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The Pierre Auger Observatory: Challenges at the highest-energy frontier

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Abstract

The Pierre Auger Observatory explores the highest-energy Universe, through the detection of air showers induced by the most energetic cosmic rays, whose nature and origin remain enigmatic despite decades of study. Exciting progress is being accomplished in measuring the characteristics of these messengers with unprecedented statistics. Their energy spectra, their arrival directions, and the properties of the cascades they initiate are studied in an attempt to elucidate their nature (mass composition, possibility of gamma-ray or neutrino primaries), provenance and propagation (sources, anisotropies, spectra). The scientific and technical challenges are extreme, and are addressed in a multiplicity of ways, including a program of enhancements to the base design of the Observatory. We review these challenges, the solutions implemented and under way, and their impact on the rich science harvest reaped by the project.

Keywords: Particle Astrophysics; Ultra High Energy Cosmic Rays; Air Showers

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1. Introduction

1.1. Energies

Cosmic rays are high-energy particles bombarding the Earth from the depths of the cosmos. Despite the fact that they were discovered 100 years ago, by Victor Hess in 1912, there remain many questions and puzzles surrounding them, not least of which are their exact nature and origin. One great challenge in detecting these fascinating objects is that they span an extraordinary range of energies as observed at Earth, from below 1 GeV up to beyond 10^{20} eV, more than 11 orders of magnitude. No single astrophysical site can account for particle acceleration over this full range [1]. At energies up to a few times 10^{15} eV, where direct measurements of the arriving particles are possible with balloon-borne or satellite instruments, the cosmic rays are known [2] to be fully ionized atomic nuclei (about 85% H, about 12% He, and 1% heavier nuclei from Li to Fe and beyond) with a small proportion of electrons (1-2%), and a smattering of antimatter particles (positrons and antiprotons). These directly observable particles are thought to be Galactic in origin. Good candidates for astrophysical acceleration sites of these cosmic rays are supernova remnants (SNR) or pulsar wind nebulae (PWN), where the particle acceleration derives from first-order Fermi shock acceleration [3-4]. Direct imaging of the sources is not possible with charged cosmic rays, whose arrival directions are randomized by magnetic deflections. However in recent years great progress has been accomplished with imaging of Galactic sources with gamma-ray instruments, and these environments have now been demonstrated to be the site of energetic processes up to about 4×10^{13} eV (see, e.g., [5-7]). Meanwhile the direct cosmic-ray measurements now extend into the range of hundreds of TeV [8]. At higher energies yet it becomes a great challenge to even conceive of acceleration mechanisms, as will be discussed below. Progress on the experimental front is further hampered by dwindling event rates with increasing energy, which we now describe.

1.2. Rates

Another great challenge in studying cosmic rays is that their arrival rate at Earth, and thus also their production rate at the source(s), plummet dramatically with increasing energy. The cosmic-ray energy spectrum exhibits a power-law behavior $dN/dE \sim E^{-\gamma}$ shown in Fig. 1 (adapted from [9,10]), with a spectral index of about $\gamma \sim 2.7$ at energies up to a few times 10^{15} eV, steepening to an index of about 3.0 above this. This spectral feature is commonly referred to as the knee in the spectrum, and is thought [11] to be associated with limiting effects of the energy reach of the acceleration process in Galactic SNR and PWN sources, and possibly also coupled with propagation effects, such as Galactic escape. At energies near the knee and beyond, particle rates become very limiting, with only 1 particle/m^2/year, further decreasing to 1 particle/km^2/year beyond 10^{19} eV. Thus indirect techniques become necessary in detecting the particles, making use of the atmosphere as part of the detection volume. Indeed, sufficiently energetic cosmic rays initiate cascades of secondary particles in the atmosphere, dubbed air showers. These showers grow in particle counts as they develop through the atmosphere, even as the median energy per particle shrinks along the trajectory. At a certain depth X_{max} (dependent on the incident cosmic-ray particle energy and primary mass), this particle count reaches a maximum, which can be as high as 10^{11} particles at an incident energy of 10^{20} eV. Deeper than X_{max} the shower shrinks as particles become depleted by the atmosphere, i.e., energy losses dominate over the processes creating new particles. At the knee and beyond, these air showers are capable of reaching the ground and thus be recorded by arrays of detectors, which can cover large areas to meet the particle-rate challenge. Alternatively, the atmosphere can be viewed with sensitive telescopes on dark nights, to detect and image the nitrogen fluorescence light generated by the ionizing shower. This fluorescence profile with altitude mirrors the longitudinal shower development, and in particular X_{max} can be measured.

