Propagación de partículas de rayos cósmicos de alta energía ultrahigh

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Abstract. We briefly describe the energy loss processes of ultrahigh-energy protons, heavier nuclei and \( \gamma \)-rays in interactions with the universal photon fields of the Universe. We then discuss the modification of the accelerated cosmic-ray energy spectrum in propagation by the energy loss processes and the charged cosmic-ray scattering in the extragalactic magnetic fields. The energy lost by the ultrahigh-energy cosmic rays goes into \( \gamma \)-rays and neutrinos that carry additional information about the sources of highest energy particles. The new experimental results of the HiRes and the Auger collaborations are discussed in view of the predictions from propagation calculations.

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1. Introduction

The high interest shown by the astrophysical community in ultrahigh energy cosmic rays (UHECR) developed after the Agasa experiment showed their energy spectrum, which continued above $10^{20}$ eV without a break [1] and with no indication of a GZK [2] structure. This is not the first time cosmic rays of such high energy were observed. In 1963, John Linsley [3] reported on the first extensive air shower above $10^{20}$ eV. Three years later, Greisen, and independently Zatsepin and Kuzmin, predicted the end of the cosmic-ray spectrum that results from the interactions of UHECR with microwave background radiation (MBR). Every giant air shower experiment has reported events exceeding $10^{20}$ eV since that time. Because of the very low flux of such particles and the various energy estimates of different experiments, it was impossible to judge whether these highest energy nuclei in the Universe obey the GZK predictions—a sharp decline of the spectrum above $4 \times 10^{19}$ eV—or not. At the time, Agasa was the highest exposure experiment and it claimed a spectrum that is not consistent with the GZK cutoff.

This result was not confirmed by the contemporary leaders in UHECR statistics, the Auger and the HiRes experiments. Both these groups have published UHECR spectra that seem to be consistent with the GZK prediction. There are, however, distinct differences between the results of these two groups that create new challenges for the scientists who are eager to establish in some detail the acceleration and propagation picture of UHECR.

It has been a common suspicion for more than 50 years that the highest energy cosmic rays are of extragalactic origin [4]. The argument is that our Galaxy is not large enough and the galactic magnetic fields are not strong enough to contain particles of such high energy and thus accelerate them. The gyro radius $R_g$ of a $10^{20}$ eV proton in a $3 \mu G$ field is higher than 30 kpc, similar to the dimensions of the whole Galaxy that does not contain shocks of the same dimensions.

If UHECR are indeed of extragalactic origin they should suffer from interactions with the MBR unless their sources are cosmologically very close to us. For this reason, a comparison of the detected UHECR spectrum with theoretical calculations of the particle propagation in extragalactic space should at least point to the distance distribution of their sources and bring us closer to identification of the source. From that point of view, the small differences between the HiRes [5] and Auger [6] spectra lead us to very different interpretations.

Figure 1 shows the published spectra and the rough fits of the observed spectra that are suggested by the two experimental groups. It is obvious that the extremely small statistics around $10^{20}$ eV makes the fit of the strong decline above $10^{19.6}$ eV very difficult. The statistics around $10^{18.5}$ eV, on the other hand, is significant and the different behavior of the spectra is confusing in addition to the different normalizations of the spectra. Another major difference between the two experiments is their estimate of the chemical composition of UHECR studied from the measured depth of the shower maximum $X_{\text{max}}$. HiRes derives a pure proton composition [7], while the Auger analysis tends to reveal a more complex mixed nuclear composition [8]. The UHECR composition at their sources affects the interpretation of the spectra because protons and heavier nuclei have different energy loss mechanisms.

This paper is organized as follows: section 2 discusses the energy loss of different possible primary particles. The next section describes the formation of the UHECR spectrum on propagation and the astrophysical parameters that are important for it. Section 4 focuses on the...
production of secondary particle fluxes in propagation and mainly focuses on the cosmogenic neutrinos. Section 5 contains a brief summary of the current knowledge.

2. UHECR energy loss

Apart from the adiabatic energy loss due to the expansion of the universe, there are two important processes for protons: photoproduction interactions and $e^+e^-$ pair production (BH) interactions identical to the pair production interactions of $\gamma$-rays in the nuclear field. The ‘back of the envelope’ estimate of the photoproduction energy loss goes like this: the average interaction length $\lambda_{ph}$ for interactions with the MBR is the inverse of the product of the interaction cross section $\sigma_{ph}$ and the photon density $n$. For $\sigma_{ph} = 10^{-28}$ cm$^2$ and $n = 400$ cm$^{-3}$, $\lambda_{ph} = 8.3$ Mpc. Since protons lose about 0.2 of their energy in each interaction, it takes about ten interaction lengths to decrease the particle energy by a factor of 10.

