ACTA PHYSICA POLONICA A No. 3 Vol. **139** (2021)

Special issue, XLVI Extraordinary Congress of Polish Physicists, Warsaw, Poland, October 16–18, 2020

CREDO — Quest for the Unexpected

T. Wibig

Faculty of Physics and Applied Informatics, University of Łódź,
Pomorska 149/153, 90-236 Łódź, Poland

Doi: 10.12693/APhysPolA.139.226

*e-mail: tadeusz.wibig@fis.uni.lodz.pl

It is quite common, and yet completely wrong, to think that cosmic radiation was discovered by accident, by a fortunate coincidence. The discovery of cosmic radiation, or more precisely what we call cosmic radiation nowadays, i.e., a stream of particles coming to Earth from space, took quite a long time. In some aspects, however, it is not really finished until today.

topics: cosmic rays, extensive air showers, ultra high energy cosmic rays, cosmic ray ensembles

1. Introduction

The date of the discovery of cosmic radiation is given as 1912 — the date confirmed by the Royal Academy of Stockholm in 1936 when the Nobel Prize was awarded to Victor F. Hess. It is widely believed that this discovery was completely unexpected, however, in order to do justice to the truth, one has to go back at least 200 years and mention the names of a few other great physicists who have contributed to a greater or lesser extent to our history.

Around 1785, Charles Augustin de Coulomb observed the escape of an electric charge from electrified bodies [1]. This effect is known as dark current. In the middle of the 19th century, Matteucci demonstrated that the value of the dark current at high values of the electric field reaches saturation. The experiments of Elster and Geitel implied that the "wind" of ionized air molecules is responsible for the dark current [2]. The works of Thompson and Rutherford indicated that the density of the saturation current could be treated as a measure of ionization of the medium.

It was quite natural to ask what is responsible for this ionization.

2. Ionization chambers and technology progress

Helmholtz in the late 19th century pointed to ionized gas atoms as the birth of vapour condensation in dust-free air. This idea was used by Wilson when he built his famous fog chamber, commonly known today as the Wilson chamber [3]. In fact, it was Wilson who was the first to postulate the existence of cosmic rays. To explain the otherwise inexplicable residual ionization appearing out of nowhere, Wilson assumed that there exist rays like X-rays or uranium rays of extra-terrestrial origin.

To confirm this hypothesis, the easiest way would be to go up and see how much ionization is growing. A series of the Hess balloon flights between 1911 and 1912 led to a solidly documented statement that the higher in the atmosphere, the more intense the ionizing factor is [4]. Hess called it "altitude radiation" (in German *Höhenstrahlung*). This result was truly surprising.

By the end of the 1920s, ionization chambers and Wilson's chambers were the primary tools for studying cosmic radiation. An important breakthrough came in 1928 when in Kiel, Geiger and Müller constructed a counter, commonly known today as the Geiger–Müller (G–M) counter [5]. The G–M counter made it possible to determine the moment when the particle passed through its active volume ionizing the gas it contained. An excellent idea was to position two G–M counters vertically, one above the other, and observe cases when an impulse appeared simultaneously in both of them. While studying the characteristics of cosmic radiation particles, Bothe and Kolhörster went as far as to put a bar of gold between the counters [6]. The cosmic radiation particles reaching Earth's surface passed through it in a surprisingly easy way. Nobody expected this. For the next few years, the problem of the nature of cosmic radiation has been occupying both experimental and theoretical attention of the greatest physicists of those times, to mention only Millikan, Anderson, Auger, Blackett, Rutherford, Heisenberg, Dirac, and even Irena and Frederick Joliot-Curie.

