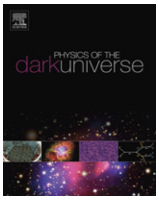
Physics of the Dark Universe 4 (2014) 23–30

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark



Ultra-high energy cosmic rays

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ARTICLE INFO

Keywords:
Cosmic rays
Ultra-high energy
GZK effect

ABSTRACT

Experimental efforts to reveal the nature and origin of cosmic rays with energy above 10^{18} eV led to several important steps forward in recent years. The existence of a suppression of the flux above 4×10^{19} eV has been confirmed. It occurs at the energy threshold for pion-production in proton collisions with the cosmic microwave background, as anticipated almost fifty years ago. The flux measurements alone are however insufficient to confidently establish whether the suppression is due to energy loss effects along propagation over cosmological distances, or else because the sources reach their maximum acceleration power. There are indications obtained with the Pierre Auger Observatory of a trend from a light towards a heavier composition as the energy increases. There is some tension between these indications and those from the HiRes and Telescope Array experiments, which are compatible with a pure proton composition. This is a most important issue to be settled in the near future. At present there is no statistically significant evidence for anisotropy in the distribution of arrival directions at the highest energies that could favor one specific astrophysical scenario for cosmic ray origin over another. There are hints for a large scale pattern in the distribution of arrival directions that need to be confirmed with independent data. In this paper we summarize recent measurements of the energy spectrum of cosmic rays with the highest energies, the evidence for their composition, and the searches for anisotropies in the distribution of their arrival directions.

1. Introduction

Cosmic rays (CRs) reach energies larger than those accessible in human-made accelerators, albeit at a rather small rate: about one particle arrives at the Earth's atmosphere per km^2 per century with energy around or above 6×10^{19} eV. Experimental efforts to improve accuracy and exposure to such a small flux aim to solve the puzzle that the nature and origin of particles with such extreme energies represent. These efforts led to several important steps forward in recent years. A suppression of the flux above 4×10^{19} eV, as compared to an extrapolation from lower energies, is now confirmed [1–3]. Relevant upper bounds have been established on the presence of photons [4,5], neutrinos [6,7] and neutrons [8] among the ultra-high energy cosmic rays. There are indications obtained with the Pierre Auger Observatory of a trend from a light towards a heavier composition as the energy of the CRs increases above approximately 3×10^{18} eV [9,10].

The suppression of the flux observed above 4×10^{19} eV is compatible with an energy-loss propagation effect over cosmological distances, as predicted almost fifty years ago [11,12]. However current data are insufficient to determine if energy losses are its only cause. Scenarios such that protons and nuclei with charge Z can no longer be accelerated at their astrophysical sources above energies of the order of a few times $Z \times 10^{18}$ eV could also explain current observations.

The possibility that the CRs become increasingly heavy at higher energies is a most pressing issue that needs to be made more precise through further measurements. The existence of a light component of CRs with energy around and above 4×10^{19} eV is crucial if their arrival directions are to tell us about their place of origin. The lack of significant clustering in the arrival directions at the highest energies [13] may be another indication that the dominant composition is relatively heavy. On the other hand, measurements performed with the High Resolution Fly's Eye (HiRes) [14] and the Telescope Array (TA) [15] do not show a trend similar to that observed in data from the Pierre Auger Observatory, and are compatible (albeit with a relatively smaller statistics) with a pure proton composition. Note that the composition of the CR primaries is derived from observations using extrapolations of particle physics properties to energies larger than those experimentally tested at human-made accelerators. A changing proton–air cross section would change the derived composition.

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http://dx.doi.org/10.1016/j.dark.2014.04.003

In this review we will first summarize different pieces of the puzzle posed by ultra-high energy cosmic rays (UHECRs), and then describe ongoing efforts to advance our understanding of their nature and origin. In particular we will discuss recent measurements by the Pierre Auger Observatory and the Telescope Array, the two largest instruments that record UHECRs, both currently in operation. For recent detailed reviews on UHECRs we refer for instance to [16–18].

2. Three pieces of a puzzle

Three major pieces need to be put together to trace back the origin of UHECRs: the amount of energy losses during propagation, the size of deflections imprinted by intervening magnetic fields, and ultimately the identification of the mechanisms and sites of acceleration. We very briefly address them in this section.

2.1. GZK effect

Fifty years ago, evidence was reported for a primary cosmic ray with energy around 10^{20} eV, obtained with the MIT Volcano Ranch array [19]. One year later the cosmic microwave background (CMB) was serendipitously discovered [20]. Soon afterwards, Greisen [11] and independently Zatsepin and Kuz'min [12] realized that protons with energy around and above 6×10^{19} eV can produce pions in their collisions with the CMB photons. They estimated the timescale for energy loss to be several hundred times smaller than the expansion time of the Universe, and concluded that if the sources are cosmologically distributed, there should be a strong flux suppression above the pion-production energy threshold. A similar suppression would also occur if the cosmic rays were heavier nuclei instead of protons, due to photodisintegration.

