A brief Introduction to Cosmic Rays and Their Observations

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Abstract

Currently, the study of cosmic ray mainly focuses on the origin, acceleration method and transmission mechanism. An important way to learn about cosmic rays is to measure the energy spectrum of cosmic rays. In recent years, people grasped a clearer understanding of the energy spectrum of cosmic rays under the rapid technical development of cosmic rays detection. This paper first introduces the detection of cosmic rays, including the detection methods and cosmic-ray knee regions. Then, recent land-based and space-based cosmic ray observation experiments are compared and summarized. Finally, the research status of cosmic rays is analyzed and discussed, and the future development is prospected.

Keywords

Cosmic rays ; gamma ray; Ultra High Energy.

1. Introduction

Ever since the Austria physicist, Victor Hess, in 1912, discovered cosmic-rays during an upper-air ballon experiment, people have never ceased to acquire more on the field of cosmic-rays, which leads to the unearthing of numerous fundamental particles, including positrons, mesons, and the laws of their interactions as well as interrelations. During the furthering on the field of cosmic rays, a new field known as particle physics was inaugurated, not to mention the great impact on astronomy during this process.

Intrinsically, cosmic-rays are high-energy radiation of charged subatomic particles generated in outer space (chiefly outside the solar system.) While being composed of mainly but not solely of protons and atomic nucleus, cosmic-rays usually also contain a minuscule number of photons, electrons, neutrinos, and anti-particles

The research on the cosmic-rays chiefly focus on three issues, namely, the origin, the acceleration method, and the transmission mechanism, of which the crux of the study lies in the answer to the problem concerning where the origins of cosmic-rays really are. (considering our inability to ascertain the acceleration and transmission mechanism of a cosmic-ray without the knowledge of its origin) Yet, the mechanism of acceleration of the cosmic-rays still provide plausible hints for us to determine some significant traits of the source celestial body. Our chief approach to determine the sources of those rays is to measure their spectrum, components, and their anisotropy, requiring some detecting works to be done. By means of detecting and analyzing the rays coming to the ground of the earth, we could steal a peep into the mysterious nature of cosmic-rays directly coming from their sources. However, the particles we spot on the ground of earth is after all not the original particles directly from the sources of the rays (they will undergo the process called Extensive Air shower which will be elaborated in the following chapters), making the outer space probes necessary. These space probes could offer us a direct view of the original particles from the outer solar system. Unfortunately, this seemingly optimized method of detecting is still flawed since we these detectors beyond the earth's atmosphere requires carriers such as satellites and balloons, which dramatically decreases the area of the detector, indicating that this method is only applicable when the cosmic-ray we study bears the energy lower than some certain threshold (10^14 eV). For those with utterly high energy, i.e., ultra-high energy cosmic rays with energy greater than 10^18 e, scientists' modus operandi is to build large on-land detectors to optimize the information we get, regardless of the fact that they are indirect detecting. By interpreting certain information and results we attain from the land-based detectors, it’s highly possible for us to get an adequate and unbiased understanding of Ultra High Energy cosmic rays’ energy spectrum, direction, and most importantly, composition. There are plenty of land-based detectors which will be elaborated in the upcoming sections.

So, the question comes to why we are putting so much efforts into the study of cosmic-rays. The answer is apparent: cosmic-rays provide us with an insight into the currently still unfathomable nature of the entire universe which could not be directly observed by us. Their obvious high-energy, their properties to spread on a cosmic scale, and the invaluable information they bear make them unique and precious lab, enabling us to dive deeper into truth of physics.

2. Detection Methods and Detection Experiments

For years, scientists’ passions on figuring out the truth behind the enigmatic cosmic rays have never subsided. Yet, as people dive deeper into this, they encountered many obstacles, of which the most significant is the difficulties of detection caused by some intrinsic traits of cosmic rays. In this chapter we will introduce the difficulties we are facing and the solutions to them.

