Origin of ultra-high energy cosmic rays in the era of Auger and Telescope Array

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Abstract. We discuss the origin of ultra-high energy cosmic rays in light of the latest observational results from the Pierre Auger Observatory, highlighting potential astrophysical sources such as active galactic nuclei, gamma-ray bursts, and clusters of galaxies. Key issues include their energy budget, the acceleration and escape of protons and nuclei, and their propagation in extragalactic radiation and magnetic fields. We briefly address the prospects for Telescope Array and future facilities such as JEM-EUSO, and also emphasize the importance of multi-messenger X-ray and gamma-ray signatures in addition to neutrinos as diagnostic tools for source identification.

1. Introduction
Several decades after their discovery, the origin of ultra-high energy cosmic rays (UHECRs), cosmic particles with energies $10^{18}-10^{20}$ eV and above, continue to be one of the biggest mysteries in physics and astrophysics [1]. During the last few years, the field has witnessed great advances, thanks to the advent of new generation, hybrid detector facilities spearheaded by the Pierre Auger Observatory in the southern hemisphere [2]. The Telescope Array [3] has begun operation in the northern hemisphere, and we eagerly await their data. Expectations are already high for future projects such as Auger North [4] or the Extreme Universe Space Observatory on the Japanese Experiment Module (JEM-EUSO), to be deployed on the International Space Station [5]. This article, by no means a thorough review, discusses selected topics in the rapidly developing field of UHECRs, focusing on the theory of potential astrophysical sources confronted with the latest observational results. Some of the issues below are covered in more detail in earlier articles [6].

2. General issues on propagation and recent observational results
We first touch upon some general issues concerning the propagation of UHECRs (see e.g. [7, 8] for more details). If UHECRs are protons of extragalactic origin, photopion interactions with cosmic microwave background (CMB) photons must induce severe energy losses at $\gtrsim 6 \times 10^{19}$ eV for propagation lengths $\gtrsim 100$ Mpc. Unless the sources lie much nearer, a spectral steepening (Greisen-Zatsepin-Kuzmin or GZK cutoff [9]) is expected above these energies. The Pierre Auger Observatory [10] as well as the HiRes experiment [11] have recently demonstrated the existence
of a strong spectral steepening at just this energy with high statistical significance, although at present it cannot be excluded that this represents instead some limit to acceleration at the sources.

The absence of super-GZK events reduces the motivation for the so-called top-down scenarios, in which UHECRs arise as decay products of higher energy entities envisaged in non-standard particle physics models, such as topological defects, superheavy dark matter, etc. [7]. Moreover, they are seriously constrained by the tight limits on the photon fraction from the latest Auger measurements [12]. In the following, we concentrate on the bottom-up, astrophysical scenarios.

A spectral steepening analogous to that for protons can also result if the highest energy UHECRs are composed mainly of heavy nuclei such as iron. For nuclei, the dominant energy loss process above \(10^{19}\) eV during intergalactic propagation is photodisintegration and pair production interactions with photons of the far-infrared background (FIRB) and the CMB [13]. Based on recent determinations of the FIRB, the energy loss length for iron nuclei at \(10^{20}\) eV is \(\sim 300\) Mpc, somewhat larger than that for protons [14]. Observationally, the nuclear composition of UHECRs, particularly at the highest energies, is quite uncertain. Fluorescence measurements of shower elongation rates by the HiRes experiment have indicated that the composition changes from heavy-dominated below \(10^{18}\) eV (presumably of Galactic origin) to light-dominated above this energy [15]. However, the latest results from Auger, based on hybrid events with higher precision and considerably higher statistics, instead reveal an intermediate composition at all energies up to \(4 \times 10^{19}\) eV, with hints of a trend toward a heavier composition at the highest energies [16]. A caveat is that systematic uncertainties in interaction models and atmospheric optical attenuation are still quite large [17]. These issues are also critical for the interpretation of the ankle feature in the spectrum at \(\sim 3 \times 10^{18}\) eV [18, 19].

Another unavoidable aspect is deflection by Galactic and extragalactic magnetic fields (EGMF), which affect the arrival directions of UHECRs and can also act to lengthen their effective propagation distance. The strength and distribution of magnetic fields in the intergalactic medium as well as at high latitudes in the Galaxy are very poorly known, both observationally and theoretically. Faraday rotation measurements of distant radio sources give only upper limits in the nanogauss range for intergalactic fields on average, subject to assumptions on the field coherence scale and ionized gas distribution [20]. Realistically, whatever their origin, EGMF can be expected to have some correlation with the distribution of large scale structure, and various EGMF models that account for this have been introduced to assess their effects on UHECR propagation [21]. The effect of Galactic magnetic fields (GMF) is also model-dependent [22, 23].