The story of the heavier nuclei energy loss is more complicated. In addition to these two processes, heavy nuclei lose energy in photo disintegration (spallation) processes, i.e. when the center-of-mass energy exceeds the giant dipole resonance the nucleus can lose a nucleon. Since less energy is required in the center of mass, the cross section is higher but the energy loss depends on the mass of the nucleus that loses only one or two nucleons. The photoproduction energy loss follows the same energy dependence as for protons but in the Lorentz factor space, i.e. in E/A units. The pair production cross section is a quadratic function of the charge of the nucleus Z.

In the case of exotic theoretical top-down models UHECR are $\gamma$-rays from the decay of very heavy $x$-particles. Although the $\gamma$-ray fraction was strongly limited by the Auger Collaboration to not more than 2% for UHECR above $10^{19}$ eV [9], this possibility cannot be totally excluded. In such a case, the energy loss is due to the $\gamma\gamma \rightarrow e^+e^-$ process.
2.1. Proton energy loss length

A photoproduction interaction is possible when at least one pion is generated in the process. This requires that the center-of-mass energy of the interaction \( \sqrt{s} \) is higher than the sum of a proton mass \( m_p \) and a pion mass \( m_\pi \). In the laboratory system the square of the center of mass energy \( s \) is

\[
s = m_p^2 + 2E_p \epsilon (1 - \cos \theta),
\]

where \( \epsilon \) is the photon energy and \( \theta \) is the angle between the proton and the photon. In a head-on collision \( (\cos \theta = -1) \) with a photon of the average MBR energy \( (6.3 \times 10^{-4} \text{ eV}) \), the minimum proton energy is

\[
E_p = \frac{m_\pi}{4\epsilon} (2m_p + m_\pi) \simeq 10^{20} \text{ eV}.
\]

There are many MBR photons with higher energy and the threshold proton energy is actually lower, about \( 3 \times 10^{19} \) eV.

The cross section for this interaction is very well studied at accelerators where photons interact with stationary protons. The highest cross section is at the mass of the \( \Delta^+ \) resonance (1232 MeV), which decays to either a proton and a neutral pion \( (p\pi^0) \) or a neutron and a positive pion \( (n\pi^+) \). At the peak of the resonance the cross section is about 500 \( \mu \text{b} \). At higher energy the cross section first decreases to about 100 \( \mu \text{b} \) and then increases logarithmically. The neutron interaction cross section is, if not identical, very similar to the proton one.

The MBR spectrum and density are also very well known, so the proton interaction length can be calculated exactly, as shown in the left-hand panel of figure 2 with a dashed line. Since protons lose only a fraction of their energy \( (K_{\text{inel}}) \), another quantity, the energy loss length \( L_{\text{loss}} = -\left(1/E\right)\left(dE/dx\right) \) becomes important. The energy loss length is higher than the interaction length by \( 1/K_{\text{inel}} \), by about a factor of 5 at the threshold. At higher energy, \( K_{\text{inel}} \) grows and this factor is about 2.

In the case of \( e^+e^- \) pair production [10], the addition of two electron masses to the center of mass energy \( \sqrt{s} \) requires a much lower proton energy and the process has a lower threshold. The cross section for pair production is higher than \( \sigma_{\text{ph}} \), but the fractional energy loss is small, of the order of the ratio of the electron to proton mass \( m_e/m_p \). The energy loss length has a minimum around \( 2 \times 10^{19} \) eV and is always longer than 1000 Mpc.

The last proton energy loss process is the redshift due to the expansion of the Universe. The current energy loss length to redshift is the ratio of the velocity of light to the Hubble constant \( (c/H_0) \) and is 4000 Mpc for \( H_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\).

The energy loss of protons in the MBR is shown in the left-hand panel of figure 2. This figure also shows the photoproduction interaction length and the decay length of neutrons. The neutron photoproduction cross section is almost identical to the proton one. This means that neutrons of energy less than \( 4 \times 10^{20} \) will most likely decay and only neutrons of higher energy are likely to have photoproduction interactions.

