The highest energy cosmic rays: what they can teach us

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We review the current knowledge of the highest energy cosmic rays and some of the models for their interpretation. The current experimental situation seems to support a conservative model that does not reveal their sources. I hope that earlier today Alan Watson has presented some hints for the future.

Please excuse me if this talk is outdated now.
The situation several years ago was more exciting

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<th>AGASA</th>
<th>HiRes</th>
<th>Auger</th>
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<tr>
<td>Events above $10^{20}$ eV</td>
<td>many</td>
<td>very few</td>
<td>few</td>
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<tr>
<td>Large scale isotropy</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Small scale isotropy</td>
<td>no</td>
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The early results of AGASA initiated hope for non-standard physics and recognition of the cosmic ray sources. The current situation favors standard models known since Greisen and Zatsepin&Kuzmin. The devil is in the details.
This is the situation from 2006:
Auger05 seems to agree with HiRes AGASA scaled down their energy estimate by 10 to 15 % as shown here (Teshima)

The only remaining(?) problem has to do more with high energy physics than with astrophysics – Auger energy estimates from the surface array are 25% higher than those from the fluorescent detectors. This does not depend on the hadronic interaction model used. The absolute normalization of the energy is an important problem.
Other problems have appeared in the interpretation of the highest energy cosmic ray spectrum. Why does it have this shape?

The initial thought was of flat acceleration spectrum (W&B) and an intersection with the galactic cosmic rays above $10^{19}$ eV (a). Cosmic ray sources should then have cosmological evolution similar to SFR.

Berezinsky et al than came with the suggestion that the spectrum is steep and the dip is due to BH pair production. The extragalactic spectrum extends down to $10^{18}$ eV and there is no need for cosmological evolution of the cosmic ray sources (b).
Because of the strong proton energy loss high redshifts $z$ do not contribute much to the highest energy cosmic rays. Here is an example with the W&B parameters.

Contribution of cosmic ray sources at different redshift to the observed flux. The solid black line is the flux in case of isotropic distribution of the cosmic ray sources.
How is such steep acceleration spectrum possible? Here is an idea put forward by P.L. Biermann (but not published) in 2004. Assume we have different sources with the same acceleration spectrum but different maximum energy. The resulting spectrum at Earth will not have the same spectrum as the acceleration spectra of all sources. In this case the spectra above $10^{19}$ eV do have $\gamma$ nearly 1.7. All 39 AGN are within 70 Mpc from us. Source density is $2.7 \times 10^{-5}$ Mpc$^{-3}$.

This simple model, however, does need fine tuning after propagation from the sources.
The energy spectra of UHECR (extragalactic) at Earth depend on:

- Acceleration spectra at the sources.

- Spatial distribution of the sources (nearby ones).

- Nuclei or gamma rays, astrophysical or exotic

- Cosmological evolution of the sources (may eliminate some of the models).

- Chemical composition of UHECRs at their sources (see Allard et al, $\gamma = 2.2-2.4$).

- Average extragalactic magnetic field (high fields may create cut-offs – we can see only a small fraction of the Universe, low fields would enhance source recognition – Tkachev and Co blazar correlation).

How do we deal with these parameters
One contemporary question (at least among theorists) is **where is the end of the galactic cosmic ray spectrum?** This closely related to the acceleration spectrum of the extragalactic cosmic rays.

We have so much freedom with the extragalactic cosmic ray spectrum that fitting the observations is easy. This is what we do:

A model spectrum is propagated in the Universe from isotropic sources to us and the result is subtracted from observations. The difference is attributed to the Galactic cosmic rays. Here is an example of such fits.

From: DeMarco and Stanev
Source distribution

This would be easier if the small scale clustering of the AGASA event sample were confirmed. It is not confirmed by HiRes or Auger.

From that clustering of the high energy event the UHECR source density was defined to be of order $10^{-5+/-1}$ per cubic Mpc. Now this estimate seems to be obsolete.

The old controversy remains:

On one hand we want to have nearby sources, within the GZK sphere of about 50 Mpc.

On the other we have not seen any sources yet.
Neutrino spectra (sum of all flavors) from the decay of supermassive X particles (Berezinsky & Kachelriess). Gamma ray spectra at source are similar.

The number of nucleons would be lower by a factor of 30 at the lower energy range and will become equal at the higher energy (or even exceed the neutrinos). The gamma ray fluxes at the source are of the same magnitude. If IHECR are not gamma rays the top-down models are out.
The fraction of gamma rays has been limited by several air shower experiments using the muon content and the angular distribution of the detected air showers to less than \( \frac{1}{2} \) of the total flux. The statistics is, however, too low to do that at the highest energies. So .... for the origin of UHECR top/down models are still possible.
The two models I showed assume that all extragalactic cosmic rays are protons. Another possibility is that extragalactic cosmic rays have mixed composition and lose energy on propagation mostly on spallation in photon fields. This changes the story quite a bit: the dip at $10^{19}$ eV becomes shallower being filled with spallation nucleons. The injection spectrum for no cosmological evolution becomes flatter.