The Auger collaboration has recently announced statistically significant evidence for UHECR anisotropy [24]. They find a \(\sim 3\sigma\) correlation between the arrival directions of 20 UHECR events above \(5.6 \times 10^{19}\) eV, and the positions of active galactic nuclei (AGNs) in the Veron-Cetty and Veron catalog with distances \(<75\) Mpc, to within 3.1 degrees. Some robust implications of this important result are that: 1) the UHECR sky is not isotropic, 2) the sources of UHECRs are extragalactic and trace large-scale structure on scales of order 100 Mpc, ruling out Galactic sources, and 3) deflections of UHECRs in the GMF and EGMF are not so severe as to isotropize the arrival directions, so that charged particle astronomy is possible.

Not much more can be said with confidence, however. A correlation with the global distribution of AGNs does not necessarily mean that they are the true sources; any other source that follows the distribution of large-scale structure, such as gamma-ray bursts (GRBs) and clusters of galaxies, may also be feasible. Inferences on the source density or UHECR composition from the current anisotropy results are dependent on assumptions regarding the EGMF and GMF (see below). In addition, the Veron-Cetty catalog is known to be highly non-uniform and incomplete, and further studies with higher statistics utilizing more suitable catalogs are warranted. Since the northern hemisphere should be less affected by the GMF, data
from the Telescope Array will be crucial, and all-sky observations by JEM-EUSO even better. We note that the AGN correlation results have not been confirmed by the northern HiRes, although their statistics is smaller [25]. At present, the true identity of the UHECR sources is still wide open.

3. Acceleration and energetics in astrophysical sources of UHECRs

A minimum requirement for astrophysical sources of UHECRs is the ability to magnetically confine particles of the requisite energies. For particles with energy $E$ and charge $Z$, this implies the Hillas condition $(R/\text{pc})(B/1\text{G}) \gtrsim (E/10^{20}\text{eV})/Z$ between the system’s size $R$ and magnetic field $B$. Only a few types of objects are known to meet this criterion, among them the jets of radio-loud AGNs, GRBs, and clusters of galaxies [26]. Below we focus on these three as representative types of potential UHECR sources (see [26] for other possibilities). The actual maximum energy attainable under different circumstances must be evaluated by comparing the timescales for particle acceleration, often that for the first order Fermi mechanism in shocks, against the timescales for limiting processes such as source lifetime, particle escape, adiabatic or radiative energy loss, etc.

Equally important is the available energy budget. Fig.3 shows estimates of the kinetic energy output averaged over the universe as a function of redshift $z$ due to AGN jets, GRB explosions and accretion onto clusters, which should be proportional to their cosmic ray output. The plotted quantity is differential per unit $z$, $dE_{\text{kin}}/dz = (dt/dz) \int L(\text{d}n/\text{d}L)\text{d}L$, where $L$ is the kinetic luminosity per object and $\text{d}n/\text{d}L$ is the $z$-dependent luminosity function, with cosmological parameters $h=0.7$, $\Omega_{m}=0.3$ and $\Omega_{\Lambda}=0.7$. For AGN jets, we have made use of the observed radio luminosity function along with the observed correlation between the radio and jet kinetic luminosities of radio galaxies [27]. GRBs were assumed to occur each with kinetic energy $E_{\text{GRB}} = 10^{53}$ erg at a rate that follows the star formation history and matches the log $N$-log $S$ distribution observed by BATSE [28], the estimate being roughly independent of the beaming factor (see below for modifications required by the latest Swift observations). The three curves each for AGNs and GRBs correspond to different evolutionary assumptions at the highest $z$, with only small differences at low $z$. For clusters with mass $M$, the rate of gas kinetic energy dissipation through accretion shocks can be estimated as $L_{\text{acc}} \approx 9 \times 10^{45}(M/10^{15}\text{M}_\odot)^{5/3}$ erg/s [29, 30]. This can be combined with the Press-Schechter mass function to evaluate $dE_{\text{kin}}/dz$ for clusters of different $M$. Note that due to the hierarchical nature of structure formation together with the nonlinear nature of gravity, the maximum is reached at $z = 0$.

