The Cosmic Rays: Origins, Propagation and Revelation Techniques.

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ABSTRACT

Cosmic rays are high-energy subatomic particles that travel through space and interact with the intergalactic, interstellar, and interplanetary medium before reaching Earth. The aim of this article is to describe their origin and propagation, detectors used to detect them, their effect on Earth and Space missions and future perspectives. Our experience in the laboratory "*to be a scientist for one day with the hands on particles*" tracing Cosmic Rays with the Pierre Auger Observatory, has made us aware of all continuous efforts made by scientists to improve these knowledgments.

1. INTRODUCTION

On February 18th and March 6th our class 4AS of Liceo Scientifico Linguistico Statale "V. Cuoco-T. Campanella" took part in two masterclasses which dealt with Modern Physics and Cosmic Rays at the University of Naples "Federico II" Department of Physics.

Be a scientist for one day with the "hands on particles"!

The discovery of cosmic rays dates back to the early 20th century**[3]**. In 1912, an Austrian physicist Victor Franz Hess conducted a series of daring balloon flights to measure atmospheric ionization at various altitudes. He observed that, contrary to expectations, ionization levels increased with altitude, suggesting the presence of highly penetrating radiation entering our atmosphere from outer space. The main scientific questions connected with cosmic ray research include the nature of astrophysical sources, propagation mechanisms in the interstellar medium, and their effects on Earth and space missions. Furthermore, their interaction with Earth's magnetic field and their impact on modern technology, such as telecommunications and space security, make their monitoring essential.

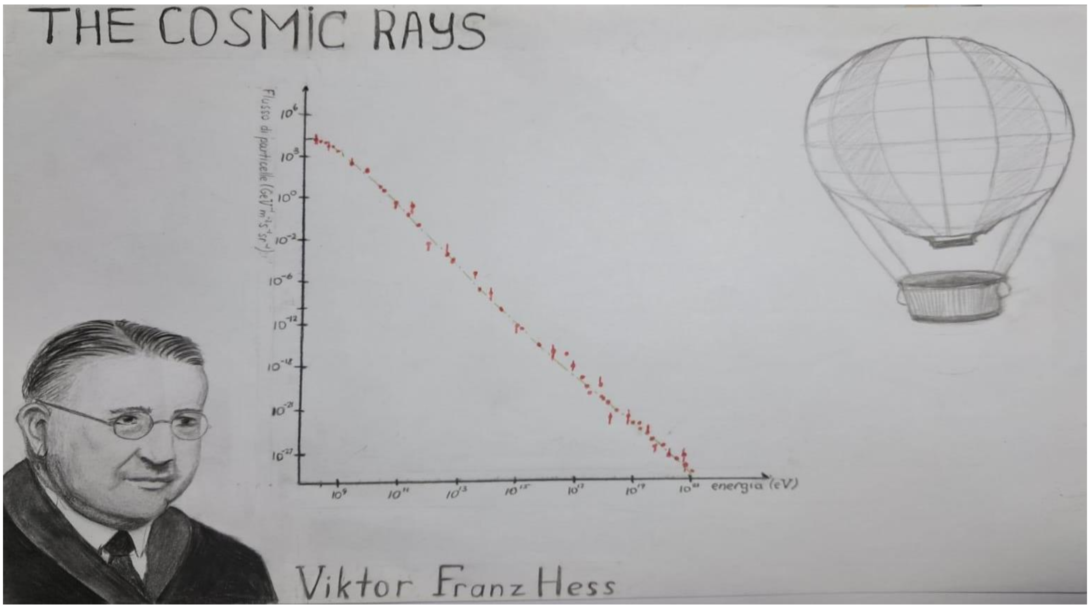

Fig.1 The image, drawn by us, shows: a Hess's portrait and a hot air balloon he used; the graph in the middle describes the cosmic-ray flux which decreses as the energy increases.

2. ORIGIN AND PROPAGATION OF COSMIC RAYS

2.1 Origin of Cosmic Rays

The origin of cosmic rays is still not fully understood, but scientists have proposed several theories based on observations and simulations. Some of the most popular theories about sources nclude:

1. *Supernovae Remnants*: Supernovae explosions are believed to be a major source of cosmic rays. The explosive energy released during these events can accelerate particles to incredibly high energies.

2. *Active Galactic Nuclei*: Active galactic nuclei (AGN) are thought to be another source of cosmic rays. AGN are incredibly luminous objects that are believed to be powered by supermassive black holes.

3. *Gamma-Ray Bursts*: Gamma-ray bursts (GRBs) are intense explosions that occur when massive stars collapse or when neutron stars or black holes merge. GRBs are also thought to be a source of cosmic rays.

