SOME CURRENT THEORETICAL ISSUES AROUND ULTRA-HIGH ENERGY COSMIC RAYS*

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We address some current theoretical issues around ultra-high energy cosmic rays. We recall that scenarios producing more γ-rays than cosmic rays up to high redshift can in general only provide a sub-dominant contribution to the ultra-high energy cosmic ray flux. This includes extragalactic top-down and the Z-burst scenarios. Finally we discuss the influence of large scale cosmic magnetic fields on ultra-high energy cosmic ray propagation which is currently hard to quantify. The views presented here represent the authors perspective.

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1. Introduction

High energy cosmic ray (CR) particles are shielded by Earth's atmosphere and reveal their existence on the ground only by indirect effects such as ionization and showers of secondary charged particles covering areas up to many km^2 for the highest energy particles. In fact, in 1912 Victor Hess discovered CRs by measuring ionization from a balloon [1], and in 1938 Pierre Auger proved the existence of extensive air showers (EAS) caused by primary particles with energies above 10^{15} eV by simultaneously observing the arrival of secondary particles in Geiger counters many meters apart [2].

After almost 90 years of research, the origin of cosmic rays is still an open question, with a degree of uncertainty increasing with energy [3]: Only below 100 MeV kinetic energy, where the solar wind shields protons coming

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from outside the solar system, the sun must give rise to the observed proton flux. Above that energy the CR spectrum exhibits little structure and is approximated by broken power laws $\propto E^{-\gamma}$: At the energy $E \simeq 4 \times 10^{15}$ eV called the "knee", the flux of particles per area, time, solid angle, and energy steepens from a power law index $\gamma \simeq 2.7$ to one of index $\simeq 3.0$. The bulk of the CRs up to at least that energy is believed to originate within the Milky Way Galaxy, typically by shock acceleration in supernova remnants. The spectrum continues with a further steepening to $\gamma \simeq 3.3$ at $E \simeq 4 \times 10^{17}$ eV, sometimes called the "second knee". There are experimental indications that the chemical composition changes from light, mostly protons, at the knee to domination by iron and even heavier nuclei at the second knee [4]. This is in fact expected in any scenario where acceleration and propagation is due to magnetic fields whose effects only depend on rigidity, the ratio of charge to rest mass, Z/A. This is true as long as energy losses and interaction effects, which in general depend on Z and A separately, are small, as is the case in the Galaxy, in contrast to extra-galactic cosmic ray propagation at ultra-high energy. Above the so called "ankle" or "dip" at $E \simeq 5 \times 10^{18}$ eV, the spectrum flattens again to a power law of index $\gamma \simeq 2.8$. This latter feature is often interpreted as a cross over from a steeper Galactic component, which above the ankle cannot be confined by the Galactic magnetic field, to a harder component of extragalactic origin. The dip at $E \simeq 5 \times 10^{18}$ eV could also be partially due to pair production by extra-galactic protons, especially if the extra-galactic component already starts to dominate below the ankle, for example, around the second-knee [5]. This latter possibility appears, however, less likely in light of a rather heavy composition up to the ankle suggested by several experiments [4]. In any case, an eventual cross over to an extra-galactic component is also in line with experimental indications for a chemical composition becoming again lighter above the ankle, although a significant heavy component is not excluded and the inferred chemical composition above $\sim 10^{18}$ eV is sensitive to the model of air shower interactions and consequently uncertain presently [6]. In the following we will restrict our discussion on ultra-high energy cosmic rays (UHECRs) above the ankle.

