2-error box, we determined the weighted mean error box; so the 2-error box means also the 2.1- or 2.2-error box, and similarly the 1-error box means also the 1.2- or 1.3-error box): 63 showers with no selection in Galactic latitude, $P_1(16) = 1.1 \times 10^{-3}$, $P_2(27) = 3.6 \times 10^{-4}$ and $P_3(29) = 2.4 \times 10^{-2}$; 54 showers with $|b| > 11.2°$, $P_1(16) = 1.2 \times 10^{-3}$, $P_2(26) = 6.5 \times 10^{-4}$ and $P_3(29) = 1.8 \times 10^{-2}$; 37 showers with $|b| > 21.9°$, $P_1(13) = 3.2 \times 10^{-3}$, $P_2(23) = 1.8 \times 10^{-4}$ and $P_3(23) = 2.5 \times 10^{-2}$; 27 showers with $|b| > 31.7°$, $P_1(14) = 5.1 \times 10^{-4}$, $P_2(23) = 2.0 \times 10^{-5}$ and $P_3(23) = 9.5 \times 10^{-3}$. Here probabilities are $P > 3\sigma$ for the 1- and 2-error boxes for showers at any latitudes, except for $|b| > 21.9°$, where $P_1 \approx 2.95\sigma$.

For nearby Seyfert galaxies having detailed classification, the probabilities are as follows: 63 showers with no selection in Galactic latitude, $P_1(12) = 1.1 \times 10^{-2}$, $P_2(23) = 3.2 \times 10^{-3}$ and $P_3(27) = 3.2 \times 10^{-2}$; 54 showers with $|b| > 11.2°$, $P_1(12) = 1.5 \times 10^{-2}$, $P_2(22) = 5.2 \times 10^{-3}$ and $P_3(27) = 2.3 \times 10^{-2}$; 37 showers with $|b| > 21.9°$, $P_1(9) = 3.0 \times 10^{-2}$, $P_2(19) = 3.0 \times 10^{-3}$ and $P_3(21) = 3.7 \times 10^{-2}$; 27 showers with $|b| > 31.7°$, $P_1(10) = 1.0 \times 10^{-2}$, $P_2(19) = 1.1 \times 10^{-3}$ and $P_3(21) = 2.2 \times 10^{-2}$. Here probabilities are $P \geq 3\sigma$ for the 2-error boxes at any latitudes, except for showers at $|b| > 11.2°$ where $P_2 \approx 2.80\sigma$.

Because of the low values of probabilities it is difficult to ignore nearby active galaxies as possible UHECR sources. (Probabilities increase with increasing z; see Uryson (1996) for $P(z)$ relations for showers arriving from sky areas located at arbitrary b.)

3.2 Blue Lacertae Objects and Radiogalaxies

For comparison, the results of identification of BL Lac objects are shown in this section.

Confirmed, probable or possible BL Lac objects have been listed by Veron-Cetty and Veron (2001). For all these objects the probabilities of chance coincidence using the 1-, 2- and 3-error boxes, $P_1(N)$, $P_2(N)$ and $P_3(N)$ respectively, are the following: 63 showers with no selection in Galactic latitude, $P_1(45) < 4 \times 10^{-5}$, $P_2(56) = 6 \times 10^{-5}$ and $P_3(57) = 2.3 \times 10^{-2}$;

54 showers with $|b| > 11.2°$, $P_1(42) < 3 \times 10^{-5}$, $P_2(51) = 3.4 \times 10^{-4}$ and $P_3(51) = 1.0 \times 10^{-1}$; 37 showers with $|b| > 21.9°$, $P_1(36) < 4 \times 10^{-5}$, $P_2(36) = 2.5 \times 10^{-3}$ and $P_3(36) = 8.7 \times 10^{-2}$; 27 showers with $|b| > 31.7°$, $P_1(27) < 4 \times 10^{-5}$, $P_2(27) = 5.2 \times 10^{-2}$ and $P_3(27) = 4.5 \times 10^{-1}$.

For confirmed BL Lac objects, the probabilities are as follows: 63 showers with no selection in Galactic latitude, $P_1(38) < 1 \times 10^{-5}$, $P_2(48) = 4.7 \times 10^{-4}$ and $P_3(53) = 1.0 \times 10^{-2}$; 54 showers with $|b| > 11.2°$, $P_1(42) < 3 \times 10^{-5}$, $P_2(43) = 6.9 \times 10^{-3}$ and $P_3(47) = 7.5 \times 10^{-2}$; 37 showers with $|b| > 21.9°$, $P_1(28) < 3 \times 10^{-5}$, $P_2(33) = 1.8 \times 10^{-3}$ and $P_3(35) = 4.0 \times 10^{-2}$; 27 showers with $|b| > 31.7°$, $P_1(24) < 1 \times 10^{-5}$, $P_2(26) = 1.2 \times 10^{-2}$ and $P_3(27) = 2.0 \times 10^{-1}$.

BL Lac objects are considered as possible UHECR sources owing to the low values of probabilities for the 1-error boxes and in some cases for the 2-error boxes. Similar results were obtained by Tinyakov and Tkachev (2001) and by Gorbunov *et al.* (2002).

