The transition from galactic to extragalactic cosmic rays

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We discuss the region of transition between galactic and extragalactic cosmic rays. The exact shapes and compositions of these two components contains information about important parameters of powerful astrophysical sources and the conditions in extragalactic space. Several types of experimental data, including the exact shape of the ultrahigh energy cosmic rays, their chemical composition and their anisotropy, and the fluxes of cosmogetic neutrinos have to be included in the solution of this problem.

1. INTRODUCTION

We believe that at some very high energy of order $10^{18}-10^{19}$ eV all observed cosmic rays come from extragalactic sources because they cannot be contained in the Galaxy long enough to be accelerated to such high energies [1]. The current knowledge of the cosmic ray spectrum and composition do not allow us to determine where exactly the transition from local (galactic) to extragalactic origin happens.

We know that extragalactic cosmic rays lose energy in propagation from their sources to us if their sources are isotropically and homogeneously distributed in the Universe. The main energy loss process is the photoproduction interaction in the microwave background (MBR) that causes the GZK effect, the steepening of the cosmic ray spectrum above $6 \times 10^{19}$ eV [2]. Several fits of the existing experimental data have been published in recent years that derived different values of the most important astrophysical and cosmological parameters: the acceleration (injection in terms of cosmic ray propagation) energy spectrum of these particles and the maximum acceleration energy, their chemical composition and the cosmological evolution of their astrophysical sources. In the assumption that most of ultrahigh energy cosmic rays (UHECR) are protons injection spectra as different as $E^{-2.7}$ [3] and $E^{-2.0}$ [4] and cosmological evolution of the type $(1 + z)^m$ with $m$ values from 0 to 3 have been obtained.

Other attempts [3,6,7] have assumed that extragalactic cosmic rays have at their sources the same mixed chemical composition as the low energy galactic cosmic rays. In such a case the main energy loss process is the disintegration of the heavy nuclei mostly in interactions in MBR. Hadronic interactions become important only after the energy per nucleon exceeds the photoproduction threshold. The fits of the observed cosmic rays spectrum under this assumption gives an intermediate $E^{-2.2-2.4}$ injection spectrum.

In all these attempts the fits of the observations show the end of the galactic cosmic rays spectrum which is obtained by subtraction of the propagated extragalactic spectrum from the experimentally observed one. This process gives some limits of the astrophysical parameters [8] when the subtraction gives unphysical negative values.

In addition to the cosmic ray spectrum there are several types of relevant data: UHECR chemical composition, the anisotropy in this energy range, and the production of cosmogenic [9] neutrinos by extragalactic cosmic rays. We will briefly discuss these parameters.

2. UHECR ENERGY SPECTRA AND COMPOSITION

Figure 1 compares two different fits of the extragalactic cosmic ray spectra in the assumption that they are purely protons and that
their differential acceleration spectrum is a power law $E^{-\gamma+1}$. The experimental data are from AGASA [10] and HiRes [11] and are normalized to each other at $10^{19}$ eV. Since we are now only interested in the shape of the spectrum the exact differential flux at the normalization points is not important. It is obvious that the two experimental measurements agree well with each other on the shape of the energy spectrum with exception of the AGASA events above $10^{20}$ eV. The most recent analysis of the AGASA data, presented this summer [12] decreases the energy assignment of the AGASA data by 10-15% and makes the spectrum closer to that of HiRes. Fit $a$ [3] derives an injection spectrum with $\gamma = 1.7$. The dip at about $10^{19}$ eV is due to the transition of proton energy loss to Bethe-Heitler $e^+e^-$ pair production to purely adiabatic loss as predicted by Berezinsky&Grigorieva [13]. The model does not need any contribution from galactic cosmic rays to describe the observed cosmic ray spectrum down to $10^{18}$ eV. There is also no need for cosmological evolution of the extragalactic cosmic ray sources, although some source evolution can be accommodated with a slight change of $\gamma$. The model predicts purely proton composition of the extragalactic cosmic rays if it is not assumed that AGASA events above $10^{20}$ eV are due to galactic cosmic rays.