Although statistically meaningful information about the UHECR energy spectrum and arrival direction distribution has been accumulated, no conclusive picture for the nature and distribution of the sources emerges naturally from the data. There is on the one hand the approximate isotropic arrival direction distribution [8] which indicates that we are observing a large number of weak or distant sources. On the other hand, there are also indications which point more towards a small number of local and therefore bright sources, especially at the highest energies: First, the AGASA ground array claims statistically significant multi-plets of events from the same directions within a few degrees [7,8], although this is controversial [9] and has not been seen so far by the fluorescence experiment HiRes [10]. The spectrum of this clustered component is $\propto E^{-1.8}$ and thus much harder than the total spectrum [7]. Second, nucleons above $\simeq 70\,\mathrm{EeV}$ suffer heavy energy losses due to photo-pion production on the cosmic microwave background — the Greisen–Zatsepin–Kuzmin (GZK) effect [11] — which limits the distance to possible sources to less than $\simeq 100\,\mathrm{Mpc}$ [12]. For a uniform source distribution this would predict a "GZK cutoff", a drop in the spectrum. However, the existence of this "cutoff" is not established yet from the observations [13] and may even depend on the part of the sky one is looking at: The "cutoff' could be mitigated in the northern hemisphere where more nearby accelerators related to the local supercluster can be expected. Apart from the SUGAR array which was active from 1968 until 1979 in Australia, all UHECR detectors completed up to the present were situated in the northern hemisphere. Nevertheless the situation is unclear even there: Whereas a cut-off seems consistent with the few events above 10^{20} eV recorded by the fluorescence detector HiRes [14], it is not compatible with the 8 events above 10^{20} eV measured by the AGASA ground array [15]. It can be remarked, however, that analysis of data based on a single fluorescence telescope, the so-called monocular mode in which most of the HiRes data were obtained, is complicated due to atmospheric conditions varying from event to event [16]. The solution of this problem may have to await more analysis and, in particular, the completion of the Pierre Auger project [17] which will combine the two complementary detection techniques adopted by the aforementioned experiments and whose southern site is currently in construction in Argentina.

This currently unclear experimental situation could have easily been solved if it was possible to follow the UHECR trajectories backwards to their sources. However, this may be complicated by the possible presence of extragalactic magnetic fields, which would deflect the particles during their travel. Furthermore, since the GZK-energy losses are of stochastic nature, even a detailed knowledge of the extragalactic magnetic fields would not necessarily allow to follow a UHECR trajectory backwards to its source since the energy and therefor the Larmor radius of the particles have changed in an unknown way. Therefore it is not clear if charged particle astronomy with UHECRs is possible in principle or not. And even if possible, it remains unclear to which degree the angular resolution would be limited by magnetic deflection. This topic will be discussed in Sect. 3.

The physics and astrophysics of UHECRs are also intimately linked with the emerging field of neutrino astronomy (for reviews see Refs. [18]) as well as with the already established field of γ-ray astronomy (for reviews see, *e.g.*, Ref. [19]). Indeed, all scenarios of UHECR origin, including the top-down models, are severely constrained by neutrino and γ-ray observations and limits. In turn, this linkage has important consequences for theoretical predictions of fluxes of extragalactic neutrinos above about a TeV whose detection is a major goal of next-generation neutrino telescopes: If these neutrinos are produced as secondaries of protons accelerated in astrophysical sources and if these protons are not absorbed in the sources, but rather contribute to the UHECR flux observed, then the energy content in the neutrino flux cannot be higher than the one in UHECRs, leading to the so called Waxman–Bahcall bound for transparent sources with soft acceleration spectra [20, 21]. If one of these assumptions does not apply, such as for acceleration sources with injection spectra harder than E^{-2} and/or opaque to nucleons, or in the top-down scenarios where X particle decays produce much fewer nucleons than γ-rays and neutrinos, the Waxman–Bahcall bound does not apply, but the neutrino flux is still constrained by the observed diffuse γ-ray flux in the GeV range. This will be discussed in the following section.

2. Severe constraints on scenarios producing more photons than hadrons

Electromagnetic (EM) energy injected above the threshold for pair production on the cosmic microwave background (CMB) at $\sim 10^{15}/(1+z)\,\mathrm{eV}$ at redshift z (to a lesser extent also on the infrared/optical background, with lower threshold) leads to an EM cascade, an interplay between pair production followed by inverse Compton scattering of the produced electrons. This cascade continues until the photons fall below the pair production threshold at which point the Universe becomes transparent for them. In todays Universe this happens within just a few Mpc for injection up to the highest energies above 10^{20} eV. All EM energy injected above $\sim 10^{15}$ eV and at distances beyond a few Mpc today is therefore recycled to lower energies where it gives rise to a characteristic cascade spectrum $\propto E^{-2.1}$ down to fractions of a GeV [22]. The Universe thus acts as a calorimeter where the total EM energy injected above $\sim 10^{15}/(1+z)\,\mathrm{eV}$ is measured as a diffuse isotropic γ-ray flux in the GeV regime. This diffuse flux is not very sensitive to the somewhat uncertain infrared/optical background [23]. Any observed diffuse γ-ray background acts as an upper limit on the total EM injection. Since in any scenario involving pion production the EM energy fluency is comparable to the neutrino energy fluency, the constraint on EM energy injection also constrains allowed neutrino fluxes.

