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Review

Messengers of the Universe-Cosmic Rays Exploring Supermassive Black Holes

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Abstract: Cosmic rays were discovered over one hundred years ago but there are still unsolved problems. One of the hot problems is the origin of cosmic rays of the highest energies. Sources are still unclear and it is neither clear how particles gain ultra-high energies. Possible sources of cosmic rays at the highest energies are supermassive black holes. From this perspective we discuss in a popular form some recent developments in cosmic ray studies along with author's recent results. The paper also offers materials for further reading.

Keywords: cosmic rays; ultra-high energies; active galactic nuclei; supermassive black holes

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Citation: Uryson, A. Messengers of the Universe-Cosmic Rays Exploring Supermassive Black Holes. *Galaxies* **2021**, *9*, 2. https://doi.org/10.3390/galaxies9010002

Received: 30 November 2020
Accepted: 23 December 2020
Published: 29 December 2020

1. Introduction

1.1. What Are Cosmic Rays?

Cosmic rays were discovered by the Austrian physicist Victor Hess in 1912. For his study he used simple portable devices—electroscopes in balloons.

For this discovery, Hess received the Nobel Prize in Physics in 1936.

Later it was demonstrated that cosmic radiation consisted mainly of charged elementary particles (protons and electrons) and fragments of atomic nuclei (then a very small admixture of gamma quanta and neutrinos was found in cosmic rays). Cosmic particles arrive to Earth from space.

In 1930–1940s cosmic ray interactions with matter were studied intensively. These studies led to the discovery of new elementary particles.

We now turn from physics history to cosmic ray astrophysics.

Physicists use different types of instruments to detect cosmic rays. These detectors can be ground-based or installed on space satellites or at high altitude balloons.

Particles at energies up to 48 Joule (J) have been detected in cosmic rays. These energies are so high that no particle accelerator built on Earth is able to provide such energy, including the most powerful Large Hadron Collider.

It is worth mentioning that in particle physics and astrophysics the energy unit electron-volt (eV) is commonly used rather than Joule. So, the maximal energy of particles detected in cosmic rays is about 3×10^{20} eV.

The energy range of cosmic rays is extremely large: from 10^6 up to 3×10^{20} eV.

Cosmic rays travel with gigantic velocities close to the speed of light. At lower energies particles also travel at the same speed.

1.2. What Is the Origin of Cosmic Rays?

Particles at energies lower than 2×10^{10} eV come from the sun, and they are called solar cosmic rays. At higher energies, up to 10^{17}–10^{18} eV, they originate from outside the solar system in our Galaxy in supernova explosions, and are called galactic cosmic rays.

Cosmic particles at higher energies, more than 10^{19} eV, are called ultra-high energy cosmic rays (UHECRs). This scientific term contains no information related to the origin of cosmic particle. It indicates only the particle energy range. Years of research revealed that cosmic ray accelerators are astrophysical objects located outside our galaxy.

What are these objects and processes accelerating cosmic rays to ultra-high energies? In the paper we consider, in a popular form, supermassive black holes as possible sources of cosmic rays at the highest energies and discuss the results and problems related to the subject.

The structure of the paper is as follows.

Methods of cosmic ray detection are given briefly in Section 2. Supermassive black holes inside active galactic nuclei are discussed in Sections 3–7 as we believe that they are involved in particle acceleration. Theoretical results on cosmic ray acceleration in supermassive black holes are shown in Section 8. Section 9 describes cosmic ray propagation in the universe. In Section 10 we show how to study processes in supermassive black holes using data on cosmic rays. In Section 11 general outlook on the study of cosmic rays is presented. Processes of cosmic ray acceleration are discussed in Section 12. The conclusion is given in Section 13. Finally, in Section 14 a short list of scientific articles, results of which are used in the paper, is presented. Section 14 also briefly describes problems discussed in these articles. It is for those readers who are interested in more details of cosmic ray astrophysics. All references are given in this section.

2. Methods of Cosmic Ray Detection

The number of cosmic particles decreases strongly with increasing energy. Due to this, cosmic rays at various energies are detected by different methods. Cosmic rays at energies of $E = 10^6$–5×10^8 eV are detected with detectors on board satellites. Cosmic rays at energies of $E = 10^9$–10^{12} eV are detected mainly with detectors on balloons. Particles at higher energies are detected using Earth's atmosphere. How is that possible? Cosmic rays—*primaries*—bombard the atmosphere and interact with its molecules. As a result new particles—*secondary* particles or *secondaries* are generated, which also interact with atmospheric elements. This process develops as an avalanche producing a huge amount of secondaries that diverge to tens and hundreds of meters. It looks like a thin disk of particles moving through the atmosphere with almost the speed of light and spreading with the atmosphere depth. The shower of particles is called extensive air shower. The axis of the disk is the shower axis and it coincides with the direction of primary's movement.

Figure 1 shows the cosmic ray observatory in Tian-Shan mountains, Kazakhstan, with a schematic view of two detectors and their location.

Cosmic rays at the energies $E \geq 10^{14}$ eV give rise to extensive air showers where particles spread around the area of hundreds square meters. Thus particles can be registered using many small detectors located at the large area.