2.2. Energy loss length of heavier nuclei

The energy loss length of heavier nuclei is shown in the right-hand panel of figure 2 as calculated in [11]. Its minimum value is significantly lower than that of protons but is achieved at higher energy: \( A \times E_p \). It is, of course, not obvious that such a high energy could be achieved at UHECR acceleration, although we always assume that the maximum acceleration energy
is proportional to the charge $Z$ of the nucleus. The effect of propagation on the accelerated UHECR cannot be calculated directly from the energy loss lengths shown in figure 2 because an accelerated nucleus changes its mass after the first photo disintegration interactions. This means that the code that treats propagation of nuclei should be able to calculate the cross sections for all nuclei and isotopes lighter than the injected nucleus. In addition to the cross sections for losing one, two and more nucleons, the codes should evaluate the decay probability for unstable nuclei that may be generated in the propagation.

Many of the cross sections necessary for a correct simulation of the propagation of nuclei have been experimentally studied at accelerators. There is still a need for approximations for some of the numerous processes taking place in the propagation of nuclei. See e.g. the early work on propagation of nuclei [12] that is based on such approximations.

2.3. Energy loss length of $\gamma$-rays

The process has $\gamma\gamma \rightarrow e^+e^-$ as a resonant character, and the cross-section peaks at $E_\gamma \epsilon = 2m_e^2$, where $\epsilon$ is the energy of the seed photons. For the average energy of MBR this corresponds to an $E_\gamma$ of $8 \times 10^{14}$ eV and the mean free path decreases with an increase in $E_\gamma$. For $\gamma$-rays of energy $10^{20}$ eV, the relevant seed photon frequency is about 1 MHz—in the radio band. This creates a big uncertainty in the estimates of the UHE $\gamma$-ray energy loss length because the density of the radio background at such frequencies is not known. One can relate the radio emission of various astrophysical objects to the much better known infrared emission and generate models to calculate the energy loss length. The results of such a modeling are energy loss lengths of the order of that of protons.

A different source of the uncertainty in the $\gamma$-ray propagation is the strength of the extragalactic magnetic fields. If they are negligible the electrons have inverse Compton interactions, whose interaction length is similar to that of the pair production, and generate a
second generation of very high-energy $\gamma$-rays. This cascading can continue for a significant distance without downgrading the $\gamma$-ray energy very much. If, however, the magnetic fields are significant, electrons lose energy very fast on synchrotron radiation. The $\gamma$-ray energy is rapidly transferred to the MeV–GeV energy range. The range of top-down cosmic-ray generation models has been restricted because of overproduction of GeV $\gamma$-rays. The energy loss distance of synchrotron radiation is $2.6E_{18}^{-1}B_{-9}^{-2}$ Mpc, where $E_{18}$ is the electron energy in units of $10^{18}$ eV and $B_{-9}$ is the strength of the magnetic field in nGauss.

3. Formation of the cosmic-ray energy spectrum after propagation

Predictions of the shape of the cosmic-ray spectrum requires much more than the energy loss in propagation. The necessary astrophysical input, currently unknown, includes at least the following four items:

- UHECR source distribution
- cosmic-ray source luminosity
- cosmic-ray injection (acceleration) spectrum
- maximum acceleration energy $E_{\text{max}}$
- cosmic-ray chemical composition
- cosmic-ray source cosmological evolution.

The UHECR source distribution was the least known one. This changed after the Auger Collaboration found a correlation of their highest energy events with nearby (redshift $z$ less than 0.018) active galactic nuclei (AGN) [13, 14]. Although there is no certainty that these AGN are indeed the sources of UHECR, this is the first time we have a suggestion for what the source distribution may be.

The other five parameters are not independent of each other. The UHECR source luminosity can, in principle, be determined by the detected UHECR flux above $10^{19}$ eV. In view of the low current statistics, the derived luminosity depends strongly on the assumed injection spectrum and composition and partially on the assumed cosmological evolution of the sources [15]. The source cosmological evolution may be the best known parameter since it should resemble that of other astrophysical phenomena such as the star formation rate in the Universe.