Fit $b$ [4] does need contribution from galactic sources with $E^{-\gamma+3.50}$ spectrum that extends well above $10^{19}$ eV. The extragalactic contribution is shown for two different cosmological evolutions with $m = 3$ (as used in Ref. [4]) and 4 (upper edge of the shaded area). The influence of the cosmological evolution on the cosmic ray propagation is modest because no protons injected at redshifts $z$ higher than 0.4 arrive at Earth with energy above $10^{19}$ eV independently of their initial energy.

Obviously these two models predict very differently the end of the galactic cosmic ray spectrum. In model $a$ the galactic cosmic ray sources do not need to accelerate particles above $10^{18}$ eV. In model $b$ they should be able to reach energies higher by one and a half orders of magnitude. This would affect very strongly the expected cosmic ray composition.

Figure 1. Comparison of two fits of the UHECR spectrum. The solid line shows model $a$ from Ref. [3] and the dashed lines show model $b$ from Ref. [4]. Short dashes show the galactic component needed to fit the observed spectrum in $b$.

The assumption that extragalactic cosmic rays have a mixed composition at acceleration gives somewhat intermediate results for the injection spectrum of UHECR [5,6,7]. The spectrum that fits the observation best has $\gamma$ values between 1.2 and 1.4. The chemical composition of cosmic rays at Earth is also different and obviously depends on the source composition.

It used to be that we considered three separate regions in the cosmic ray spectrum - energy below $10^{15}$ eV where the acceleration is at supernova remnants, $10^{15}$-$10^{19}$ eV where acceleration is at unknown galactic sources and extragalactic component. Since stochastic shock acceleration is rigidity dependent (as is the escape from the Galaxy) this picture predicts a complicated composition energy dependence. When a source cannot accelerate protons any more, there are only heavier nuclei, initially He, then CNO, then Si and finally Fe nuclei that are accelerated. One may imagine the composition becoming heavier between $10^{15}$ and $10^{16}$ eV, then lighter at higher energy when the $unknown$ sources take over, then heavier again when they are exhausted, then lighter again when extragalactic cosmic rays start dominating. Recent developments in the acceleration theory [14] show that the maximum ac-
acceleration energy may be much higher \cite{15} and galactic sources can cover the whole energy range to $10^{15}$-$10^{19}$ eV, i.e. we expect one single transition region. The Kascade experiment has already observed \cite{16} the beginning of the exhaustion of the galactic cosmic ray sources and the respective change of the composition.

Figure 2 shows the predicted composition as a function of the total energy per nucleus in the transition region in the classical cosmic ray units of $<\ln A>$. This is very appropriate when the detection is through air showers with logarithmic sensitivity to both energy and composition. Model a presents the easiest case to explain. All composition changes happen below $10^{18}$ eV. We do not plot the composition below that energy as it is not very well defined. The results for the other two models are presented using our own understanding of them. For model b we assume that at $10^{17.5}$ eV all cosmic rays are iron and assign $<\ln A>$ value of 4. At higher energy we use the fraction of galactic cosmic rays to iron nuclei and thus calculate the corresponding $<\ln A>$ value. For the mixed composition we use Fig. 3 of Ref. \cite{6} where the cosmic ray composition at Earth is plotted for $\gamma=1.3$ and $E_{\text{max}}$ is given as $Z\times10^{20.5}$ eV.

Surprisingly the difference in the energy dependence of $<\ln A>$ of model b and of the mixed composition model is not that big, although in the model b case the composition only consists of a combination of Fe and H, and in the mixed composition case we have five groups of nuclei.

Model a gives a very different picture, at least above $10^{18}$ eV, where the composition is purely Hydrogen. It is definitely distinguishable from the other two models. The prediction that the composition does not change above $10^{18}$ eV and is very light is supported by the HiRes $X_{\text{max}}$ measurement \cite{17}, indicated with heavy dashes in Fig. 2. What is the exact meaning of the detected light composition is not known because of the differences between the hadronic interaction models used for data analysis.

On the other hand, other experiments support a much milder energy dependence of the cosmic ray chemical composition, that is more in line with the prediction of of models b and that of mixed extragalactic cosmic ray composition.

