## Sources of UHECRs in view of the TUS and JEM-EUSO experiments

## N N Kalmykov, B A Khrenov, G V Kulikov and M Yu Zotov

Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics, Moscow, Russia, 119234

E-mail: zotov@eas.sinp.msu.ru

**Abstract.** The origin of ultra-high-energy cosmic rays (UHECRs) is one of the most intriguing problems of modern cosmic ray physics. We briefly review the main astrophysical models of their origin and the forthcoming orbital experiments TUS and JEM-EUSO, and discuss how the new data can help one solve the long-standing puzzle.

In 1984, Hillas suggested a simple necessary condition for an astrophysical object to be able to accelerate charged particles to ultra-high energies [1]. The criterion is based on the demand that the Larmor radius of a particle of charge Z in a magnetic field B should not exceed the size R of the acceleration region. In its simplest form, this boils down to the following estimate of the maximum energy that can be obtained by a particle:  $E_{\text{max}} \leq \beta ZBR$ , where B is expressed in units of  $\mu$ G, R is in kpc, energy is in the units of EeV, and  $\beta$  represents the velocity of the accelerating shock wave or the efficiency of the accelerator. The criterion can be illustrated by a now famous Hillas diagram. Different estimates of parameters of cosmic accelerators result in slightly different Hillas diagrams, compare, for example, those given in [2, 3, 4, 5]. Still, almost all authors select the following four major classes of possible sources of UHECRs: large-scale shocks due to merging galaxies or clusters of galaxies, the core and jets of active galactic nuclei (AGN), newly-born neutron stars and other similar objects, and gamma-ray bursts.

Cluster accretion shocks are the largest systems in the known universe that satisfy the Hillas criterion. They have been considered as possible sources of UHECRs by various authors, see, e.g., [6, 7] for the early discussions. In particular, Kang et al. [7] suggested that protons can be accelerated by these accretion shocks up to energies  $\sim 6 \times 10^{19}$  eV assuming acceleration is performed via the first-order Fermi process and provided the mean magnetic field strength in the region around the shocks is  $\gtrsim 1\mu G$ . Later calculations that were based on the framework of diffusive shock acceleration (DSA) and included energy losses due to interactions of protons with photons of the CMBR lead to somehow more modest estimates of the maximum achievable energy but the conclusion remained intact: under certain conditions, galaxy clusters are able to accelerate protons and heavier nuclei to ultra-high energies [8]. It is worth mentioning that particles accelerated via DSA in shocks that occur during cluster mergers, together with magnetic fields, emit synchrotron radiation and may form so-called radio relics. One such relic with the size of 2 Mpc and highly aligned magnetic fields has been detected recently in the northern outskirts of the galaxy cluster CIZA J2242.8+5301 (z = 0.1921) providing evidence that DSA can operate on scales much larger than in supernova remnants and that shocks in galaxy clusters are capable of producing UHECRs [9].

Active galactic nuclei are probably the most popular astrophysical objects potentially capable to produce and accelerate particles up to the highest energies. They are composed of an accretion disk around a central super-massive black hole and are sometimes associated with jets terminating in lobes (or hot spots) that can be detected in radio, see, e.g., [3]. AGN can be divided into two groups: radio loud objects with jets and radio quiet ones with no prominent radio emission or jets. AGN jets have dimensions of the order of a parsec with magnetic fields of the order of a few Gauss and can in principle accelerate protons up to tens of EeV. In their turn, AGN cores with a magnetic field ~  $10^3$  G and the size of a few  $10^{-5}$  pc can reach approximately the same energy [4]. However, these maxima are unlikely to be reached because of adiabatic losses, energy losses due to synchrotron radiation and inverse Compton processes, as well as photodisintegration of heavy nuclei thus reducing the maximum achieved energy to only a fraction of EeV [10]. To get around the problem, the acceleration site must be away from the AGN center and in a region with a lower radiation density. Among radio loud galaxies, the Fanaroff–Riley galaxies of class II are of special interest because they combine a powerful engine and relativistic blast wave together with a relatively scarce environment.

AGN as possible sources of UHECRs attract special attention after the Pierre Auger Observatory (PAO) reported correlation of their higher energy events with the nearby AGN (distances within 75 Mpc) [11, 12, 13]. The largest excess of arrival directions relative to isotropic expectations was found around the position of Cen A, the nearest radio loud AGN located at a distance of 3.8 Mpc from the Solar system. Still, this is not a proof that AGN are sources of UHECRs. A similar analysis performed by the HiRes experiment did not reveal any deviation from the isotropic distribution [14]. One should note though that an analysis of anisotropy of arrival directions of UHECRs is not a trivial task and different conclusions can be obtained with the same data, see, e.g., [15].

**Pulsars** attracted attention as possible accelerators of UHECRs soon after they were identified with rotating neutron stars possessing huge magnetic fields. It was suggested that protons can obtain energies up to  $10^{21}$  eV by riding in the outgoing strong wave field beyond the light cylinder of a pulsar [16]. It was soon demonstrated though that maximum energies to which particles are accelerated may be considerably lower because even a small contamination of plasma in the waves would destroy the necessary phase locking [17].

An interest to pulsars as possible accelerators received another impetus when it was demonstrated that young strongly magnetized neutron stars with short enough initial spin periods are able to accelerate iron nuclei to energies  $\geq 10^{20}$  eV through relativistic MHD winds [18]. Recent calculations [19] show that, at early times, when protons can be accelerated to energies  $E > 10^{20}$  eV, the young supernova shell tends to prevent their escape. In contrast, because of their higher charge, iron-peaked nuclei are still accelerated to the highest observed energies at later times, when the envelope has become thin enough to allow their escape. Ultrahigh energy iron nuclei escape newly-born pulsars with millisecond periods and dipole magnetic fields of ~  $10^{12}-10^{13}$  G, embedded in core-collapse supernovae. It is remarkable that due to the production of secondary nucleons, the envelope crossing leads to a transition from light to heavy composition at a few EeV, as was recently found by the PAO [20, 21] (provided that the models used give a fairly proper description of the physical processes at these energies). According to [19], the escape also results in a softer spectral slope than that initially injected via unipolar induction, which allows for a good fit to the observed UHECR spectrum.

