Introduction to Cosmic Rays

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1.What are cosmic rays?

Cosmic rays are high-energy charged particles, mainly protons and atomic nuclei, traveling at relativistic speeds. They come from outside our solar system. Earth is constantly bombarded by them from all directions. They are composed of about 90% Hydrogen (protons), 9% Helium (alpha particles) and 1% of all other heavy elements like C, N, O, Si, Al, Fe, etc [1]. Cosmic rays are a good representation of the entire periodic table. Their composition matches with that of our solar system with some differences, suggesting that they are of stellar origin [1]. They are the most energetic radiation known to be present in nature. They span over an incredibly large energy range (10^8 eV to 10^{20}eV) where 1 eV (1.6×10^{-19} joule) is defined as the energy gained by an electron or proton when subjected to a voltage of 1 Volt. To give a comparison, the energy of visible light is an order of 1 eV. The energy of X-ray is of order 10^3 eV and the emission from radioactivity such as alpha, beta and gamma rays is of order 10^6 eV. Electrons and protons in the solar corona where the temperature is about 1 million degrees have an average energy of 10^2 eV. The energy density of cosmic rays is ~1 eV/cm^3 which is comparable to that of magnetic field, starlight, kinetic energy of gas, and black body radiation in the universe. The rate or flux of cosmic rays falls rapidly with energy. For example at 10^{11} eV, it is about 1 per m^2 per second. At energy 10^{15} eV (PeV), it is about 1 per m^2 per year, and at 10^{18} eV (EeV), it is 1 per km^2 per year.

Therefore, different sizes of detectors are required to detect cosmic rays at different energies.