3.1. Formation of the proton spectrum in propagation

As an example we will discuss the formation of the cosmic-ray spectrum in the case that all UHECR are protons. The left-hand panel of figure 3 shows the evolution of monochromatic protons of injection energy $10^{21.5}$ eV after propagation from different redshifts. After propagation on $z = 0.0005$ (approximately 2 Mpc), a large fraction (approximately 60%) of the injected protons have not interacted. Some of them, however, have interacted a couple of times and their energy has decreased by as much as a factor of 10 as such high energy protons lose much more than 20% of their energy in photoproduction interactions. Almost all protons have interacted at $z = 0.0078$ and the average proton energy at this distance is $2 \times 10^{20}$ eV. In further propagation, the energy distribution at arrival becomes narrower as the highly stochastic photoproduction energy loss becomes lower than the almost continuous pair production, and later the adiabatic loss from the expansion of the Universe. The width of the arrival energy
Figure 3. Left-hand panel: arrival energy distribution of $10^{21.5}$ eV protons after propagation from different redshifts that are indicated by the distributions. Right-hand panel: the contribution of different redshifts to the arrival spectrum for the $E^{-2}$ injection spectrum with no cosmological evolution. The thick gray line shows the sum of the contributions from these five redshifts, while the black line is the result of a full integration.

decreases until the pair production energy loss length is smaller than the adiabatic energy loss length.

The right-hand panel of figure 3 shows the contribution to the observed UHE cosmic-ray proton flux from sources located at different low redshifts that inject protons on a $E^{-2}$ spectrum with an exponential cutoff at $10^{21.5}$ eV. One can see how the energy loss increases the contribution to the $2-6 \times 10^{19}$ eV energy range after propagation to $z = 0.1$. In models with cosmological evolution of the sources, the effect is stronger and proportional to the strength of the source evolution.

A simplified assumption for the source distribution is that sources are isotropically and homogeneously distributed in the Universe because we do not inhabit a special part of it, and the contributions of all sources are identical. In such a case, the cosmic-ray flux at the Earth can be determined by an integration of the fluxes from different redshifts shown in the right-hand panel of figure 3 with a black line. In the case of cosmological evolution of the sources, the integral is

$$ N(E) = \int_{E_0}^{E_{\text{max}}} \int_0^z L(z) N_0(E_0) P(E_0, E', z) \frac{dt}{dz} dE' dz, $$

where $L(z)$ is the cosmic-ray source luminosity as a function of redshift and $N_0(E_0)$ reflects the injection spectrum, $P(E_0, E', z)$ is the probability for a proton injected with energy $E_0$ at redshift $z$ to reach us with energy $E'$. The derivative $dt/dz$ depends on the cosmological model and is

$$ \frac{dt}{dz} = \frac{1}{H_0(1 + z)[\Omega_M(1 + z)^3 + \Omega_\Lambda]^{-1/2}} $$

and is simplified to $(1 + z)^{-5/2}/(H_0(1 + z))$ for the Einstein–deSitter Universe.

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It is important to note that the contribution of different redshifts depends not only on the cosmological evolution but also on the injection spectral index as the photoproduction energy loss is a strong function of the injection energy. Since in steep injection spectra a larger fraction of the observed flux comes from lower primary energy (that does not change as much on propagation), the contribution of higher redshifts is larger.

One can see in the right-hand panel of figure 3 that even \( z = 0.05 \) contributes to UHECR above \( 6 \times 10^{19} \text{eV} \), which was observed by Auger to be correlated to AGN within distances of only 71 Mpc \((z \leq 0.017)\). There are several ways to deal with this seeming controversy. One way would be to claim that the energy scale of Auger is not correct and it should be higher by about 25–30%. This would make the contributions of higher redshifts smaller and bring the GZK sphere closer to the expectations for protons.

Another way is to claim that the feature observed by Auger and HiRes is not a result of the GZK process, as the experimental groups claim, and is just the end of the acceleration power of the sources that does not much exceed \( 10^{20} \text{eV} \). The shape of the spectra observed by both experiments (that are shown in figure 1) is, however, very close to what we expect from the GZK cutoff. If one attempts to fit these spectra with the same model, some problems start to show up. The model of Berezinsky et al [16] that has pure proton composition with a steep injection spectrum \((E^{-2.7})\) fits perfectly the HiRes spectrum and does not require other contributions (such as galactic cosmic rays) above \( 10^{18} \text{eV} \). The same model, however, does not appear to fit well the current Auger data.

One can also involve the extragalactic magnetic fields in the explanation. If they are high, the UHECR would scatter often and their real pathlength would be considerably larger than the distance to the sources.