This diffuse extragalactic GeV γ-ray background can be extracted from the total γ-ray flux measured by EGRET by subtracting the Galactic contribution. Since publication of the original EGRET limit in 1995 [24], models for this high latitude Galactic γ-ray foreground were improved significantly. This allowed the authors of Ref. [25] to reanalyze limits on the diffuse extragalactic background in the region 30 MeV–10 GeV and to lower it by a factor 1.5–1.8 in the region around 1 GeV. There are even lower estimates of the extragalactic diffuse γ-ray flux [26]. In this article, however, we will use the more conservative limits from Ref. [25].

The energy in the extra-galactic γ-ray background estimated in Ref. [25] is slightly more than one hundred times the energy in UHECR above the GZK cutoff. The range of such trans-GZK cosmic rays is about $\simeq 30\,\mathrm{Mpc}$, roughly one hundredth the Hubble radius, and only sources within that GZK range contribute to the trans-GZK cosmic rays. Therefore, any mechanism involving sources distributed roughly uniformly on scales of the GZK energy loss length $\simeq 30\,\mathrm{Mpc}$ and producing a comparable amount of energy in trans-GZK cosmic rays and photons above the pair production threshold can potentially explain this energy flux ratio. The details depend on the exact redshift dependence of source activity and other parameters and in general have to be verified by numerically solving the relevant transport equations, see, *e.g.*, Ref. [27]. Such mechanisms include shock acceleration in powerful objects such as active galactic nuclei [28].

On the other hand, any mechanism producing considerably *more* energy in the EM channel above the pair production threshold than in trans-GZK cosmic rays tend to predict a ratio of the diffuse GeV γ-ray flux to the trans-GZK cosmic ray flux too high to explain both fluxes at the same time. As a consequence, if normalized at or below the observational GeV γ-ray background, such scenarios tend to explain at most a fraction of the observed trans-GZK cosmic ray flux. Such scenarios include particle physics mechanisms involving pion production by quark fragmentation, *e.g.* extragalactic top-down mechanisms where UHECRs are produced by fragmenting quarks resulting from decay of superheavy relics [29]. Most of these quarks would fragment into pions rather than nucleons such that more γ-rays (and neutrinos) than cosmic rays are produced. Overproduction of GeV γ-rays can be avoided by assuming the sources in an extended Galactic halo with a high $\gtrsim 10^3$ overdensity compared to the average cosmological source density, which would also avoid the GZK cutoff [30]. These scenarios, however, start to be constrained by the anisotropy they predict because of the asymmetric position of the Sun in the Galactic halo for which there are no indications in present data [31]. Scenarios based on quark fragmentation also become problematic in view of a possible heavy nucleus component and of upper limits on the photon fraction of the UHECR flux [6].

As a specific example for scenarios involving quark fragmentation, we consider here the case of decaying Z-bosons. In this "Z-burst mechanism" Z-bosons are produced by UHE neutrinos interacting with the relic neutrino background [32]. If the relic neutrinos have a mass m_ν, Z-bosons can be resonantly produced by UHE neutrinos of energy $E_\nu \simeq M_Z^2/(2m_\nu) \simeq$

4.2×10^{21} eV (eV/m_ν). The required neutrino beams could be produced as secondaries of protons accelerated in high-redshift sources. The fluxes predicted in these scenarios have recently been discussed in detail, for example, in Refs. [27,33]. In Fig. 1 we show an optimistic example taken from Ref. [27]. It is assumed that the relic neutrino background has no significant local overdensity. Furthermore, the sources are assumed to not emit any γ-rays, otherwise the Z-burst model with acceleration sources overproduces the diffuse GeV γ-ray background [43]. We note that no known astrophysical accelerator exists that meets the requirements of the Z-burst model [43,44].