Cosmic rays at ultra-high energies, higher than 10^{19} eV are rare: 1 particle per km^2 per year. Thus very large arrays are required to study ultra-high energy cosmic rays. Those are the Pierre Auger Observatory (PAO) in Argentina called after French physicist Pierre Auger, one of the pioneers in study atmospheric showers, and the telescope array (TA) in Utah, USA. The PAO consists of a 3000 km^2 array of 1660 particle detectors, and the TA consists of more than 500 detectors sampling events over 780 km^2. Figures 2 and 3 give a look on the landscape and detectors of the PAO and the TA. Scientists from different countries team up to maintain activity of the arrays and analyze the data.

Figure 1. Cosmic ray observatory of Lebedev Physical Institute of Russian Academy of Sciences, Tian-Shan mountains. Location and designation of two of the detectors are shown schematically. Source: https://sites.lebedev.ru/ru/lgase/.

Figure 2. Several detector components of the Pierre Auger Observatory in Argentina. Photo Credit: Tobias Winchen-Own work, CC BY-SA 3.0, Source: https://commons.wikimedia.org/w/index.php?curid=18816298.

Figure 3. One of the detectors of the telescope array cosmic ray observatory in Utah, USA. Photo Credit: John Matthews, University of Utah, Source: archive.unews.utah.edu.

2.1. What Data Are Obtained with These Arrays?

Those are particle energies, arrival directions and cosmic ray composition (protons or atomic nuclei fragments), which are determined using special computer codes.

2.2. How Are These Data Used to Reveal Cosmic Ray Origin?

Cosmic ray arrival directions on Earth are unusable as pointers on sources because charge particles are deflected by extragalactic magnetic fields. Particle energies are used to investigate some parameters of sources. This is discussed in Sections 9 and 10.

The cosmic ray energy distribution (energy spectrum) of the PAO and the TA are shown in Figure 4.

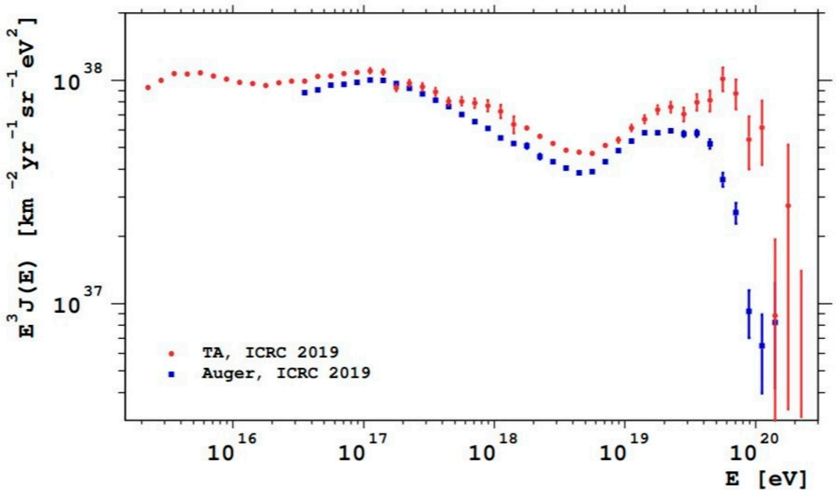

Figure 4. Cosmic ray energy distribution (energy spectrum) obtained at the Pierre Auger Observatory (PAO) (blue points) and the telescope array (TA) (red points) scaled by E^3. In each experiment data of different techniques are combined to obtain the spectrum over wide energy range. The figure is taken from the joint report of the PAO and TA collaborations presented at the International Cosmic Ray Conference (ICRC) in 2019. The discrepancy between the PAO and the TA results is also discussed in the report. The reference is in Section 14.

Satellites are also used to obtain some information on ultra-high energy cosmic rays, in addition to ground based arrays. The flux of these particles is extremely low and the indirect method is used. Ultra-high energy particles propagating in space interact with photons and contribute to the gamma-radiation that is registered with apparatus on board. Knowing the value of the gamma-radiation and using theoretical results some parameters of particle sources can be derived. Figure 5 shows the cosmic ray observatory Fermi to obtain data for ultra-high energy cosmic ray studies.

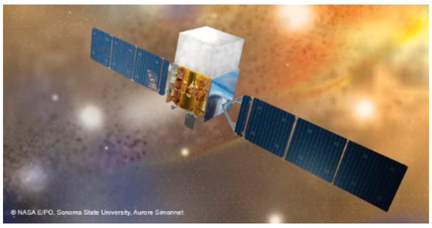

Figure 5. The Fermi gamma-ray space telescope. Photo Credit: NASA E/PO. Sonoma State University, Aurore Simonnet, Source: https://astro.desy.de/gamma_astronomy/fermi/index_eng.html.

Neutrinos are also produced in cosmic ray interactions with photons. Neutrino flux is used to define source parameters as well. It is measured at ground-based neutrino observatories. One of them, the IceCube neutrino observatory is located near the South Pole. Thousands of sensors deep within the Antarctic ice are distributed over a cubic kilometer. The IceCube observatory is shown in Figure 6.

