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The origin of ultrahigh energy cosmic rays

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The origin of the highest energy cosmic rays is still unknown. The discovery of their sources will reveal the workings of the most energetic astrophysical accelerators in the universe. Candidate sources range from the birth of compact objects to explosions related to gamma-ray bursts or to events in active galaxies. We discuss the observable signatures that help narrow down this list of candidates, namely the distribution of the arrival directions of ultrahigh energy cosmic rays in the sky, their energy spectrum, their chemical composition, and their multi-messenger signatures. We focus in particular on one candidate source: young isolated pulsars. The production of ultrahigh energy cosmic rays in these objects could give a picture that is surprisingly consistent with the latest data measured with the Auger Observatory.

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1 Introduction

The observation of ultrahigh energy cosmic rays (UHECRs), particles with energy that can exceed 10^{20} eV, has posed some fundamental questions that have been unanswered for the past decades: Where do they come from? How can they be accelerated to such high energies? Here we give a short review of recent progress towards answering these questions. For more complete reviews, the reader might refer to, e.g., [1, 2].

The quest for sources of UHECRs is first rendered difficult by sheer astrophysical issues. Cosmic rays are charged particles and the Universe is magnetized on various scales. Our poor knowledge of these magnetic fields makes the task of back-tracking particle trajectories to their sources quasi-impossible to date. Besides, the intricate workings of the most powerful astrophysical objects of the Universe, which likely are the sources of UHECRs is not well understood, which complicates further the problem. To these astrophysical issues are added Particle Physics issues: UHECRs arrive on Earth with energies that cannot be reproduced on Earth. The hadronic interactions governing the airshower development of a UHECR entering the Earth atmosphere, is thus not unknown. This element is albeit crucial, as this airshower is the information we detect experimentally, from which one has to deduce the properties of the primary particle. Most of all, the difficulty of UHECR science resides in their natural low flux impinging the Earth, that necessitates the construction of larger and larger observatories, in order to be able to collect enough particles and increase statistics.

After many decades of efforts to discover the origin of cosmic rays, current observatories are now reaching the necessary exposure to begin unveiling this longstanding mystery. Completed in 2008, the Pierre Auger Observatory is the largest observatory at present [3]. Constructed in Argentina, it consists of a 3,000 km^2 array of water Cherenkov stations with 1.5 km spacing in a triangular grid overlooked by four fluorsescence telescopes. The combination of the two techniques into a hybrid observatory maximizes the precision in the reconstruction of air showers, allowing for large statistics with good control of systematics. The largest observatory in the northern hemisphere, the Telescope Array (TA), is also hybrid [4, 5]. Situated in Utah, it covers 762 km^2 with scintillators spaced every 1.2 km overlooked by three fluorescence telescopes. By end of 2013, each telescope has collected about 100 and 30 events above 5.7×10^{19} eV for Auger and TA respectively.

To answer the question of the origin of UHECRs, the observational information we possess are the following: from the detection of UHECRs themselves, we have measurements of their energetics, their arrival directions in the sky, and their chemical composition. One might also want to cross-correlate this information with observations of secondary messengers that are produced together, or by these ultrahigh energy particles, namely gamma-rays and neutrinos. In what follows, we will examine these pieces of information one by one to try to dig out the most of each observable.

2 The energy spectrum

The observed UHECR energy spectrum is a well of quite solid information. The measurement of the flux first gives us an indication on the energy budget that the population of UHECR sources have to supply. The estimated budget is of order $\dot{\mathcal{E}}_{\rm UHECR} \sim 0.5 \times 10^{44}\,{\rm erg\,Mpc^{-3}\,yr^{-1}}$ at $E = 10^{19}\,{\rm eV}$ [6].

The steep decline in flux above about 30 EeV is reminiscent of the effect of interactions between extragalactic cosmic rays and the cosmic background radiation, named the Greisen-Zatsepin-Kuzmin (GZK) cutoff [7, 8]. A similar cutoff could however be produced by a maximum acceleration energy $E_{\rm max}$ at the source. Another important feature is the hardening of the spectrum at a few EeV (the ankle), which may be caused by the transition from Galactic to extragalactic cosmic rays or by propagation losses if UHECRs are mostly protons.