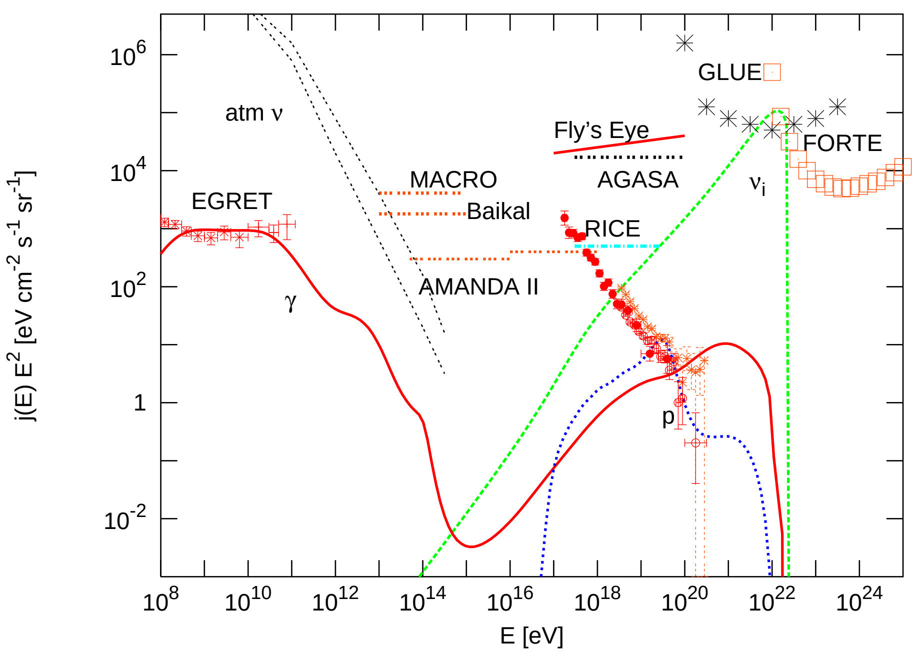

Fig. 1. Flux predictions for a Z-burst model averaged over flavors and characterized by a neutrino injection flux per comoving volume $\propto E^{-1}$ up to 3×10^{22} eV and for redshifts between 0 and 3. The sources are assumed to be exclusive neutrino emitters. All neutrino masses were assumed equal with $m_\nu = 0.33$ eV and we again assumed maximal mixing between all flavors. Also shown are predicted and observed cosmic ray and γ-ray fluxes, the atmospheric neutrino flux [34], as well as existing upper limits on the diffuse neutrino fluxes from MACRO [35], AMANDA II [36], BAIKAL [37], AGASA [38], the Fly's Eye [39] and RICE [40] experiments, and the limits obtained with the Goldstone radio telescope (GLUE) [41] and the FORTE satellite [42], as indicated. The cosmic ray data are from the AGASA [15] and HiRes [14] experiments, and the new EGRET estimate of the extra-galactic diffuse γ-ray flux is shown to the left. From Ref. [27].

However, a combination of new constraints allows to rule out that the Z-burst mechanism explains a dominant fraction of the observed UHECR flux, even for pure neutrino emitting sources: A combination of cosmological data including the WMAP experiment limit the sum of the masses of active neutrinos to $\lesssim 1\,\text{eV}$ [45]. Solar and atmospheric neutrino oscillations indicate that individual neutrino masses are nearly degenerate on this scale [46], and thus the neutrino mass per flavor must satisfy $m_\nu \lesssim 0.33$ eV. However, for such masses phase space constraints limit the possible over-density of neutrinos in our Local Group of galaxies to $\lesssim 10$ on a length scale of $\sim$ 1Mpc [47]. Since this is considerably smaller than the relevant UHECR loss lengths, neutrino clustering will not significantly reduce the necessary UHE neutrino flux compared to the case of no clustering. For the maximal possible value of the neutrino mass $m_\nu \simeq 0.33\,\text{eV}$, the neutrino flux required for the Z-burst mechanism to explain the UHECR flux is only in marginal conflict with the FORTE upper limit [42], and factor 2 higher than the new GLUE limit [41], as shown in Fig. 1. For all other cases the conflict with both the GLUE and FORTE limits is considerably more severe. Also note that this argument does not depend on the shape of the low energy tail of the primary neutrino spectrum which could thus be even mono-energetic, as could occur in exclusive tree level decays of superheavy particles into neutrinos [48]. However, in addition this possibility has been ruled out by overproduction of GeV γ-rays due to loop effects in these particle decays [49].

The possibility that the observed UHECR flux is explained by the Z-burst scenario involving normal astrophysical sources, which produce both neutrinos and photons by pion production, is already ruled out by the former EGRET limit: In this case the GeV γ-ray flux level would have roughly had the height of the peak of the neutrino flux multiplied by the squared energy in Fig. 1, thus a factor ~ 100 higher than the EGRET level.

Any further reduction in the estimated contribution of the true diffuse extra-galactic γ-ray background to the observed flux, therefore, leads to more severe constraints on the total EM injection. For example, future γ-ray detectors such as GLAST [50] will test whether the diffuse extragalactic GeV γ-ray background is truly diffuse or partly consists of discrete sources that could not be resolved by EGRET. Astrophysical discrete contributions such as from intergalactic shocks are in fact expected [51]. This could further improve the cascade limit to the point where even acceleration scenarios may become seriously constrained.