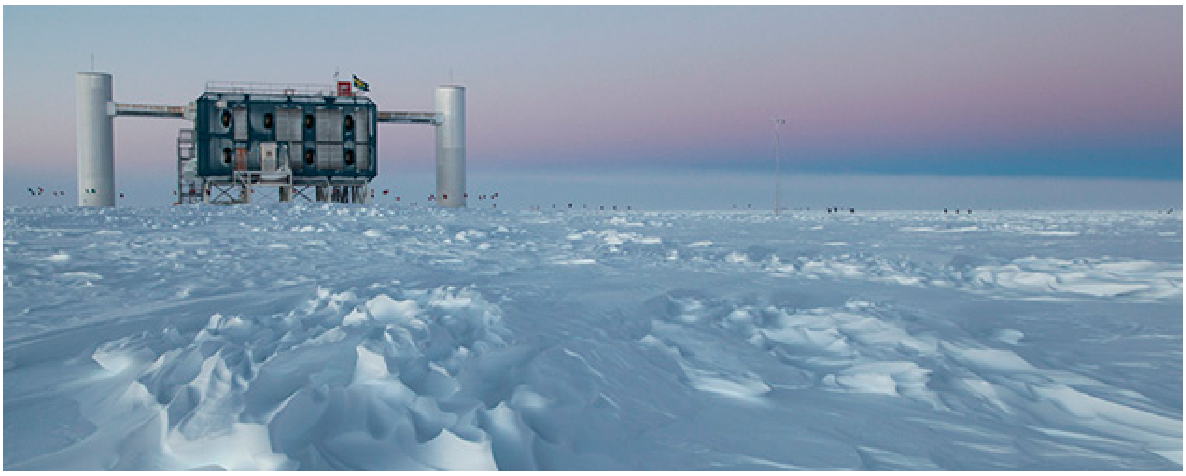

Figure 6. The IceCube Lab at the South Pole in Antarctica. Image: S. Lidstrom/NSF, Source: icecube.wisc.edu.

Study of particle origin using data of ground-based arrays and satellites is discussed in Sections 9–11.

3. Outside the Milky Way; Active Galactic Nuclei

Our galaxy the Milky Way that contains the solar system is one of many galaxies in the universe.

A galaxy is a gravitationally bound system consisting of stars (sometimes with planet systems), star remnants, interstellar gas and dust and dark matter.

The central part of many galaxies contains a compact, massive cluster of matter. It is called galactic nucleus. Higher density of matter in the central region is caused by gravitation. It pulls the stars and interstellar matter towards the center and form the nucleus. Galaxies with small mass have no nucleus as its gravity is insufficient to pull the matter towards the center.

Galaxies vary in many features: in appearance, dimension, intensity of star formation, relation between old and young stars. Galaxies are classified according to these features. In addition galaxies differ in characteristics of the nucleus.

In most galaxies, the main part of energy is emitted by stars, and stars also provide the nucleus emission. These galactic nuclei are called inactive.

However, there is a small amount of galaxies where nucleus emission is extremely powerful compared to the rest of the galaxy: A huge energy stream breaks away from a nucleus, as if one hundred million sun-like stars shine in the galactic center. The nucleus emission is highly variable, sharply diminishing and increasing during a very short period of time (on the scale of hours, days, months and years). A nucleus emits energy in different bands: radio, X-rays, ultraviolet, infrared and gamma ranges. Plasma portions are spread outwards a nucleus; gas clouds move rapidly in its vicinity. These processes cannot be caused by high volume density of stars or interstellar matter. Such galactic nuclei are called active. There is only 1% of galaxies of this type in the universe.

Active galactic nuclei are classified in types depending on the form of their activity. For instance, the most powerful galactic nuclei are called quasars, galaxies with powerful radio emission in nuclei are called radio galaxies. Another example: galaxies with extremely variable emission but no so bright as quasars are called Seyfert galaxies (named after astronomer Seyfert).

Detailed description of the active nucleus classification is not important for our study. Its main goal is given in the next section.

4. Active Galactic Nuclei and Cosmic Rays

Each active galactic nucleus emits gigantic amount of energy. Possibly cosmic rays gain ultra-high energies in energetic processes ongoing in nuclei. Then accelerated particles fly out of the region where they gain the energy, escape from the galaxy, travel huge distances in space and finally reach Earth. Is it possible to study active galactic nuclei by detecting cosmic rays on Earth, despite particles' long flight in the cosmos?

In this study it is important to answer the questions: what is the source of energy in active galactic nuclei, how particles are accelerated, and what happens to the particles during their flight through the extragalactic space. Before discussing these points a short description of possible cosmic ray sources is given in next sections.

5. The Source of Energy in Active Galactic Nuclei and Supermassive Black Holes

It is of the current opinion now that nucleus activity is caused by a supermassive black hole in the galactic center. What are black holes? A black hole is a celestial object with a very strong gravitational field. It is so strong that nothing, even light, can escape from there. How can that be? To overcome the attractive force of any celestial object, a body should move with the escape velocity. However, in black holes it is higher than the speed of light. Nothing travels faster than the speed of light in the universe, and because of this it is impossible to escape from black holes. As light is not able to leave black holes, they are dark and invisible for observer.

At large distances black hole gravitation weakens to the level of an "ordinary" star. The radius of the black hole vicinity from which nothing including signals come out is called the event horizon.

When the black hole mass is higher than 10^5 solar mass ($M_\odot$) the black hole is called supermassive. Evidence of black holes with masses $M \approx (10^5–10^{11})$ $M_\odot$ are observed in active galactic nuclei.

Black holes are so extraordinary that people (not physicists) believe that they are mysterious.

Black holes are quite unusual celestial objects that were first considered by a brilliant English scientist and parson Michell in 1783 and by a great French mathematician, physicist and astronomer Laplace in 1796. In 1916 they were rediscovered by Schwarzschild based on Einstein field equations in general theory of relativity. (The 2020 Nobel prize in Physics was awarded for the theory and astronomical observations of black holes).

