Cosmic Rays: Invisible Particles from Outer Space

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We provide a short introduction of what cosmic rays are. We also discuss how they are detected, and how they behave in the presence of homogenous magnetic fields.

1. INTRODUCTION

Cosmic rays are highly energized particles (90% are protons, but there are alpha and beta particles as well) from space that collide with the Earth's atmosphere. A common misconception is that cosmic rays are actual rays; in reality, this phenomenon occurs as a slew of single particles. Most of them can penetrate through Earth's magnetic field to the atmosphere, where they interact and scatter, as we will later show. What makes this phenomenon so fascinating is that these particles are constantly barraging and entering the atmosphere, though many people do not even realize it. What is more, cosmic rays travel incredibly long distances; not only do they come from the sun, but other celestial bodies as well. Research on cosmic rays has its benefits. It is possible to gain insight into the intricate workings of the vast universe, and developments for protection from the side effects of cosmic rays on living creatures can be made.

2. WHAT ARE COSMIC RAYS?

It is necessary to establish a clear foundational understanding of basic particle physics in order to comprehend the characterization, behavior, and detection of cosmic rays. The Standard Model is a theory which explains the fundamental particles and their interactions. Three types of fundamental particles exist: i) quarks (which make up protons and neutrons) ii) leptons (such as the well known electron) and iii) force carrier particles (like the photon). Quarks exist only in groups of two (known as mesons) or three (known as baryons). In particular, there are two mesons that are associated with cosmic rays—kaons and pions. Leptons, the second classification, can exist alone. Other leptons are muons, a charged particle whose mass is much greater than that of the electron, and neutrinos, hard-to-find neutral particles with very little mass. The third classification, force carrier particles, is involved in interactions between particles. These particles, however, are not crucial to a basic understanding of cosmic rays, so they will not be thoroughly discussed. Of these, it has been established through observation that some are more stable than others, and that the more unstable particles will decay into the more stable ones. For example, the heavy muon, once produced, quickly decays into neutrinos and the more stable electron.

Cosmic rays are charged particles. Once they encounter the atmosphere, the particle breaks down and sets a chain reaction of several decays. For instance, a produced gamma ray can break down into an electron and positron, which can emit more gamma rays, which in turn decays into more electrons and positrons. The main constituent of cosmic rays, the proton, strikes the atmosphere and almost immediately breaks down into unstable pions and kaons, which in turn decay further into the more stable electrons, muons, and neutrinos. The result is a cascade of various types of particles known as a cosmic shower.

Out of all these numerous traveling particles, only certain types actually reach the surface of the earth. The original proton, for example, never actually reaches the surface, and thankfully so: if it did, its immensely powerful collisions would damage living creatures. Those that do reach the earth, such as electrons and muons, are not as damaging.

Cosmic rays are strange forms of matter, as they generally travel velocities near the speed of light and they are extremely tiny. Because of these factors the particles emitted by the cosmic rays display unusual
FIG. 2: A cosmic ray shower

behaviors, which create a variety of problems for classical mechanics. One easily observable problem is the fact that scientists are even able to detect cosmic ray particles on the earth. In reality, most particles should decay before they reach the surface of the earth, but they don’t. Using Albert Einstein’s Theory of Special Relativity this problem can easily be solved, for as an object moves faster time flows faster in comparison to the time of a stationary observer. One can use the muon to help explain this problem and its solution. A muon travels approximately 2.997 × 10^8 meters per second. A muon must be able to travel at least 50 km from the atmosphere to the surface; however, because the average lifetime of a muon is only 2.197 × 10^{-6} seconds, a muon should decay after traveling at most 658.638 meters. Although this event seems contradictory, because the muon should decay before it reaches the surface, it can in fact be explained by time dilation. Time dilation shows that when traveling near the speed of light, an observer sees that the muon actually decays slower than if it was stationary.

\[ c = \text{speed of light} = 2.97 \times 10^8 \text{m/s} \]
\[ v = \text{speed of muon} = 0.99999c \]
\[ t = \text{decay time of muon} = 2.197 \times 10^{-6} \text{s} \]
\[ t' = \text{relativistic muon decay time} = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]
\[ t' = 4.192 \times 10^{-4} \text{s} \]

After calculating the time dilation one finds that an average muon decays in approximately 4.912 \times 10^{-4} seconds from the perspective of an Earth observer; thus, the muon can actually travel 1.474 \times 10^4 meters before decaying. This allows for the muon to be detected on the surface of the earth.

3. HOW DO COSMIC RAYS BEHAVE?

Since cosmic rays are usually charged particles, they are affected by the Lorentz force. The Lorentz force, written

\[ \mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \]

dictates a single particle’s behavior in relation to electric and magnetic fields, where \( \mathbf{F} \) is force on the particle, \( q \) is its charge, \( v \) is its velocity, \( \mathbf{E} \) is the electric field, and \( \mathbf{B} \) is the magnetic field. For the moment, we ignore the electric field component and focus on the behavior of a particle only in a magnetic field; the equation then simplifies to \( \mathbf{F} = qv \times \mathbf{B} \). We can then use Newton’s second law, \( \mathbf{F} = m\mathbf{a} \) to calculate the acceleration of the particle; summing this acceleration over time gives us the particle’s velocity and trajectory.