The detection of particles at energies above $10^{20}\,{\rm eV}$ implies 1) that sources have to be able to accelerate particles up to these energies, and 2) that the sources of these particles lie within a few hundreds of megaparsecs, as they would have experienced severe energy losses if they had travelled from further away.

Criterion 1) can be further translated into a necessary condition on the source parameters. In order to be able to accelerate particles to $E > 10^{20}\,{\rm eV}$, sources must first confine them, i.e., the Larmor radius of the particles in the acceleration site has to be smaller than the size of the source [9]. This statement, called the Hillas criterion, is helpful to make a first selection of sources that could be potential accelerators. The surviving candidates are Active Galactic Nuclei (AGN) with their black holes, their jets and their hot spot regions as possible acceleration sites, shock regions in clusters of galaxies, gamma-ray bursts (GRBs) and strongly magnetized pulsars. A more accurate criterion can be derived by taking into account the Lorentz boost factor and other parameters of the acceleration regions. In terms of the magnetic luminosity of the source (defined as a fraction $\epsilon_{\rm B}$ of the luminosity in the accelerating outflow: $L_{\rm B} = \epsilon_{\rm B} L_{\rm jet}$), necessary to accelerate particles above $E > 10^{20}\,{\rm eV}$, the condition reads: $L_{\rm B} > 10^{45.5}\,{\rm erg\,s^{-1}}\Gamma^2\beta^{-1}$, where Γ and β are the Lorentz factor and the velocity of the flow [10]. Note that the possible candidate sources can be split into two categories: steady sources emitting particles continuously over the long lifetime of the object, and transient source producing a short burst of cosmic-rays. We will see in the following that these two types of sources can lead to different observable signatures.

3 Chemical composition

The composition measurements at the highest energies of the Auger Observatory are surprising. Auger [11] report a trend from a proton dominated composition at a few EeV toward a heavier composition at around 40 EeV (continuing up to 60 EeV). This trend is consistent within quoted statistical and systematic errors with the preliminary data of the Telescope Array [12].

If there were indeed a transition towards heavy composition at the highest energy, one would need to look for a source that would be able to inject a non negligible amount of heavy nuclei in the acceleration site. Because of the natural low abundance of such elements, the source would have to be either metal-rich, or to nucleosynthesize heavy nuclei. Injection is not the only weak point of this scenario: because the acceleration sites are usually dense in radiative and baryonic backgrounds, the escape of nuclei from these regions is not obvious. Many works have shown the difficulty to overcome these problems in AGN, clusters and GRBs [13, 14, 15, 16, 17]. On the other hand, pulsars, due to their metal-rich surfaces are a naturally good candidate for iron injection and acceleration. [18, 19, 20, 21] further argued that accelerated particles could escape the site and the environment of the source.

4 Arrival directions in the sky

The interpretation of arrival directions of UHECRs in the sky is intricate, and intimately linked to our (yet poor) understanding of the magnetic fields in the Universe. Intergalactic magnetic fields that spread between the sources and us induce deflections on the charged UHECR trajectories, causing spatial and temporal decorrelations. The latter is noticeable if the source is of transient type: deflected cosmic rays arrive on Earth with a time delay compared to the photons and other undeflected particles. This delay is of order 10^4 yrs for one degree deflection over 100 Mpc. This implies that by the time UHECRs reach us, the transient source is already extinguished, erasing any direct event/object correlation.