1.3. Ultrahigh-energy sources

At the highest cosmic-ray energies, beyond 10^{19} eV or so, magnetic gyroradii become comparable to the size of the Milky Way, and thus the astrophysical origin of cosmic rays is thought to be extragalactic [12,13]. This idea is reinforced by another feature in the spectrum illustrated in Fig. 1, at around 10^{19} eV, where the spectral index is observed to flatten. This feature is referred to as the ankle in the spectrum. To be sure, alternative interpretations of the physical origin of the ankle exist, some connected with cosmological propagation effects [14]. The region between the knee and the ankle probably illustrates the decreasing efficiency of the Galactic accelerators (e.g., as the SNR shocks weaken over time as the blast radius increases), coupled with Galactic propagation effects. But this region is poorly understood, and theoretical scenarios of Galactic acceleration sites and mechanisms capable of reaching energies as high as 10^{17} – 10^{18} eV are severely challenged. Further inspection of the right-hand panel of Fig. 1 shows that additional structure in the spectrum must be understood, such as a second-knee at an energy of about 10^{18} eV where the data reveal a subtle feature.

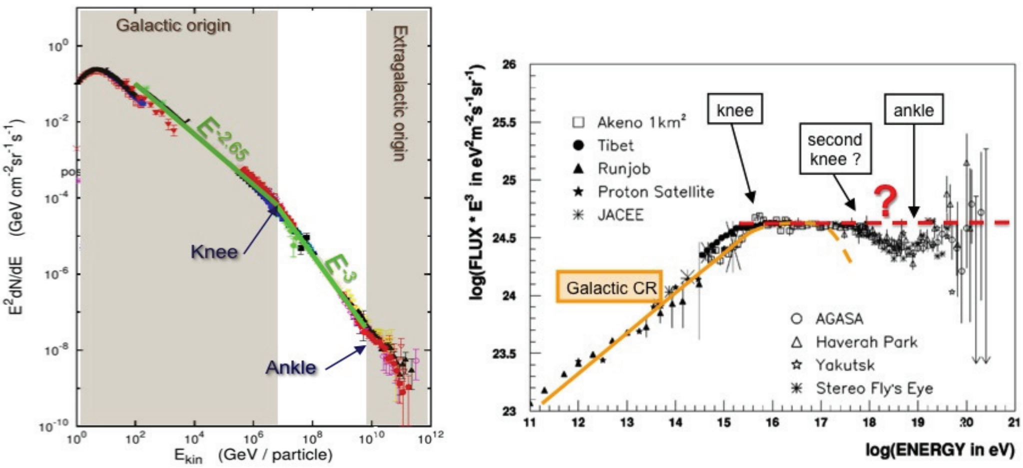

Fig. 1. Cosmic-ray differential energy spectrum, with fluxes rescaled by E^2 (left-hand panel) or E^3 (right-hand panel) to enhance spectral features. The experimental results summarized here are listed in [9] and [10]. The direct measurements below 10^4 GeV/particle are for H primaries only, whereas at higher energies the indirect measurements are for all particles combined (H to Fe). The right-hand panel illustrates the ultrahigh-energy regime measurements as of 2000; the dashed line with a question mark represents a possible inferred flux of particles in the 10^{20} eV range.

Looking for astrophysical settings outside the Milky Way, capable of producing particle energies beyond the ankle, a number of candidate objects suggest themselves, such as active galactic nuclei (AGN) or gamma-ray bursts (GRB). Such sites simultaneously meet the energetic requirements for particle production up to the highest energies, have the requisite scale size and magnetic field strength to permit this [15], and may have radiation field configurations suitable to allow escape from the acceleration region (without overly large energy losses due to synchrotron losses, photopion production or photodisintegration) [16]. While attractive in general terms, the detailed modeling of the acceleration of ultrahigh-energy (UHE) cosmic rays in such sources has proven challenging, and no clear consensus exists. The origin of the highest-energy particles in the Universe today remains elusive. Coupled to this is the requirement that the sources of these particles must be cosmologically near enough that the particles not be depleted in transit owing to their interactions with the cosmic microwave background. Indeed, due to this cosmic fog, there is an event horizon beyond which particles can no longer reach us [17,18]. A corollary to this is that there is an expectation of an effective upper limit to observable particle energies at Earth, at a few times 10^{20} eV, the so-called GZK suppression. Thus any observed cosmic rays at Earth with an energy above 10^{20} eV are expected to have originated within about 100 Mpc of the Milky Way [19], which constrains their possible cosmological origins. A puzzling state of affairs at the turn of the century was that the experimental measurements of the highest-energy cosmic rays showed no evidence of such a suppression, as illustrated in the right-hand panel of Fig. 1.

