Ultra-high energy cosmic ray propagation in the Universe

Martin Lemoine
Institut d’Astrophysique de Paris, C.N.R.S.,
98 bis boulevard Arago, F-75014 Paris, France

This paper summarizes recent developments in the study of the propagation of ultra-high energy cosmic ray protons or nuclei in the Universe, with emphasis on the consequences of energy losses and on the influence of extra-galactic magnetic fields.

1 Introduction

Despite some forty years of intensive research, the origin and nature of the highest energy cosmic rays ($E \sim 10^{20}$ eV) remains elusive (see Ref. [1] for a review). On the experimental side, the matter is clearly one of statistics: with a flux as low as $\sim 1/{\text{km}^2/\text{century}}$, only a handful of events with $E \sim 10^{20}$eV have been gathered. On the theoretical side, it appears notoriously difficult for known astrophysical objects to produce particles of that energy. It is furthermore problematic to explain how such particles could reach the detectors with energy $E \sim 10^{20}$ eV, since the energy loss length $\sim 50$ Mpc is very small by cosmological standards. Finally, there is no observed counterpart in the arrival direction of these ultra-high energy cosmic rays (UHECRs).

In the last decade, it has become apparent that propagation effects could play a key rôle in the solution to this riddle. The aim of the present paper is to present the salient features of these effects, with particular emphasis on the influence of energy losses and of extra-galactic magnetic fields. The following discussion assumes that UHECRs are protons or nuclei accelerated in an astrophysical source.

2 What are UHECRs?

Up to a few years ago it was generally admitted that the so-called UHECR component emerged out of the all-particle cosmic ray spectrum at the “ankle”, a feature at $E \sim 10^{19}$ eV where the spectrum index changes from $\approx -3.2$ to $\approx -2.7$, see [1]. A break associated to the flattening
of the spectrum is indeed characteristic of the emergence of a new (harder) component. As protons with \( E \gtrsim 10^{19} \) eV cannot be confined in the Galactic magnetic field, it is assumed that UHECRs are of extra-galactic origin. This interpretation agrees well with the overall isotropicty of reported UHECRs arrival directions. However, if the sources of UHECRs are located at cosmological distances, one would expect to see a high-energy GZK (Greisen-Zatsepin-Kuz'min) cut-off around \( \epsilon_{\text{GZK}} \approx 6 \cdot 10^{19} \) eV as a result of photomeson production of UHE protons on the cosmic microwave background (CMB). A similar cut-off is expected for heavy nuclei due to photodisintegration by the CMB. The small energy loss length implies that sources of particles with observed energy \( 10^{20} \) eV should lie closer than \( \sim 50 \) Mpc. At lower energies, the energy loss length for protons increases to \( \sim 1 \) Gpc due to pair production on the CMB and to \( \sim 4 \) Gpc due to redshift losses when \( E \lesssim 10^{18.5} \) eV.

Present experimental data suggest the presence of some form of cut-off around \( \epsilon_{\text{GZK}} \). However it is not clear at present how pronounced or how mild this cut-off is. As a matter of act, the two experiments with the highest statistics, namely HiRes and AGASA, disagree with one another: while HiRes claims to detect a sharp cut-off at \( E \simeq \epsilon_{\text{GZK}} \), the AGASA experiment has reported a spectrum that extends in a featureless way beyond \( 10^{20} \) eV, down to the experimental sensitivity limit. These two experiments use different techniques for reconstructing the primary energy, and one major objective of the ongoing Pierre Auger Observatory, which will use both techniques simultaneously, will be to resolve this discrepancy and to produce a single coherent spectrum at the highest energies.

In the recent years, an interesting phenomenon has been noted by Berezinsky and collaborators. These authors have shown that pair production losses of UHECR protons emitted by a cosmological population of sources would modify the energy spectrum in such a way as to mimic the ankle. The ankle would no longer mark the emergence of UHECRs out of the all-particle spectrum but rather the signature of sources at cosmological distances! Obviously a cut-off at \( \epsilon_{\text{GZK}} \) is then expected unless another (unspecified) source conspires to produce trans-GZK particles. It seems reasonable to assume that counterparts have not been detected in this case as they are too faint because too far. Nonetheless one may note that intriguing correlations between catalogs of UHECR arrival directions and catalogs of BL Lacertae sources have been reported. The chance of coincidence is as low as \( 10^{-3} \rightarrow 10^{-5} \) depending on the catalogs and cuts chosen, however there is an ongoing debate on the actual significance of these correlations, see Ref.