3. ANISOTROPY

Low energy cosmic rays diffuse in the magnetic fields of the Galaxy and lose memory of the location of their sources. The anisotropies are very small, well below 1% and are difficult to measure. The measurement of a small anisotropy with air shower experiments requires an exact knowledge of the experimental acceptance and of the lifetime of the shower array.

At higher energy things are supposed to change as the cosmic ray rigidity increases and their diffusion in the Galaxy becomes faster. The first question we still cannot answer is of the rigidity (energy) dependence of the cosmic ray diffusion coefficient. An energy dependence of $E^{-0.5-0.6}$ is derived from the ratio of secondary to primary cosmic rays. If this dependence is extended by seven orders of magnitude then galactic UHE protons should show very strong anisotropy that is not observed. The two spots with increased cosmic ray flux identified by the AGASA group \cite{13}
(one in the general direction of the Galactic center and one in the direction of Orion) are not confirmed by other experiments. Theoretically we expect Kolmogorov turbulence in the Galaxy, that should under some circumstances give $E^{1/3}$ energy dependence.

One way to explain the low anisotropy in the beginning of the transition region is to assume that all galactic cosmic rays are heavy nuclei. If they were indeed heavy nuclei the average particle rigidity would significantly decrease and would maintain the high isotropy of the galactic cosmic rays. In the transition region, however, the cosmic ray chemical composition becomes lighter and correspondingly we expect to see some degree of anisotropy.

I am convinced that in the case of high experimental statistics (as expected from the Pierre Auger Observatory [19]) the anisotropy in the transition region between galactic and extragalactic cosmic rays deserves a careful study. A part of it is theoretical. We should propagate particles of different rigidity in the Galaxy and attempt to understand their general behavior. Analytic solutions of the diffusion equation are not any more suitable for this problem. Particle trajectory has to be numerically solved, most likely in a Monte Carlo fashion, and in detailed enough magnetic field models. Such models should be tested to match analytic calculations when applied to the appropriate simplified models.

4. COSMOGENIC NEUTRINOS

Cosmogenic neutrinos are produced in the same photoproduction interactions of the UHECR protons that create the GZK effect. They were first proposed by Berezinsky & Zatsepin in 1969 [9] and were the subject of many calculations afterward. Cosmogenic neutrinos are often considered a ‘guaranteed source’ of ultrahigh energy neutrinos. They are indeed guaranteed, since we know UHECR exist, but their flux is uncertain.

An essential quality of neutrinos is that they have a low interaction cross section. This makes neutrino detection a difficult problem that requires huge detectors of at least km$^3$ scale. Such detectors are now in the stage of planning [20] and construction [21][22]. The question of the cosmogenic neutrino flux and of its relation to other data from ultra-high astrophysics experiment is very timely.

The low interaction cross section is not only a deficiency. While protons emitted at redshifts $z$ exceeding 0.4 do not reach us with energy above $10^{19}$ eV the cosmogenic neutrino production peaks at redshifts exceeding 2 for $(1 + z)^3$ cosmological evolution of the UHECR sources. This is the main link between the extragalactic UHECR and cosmogenic neutrinos. The detection of cosmogenic neutrinos may help the degeneracy in modeling of the extragalactic cosmic rays spectra shown in Fig. 1.

The point is that models that use flat cosmic ray injection spectrum and require strong cosmological evolution of the UHECR sources, such as model $b$ would produce significantly more cosmogenic neutrinos than steep injection spectrum models with no cosmological evolution. Such a comparison between the two models is shown in Figure 3. The figure shows cosmogenic neutrino fluxes generated by proton interactions in MBR [23] and in the infrared/optical background (IRB) [24] with the injection spectrum and cosmological evolution of the two models as indicated in the two panels. The injection spectra of the two models are normalized to the UHECR differential flux at $10^{19}$ eV.

