

Roadmap for Ultra-High Energy Cosmic Ray Physics and Astronomy (whitepaper for Snowmass 2013)

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The origin and nature of the highest energy particles ever observed are fundamental questions whose answers appear to be within our reach in the coming decade. The history of cosmic ray studies has witnessed many discoveries central to the progress of high-energy physics, from the watershed identification of new elementary particles in the early days to the confirmation of long-suspected neutrino oscillations, to measuring cross-sections and accessing particle interactions far above accelerator energies. A major recent achievement is establishing the suppression of the spectrum at the highest energies; this may be the long-sought “GZK” cut-off predicted by Greisen, Zatzepin and Kuzmin in 1966 [1], discussed in greater detail below. The GZK suppression is a remarkable example of the profound links between different regimes of physics, connecting as it does the behavior of the rarest, highest-energy particles in the Cosmos to the existence of Nature’s most abundant particles – the low energy photons in the relic microwave radiation of the Big Bang – while simultaneously demanding the validity of Special Relativity over a mind-boggling range of scales.

Ultra-high energy cosmic rays (UHECRs), now commonly taken to be CRs with energies $> 6 \times 10^{19}$ eV, were first reported just over 50 years ago by John Linsley [2]. These are the only particles with energies exceeding those available at terrestrial accelerators. The Large Hadron Collider (LHC) will reach an equivalent fixed-target energy of 10^{17} eV, whereas UHECRs have been observed with energies in excess of 10^{20} eV. With UHECRs one can conduct particle physics measurements up to two orders of magnitude higher in the lab frame, or one order of magnitude higher in the center-of-mass frame, than the LHC energy reach. As discussed in more detail below, the properties of UHECR air showers appear to be inconsistent with models which are tuned to accelerator measurements; one possible explanation is that new physics intervenes at energies beyond the LHC reach. UHECR experiments are the only way to access this energy range and make detailed measurements of air showers in order to address this question. It is worth noting that cosmic ray experiments have already yielded particle physics results at energies far exceeding those accessible to the LHC, one of the latest being a measurement of the p -air cross-section at $\sqrt{s} = 57$ TeV [3], a result which excludes some hadronic models extrapolations beyond LHC energies.

The two largest currently operating UHECR observatories are the Pierre Auger Observatory in the Southern hemisphere, covering an area of 3000 km^2 , and the Telescope Array (TA) in the Northern hemisphere, covering about 700 km^2 . Both observatories employ hybrid detection techniques, sampling cosmic ray air shower particles as they arrive at the Earth’s surface and also detecting the fluorescence light produced when UHECR air showers excite atmospheric nitrogen, for the $\sim 10\%$ of events arriving on dark, moonless nights. Both Auger and TA feature “low energy” extensions, which will provide an overlap with the LHC energy regime, while also allowing measurements in the galactic-to-extragalactic transition region.

The most important result so far from the present generation of observatories is the conclusive evidence that the UHECR flux drops precipitously at high energy, as shown in Fig. 1. The discovery of a suppression at the end of the cosmic ray spectrum was first reported by HiRes and Auger [4, 5] and later confirmed by TA [6]; by now the significance is well in excess of 20σ compared to a continuous power law extrapolation beyond the ankle feature [7]. This suppression is consistent with the GZK prediction that interactions with cosmic background photons will rapidly degrade UHECR energies [1]. Intriguingly, however, there are also indications that the source of the suppression may be more complex than originally anticipated.