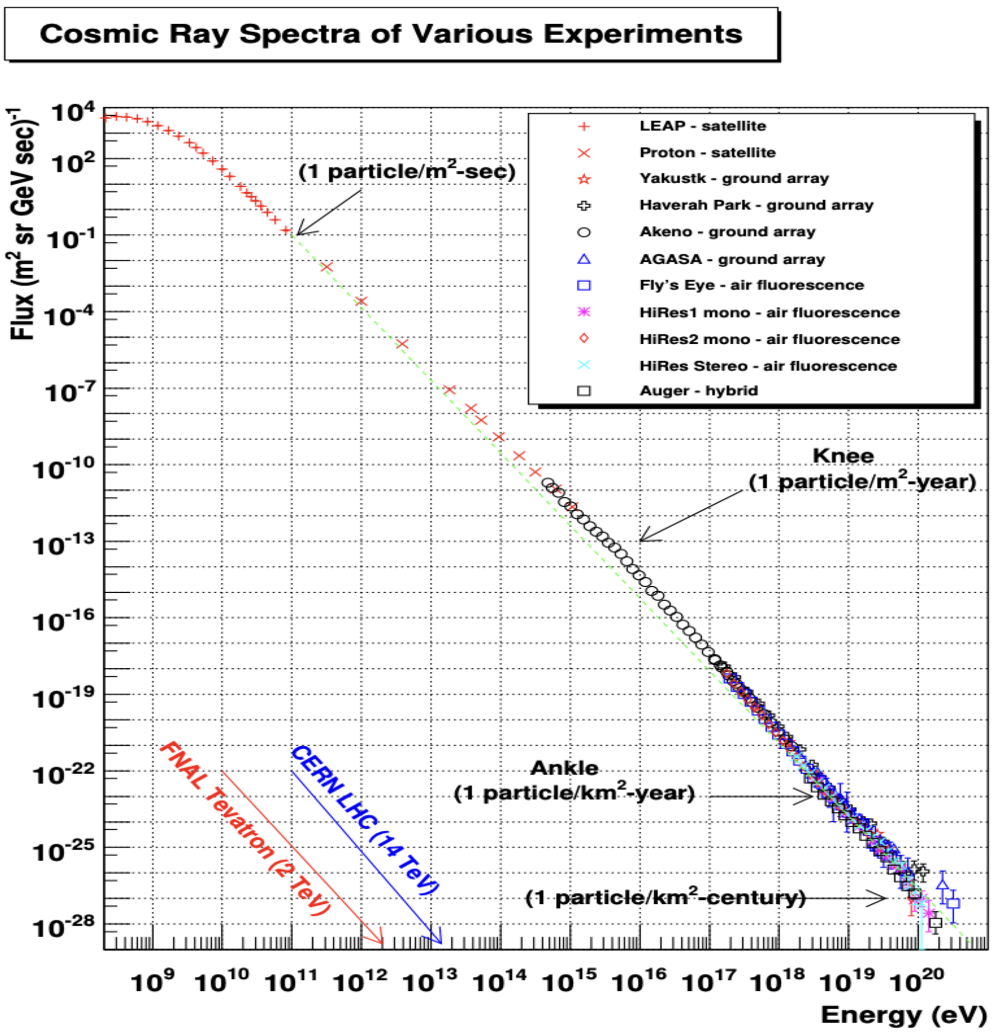

Figure 1: Measurement of cosmic ray energy spectrum by various space and ground experiments [2].

2. A historical perspective of cosmic discovery

The study of cosmic rays started at the beginning of the 19th century. While studying the conduction of gas using a gold leaf electroscope, scientists found that the electroscope discharged by itself even when isolated from all possible sources of radiation. This phenomenon was studied in 1901 by two groups of scientists, J. Elster and H. Geitel in Germany, and C.T. R. Wilson in England. Both groups concluded that there exists some unknown source of ionizing radiation. In 1907 Father Theodore Wulf, invented a new electroscope that could be taken outside the labs and used for studying these radiations into the mountains, atop the Eiffel Tower, and, ultimately, aloft in balloons. It was assumed that the radiation came from the ground, so they

Figure 2: Victor Hess balloon flight and discovery of cosmic rays

(Image: VF Hess Society/Echophysics/Schloss Pöllau/Austria)

expected a decrease in the radiation at a higher altitude but on the contrary, they found some increase in the radiation. Amazed at these results, in 1911 Father Theodore Wulf and his colleague Victor Hess, an Austrian Nuclear Physicist, with the support of the Austrian Imperial Academy of Sciences and the Royal Austrian Aero Club, conducted a series of balloon flights to further study these radiations. On 12th August 1912, Victor Hess reached a height of 5350 meters. With the two sealed ion chambers he took along, he found that the ionization rate decreased initially, but at 1500m it started increasing and at around 5000 meters it became twice the surface value. He concluded that the observations can be best explained by assuming that these radiations of very high penetrating power coming from above enter the atmosphere, and cause partial ionization in the enclosed instruments, even at lower atmospheres. Victor Hess received the Nobel Prize in Physics in 1936 for discovering cosmic rays [3].

Before the particle accelerator era, several elementary particles were discovered from cosmic ray observations. In 1932, Carl Anderson discovered antimatter in the form of anti-electron, subsequently dubbed the positron, while observing the tracks of cosmic ray particles going through his cloud chamber. In 1937, Seth Neddermeyer and Carl Anderson found the muon, an elementary subatomic particle in cosmic rays. In 1947, pion, the first meson was discovered by Lattes, Occhialini and Powell which was predicted by Yukawa in 1935. The same year the first strange particle namely Kaon was discovered by Rochester and Butler. In 1951, the first strange baryon was discovered by Armenteros.

3. Origin of cosmic rays

The origin of cosmic rays has been a long standing problem since their discovery more than a century ago. This is due to the fact that cosmic rays are charged particles. Hence the interstellar magnetic field deflects their trajectories from their original path making their distribution almost isotropic (similar intensity in different directions). Thus, when cosmic rays are observed on the Earth, their trajectories cannot be traced back to their sources. However, the measurements of their mass composition makes us infer that they are of stellar origin. Supernova remnants are believed to be the most possible source of cosmic rays [4].