Interestingly, our galaxy the Milky Way evidently contains the central supermassive black hole with the mass of 10^6 solar masses. At present its activity is weak. However black hole activity varies in time, and there are evidences that “our” black hole was apparently active, e.g., ~300–400 years ago and ~25,000 years ago. Evidence of the supermassive black hole in the center of our galaxy along with evidence of its activity is the result of astronomical observations during last 20 years.

6. The Accretion Disk around a Supermassive Black Hole

Due to the attractive force matter in the vicinity of a black hole falls into it. This matter consists of nearby stars and interstellar gas and dust. Stellar gas from surfaces of nearby stars is also “swallowed” by black holes (dust and interstellar gas contribute much less than the stellar one).

Stellar matter falls not vertically but whirling (as stars move on orbits) and thus forming disk around a black hole. The accretion disk is dense. Its thickness depends on black hole characteristics.

Matter falling in the black hole gravitational field, its potential energy transforms into kinetic energy. As a result the matter accelerates to tremendous velocity, close to the speed of light. Acceleration of the falling matter occurs in exactly the same way as acceleration of a stone falling to the ground.

In the disc gas layers move around the center, however with different velocities: the closer to the center, the higher is the speed. The friction between the layers transforms the layer kinetic energy into thermal energy of atoms in the gas. As a result the gas is heated to very high temperature and the disc shines in radio, infrared and optical bands, in X-rays and gamma rays.

7. Magnetic Field of Accretion Discs; Jets

Magnetic field threads through interstellar gas and stars:

Almost all matter in interstellar medium and stars is ionized, consisting of charged particles. These factors lead to magnetic field line freezing-in: charged particles are as if “fastened” to the line, and it has to move along with moving particles. As magnetic field moves with the falling gas the disc is magnetized. Gas density increasing, the magnetic lines get closer and the field increases. As the result the magnetic field in discs can be much stronger than the field threading through interstellar gas and stars.

In the accretion disc, gas not only rotates but also slowly moves in a radial direction (the speed of moving depends on mass and temperature of the disc).

In some disks moving and rotating magnetic fields frozen in plasma collimate plasma in columns (protuberances) rising up near the poles. The columns eject plasma blobs that form narrow jets along the disc axis, perpendicularly to the disc plane. In a simplified manner jets can be explained in the following way. Rotating gas moves in the radial direction, the radial velocity depending on the disk mass and temperature. There are discs where gas radial motion is so fast that too much gas arrive to the disc center. The black hole is not able to “eat” the gas completely, and its excess is ejected outward forming jets.

A supermassive black hole with the accretion disc and jets is shown in Figure 7.

Figure 7. A supermassive black hole with the accretion disc and jets painted by an artist. The author: Victor Habbic Visions. Source: newshub.co.nz.

Disk magnetic field encircles the black hole forming its magnetosphere.

8. Particle Acceleration in the Vicinity of Supermassive Black Holes

Supermassive black holes have three areas where particles can be accelerated. They are magnetosphere of a black hole, its accretion disc and jets. The accelerating mechanism in each area is different and accelerated particles have different *energy spectra*.

What is an energy spectrum? Let us define the number of particles at equal energies and plot the number against the particle energy. This dependence is called the *particle energy spectrum*. The energy spectrum can be obtained also analytically, represented as a formula. The strict definition of energy spectrum is the number $\mathrm{d}N$ of particles at the energy E in the unit energy interval $\mathrm{d}E$. Energy spectra produced in sources are called *injection spectra*. It was found theoretically that particles accelerated by the varied mechanisms have different injection spectra (or, in some cases, possibly different spectra). The accelerating mechanisms and some models are discussed in Section 12.

Two different ways of particle acceleration are by shock fronts and by electric fields (a description of mechanisms is given in Section 12.)

Based on the theoretical results, in the former case the cosmic ray energy spectrum is described as $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha}$, with spectral index α equal to $\alpha \approx$ (2–2.5). This type of spectra is called exponential. The higher the energy, the faster the number of particles decreases (or the higher is the rate of particle number reduction). This mechanism works in jets.

When particles are accelerated by electric fields in the black hole vicinity, two different injection spectra can be produced.

First, particles can gain approximately equal amounts of energy. In this case the injection spectrum is called monoenergetic. It is shown theoretically that this spectrum is realized in black hole magnetospheres.

Next, the spectrum can be exponential with spectral indices $\alpha \approx$ (0–2.1). It means that the number of particles decreases not so fast with energy, as when $\alpha > 2.1$. The index value 0 is realized in processes where the number of accelerated particles is the same at any energy. We suppose that this energy spectrum possibly is produced in accretion discs and jets.

At present it is unknown what mechanisms are realized in the vicinity of supermassive black holes. Can we determine in what processes particles have been accelerated? At this point it seems like we have found a very simple way to answer the question. First, we obtain cosmic rays energy spectrum on Earth. Next, we compare the data with theoretical injection spectra, find the best fitting and corresponding values of α. Thus we reveal how and where cosmic rays have been accelerated.

However, this simple idea does not work for the following reasons.

9. What Happens with Cosmic Rays Flying through the Universe

Leaving their accelerator, cosmic rays then fly away from the galaxy and propagate in extragalactic space. Particles reaching the Earth cover distances of tens of millions and hundreds of millions of light years. Those are massive distances. Even photons moving with the fastest speed in the universe cover them in tens of millions and hundreds of millions of years.