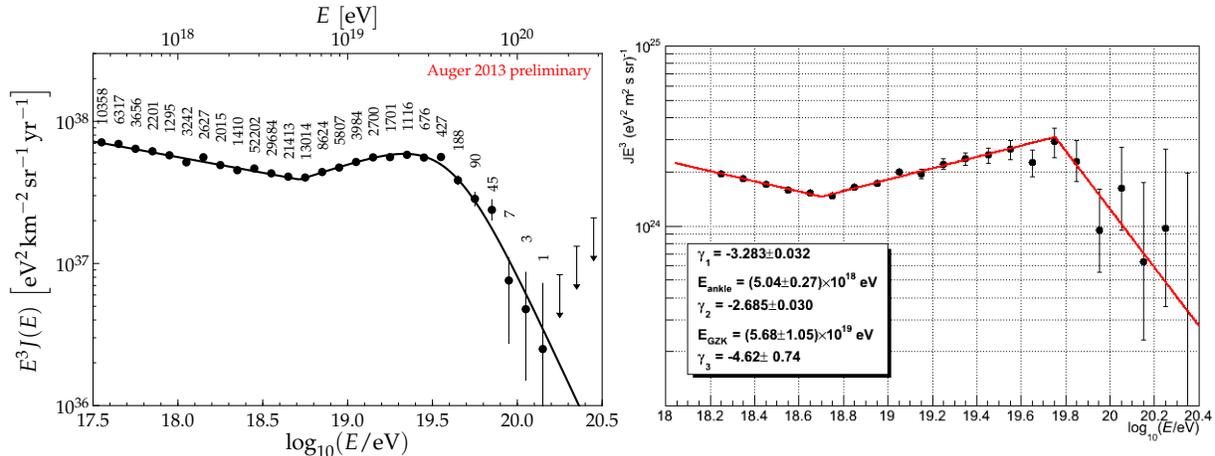


FIG. 1: Energy spectra presented at ICRC 2013 by the Pierre Auger (left panel) and TA (right panel) collaborations. The Auger plot is labeled with the total number of events in each bin, with the last three arrows representing upper limits at 84% CL [8]. In the TA plot, the legend gives the spectral indices and locations of energy breaks in a simple broken-power-law fit.

Lower energy observations of the elongation rate (the rate of change with energy of the mean depth-of-shower-maximum, X_{max}) [9–12], indicate that the composition becomes lighter as energy increases toward $\sim 10^{18.3}$ eV from below, fueling a widespread supposition that extragalactic cosmic rays are primarily protons. However the Auger Observatory’s high-quality, high-statistics data sample exhibits a *decreasing* elongation rate as well as a decreasing spread in X_{max} with increasing energy. Interpreted with present shower simulations, this implies that the composition is becoming gradually heavier beginning around 5×10^{18} eV [13, 14]. If true, this would have important implications for the astrophysics of the sources. A trend toward heavier composition could reflect the endpoint of cosmic acceleration, with heavier nuclei dominating the composition near the end of the spectrum – which coincidentally falls off near the expected GZK cutoff region [15]. In this scenario, the suppression would constitute an imprint of the accelerator characteristics rather than energy loss in transit. It is also possible that a mixed or heavy composition is emitted from the sources, and photodisintegration of nuclei and other GZK energy losses suppress the flux [16].

An alternative possibility for the origin of the break in the elongation rate could be even more interesting: this feature might arise from some change in the particle interactions at UHE not captured by event generators tuned to LHC and other accelerator data. Adding weight to this possibility are the Auger measurements, using three independent methods, showing that existing hadronic interaction models do not simultaneously fit all shower observables. For example, the actual hadronic muon content of UHE air showers measured in hybrid events is a factor 1.3 – 1.6 larger than predicted by models tuned to LHC data [17], even allowing for a mixed composition. Thus a critical step required to fully understand X_{max} observations is to identify and correct the deficiencies in current shower models. This is a strong motivation for upgrading present-generation detectors to enable full understanding of the hadronic interactions involved in air shower development. Fortunately, the information which will be accessible in shower observations – including the correlation between X_{max} and the ground signal in individual hybrid events [18], the comparison between X_{max} and X_{max}^μ (the atmospheric depth where muon production is maximum), the dependence of ground signal on zenith angle, and other detailed shower observations – is so rich and multifaceted that it will enable composition and particle physics to be disentangled [18].

An additional intriguing twist in the present observational situation is that the HiRes and TA results are consistent with a proton dominated flux everywhere above the ankle [19, 20], although with present statistics the TA and Auger elongation rates agree within errors [21]. Since the sources seen by the HiRes and TA in the Northern hemisphere may not be the same sources as seen by the Auger Observatory in the South, the composition need not be the same.

When TA statistics are sufficient to clearly determine whether the elongation rate observed in the North is the same as recorded by the Auger observatory in the South, it will be of great consequence for astrophysics even without knowing exactly how to translate from elongation rate to composition. If the composition (elongation rate) in North and South are not the same, it will mean *i*) that there are at least two source types, one accelerating primarily protons and another accelerating a mixed composition, and *ii*) that in at least one hemisphere, the UHECRs are produced mainly by one or a small number of sources.

Another major result of the present generation of observatories is the search for anisotropy in the distribution of arrival directions. Around 10^{18} eV, Auger has provided a strong upper limit on the dipole anisotropy [22, 23] which is almost sufficient to rule out a Galactic origin assuming these cosmic rays are indeed predominantly protons and making reasonable assumptions about the Galactic magnetic field (GMF). When the TA and Auger data are combined, the limit will be even stronger or a signal will be found [24].