3. Cosmic magnetic fields and their influence on ultra-high energy cosmic ray propagation

Cosmic magnetic fields are inextricably linked with cosmic rays in several respects. First, they play a central role in Fermi shock acceleration. Second, large scale extra-galactic magnetic fields (EGMF) can cause significant deflection of charged cosmic rays during propagation and thus obviously complicate the relation between observed UHECR distributions and their sources.

Magnetic fields are omnipresent in the Universe, but their true origin is still unclear [52]. Magnetic fields in galaxies are observed with typical strengths of a few micro Gauss, but there are also some indications for fields correlated with larger structures such as galaxy clusters [53]. Magnetic fields as strong as $\simeq 1\mu$ G in sheets and filaments of the large scale galaxy distribution, such as in our Local Supercluster, are compatible with existing upper limits on Faraday rotation [53–55]. It is also possible that fossil cocoons of former radio galaxies, so called radio ghosts, contribute significantly to the isotropization of UHECR arrival directions [56].

To get an impression of typical deflection angles one can characterize the EGMF by its r.m.s. strength B and a coherence length $l_{\rm c}$. If we neglect energy loss processes for the moment, then the r.m.s. deflection angle over a distance $r \gtrsim l_{\rm c}$ in such a field is $\theta(E,r) \simeq (2rl_{\rm c}/9)^{1/2}/r_{\rm L}$ [57], where the Larmor radius of a particle of charge Ze and energy E is $r_{\rm L} \simeq E/(ZeB)$. In numbers this reads

$$\theta(E,r) \simeq 0.8^\circ\, Z \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{r}{10\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{l_{\rm c}}{1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\,\mathrm{G}}\right), \quad (1)$$

for $r \gtrsim l_{\rm c}$. This expression makes it immediately obvious that fields of fractions of micro Gauss lead to strong deflection even at the highest energies. This goes along with a time delay $\tau(E,r) \simeq r\theta(E,d)^2/4 \simeq 1.5 \times 10^3\, Z^2 (E/10^{20}\,\mathrm{eV})^{-2} (r/10\,\mathrm{Mpc})^2 (l_{\rm c}/\mathrm{Mpc}) (B/10^{-9}\,\mathrm{G})^2$ yr which can be millions of years. A source visible in UHECRs today could therefore be optically invisible since many models involving, for example, active galaxies as UHECR accelerators, predict variability on shorter time scales.

Quite a few simulations of the effect of extragalactic magnetic fields (EGMF) on UHECRs exist in literature, but usually idealizing assumptions concerning properties and distributions of sources or EGMF or both are made: In Refs. [58–62] sources and EGMF follow a pancake profile mimicking the local supergalactic plane. In other studies EGMF have been approximated in a number of fashions: as negligible [63, 64], as stochastic with uniform statistical properties [65–67], or as organized in spatial cells with a given coherence length and a strength depending as a power law on the local density [68]. Only recently attempts have been made to simulate

UHECR propagation in a realistically structured Universe [69, 70]. For now, these simulations are limited to nucleons.

In Ref. [69] the magnetized extragalactic environment used for UHECR propagation is produced by a simulation of the large scale structure of the Universe. The simulation was carried out within a computational box of $50\,h^{-1}$ Mpc length on a side, with normalized Hubble constant $h \equiv H_0/(100$ km s^{-1} Mpc$^{-1}) = 0.67$, and using a comoving grid of 512^3 zones and 256^3 dark matter particles. The EGMF was initialized to zero at simulation start and subsequently its seeds were generated at cosmic shocks through the Biermann battery mechanism [71]. Since cosmic shocks form primarily around collapsing structures including filaments, the above approach avoids generating EGMF in cosmic voids.

In Ref. [70] constrained simulations of the local large scale structure were performed and the magnetic smoothed particle hydrodynamics technique was used to follow EGMF evolution. The EGMF was seeded by a uniform seed field of maximal strength compatible with observed rotation measures in galaxy clusters.

The questions considered in these two works were somewhat different, however. In Ref. [70] deflections of UHECR above 4×10^{19} eV were computed as a function of the direction to their source which were assumed to be at cosmological distances. This made sense, because *(i)* the constrained simulations give a viable model of our local cosmic neighborhood within about 100 Mpc, at least on scales beyond a few Mpc and *(ii)* the deflections typically were found to be smaller than a few degrees. Concrete source distributions were not considered.