2. The Pierre Auger Observatory

2.1. Design

The Pierre Auger Observatory was conceived [20] to address the mystery of the nature and origin of the UHE cosmic rays. It was designed as a hybrid instrument, utilizing both an array of surface detectors (SD) overseen by nitrogen fluorescence detectors (FD). These are illustrative of the two main techniques used up to that point in exploring the energy frontier, such as by the AGASA experiment [21], covering an area 100 km^2 with scintillation counters, and by the Fly's Eye [22] and HiRes [23] experiments that pioneered the use of the nitrogen fluorescence telescope technique. The AGASA experiment accumulated a total final exposure of 1,600 km^{2}yr sr, whereas for the HiRes project the final figure was 2,500 km^{2}yr sr (in stereo mode, with two FD stations reconstructing the air shower; when operated in mono mode, with just one FD station used to reconstruct the event, the total exposure was roughly a factor of 2 larger).

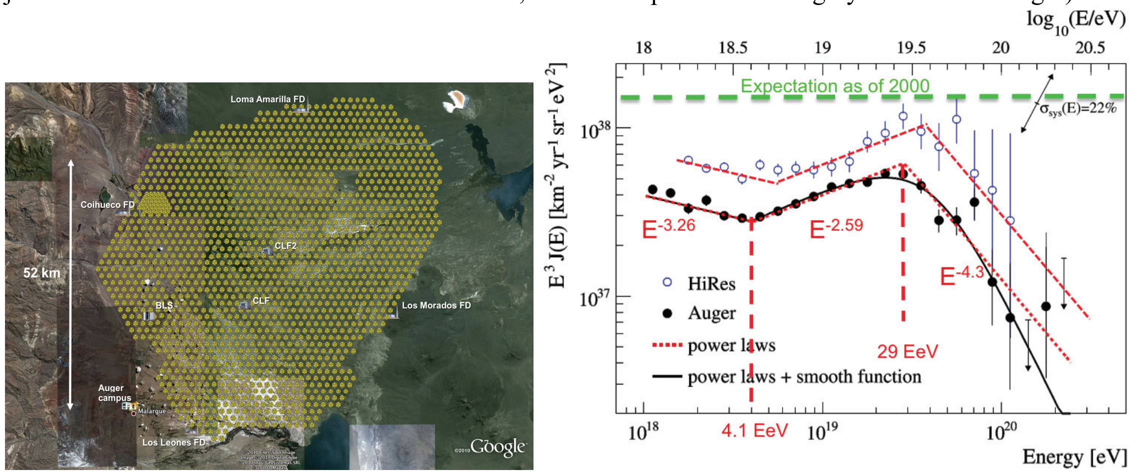

Fig. 2. Left-hand panel: Pierre Auger Observatory layout in western Mendoza Province of Argentina. Small circles represent SD stations, and also indicated are the FD telescopes (Loma Amarilla, Los Morados, Los Leones and Coihueco). CLF and CLF2 are calibration laser facilities, and BLS is a balloon launch station. Right-hand panel: Measured Auger spectrum [25], rescaled by E^3, compared with the HiRes stereo spectrum [23].

The Auger project design philosophy was to scale up previous efforts by a significant factor. The observatory layout is illustrated in Fig. 2 (left-hand panel). An array of 1,663 SD stations (water Cherenkov tanks) was constructed over an area 3,000 km^2 in western Mendoza Province of Argentina.