Though intergalactic magnetic fields are the key to back-track cosmic-ray trajectories to their sources, our knowledge of the subject is limited, due to the lack of observations. The *non*-detection of any signal sets an upper limit to the field strength B and its coherence length λ of $Bl_{\rm coh}^{1/2} < 1 - 10\,{\rm nG\,Mpc}^{1/2}$ [22, 23]. The heavy numerical simulations that try to construct a mock magnetic field distribution by injecting MHD equations into cosmological simulations lead to discrepant results [24, 25, 26]. The study of propagation of UHECRs in such a situation is complicated, but many authors have endeavored to build up predictions and models [24, 25, 26, 27, 28]. The precise role of extragalactic magnetic fields in UHECR propagation may be clarified in the future through extensive Faraday rotation surveys (see, e.g., [29]) and indirect measurements of gamma-ray halos around blazars (e.g., [30]). Meanwhile, it is interesting to note that for standard types of intergalactic magnetic fields, studies converge on predicting deflection of less than $\sim 3^\circ$ above $E_{\rm GZK} \equiv 6 \times 10^{19}\,$eV for protons. The Galactic magnetic field, comparatively better known, should also be taken into account (see [1] for references).

The arrival directions of UHECR above $E_{\rm GZK}$ seen by Auger present two main characteristics: Auger reports a hint of correlation with the large scale structures [31], but most striking, one observes no powerful source in the arrival direction of the highest energy events. Because standard intergalactic magnetic fields should lead to low proton deflection, one expects that steady sources (such as AGN), should be visible behind the arrival directions of UHECRs, unless they are heavy nuclei or if the intergalactic magnetic field is particularly strong, inducing in both cases important deflections. For transient sources (such as gamma-ray bursts or newly born pulsars), due to the time delay between rectilinearly propagating photons and the deflected cosmic rays, one does not expect to observe correlating counterparts. The distribution of events in the sky should however follow closely the large scale structure with a possible bias [32]. The measurement of such a bias could be an evidence to help distinguish between transient and steady sources. It requires however more than 10^3 events, which can be collected by the next generation of UHECR detectors.

Another information given by the distribution of the arrival directions is the absence of multiplets, namely cosmic ray events arriving with little angular separation in the sky. This lack can be used to constrain the apparent number density of sources to $n_0 > 10^{-5}\,{\rm Mpc}^{-3}$, if cosmic rays are protons [33, 34], a simple evaluation leading to $n_0 \sim 10^{-4}\,{\rm Mpc}^{-3}$ [34]. The low density of steady candidates: clusters of galaxies ($10^{-6}\,{\rm Mpc}^{-3}$), FRI-type ($10^{-5}\,{\rm Mpc}^{-3}$), and FRII-type radio-galaxies ($10^{-8}\,{\rm Mpc}^{-3}$) might not be compatible with the lack of multiplets in the case of proton composition. For transient sources, the apparent n_0 and real ρ_0 number densities of proton UHECR sources are related via the cosmic ray arrival time spread δt due to magnetic fields: $\rho_0 \sim n_0/\delta t$ [35]. The time spread δt is bounded on its lower end by the lower limit of the Galactic magnetic field, and on its upper end by the upper limit on the intergalactic magnetic field. By intersecting the information on the required density with the required energy budget estimated earlier, one finds that most transient sources (AGN flares, High and Low luminosity GRBs) only tightly meat the requirements for UHECR production [35]. On the other hand, pulsars seem to easily fulfill both criteria.

To be able to dig more information out of the available UHECR observables, it appears necessary to increase drastically the statistics and to turn to the next generation of cosmic ray experiments, such as JEM-EUSO [36, 37]. Meanwhile, one might perform a case by case study of candidate sources, and examine their acceleration potential using, for example, multi-wavelength observations of these objects. In the next section, we will concentrate on the case of newly-born isolated pulsars, which, from the criteria covered above, seem to be a promising candidate.