### 3.2. Propagation in magnetic fields

Our knowledge of the extragalactic magnetic fields is quite limited. We do know that they exist and are most likely proportional to the mass density in the Universe, i.e. high in regions of high matter concentration and low in voids. Magnetic fields introduce three main effects. The cosmic-ray scattering increases the propagation pathlength and thus restricts the radius of the possible sources. The scattering creates a deviation of the arrival direction of the UHECR from the direction of the source. The gyro radius of a \( 10^{20} \text{eV} \) proton in a \( 10^{-9} \text{G} \) (nG) field is 100 Mpc.

If the field is random with a correlation length \( \ell \), the deviation angle \( \langle \theta \rangle \) after propagation on distance \( D \) is

\[
\langle \theta \rangle \simeq 2.5^\circ B_{-9} D_{100}^{1/2} \ell_1^{1/2} E_{20}^{-1},
\]

where \( B_{-9} \) is the r.m.s. field strength in nG, \( D_{100} \) is the distance in units of 100 Mpc, \( \ell_1 \) is the correlation length in units of 1 Mpc and \( E_{20} \) is the energy in units of \( 10^{20} \text{eV} \). Protons below \( 10^{20} \text{eV} \) would scatter much more around the direction of the source but the highest energy particles would point at the source with an angle comparable with the experimental resolution. The scattering angles for heavier nuclei are proportional to their charge.

The scattering also introduces a time delay compared with the rectilinear propagation of light. The time delay \( \delta \tau \) has a much stronger dependence on the particle energy, magnetic field strength and propagation distance. For small angle scattering, it is

\[
\delta \tau \simeq 3 \times 10^5 B_{-9}^2 D_{100}^2 \ell_1 E_{20}^{-2} \text{ years}.
\]
If the source of the observed UHECR were an explosive process, such as a $\gamma$-ray burst at a
distance of 100 Mpc, all protons would accelerate at once, but because of the time delay they
would arrive at the Earth in a reverse order of their energy. The highest energy particles would
reach us first, while the lower energy ones would be delayed by millions of years. It is important
to note that the time delay depends on the square of the particle charge. Iron nuclei coming from
10 Mpc will be still delayed seven times more than protons arriving from 100 Mpc.

Time delays could prevent some of the extragalactic protons from reaching us, because
their travel time could exceed the age of the Universe. Particles of energy below $5.5 \times 10^{17}$ eV
from a $\gamma$-ray burst at 100 Mpc, for example, propagating in a 1 nG field will not reach us,
because their time delay will exceed the Hubble time, taken here as $10^{10}$ years for simplicity.

In a simulation that propagated protons in a 1 nG random field [17], we calculated the
proton horizon $R_{50}$, which is the distance at which the $1/e$ fraction of protons maintain at least
one-half of their injection energy. This distance is smaller than the proton energy loss length
even for $10^{20}$ eV protons. The ratio $R_{50}$ to the energy loss length in the 1 nG field is proportional
to $E^{1.2}$ at the approach to $10^{20}$ eV. Using equation (5) one can estimate the additional pathlength
in the 1 nG field for $6 \times 10^{19}$ eV (60 EeV) protons emitted at a distance of 70 Mpc to 66 kpc.
This does not make a huge difference, but remember that in a 10 nG field it would grow to
6.6 Mpc. For iron and the 1 nG field the additional pathlength would increase to 45 Mpc—for a
total pathlength of 115 Mpc.

The numbers quoted above do not include the cosmic-ray energy loss, which contributes
significantly to the low $R_{50}$ values. At 60 EeV, $R_{50}$ is only 35% of the proton energy loss length
and would be less than a Mpc for Fe nuclei.

The magnetic field of our Galaxy is a good example of combinations of organized and
random magnetic fields, which most likely exist on different scales in the Universe. The regular
field $B_{\text{reg}}$ in the Galaxy has a spiral structure of axisymmetric or bisymmetric type resembling
the matter distribution. The local strength of the field is about 1.8 $\mu$G with the direction pointing
inwards approximately along the Orion arm. The strength of the random field is not known
exactly, with estimates between 1/2 and $2B_{\text{reg}}$. The correlation length $\ell$ of the random galactic
fields is of the order of 50–100 pc. More general estimates of the total field strength over the
whole Galaxy give 5–6 $\mu$G [18], and it is possible that a galactic halo field, which does not
contribute much locally, also exists. It is likely that the random field dominates the total field
strength within the galactic arms, while the regular field is dominant in the inter-arm space.

