

Can Experiments Studying Ultrahigh Energy Cosmic Rays Measure the Evolution of the Sources?

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Abstract

Interactions between cosmic ray protons and the photons of the cosmic microwave background radiation, as well as the expansion of the universe, cause cosmic rays to lose energy in a way that depends on the distance from the cosmic ray source to the earth. Because of this, there is a correlation between cosmic ray energies and the average redshift of their origin. This correlation may be exploited to measure the evolution of the sources of cosmic rays.

Sky surveys of Quasi Stellar Objects (QSO's) and Active Galactic Nuclei (AGN's), made at optical and x-ray wavelengths, are consistent in showing that the evolution of such objects exhibits a break at a redshift, z , of about 1.6. At smaller redshifts, the luminosity density of QSO's and AGN's follows a $(1+z)^m$ distribution, with $m \sim 2.6$, and exhibit a much flatter distribution above the break. Measurements of the star formation rate are also consistent with this picture.

If QSO's and AGN's are sources of ultrahigh energy cosmic rays the break in their evolution should appear in the cosmic ray spectrum at an energy of about $10^{17.6}$ eV. This is the energy of the second knee.

1 Introduction

Some of the most interesting questions in physics today involve ultrahigh energy cosmic rays: what is their origin and how do they interact with the Cosmic Microwave Background Radiation (CMBR) [1]. Identifying sources by searching for anisotropy is made difficult by the fact that the cosmic rays are charged and galactic and extragalactic magnetic fields have a strong effect on their trajectories.

A second technique for studying the sources of cosmic rays uses spectrum [2] and composition [3] measurements. These measurements are detailed enough that one can identify, in a plausible way, the flux both of galactic and extragalactic cosmic rays. To learn about the sources of the extragalactic cosmic rays, one can make a model of these sources and fit it to the data [4]. This process is aided by the fact that recent composition measurements indicate that the transition from galactic sources of cosmic rays to extragalactic sources is complete by about 10^{18} eV, and that throughout the 10^{17} eV decade a considerable fraction of cosmic rays are of extragalactic origin.

There are three energy loss mechanisms that affect extragalactic cosmic ray protons. Two of these mechanisms are interactions with photons of the CMBR: pion production, which causes the GZK suppression [5], and e^+e^- pair production [6]. The third mechanism is the expansion of the universe. These energy loss mechanisms cause there to be a correlation between the energy of cosmic rays and the average redshift, z , of their sources; i.e., cosmic ray protons of a given energy come, on average, from sources at a certain redshift. This correlation can be exploited to measure the evolution of cosmic ray sources.

Astronomical surveys of the distance and luminosity of QSO's and AGN's have been performed at optical and x-ray wavelengths [7]. Upon correcting for observational biases, the luminosity density of QSO's and AGN's has been measured. These measurements show that the z -dependence follows a $(1+z)^m$ distribution, with $m \sim 2.6$, for redshifts less than about 1.6, and exhibit a much flatter distribution for higher redshifts. This picture is also consistent with the star formation rate as measured at infrared wavelengths [8].

An interpretation of these observations is that at earlier times, or at higher redshifts, the large black holes that power the sources were just forming. By a redshift of about 1.6 they reached their mature state, and the source density subsequently follows an evolution similar to that of the universal expansion.

This means that, if QSO's and AGN's are sources of cosmic rays, their luminosity at earlier times was considerably lower than one would expect from observations of closer sources. Because of the correlation between cosmic ray energy and the redshift of their sources, the break in the source luminosity

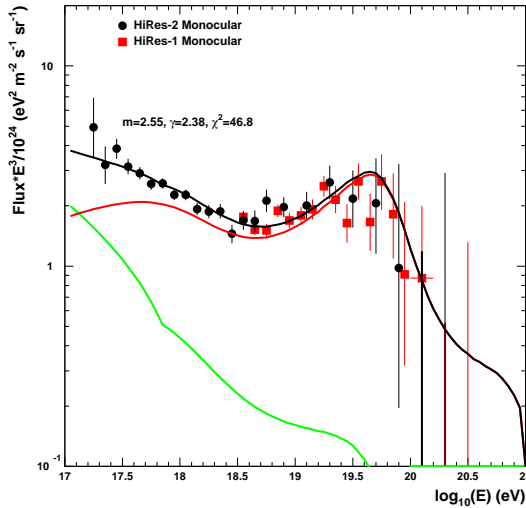


Fig. 1. Spectrum of ultrahigh energy cosmic rays as measured by the HiRes experiment. Also shown is the result of a fit to the data of a model incorporating galactic (green) and extragalactic (red) sources (with the sum in black) described in the text.

density should show up as a break in the spectrum of extragalactic cosmic rays, with lower fluxes at lower energies than one would expect if the source evolution were smooth. A break in the source evolution at $z=1.6$ should produce a break in the spectrum at an energy of about $10^{17.6}$ eV. Near this energy there is a feature in the cosmic ray spectrum called the second knee.