2.2 Propagation Mechanisms

Once cosmic rays are accelerated to high energies, they must travel through the interstellar medium (ISM) to reach Earth **[2].** During this journey, they interact with various components of the ISM, including:

1. *Magnetic Fields*: Magnetic fields in the ISM can deflect and scatter cosmic rays, affecting their trajectory and energy.

2.*Gas and Dust*: Cosmic rays can interact with gas and dust in the ISM, leading to energy losses and changes in their composition.

3.*Radiation Fields*: Cosmic rays can also interact with radiation fields in the ISM, such as the cosmic microwave background radiation.

The travel through the interstellar medium is different for charged particles (cosmic rays) and neutral particles, as neutrinos and gammas produced in the same sources of charged particles. See the effect of magnetic fields on charged and neutral particles in **Fig. 2**.

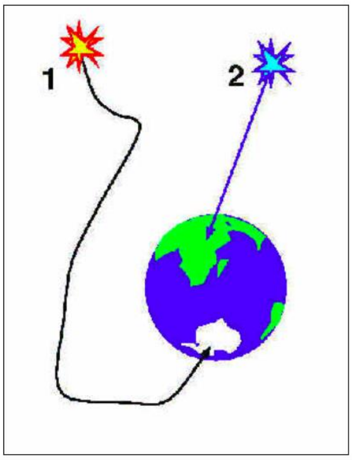

Fig.2 This image shows the trajectory of two cosmic particles. The charged particles (1), is deflected from the Earth's magnetic field, while a neutral particle (2) maintains the direction of origin

3. TECHNIQUES FOR DETECTING COSMIC RAYS

Cosmic rays, high-energy particles originating from extraterrestrial sources, are detected using various techniques based on their interactions with Earth’s atmosphere and detectors. Below are some of the primary methods used in cosmic ray detection.

3.1 Balloon-and Space-Based Detectors

•*Magnetic Spectrometers*: Instruments like the Alpha Magnetic Spectrometer (AMS-02) aboard the International Space Station use strong magnetic fields to measure the charge and momentum of cosmic ray particles.

•*Calorimeters*: These detectors measure the energy of cosmic rays by analyzing their interactions with dense materials, producing secondary particles that can be tracked.

•*Cherenkov and Transition Radiation Detectors*: These detect the Cherenkov radiation emitted when high-energy cosmic rays pass through different media at speeds exceeding the local speed of light.

3.2 Ground-Based Detection

•*Extensive Air Shower (EAS) Arrays*: When high-energy cosmic rays enter Earth's atmosphere, they produce cascades of secondary particles called air showers. Ground-based detector arrays, such as the Pierre Auger Observatory, use scintillators, water-Cherenkov detectors, or resistive plate chambers to measure these showers.

•*Radio Detection*: The interaction of cosmic rays with the atmosphere generates radio emissions through geomagnetic and Askaryan effects. Radio antennas capture these signals, providing insights into the primary cosmic ray properties.

3.3 Atmospheric Fluorescence and Čerenkov Telescopes

•*Fluorescence Detectors*: Instruments like the Fly's Eye and High-Resolution Fly's Eye (HiRes) detect ultraviolet fluorescence emitted when cosmic rays ionize atmospheric nitrogen.

•*Imaging Atmospheric Čerenkov Telescopes (IACTs)*: Telescopes such as H.E.S.S., MAGIC, and VERITAS observe Cherenkov radiation from high-energy gamma rays and secondary particles in cosmic ray showers.

Each of these techniques provides complementary data, enabling a comprehensive understanding of cosmic ray origins, energy spectra, and composition. The integration of multiple detection methods improves sensitivity, accuracy, and coverage, enhancing our knowledge of high-energy astrophysical processes.

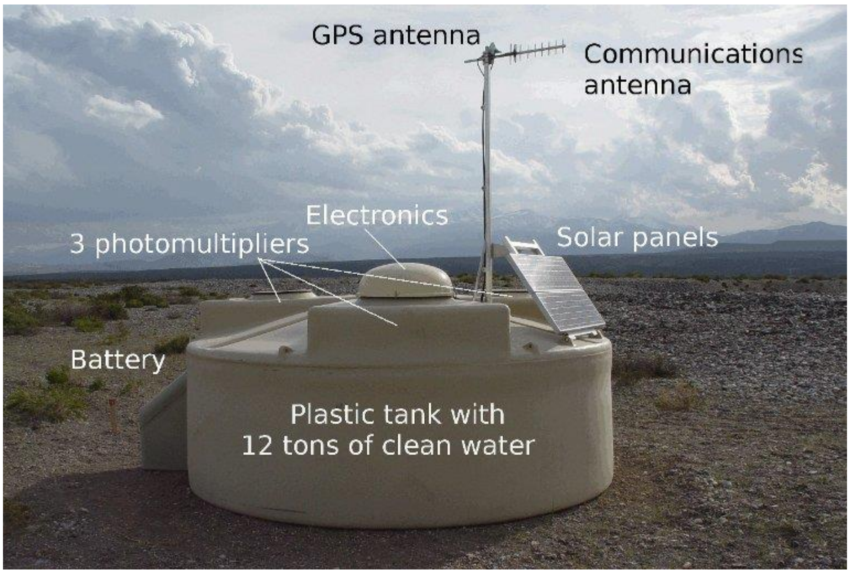

Fig.3 This image shows a typical surface detector with its components.