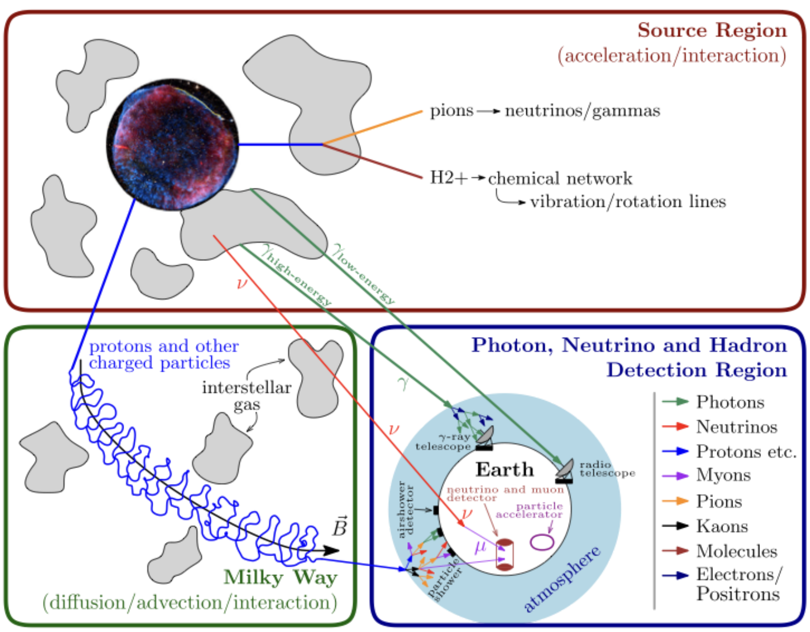

Figure 3: A schematic showing charged particles (cosmic rays) from a source undergoes many deflections before reaching the Earth. Whereas neutral particles such neutrino or gamma rays can come straight from the source to the Earth [4].

It is believed that the low energy charged particles are repeatedly encountered by the shocks of the supernova explosion while gaining energy in each encounter. Energy released by one supernova explosion is ~10^{44} joule. If 10% of the energy released from a supernova explosion goes to cosmic rays' acceleration, that can count the energy budget of cosmic rays. One supernova explosion in 30 years is enough to maintain the cosmic ray balance in our Galaxy.

Cosmic ray interactions near the source environment can produce neutral radiation such as gamma rays and neutrinos which can come straight from the source to the Earth. Therefore, observation of these neutral radiation can help us to identify the sources of cosmic rays. Considerable progress has occurred in the observation of gamma rays and neutrinos during the past two decades, hinting us about the sources of cosmic rays. Further observations and interpretation are required to get a precise answer on the cosmic ray origin.

4. Cosmic ray in the Earth's magnetic field and atmosphere

The magnetic field of the Earth is generated by electric current due to the mixture of molten iron and nickel in the Earth's outer core. It extends more than 1,00,000 km from the interior of Earth into space. Cosmic rays in the polar region can easily enter the Earth as the magnetic field lines are parallel to their direction, experiencing less Lorenz force. However, in the equatorial region, magnetic field lines are perpendicular to the cosmic ray direction, experiencing maximum Lorentz force.

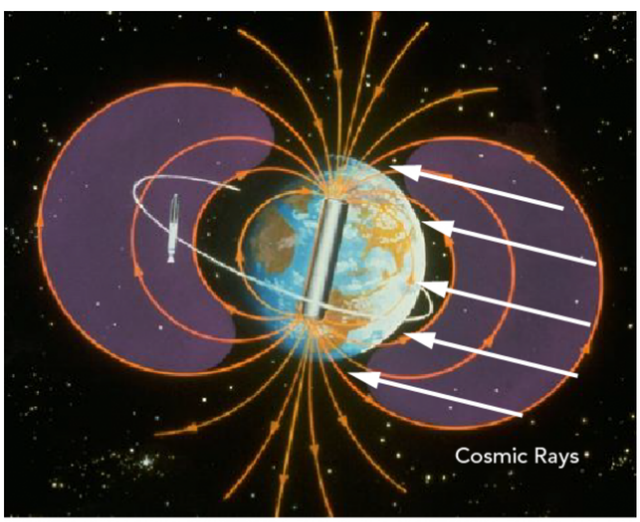

Figure 4: A schematic showing the magnetic field of the Earth and entering of cosmic rays [image credit: NASA].