In contrast, Ref. [69] was not concerned with concrete sky distributions or deflection maps because the simulation was unconstrained and thus only gave a typical large scale structure model and not our concrete local neighborhood. Instead, the question was asked which observer positions and source distributions and characteristics lead to UHECR distributions whose spherical multi-poles for $l \leq 10$ and auto-correlation at angles $\theta \lesssim 20^\circ$ are consistent with observations. As a result it was found that *(i)* the observed large scale UHECR isotropy requires the neighborhood within a few Mpc of the observer is characterized by weak magnetic fields below $0.1\,\mu$G, and *(ii)* once that choice is made, current data do not strongly discriminate between uniform and structured source distributions and between negligible and considerable deflection. Nevertheless, current data moderately favor a scenario in which *(iii)* UHECR sources have a density $n_s \sim 10^{-5}$ Mpc^{-3} and follow the matter distribution and *(iv)* magnetic fields are relatively pervasive within the large scale structure, including filaments, and with a strength of the order of μG in galaxy clusters. A two-dimensional cut through the baryonic density and EGMF environment of the observer in a typical such scenario is shown in Fig. 2.

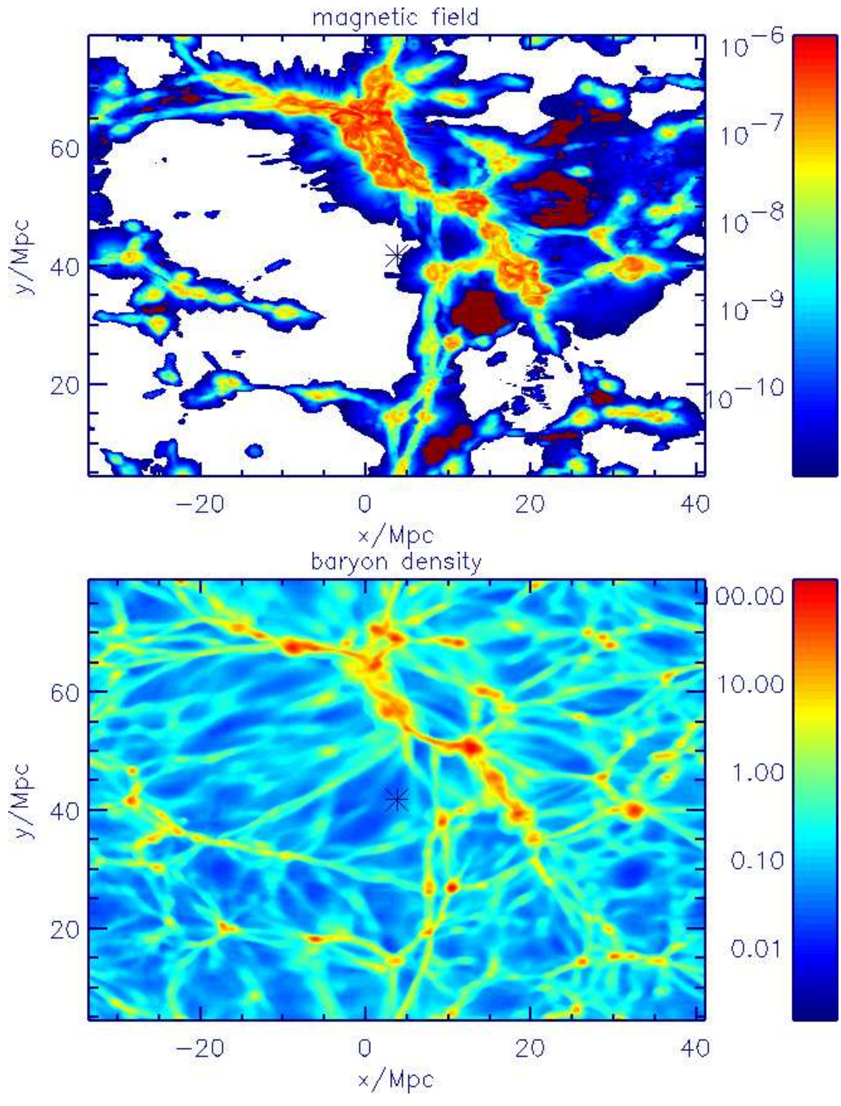

Fig. 2. Log-scale two-dimensional cut through magnetic field total strength in Gauss (color scale in Gauss, upper panel) and baryon density in units of average baryon density (color scale, lower panel), for a scenario in good agreement with UHECR data studied in Ref. [69]. The observer is in the center of the figures and is marked by a star. The EGMF strength at the observer is $\simeq 10^{-11}$ G. Note that both panels correspond to the same cuts through the full large scale simulation box used.