Another technological leap was made by Rossi [7]. He constructed an electronic circuit, in which G–M counters controlled grids of electron tubes connected in a system called coincidence circuit. The coincidence signal could now be used to trigger Wilson's chamber. The rich experimental material gathered by this technique in the early 1930s included photographs of high-energy electrons (and positrons), but also occasionally observed strange photographs, which showed the passage of a few (up to four in Skobeltsin's photographs [8]) and even more (up to 20 in Blackett and Occhialini's experiment [9]) almost parallel tracks through the chamber. The same phenomenon was also observed by Carmichael. He recorded a signal corresponding to the simultaneous appearance of more than one hundred million ions in his large ionization chamber [10]. All this was unexpected and very hard to explain, but that is not all. In his experiments with the coincidence circuit, Rossi placed three counters (in a lead shielded box) setting them in an unusual configuration: two in one horizontal plane and one underneath them in such a way that a single particle was not able to activate the triple coincidence circuit. It turned out, however, that such coincidences appear in nature [11].

3. Cascade theory followed by progress of experiments

A theoretical solution to the puzzle of multiple tracks appeared in 1937 in a work by Bhabha and Heitler [12] and is known as a cascade theory. It found full and quite surprising confirmation already in 1938, when Auger and Maze discovered extensive air showers (EAS) [13]. The idea of their experiment was exactly the same as in Rossi's experiment. The difference was only in the scale. When the distance between the counters was small, the appearance of an unusual coincidence caused by more than one particle was nothing more than the observations of Rossi, Skobeltsin, Blackett and Occhialini, and Carmichael. However, no one expected that the particle cascades would have the size measured in meters. Auger estimated that if the energy of all the particles that had to reach Earth's surface at that moment in the cosmic cascade predicted by Bhabha and Heitler was summed up, it would have to be at least a million times greater than the energy triggered by the decay of radioactive nucleus. No one could have imagined even such incredible energetic particles. Later on, Auger discovered the existence of EAS of at least hundreds of meters in size. The energies of the particles that initiate them at the top of the atmosphere had to be billions of times greater than typical nuclear energies. The question arose as to where such particles come from, where and how they are created and accelerated and what they actually are.

After the interruption caused by World War II, systematic research was started. In an experiment at Mt. Evans, Echo Lake, Colorado, built in 1948 by Rossi's group, then employed at MIT, three ionization chambers were placed in the apexes of an equilateral triangle with a side of 6 m (and one more in the middle) [14]. At the beginning of the 1950s, Great Britain built a big shower array in Harwell consisting of 80 stations of G–M counters located within an equilateral triangle with a length of almost 1200 m [15]. In response, the Americans built the Agassiz Station, where 12 scintillation detectors were deployed over an area of approximately one square kilometer. The technique of scintillation counters allowed for the first time to use fast timings for directional measurements [16]. In 1957, this apparatus recorded a record-breaking eV energy shower.

Liquid, flammable scintillators were replaced by safe plastic [17] and these were finally set up in the mountains of Bolivia in El Alto (4200 m) and later in Chacaltaya (5200 m) to investigate how showers develop at high altitudes in the atmosphere [18], and the experiment itself from the Agassiz station was moved to Volcano Ranch (1770 m) near Albuquerque in New Mexico. The detectors were placed there symmetrically in a hexagon of about 3 km in size. The UK responded with an equally large array in Haverah Park, where the Cherenkov detector technology was used [19].

4. Cosmic ray physics

The most important discovery was made in February 1962. The Volcano Ranch experiment recorded a shower containing about 50 billion particles and its energy was estimated at 10^{20} eV [20]. Initially, it was just another record-breaking result, but this discovery became really important after 1964, when the microwave background radiation was discovered. As Zatsepin and Kuzmin [21] and independently Greisen [22] noticed almost immediately, the cosmic ray protons of very high energies interacting with the microwave background photons should lose energy quickly, if they only exceed the energy to create a resonance Δ in the process. This resonance is decaying back to proton and meson π and of course the proton has already less energy and this process is repeated until the proton energy decreases to about 5×10^{19} eV. The time between interactions is determined by the respective cross-section and accurate calculations show that if somewhere in space there are sources of protons with an energy of say 10^{21} eV or even higher, they cannot reach us with energies greater than 10^{20} eV from distances greater than a few dozen megaparsecs (some say, hundred). In the scale of the Universe, it is very few and practically there should be no 10^{20} eV particles at all. This effect is called the GZK cut-off from its explorers' names.