Therefore, the intensity of cosmic rays varies with magnetic latitude. It is minimum at magnetic equator and maximum at magnetic poles. This is known as the latitude effect of cosmic rays. In addition, cosmic rays have higher intensity from the west direction than the east direction which is known as the east-west effect [5].

Primary cosmic rays upon entering into the Earth's atmosphere interact with the atomic nucleus of nitrogen or oxygen molecules. The interaction leads to the production of secondary particles as shown in the schematic in Figure 5. A shower is developed which includes both charged and neutral particles. The multiplication of the particles occurs up to a certain depth in the atmosphere depending on the energy of the primary cosmic rays and after that the secondary particles start to get absorbed due to the ionization losses.

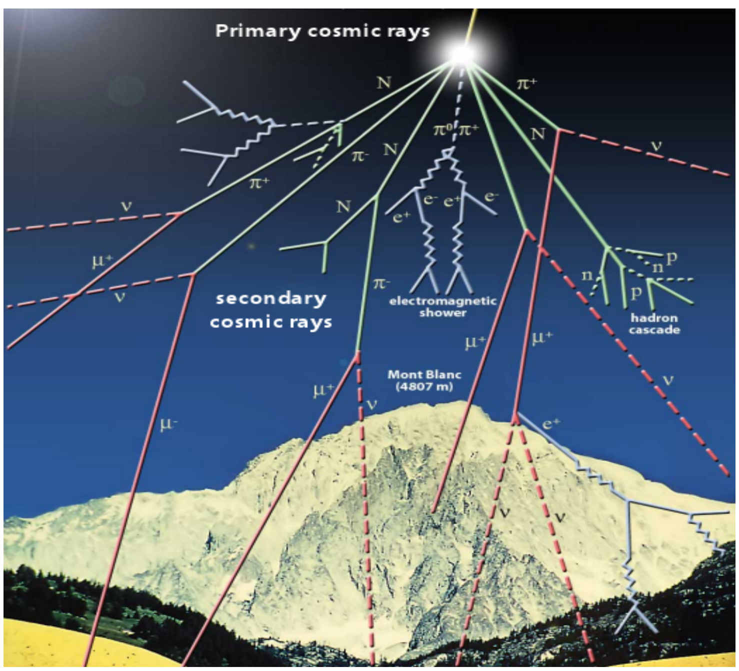

Figure 5: Interaction of a primary cosmic ray in the atmosphere and development of a shower [image credit: CERN].

The most numerous particles in the shower at the observational level include photons (gammas), electrons, positrons (antiparticles of electrons) and muons (about 210 times more massive than electron) can penetrate deeper in the atmosphere, even the higher energy muons can pass kilometers underground. Due to the time dilation effect, a major fraction of muons which are produced in the upper atmosphere could reach the ground level as they can travel a longer distance before they decay.

Neutrinos are also produced in the shower, however they are weakly interacting particles and need large volume detectors for their detection. Many of them can pass from one to the other side of the Earth. Particles in the shower travel nearly the speed of light as they are relativistic. They are spread over several tens of square meters to even several square kilometers on the ground. The energy of primary cosmic rays that hit at the top of the atmosphere gets distributed among thousands to millions of secondary particles produced in the shower.