The flux suppression caused by the "GZK effect" can be understood in terms of an effective "horizon" within which a source can contribute significantly to the flux measured at Earth above a given energy threshold. For instance, approximately 90% of the flux of protons that arrive at Earth with $E > 6 \times 10^{19}$ eV should come from distances smaller than 200 Mpc (assuming sources distributed uniformly across the Universe and an almost straight line propagation, otherwise the constraint is on the travel time rather than on the rectilinear distance to the sources). The horizon decreases for higher energy thresholds. The flux at the highest energies should be strongly suppressed (compared to its extrapolation from lower energies) as the effective volume within which sources can contribute shrinks. The "GZK horizon" is of comparable size for protons and iron nuclei, and is smaller for intermediate-mass nuclei. It is illustrated in the top-left panel of Fig. 1.

The reduction of the CR rate above the GZK energy threshold increases the challenge for the identification of the sources of the most energetic particles. On the other hand, the GZK effect provides a potential handle to find them. The distribution of extragalactic matter within the GZK horizon is inhomogeneous. Comparison of the arrival directions of CRs with the celestial positions of different populations of relatively nearby astronomical objects may help identifying their origin, at least if the deflections of the trajectories across intervening magnetic fields are not too large or uncertain.

2.2. Composition and magnetic lensing

The identification of the sources of UHECRs is complicated because the trajectories of protons and heavier nuclei are deflected by intervening magnetic fields, both in the galaxy as well as in the intergalactic space. A cosmic ray with charge Ze that travels a distance D in a regular magnetic field B has its arrival direction deflected with respect to the direction to its source by an angle $2.7^\circ \frac{6\times 10^{19}\ \mathrm{eV}}{E/Z} \left| \int_0^D \frac{d\mathbf{x}}{\mathrm{kpc}} \times \frac{\mathbf{B}}{3\mu\mathrm{G}} \right|$. The top-right panel in Fig. 1 displays examples of CR trajectories in a conventional model for the galactic magnetic field. Protons with energies around 6×10^{19} eV are expected to deviate by no more than a few degrees from a straight propagation in most parts of the sky. Instead iron nuclei ($Z = 26$) with the same energy will not preserve a correlation between their arrival directions and the position of their sources. The existence of a light component in the CR flux at the highest energies is crucial for astronomy with charged particles to be feasible.

2.3. Candidate sources

The magnetic field of the Milky Way is most likely unable to confine CRs with energy above $Z \times 10^{18}$ eV. No significant excess of CRs from the directions to the galactic plane is observed at these energies. Acceleration at extragalactic astrophysical sites is thus a plausible origin for the highest energies observed in CRs. This speculation requires confirmation, and can still be challenged by models based on a galactic origin.

The requisite that candidate sources be able to confine particles up to a maximum energy $E_{\max}$ translates into a condition on the magnetic field strength B and extension R of astrophysical accelerators [21]: $E_{\max} = Z \times 10^{18}\ \mathrm{eV} \frac{B}{1\mu\mathrm{G}} \frac{R}{1\mathrm{kpc}}$. This criterion is a necessary condition, but not a sufficient one. The bottom panel in Fig. 1 reproduces the "Hillas plot", that classifies potential astrophysical accelerators in terms of their characteristic values for B and R. The best candidate sources for UHECR acceleration are considered to be neutron stars, active galactic nuclei, and gamma ray bursts [16].

3. The Pierre Auger observatory and the telescope array

Measurements of extensive air showers (EAS) produced by CRs with energies above 10^{19} eV have been performed since the 1960's at Volcano Ranch [19], Haverah Park [24], Sydney University Giant Air Shower Recorder (SUGAR) [25], Yakutsk [26], Akeno Giant Air Shower Array (AGASA) [27], Fly's Eye [28], HiRes [1], Auger [2] and TA [3]. In this section we briefly summarize and compare properties of the two largest experiments, both currently in operation, the Pierre Auger Observatory and the Telescope Array. Both instruments operate in a hybrid approach, able to sample EAS at ground level with an array of surface detectors (SD), as well as measuring their development in the atmosphere through fluorescence detectors (FD). The SD, with nearly 100% duty cycle, provide the "statistical power" of the experiments. The FD, restricted to a smaller duty cycle of order 13%, provide a complementary view. Hybrid operation improves the precision of energy and angular calibration, and allows cross-checks and redundancy in the measurement of the parameters of the EAS. An extensive monitoring program is implemented in each experiment to correct the measurements for the effects introduced by atmospheric fluctuations.

The Pierre Auger Observatory is located in the Province of Mendoza, Argentina, at 35.3° S, 69.3° W, 1400 m above sea level. Its construction and operation is a collaborative effort of institutions from Argentina, Australia, Brazil, Croatia, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, United Kingdom, USA, as well as Bolivia, Romania and Vietnam as associated countries. Its SD array [29] consists of 1660 water-Cherenkov stations laid out over 3000 km^2 on a triangular grid of 1.5 km spacing and a smaller (25 km^2) denser array of 0.75 km spacing. Each station is filled with 12 m^3 of high purity water, viewed by three photomultipliers. The SD array has been in operation since 1 January 2004, increasing its size from 154