Part of this is a more densely instrumented subarray near the Coihueco FD station identified on the figure. With these tanks, the air shower is sampled when it impacts the ground, and the distribution of energy deposit in the stations is used to infer the total energy of the incident cosmic ray. In addition the timing of signals in the various SD stations is used to reconstruct the cosmic-ray arrival direction on the sky. The array is operational essentially 100% of the time. In addition, four FD buildings are deployed on the edges of the array, each containing 6 telescopes for a total of 24 fluorescence telescopes (with 3 additional recently deployed high-elevation FD telescopes near the Coihueco FD building). These are only operated on dark, clear, moonless nights, for an operational duty cycle of about 13%. The FD observations provide a calorimetric view of the shower development through the atmosphere, and thus the most complete and accurate reconstruction of the total energy of the incident cosmic ray. Taken together, the SD and FD reconstructions are combined for the hybrid events that trigger both detector systems: the SD signals provide an accurate time stamp for shower impact on the ground, against which the longitudinal shower development traced by the FD is anchored. The hybrid technique is extremely powerful in providing a complete and accurate view of the air showers, and in cross-calibrating the SD and FD techniques against each other.

The Auger Observatory was envisioned [20] as a twin detector array, with one in the southern hemisphere in Argentina and another in the northern hemisphere, in the southwestern United States. With this configuration, the twin observatory would have provided sensitivity to potential cosmic-ray sources across the entire celestial sphere. However, only the southern site was funded initially and constructed between 2002 and 2010. A northern array was proposed recently [24] but funding limitations preclude selection of this as of this writing (2011). Still, with the southern array operational throughout the deployment phase, an accumulated exposure of nearly 21,000 km^2yr sr has been reached up to now, so that Auger dominates the world statistics of measurements at the energy frontier.

2.2. Energy spectrum

The right-hand panel of Fig. 2 shows the UHE cosmic-ray spectrum measured by Auger [25], with flux values on the ordinate axis rescaled by E^3. For comparison, measurements by the HiRes experiment in stereo mode [23] are also shown. Also shown on the figure as the upper dashed line is a reasonable expectation of the UHE spectrum based on the measurements existing in 2000, used in defining the design of the Auger Observatory. While the size of the Auger array was fixed to yield an expected crop of some 30-50 events per year above 10^{20} eV, it is clear that the measured rate ended up far short of this prediction, with only about 1 event per year. The proposed northern Auger site [24] would be larger (20,000 km^2) than the southern array to help alleviate this.

A remarkable feature of the measured UHE spectrum is that in fact a depletion of the particle flux is observed, starting around a few times 10^{19} eV, very similarly to the GZK expectations predicted in 1966. As of 2000 none of the existing experiments reported evidence of this effect, leading to much puzzlement over the physics of UHE cosmic rays (indeed claims of “super-GZK” events at the time caused much excitement and speculation regarding exotic origins of UHE cosmic rays). It was finally the HiRes project that reported [26] first evidence of this GZK suppression, an effect now clearly confirmed in the Auger spectrum. Thus the corollary should obtain, that due to UHE cosmic-ray interactions with the cosmic microwave background, astrophysical sources should be located cosmologically nearby (within 100 Mpc or so), leading to an expectation of possible anisotropies in the arrival directions of the highest-energy particles, even if they may be electrically charged and thus subject to magnetic deflection. This will be addressed in the next section.

The apparent discrepancy between the Auger and Hires data in Fig. 2 is not so worrisome as might first be thought. The reconstruction of event energies is a complex procedure, relying on an understanding of cascade development in the atmosphere, and of a detailed accounting of atmospheric attenuation and scattering effects. In the case of Auger a large battery of calibrations is brought to bear on event reconstructions. The array is equipped with weather stations, cloud cover monitors, lightning detection equipment, a balloon launching station, 2 central laser facilities and 4 lidar facilities (with which calibrated light pulses are flashed across the sky to understand atmospheric transparency and scattering effects on the FD reconstructions) [27]. Thus, the event reconstructions, and in particular the hybrid event reconstructions, are carried out with the best possible understanding of a number of time-dependent, weather-dependent, season-dependent effects. The net result is an estimated energy reconstruction systematic accuracy of 22%, which is indicated by a diagonal error bar at the top right of the right-hand panel of Fig. 2 (the error on the energy appears diagonally because the energy is folded into the ordinate axis values on the graph). The Auger spectrum is well represented by three power-law fits as shown in the figure, with spectral breaks at 4.1 EeV (the ankle) and 29 EeV (the GZK suppression). Simply sliding these best-fit lines diagonally along the energy systematic uncertainty direction, by an amount comparable to this uncertainty, yields an excellent match with the HiRes measurements, as shown by the short-dashed line in the figure.