In this paper, we first describe the spectrum and composition measurements of the High Resolution Fly’s Eye (HiRes) experiment. Next we describe a model of galactic and extragalactic cosmic rays that fits both measurements simultaneously. We then introduce the evolution of QSO’s and AGN’s into the model to see the effect in the region of the second knee. Finally, we comment on the further experimental work that must be done to learn more about the sources of extragalactic cosmic rays.

2 HiRes Spectrum and Composition Measurements

The measurements of the cosmic ray spectrum [2] and composition [3] by the HiRes experiment are shown in Figures 1 and 2. The main features of the spectrum are a strong dip near $10^{18.5}$ eV called the “ankle”, and a suppression above $10^{19.8}$ eV which is consistent with the GZK cutoff. Below about $10^{17.5}$ eV, the HiRes data have large statistical (and systematic) uncertainties, and one cannot claim to see the second knee in these data.

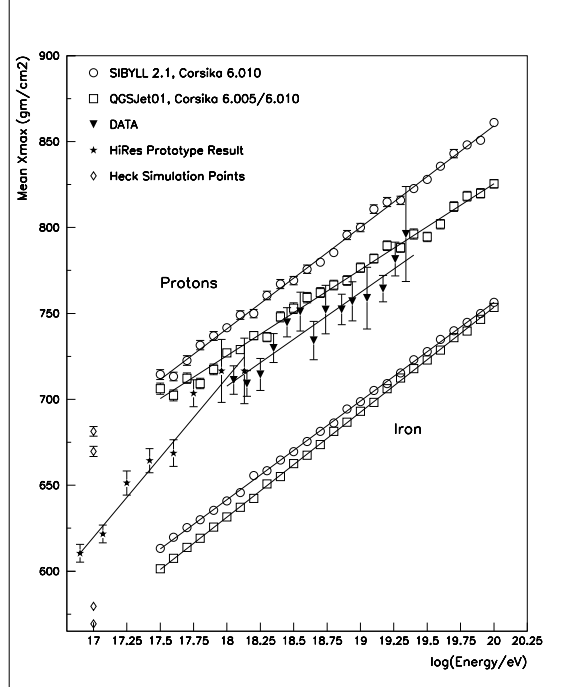


Fig. 2. Mean Depth of Shower Maximum, X_{max} , measured by the HiRes/MIA and HiRes Stereo experiments. The data, plus predictions of Corsika and QGSjet or Sibyll are shown. The plot indicates a transition from heavy to light nuclei (the galactic - extragalactic transition) from 10^{17} to 10^{18} eV. The transition is complete by about 10^{18} eV. The composition is light and constant above this energy.

Figure 2 shows the mean value of X_{max} , the slant depth of shower maximum, as a function of $\log E$. Results from the HiRes Prototype - MIA hybrid experiment are shown at lower energies, and of HiRes stereo above 10^{18} eV. The line fit to the HiRes-MIA data has a slope of $93 \text{ g/cm}^2/\text{decade}$, where at higher energies the slope is $55 \text{ g/cm}^2/\text{decade}$. For comparison the results of Corsika and two hadronic generator programs, QGSjet and Sibyll, are shown. An interpretation of these data is that below 10^{18} eV the composition is getting lighter, and above it is constant; i.e., since the highest energy galactic cosmic rays are expected to have heavy composition, and extragalactic to be mostly protons, the transition from galactic to extragalactic cosmic rays is complete by about 10^{18} eV.