It was also studied in Ref. [69] how future data of considerably increased statistics can be used to learn more about EGMF and source characteristics. In particular, low auto-correlations at degree scales imply magnetized sources quite independent of other source characteristics such as their density. The latter can only be estimated from the auto-correlations halfway reliably if magnetic fields have negligible impact on propagation. This is because if sources are immersed in considerable magnetic fields, their images are smeared out, which also smears out the auto-correlation function over several degrees. For a sufficiently high source density, individual images can thus overlap and sensitivity to source density is consequently lost. The statistics expected from next generation experiments such as Pierre Auger [17] and EUSO [72] should be sufficient to test source magnetization by the auto-correlation function [69].

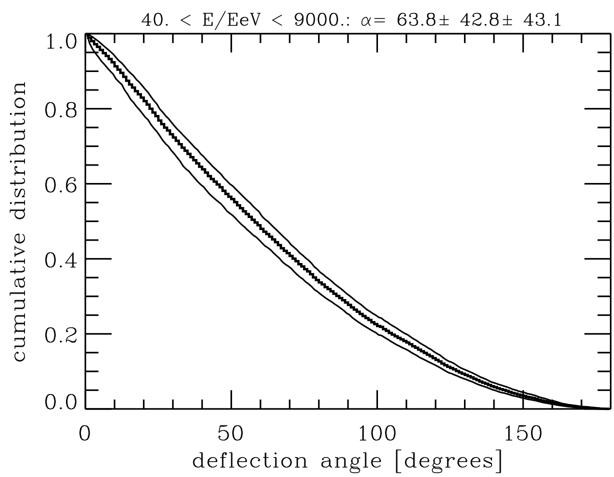

Fig. 3. The cumulative distribution of minimal UHECR deflection angles α with respect to the line of sight to the sources. This is for a scenario from Ref. [69] in good agreement with UHECR data, where the sources follow the baryon density and have average density $n_s = 2.4 \times 10^{-5}\,\mathrm{Mpc}^{-3}$, and the EGMF included in the large scale structure simulation reaches several micro Gauss in the most prominent galaxy cluster. Shown are the average (middle, histogram) and 1-σ variations (upper and lower curves) above $4 \times 10^{19}\,\mathrm{eV}$, over 24 realizations varying in the positions and luminosities Q_i of individual sources, the latter assumed to be distributed as $dn_s/dQ_i \propto Q_i^{-2.2}$ with $1 \leq Q_i \leq 100$ in arbitrary units. Also given on top of the figure are average and variances of the distributions.

Interestingly, however, there is a considerable quantifiable difference in the typical deflection angles predicted by the two EGMF scenarios in Refs. [69, 70] that *cannot* be compensated by specific source distributions:

Even for homogeneous source distributions, the average deflection angle for UHECRs above 4×10^{19} eV obtained in Ref. [69] is much larger than in Ref. [70], as can be seen in Fig. 3. In fact, even if the magnetic field strength is reduced by a factor 10 in the simulations of Ref. [69], the average deflection angle above 4×10^{19} eV is still $\sim 30°$, only a factor $\simeq 2.2$ smaller. This non-linear behavior of deflection with field normalization is mostly due to the strongly non-homogeneous character of the EGMF.

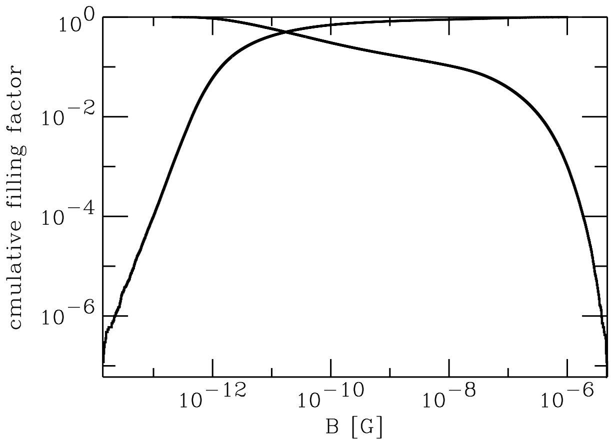

Fig. 4. The cumulative filling factors for EGMF strength in the simulations used in Ref. [69] above (decreasing curve) and below (increasing curve) a given threshold, as a function of that threshold.

