Ultra High Energy Cosmic Rays: Observations and Theoretical Aspects

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Summary. We present a brief introduction to the physics of Ultra High Energy Cosmic Rays (UHECRs), concentrating on the experimental results obtained so far and on what, from these results, can be inferred about the sources of UHECRs.

1 Introduction

Since the discovery of cosmic rays (CRs) by Victor Hess in 1912 there has been a constant search for the end of the cosmic-ray spectrum. This end has long been thought to be determined by the highest energy the cosmic accelerators might be able to achieve, but despite several decades of research no end of the spectrum was in sight until 1966. In 1966, right after the discovery of the cosmic microwave background (CMB), it was understood [1] that protons with sufficiently high energy would interact inelastically with the photons of the CMB and produce pions. This process rapidly degrades the proton energy and, if the sources of CRs are homogeneously distributed, it produces a drastic suppression in the CR flux around $10^{20}$ eV, where the so-called photopion production starts to be kinematically allowed. The physical reason for this suppression is that at energies around $10^{19}$ eV the loss length for protons propagating in the CMB is of the order of a Gpc and we are receiving particles from almost all the visible universe, whereas at $10^{20}$ eV the loss length is about 100 Mpc and we are receiving particles only from a tiny fraction of the universe. This suppression is usually called the GZK cutoff [1]. After several more decades of experimental activity we have now experiments exploring the energy region around $10^{20}$ eV and beyond, but the end of the spectrum is still eluding us and whether the GZK cutoff is present or not in the observed spectra is still an open question.

In §2 we briefly review the present UHECR data sets and the issues they raise and in §3 we briefly discuss how we can improve our understanding of the sources of UHECRs using the new data that is now being collected by the Pierre Auger Observatory (PAO).
2 UHECRs: present

Until a year ago the two largest experiments measuring UHECRs were AGASA and HiRes. In 2005 the PAO [2] reported the results of the first year of data taking [3], but, since those results are still preliminary and the error-bars are still quite large, in the following discussion we will concentrate on AGASA and HiRes. We are considering particles of ultra high energy, around and above $10^{19}$ eV, and CRs of such high energies, entering the earth atmosphere, interact with it producing extensive showers of secondaries that propagate in the atmosphere close to the speed of light. The two above mentioned experiments use two complementary techniques to detect these extensive air showers (EAS): AGASA used an array of detectors on the ground that sampled the lateral distribution of the EAS when it hit the ground while HiRes uses a telescope to observe the fluorescence light produced by the shower while it propagates in the atmosphere. For a review of the detection techniques see Ref. [4].

Despite the fact that two completely different methods were used, the two experiments report somehow similar results for what concerns the energy spectrum at low energy, with some conflicts at high energy. At low energy, where the number of detected events per energy bin is big the two experiments report fluxes that differ by about a factor 2, but this discrepancy can be accounted for by correcting for the systematic errors on the energy determination reported by the two collaborations, about $\pm 15\%$. Doing this shift the two experiments agree perfectly in this energy range ($\leq 10^{20}$ eV) [5, 6].

At $E > 10^{20}$ eV, where the statistics of events is very sparse due to the steepness of the spectrum of CRs, the two experiments report opposite results: AGASA claims [7] to have observed a continuation of the spectrum beyond the expected cutoff whereas HiRes claims [8] to have observed the expected suppression. The statistics of events above $10^{20}$ eV is however really small and the discrepancy between the two experiments is just about $3\sigma$. Taking into account the systematic errors as in the low energy region this discrepancy is reduced to about $2\sigma$ [5]. Recently the AGASA collaboration revised down their energy assignments [9] by about 10% further reducing the alleged discrepancy.

Even if nowadays the presence of the GZK suppression in the spectrum seems more plausible than its absence the fact still remains that events with energies above $10^{20}$ eV have been measured several times by different experiments. Where did those particles come from? For astrophysical accelerators it is extremely challenging to accelerate particles to such high energies [10] and in the few plausible models the sources are usually too far away from us for the particles to be able to propagate to the earth without suffering sensible energy losses. Indeed no suitable sources have been found within reasonable distances around the arrival directions of the highest energy events. For a review on the origin of UHECRs see Ref. [11] and references therein.

From the measurement of an EAS we can basically obtain three informations about the primary particle: its energy, its direction and its nature or
chemical composition. Each one of these informations is important and can provide useful clues about the sources. Some experimental techniques are better suited to measure one of them or another one [4], but in general all the experiments are in the end reconstructing those three quantities. We already discussed the energy spectrum, we will skip the discussion of the chemical composition (for a review of the experimental results see Ref. [12] while for discussions of the interesting problem of the galactic–extra-galactic transition see Ref. [13, 14]) and we will now concentrate on the arrival directions of those UHE events.

AGASA reported [15] the presence of clustering in its set of events with energies above $4 \times 10^{19}$ eV. While on large scales the arrival directions of these events appear to be isotropic, on small scales they appear to arrive in clusters. AGASA observed 6 doublets and 1 triplet with angular separation less than 2.5° on a set of about 70 events. These data point in the direction of astrophysical point sources with a density of about $10^{-5}$ Mpc$^{-3}$, with large error bars of about one order of magnitude. Combining this result with the energy spectrum it is possible to obtain information about the luminosity of the sources themselves [16, 17]. The significance of this result is however still debated. First of all because the statistical significance of the clustering signal, that in the beginning was quite high, turned out to be lower in subsequent analyses [18], and also because HiRes did not see any anisotropy in its data set [19] though in this case too the statistical significance of the absence of clustering is not very high [20]. Moreover it seems that the AGASA data set itself presents some internal inconsistency and the probability of reproducing the AGASA result on the spectrum is reduced by a large factor when taking into account a source density of $10^{-5}$ Mpc$^{-3}$ [5].

3 UHECRs: (near) future

The PAO, being built in Argentina, is a new kind of experiment that combines the two above-mentioned measuring techniques [2]. It consists of four fluorescence telescopes overlooking a ground array of 1600 surface detectors covering an area of 3000 km$^2$. The ground array exposure, above $10^{19}$ eV, after 10 years of data-taking will be 70000 km$^2$ sr yr, to be compared for example with 1645 km$^2$ sr yr that was the AGASA exposure after 10 years of operation. About 10% of the detected events will be hybrid events, detected at the same time by the ground array and by the fluorescence telescopes. The Auger data set will help tremendously in our understanding of UHECRs and of their sources. First of all because measuring hybrid events it will be possible to solve the discrepancy in the energy assignments between fluorescence and surface detectors. Moreover, with the huge statistics of events it will collect at high energy, the spectrum in the GZK region will no longer be dominated by statistical fluctuations as in the AGASA and HiRes case and we will be able to observe the presence or absence of the GZK feature in the spectrum and
maybe the end of the CR spectrum \[5\]. The huge statistics will be even more important to study the anisotropies in the event arrival directions. The PAO will be able, already after a few years of operations, to detect the presence of anisotropies both on large \[21\] and small \[17\] scales. For example it will be able to distinguish between a uniform distribution of sources and a discrete distribution of sources with a given density already after 5 years if the density is smaller than \(10^{-3} \text{Mpc}^{-3}\), whereas in order to distinguish between different densities 15 years of operations are required or even a bigger experiment (for example Auger North).

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