It would seem that the observation of particles with energies above the GZK cut-off indicates that if they are not protons, they must be heavy atomic nuclei (photons are excluded by other observations). It turns out, however, that even the atomic nuclei with very high energies interact intensively with electromagnetic radiation in many ways. One of them is the photodisintegration through the excitation called giant dipole resonance. The excited nucleus finally disintegrates and the products of fragmentation have the total energy proportional to their atomic mass. The process of photodisintegration of the cosmic ray nuclei takes place only a little further on the energy scale than the GZK process for protons. Heavy nuclei with energies of about 10^{20} eV should not be there either.

The Volcano Ranch event contradicted our knowledge of nuclear physics. This observation had to be confirmed, or it had to be shown that it was a one-time mistake, a fluctuation, a pure coincidence.

In the late 1960s, the American-British race in the construction of the largest shower experiments and the search for particles with the highest energy was joined by the Australians, who constructed the SUGAR (Sydney University Giant Air-shower Recorder), and in the 1970s, by the Russians, who built their array in Yakutsk on the shore of the Lena River, which expanded, and measured showers in many different ways [23]. However, all of them were beaten by the Japanese. In the small town of Akeno, in 1979, they built a shower array on 1 km^2 (A1), expanded in 1984 to 20 km^2 (A20), and in 1990, the Akeno Giant Air Shower Array (AGASA) was launched, covering an area of 100 km^2 (A100) [24].

The results obtained by the AGASA array have confused physicists dealing with cosmic ray physics. They indicated the existence of a large number of cases with energies exceeding the energy allowed by the GZK cut-off. The highest energy was recorded in May 2001 and was $\approx 2.5 \times 10^{20}$ eV [25].

Since the 1980s, the Fly's Eye experiment has been operating in the Utah desert [26]. After expansion in 1997, when the ordinary "eye of the fly" was replaced with a high-resolution eye, it was called the High Resolution Fly's Eye or simply HiRes [27].

The results of the experiments in Utah did not match those obtained by the Japanese. The Americans saw a spectrum cut-off below 10^{20} eV, but at the same time they recorded several events beyond this cut-off energy, including a 1991 shower with the highest energy 3.2×10^{20} eV recorded so far. Summarizing the great experiments at the end of the 20th century: the cosmic ray energy spectra published by them appear to be mutually contradictory in the area of the highest energies; and the difference was large.

Energy values 3.2×10^{20} eV is over 50 J! The question is how a single proton has been given such giant energy. This is one of the most important questions, to which no one knows the answer. If we found out how it is done, who knows how we could use it.

Particles with energies of 10^{20} eV and more, as mentioned above, cannot reach over from far distances, whether they are protons or heavy atomic nuclei. The limit is possibly several dozen megaparsecs. This is so close that in intergalactic magnetic fields, which are very weak but omnipresent, the direction in which we will see them on Earth will point to the place where they were created. The directions from which particles initiating EAS of the highest energies came in are determined quite precisely. A map of these directions has been made in the expectation that it will indicate the sources. Despite great efforts and intensive search, no statistically significant anisotropy was found. No correlation was noticed with close astrophysical objects, which could potentially be the sources. This negative result was very frustrating, meaning that the sources must be far away, and yet they cannot be far away — another contradiction!

Taking into account the importance of the issue — after all it concerns our knowledge about the micro-world, about the interactions of very high energies, about extreme astrophysical objects, and finally about the Universe on a far extragalactic scale — large-scale experimental activities on a 21st-century scale have been undertaken.