**Gamma-ray bursts** were independently suggested as possible candidate sources of UHE particles in [22, 23, 24]. Waxman and Vietri demonstrated basing on the fireball model by Mészáros and Rees [25] that protons can be accelerated to energies  $\sim 10^{20}$  eV by the conventional Fermi mechanism at highly relativistic shocks. The model predicted a mostly isotropic, time-independent distribution of arrival directions of UHECRs because so are GRBs, and correctly predicted the total flux of UHECRs at Earth by an order of magnitude.

In 1997, Waxman and Bahcall found that a large fraction ( $\geq 10\%$ ) of the energy of a fireball producing a gamma-ray burst is expected to be converted by photomeson production to a burst of ~ 10<sup>14</sup> eV neutrinos [26]. More than this, it was demonstrated that a kilometer-scale neutrino detector would observe at least several tens of events per year correlated with GRBs in case the GRB model of UHECR origin is correct. Since then, the model received much attention even though some authors remained sceptical about it. One of the challenges for the GRB model relates to the trend toward a heavy composition at the highest energies found by the PAO [20, 21].

Doubts in the validity of the model became stronger after the IceCube collaboration published their latest results on the search for neutrinos associated with GRBs [27], confirming the earlier conclusions [28, 29]. Namely, the IceCube collaboration studied the data obtained while the telescope was under construction using the 40- and 59-string configurations of the detector. which took data from April 2008 to May 2009 and from May 2009 until May 2010, respectively. Totally, around 300 GRBs were observed and reported via the GRB Coordinates Network during the two data taking periods and included in the study. Two analyses of the IceCube data were performed. In a model-dependent search, all data during the period of gamma emission reported by any satellite was examined, with the energy spectrum predicted from gamma-ray spectra of individual GRBs. The models tested were different formulations of the same fireball phenomenology, producing neutrinos at proton-photon interactions in internal shocks with their standard parameters and uncertainties on those parameters. The model-independent analysis searched more generically for neutrinos on wider time scales, up to the limit of sensitivity to small numbers of events at  $\pm 1$  day, or with different spectra. As a result, an upper limit on the flux of UHE neutrinos associated with GRBs was found to be at least a factor of 3.7 below the predictions of the models considered. It was thus concluded that GRBs are not the only source of UHECRs or the efficiency of neutrino production is much lower than has been predicted.

However, Li argued after [28, 29] were published that the theoretical prediction of neutrinos from GRBs by IceCube overestimates the GRB neutrino flux by a factor  $\sim 5$  because they ignore both the energy dependence of the fraction of proton energy transferred to charged pions and the radiative energy loss of secondary pions and muons when calculating the normalization of the neutrino flux [30]. This point of view was later supported by Hümmer et al. [31]. They kept intact the astrophysical parameters of the fireball model used for the analysis of the IceCube data made in [28] but included the full spectral dependencies of the proton and photon spectra, the cooling of the secondaries, flavour mixing and additional multi-pion, kaon, and neutron production channels for the neutrinos. As a result, a significant deviation in the normalization of the predicted neutrino flux of about an order of magnitude, with a very different spectral shape peaking at slightly higher energies was found. Different arguments were put forward by Dar to demonstrate that the IceCube collaboration over-interpreted their results and they do not exclude GRBs as the main source of UHECRs [32].

There is also a class of so called "top-down" models, which predict UHECRs from the decay of super-heavy relic particles, see, e.g., [10] for a review. These models are currently disfavoured by the limits of the PAO on the photon fraction [33], and we do not discuss them here.

As we have seen above, the problem of the origin of UHECRs might be far from its solution, and the existing experiments will not necessarily provide data sufficient for obtaining the final answer. That is why special attention is now paid to the forthcoming orbital experiments TUS aboard the Mikhail Lomonosov satellite [34] and JEM-EUSO aboard the International Space Station [35]. Recall that TUS is the first orbital detector of UHECRs. It consists of the two main parts, a Fresnel-type segmented mirror-concentrator of  $\sim 2 \text{ m}^2$  area and a photo receiver built of 256 photomultiplier tubes. The field of view (FoV) of the detector equals 4.5° and covers an area of  $(H \times 0.16)^2 \text{ km}^2$ , where H changes from 550 km to 350 km in three years of operation. The energy threshold of the detector is  $\sim 70 \text{ EeV}$ .

The TUS detector is to a large extent a pathfinder aimed to test the concept of registering

UHE particles from space suggested by Benson and Linsley more than 30 years ago [36]. The JEM-EUSO mission is a much more advanced experiment with a 2.5 m telescope with a superwide (60°) FoV as the main instrument. It is expected that the cumulative exposure of JEM-EUSO will be of the order of  $10^6 \text{ km}^2$  sr yr at 300 EeV, which is approximately an order of magnitude greater than possibly achieved by the PAO. With JEM-EUSO, baryons, photons and neutrino primaries can be discriminated with considerable accuracy, and upper limits to the fluxes of the last two will be improved by at least a factor of 10 beyond present experiments. The mass target inside the FoV is  $\sim 10^{12}$  ton, which depending on the actual astrophysics scenario makes likely the observation of up to a few cosmogenic neutrinos per year, thus providing an additional opportunity to test the above models of sources of UHECRs.

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