4. METHODS

Analyzing real cosmic ray events from the Pierre Auger Observatory was an incredible experience. We worked in group and the task of each group was to reconstruct the arrival direction and energy of up to 50 cosmic ray events, searching for clues about their origins in the universe.

We are going to describe the reconstruction steps for the events collected by the surface detector (SD data) of the Pierre Auger Observatory.

Step 1: *Selecting Detection Stations*

First of all it is necessary to choose which detector stations have to be included in our analysis. More stations meant better accuracy, but observer has to be careful to exclude background noise. It was a delicate balance between gathering enough data and avoiding misleading results.

Step 2: *Determining Arrival Direction*

Using time delays between signals at different detectors, we calculated the azimuth and zenith angles, reconstructing the cosmic ray's trajectory. It was exciting to see how simple timing data could reveal the path of a particle traveling from deep space.

Step 3: *Estimating Energy*

At this step, we fitted a function to the data to determine the shower size at 1000 meters, which, after corrections, gave us the energy of the original cosmic ray. Some events displayed astonishingly high energies, hinting at origins in extreme astrophysical phenomena.

Step 4: *Event Selection*

Finally, we assessed whether each event met quality criteria. If the reconstruction was reliable, we recorded its arrival direction; otherwise, we discarded it.

5. RESULTS

During our experience **A day as a Scientist: Tracing Cosmic Rays with the Pierre Auger Observatory** using open source Auger data and following the steps described above, we obtained:

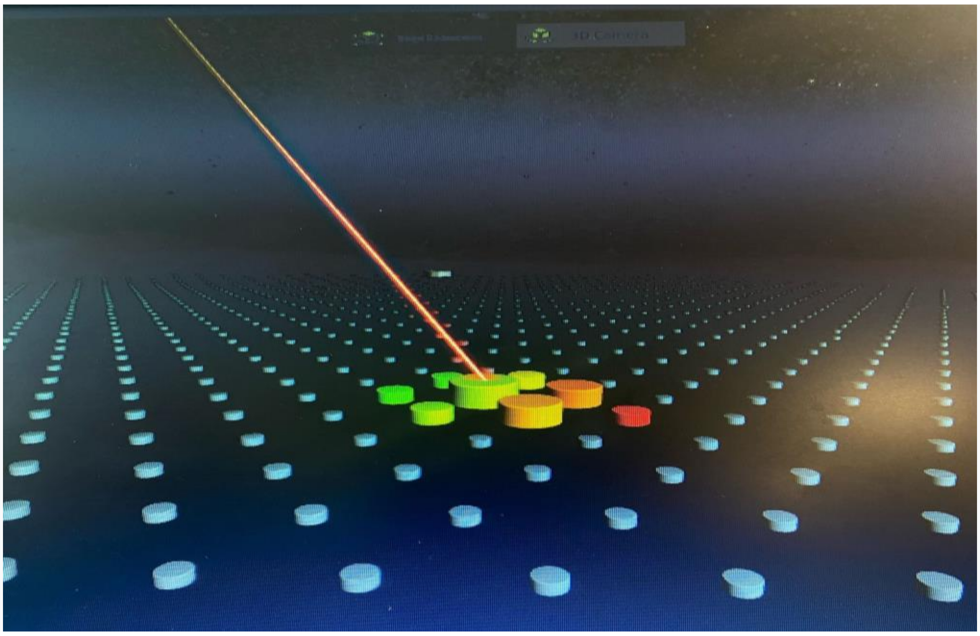

Fig.4 this image shows the result of the third step of the reconstruction datas.

Comparing our results, some cosmic rays appeared to come from regions with active galaxies, suggesting an extragalactic origin. Others were more randomly distributed, likely due to deflection by cosmic magnetic fields. This hands-on experience gave us a glimpse into the complexities of astrophysics, showing how scientists use real data to unravel the mysteries of the universe. In the end after our reconstructio we could approximate the direction of origin of the cosmic-ray flux using the **fig.5**.