As the energy increases, evidence for anisotropy mounts. Auger has reported a notable correlation of cosmic ray arrival directions with nearby galaxies of the Veron-Cetty and Veron catalog of Active Galactic Nuclei (AGN) [25]. With more data accumulated, the central value of the correlation fraction has decreased but the significance has remained at the 3-sigma level [26, 27]. The HiRes experiment did not observe such a correlation [28], but the most recent results from TA [29, 30] show a degree of correlation compatible with that seen by Auger in its full data set, and with a similar pre-trial significance. Furthermore, TA finds a significant correlation between the highest energy events' pointing directions and the local large-scale structure of the universe [31].

While indications of anisotropy are becoming stronger, a completely clear picture is thus far elusive, especially regarding the identity of the sources themselves. Perhaps a clear picture should not be expected, given the possibility of multiple types of sources and the fact that the composition in the South could be mixed or become heavy at the highest energies, while the flux could be more proton-dominated in the North. Adding to the difficulty of comparing correlation results of Northern and Southern hemisphere observatories is the fact that the magnitude and directions of magnetic deflections and the degree of multiple-imaging are expected to vary quite strongly across the sky [32]. Fortunately astrophysics observations and theoretical effort are rapidly improving GMF models [33, 34], so that the back-projection to correct for deflections should become feasible, to some extent, on the time-scale of the next generation of experiments.

Finally, we note the importance of limits which have already been placed on UHE photons and neutrinos. Searches for UHE photons have rather dramatically changed our understanding of the early universe. In particular, topological defects and super heavy relics surviving to the present day would decay to UHE photons and neutrinos. Existing UHECR experiments have already provided powerful bounds on the UHE photon flux, ruling out many existing models [35]. Future space missions will probe this landscape even further, testing beyond-standard-model physics models [36]. Furthermore, though not designed specifically to detect neutrinos, UHECR observatories have been able to achieve respectable neutrino sensitivity [37] in an energy regime complementary to the energy ranges in which dedicated neutrino experiments like IceCube and ANITA achieve the best sensitivity.

The next-generation UHECR observatories have three primary goals:

- *Increased statistics in both Northern and Southern hemispheres.* A large increase in statistics is obviously important to increase the significance and resolution of all results. In particular, it will improve the chances of finding multiplets and resolving large scale structure at higher energies, allow a more sensitive measurement of the spectral suppression and potentially establish variations in the spectrum in different regions of the sky. Furthermore, increased statistics will aid in reducing systematic uncertainties (of all sorts) for all measurements.
- *Composition-tagging for each individual event.* Probabilistic composition-tagging for all events will address the question of how the composition evolves with energy, thereby clarifying the nature of the spectral cutoff and the acceleration mechanism(s). It will also aid in source identification by allowing events to be backtracked through the GMF, with reduced ambiguity from their charge assignment, and allow correlation studies to be restricted to proton-like events with smaller deflections.
- *Detailed observations of UHECR showers to understand hadronic interactions in the UHE regime.* It is essential to have reliable shower-development models and UHE cross sections to be able to infer composition from the shower properties. UHECRs are also Nature's highest energy particle beam and thus present an opportunity to search for new types of particle physics.

Resolving the fundamental questions of UHECR composition and origins, and investigating particle physics above accelerator energies, will require both enhanced experimental techniques implemented at the existing observatories, as well as a significant increase in exposure to catch the exceedingly rare highest energy events. Pursuing improved ground-based detection techniques and pioneering space-based observation will offer complementary tools to piece together answers to these important but challenging puzzles.

The Auger Collaboration is preparing an upgrade proposal, to be implemented starting in 2015 [38]. The surface detector electronics will be improved to have 3 times better time resolution and to allow the signal to be measured accurately much nearer to the shower core. The surface detector stations will be equipped to provide superior muon-electromagnetic (EM) separation, either by segmenting the tank liners into an upper and lower portion (taking advantage of the different energy deposition characteristics of the EM and muon components) or by adding direct muon or EM detectors underneath, on, or beside the existing tanks. Not only are these upgrades essential to clarify the composition puzzle and elucidate the nature of the suppression, they will also allow us to test the validity of existing hadronic interaction models and possibly even reveal evidence of new physics at energies beyond the reach of the LHC [39]. By enabling event-by-event muon reconstruction and composition tagging with the surface detector alone, the effective exposure for the precious composition-tagged events will increase by an order of magnitude, dramatically increasing the power to identify sources and test hadronic interactions. The enhanced ability to reconstruct events, by exploiting the improved understanding of shower physics, will be backwardly-applicable to events observed with the original detector, increasing their value as well. The Auger dataset will roughly triple in the next 10 years.