One may wonder where and how does the UHECR component emerge out of the all-particle spectrum in this scenario. It turns out that it is necessary for the extra-galactic UHECR spectrum to cut off somewhere below \( \sim 10^{18} \) eV, otherwise it would overproduce the all-particle flux; in Ref. a cut-off on the UHECR injection spectrum at this energy was postulated. Interestingly another feature of the all-particle spectrum is seen at this energy, namely the “second knee”, where the differential spectrum steepens. Moreover, results of the HiRes experiment suggest that protons dominate the chemical composition at energies \( E \gtrsim 10^{18} \) eV, and that heavy nuclei dominate below. It is then tempting to believe that the transition between the Galactic and extra-galactic cosmic rays actually occurs around the second knee and not at the ankle, as previously thought.

This scenario thus proposes the following interpretation of the cosmic-ray spectrum. The “first knee” at \( E \sim 2 \cdot 10^{15} \) eV is generally believed to correspond to the steepening of the Galactic proton spectrum, either because of a change of propagation regime or because of a maximal energy limitation at the source. Recent KASCADE data suggest that the region between \( \sim 10^{15} \) eV and \( \sim 10^{17} \) eV is the superposition of the knees of chemical species of increasing mass, with a knee position scaling with the atomic number; the knee for iron group elements, in particular, is expected at \( E \sim 7 \cdot 10^{16} \) eV. Finally the region between this iron knee and the second knee would be the superposition of the iron (heavy) Galactic component and of
the emerging extra-galactic proton component, in agreement with the HiRes measurements of chemical composition. In this economical scenario, there is no need for a third source of cosmic rays to account for the intermediate region between the iron knee and the ankle, which is certainly attractive.

This scenario requires to tune the low-energy cut-off of the extragalactic spectrum to the high energy cut-off of the Galactic component. Recently, it was suggested that the low-energy cut-off might not be a result of injection processes but of propagation effects in extra-magnetic fields. The basic mechanism is that below some critical energy, particles take longer than the age of the Universe to travel from the source to the detector. Hence this latter is actually shielded at low energies by a cosmological magnetic horizon and the spectrum cuts off. In detail, the distance traveled in a Hubble time \( H_0^{-1} \) by particles of energy \( E \) and scattering length \( \lambda \) in extra-galactic magnetic fields is
\[
d \sim \left( \lambda H_0^{-1} \right)^{1/2} \sim 65 \text{ Mpc} \lambda_{\text{Mpc}}^{1/2} (H_0 = 70 \text{ km/s/Mpc}),
\]
with \( \lambda_{\text{Mpc}} \) in units of Mpc. If the typical UHECR source distance is \( \sim 50 \text{ Mpc} \), as suggested by statistical studies of clustering at the highest energies, a low energy cut-off appears for energies such that \( \lambda \ll 1 \text{ Mpc} \) (the scattering length is an increasing function of energy). For continuously emitting sources and a scattering length \( \lambda \propto E^2 \), a value of \( B \sqrt{\ell_c} \sim 2 \cdot 10^{-10} \text{ G-Mpc}^{1/2} \) produces a nice fit of the all-particle cosmic ray spectrum.

It is quite interesting to note that in this scenario, future experiments such as KASCADE-Grande, which will probe the chemical composition and the spectrum around the second knee would also probe the energy scaling of the scattering length, hence the configuration and strength of extra-galactic magnetic fields. This scenario has been revisited recently and results in agreement with those of were obtained. For the range of values of \( B \sqrt{\ell_c} \) which would explain the transition between the Galactic and extra-galactic components, one predicts deflection angles \( \sim O(1^\circ) \) at \( E \sim 10^{20} \text{ eV} \), hence the angular images of point sources could help probe the extra-galactic magnetic field strength, and test this scenario.