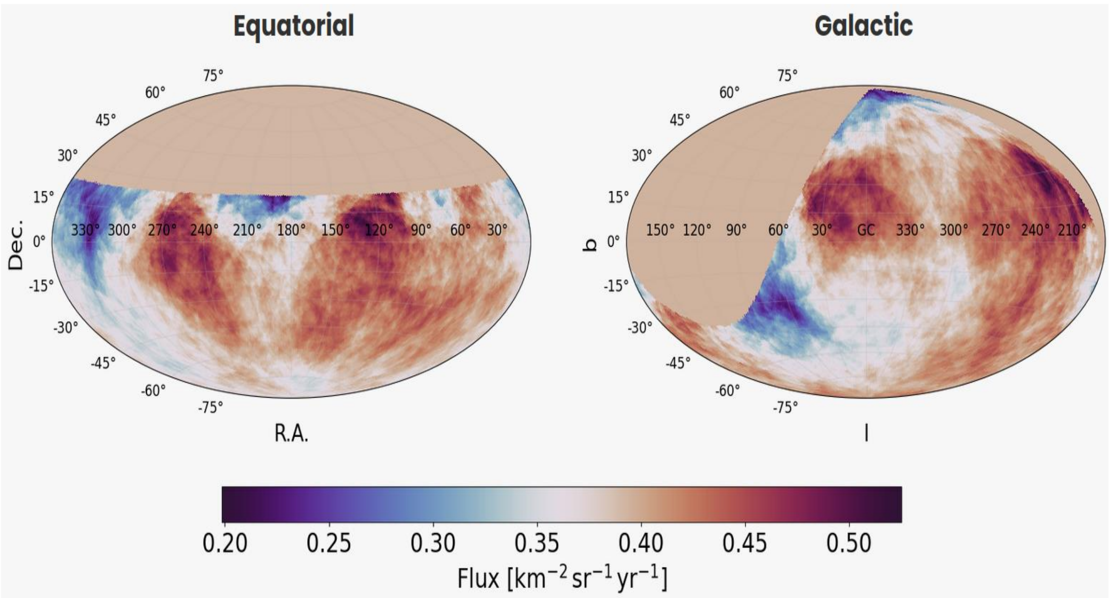

Fig.5 The image shows the intensity of cosmic ray flux across the entire celestial sphere; the blu highlights indicate the low intensity regions, the red ones indicate the high intensity regions. We only used for this relevation the Cosmic Rays with higher intensity with the lower limit of 10^18, because of their major probability of revelation.

Effects on Earth and Space Missions

The Earth's atmosphere and magnetic field provide effective protection against most cosmic rays, preventing them from reaching the surface. However, it is believed that this constant radiation has influenced the evolution of life forms by causing genetic mutations, which have contributed to biological diversity.
In space, the absence of a protective atmosphere exposes astronauts and equipment to higher levels of cosmic radiation. This poses several risks**[1]**:

•*Astronaut Health*: Prolonged exposure to cosmic rays can increase the risk of developing cancer and cause damage to the central nervous system, impairing cognitive and motor functions. Studies have shown that such exposure could negatively affect astronauts' cognitive health during long-duration missions to Mars.

•*Physiological Dysfunctions*: Some research suggests that exposure to cosmic rays during deep-space missions could contribute to erectile dysfunction in astronauts.

•*Damage to Equipment*: Radiation can damage the electronic components of spacecraft, causing malfunctions or failures. The chronic exposure to low-dose cosmic radiation is associated with a modest increase in stochastic health risks, particularly carcinogenesis, due to DNA damage and genomic instability. While DNA repair mechanisms mitigate much of this damage, cumulative effects over a lifetime warrant consideration in radiobiological risk assessments.
The exposure is modulated by altitude, geomagnetic latitude, and solar activity. Higher doses are observed in aviation personnel, residents at high altitudes, and individuals in polar regions, where geomagnetic shielding is reduced. Solar modulation also plays a critical role; decreased solar activity corresponds with increased galactic cosmic ray flux at the Earth's surface.

6. CONCLUSIONS AND FUTURE PERSPECTIVES

Cosmic rays are key to understanding high-energy astrophysics, particle physics, and space weather. Their origins range from supernovae to active galactic nuclei, and their propagation through the galaxy involves complex interactions with magnetic fields and matter. While they impact Earth's atmosphere and space missions, their exact acceleration mechanisms and highest-energy sources remain unclear.

Future Perspectives:

•*Advanced Observatories*: Next-generation telescopes (CTA, SWGO) and space missions (CREAM) will improve cosmic ray detection.
•*Multi-Messenger Astronomy*: Combining cosmic ray data with neutrinos and gravitational waves will refine source identification.

•*Space Exploration*: Better radiation shielding is needed for deep-space missions to Mars and beyond.

•*Fundamental Physics*: Cosmic rays could reveal new physics, including insights into dark matter and beyond-Standard-Model phenomena.

As technology advances, cosmic ray research will continue to unlock new discoveries about the universe.

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