Figure 1. Energy budget of candidate UHECR sources: AGN jets (dotted), GRBs (dashed) and cluster accretion shocks (solid), the latter separately for each log $M$ as labelled. See text for more details.
The results at low $z$ can be compared with the observed energy density of UHECRs, \( \simeq 10^{-19} \text{erg cm}^{-3} \simeq 3 \times 10^{19} \text{erg Mpc}^{-3} \) above \( 10^{19} \text{eV} \). Considering further factors for energy loss during propagation, it is apparent that whereas AGN jets and cluster accretion shocks have reasonable margins to accommodate the energetics of UHECRs, GRBs, with a substantially smaller energy budget, require a high efficiency of energy conversion into UHECRs.

4. Active galactic nuclei

AGNs are luminous active objects in the centers of some galaxies that are thought to be powered by accretion of matter onto supermassive black holes [31]. Roughly 10% of them are known to be radio-loud, ejecting powerful, relativistic jets away from the nucleus, but the majority of AGNs are of the radio-quiet type with no strong jets. In contrast to the former, the latter are considered unlikely to be UHECR sources due to the severe radiative losses expected near the nucleus [32], and the absence of nonthermal emission components.

In the jets of radio-loud AGNs, different locations along the outflow can be UHECR production sites, since one expects $B \propto R^{-1}$ under the naive assumption that the ratio of magnetic to kinetic energy is constant. One candidate is the inner jet region with $R \sim 10^{16} - 10^{17}$ cm and $B \sim 0.1 - 1$ G, known through observations of blazars to be a site of particle acceleration, perhaps due to internal shocks. Estimates assuming Bohm-type acceleration (i.e. acceleration time comparable to gyration time in fully turbulent magnetic fields) show that the maximum proton energy should be limited by photopion interactions with low frequency internal radiation to somewhat below $10^{20}$ eV [33]. However, plausible models of broadband blazar emission based on electron acceleration generally indicate that the acceleration conditions in inner jets are far from the Bohm limit [34]. Furthermore, efficient conversion to neutrons may be necessary for the particles to escape the jet without suffering adiabatic expansion losses and contribute to UHECRs by decaying back to protons outside. A less problematic site may be the hot spots of powerful radio galaxies, termination shocks where large-scale jets are decelerated by the external medium, with $R \sim 10^{21}$ cm and $B \sim 1$ mG. Here the maximum energy may exceed $10^{20}$ eV, limited by escape [35]. However, note that these particles must further traverse the extensive cocoon of shocked, magnetized jet material in order to completely escape the system, an issue that has not been examined in detail. A further possibility is acceleration by the bow shocks being driven into the ambient gas by the expansion of the cocoon [36]. In view of the Auger composition results [16], another interesting question is whether heavy nuclei such as iron can be accelerated and survive photodisintegration in these environments [37].

In order to verify an AGN origin, detailed analysis of observed UHECR arrival directions and cross correlations with known source positions is undoubtedly essential, and the recent Auger results are an important step in this direction. However, it is not a trivial task, given the uncertainties in the intervening GMF and EGMF and the UHECR composition (Sec. 2). In addition to deviations in the arrival directions, deflections in the EGMF during propagation also entail significant delays in the arrival times of UHECRs, which can be of order $10^7$ yr or more for distances 100 Mpc, depending on the properties of the EGMF [38]. This is in fact comparable to or longer than the typical lifetime or duration of AGN activity, particularly for radio-loud AGNs [39], so that they can effectively behave as transient sources, in much the same way as GRBs. Before the UHECRs emitted by an AGN reaches the observer, the object may significantly evolve in its radio power, or possibly shut off its activity altogether. Another implication is that an effectively larger number of sources contribute to small scale clustering, underscoring the need for high event statistics as might be provided by JEM-EUSO or Auger North.

Because of these concerns, it is also highly desirable to have some means to pinpoint individual sources through characteristic, UHECR-induced signatures of secondary neutral radiation. Neutrinos are ideal in providing an unambiguous earmark of high energy hadrons.
However, even with km$^3$ detector facilities such as IceCube or KM3NeT, it may not be easy to resolve individual AGNs. Thus, distinctive electromagnetic signals will also be extremely valuable. For radio galaxy hot spots, synchrotron emission from UHE protons can produce nonthermal X-rays that could be distinguished from other processes such as electron inverse Compton through multiwavelength observations [41]. If the medium surrounding the source is sufficiently magnetized, UHE protons propagating in the source’s vicinity can lead to diffuse gamma-ray emission from photomeson-triggered cascades that may be detectable by current and upcoming instruments [42].