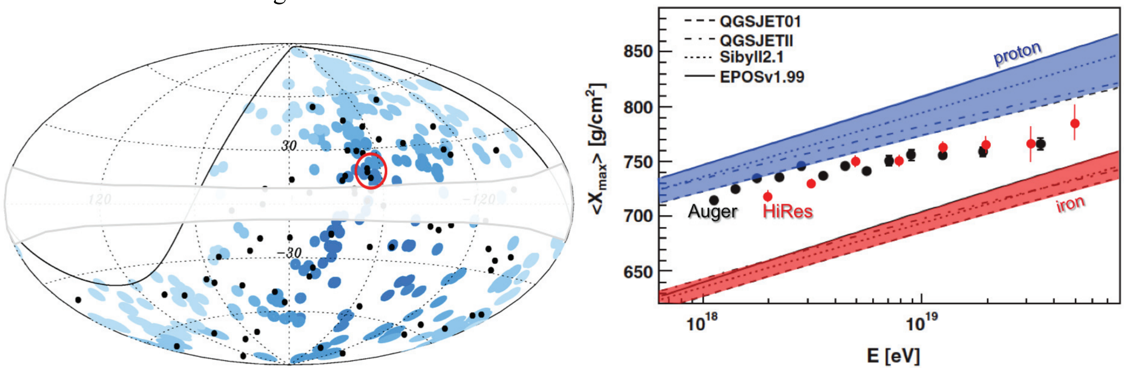

Fig. 3. Left-hand panel: Auger event (with E>57EeV) arrival directions (points) on the sky, plotted in Galactic coordinates, with nearby (z <0.018) AGNs from the VCV catalog also shown (ellipses, shaded by Auger exposure), adapted from [29]. A band within ±10° of the Galactic plane is removed from consideration. The strongest correlation is in the direction of the Centaurus A AGN, illustrated with the red circle. Right-hand panel: UHE cosmic-ray elongation rate – evolution of the depth of shower maximum as a function of primary energy. Shown are measurements by Auger [32], by HiRes [33], in comparison with simulation-derived expectations *for the Auger measurements* under the assumption that the primaries are either protons or else iron nuclei.

2.3. Search for anisotropies

The flux suppression at the highest energies indicated in Fig. 2 leads in turn to an expectation that the sources of the UHE cosmic rays lie within a sphere of 100 Mpc radius. At the highest energies of interest, magnetic deflections can be small enough, perhaps on the order of a few degrees within the GZK event horizon, that the cosmic rays can retain a memory of their direction of origin, and thus one can expect anisotropies to be present. Therefore it is reasonable to compare arrival directions of the highest-energy events with the locations on the sky of candidate sources, such as AGNs. The angular resolution on the arrival direction reconstructed from the relative times of firing of the SD stations is about 0.9°, less than the expected magnetic deflections. A statistically significant correlation was found [28] between the arrival directions of Auger events at energies beyond 57 EeV, within a 3.1° error circle, and the locations on the sky of AGNs from the Veron-Cetty and Veron (VCV) catalog, within a redshift of 0.018 (75 Mpc). A first set of 14 events had been used to establish the parameters of the correlation. Of the 13 events recorded following the prescription so established, 69% (9 out of 13) of events were found to correlate with AGN locations on the sky. This was used to reject an isotropic arrival distribution at the 99% confidence level.

In a higher-statistics follow up analysis [29], the correlation was found to have weakened to 38% (21 out of 55) of events within 3.1° above the same energy threshold and from the same GZK horizon radius. An isotropic distribution would have yielded a 21% correlation, and thus while the correlation is now weaker than first reported, it remains statistically significant. Moreover, the VCV AGN catalog is known to be incomplete in the plane of the Milky Way Galaxy, as AGNs are obscured by dust; if a band within ±10° of the Galactic plane is excluded, the correlation rate strengthens to 46% of events, with a 24% chance correlation expected in case of isotropy. The distribution of Auger event arrival directions on the sky is shown in Fig. 3 (left-hand panel), with the plane of the Galaxy removed from consideration.