5 A promising candidate: newly-born isolated pulsars

The acceleration of particles in pulsar environments has been suggested since their discovery [38]. While nearby pulsars show direct evidence of accelerated electrons and positrons, the acceleration of hadrons is still unclear. The suggestion of pulsars as cosmic ray accelerators of VHECRs has been discussed in [39, 40, 41, 42, 43] while for UHECRs the main proposals are by [18, 19]. In [18] Iron nuclei stripped off the neutron star surface are accelerated to UHEs by the fastest spinning young neutron stars with typical pulsar magnetic fields (between 10^{12} and 10^{13} G). Neutron stars with much larger surface magnetic fields, i.e., magnetars, have been proposed as sources of ultrahigh energy protons by [19]. Given their faster spin down rate, the acceleration to UHEs is at earlier stages of the pulsar evolution when gravitational radiation is significant and a disruption of the supernova envelope is needed to allow the escape of accelerated particles [19, 44].

Reference [20] concentrates on pulsars with typical magnetic fields and millisecond rotation periods at birth, embedded in standard core-collapse supernovae. Their calculations show that, at early times, when protons can be accelerated in pulsar winds to energies $E > 10^{20}\,\mathrm{eV}$, the thickness of the supernova ejecta makes their escape difficult. In contrast, because of their higher charge, iron-peaked nuclei are accelerated to the highest energies at later times, when the envelope has become thin enough to allow their escape. Due to the production of secondary nucleons, the envelope crossing leads to a transition of composition from light to heavy elements at a few EeV, as observed by the Auger Observatory [11]. The escape also results in a softer spectral slope than that initially injected via unipolar induction, which allows a good fit to the observed UHECR spectrum.

The source of UHECRs in our model are the rare, extremely fast spinning, young pulsars. The majority of pulsars were born spinning slower and therefore contribute to the flux of lower energy cosmic rays. The total cosmic ray spectrum contributed by the entire pulsar population, taking into account the propagation in the intergalactic medium, can give good fits to the Auger and TA data. To fit the Auger spectrum a balanced ratio between Hydrogen and CNO, with a minor presence of Iron suffices, while to fit the TA spectrum a higher percentage of Iron is needed. Determining the absolute energy scale is thus an important goal for current observatories, as it would help select between possible explanations for the origin of UHECRs.

The composition mixture chosen to fit the Auger spectrum, gives a very good fit to the average shower maximum ($\langle X_{\max} \rangle$) and the fluctuations around the mean

(RMS($X_{\max}$)) observed by Auger. This is a unique aspect of the pulsar model as most models of astrophysical accelerators of UHECRs do not explain these shower maximum data. This challenge has led to the notion that the change in $\langle X_{\max}\rangle$ and RMS($X_{\max}$) is due to new physics in hadronic interactions at these energies, which are well above those reached by the Large Hadron Collider.

Another aspect of this model worth highlighting is the connection between parameters needed to fit the extragalactic component and the presence of a Galactic component from Galactic pulsar births in the very high energy range (between 10^{16} and 10^{18} eV). This Galactic pulsar population could bridge the gap between the supernova remnant contribution and the extragalactic component starting from the ankle energy.

In Ref. [45], we showed that this pulsar scenario for UHECRs is testable in the coming years with IceCube. We calculated that this same pulsar population should produce a diffusive neutrino flux that lies sensibly above the IceCube-5 years sensitivity in the 10^{18} eV energy range, and is below the current IceCube sensitivity. Even in the most pessimistic case, one expects a minimum flux of neutrinos, detectable with IceCube within a decade. This conclusion stands for any pulsar scenario that explains the UHECR data, regardless of the uncertainties on UHECR production.

While they spin down, pulsars release their rotational energy in the form of a relativistic magnetized wind. [46, 47] discussed that magnetars could deposit their rotational energy into the surrounding supernova ejecta in a few days. This mechanism would brighten considerably the supernova, making them appear ultra-luminous. The potential candidate sources for UHECRs that we described above and in [20] are millisecond rotators at birth, and are mildly magnetized ($B \sim 10^{12-13}\,$G). Higher magnetization would imply indeed a fast spin-down, and hence that lower energy particles be produced when the supernova ejecta has become diluted enough to allow their escape. Such objects are expected to inject their equally tremendous rotational energy in the supernovae ejectas, but over longer times (of order of a few years).