In a 5 $\mu$G galactic field, the gyro radius of a $10^{20}$ eV proton would be 20 kpc. The real
deflection depends on the distance of the proton trajectory from the galactic center and on the
pitch angle of the trajectory to the regular field. The Auger analysis attributes a scattering angle
of about 3° to their events above 60 EeV which often pass relatively close to the galactic center.
This is consistent with the correlation angle with nearby AGN measured by the collaboration.
Events in the HiRes field of view will on average have smaller scattering than those of Auger.

The amount of scattering depends strongly on the exact magnetic field model. Field
models with alternating polarity, such as BSS [19], give the smallest deflections. Models with a $z$
component of the field (perpendicular to the galactic plane, which may be due to a dipole
field) cause the largest deflections.

The possible existence of regular large-scale fields makes the consequences of proton
propagation even more complicated. The following exercise in [22] demonstrates the problems
in the following geometry: a cosmic-ray source at the origin injects isotropically protons above
$10^{18.5}$ eV on a power law spectrum with spectral index of 2 and exponential cutoff at $10^{21.5}$ eV.
The source is in the central $yz$ plane of a 3 Mpc-wide magnetic wall, which is a simplified version of the supergalactic plane (SGP), which is the plane of weight of galaxies within a redshift of 0.04. A magnetic field with a strength of $B_{\text{reg}} = 10 \, \text{nG}$ fills the SGP, points in the $z$-direction and decays exponentially outside the SGP. The regular field is accompanied by a random field with strength $B_{\text{rndm}} = B_{\text{reg}} / 2$.

Under these conditions the protons leaving the 20 Mpc sphere have not only very large deflections, but also modified energy spectra. Protons with trajectories perpendicular to the magnetic field lines exhibit a much flatter spectrum since the lower energy protons are caught up in the magnetic walls. Protons with trajectories parallel to the magnetic field lines have softer spectra that include the particles that could not penetrate the SGP.

In these simple cases one can scale the effects on proton energy as a function of the magnetic field strength. If $B_{\text{reg}}$ were $1 \, \mu\text{G}$, for example, all effects would be the same in a 200 kpc sphere. There are lobes of radio galaxies, including Cen A, that have bigger lobes that may have ordered magnetic fields of that strength and may also cause significant deflections and modifications of the injection spectra depending on the position of the observer.

4. Production of secondary fluxes in propagation

The energy that UHECR lose in propagation ends up in fluxes of $\gamma$-rays and neutrinos from $\pi^0$ and $\pi^\pm$ as well as other charged and neutral meson decays. $\gamma$-rays have even shorter energy loss length than nuclei and develop pair production/inverse Compton cascades where synchrotron radiation may play an important role. In the presence of a noticeable (1 nG) extragalactic field, $10^{18} \, \text{eV}$ electrons quickly lose energy to GeV synchrotron photons.

Neutrinos, however, have a very low interaction cross section and arrive at the Earth with just redshift energy loss from almost any distance. For this reason, the cosmological evolution of the cosmic-ray sources is a very important input in the calculation of these cosmogenic [20, 21] neutrinos.

The left-hand panel of figure 4 shows what fraction of the injection energy of the $E^{-2}$ cosmic ray spectrum above $10^{19}$ is contained in nucleons and secondary particles. After propagation on 200 Mpc, less than 50% of the primary energy content is in nucleons. The rest is distributed between neutrinos, $\gamma$-rays and electron–positron pairs. The largest fraction of the energy loss is in $\gamma$-rays from neutral meson decays. The reason for this is that the $\Delta^+$ decays to $p + \pi^0$ twice as often as it decays to $n + \pi^+$. The muon neutrino flux consists of approximately equal numbers of muon neutrinos and antineutrinos. The electron neutrino flux is mostly electron neutrinos.

The production of cosmogenic particle fluxes depends on the same general astrophysical parameters as the cosmic-ray flux. The main difference is that the cosmological evolution of the cosmic-ray sources is much more important. As we saw above, UHE cosmic-rays arrive only from very small redshifts, where even a very strong cosmological evolution would make a 10% difference, while the cosmogenic neutrinos may easily come from $z = 2$, which would correspond to an increase of an order of magnitude or more.

The infrared background (IRB) is also a target worth considering when the production of cosmogenic neutrinos is discussed. Its number density is a factor of 400 or more less than that of the MBR, but its energy is significantly higher. This means that lower energy nucleons will occasionally interact with IRB photons and generate lower energy neutrinos. Since even in a flat ($\gamma = 1$) injection spectrum there are many more lower energy protons, the contribution

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of interactions in the IRB to the cosmogenic neutrino flux, although of lower energy, may be significant. The contribution of the IRB increases with the steepness of the UHECR spectrum.