The TA experiment is proposing a project called TA_{x4} to increase the size of its surface detector (SD) by a factor of 4 by adding 500 additional scintillation counters on a 2.08 km grid. An additional fluorescence detector (FD) site will be added overlooking the new surface detectors. The SD (FD) proposal will be made to the Japanese (American) funding agencies. The size of TA_{x4} is matched to the TA large-scale structure anisotropy signal, in that the larger detector will be able to definitively observe (or rule out) the effect in three years of running. Also upcoming is a TA muon detector: TA is funded to build, deploy, and operate a dedicated muon detector which will augment our detailed current understanding of cosmic ray air showers. Detectors of the TA Low Energy Extension (TALE) are currently being deployed. This will lower the low end of the TA energy range from 10^{18} eV to $10^{16.5}$ eV, providing excellent coverage of the LHC energy range, and accessing the astrophysics of the galactic-to-extragalactic transition.

To maximize the utility of these existing and upgraded UHECR observatories, the Auger and TA teams have established joint working groups to discuss experimental methods, pose questions to one another on measurement techniques, compare data analyses and modeling, and even share equipment. This collaborative approach not only aids in comparing results but also fosters a healthy environment of mutual evaluation and constructive criticism of one another's techniques [40].

Moving beyond existing technologies, it is inspiring to note that some 5 million UHECRs above about 5.5×10^{19} eV strike the Earth's atmosphere each year, from which we currently collect only about 50 or so with present observatories. In this sense, there exists some 5 orders of magnitude room for improvement! It may well be that the best hope to make inroads in this area is to take the search for UHECR sources into space, realizing a suggestion put forward by John Linsley in the early 1980's [41].

The project closest to realizing this objective is the JEM-EUSO mission [42], which is planned for launch no earlier than 2017 aboard the Kibo module of the International Space Station [43]. The primary objective of this mission is to launch a new era of particle astronomy and astroparticle physics and potentially make the first individual UHECR source identifications. This instrument will employ wide field of view Fresnel optics and a highly sensitive focal surface, complemented by a real-time atmospheric monitoring system [44]. A Global Light System comprising a ground-based global network of calibrated light sources, operated remotely and cross-checked by several aircraft flights per year, will validate and monitor key parameters of the JEM-EUSO instrument over its planned mission [45]. Operating in nadir (down-looking) mode, JEM-EUSO mission will achieve, at 10^{20} eV, an annual exposure of 5.6×10^4 km²sr yr after factoring in the duty cycle, cloud coverage, and light pollution estimates (assuming losses from reconstruction efficiency are minimal, as anticipated). The observatory will also be able to operate in tilt mode, increasing the exposure and energy threshold: a 30° tilt will result in an annual exposure of about 10^5 km²sr yr [46]. As the ISS orbit is inclined at 51.6°, JEM-EUSO will enjoy uniform exposure in both the Northern and Southern hemispheres, better facilitating searches for full-sky anisotropy [47] and other signs of the cosmic variance such as ensemble fluctuations [48]. The instrument will also have the capacity to distinguish extreme energy photons and neutrinos from baryonic showers [49], though the mission will not add much to the debate over baryonic mass composition discussed above.

In addition to its physics potential, JEM-EUSO will serve as a pathfinder for future space-based missions, establishing feasibility and cost-effectiveness, uncovering challenges and opportunities, and stimulating development of second-generation technology for more ambitious projects. Even before we know the results from the upcoming generation of UHECR observatories – JEM-EUSO and upgraded Auger and TA – it seems clear that still larger aperture observatories with much better energy and X_{\max} resolution will be called for, in order to measure the spectra and composition distribution of individual sources. The individual source spectrum is a key diagnostic of the acceleration mechanism, being peaked from a bursting source [50] and falling from a continuous one. Furthermore, as the exciting IceCube cosmic neutrino observations have recently shown [51, 52], we are entering the era of neutrino astronomy, so the time is ripe for redoubled efforts on this front. Observation of cosmogenic neutrinos would make the case for

the reality of the GZK effect. Further, neutrino observations can provide clues about the location of the galactic to extra-galactic UHECR transition [53]. Finally, if neutrinos with energies above 10^{21} eV exist, JEM-EUSO and other satellite instruments will have the potential to detect them. Such an observation would have dramatic implications, as the famous Hillas acceleration constraints [54] seem to exclude known astrophysical objects from endowing neutrinos with such energies.