In 1991, the idea of building two great experiments was put forward. One was to stand in the southern hemisphere, the other in the northern hemisphere, so that both would cover the entire sky. Since the particle statistics over the GZK cut-off are collected very slowly, roughly one event per square kilometer per century, to await the final results was set to size. While the experiments so far have reached 100 km^2 on the ground, this time the plans were much more ambitious, measured in thousands of square kilometers. In the northern hemisphere, the equipment was built on an American army training ground in Dugway while in the south, pampa was chosen near Mendoza in Argentina. In both experiments, EAS were to be recorded on dark nights by sets of very sensitive fluorescent light detectors, and around the clock by networks of surface detectors. In 2000, the construction of the Pierre Auger Observatory (PAO) began in Argentina [28]. In 2003, PAO reached a size that exceeded the AGASA experiment.

In 2007, the statistic of the highest energy bundles recorded was already large enough to be able to analyze the anisotropy of their directions of arrival. No effect! So they checked if there were any correlations with any objects in the sky and finally found one [29]. A significant correlation (at a 99% confidence level) was found with close objects from the quasars and Active Galactic Nuclei catalog by Véron–Cetty and Véron [30]. It seemed that the mystery of the end of the highest energies in cosmic radiation is close to solution, especially when in 2008 PAO showed the results of measurements of the cosmic ray energy spectrum where the cut-off above 4×10^{19} eV energy was clearly visible [31].

In the meantime, the Telescope Array (TA) experiment was developed in the northern hemisphere. The construction began in 2003 and the first results started to appear in 2008. Since 2012, TA has shown its energy spectrum with a clear cut of GZK at 4×10^{19} eV [32]. A map of directions has been tested especially carefully to confirm the correlation proposed by PAO. Unfortunately, nothing was found [33].

However, the compatibility of energy spectra is only apparent. Although both experiments show a cut-off, but with other, significantly different energies. Also the most recent works of PAO [34, 35] and the group established jointly by PAO and TA [36] indicate that the fluxes measured by PAO are much smaller than the TA results. One can proceed as proposed by some [37], summarizing the current situation with the conclusion "nothing happened": let us scale TA energy down by 5.2% or PAO by 5.2% up (or only PAO, or TA by 10.5%) and it will be fine. This ensures compliance in the area from 10^{19} eV to 3×10^{19} eV, but outside this area the results are still not consistent.

With regard to anisotropy, the situation has somewhat changed in recent years. The first PAO results indicated a correlation with active galactic nuclei, which TA strongly denied. The registration of new events and their distribution in the sky did not confirm the first PAO reports. Years later, the strong, definitely not accidental correlation left only a slight suggestion. On the other hand, the initially isotropic distribution of the directions of particle arrival in the northern hemisphere (TA) after five years of data collection was no longer so isotropic [38]. The EAS were distributed with a clear indication of a significant excess near the coordinates, i.e., RA: 144°, dec: 40°. So far, the discrepancy between PAO and TA has not been overcome [34–36].

5. Prospects for future

What should we do in this situation? Create a new bigger, more modern, better experiment that will finally measure what we would like to measure and answer the fundamental questions clearly and definitively. This is where physics collides with economics. PAO was supposed to cost 50 million (euros). For twenty years, all costs have amounted to hundreds of millions. This is difficult even to count. Who can afford to build something that should cost billions? The question is rather rhetorical. Many institutions, countries and even millionaires would be able to afford it, but will someone do it? This is not certain. Placing thousands of large detectors on the surface and setting up telescopes looking for subtle flashes in the sky is logistically quite complicated, and assurances that after a few (next) years we will be smarter are not very convincing either, especially considering the previous undertakings described above. We would have to come up with something new, something definitely different. And it was invented: Extreme Universe Space Observatory (EUSO) [39] — a space telescope that looks down on Earth. And what can it see? The same flashes as PAO and TA experiment saw, but looking from the height of the International Space Station, from some 400 km above Earth, it will monitor not thousands of square kilometers, but areas the size of Poland, and looking in a inclined mode even several times bigger.