Before discussing the magnitude of the two fluxes I want to attract your attention to the flux of electron neutrinos and antineutrinos that exhibits two maxima separated by about two orders of magnitude of energy. The higher energy one is due to the $\pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e$ decay final state and consists mostly of electron neutrinos. It peaks at the same energy where $\mu$ and $\bar{\nu}_\mu$ do. The lower energy maximum is due to electron antineutrinos from neutron decay. Comparison between the neutron interaction length and their decay length show that all neutrons of energy below $10^{20.5}$ eV decay rather than interact.

The number density of IRB is of order 1 and varies by about a factor of 2 in different models, but its energy extends to energies exceeding 1 eV. What that means is that extragalactic particles of much lower energy would interact in IRB
and will generate neutrinos. Reference [24] shows the neutrino yields generated by protons of energy as low as $10^{18}$ eV. This yield is small but has to be weighted by the much higher number of particles at that energy - almost 1,000 higher that that of $3\times10^{19}$ eV for a flat $E^{-2}$ injection spectrum. A more recent calculation that also includes UV photons [27] employs interactions of $10^{17}$ eV nucleons that have to be weighted still higher. The cosmological evolution of IRB is not as strong as that of MBR, as the radiation is generated through emission directly by stars and after absorption by dust, but still significant up to redshift of 3. The IRB model of Ref. [28] is used for the shown calculation.

Model $b$ generates much higher cosmogenic neutrino fluxes than model $a$ because of two reasons that contribute roughly the same increase of the cosmological neutrinos. Firstly, it uses much flatter injection spectrum $E^{-2.0}$ which means equal amount of energy per decade. It thus contains many more particles above the photoproduction interaction threshold in the MBR is about $3\times10^{19}$ eV and, of course, decreases as $(1+z)^{-1}$.

The other reason is that model $b$ employs a strong cosmological evolution of the cosmic ray sources. This increases by $\sqrt{3}$ the number of particles injected at redshift of 2, but in addition increases by a factor of three the number of particles above the interaction threshold. This way the total neutron flux is increased by the cosmological evolution of the sources by a factor of five.

The difference in the peak values of the cosmological neutrinos generated by the two models is more than one order of magnitude. In practical terms, after the energy dependence of the $\nu N$ cross section is taken into account, this means that model $b$ generates fluxes that are in principle detectable by IceCube at the rate of roughly less than one event per year, while model $a$ generates undetectable fluxes of cosmogenic neutrinos in km$^3$ detectors.

Ice and water neutrino detectors are generally not very suitable for cosmogenic neutrino detection. Much better strategies for these UHE neutrinos are the radio and acoustic detectors that have very high detection threshold, but also will have higher effective volume. The other option are giant air shower arrays such as Auger, that can reach effective volume of 30 km$^3$ and, with sufficiently low threshold ($10^{18}$ eV) could detect several events per year.

Cosmogenic neutrinos are also generated in the mixed composition scenario [25,26]. Since the major energy loss process is the disintegration of heavy nuclei, the main flux component of $\bar{\nu}_e$ from neutron decay. The $\bar{\nu}_e$ flux exceeds by a factor of 5 the sum of the neutrino fluxes of all other flavors in Ref. [26]. The absolute magnitude depends again mainly on the injection spectrum and the cosmological evolution of the sources.
5. DISCUSSION

The transition region between galactic and extragalactic cosmic rays is currently not very well defined and studied. It has a significant astrophysical importance, because the energy content of the extragalactic cosmic rays, as well as their injection spectrum and composition, will define much better the type of their sources. In addition, a derivation of the cosmological evolution of the sources will not only restrict the number of available scenarios, but also provide an additional measure of the cosmological evolution of powerful astrophysical objects.

The first experimental result on the shape of this transition presented by the Fly’s Eye group [29] used the simultaneous change of the cosmic ray composition and energy spectrum shape. We should now employ all available types of measurements to solve this problem. These measurements include the cosmic ray composition in the transition region and above it, the cosmic ray anisotropies, and the possible detection of cosmogenic neutrinos.

The possible detection of cosmogenic neutrinos would be a powerful test if we succeed in collecting a reasonable statistics of such events. It is unlikely this will happen very soon, but the expanding efforts for designing and building detectors for ultrahigh energy neutrinos are very encouraging.

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