Strategies and new devices to greatly enlarge terrestrial observatories are under discussion, e.g., at the International Symposium on Future Directions in UHECR Physics, CERN, Feb. 2012, and planning for space-based observatories are underway. One such next-generation proposal is the OWL (Orbiting Wide-angle Light-collectors) mission [55], a pair of co-orbiting satellites with f/1 Schmidt telescopes using deployable optics and inflatable light shields, launched as a dual manifest on a single rocket. Stereo event reconstruction, sub-pixel-crossing event timing, and sophisticated atmospheric monitoring systems are expected to give measurements nearly independent of track inclination and tolerant of atmospheric conditions. In 1000 km low inclination orbits, the OWL annual exposure is 2×10^5 km² sr yr above $\sim 6 \times 10^{19}$ eV. Initially, the spacecraft would fly close together to detect Cherenkov light from upward-going neutrino showers [56] and then separate. A monocular mode could double the detection aperture with the same energy threshold and tilting the satellites could increase the aperture at higher energies. Part of the mission at 600 km would lower the detection threshold.

A study has also begun on GreatOWL [57] which will employ inflatable optics ~ 36 times the OWL area together with solid-state sensors at the focal surface, and more modest launch requirements. GreatOWL's energy threshold of $\sim 10^{18}$ eV, will enable GZK-cosmogenic neutrino measurements and a significant improvement X_{\max} resolution, allowing composition determination above 10^{19} eV [58]. Inflatables could allow JEM-EUSO or OWL class telescopes to use yet smaller rockets for lower cost mission opportunities. Larger numbers of these, possibly launched as multiple manifests, could form a "constellation" of UHECR telescopes. Other space-based observatories have been proposed as possible concepts, including quite recently the SWORD [59] concept, which would employ satellite-born radio detection of air shower radio emissions reflected off the Earth, possibly leading to observation of ~ 100 events above 10^{20} eV per year in a cost-effective mission.

Some of the technologies needed to enable the next generation of UHECR observatories are already in development. For example, there are very active efforts underway to develop solid-state detectors for future UHECR telescopes, for the Cherenkov Telescope Array and for direct particle detectors [60]. The current focus is on (SiPM) [61] optimized for UV with quantum efficiencies $\sim 60\%$ at 330 nm, over twice that of PMTs.

We also mention the interdisciplinary science derived from the simultaneous function of these detectors as Earth observatories. The interdisciplinary science program at the Pierre Auger Observatory is quite extensive [62]. Through serendipity, Auger has turned out to be the world's best detector for measuring atmospheric transient luminous events known as Elves that are created above some thunderstorms. Elves are part of the planet's electrical system. Their detailed measurement by Auger provides a probe of the ionosphere. In the near future, the space-based TUS experiment [63] will perform measurements of these atmospheric phenomena in the near-UV while also serving as proof of principle for detection of UHECR with energy $> 10^{20}$ eV. Auger has also detected a major earthquake, measured Forbush decreases associated with solar activity, and developed many new techniques for measuring atmospheric properties.

In conclusion – thanks to a prodigious experimental effort – the origin and nature of the highest energy particles in the Universe are beginning to be revealed. Nonetheless, 50 years after their discovery much remains a mystery. The way forward is clear and practical. Upgrades to the Auger and TA ground-based detectors, focusing especially on enhancing the capacity to infer UHECR composition at the individual-shower level and improving our understanding of UHE particle physics, will produce a major increase in science output at modest cost. Attaining the exposure necessary to pin down UHECR sources could require taking the search to space, with the pioneering JEM-EUSO mission as our current best opportunity. The high statistics achievable with JEM-EUSO will complement the efforts of precision ground based experiments in revealing the nature of the high energy flux suppression; for instance if the GZK effect is indeed responsible for the observed suppression, the spectrum should display a recovery if source injection energies exceed 5×10^{20} eV. With the combined power of the space and ground-based approaches, a decade from now we should be much closer to knowing what UHECRs are, where they come from, and how they are produced; we may even have harnessed the study of UHECR showers to explore particle physics at energies inaccessible to terrestrial accelerators.

This work was supported by the US National Science Foundation (NSF), the US Department of Energy (DoE) and

the US National Aeronautics and Space Administration (NASA).

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