3 A Model of Galactic and Extragalactic Cosmic Rays

One can construct a model that agrees with all the data described in the previous section. If one uses the QGSjet prediction for mean X_{max} as a guide,

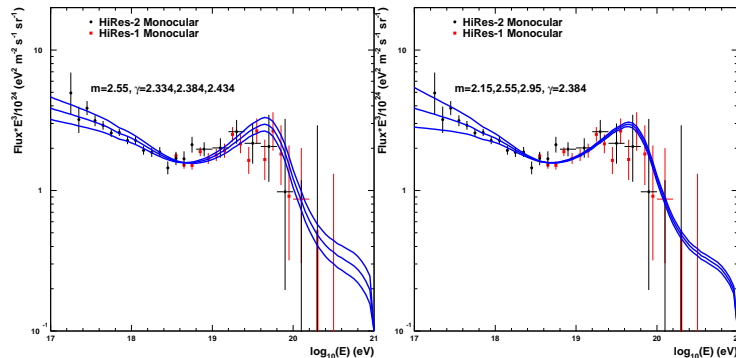


Fig. 3. Effect of changing the spectral index, γ (left), and evolution parameter, m (right), in fits to the HiRes spectrum, showing that the ankle region is sensitive to γ , and that the region just below the ankle is most sensitive to m .

the fraction of cosmic rays that are protons is about 50% at 10^{17} eV and about 80% for energies above 10^{18} eV. In this model, we ascribe the protons to extragalactic sources and use the three energy loss mechanisms described above in tracing their path from source to detection.

In Figure 1, the curve drawn through the data is the result of this model. We assume the galactic/extragalactic mixture described above, that the spectrum at the source is a power law of index γ which continues to 10^{21} eV then is cut off sharply. The source density is a constant times a factor $(1+z)^m$, where m is known as the evolution parameter. In this fit, one value of m is allowed for all redshifts. The values of m and γ are allowed to vary in the fit. A complete calculation of energy losses is performed, and pion production is treated by the Monte Carlo method.

The fit has a satisfactory χ^2 of 43 for 35 degrees of freedom. It agrees well with the data in the region of the ankle. The ankle is especially important because, in this region, the fit is sensitive to both the average power law index and to the evolution parameter. The two parts of Figure 3 show the same data with three fits in each part, with different values of γ (m) on the right (left) side. The spectrum is sensitive to γ throughout the ankle region, and m on the lower side of the ankle, showing that the two parameters' values can be extracted from the data.

Between $10^{19.4}$ and $10^{19.7}$ eV the fit is above the data points. This may be due to the model's abrupt cutoff at 10^{21} eV, whereas sources really have a distribution of maximum energies. This is an interesting piece of information that bears on the distribution of the size and magnetic fields of sources, and should be investigated further.

Experiments studying lower energy regions than HiRes [9] observe a spectrum that is flat on an $E^3 J$ plot (i.e., falls like $E^{-3.0}$) below the second knee. The

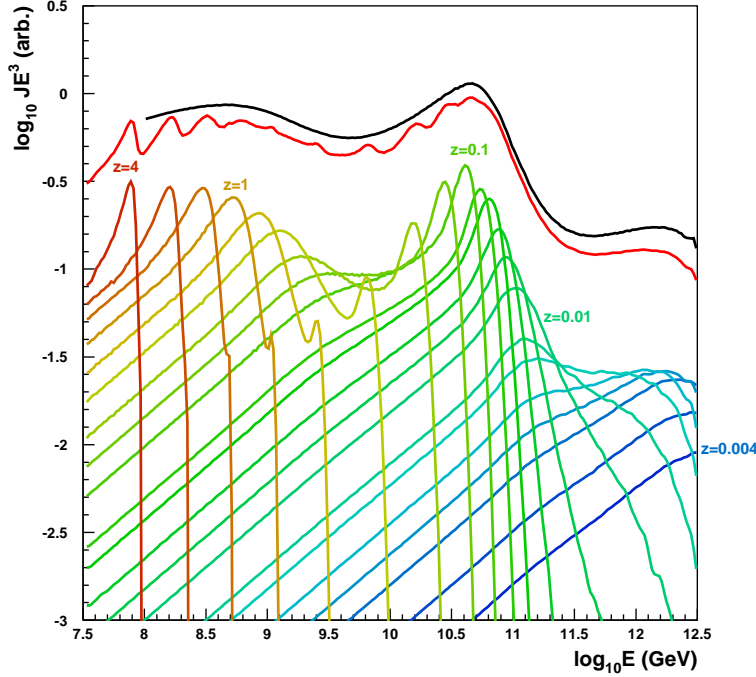


Fig. 4. Contributions from sources within shells in redshift according to our energy loss model.

second knee was observed by the Fly's Eye experiment at $10^{17.6}$ eV. The behavior of the model below $10^{17.6}$ eV is not what one would expect from the world's data: the model's prediction is that the spectrum should be steeper, at about $E^{-3.2}$. Another way of saying this is that the appearance of the second knee is too weak in this model.