There is another possibility. In 1985, Linsley, the same one who detected giant air showers in 1962, proposed to build the apparatus consisting of autonomous small, miniature arrays detecting small showers very locally [40]. Many of these networked stations were to be of new quality and provide answers to important questions. At that time, however, almost 40 years ago, this idea was very difficult to implement. Today, various networks easily entwine the world, phones and smartphones form networks of hundreds of millions, maybe billions of nodes. Every phone has a built-in camera. Cameras are detectors of photons falling through the lens onto a semiconductor pixel matrix. If the phone were to cover the lens, they would still be a detector of charged particles coming sometimes as EAS. You can imagine that many phones will register the particles at one instant. If you collect this information, you could not only build a library of registering EAS and increase the statistics of the most interesting, most energetic events, but you could also be tempted to find something new, something that nobody has seen before and what actually nobody expects.

One of such postulated phenomena are the cosmic ray ensembles (CRE). From distant unexplored spaces of the cosmos, an unknown, yet unseen very massive particle comes to the vicinity of the Solar System. It could have been created at the very beginning of the Universe and be stable enough to survive 14 billion years and quite accidentally reach the vicinity of Earth. It could have interacted with the magnetic fields of the Sun, or simply decayed into smaller elementary particles known to us from the laboratories. They would still have incredibly high energies and would probably also disintegrate, sometimes interact and such a cascade passing through the Solar System could hit Earth and initiate in the atmosphere a large number of EAS. All of them would be time-correlated and only the global network of detectors could detect them. The observation of the CRE would be just as unexpected as the detection of the cosmic rays itself by Hess, or the extensive air showers by Auger and Maze and would shed new, unknown light on the surrounding Universe.

6. Conclusions

Of course, we do not know if the CRE exist at all. We do not know either whether they can be easily picked up among the huge number of signals coming to us from space. Combining millions (billions?) of tiny detectors in smartphones into one network is an extremely ambitious task, but the efforts are ongoing. One such experiment is the CREDO Project (Cosmic Ray Extremely Distributed Observatory) [41] with the interesting motto "the quest for the unexpected".

Actually, it would be great to catch a bunny, but the chase itself is, first of all, fascinating, and secondly, who knows if not more important, and it can also be very educational for young people with smartphones in their hands to chase after elementary particles. (To foreigners not familiar with Polish songs of the late 1960s, the last sentence may seem slightly unclear, but...).

References

[1] C.A. Coulomb, *Mem. De l'Acad. Paris*, 616 (1795).

[2] J. Elster, H. Geitel, *Terrest. Magn.* **4**, 213 (1899).

[3] C.T.R. Wilson, *Proc. R. Soc. Lond. A Math. Phys. Sci.* **85**, 285 (1911).

[4] V.F. Hess, *Phys. Zeits.* **12**, 998 (1911); V.F. Hess, *Phys. Zeits.* **13**, 1084 (1912).

[5] H. Geiger, W. Müller, *Phys. Zeits.* **29**, 839 (1928).

[6] W. Bothe, W. Kolhörster, *Z. Phys.* **56**, 751 (1929).

[7] B. Rossi, *Nature* **125**, 636 (1930).

[8] D. Skobeltsyn, *Z. Phys.* **54**, 686 (1929).

[9] P.M.S. Blackett, G.P.S. Occhialini, *Nature* **130**, 363 (1932).

[10] H. Carmichael, "The Nature of Large Cosmic-Ray Bursts", *Proc. R. Soc. Lond. A Math. Phys. Sci.* **154**, 223 (1936).

[11] B. Rossi, *Z. Phys.* **82**, 151 (1933).

[12] H.J. Bhabha, W. Heitler, *Proc. R. Soc. Lond. A Math. Phys. Sci.* **159**, 432 (1937).

[13] P. Auger, R. Maze, T. Grivet-Mayer, *Compt. Rend. Acad. Sci.* **B206**, 1721 (1938) (in French); P. Auger, R. Maze, *Compt. Rend. Acad. Sci.* **B207**, 288 (1938) (in French).

[14] B. Rossi, H. Staub, *Ionization Chambers and Counters*, McGraw-Hill, New York 1949.

[15] T.E. Cranshaw, W. Galbraith, *Philos. Mag.* **45**, 1109 (1954).

[16] P. Bassi, G. Clark, B. Rossi, *Phys. Rev.* **92**, 441 (1953).