3 Large-scale magnetic fields.

The previous discussion has brought in the possible importance of extra-magnetic fields in high energy cosmic ray phenomenology. As a matter of fact, as this section is to show, extra-galactic magnetic fields are at the heart of the enigma of ultra-high energy cosmic rays. With one or two exceptions, all astrophysical models for the origin of UHECRs (i.e., those not invoking new physics) require the existence of widespread magnetic fields to explain the absence of counterparts in the arrival directions of the highest energy events. One main unknown in this area of research remains the strength and configuration of these magnetic fields.

Their existence has been asserted notably by the detection of synchrotron emission bridging two components of a supercluster of galaxies. Whether these fields are patchy, all pervading, and what their amplitude is, remains however unknown; if at equipartition with the ambient supercluster gas, one expects \( B \sim 0.1 \mu \text{G} \). Observations of the Faraday rotation of distant polarized sources have revealed magnetic fields of strength \( \sim \mu \text{G} \) in the heart of clusters of galaxies but yielded only upper limits on the average extra-galactic \( B \sqrt{\ell_c} \). For a homogeneous random magnetic field (meaning that \(|\mathbf{B}|\) is homogeneous, and \( \mathbf{B} \) random), this limit is \( B \sqrt{\ell_c} \lesssim 10^{-8} \text{ G-Mpc}^{1/2} \). Since magnetic fields tend to follow the baryon density, it is reasonable to expect magnetic fields stronger in superclusters and filaments of large scale structure than in voids. In these walls and filaments, the upper limit is \( B \sqrt{\ell_c} \lesssim 10^{-6} \text{ G-Mpc}^{1/2} \).

Theoretical predictions for \( B \) and \( \ell_c \) are not reliable because the origin of the extra-galactic (and even of the Galactic) magnetic field is unknown. Sites proposed range from the inflationary area to reionization to galactic pollution of the intergalactic medium. In the end, one cannot predict reliably the strength, coherence length and distribution of extra-galactic magnetic fields.
to within orders of magnitudes.

Consequently, with regards to ultra-high energy cosmic ray phenomenology, various cases have been considered. The present discussion will consider in turn the two extreme cases: that of “weak” magnetic fields $10^{-12} \, G \cdot \text{Mpc}^{1/2} \ll B \sqrt{\tau_c} \ll 10^{-8} \, G \cdot \text{Mpc}^{1/2}$, and that of “strong” magnetic fields $10^{-8} \, G \cdot \text{Mpc}^{1/2} \lesssim B \sqrt{\tau_c}$. Magnetic fields with strength $B \sqrt{\tau_c} \lesssim 10^{-12} \, G \cdot \text{Mpc}^{1/2}$ are too weak to affect UHECR protons in a significant way.

3.1 “Weak” extra-galactic magnetic fields and bursting sources.

For magnetic fields in the range $10^{-12} \, G \cdot \text{Mpc}^{1/2} \ll B \sqrt{\tau_c} \ll 10^{-8} \, G \cdot \text{Mpc}^{1/2}$, UHECRs with energy close to the GZK cut-off $\epsilon_{\text{GZK}}$ propagate quasi-rectilinearly, performing a random walk with deflection angles $\delta \theta \ll 1$ at each crossing of a cell of coherence of the magnetic field. The total rms deflection angle for a source at distance $d$ read

$$\theta_{\text{rms}} \simeq 2.5^\circ \left( E/10^{20} \text{ eV} \right)^{-1} \left( d/100 \text{ Mpc} \right)^{1/2} \left( B \sqrt{\tau_c}/10^{-9} \, G \cdot \text{Mpc}^{1/2} \right).$$

The associated time delay with respect to straight line propagation can be expressed as:

$$\tau \simeq 1.5 \cdot 10^5 \, \text{yr} \left( E/10^{20} \text{ eV} \right)^{-2} \left( d/100 \text{ Mpc} \right)^2 \left( B \sqrt{\tau_c}/10^{-9} \, G \cdot \text{Mpc}^{1/2} \right)^2.$$