It is interesting to note that the strongest correlation is in the direction of the Centaurus A AGN, the nearest such source to the Milky Way, only 3.8 Mpc away. This source is quite extended on the sky, with radio lobes spanning about 8°. In a region 18° in radius centered on Centaurus A, 13 events are found in the Auger catalog where only 3.2 are expected if arrival directions are isotropic. While no clear source identification can be claimed in this sort of a posteriori analysis, the result is intriguing. At the same time, the large-scale distribution of matter follows largely that of the AGN population, so that an unambiguous association of Auger events with AGNs is not possible at this time. For instance, the Centaurus A region marks a great concentration of matter on the sky in any case. If indeed the observed anisotropies in the UHE cosmic-ray arrival directions seem to be largely consistent with the GZK suppression observed in the energy spectrum, one expected consequence of this would be that the primary particles at these energies should be protons. More highly charged nuclei such as Fe would be deflected far too much to preserve the angular correlation. This leads us to the science challenge of the next section, on attempting to decipher the nature of the primary objects.

2.4. Nature of the primary UHE cosmic rays

Because of the indirect techniques necessary to detect and study the UHE cosmic rays, through their atmospheric cascades, a direct determination of the primary particle type is not possible. If the primaries were neutral messengers, such as photons or neutrinos, then a memory of their directional origin would be automatically preserved. Searches have been carried out [30] to test these possibilities. In the case of photons, air showers would have a reduced muon yield compared to hadron-induced cascades (and an estimate of the muon content of the shower front as it hits the ground can be extracted from the digitized signals in the SD stations). A photon shower is expected to develop deeper in the atmosphere owing to reduced particle multiplicities in successive generations as the cascade evolves; this in turn would yield a smaller shower-front curvature at the ground, as well as a larger spread of particle arrival times, which are measurable from the digitized SD station signals. Searches for evidence of photons in the Auger event sets have resulted in no candidates [30]. On the basis of this it is estimated that no more than a few percent of all incident UHE messengers can be photons up to 30 EeV, with a weaker constraint at higher energies. A neutrino primary could penetrate deeply in the atmosphere before interacting, and in particular in the horizontal direction a deep shower would yield a characteristic signature for a neutrino-induced event. Slightly up-going showers from a tau neutrino event traveling through the Earth (via the τ-ν_τ regeneration mechanism) would also yield a clear signature, with an increased sensitivity volume. Here also no candidate neutrino showers have been seen [31], yielding the most sensitive limits on neutrino fluxes in the range of a few times 10^{17} eV to 10^{19} eV. Thus the primary UHE cosmic rays are thought to be hadronic, atomic nuclei, just as they are at energies where they can be directly measured with balloon or satellite payloads.

The evolution of air showers in the atmosphere is expected to be statistically different on average depending on whether the primary particle is a proton or a higher-mass nucleus. At a given primary energy, more massive particles yield showers that develop sooner, for which the depth of maximum development X_{max} is at a higher altitude, or shallower atmospheric depth. At the same time, for a given primary particle type, a more energetic shower develops later in the atmosphere, with a deeper X_{max}. Thus a measurement of the depth of shower maximum and its evolution as a function of primary energy – the so-called elongation rate distribution – contains information on the composition of the primary particle flux. Additionally the fluctuation in the X_{max} parameter over a number of air showers of the same energy carries sensitivity to the mass composition, with heavier primaries yielding a narrower distribution of X_{max} values. The right-hand panel of Fig. 3 shows a measurement of this elongation rate distribution [32] with a sample of 3,754 well-reconstructed hybrid events above 1 EeV. Also shown on the figure are measurements [33] by the HiRes project for 815 events observed in stereo mode. The two experimental event sets agree substantially with each other.