2.1 Detection Methods

Since cosmic rays are important messengers carrying numerous information to us, the significance of studying comes without saying. Scientists have already given several ways to detect the presence and the nature of the cosmic rays, of which each has its own pros and cons. The method by which we detect the cosmic rays can be generally classified as direct detection and indirect detection. Direct detection generally indicates the usage of satellite-based detectors located in the space to detect the primary cosmic rays, because they are free of the impacts from the earth’s atmosphere. Indirect detection, on the other hand, means that we trace the cosmic rays through very large arrays of detectors right on the ground of earth. The cosmic rays we receive through the land-based array are secondary cosmic rays that went through some complex process because of the presence of the earth atmosphere, a medium. During their journeys through the universe, cosmic-rays inevitably interact with their transmission medium, which offers us chance to trace their spatial distribution and even their source from the earth. Nevertheless, when the cosmic-rays approach the earth, the atmosphere is still causing some knotty problems. When the cosmic-rays encounter the atmosphere of earth, the particles will react with the nucleus of oxygen or nitrogen in an exceedingly intense way, causing the original particles of the rays to break down into smaller ones. The broken particles then carry energy high enough to repeat this process. This process of colliding and disintegrating could repeat incessantly (dozens of repetitions before it reaches the ground like a meteor shower.) The primary particles from the universe collides and disintegrate into secondary ones; the secondary particles disintegrate into the third, the third into the fourth… To make it easier, we call all the particles derived from the primary ones the secondary particles with its components classified into Hadronic part, Muonic part, and electromagnetic part. We trace these secondary particles, and derive back to get the major information of the primary cosmic rays.

So why are we in need of ground detecting methods even though they are not even receiving the primary rays and requires such a complicated work? The answer lies in the character of the energy spectrum of the cosmic rays.

For most cosmic rays arriving at the atmosphere of the earth, the energy is commonly ranged from 10^9 eV to 10^20 eV, which is certainly a wide range. Fortunately, for cosmic rays with energy in this range, we could generally assert that their spectrums are basically power law spectrum which suggests that their differential flow is proportional to E^-gamma, where E stands for energy and gamma stands for energy spectrum index. Though, if we take a finer looker at this, we have to take into consideration that the energy spectrum index changes with the energy of cosmic rays. To be more accurate, as the energy level goes up, there will be some shifts in energy spectrum index at some certain points. For example, when the index shift from -2.7 to -3.1 at around the energy level of 3*10^15 eV, we call this part “knee”; when the index shifts again from -3.1 to -3.3 at around the energy level of 4*10^17 eV, we call this part the “second knee”; when the index shifts back to -2.7 at around the energy level of 4*10^18 eV, we name this the “ankle”. We name these areas as such because when we draw the plot of with the y-axis of differential flow (Gev m^-2 sr^-1 s^-1) and x-axis of energy level (Gev), we will find a leg like line. The bending point of the line resembles the knee and ankle of the leg. Thus, the area around the bending points are named as joints.

So, when we grasp the essence of energy spectrum for cosmic rays, it’s easy for us to see that when the energy levels of the cosmic rays increase, the differential flow drastically decrease. For cosmic rays at 10^10 eV energy level, their could be roughly 1000 particles passing through 1 square meter each second. Yet when the energy level rises to about 10^20 eV, their would only be about 1 particle passing through the area of one square kilometer each year. This special trait of cosmic rays makes high energy cosmic rays unable to be detected directly through probes above the atmosphere including balloons and satellite—based probes since the particles that could be captured by the rather limited areas of these probes are extremely scarce. So the only choice left is to build detectors with larger areas on the ground. In this way we sacrifice the simplicity of detection for larger area. The threshold energy level is around 10^14 eV. Above this level, we have to use grounds detection; under this level, we can detect them directly above the atmosphere.

2.2 Detectors and Detection Experiments

In the previous section, we mentioned the different ways to detect cosmic rays, including the extraterrestrial one and the land-based one.