If the time delay is greater than the characteristic timescale on which the source is active, one cannot expect to see a counterpart. A prototypical model is the $\gamma$-ray burst scenario of UHECR origin. There the existence of magnetic fields is also required to reconcile the observed $\gamma$-ray burst rate in the GZK sphere with the detection rate of particles of energy $\sim \epsilon_{\text{GZK}}$. In effect, the former is $\sim 5 \cdot 10^{-4}$ $\gamma$-ray burst per year in a (GZK sphere) volume $(100 \, \text{Mpc})^3$, while the latter is much higher, being $\sim 0.1 - 1$ UHECR with energy $\sim 10^{20} \text{ eV}$ per year. Since particles suffer stochastic energy losses and propagate through stochastic magnetic fields, UHECRs of a given energy arrive at any given point with a finite time spread $\Delta \tau$. Provided this time dispersion is much larger than the time interval between two consecutive $\gamma$-ray bursts in the GZK sphere, the detector registers a “continuous” flux of UHECRs. Assuming that $\Delta \tau \approx \tau$, one finds that $B \sqrt{\tau_c} \gtrsim 3 \cdot 10^{-10} \, G \cdot \text{Mpc}^{1/2}$ suffices to reconcile these rates.

From the point of view of the detector, the $\gamma$-ray burst is seen in a limited band of energy since $\tau \propto E^{-2}$; at a given time one sees only UHECRs of a given energy, others have passed by or are yet to pass. However one should not expect to detect this correlation between arrival time and energy, since the scatter $\Delta \tau$ is expected to be much larger than the lifetime of an experiment. However, the energy width of the signal depends on the ratio $\Delta \tau/\tau$ which in turn depends on the configuration of the magnetic field. Hence there is hope to constrain this latter with the collection of a significant number of UHECR events from a single $\gamma$-ray burst.

3.2 “Strong” localized magnetic fields.

As mentioned previously, extra-galactic magnetic fields of strength $B \sqrt{\tau_c} \gtrsim 10^{-8} \, G \cdot \text{Mpc}^{1/2}$ must be distributed inhomogeneously; they are likely to be enhanced in the regions of high baryon density, i.e. walls and filaments of large-scale structure. It then becomes mandatory to model the configuration of these magnetic fields, which brings in more unknown and unconstrained parameters. Although this area of research has been quite active in the past years, it is probably fair to say that its rich phenomenology has not been explored thoroughly yet. However, a few trends and several main effects have been noted, as discussed below.

One major difference with the case of “weak” magnetic fields is that UHECRs diffuse instead of wandering in a quasi-rectilinear fashion. Hence the spectrum itself is affected by propagation. Not all UHECRs diffuse however: those of the highest energies suffer little angular deflection and quasi-rectilinear propagation remains a good approximation. The critical energy at which this separation of propagation regime occurs can be found
by matching the time of quasi-rectilinear propagation, accounting for the time delay given above, and the diffusive propagation time $\tau_{\text{diff}} = d^2/(4D)$, where $d$ denotes the linear distance to the source and $D$ the diffusion coefficient. This latter is a function of energy that depends on the configuration of the magnetic field. For instance, for Komogorov turbulence $\langle B^2(k) \rangle \propto |k|^{-11/3}$, one finds $D(E) \propto E^{1/3}$ for $r_L \ll l_c$ and $D(E) \propto E^2$ for $r_L \gg l_c$, with $r_L = 1.1 \text{Mpc} \,(E/10^{20} \text{eV})(B/1 \mu \text{G})^{-1}$ the Larmor radius. For this case, one finds that particles with energy $E \ll 5 \cdot 10^{19} \text{eV}$ diffuse if the source lies at linear distance $d \sim 10 \text{Mpc}$ and the magnetic field $B \sqrt{l_c} \sim 0.1 \mu \text{G-Mpc}^{1/2}$. One general trend is that diffusion of sub-GZK energy particles tends to soften the GZK cut-off. In effect diffusion steepens the spectrum at sub-GZK energies since the propagated differential spectrum $j(E) \propto Q(E)/D(E)$ [$Q(E)$ injection spectrum] due to the increased residence time. Hence the fit to the measured flux requires a comparatively harder injection spectrum. Consequently the flux at trans-GZK energies, where the spectrum is unaffected by the magnetic field, is comparatively higher.

