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Review

Progress in high-energy cosmic ray physics

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A B S T R A C T

We review some of the recent progress in our knowledge about high-energy cosmic rays, with an emphasis on the interpretation of the different observational results. We discuss the effects that are relevant to shape the cosmic ray spectrum and the explanations proposed to account for its features and for the observed changes in composition. The physics of air-showers is summarized and we also present the results obtained on the proton–air cross section and on the muon content of the showers. We discuss the cosmic ray propagation through magnetic fields, the effects of diffusion and of magnetic lensing, the cosmic ray interactions with background radiation fields and the production of secondary neutrinos and photons. We also consider the cosmic ray anisotropies, both at large and small angular scales, presenting the results obtained from the TeV up to the highest energies and discuss the models proposed to explain their origin.

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1. Introduction

Cosmic rays were discovered more than a century ago as particles arriving to the Earth from outer space. They consist mostly of ionized atomic nuclei, although electrons, positrons, antiprotons, gamma rays and neutrinos also arrive. We will focus here on the nuclear component, and the main observables that can be studied to learn about it are the spectrum (i.e. the distribution in energy), the composition (i.e. the distribution of nuclear masses at any given energy) and the anisotropies (i.e. the features in the distribution of arrival directions at different energies).

The spectrum of the primary cosmic rays (CRs) extends from somewhat below 1 GeV up to beyond 100 EeV, i.e. spanning more than 11 orders of magnitude[1] . In order to observe them, different techniques are adopted, depending on the CR energies under study. Below a few hundred TeV, CRs have very large fluxes, where for instance $\Phi(>\text{ TeV}) \simeq 5\times 10^6\ \text{m}^{-2}\,\text{sr}^{-1}\,\text{yr}^{-1}$, and can be directly detected with instruments on balloons or satellites before they interact in the atmosphere (see [1] for a recent overview and references). The precise mass or charge (sometimes even the isotope) can be measured combining detectors such as magnetic spectrometers, calorimeters, transition radiation detectors, etc. At CR energies above few hundred TeV the fluxes become so low, with for instance $\Phi(>\ \text{PeV}) \simeq 50\ \text{m}^{-2}\,\text{sr}^{-1}\,\text{yr}^{-1}$, that the direct detection is no longer practical. However, when energetic CRs interact in the atmosphere they lead to the generation of air showers, also named atmospheric cascades, consisting of a very large number of secondaries, some of which may eventually reach ground level. These showers include a hadronic component consisting of protons, neutrons, pions, kaons and heavier mesons and baryons, an electromagnetic component consisting of electrons, positrons and photons as well as a muonic component and neutrinos. Hence, detectors at high elevation mountains, such as those in the Tibet YBJ laboratory, are used to study CRs with TeV–PeV energies, while lower elevations are preferred for the study of the more penetrating showers from CRs with higher energies (see [2] for a recent overview and references).

Besides the sampling of the particles at ground level with arrays of detectors, also the light emitted by the passage through the atmosphere of the electrons and positrons in the shower can be detected using telescopes on the ground. This light is produced as forward Cherenkov radiation when these particles travel faster than the speed of light in air or as isotropic fluorescence due to the emission from molecular nitrogen that got excited by the passage of the charged particles. Actually, imaging the Cherenkov emission with telescopes, in observatories such as H.E.S.S. or in the future with CTA (see [3] for a recent overview and references), it is also possible to do astronomy in the energy range between tens of GeV and up to tens of TeV by discriminating the showers initiated by photons from the much larger background from hadronic showers. Using arrays of non-imaging detectors of atmospheric Cherenkov light, such as those in TUNKA or Yakutsk, it is possible to study CRs from PeV up to EeV energies, while the detection of fluorescence light becomes competitive above 100 PeV. Also the radio emission at frequencies from 30 to 80 MHz, produced by the charge separation of the electrons and positrons of the shower by the Earth magnetic field, as well as due to the negative charge excess from the atomic electrons entrained by the electromagnetic component of the shower (Askaryan effect), is becoming a complementary way to detect CRs with energies in excess of 10 PeV [4].

Regarding the direct detection experiments, some of the recent ones are those on balloons, such as ATIC, TRACER or CREAM, satellite-based ones such as PAMELA or those in the International Space Station, such as AMS or the ISS-CREAM experiment. We note that underground detectors, such as the IceCube experiment in the South Pole, can detect the muonic component of air showers. Although they are mainly focused on the detection of neutrinos, they also study CRs with energies above the TeV. Among the surface detector arrays, the IceTop experiment above the IceCube detector, consisting of frozen water-Cherenkov detectors (WCD) spread over an area of about 1 km^2, and the KASCADE and KASCADE-Grande detectors in Karlsruhe, that used scintillator detectors deployed over an area of about 0.04 and 0.5 km^2 respectively, focused in the range from few PeV up to EeV energies. The AGASA experiment in Japan covered an area of 100 km^2 with a sparser array of scintillators, exploring energies above 100 PeV. The Haverah–Park experiment in England pioneered the technique of using WCD to observe the Cherenkov emission from the charged particles traversing the water in the detector while the Fly's Eye and Hi-Res experiments in Utah pioneered that of observing the air fluorescence UV light.

Since the fluxes of CRs with energies above 1 EeV are extremely small, with e.g. $\Phi(>\ \text{EeV}) \simeq 10\ \text{km}^{-2}\text{sr}^{-1}\text{yr}^{-1}$, huge detectors are required to observe a significant number of these events. At present the largest detector array in operation is the Pierre Auger Observatory in Argentina, sampling an area of 3000 km^2 with WCD on the surface and several telescopes that observe the atmospheric fluorescence. The Telescope Array (TA) is the largest one in the northern hemisphere, currently sampling an area of 700 km^2 with an array of scintillators and having also fluorescence telescopes. These hybrid detectors have the great advantage that they can study the lateral distribution of the showers at ground level with the surface detector (SD), as well as the longitudinal development of the shower in the atmosphere with the fluorescence detector (FD). Acting the atmosphere almost as a calorimeter for the air showers, the FD leads to a good determination of the CR energies and hence enables a robust calibration of the energy assignment performed with the SD. Note that the duty cycle of FD is only about 15%, corresponding to the moonless nights with no clouds, while the SD is operational in principle all the time, and hence provides most of the events. The study of the shower development with FD allows, in addition, to obtain important information on the CR composition, since at a given energy proton showers are more penetrating (and also fluctuate more) than those from

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[1] Energy units are, in increasing powers of 1000, (k,M,G,T,P,E)eV, where in particular EeV $\equiv$ 10^{18} eV. We use in this review natural units with $\hbar = c = k_B = 1$.

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