5. Cosmic ray measurements in space and ground

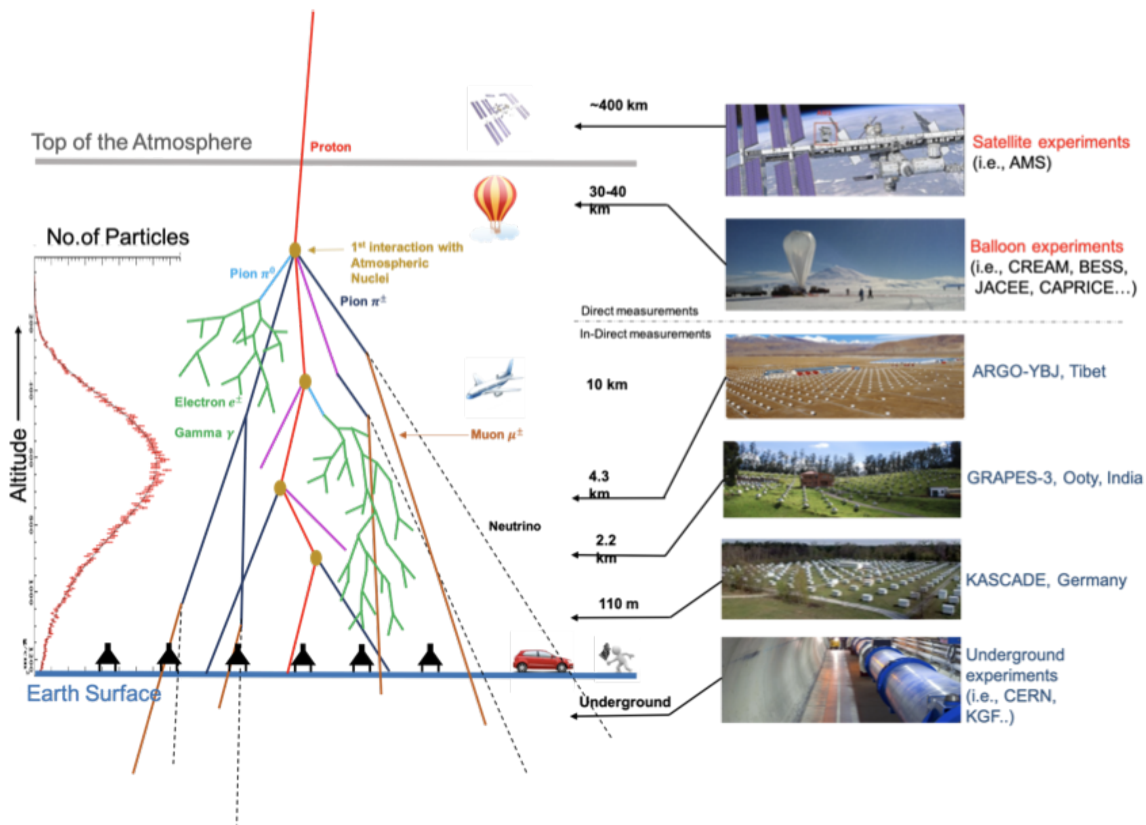

Figure 6: Experiments at different altitudes and detection mechanisms for measuring cosmic ray showers developed in the atmosphere [6].

Cosmic rays below about 10^{14} eV (100 TeV) are mainly observed in space by satellite or balloon borne experiments. The space based measurements are more accurate as cosmic rays are detected directly before they interact in the Earth's atmosphere. However, the low flux of cosmic rays at higher energy and the small size of the detectors that can be carried in a space-based detector limits the observation above 100 TeV. Some of the on-going space-based cosmic ray experiments are, (1) Alpha Magnetic Spectrometer (AMS-02) and Calorimetric Electron Telescope (CALET) on international space station, and the DArk Matter Particle Explorer (DAMPE). Beyond the reach of the direct experiments up to the highest energy (10^{20} eV), cosmic rays are studied by the ground based detector arrays. Cosmic ray observations in the energy of 10^{15} eV to 10^{18} eV are accomplished through detector arrays spread over an area of 0.1 to 1 square kilometer. A few examples of such arrays include Tibet AS_gamma in Tibet, GRAPES-3 experiment in Ooty, and KASCADE-Grande in Karlsruhe, Germany. The observation of ultra high energy cosmic rays ($>10^{18}$ eV) are made through detector arrays spread over several thousand square kilometers. Examples of such arrays include Pierre Auger Observatory in Argentina and Telescope Array in Utah, USA.