The Earth has a magnetic field, so we can use this equation to see how much of the cosmic rays get deflected due to Earth’s magnetosphere. We need to make a number of assumption in order to simplify the calculations: we assume that the Earth’s magnetic field is homogeneous and perpendicular to the direction of the cosmic ray’s travel, and that there are no other forces than the Lorentz force acting upon the cosmic ray. For these calculations, we used a proton (the most common “cosmic ray”) with an energy of 300 MeV and assumed that Earth’s magnetic field is a homogenous 6.0 \times 10^{-5} Tesla (0.6 Gauss). This is a very generous assumption: the value of the magnetic field comes from an average of values on the Earth’s surface; since field drops off as the cube of distance, the field in outer space is much, much smaller.

FIG. 3: A particle flies into the magnetosphere and feels a force

We start with the Lorentz force equation:
FIG. 4: The orbit of a deflected, trapped particle, and the right hand rule/cross product that leads to it.

\[ \mathbf{F}_{\text{Lorentz}} = q \mathbf{v} \times \mathbf{B} \]

Since the Lorentz force is always perpendicular to the velocity of the particle, it will lead to circular motion: constant acceleration perpendicular to the velocity leads to a circular orbit. Therefore, we set it equal to the centripetal force required to bend the particle into a circular orbit:

\[ F_{\text{centripetal}} = \frac{v_{\text{tangential}}^2}{r} \]

\[ |F_{\text{centripetal}}| = |F_{\text{Lorentz}}| \]

\[ \frac{mv_{\text{tangential}}^2}{r} = q(vB\sin(\theta)) \]

\[ v_{\text{tangential}} = v \]

\[ r = \frac{v^2m}{qB} = \frac{v}{qB} \]

We can find the proton’s velocity, given its kinetic energy:

\[ v = \sqrt{c^2 \left(1 - \frac{m_0c^2}{KE + m_0c^2}\right)} \quad (1) \]

(relativistic effects apply to protons above 50MeV or so).

We then plug our values in to find the radius of the orbit (and deflection) that the proton would take in Earth’s magnetic field. The number turns out to be large, 25,674 meters. If the proton traveled toward the Earth from outer space, it would experience an extremely small field until it came into close proximity. This bending radius indicates that if the proton experienced a homogenous .6 Gauss field, it would turn around in a 25km radius. Since the field is decidedly not homogenous, it would likely turn in much greater than 25km and would not be deflected.

Protons are quite heavy, and when in cosmic rays, are travelling quite fast. Suprisingly, the Earth’s magnetosphere blocks nearly none of the cosmic proton flux; the protons are simply traveling too fast and the Earth’s magnetic field is too low. A generalized form of the equations above were plotted; they show that in order for a proton to be deflected just by the Earth’s magnetic field, it would need to be traveling extremely slowly and have a near thermal speed.

4. HOW DO WE DETECT COSMIC RAYS?

Since cosmic rays are made up of extremely small particles nearly traveling at light speed, it is impossible to detect these particles by the naked eye. Moreover, the traditional methods of observing sub-atomic particles, such as electrode microscopes, are totally useless because of the intense speed of the particles. Generally, although some particles that result from cosmic showers react with the surrounding environment, such interactions are difficult to trace; thus, they pass through most matter undetected and without any visible changes or alterations to the subsequent matter. Hence in order to observe and analyze these particles one must be able to observe the interactions between the particle and matter. There are various methods to observe such interactions; however, for one to view these interactions certain conditions must be met, such as the ability of the device to display ionization caused by the particles. Scientists have developed many devices that display these interactions which generally alter a certain type of matter so that the interactions (seen as tracks or trails in the matter) can be observed. Such devices include the cloud chamber, bubble chamber, wire chamber, spark chamber, and drift chamber.

The most simplistic of these chambers is the cloud chamber, which detects fundamental particles and particles of ionizing radiation. However, its overall function is similar to the other chambers. In short, the cloud chamber is filled with super cooled water or alcohol vapor.
Because the mixture inside the chamber is at the threshold of condensation a fine mist can be seen throughout the chamber. Particles are detected in this mist because their charges ionize the mist with which it comes into contact. Thus, the mist enables for an observation of the particles path.

Much analysis can be done based on the shape, speed, and size of the formed ion trails. For example, a trail that seems to fork into two trails depicts the decay of one particle into two. Likewise, one can also observe how negatively charged particles curve in opposite directions upon encountering a magnetic or electric field.

We observed particle tracks ourselves at the Caltech cloud chamber; while the chamber needed maintenance (notably, it had puddles of condensation at the bottom), the tracks were clearly visible. We saw alpha particles, muons as a result of cosmic showers, and electrons. A V shaped trail can be particle decay, annihilation, or particle creation by the fusion of matter and antimatter. The majority of trails observed in a cloud chamber are skinny white lines. These trails can be created from a variety of charged particles such as positrons. Spiral trails are created by low energy Beta particles such as electrons or muons. Specifically, electron trails are more exaggerated and random, compared to muon trails. Since an electron's mass is relatively small compared to atomic nuclei, electrons are bounced around by the various nuclei in the alcohol vapor. Larger particles, like muons, contain a much greater mass thus remain virtually undisturbed upon contact with the nuclei.

5. CONCLUSION

We now know that cosmic rays are 90% protons, and that they are easily detected on the Earth’s surface. We know what sort of particles arise from cosmic ray showers (mostly muons and electrons), and we know how these highly energetic, charged particles behave in a magnetic field (and how they are sometimes trapped by the Earth’s own magnetic field).

Cosmic rays are all around us, shooting through our bodies even now as we are writing this. Careful study of cosmic rays have a number of useful applications—cosmic ray astronomy and spectroscopy can discover the secrets of the universe. This introduction to cosmic rays is just the tip of the iceberg.

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7. BIBLIOGRAPHY