For comparison, we obtain large probabilities $P \approx 0.01$–0.1 using the same procedure for identifying radio galaxies.

4 CONCLUSION

We repeated direct identification of UHECR possible sources, this time with statistics of 63 showers at energies above 4×10^{19} eV and with the catalogue by Veron-Cetty and Veron (2001). It is confirmed that UHECR sources could be near active nuclei with red shifts $z < 0.01$, as we showed earlier (Uryson, 1996, 1999, 2001a, b, c). BL Lac objects also could be candidates for accelerators of UHECRs, as was found by Tinyakov and Tkachev (2001), Uryson (2001a, b, c), and Gorbunov *et al.* (2002).

Acceleration of particles up to 10^{21} eV in moderate active nuclei has been described by Uryson (2001d).

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References

Afanasiev, B. N., Dyakonov, M. N., Egorova, V. P., Efremov, N. N., Glushkov, A. V., Ivanov, A. A. *et al.* 1996, In: Nagano, M. (Ed.), Proceedings of the International Symposium on Extremely High Energy Cosmic Rays: Astrophysics and Future Observatories, Institute for Cosmic Ray Research, Tokyo, p. 32.
Berezinsky, V., Kachelries, M. and Vilenkin, A., 1997, Phys. Rev. Lett. 79, 4302.
Berezinsky, V. and Vilenkin, A., 1997, Phys. Rev. Lett. 79, 5202.
Bhattacharjee, and Sigl, G., 2000.
Farrar, G. R. and Biermann, P. L., 1998, Phys. Rev. Lett. 81, 3579.
Forsythe, G. E., Malcolm, M. A. and Moler, C. B., 1977, Computer Methods for Mathematical Computations, Prentice-Hall, Englewood Cliffs, New Jersey.
Gorbunov, D. S., Tinyakov, P. G., Tkachev, I. I. and Troitsky, S. V., 2002, Astrophys. J. 577, L93.
Greisen, K., 1996, Phys. Rev. Lett. 16, 748.
Hayashida, N., Honola, K., Honda, M., Inoue, N., Kadota, K., Kakimoto, F. *et al.* 1996, Phys. Rev. Lett. 77, 1000.
Hill, C. T., Schramm, D. N. and Walker, T. P., 1987, Phys. Rev. D 36, 1007.
Hillas, M., 1998, Nature 395, 15.
Hoffman, C. M., 1999, Phys. Rev. Lett. 83, 2471.
Hudson, D. J., 1964, Statistics, Lectures on Elementary Statistics and Probability, CERN Geneva.

Kuzmin, V. A. and Rubakov, V. A., 1998, Yad. Fiz. 61, 1122 (Engl. Transl. 1998, Phys. At. Nucl. 61, 1028).
Sakaki, N., Chikawa, M., Fukushima, M., Hayashida, N., Honda, K. *et al*. Proceedings of the 27th International Cosmic Ray Conference, Hamburg, HE1.5, p. 551. Editors: Kampert, K.-H., Hainzelmann, G. and Spiering, C.
Sigl, G., Torres, D. F., Anchordoqui, L. A. and Romero, G. E., 2001, Phys. Rev. D 63, 081302(R).
Stecker, F. W., 1968, Phys. Rev. Lett. 21, 1016.
Stecker. F. W., 1998, Phys. Rev. Lett. 80, 1816.
Squires, G. L., 1968, Practical Physics, McGraw-Hill, New York.
Tinyakov, P. G. and Tkachev, I. I., 2001, Pis'ma Zh. Éksp. Teor. Fiz. 74, 499.
Uryson, A. V., 1996, Pis'ma Zh. Éksp. Teor. Fiz. 64, 71 (Engl. Transl. 1996, JETP Lett. 64, 77).
Uryson, A. V., 1999, Zh. Éksp. Teor. Fiz. 116, 1121 (Engl. Transl. 1999, Soviet Phys. JETP 89, 597).
Uryson, A. V., 2001a, Astron. Zh. 45, 591 (Engl. Transl. 2001, Astron. Rep. 45, 686).
Uryson, A. V., 2001b, Astron. Astrophys. Trans. 20, 347.
Uryson, A. V., 2001c, Proceedings of the 27th International Cosmic Ray Conference, Hamburg, HE1.5, p. 551. Editors: Kampert, K.-H., Hainzelmann, G. and Spiering, C.
Uryson, A. V., 2001d, Pis'ma Astron. Zh. 27, 901 (Engl. Transl. 2001, Astron. Lett. 27, 775).
Veron-Cetty, M. P. and Veron, P., 2001, Astron. Astrophys. 374, 92.
Watson, A. 1995, In: Kolb, E. W. and Peccei, R. D. (Eds.), Particle and Nuclear Astrophysics in the Next Millenium, World Scientific, Singapore, p. 126.
Zatsepin, G. T. and Kuz'min, V. A., 1966, Pis'ma Zh. Éksp. Teor. Fiz. 4, 114 (Engl. Transl. 1966, JETP Lett. 4, 78).