What happens with cosmic rays propagating through the universe? Galaxies are rare in space and very small on the universe scale. Thus almost all the way cosmic rays fly in the extragalactic space that with a traditional optical telescope seems to be completely empty and dark. However it is not true. There are photons, gas molecules, dust and there are magnetic fields as well. Photons are emitted by stars or left over from the birth of the universe (Big Bang). The photons originated during Big Bang are *relic photons*. All photons constitute *extragalactic background radiation*. Gas molecules and dust have no influence on cosmic ray propagation. Extragalactic magnetic fields deflect a charge particle (making particle arrival directions on Earth unusable as pointers on sources).

Backgrounds photons influence cosmic rays. Cosmic rays interact with photons and that leads to two effects: modification of the cosmic ray spectrum on Earth and production of extragalactic electromagnetic cascades.

The first reveals itself as the lack of particles with energies about 10^{20} eV (and higher) in the spectrum observed on Earth. On the way through the universe ultra-high energy cosmic rays interact with relic photons producing elementary particles (an interaction with other photons is minor). Thus cosmic rays lose energy. As a result ultra-high energy particles convert to cosmic rays at lower energies and the count of ultra-high energy particles decreases. So, cosmic ray energy spectrum becomes modified. This is called the *GZK-effect*, and a theoretical upper limit on the energy of cosmic ray protons traveling through the universe to our galaxy is called the *GZK-limit* (the abbreviation of names Greisen, Zatsepin and Kuzmin, who have predicted in 1966 the spectrum modification). The lower-energy cosmic rays travel practically without interactions as they have insufficient energy for particle production.

The second effect—*extragalactic electromagnetic cascades*, arises in the following way.

Interacting with relic photons cosmic rays produce elementary particles. They are short-lived and decay giving rise to electrons, positrons, neutrinos and gamma-quanta. These new particles (except neutrino that travels almost without interaction) in turn interact with background emission generating other electrons, positrons, neutrinos and quanta. This avalanche-like process leads to formation of a gigantic cascade, the particles of which interact with extragalactic emission. Cascade particles diverge at distances that exceed the solar system size. Extragalactic cascades were described independently by Hayakawa and Prilutsky with Rozental in 1966–1970s (in the paper we use “photons” for background particles and “quanta” for the cascade ones).

10. Information Obtained Studying the Cosmic Ray Spectrum and Extragalactic Cascades

For the GZK-effect to arise, cosmic rays should interact with relic photons. The probability of interaction is proportional to the distance of particle flight. Thus the cosmic ray spectrum has no GZK-effect, if cosmic ray sources are not far in the scale of the universe (at distances less than ~50 Mpc = 1.5×10^{21} km). It was found experimentally that the spectrum has the GZK-limit and therefore distances from possible sources are more than ~50 Mpc.

Now the analysis of the cosmic ray spectrum includes two items. One is the particle injection spectrum (we talk about injection spectra in Section 8). In extragalactic space cosmic ray interactions disturb it. Nevertheless the spectrum of cosmic rays on Earth contains information about injection spectra.

Another item is *cosmological evolution of sources*. Cosmic rays arriving on Earth are emitted by sources distributed in the universe. With the distance to a source increasing, particles travel longer times to arrive on Earth, and therefore we observe particles that were emitted at different times: remote sources emitted particles prior to near ones. Therefore at the time of emission they were younger than the latter. So, with distances increasing, the sources are younger.

Additionally, when sources were younger their power and the spatial density were higher. Cosmological evolution of sources accounts for time dependence of power and spatial density of sources. The spectrum of cosmic rays on Earth contains this information about sources.

How to extract this information? Models of cosmic ray propagation in extragalactic space are considered taking into account injection spectra and varying parameters of cosmological evolution of sources as well. We calculate cosmic ray spectra and compare it with that measured, and the injection spectra along with parameters of cosmological evolution are selected that provide the best fit to the measured spectrum.

Extragalactic Background Radiation

The further step toward the revealing of cosmic ray sources involves extragalactic electromagnetic cascades.

Quanta produced in cascades are the component of extragalactic background radiation (to distinguish particles constituting background radiation from cascade particles we use "photons" for background particles and "quanta" for the cascade ones).

Its main part is emission of discrete extragalactic sources, sources being so faint or far that they cannot be detected using instruments. We believe that there also can be some other processes and particles that contribute to the background emission. For example, dark matter particles (that are hypothetical at the moment) decaying also produce quanta. Extragalactic background emission is measured with scientific apparatus on board satellites. Its studying makes it possible to identify background components and to determine how much cascade quanta contributes to the background emission. Why is it important?

The portion of cascade quanta in the extragalactic background radiation depends on cosmic ray injection spectra. They are different depending on the area of particle acceleration, so the portion of cascade quanta reveals the area and mechanism of acceleration (it will be remembered that each area has the own way to accelerate cosmic rays).

At present the flux of neutrinos produced in electromagnetic cascades is also used in cosmic ray studies. The method is as follows. Neutrinos arriving from the universe are detected on based-ground arrays. The flux of cascade neutrinos is calculated in models of cosmic ray sources. Models having no contradiction with the measured neutrino flux are selected to determine parameters of possible sources.

11. Study of Ultra-High Energy Cosmic Rays Today

Today astrophysicists study ultra-high energy cosmic rays using both ground arrays and satellites.

On Earth they measure the cosmic ray spectrum and neutrino flux, while in space it is extragalactic background radiation, the part of which is radiation produced in extragalactic cascades.