In Ref. [48], we have estimated the thermal and non thermal radiations expected from these specific objects, concentrating at times a few years after the onset of the explosion. We find that the bolometric light curves present a high luminosity plateau (that can reach $10^{43-44}\,$erg/s) over a few years. An equally bright TeV gamma-ray emission, and a milder X-ray peak (of order $10^{40-42}\,$erg/s) could also appear a few months to a few years after the explosion, as the pulsar wind nebula emerges, depending on the injection parameters. The observations of these signatures by following the emission of a large number of supernovae could have important implications for the understanding of core-collapse supernovae and reveal the nature of the remnant compact object.

6 Secondary messengers

Secondary neutrinos and photons can be produced by UHECRs when they interact with ambient baryonic matter and radiation fields inside the source or during their propagation from source to Earth. These particles travel in geodesics unaffected by magnetic fields and bear valuable information of the birthplace of their progenitors. The quest for sources of UHECRs has thus long been associated with the detection of neutrinos and gamma rays that might pinpoint the position of the accelerators in the sky.

The detection of these particles is not straightforward however: first, the propagation of gamma rays with energy exceeding several TeV is affected by their interaction with CMB and radio photons. These interactions lead to the production of high energy electron and positron pairs which in turn up-scatter CMB or radio photons by inverse Compton processes, initiating electromagnetic cascades. As a consequence, one does not expect to observe gamma rays of energy above ~ 100 TeV from sources located beyond a horizon of a few Mpc [49, 50, 51]. Above EeV energies, photons can again propagate over large distances, depending on the radio background, and can reach observable levels around tens of EeV [52]. Secondary neutrinos are very useful because, unlike cosmic-rays and photons, they are not absorbed by the cosmic backgrounds while propagating through the Universe. In particular, they give a unique access to observing sources at PeV energies. However, their small interaction cross-section makes it difficult to detect them on the Earth requiring the construction of km^3 detectors (see, e.g., [53]).

Secondary neutrinos and gamma-rays generated at UHECR sources and from interactions during the propagation have been investigated by a number of authors who predict promising detections with instruments such as IceCube and Fermi for proton dominated compositions (see refs. in [1], and in [54]).

It should be highlighted that due to the delay induced by EGMF on charged cosmic rays, secondary neutrinos, photons, and gravitational waves should not be detected in time coincidence with UHECRs if the sources are not continuously emitting particles, but are transient such as GRBs and young pulsars.

Most recently, the IceCube experiment has reported the detection of two PeV neutrinos. A follow-up analysis by the IceCube collaboration uncovered 26 additional sub-PeV neutrinos, and the collaboration published the corresponding sky map and energy spectrum. This result marks the birth of neutrino astronomy, and will have important implications for the understanding of the origin of PeV-EeV cosmic rays.

7 Conclusion

The most direct route to solving at last the mystery of the origins of UHECRs would be a precise measurement of the three pillars of UHECR observations: spectrum, anisotropies, and composition, for example with Auger North or JEM-EUSO. The precise shape and energy scale of the ankle and the cutoff are excellent selectors of models. More discriminating, but much harder to plan for success, is a clear observation of anisotropies. A nearby source, the first UHECR source, will clearly be a watershed in the field. A clear correlation with the large scale structure within 200 Mpc will also clear the path to zeroing in at the possible accelerators. The most difficult but key observable of the three pillars is a clear composition measurement. The dependence on hadronic models to translate shower properties into composition measurements make it difficult to reach clear conclusions. Progress on enlarging the range of cosmic ray measurements to higher energies from the knee (Kascade-Grande) and to lower energies from the ankle (Auger HEAT and AMIGA, and TALE) will help construct a unified model of the cosmic ray properties in a region that hadronic models can be tested at the LHC. Finally, observations of photons and neutrinos at ultrahigh energies will also be extremely useful in distinguishing proposed scenarios (e.g., by IceCube, Auger, JEM-EUSO, and ANITA).

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