The devices currently in use for detection generally share the same goal and some has different ones: many of them are for tracing dark matters and dark energies which are the current spotlight of cosmology, while many of them are just for determining the origin and the mechanisms of cosmic-rays. The working mechanisms of each one of the cosmic rays’ probes could also be drastically distinct from each other even though they serve the similar purpose.

In this case, the primary focuses of this section would be giving readers some basic knowledges of the cosmic rays’ probes by introducing some major and renowned detectors, most of which belong to the categories of extraterrestrial detectors and land-based detectors.

2.2.1 Extraterrestrial Detectors

For the extraterrestrial detectors, we will mainly cover three specific examples: PAMELA, CREAM, and AMS-02.

PAMELA, short for Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics, is the first satellite-based cosmic rays probe human beings ever sent into the space. Its main focus is on the anti-particles which are rare to observe. While being especially suitable for detecting anti-matters like anti-protons and positrons, PAMELA also aims the annihilating phenomenon of dark matters. With a magnetic spectrograph inside, PAMELA could trace the movement of the captured particles to acquire their electromagnetic parameters. The calorimeter used in the detector is for discriminating between matters and their anti counterparts by measuring the emitted energy.

CREAM, short for Cosmic Ray Energetics And Mass, is a detecting experiment operated in High air balloons above the South Pole. Since the detection is done high above the ground and the atmosphere in South Pole generally exerts no influence on the detection, what CREAM measures are primary cosmic rays.

CREAM offers us with the spectrum of various particles in the cosmic rays with atomic numbers ranging from 1-26 and their energy levels between 10^11 eV to 10^15 eV. Specifically, it offers the energy spectrum of hydrogen, protons and some other low-mass compositions.

AMS-02 stands for Alpha Magnetic Spectrometer. 02 suggests that AMS-02 is the upgrade version of AMS-01.The idea of the AMS program was brought up to table by Samuel Chao Chung Ting. The objectivity of the AMS detectors is to detect electrons, protons and their anti counterparts. The result is potentially helpful for us to trace the dark matters which could account for a tons of phenomenons that can’t be explained by the matters we can see in the universe. AMS-02 is regarded as the most accurate precise particle detectors that human beings have ever sent into the space. It also yields some interesting results such as the positrons far exceeds the electrons in terms of their total energy spectrum. This could be explained by the presence of dark matters, but it also could be something else such as supernovae remnants. Thus, it leaves us with some space to interpret and a lot of follow up works to do. Nevertheless, we can clearly see the great prospect of this research and what it could bring to the astrophysics field.

2.2.2 Land Based Detectors

As for ground-based detectors, most commonly, they are built to reconstruct the components and characters of the primary cosmic rays through secondary rays that we can directly measure. They are primarily specified for high energy cosmic rays that are extremely low in flux, yet very crucial for the study of the knee area cosmic rays. The reasons that lead to the formation of the knee area is still unknown and many scientists, in order to explain this, propound some plausible points, many of which are controversial. ARGO-YBJ and Tibet AS-gamma, both located in YangBaJing, are two good examples of such ground-based probes.

Located in a village called YangBaJing in tibet China, ARGO-YBJ sits under the Danggula mountains, which makes it the highest cosmic rays observatory in the Northern hemisphere (roughly 4300m). It’s also thought to be one of the best high-altitude detectors due to its high sensitivity, low threshold energy (300 Gev), and its capability to operate regardless of the weather. It has a total area of 10000 square meters and 6300 square meters of RPC which is a relative new detector for charged particles and is what makes ARGO-YBJ different from other high-altitude detectors like the AS-gamma. RPC is short for Resistive Plate Chamber, a plate detector that is especially suitable for measuring the secondary particles in the EAS in a large area. Another aspect that is special about this detector array is that this array is entirely covered by RPC arrays, which makes the particle capturing more efficient.