6. Cosmic ray research in India

There is a long and rich history of cosmic ray research in India since the early 1940's which is described in [7]. Four pioneers who led the cosmic ray research in India were D.M. Bose, H.J. Bhabha, P.S. Gill and V.A. Sarabhai. D.M. Bose and his associates were the first to identify the cosmic ray muons by exposing photographic emulsion plates to CRs at Darjeeling in the Eastern Himalaya region during 1932-42.

H.J. Bhabha had developed the cascade theory of cosmic rays along with Heitler. The experimental cosmic ray research in India got a big boost when Bhabha established the Tata Institute of Fundamental Research (TIFR) at Bombay in 1945 as he started different cosmic ray research programs with his students and coworkers in TIFR. Some of those programs were centered around in deep underground mines of Kolar Gold Fields (KGF), where experiments on muons and their interactions at deep underground, variation of intensity of cosmic rays with depths, and proton decays were conducted during the period of 1950–1981 using Geiger Muller counter, proportional counter etc. Renowned scientists like B. V. Sreekantan, S. Narayan, P. V. Ramanamurthy, M. G. K. Menon *et al.* were involved in collaboration with the scientists from University of Durham, U. K. and Osaka City University, Japan. Some of the important results of these experiments include understanding the role of muons in various interactions including vector bosons, their role in weak interactions, first detection of an atmospheric neutrino in KGF mines, setting the best lower limit on the lifetime of protons etc. Some other important programs of Bhabha in cosmic ray research were started with the establishment of the Cosmic Ray Laboratory (CRL) at Ooty (2200 m a.s.l.) in the Nilgiri hills in Tamil Nadu in the year 1954 along with B.V. Sreekantan, P. V. Ramanamurthy and others. Initial aim of this laboratory was to search for new particles, such as strange particles produced in cosmic ray interactions using two multi-plate cloud chambers.

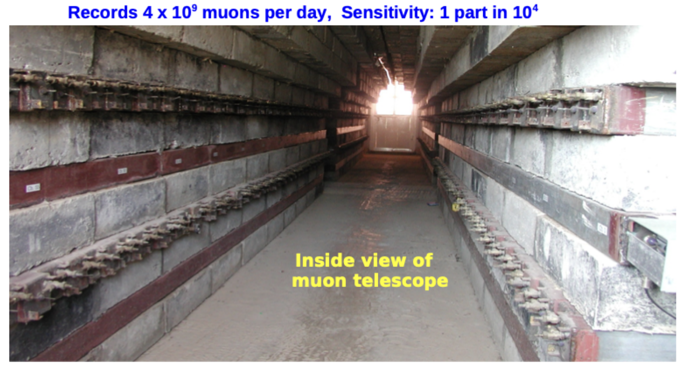

Figure 7: A view of the GRAPES-3 experiment (left image). The white conical structures are scintillator detectors. The right side image shows the inside view of one of the four stations of the muon telescope.

The CRL group has built a large cosmic ray air shower array namely GRAPES-3 (Gamma Ray Astronomy at PeV EnergieS Phase-3) in late 1990s which is about 8 km from Ooty center. The objectives of the experiment are to study (1) cosmic ray energy spectrum and composition, (2) gamma ray astronomy, and (3) solar physics. The experiment currently consists of an array of 400 plastic scintillator detectors spread over an area of 25,000 m^2 as shown in Figure 6 and a 560 m^2 area muon telescope (largest in the world) which are built indigenously. Secondary particles in cosmic ray showers are recorded by the scintillator detectors including their density and arrival times. The muon telescope records muons in the shower.