Figure 4 shows how sources grouped in shells of redshift contribute to the cosmic ray spectrum, and the correlation between energy and redshift. As an example, one can see the correlation by observing that at $\log E$ of 8.8 (E in GeV), at the peak of the shell at $z=1.0$, the contribution from the shell at $z=0.1$ is lower at this energy by an order of magnitude. The correlation is not perfect, but it is significant.

This correlation is due to the effect of energy loss mechanisms working on cosmic rays as they traverse large distances across the universe. To again take the example of sources at $z=1.0$, the highest energy cosmic rays, in this model 10^{21} eV, are reduced to an energy of about $10^{17.9}$ eV at the earth by these effects.

4 QSO and AGN Evolution and the Second Knee

Astronomical sky surveys have been performed for QSO's and AGN's at optical and X-ray wavelengths [7]. In such a survey, sources are tabulated by magnitude and redshift. After correcting for observational biases, the luminosity density of these astronomical objects is normally calculated as a function of redshift. Surveys at each wavelength consistently show a density that rises at low z like $(1+z)^m$, with $m \sim 2.6$. At higher z , the density flattens out considerably. Infrared measurements of the star formation rate [8] are consistent with this picture.

The interpretation is that as time progressed - or as z decreased - the large black holes that power QSO's and AGN's first grew to significant size, then their activity reached a plateau at $z \sim 1.6$. The source evolution after this almost followed that of the universal expansion (which would be $m=3$). The effect of this, on the flux of extragalactic cosmic rays, is that at energies lower than about $10^{17.6}$ there would be fewer cosmic rays than one would expect from the density of sources at redshifts less than 1.6.

To test the effect of the break in source evolution on the cosmic ray spectrum, we introduced the break into our model of galactic and extragalactic cosmic rays. The left part of Figure 5 shows three density curves as a function of redshift. In black is the standard $(1+z)^{2.6}$ as in previous figures, in blue is $(1+z)^1$ above $z=1.6$, and in red is $(1+z)^0$ above $z=1.6$. The result of including these density functions is shown in the right half of Figure 5. This shows that the effect of changing the evolution of cosmic ray sources to conform to the break in QSO and AGN evolution at $z=1.6$ also appears as a break in the cosmic ray spectrum at an energy of $10^{17.6}$ eV. This is the approximate location of the "second knee" of the cosmic ray spectrum. The $(1+z)^1$ density function yields the flattest spectrum below $10^{17.6}$ eV.

We do not believe that this constitutes a determination of the evolution of cosmic ray sources, but rather is an example of what might be done with data from a well-designed future cosmic ray experiment.

5 Future Experiments

The modeling exercise above clearly shows the limitations of the present state of the world's cosmic ray data. Two essential elements of fits like these are a measurement of the spectrum of cosmic rays by a single experiment covering a very wide energy range, and a measurement of X_{max} again covering a very wide energy range. The X_{max} measurement must be made by a fluorescence de-

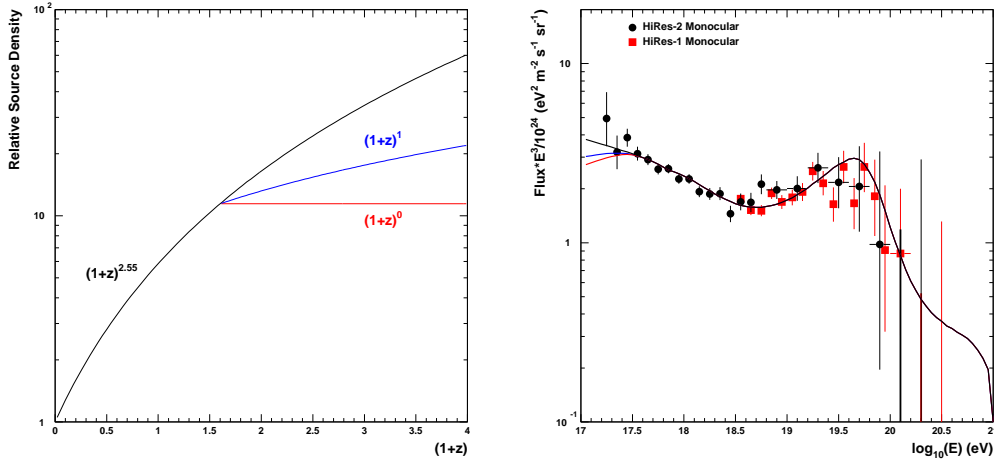


Fig. 5. Left figure: Three curves of the density of cosmic ray sources. Evolution as $(1+z)^{2.6}$ for all z (black), $(1+z)^1$ above $z = 1.6$ (blue), and $(1+z)^0$ above $z = 1.6$ (red). Right figure: Model fits to the HiRes data using the three forms of source evolution as in the left part of this figure. Note the variation below $10^{17.5}$ eV. This indicates that a more precise measurement of the spectrum below $10^{17.5}$ eV can be sensitive to the evolution of the sources.