Data and theoretical results are interpreted as follows. Astrophysicists look for the models of possible sources that provide the best fit to the experimentally obtained energy spectrum. Next, using these models they compute the intensity of cascade quanta and neutrinos. Flux of cascade quanta is a minor part of extragalactic background radiation, and calculated flux should be a minor part of that measured. Similarly flux of cascade neutrinos is analyzed: as it is a minor part of the measured neutrino flux the calculated flux should be a minor part of that measured. Parameters of sources satisfying these criteria are refined in a further study.

This is the general outline of how astrophysicists study processes in the black hole vicinity using ultra-high energy cosmic rays.

In the next section we describe how particles can be accelerated to ultra-high energies near black holes.

12. Particle Acceleration in the Vicinity of Supermassive Black Holes

Supermassive black holes have three areas where particles can be accelerated. They are the magnetosphere of a black hole, its accretion disc and jets. The accelerating mechanism in these areas can be different. We consider two possible mechanisms: Fermi acceleration and particle acceleration in electric fields.

The first mechanism was described by E. Fermi in 1949 (Fermi acceleration).

Before the description of how Fermi acceleration is applied in jets we discuss shocks on the jet surface.

12.1. Shocks in Jets

Plasma blobs composing a jet are ejected from the disc through a funnel-shaped channel along the axis of disc rotation. Blobs fly across the disc during months and years (the time depends on disc thickness). All this time a blob interacts with channel sides, i.e., the disc matter, along with the disc emission, as the disc is filled with photons of various types.

On the blob surface interactions disturb some area giving the plasma a push. As a result the plasma layers moves along the blob and puts in motion layers in front. Propagating disturbance moving faster than the speed of sound, the *shock front* arises. What is a shock front?

A disturbance in plasma that moves faster than the speed of sound in the medium is called a *shock wave*. The boundary between the moving plasma and that which is motionless is sharp. It is called the shock front. The plasma density, pressure, temperature and velocity undergo an abrupt change over it.

12.2. Fermi Acceleration Applied to Jets

A shock wave makes plasma in a blob move as a stream. A part of energetic particles in the stream cross the shock gaining energy.

What happens next? The plasma stream carries the accelerated particle downstream, away from the shock. If the particle returns to the shock front, its energy increases. Can the particle return? Yes, it can and more than once. It occurs as follows.

Magnetic field is frozen in a plasma blob. There are areas in the blob that acts as scattering centers: their field is oriented in such a way that it deflects the flying particle towards the shock front. Thus the particle returns on it.

The higher is the magnetic field the stronger it makes the particle to deflect. Additionally, the higher is the particle energy, the less is its deviation in the field. Therefore the particle returns at the shock front until its energy increases so high, that the magnetic field in the blob is unable to deflect it back toward the shock front.

Particle motion in an inhomogeneous magnetic field near a shock front is shown schematically in Figure 8.

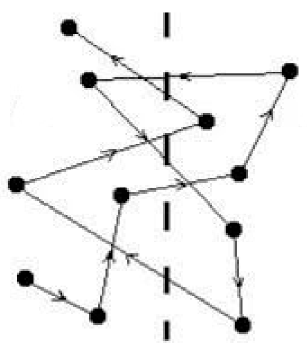

Figure 8. A particle motion in an inhomogeneous magnetic field near a shock front. The particle is shown by a black circle, the shock front is shown by dotted line, arrows indicate moving particle direction.

12.3. Particle Acceleration in Electric Fields

The simple case of particle acceleration by electric field is well known from textbooks: a particle with a charge q traveling a distance L in a uniform electrostatic field with a magnitude E gets energy W, equal to $W = qEL$.

In a black hole accretion disc and magnetosphere electric field is induced by the inhomogeneous magnetic field of the rotating accretion disc (the magnetic field is inhomogeneous since gas density is nonuniform).

In the accretion disc, particles can be accelerated as follows (see the reference in Section 14). In different places of the disc the plasma (with the frozen-in magnetic field) rotates at different speed (this is called *differential rotation*). As a result in some regions electromagnetic field grows explosively (faster than exponentially in time). These fields are capable of rapidly accelerating charge particles from the disc. For example, in a disc around a black hole with the mass of $10^8\ M_\odot$, particles can be accelerated to 10^{21} eV.

In the magnetosphere, particles can be accelerated in the following way. In a rotating black hole an induced electric field is parallel to the magnetic one on the symmetry axis. The electric field direction depends on the directions of both the magnetic field and the hole's rotation velocity. Thus in the regions near the rotation axis the electric field accelerates particles moving along magnetic lines. The maximal energy of protons is of 10^{21} eV.

Finally, in jets, protons can be accelerated in the following process. Initially they are preaccelerated to relativistic energies by induced electric field in the magnetosphere. A rotating black hole creates the potential difference that is transmitted along magnetic field lines into the jet. Thus in the jet the voltage between the jet axis and the periphery exists. In the jet, preaccelerated protons can gain ultra-high energy passing the total potential difference between the jet axis and the periphery. This mechanism accelerates protons to 10^{21} eV, the maximal energy depending on the parameters that characterize the structure of the jet.

The voltage drop in many situations may be shorted out by plasma. For example, the electric field inside the main part of the disc is fully compensated by the volume charge of the plasma. Nevertheless, there can be regions in the disc where the density of the plasma is usually small. Most likely it takes place during a quiet phase of the supermassive black hole, in contrast to active stages in the black hole evolution. The strong electric field exists possibly without compensation in an area of spinning axis and magnetic poles. There is no compensation of electric field in the black hole magnetosphere: the rotating magnetic field induces the electric field, due to which electromotive force arises (electric currents flow) and the voltage drop is maintained as if by an electrical battery.