7. Cosmic rays and space weather

Space weather refers to conditions around a star, like our Sun, and its interplanetary space, the planet's atmosphere that may affect space & ground-based assets, and human life. Space weather can create complex and sometimes dangerous conditions. Space weather is primarily driven by transient solar phenomena such as solar flares and coronal mass ejections (CMEs). The CMEs are transient eruptions from the Sun's atmosphere, ejecting vast quantities of solar material into the interplanetary medium.

When CME reaches the Earth, it interacts with the Earth’s magnetosphere, triggering solar storms or geomagnetic storms.

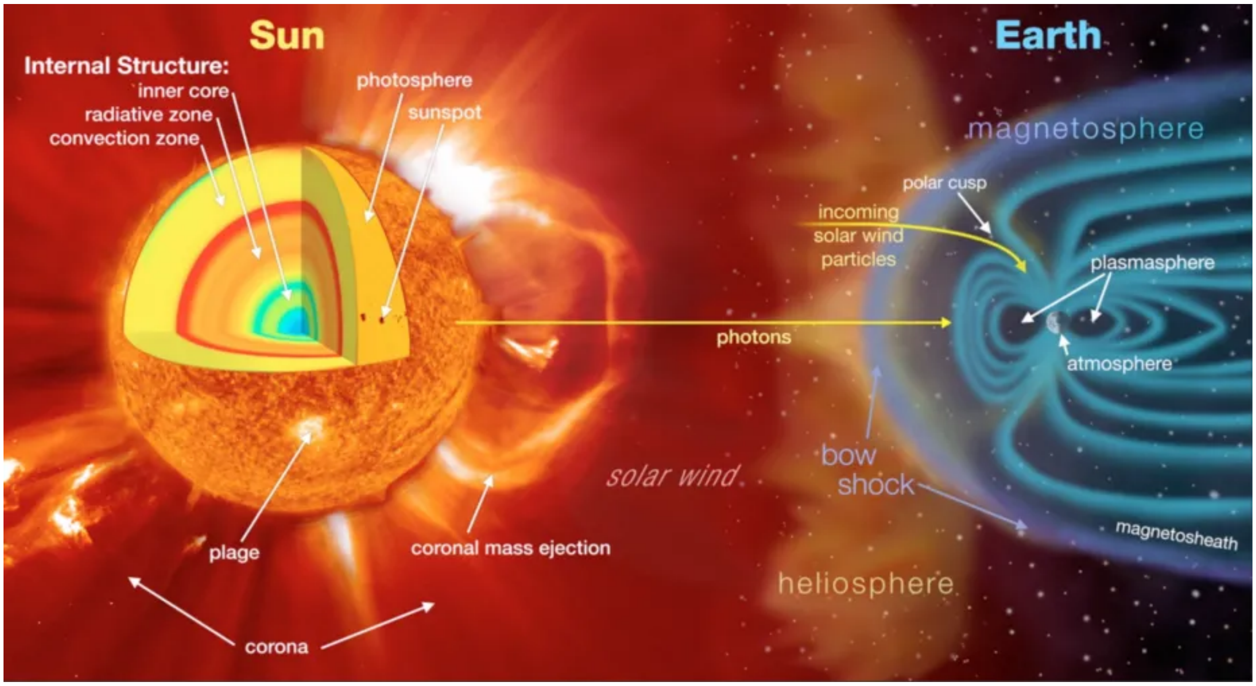

Figure 8: Coronal mass ejection from the Sun interacting with the Earth’s magnetosphere [Image credit: NASA Goddard Space Flight Center].

The magnetic reconnection is favored when the CME magnetic field is counter-aligned to that of the Earth. Geomagnetic storms produce major changes in the currents, plasma, and fields in Earth’s magnetosphere which can severely impact the technological infrastructures including satellites for communications, GPS, etc as well as terrestrial power grids [8]. If an event like the Carrington super geomagnetic storm of 1/2 September 1859 were to occur today, it could cause unimaginable economic loss to the world. The field is growing rapidly and is increasingly being recognized as a severe source of risk by many national and international governmental agencies and corporations. A recent example is the loss of 38 new Starlink satellites of the SpaceX company due to a minor space weather event that occurred on 4th February 2022 [9]. Thus, understanding space weather disturbances and forecasting them has become a need of the time.