tector, since only fluorescence detectors actually observe X_{max} . Ground array experiments must infer X_{max} , with their attendant model-dependent systematic uncertainties. In order to be sensitive to the evolution of cosmic ray sources an experiment must observe all the structures in the spectrum between the second knee and the GZK cutoff. In a fit to the spectrum, each structure will yield information about cosmic ray sources. Hence it is necessary for a single experiment to have fluorescence coverage between about $10^{16.5}$ and $10^{20.5}$ eV.

Although the HiRes experiment covers about three orders of magnitude in energy, from $10^{17.5}$ to $10^{20.5}$ eV, and can measure the evolution parameter, it does not reach low enough energies to be sensitive to a break at $z=1.6$ (an energy of $10^{17.6}$ eV) in the evolution of QSO's and AGN's via the cosmic ray spectrum.

The sole experiment, built or planned, that has the capability of performing this test is the Telescope Array (TA). The TA experiment, currently being constructed in Millard County, Utah, will consist of a ground array of 576 scintillation counters, deployed on a grid of spacing 1.2 km, and overlooked by three fluorescence detectors for hybrid coverage. The TA experiment will be fully efficient above 10^{19} eV.

Two further detectors are planned to extend the coverage in stereo and hybrid mode to lower energies. The first is a pair of fluorescence detectors located 6 km from two of the main TA fluorescence detectors. These will observe the ankle region stereoscopically. They will extend the stereo coverage below 10^{18}

eV and will provide an excellent measurement of both the average power law of extragalactic sources and the evolution parameter. The second is a detector with larger mirrors observing cosmic ray showers at higher elevation angles. It will be deployed with an infill array in front of it and will cover the energy range from $10^{16.5}$ to 10^{18} eV in hybrid mode. This detector is designed to study the region of the second knee. This suite of detectors is called the Telescope Array Low Energy Extension (TALE).

The TA and TALE detectors will provide seamless coverage over four decades in energy, from $10^{16.5}$ to $10^{20.5}$ eV. The same events will be seen by several of the detectors and cross correlation of energy scales will be possible. Only a suite of detectors like this can measure the evolution of extragalactic cosmic ray sources.

Performing a study of spectral structure, in correlation with observed X_{max} , can determine if the second knee is of galactic or extragalactic origin. One can select events based on deep X_{max} values to isolate the protonic, and hence extragalactic, component of the cosmic ray flux (and conversely choose the heavy or galactic component by choosing events with shallow X_{max}). If the second knee shows up in the extragalactic component, it strengthens the evolution argument presented here. If the second knee proves to be of galactic origin, it would be very interesting, but would invalidate the evolution-origin hypothesis.

6 Summary

The technique of measuring the spectrum and composition over a wide energy range by a fluorescence detector is a very powerful one for understanding the sources of ultrahigh energy cosmic rays. Observing in monocular or stereo modes for the spectrum measurement, and in stereo mode for the composition measurement is important. Hybrid mode is only marginally better than monocular mode for spectrum measurement (it is noticeably better for composition studies), but nothing approaches the excellence of stereo, with its ability to make two determinations of energy and X_{max} and measure the uncertainties in those quantities on an event-by-event basis.

Astronomical sky survey experiments have observed that the evolution of QSO's and AGN's exhibits structure at a redshift of $z \sim 1.6$. If QSO's and AGN's are sources of cosmic rays, this has the implication that the generation of extragalactic cosmic rays by sources more distant than $z=1.6$ is weaker than one would expect from observations of closer sources.

There is a correlation between the energy of cosmic ray protons and the red-

shift of their sources due to the strong energy loss mechanisms at work when the cosmic rays traverse long distances across the universe. This means that the break in source evolution should show up as a break in the extragalactic cosmic ray spectrum as well. A break at a redshift of 1.6 should show up at an energy of $10^{17.6}$ eV, which is the approximate location of the second knee of the cosmic ray spectrum.

No running experiment has the capability of observing this effect. The energy range of the HiRes experiment does not extend to low enough energies for this observation and that of the Auger Observatory is certainly too narrow. Only the Telescope Array experiment will cover a wide enough energy range to test this prediction.

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