The AS-gamma detector is a built under the cooperation of China and Japan. Similar to the ARGO-YBJ, it is also located in the YangBaJing village. As a detector detecting secondary rays, it is especially suitable for detecting the UHE cosmic rays because of its specific altitude and atmospheric depth. For extensive air shower (EAS), the shower size is different for different energy levels at different atmospheric depth which means the shower size for different energy levels are correlated to the altitude. With an altitude of 4300 meters and depth of approximately 600g/cm^2, the AS-gamma makes a extremely ideal place for measuring Ultra High Energy cosmic rays (UHE cosmic rays). And it’s also believed to be a perfect location for detecting the knee area cosmic rays, a significant field which is potentially capable of explaining the abnormalities of the energy level change in the cosmic rays energy spectrum. It could be the supernovae remnants which offers extra acceleration effect, or it could be the adjacent pulsars. This further dive could even help us to ascertain the acceleration mechanisms and the origin of the cosmic rays.

As a typical EAS array, AS-gamma observes the fundamental process physicist use to reconstruct the primary rays. Physicists reconstruct the energy of the primary rays by with the total number of particles received by the ground array and estimate the age of the air shower by measuring the lateral distribution of electrons. Different types of secondary particles in the EAS (like electrons, muons, and hadrons) have different lateral distributions: electrons spread because of their repeating scatterings; hadrons scatter because of the horizontal momentum they get when they emerge. When we talk about the horizontal spreading of muons, it’s really a completely differently story. They actually spread a lot and are generally far away from the EAS center because the lower energy level acquired away from the scattering center encourages the pions to decay and also enlarges the scattering angle. Thus, when physicists know about these traits of the EAS, it is actually possible for us to push back and reconstruct the primary rays with the help of some sophisticated facilities that AS-gamma uses.

3. Conclusion

As the messenger that brings us numerous information of the universe, the cosmic rays certainly deserve much attention. The study of cosmic rays contributes greatly to astrophysics and particle physics which are both the vanguard of modern physics. For astrophysics, a large part of what we know about the distant celestial bodies come from the detection of cosmic rays. For particle physics, it's commonly known that almost all of the stable fundamental particles are first discovered in cosmic rays. Also, we can't neglect the fact that since the limitation of our accelerators, many ultra-high energy studies have to use cosmic rays as their laboratories.

Fortunately, physicists are paying much attention to cosmic rays and this effort leads to the blooming of this field. It's only been several decades since human beings began to study the cosmic rays and we undoubtedly has already got a pretty thorough understanding of cosmic rays. We've got abundant knowledge of the composition and energy distribution of the cosmic rays; we've figured out various ways to detect cosmic rays despite of all kinds of obstacles; we've analyzed and interpreted numerous data to back the current theories.

In spite of all the great accomplishments, we shall admit that there are still tons of pending problems about cosmic rays, including the center of the study of cosmic rays—the origin.

We do have clues of what the origins of the cosmic rays should be: it could be supernovae, pulsars, sun itself, and so on. However, scientists weren't able to decide the certain answer through a decade's length debate. The lack of precise and high-quality experimental support should be the main reason why scientists can't reach into accordance. We can take the knee part as an example.

The knee part of the cosmic rays' energy spectrum is one of the factors that make the study of the origin especially hard. It's indispensable for studying the origin and the mechanisms of acceleration of the cosmic rays, yet it has an extremely weak flow which makes it only possible to be observed from the ground. With the rapid development of our ground-based detectors like the aforementioned ARGO-YBJ and AS-gamma, we can see a positive prospect for us to conquer this problem.

Once we make breakthroughs in deciding the origins of the cosmic rays, then our follow up studies about its origins which are very likely to be some high energy celestial bodies has the potential to allow us to steal a peep into the ultra-high energies and the mechanism that yields them. This is very likely to pave the way for our studies of new sustainable energy on earth.

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