Two of the Auger results presented above may have an important connection with the flux of cosmogenic neutrinos—the correlation of the highest Auger events with nearby AGN and the high cosmological evolution required by one of the spectra fit with a relatively flat proton injection spectrum.

The cosmological evolution of different types of astrophysical objects is studied mostly in star forming regions (SFR) by infrared observations or in AGNs from their x-ray emission. The cosmological evolution of SFR is derived as \((1 + z)^3\) on average for up to redshifts close to 2.

It is indeed impossible to judge what is the best proxy for the cosmic-ray source evolution, infrared radiation or x-rays in the 0.5–2 KeV range where most of the statistics is. The conclusions from the x-ray observations are that the evolution of AGN is close to \((1 + z)^5\) [23, 24]. Very powerful AGN have an even stronger evolution but the large number of AGN correlating with the Auger UHECR require the evolution of average ones to be used.

It may be just a coincidence, but the Auger collaboration analysis of the spectrum shown in figure 1 can be best described by two proton models [25]: one with \(\gamma = 1.55\) and no cosmological evolution, and another one with \(\gamma = 1.3\) and cosmological evolution \((1 + z)^5\), the same as that of AGN. The right-hand panel of figure 4 shows the cosmogenic neutrino spectra generated by these two models. The higher energy peak of these energy spectra consists mostly of \(\nu_\mu\), \(\bar{\nu}_\mu\) and \(\nu_e\) from charged meson decays. The peak at about \(10^{15}\) eV consists only of \(\bar{\nu}_e\) from neutron decay. The difference between the two neutrino models is huge, almost two orders of magnitude at the maximum. One can also see the redshift of the maximum in the \(\gamma = 1.3\) model where most of the neutrinos are generated at high redshift. This also shows up in the lower energy \(\bar{\nu}_e\) peak that is enhanced because of the higher number of protons (and, respectively, secondary neutrons) injected at high redshifts. The \(\gamma = 1.55\) model flux will

Figure 4. Left-hand panel: fraction of the energy of the injected proton beam above \(10^{19}\) eV (\(\gamma = 1\) spectrum) in nucleons and secondary particles. Right-hand panel: cosmogenic neutrinos from the two-proton models that fit the Auger cosmic-ray spectrum best. Note that this is only the production in interactions with MBR.
significantly increase if the production in the IRB is included. This would, however, be at lower energy and the detection rate will not change a lot.

The two other models that fit the Auger spectrum are mixed composition ones. If UHECR are heavy nuclei they generate a few cosmogenic neutrinos and only the proton fraction is efficient in producing meson decay neutrinos. Since there are many neutrons that are released in the spallation process, there is a significant flux of $\bar{\nu}_e$ from neutron decay. There are several calculations [26] of the cosmogenic neutrino fluxes from mixed composition models that show this effect.

A possible detection even of a few cosmogenic neutrinos would greatly help the interpretation of the detected UHECR fluxes. Because of the big difference in the neutrino flux, only models with a strong cosmological evolution may lead to detection. For those without cosmological evolution, we need gigaton neutrino detectors.

5. Summary

- All known stable particles that are candidates for the UHECR lose energy in interactions with the cosmic microwave background and other astrophysical photon fields. The cosmic-ray spectrum measured by the HiRes Collaboration agrees very well with a model of pure proton composition, while the Auger Collaboration spectrum may require mixed primary composition.
- The energy loss sets a horizon for the sources of such particles (a maximum distance from the observer) and modifies the injection spectrum of these cosmic rays.
- Charged UHECR, such as protons and heavier nuclei, scatter in the extragalactic magnetic fields. This scattering causes increased pathlength, decreases the particle horizon and introduces deflection from the source direction and significant time delay.
- The cosmogenic neutrino fluxes generated in cosmic ray propagation are currently close to detection in the $\text{km}^3$ detectors if the models with strong cosmological evolution of UHECR are correct.
- Only protons of energy approaching $10^{20}$ eV reveal the source position and spectrum after taking into account the energy loss and scattering in propagation.
- The identification of the UHECR sources will bring very valuable general information about the power and size of the sources and the magnetic fields in them, as well in intergalactic space.

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