Fig. 3 also indicates a series of predicted elongation rate distributions obtained from Monte Carlo simulations utilizing various hadronic interaction generator packages (QGSJET1 or 2, Sibyll or EPOS, see [32] for details). Simulations are carried out under a scenario where all primaries are protons, or at the other extreme where they are iron nuclei. The predictions exhibit a range of values (the blue-shaded region for protons, the red one for iron nuclei), which are indicative of the possible systematic uncertainties in these calculations. This is to be expected, given that guidance from accelerator-based particle physics is limited in understanding particle interactions at the very highest energies (with center-of-mass collision energies in the hundreds of TeV), in a regime out of reach of terrestrial laboratories for the foreseeable future. But the trend is certainly evocative, with an indication that while UHE cosmic rays tend to be the lightest nuclei at 10^{18} eV, the distribution appears to become progressively better aligned with heavy nuclei beyond 10^{19} eV. A study of the fluctuations in the X_{max} distribution results in the same interpretation (this is not shown here, but refer to [32]). This result is a direct challenge to the expectation that at the very highest energies, beyond 57 EeV where the angular correlation with the large-scale structure obtains, the UHE cosmic rays must be protons to escape overly large magnetic deflections, which would have erased the angular correlation. Note that the simulation results in Fig. 3 were obtained specifically for the Auger event reconstructions; separately, the HiRes collaboration carried out simulations of their own [33] optimized for their event reconstructions, from which they derived a preference for a lighter composition instead.

What the ultimate resolution of this conundrum will turn out to be is unclear at the moment. Perhaps the air shower simulation packages available at this time have difficulties accurately representing physics at trans-LHC energies. Indeed there is evidence that the simulated muon yield in the highest-energy air showers is lower than that measured in Auger SD stations [34]. It is possible to adjust the cross-sections for proton-air interactions to change the profile of shower development, so that proton-induced showers can be made to resemble the present expectation for iron-induced showers. Much needed guidance here will derive from the detailed QCD studies now under way at the LHC. If we accept however the idea that the UHE cosmic rays are iron nuclei, that somehow benefit from weak enough magnetic fields such that their arrival directions are not completely scrambled, then there should also appear a conjugate anisotropy pattern for protons at the same magnetic rigidity, and thus at an energy 26 times less (e.g., starting at (56 EeV)/26 = 2.2 EeV). This effect has been sought but not yet seen in the Auger event set [35].

3. Outlook and Conclusions

The Pierre Auger program is still in its early stages, with many more years of data-taking anticipated, with the attendant increased statistical power which will help refine the measurements alluded to here, as well as others not discussed due to space constraints. It remains to be seen whether an even greater increase in statistics can eventually derive from a northern, larger, version of the array deployed in Argentina. Certainly in the meanwhile a fertile interchange will continue to derive from the multiplicity of QCD studies to occur at the LHC. This will result in improved modeling of the complex air shower processes.

In addition, the Auger collaboration has embarked on a program of enhancements to the Observatory baseline design [36]. These include a densely instrumented subarray of SD stations near the Coihueco FD telescope, dubbed AMIGA for Auger Muons and Infill for the Ground Array, accompanied by muon counters buried under 2.3 m of soil. This will permit the study of many systematic effects affecting SD event reconstructions, the study of air showers of reduced energies down to 10^{17} eV, and a better understanding of the relative contributions of muons and electromagnetic components of air showers. Another enhancement is a set of three high-elevation FD telescopes, also near the Coihueco FD telescope and overseeing the AMIGA subarray. These, dubbed HEAT for High Elevation Auger Telescopes, permit the detection of lower-energy showers that develop higher in the atmosphere, and would otherwise not be fully in the field of view of the baseline FD telescopes. In combination with AMIGA, they will permit additional studies of systematic effects affecting hybrid event reconstructions. Moreover the power of the Auger hybrid technique has been amply demonstrated, and yet the statistical reach remains limited in hybrid mode because of the reduced FD duty cycle due to the restriction of operation on dark clear nights. Thus alternative techniques are under development to introduce radio and microwave detections of air showers coincident with the SD detections (with their 100% duty cycle). These efforts include the AERA (Auger Engineering Radio Array), AMBER (Air-shower Microwave Bremsstrahlung Experimental Radiometer), MIDAS (Microwave Detection of Air Showers), FDWave and EASIER (Extensive Air Shower Identification using Electron Radiometer) projects.

Thus, 100 years after the discovery of cosmic rays by Victor Hess in 1912, 70 years after the discovery of extensive air showers by Pierre Auger in the 1930s, 45 years after the prediction of the GZK suppression and an end to the cosmic energy frontier, the field of ultrahigh-energy particle astrophysics remains as active as ever. Many technical challenges were overcome, some new surprises and scientific challenges were encountered, some have been resolved, others are pending. Meanwhile the tools needed to address the next round of challenges are being commissioned. These are heady and exciting times indeed.

Acknowledgements

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