12.4. The Hillas Criterion

A particle is accelerated as long as it is confined in the accelerating region. Thus the size L of the essential part of the region containing the field B should be greater than the Larmor radius r_{L} of a relativistic particle of charge Ze: $L > r_{\mathrm{L}}$. Considering gradual modes of acceleration with characteristic velocity of scattering centers $\beta = v/c$, B-L relation limiting a particle energy E is: $BL > 2E/Z\beta$. From this relation the energy limit is: $E \leq 0.5\ BLZ\beta$ (here B is in μG, L is in pc and E is in units of 10^{15} eV).

This limitation has been drawn by the English physicist Hillas and is called the Hillas criterion. The plot showing the magnetic field B versus size L is called the Hillas plot. It is shown in Figure 9.

Many possible sites of particle acceleration were analyzed, from interplanetary space to clusters of galaxies, i.e., with sizes ranging from kilometers to megaparsecs, and the magnetic field ranging from 1 μG to 10^{12} G. Very few of them remain as possibilities. Supermassive black hole sites—jets, accretion discs, and magnetospheres—satisfy the Hillas criterion. Accretion disc size is L~1–10 pc, jets are of 1–10's pc in length (can be longer) and the magnetic field is in the range B~10–10^3 G or higher.

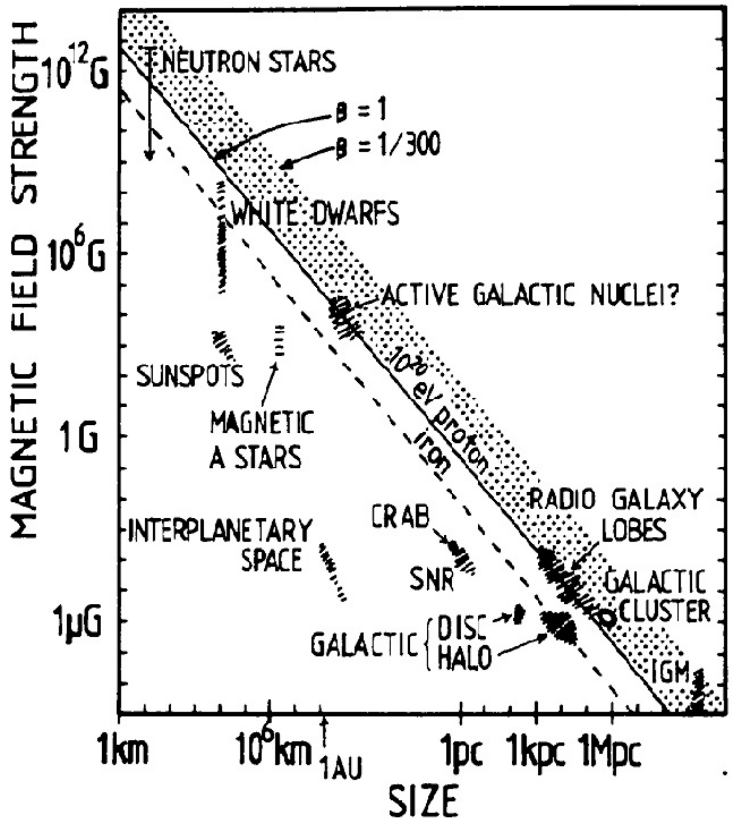

Figure 9. Size and magnetic field strength of possible sites of particle acceleration. Objects below the diagonal line cannot accelerate protons to 10^{20} eV. This is the plot from the classical article by Hillas, published in 1984 (see Section 14 for the reference) and no supermassive black hole sites are shown in it.

12.5. Particle Energy Losses in Accelerating Regions

In both acceleration mechanisms cosmic rays not only gain energy but also lose it. Why?

Magnetic field in space deflects particles (due to Lorentz force) and the particle trajectory bends. A particle moving along a curved path emits energy, which results in particle energy decreasing. In this case the particle emission is called *synchrotron radiation*.

A particle moves without deviation only along straight lines of force. When the particle reaches a region where lines of force bend, the particle deviates emitting energy. The emission caused by the curvature of magnetic force lines is called *curvature radiation*.

Nevertheless particles gain ultra-high energy in the black hole vicinity. That is the result of theoretical studies of cosmic ray acceleration in possible sources.

In jets particles move in the flow of gas where the magnetic field is directed along the flow. Thus synchrotron losses in jets are insignificant. As field lines curve with distance curvature radiation restricts particle energy. Nevertheless some particles escape the acceleration region without significant curvature losses. The fraction of these particles is one in 300 (for the estimate see the reference in Section 14).

In the magnetosphere particles are accelerated by electric fields near the black hole poles, where magnetic and electric fields are uniform or radial. Thus neither curvature emission nor synchrotron one restricts particle energy.

In the accretion disc, particles accelerated by electric fields have unimportant synchrotron losses when the velocity of the particle and the magnetic field are coaligned. In addition, synchrotron losses are unimportant in cases where the so-called "surfatron condition" takes place.

We described two mechanisms of particle acceleration in the universe: the acceleration through induced electric field and Fermi acceleration. Study of cosmic rays will show the role of each process in the black hole vicinity.

13. Conclusions

Cosmic rays were discovered in the 1910s, more than 100 years ago.

Over these years we learned that they originate in space and bombard the Earth atmosphere producing cascades of elementary particles-extensive air showers.