An important consequence of the presence of “strong” extra-galactic magnetic fields is the isotropization of the arrival directions for UHECRs regardless of the source distribution. Obviously, this would explain the absence of counterpart to the highest energy events. For instance, a population of sources concentrated in the Local Supercluster, which is seen in the sky as a band of $\sim 10^\circ$ width, could produce an isotropic UHECR sky as seen from Earth (to within present instrumental sensitivity), provided $B \sim 0.1 - 0.3 \mu \text{G}$. Searches for anisotropy remain important, as they might allow to constrain the source distribution and the amount of magnetic bending. In the same models, it has been found that if the distance scale to the sources is $\sim 10 \text{Mpc}$, one could also reproduce the rather hard energy spectrum recorded by AGASA. A larger distance scale would result in a more pronounced GZK cut-off, which depending on the resolution of the HiRes-AGASA discrepancy, might be in better agreement with the data.

Yet another effect is that of magnetic lensing. It has been found that chaotic magnetic fields tend to focus and defocus the trajectories of UHECRs in a process akin to gravitational lensing of light rays. Interestingly, the doublets and triplets of events seen in the same direction by different experiments might be magnetic mirages instead of pointing back to a point-like source. Magnetic lensing is not restricted to strong turbulent magnetic fields, but could also be produced by “weak” magnetic fields and by the Galactic magnetic field in the case of UHECR nuclei. Sophisticated analytical methods borrowed from gravitational lensing studies have been developed to reconstruct the magnetic field from (hopefully future) observations of magnetic lenses.

Previous considerations have assumed that the magnetic field is purely random and the turbulence isotropic. However one cannot exclude the possibility of a coherent component, for instance aligned along the filament or the plane of the supercluster. This case implies energy dependent anisotropy. This can be understood by the fact that transport perpendicular to the coherent magnetic field is inhibited with respect to longitudinal transport. Hence the exact spectrum as seen by the detector depends on the orientation of the intervening magnetic fields.

Several studies have examined the propagation of heavy nuclei in extra-galactic magnetic fields in a first approximation, one finds effects similar to those seen for protons, albeit for a magnetic field strength rescaled by the atomic number.

Some recent studies have considered the possible influence of localized strong magnetic fields on the propagation of UHECRs, notably in clusters of Galaxies. However, the covering factor of clusters of Galaxies is so small that only those UHECRs emitted by sources inside the clusters themselves are likely to be affected. Along similar lines, one should note the studies related to the Galactic magnetic field and its influence on the propagation of UHECRs. In particular, one important aspect is how to deconvolve the effect of the Galactic field from the data in order to recover the extra-galactic signal. The magnitude of the angular deflection suffered
by $10^{20}$ eV protons coming from $b = 0^\circ$ Galactic latitudes is $\sim 5^\circ$, while at higher Galactic latitudes, $b = \pm 45^\circ$, the deflection falls to $\sim 1^\circ$.

Finally, two groups have attempted to obtain definite predictions for the effect of extra-galactic magnetic fields on UHECR propagation by performing ab-initio MHD simulations of large-scale structure formation, scaled to reproduce existing magnetic field data in clusters of galaxies\footnote{41}. The results obtained differ widely between these two groups, however. One group\footnote{11} finds typical deflections $\lesssim 1^\circ$ at $E \sim 4 \cdot 10^{19}$ eV, concluding that UHECRs should point back to the sources. The other group\footnote{10} finds that angular deflection is so large ($\gtrsim 50^\circ$) at the same energy that charged particle astronomy with future experiments should not be possible. The difference stems mostly from the assumptions made on the origin of the magnetic field, and stands as a clear demonstration of how little is known about extra-galactic magnetic fields.

4 Outlook.

Many questions have been raised and left unanswered, and the current theoretical understanding of ultra-high energy cosmic ray phenomenology might appear slightly confused. At which energy does the UHECR component emerge out of the all-particle spectrum? Does the ankle mark this transition? Does it rather say that UHECR sources are located at cosmological distances? What is the effect of extra-galactic magnetic fields on the spectrum and angular images of ultra-high energy cosmic rays? Do the arrival directions of UHECRs point back to the sources?

This apparent confusion actually attests of the wealth and of the maturity of this field of research. One may hope that future large-scale experiments, notably the Pierre Auger Observatory, will answer the above questions and show the way to the source of UHECRs.

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