[17] G.W. Clark, F. Scherb, W.B. Smith, *Rev. Sci. Instrum.* **28**, 433 (1959).

[18] J. Hersil, I. Escobar, D. Scott, G. Clark, S. Olbert, *Phys. Rev. Lett.* **6**, 22 (1961).

[19] M.A. Lawrence, R.J.O. Reid, A.A. Watson, *J. Phys. G* **17**, 733 (1991); M. Ave, J.A. Hinton, J. Knapp, J. Lloyd-Evans, M. Marchesini, A.A. Watson, in: *Proc. 27th Int. Cosmic Ray Conf.*, 2001, p. 385.

[20] J. Linsley, *Phys. Rev. Lett.* **10**, 146 (1963).

[21] G.T. Zatsepin, V.A. Kuzmin, Upper Limit of the Spectrum of Cosmic Rays, *JETP Lett.* **4**, 78 (1966).

[22] K. Greisen, *Phys. Rev. Lett.* **16**, 748 (1966).

[23] M.M. Winn, J. Ulrichs, L.S. Peak, C.B.A. McCusker, L. Horton, *J. Phys. G* **12**, 653 (1986); M.M. Winn, J. Ulrichs, L.S. Peak, C.B.A. McCusker, L. Horton, *J. Phys. G* **12**, 675 (1986).

[24] A. Ivanov for the Yakutsk array group, *EPJ Web Conf.* **53**, 04003 (2013); S. Knurenko, I. Petrov, Z. Petrov, I. Sleptsov, *EPJ Web Conf.* **99**, 04001 (2015).

[25] N. Chiba, K. Hashimoto, N. Hayashida et al., *Nucl. Instrum. Methods Phys. Res. A* **311**, 338 (1992).

[26] N. Hayashida, K. Honda, M. Honda et al., *Phys. Rev. Lett.* **73**, 3491 (1994).

[27] R.M. Baltrusaitis, R. Cady, G.L. Cassiday et al., *Nucl. Instrum. Methods Phys. Res. A* **240**, 410 (1985).

[28] T. Abu-Zayyad, M. Al-Seady, K. Belova et al., *Nucl. Instrum. Methods Phys. Res. A* **450**, 253 (2000).

[29] Pierre Auger Collaboration, Auger Collaboration Presentations, in: *Proc. 27th ICRC*, Hamburg, 2001, p. 699.

[30] Pierre Auger Collaboration, *Science* **318**, 938 (2007).

[31] M.P. Véron-Cetty, P. Véron, *Astron. Astrophys.* **455**, 773 (2006).

[32] Pierre Auger Collaboration, *Phys. Rev. Lett.* **101**, 061101 (2008).

[33] T. Abu-Zayyad et al. (TA Collaboration), *Astropart. Phys.* **39-40**, 109 (2012).

[34] R.U. Abbasi et al. (TA Collaboration), *Astrophys. J. Lett.* **790**, L21 (2014).

[35] A. Aab et al. (The Pierre Auger Collaboration), *Phys. Rev. Lett.* **125**, 121106 (2020).

[36] A. Aab et al. (The Pierre Auger Collaboration), *Phys. Rev.* **102**, 062005 (2020).

[37] T. Abu-Zayyad et al. (TA Collaboration), *Astrophys. J.* **757**, 26 (2012).

[38] D. Ivanov for the Pierre Auger Collaboration and the Telescope Array Collaboration, in: *Proc. 35th Int. Cosmic Ray Conf.* arXiv:1801.01018, BEXCO, Busan (Korea), 2017.

[39] F. Kajino for the JEM-EUSO collaboration, *Nucl. Instrum. Methods Phys. Res. A* **623**, 422 (2010).

[40] J. Linsley, in: *Proc. 19th Int. Cosmic Ray Conf., La Jola (USA)*, 1985, Ch. OG9.4-9, p. 434.

[41] D. Góra et al. (CREDO Collaboration), *Universe* **4**, 111 (2018).