Cosmic rays are a good probe for studying space weather. The interplanetary magnetic field and solar wind variation during CME also changes the flux of the incoming cosmic rays being observed on the Earth. One example of a space weather event that occurred on 22 June 2015 was detected by the GRAPES-3 experiment. For a duration of two hours, the flux of muons detected by the GRAPES-3 muon telescope increased about

1%. During this period, it was observed the interplanetary magnetic field in the CME changed by 40 nT with a south orientation (opposite to that of the Earth's magnetic field). It was interpreted that the interplanetary magnetic field reconnected with the Earth's magnetic producing a weakening of Earth's magnetic that had allowed more low energy cosmic rays to enter into the Earth's atmosphere producing more muons. The discovery has been reported in more than a thousand news articles (link).

8. Muon tomography

As we discussed in section 4, muons are produced in the interaction of cosmic rays in the Earth's atmosphere. Muons can be used for imaging like X-ray, CT scan etc. This is called muon tomography [8]. Muons have a larger penetrating power in the matter (even several kilometers) than X-ray or gamma rays. Large objects like a void in Pyramid or a volcanic region in a mountain can be probed by muon tomography. Since a muon loses energy primarily by ionization process, the absorption of muons depends on the density of the matter they traverse through. The number of muons detected passing through the void or low density region as compared to other regions will be higher. So imaging of the muon flux can be used for finding a void or low density region.

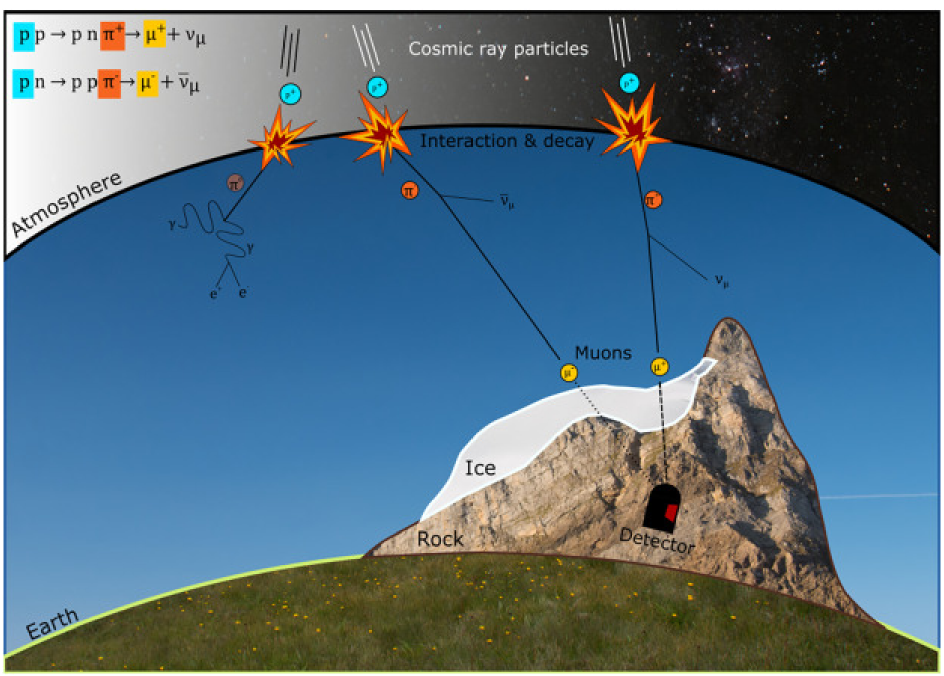

Figure 9: Sketch illustrating the components that are involved in an experiment where muon tomography is used [9].

Further, muon tomography can be used to identify materials of different densities. This works in the principle that muon traversing through a high density material will have higher scattering from the incident direction than a low density material. By measuring the scattering angle, different materials can be identified.

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