Numerous studies revealed that cosmic rays come from different areas in the universe. Cosmic rays at energies lower than 2×10^{10} eV are ejected from the sun while more energetic particles, at energies up to 10^{17}–10^{19} eV are produced in our Galaxy in supernova explosions. What is the origin of cosmic rays at higher energies?

Latest studies indicate that ultra-high energy cosmic ray sources are located outside our galaxy, inside active galactic nuclei. Supermassive black holes are the objects that supply energy for the nuclei activity, and particles can obtain huge energies in the black hole vicinity. Leaving the area of acceleration cosmic rays travel through the universe interacting with the photons of extragalactic background radiation. These interaction leads to modification of cosmic ray spectrum (the GZK-effect) and generation of extragalactic electromagnetic cascades. Quanta produced in cascades are the component of extragalactic background radiation.

The problem from which we began was how particles gained ultra-high energy in active galactic nuclei. Solving this problem we faced the challenge of supermassive black holes: what are processes of particle acceleration in the black hole vicinity? Analyzing these processes we formulated the inverse problem: is it possible to study these processes using cosmic ray data along with theoretical results?

The answer is "Yes", despite cosmic ray interactions in extragalactic space.

Here is how it is done:

We register cosmic rays, extragalactic background radiation and neutrino flux.

Data derived from these experiments are compared with energy spectra of computer models. The models that provide the best fit are used to compute the intensity of cascade quanta and neutrinos. Calculated fluxes of cascade quanta and neutrinos should be a minor part of the measured extragalactic background radiation and neutrino flux. Models satisfying this condition are selected and in these models parameters of source can be used to constrain characteristics of processes of particle acceleration in the black hole vicinity.

Certainly, we never can travel or send instruments close to any supermassive black hole, but we have a natural probe for our research—cosmic rays of ultra-high energies.

14. Scientific Articles for Supplementary Reading

In this section we present the articles, results of which were used in our paper. Additionally, a short description of analyzed problems is given in the section. The list of articles reflects the author's interests and is not complete.

The ground based arrays registering cosmic rays at ultra-high energies that are the Pierre Auger Observatory and the Telescope Array are described in [1,2]. The results obtained (including spectra and discrepancies between them) are analyzed in, e.g., [3,4].

The particle of the highest energy 3×10^{20} eV was registered in October of 1991 by the High Resolution Fly's Eye [5], which was previous to the TA.

The GZK-effect is presented in papers [6,7] and features of cosmic ray energy spectrum at ultra-high energies are analyzed in [8,9]. Pioneering papers describing extragalactic cascades are [10,11]. The scientific devices for the measurement of background emission (galactic+extragalactic) are Fermi LAT (active) [12], GAMMA-400 (ready for launch) [13] and one of the projects is MAST [14]. Fermi LAT is placed on board the cosmic observatory (satellite) Fermi, and the results obtained with Fermi LAT are given in [12]. Mechanisms of jet formation in black holes are described in [15] (the Blanford-Znajek process) and [16] (the Blanford-Payne process). The simple explanation of jet formation is taken from the popular lecture (in Russian) [17]. We now turn to mechanisms of particle acceleration in the black hole vicinity. Particle acceleration in shock fronts in space was deduced in pioneer articles [18–20]. The mechanism produces exponential particle spectra with the spectral indices of 2–2.5. This mechanism applied to jets is analyzed in, e.g., ([21] and references therein), and application of particle acceleration to ultra-high energies is given in [22]. Cosmic ray acceleration by electric field in magnetospheres of supermassive black holes was described first in [23]. The observational data illustrating validity of the model [23] are given in [24]. The model [23] did not predict the particle injection spectrum. Based on the mechanism [23], in [25] the monoenergetic injection spectrum was suggested and the resulting particle spectra on Earth were compared with cosmic ray data. Injection spectra (very) close to monoenergetic are obtained in the model [26], which is analyzed in [27].

A mechanism of particle acceleration by electric fields in accretion discs is proposed in [28]. It is shown that in some cases particles escape without synchrotron energy losses. The model presented in this paper does not predict the injection spectrum. Based on the described accelerating process the exponential injection spectra with indices of 0–2.2 are suggested in [29], where this mechanism is applied for cosmic ray data analyses.

Particle acceleration by electric field in jets is described in [30,31]. Observational data on active galactic nuclei confirming the model are also given in the papers. No results on particle injection spectra are presented. Based on the described accelerating process the spectrum can be assumed as monoenergetic or exponential with indices of 0–2.2.

Possible sites of particle acceleration are analyzed in [32], in which Hillas plot is presented.

Transport of accelerated particles without energy losses is discussed in [22,30,31] (when particles are accelerated in jets), [23,27] (when particles are accelerated in black hole magnetospheres) and in [28] (when particles are accelerated in accretion discs).

There are a number of codes for computer simulation of particle flying in extragalactic space. Public available codes are, for example, ELMAG [33] and TransportCR [34].

Joint analyzes of data on cosmic rays and extragalactic emission as a tool to solve cosmic ray problems is given in, e.g., [29,35,36].

Theoretical description of black holes in the universe is given in ([37] and references therein). Astronomical observations that prove the existence of the supermassive black hole in the center of our galaxy the Milky Way are given in ([38,39] and references therein).

Funding: This research received no external funding.

Acknowledgments: The author thanks reviewers for their comments. The author thanks M. Zelnikov for the discussion of conditions under which particles can be accelerated in the black hole magnetosphere.

Conflicts of Interest: The authors declare no conflict of interest.

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