Most of these differences are probably due the different numerical models for the magnetic fields. Although Ref. [70] start with uniform seed fields, whereas in Ref. [69] seed fields are injected at shocks, by itself, this difference should not influence the resulting EGMF very much at late times, at least inside galaxy clusters [54]. It should be noted, however, that in the filaments, where the gas motions are more uniform, the simulated magnetic fields may depend to a certain extent on the initial seed fields although that is not trivial to quantify in general terms. In addition, numerical resolution may play an important role because it affects the amplification and the topological structure of the magnetic fields, both of which are important for the normalization procedure, see below. The resolution in Ref. [69] is constant and much better in filaments and voids but worse in the core of galaxy clusters than the (variable) resolution in Ref. [70]. If in both simulations the magnetic fields are normalized to (or reproduce) the same "observed" values in the core of rich clusters then obviously their values in the filaments will be very different for the reasons outlined above. This may partly explain why the contribution of filaments to UHECR deflection is more important in

Ref. [69], although a more detailed analysis and comparison are required to settle the issue. In any case, the magnetic fields obtained in Ref. [69] seem to be quite extended, as can be seen in Fig. 4: About 10% of the volume is filled with fields stronger than 10 nano Gauss, and a fraction of 10^{-3} is filled by fields above a micro Gauss. The different amounts of deflection obtained in the simulations of Refs. [69, 70] show that the distribution of EGMF and their effects on UHECR propagation are currently rather uncertain.

Finally we note that these studies should be extended to include heavy nuclei [73] since there are indications that a fraction as large as 80% of iron nuclei may exist above 10^{19} eV [6]. As a consequence, even in the EGMF scenario of Ref. [70] deflections could be considerable and may not allow particle astronomy along many lines of sight: The distribution of deflection angles in Ref. [70] shows that deflections of protons above 4×10^{19} eV of $\gtrsim 1^\circ$ cover a considerable fraction of the sky. Suppression of deflection along typical lines of sight by small filling factors of deflectors is thus unimportant in this case. The deflection angle of any nucleus at a given energy passing through such areas will therefore be roughly proportional to its charge as long as energy loss lengths are larger than a few tens of Mpc [74]. Deflection angles of $\sim 20^\circ$ at $\sim 4 \times 10^{19}$ eV should thus be the rule for iron nuclei. In contrast to the contribution of our Galaxy to deflection which can be of comparable size but may be corrected for within sufficiently detailed models of the galactic field, the extra-galactic contribution would be stochastic. Statistical methods are therefore likely to be necessary to learn about UHECR source distributions and characteristics. In addition, should a substantial heavy composition be experimentally confirmed up to the highest energies, some sources would have to be surprisingly nearby, within a few Mpc, otherwise only low mass spallation products would survive propagation [75].

The clustered component of the UHECR spectrum may play a key role in this context and may be caused by discrete sources in directions with small deflection. Since, apart from energy losses, cosmic rays of same rigidity Z/A are deflected similarly by cosmic magnetic fields, one may expect that the composition of the clustered component may become heavier with increasing energy. Indeed, in Ref. [76] it was speculated that the AGASA clusters may be consistent with consecutive He, Be–Mg, and Fe bumps.

4. Conclusions

We have reviewed two current issues in theoretical ultra-high energy cosmic ray research.

The first one concerns constraints on scenarios attempting to explain the highest energy cosmic rays by extra-galactic sources producing not only cosmic rays but also photons: Improved data analysis and, in the future, improved data for example from GLAST can considerably reduce estimates of the true extra-galactic GeV γ-ray background which acts as a calorimeter of electromagnetic energy injected above $\sim 10^{15}/(1+z)$ eV. Already current estimates imply that scenarios producing considerably more photons than hadrons, such as extra-galactic top-down scenarios and the Z-burst mechanism, cannot explain all of the highest energy cosmic ray flux. A further reduced diffuse GeV γ-ray background will start to constrain even normal acceleration scenarios.

As for the second issue we pointed out that the influence of large scale cosmic magnetic fields on ultra-high energy cosmic ray propagation is currently hard to quantify and may not allow to do "particle astronomy" along most lines of sight, especially if a significant heavy nucleus component is present above 10^{19} eV. In this case extensive Monte Carlo simulations including nuclei and based on constrained large scale structure simulations will be necessary to fully exploit data from future instruments such as the Pierre Auger [17] and EUSO projects [72].

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