5. Gamma-ray bursts
GRBs are explosive phenomena that are believed to arise in a fraction of stellar collapse events, characterized by highly variable, ultrarelativistic outflows lasting for $\sim 10 - 100$ s [43]. As with AGN jets, these outflows can be host to different sites for UHECR acceleration. Potential locales include internal shocks, external reverse shocks, and external forward shocks, believed to be the emission sites of the prompt X-rays and gamma-rays, optical flash and radio flare, and the radio to X-ray afterglow, respectively [44]. The external forward shock may possibly be disfavored due to the ultrarelativistic velocity and weak upstream magnetic field [45], but this is controversial [46]. For the mildly relativistic internal and external reverse shocks, a different problem is that for the particles to escape the acceleration site without significant losses, neutron conversion may be required, as with AGN inner jet regions. This entails some reduction in efficiency, which cannot be too severe in view of the tight energy budget, as discussed above.

A crucial distinguishing feature of UHECRs from GRBs is the narrow dispersion in CR energy expected for individual sources, due to the time delay during propagation in EGMF [38]. Clear detections of this effect demand substantial event statistics that may only be achievable with future facilities. Even then, it would only demonstrate that UHECRs come from bursting sources, and their GRB origin will remain ambiguous. Thus, multi-messenger photon and neutrino signatures are particularly essential in the case of GRBs.

Identification of high energy neutrino signals from GRBs are facilitated through time coincidence, but studying individual bursts in detail may be difficult. Thus, photon signatures of UHECR production will also be crucial [47]. Detailed studies of this issue were conducted for the GeV-TeV emission from internal shocks, utilizing a comprehensive Monte Carlo code that includes a wide variety of physical processes related to high energy protons and electrons [48, 49]. Besides inverse Compton emission from primary electrons, interesting proton-induced components can become clearly visible, such as synchrotron emission from high energy protons and muons, as well as emissin from secondary pair cascades injected by photomeson interactions, serving as unique signatures of ultra-high-energy protons.

Particularly interesting are proton-dominated GRBs, which contain a significantly larger amount of energy in accelerated protons compared to accelerated electrons [49]. Such conditions are motivated not only by the physics of particle acceleration in collisionless shocks, but also by the latest Swift measurements of the GRB $z$-distribution. Post-Swift estimates of the local GRB rate [50] may imply that the proton energy content per burst may need to be substantially higher than previously thought in order for them to remain viable as UHECR sources. Unique UHECR-induced GeV-TeV components are expected, n some cases leading to GeV-dominated bursts or luminous TeV bumps (Fig.2).

Note that the conditions favorable for GeV-TeV emission may also imply efficient UHECR acceleration and escape, but not necessarily strong neutrino emission [48]. The observational prospects are promising for GLAST, atmospheric Cerenkov telescopes such as MAGIC (II), H.E.S.S. (II), VERITAS and CANGAROO III, as well as wide-field surface detector facilities, which should test these expectations and provide important information on the physical conditions in GRB outflows.
Figure 2. Prompt emission spectra from internal shocks in proton-dominated GRBs. See [49] for more details. (Left) For for $\Gamma = 300$ and different proton/electron ratios. Solid curves are the total emission, and dot-dashed curves denote separately electron synchrotron (eSY) and electron inverse Compton (eIC) components without $\gamma\gamma$ absorption effects. Dashed curves are primary electron components only. (Right) Similar to left panel, except for $\Gamma = 1000$ and different magnetic fields. Dot-dashed curves denote separately proton (pSY) and muon synchrotron ($\mu$SY) components.

A different class of low luminosity GRBs have been proposed to be more important than high luminosity GRBs for the integrated energy budget, and hence potentially more relevant as sources of UHECRs [51]. As with AGN jets, the acceleration and survival of heavy nuclei in in the environments of both high and luminosity GRBs is an important question [52].

6. Cluster accretion shocks

Clusters of galaxies are the largest gravitationally bound systems in the universe, composed of stars, hot gas and dark matter. According to the currently favored picture of hierarchical structure formation in the CDM cosmology, they are the latest objects to form, and should be surrounded by strong accretion shocks as a consequence of continuing infall of dark matter and baryonic gas [54]. Such shocks should be interesting sites of particle acceleration and have been proposed as sources of UHECRs [36]. However, estimates of the maximum energy $E_{\text{max}}$ for protons seem to fall short of $10^{20}$ eV by 1-2 orders of magnitude [55, 30].

We have shown that invoking UHECR nuclei in cluster accretion shocks may offer a possible solution [53]. Heavy nuclei with higher Z have correspondingly shorter acceleration time so that Fe may be accelerated up to $10^{20}$ eV in the same shock conditions, notwithstanding energy losses by photodisintegration with the FIRB and CMB. With reasonable assumptions regarding the number density and CR power of the sources, detailed propagation calculations demonstrate that the model compares favorably with the existing observations, as long as the source composition of Fe is similar to that of Galactic CRs (Fig.3). See also [56] for related studies.

The mass composition at $\approx 3 \times 10^{19}$ eV should be predominantly light and consistent with HiRes reports [15]. The rapid increase of the average mass at higher energies is a clear prediction of the scenario, in line with the latest Auger elongation measurements [16], and to be tested further by new generation facilities including Telescope Array and JEM-EUSO.

Despite the relative rarity of massive clusters in the local universe, strong deflections of the highly charged nuclei in EGMF allow consistency with the global isotropy. On the other hand, with a sufficient number of accumulated events, anisotropies toward a small number of
Figure 3. Observed UHECR spectrum (left) and mean mass composition (right) versus energy $E$ ($1 \text{ EeV} \equiv 10^{18} \text{ eV}$) from cluster accretion shocks for $\alpha = 1.7$ and $\beta = 0.5$ [53]. Compared are current data for HiRes [57] (bars) and Auger [10] (asterisks). The histograms are the average over different model realizations for the cases with (thick) and without (thin) EGMF, and the thin curves outline the median deviations due to cosmic variance for the former case only. The straight line in the top panel denotes the injection spectrum.

individual sources should appear, although this expectation is subject to uncertainties in the EGMF and GMF. Whether it is consistent with the latest Auger anisotropy results calls for a deeper investigation. It could possibly be the case, including the observed deficit of events from the Virgo direction, if the GMF is of the plausible, bisymmetric spiral type, for which deflection angles can be minimal in selected regions of the sky around the supergalactic plane, particularly around Centaurus [23] (see also [58] for related discussions). Note that the Centaurus cluster at distance $\sim 50 \text{ Mpc}$ is one of most prominent clusters in the local universe, somewhat more massive than Virgo [59].

We mention that the escape of CRs from clusters can be mediated by diffusion in directions away from the filaments, or perhaps by advection in partial outflows during merging events. Energy-dependent escape upstream of the shock may also be possible. An aspect of this scenario that warrants further study is the spectral domain $< 10^{19} \text{ eV}$ and the implications for the Galactic-extragalactic transition region. Alternatively, provided that EGMF horizon effects are effective $< 10^{17} \text{ eV}$ [60], cluster accretion shocks may give an appreciable contribution to CRs between the second knee and the ankle, in which case they may also be interesting as high energy neutrino sources [61] (see also [62]).

Finally, we may look forward to very unique signatures in X-rays and gamma-rays. Protons accelerated to $10^{18}-10^{19} \text{ eV}$ in cluster accretion shocks should efficiently channel energy into pairs of energy $10^{15}-10^{16} \text{ eV}$ through interactions with the CMB, which then emit synchrotron radiation peaking in hard X-rays and inverse Compton radiation in TeV gamma-rays [30]. The detection prospects are promising for Cerenkov telescopes such as HESS, and hard X-ray observatories such as Suzaku and the future NeXT mission. Photopair production by nuclei may also be efficient and induce further interesting signals that are worth investigating.

7. Conclusion and outlook
Besides AGNs, GRBs and clusters, other proposals for the astrophysical origin of UHECRs not covered in this brief review include starburst galaxies, merging galaxies, extragalactic magnetars, dormant black holes, etc. (see [26]). The true source of UHECRs could be one or more of these; alternatively, we should not discount the possibility that it is actually none of them, and the truth something totally unexpected.
In this regard, we may recall the history of GRB research. Before the launch of BATSE in 1991, the sample of GRBs numbered \( \sim 200 \), with no clear anisotropy observed in the sky distribution. However, most believed, based on theoretical plausibility, that they were generated by Galactic neutron stars, while a very small minority advocated neutron star mergers at cosmological distances. After several years and a sample of more than 3000 bursts, the currently most favored scenario for the progenitors of long GRBs is related to the collapse of massive stars, a concept that didn’t exist before BATSE. The lesson is that we should be cautious about jumping to conclusions on the origin of UHECRs based on just 20 observed events and our limited theoretical understanding of cosmic objects.

Regardless of theoretical prejudice, the quest for the solution of the UHECR mystery is progressing in earnest with ongoing measurements by Auger and Telescope Array. An order of magnitude greater statistics for the highest energy events expected from JEM-EUSO or Auger North-South, and the combined effort of upcoming neutrino, X-ray and gamma-ray observations is expected to lead us toward the true answer in the near future.

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