From: Allard, Parizot & Olinto, 2005
Cosmological evolution of the extragalactic cosmic ray sources

UHECR by themselves are not very sensitive to the cosmological evolution of their sources as shown above. We have to look for parameters that are sensitive. Such are the neutrino and gamma ray fluxes produced by UHECR on propagation to us. We will touch the question of cosmogenic neutrinos a bit later.
What types of data we can use to learn all these parameters:

- Better spectra of the highest energy cosmic rays. *Will be achieved with higher exposure – Auger, TA, ?*

- Chemical composition above $10^{18}$ eV. A very difficult question because it does have hadronic interaction model dependence.

- Anisotropy studies. *Even more difficult since we can not understand the propagation of the high energy cosmic rays in the Galaxy.*

- Possibly signals created on propagation from the sources to us. *Cosmogenic neutrinos come to mind since they are very sensitive to the cosmological evolution of the cosmic ray sources. Cosmogenic gamma rays after cascading to GeV?*
What do we know about the chemical composition of the high energy cosmic rays? Here is a rough picture mostly from the data of the Kascade experiment. At higher energy we only have $X_{\text{max}}$ data of Fly's Eye and HiRes + some Agasa analyses.
The HiRes experiment derives the UHECR mass composition by statistical studies of the depth of shower maximum $X_{\text{max}}$. Comparisons to Monte Carlo results show a transition from heavy nuclei to protons when approaching $10^{18}$ eV. This would be a transition from galactic to extragalactic CR origin. The composition does not seem to change much after that. AGASA measures CR composition by the shower muon content and does not detect such drastic change. Neither does Auger we learned today.

Note the uncertainty due to hadronic interaction models. It would grow if other interaction models were included.
Approximate calculation of the average $\ln A$ for the two extragalactic proton models (assuming very heavy composition at $10^{17} \text{ eV}$) and of the mixed composition model of Allard et al.

Mixed composition $<\ln A>$ from the $X_{\text{max}}$ graphs in the latest paper of Allard et al (2007) using Sibyll 2.1.
High energy cosmic rays propagation in the Galaxy. Two numerical approaches in addition to analytical diffusion work:

- backtracking of negatively charged nucleons from the Solar system.

- forward propagation from the sources to the Solar system or to the edge of the Galaxy. This requires knowledge of the CR source distribution and could lead to calculation of expected anisotropy.

Numerical propagation work is important because of the complexity of the galactic magnetic field models.

Note that there are many (not always consistent) and very complicated models of the Galactic magnetic field. We have two of the best experts at this meeting.
Containment time (distance) in a disk with radius 15 kpc and half height of 4 kpc for protons injected at Earth. Calculation with different values of $\delta B/B$. When the truth is established we can combine such calculations with the composition measurements and determine the acceleration spectrum of the Galactic cosmic rays. Containment time is very long – a few million years – as much as derived for GeV cosmic ray from observations. This would lead to very high level of isotropy.

It is not a priori obvious that results for different levels of turbulence are not compatible. The errors are not statistical – the pathlength distributions are very wide.
Exit points from the Galaxy of protons injected isotropically at the Solar system. There is no guarantee that the same fields will generate observable anisotropy. More data are still very important and could be useful.
Models of the galactic magnetic field are very complicated: there is spiral field (close to azimuthal with maxima and minima, field reversals and radial dependence.

From: Daniel DeMarco

As an example we show the drift velocity that one field model creates on the distance from the galactic center to us. We may never sort out the particle propagation in such complicated field models.
The propagation of UHECR is influenced very strongly by the extragalactic magnetic fields if they are above 1 nG.

Random extragalactic fields, if they have strengths of nG on Mpc scale, can impose a relatively small 'horizon'. Protons of energy below $10^{20}$ eV scatter and lose energy so much that they cannot reach us in Hubble time.

Points are results of Monte Carlo propagation. The heavy grey line shows propagation time (analytic estimate, Achterberg) exceeding Hubble time.
The worst scenario would be if organized extragalactic fields of strength of 10 nG extend on the scale of 10 Mpc. In such case the cosmic ray spectrum after propagation will depend strongly on the relative geometry of the source and observer in respect to the magnetic field lines.

The left hand graph in this example shows the spectrum of protons propagating to the observer along the magnetic field lines. The right hand panel shows protons propagating across the field lines. Propagation distance is 20 Mpc. Magnetic field is a `supergalactic' plane of width 3 Mpc and 10 nG field with a source at the origin.
**Cosmogenic neutrinos** are neutrinos from the propagation of extragalactic cosmic rays in the Universe. These neutrinos were first proposed and their flux was calculated in 1969 by Berezinsky & Zatsepin. An independent calculation was done by Stecker in 1973. In 1983 Hill & Schramm did another calculation and used the non-detection by Fly's Eye of neutrino induced air showers to set limits on the cosmological evolution of the cosmic rays sources.

The main difference with the processes in AGN and GRB is that the main photon target is the microwave background (2.75 oK) of much lower temperature than the photon emission of these sources. This raises the proton photoproduction threshold to very high energy:

\[
E_{p}^{\text{min}} \simeq \frac{m_{\Delta}^2 - m_{p}^2}{2(1 - \cos \theta) \varepsilon} \simeq \frac{5 \times 10^{20}}{(1 - \cos \theta)} \text{ eV}
\]

in the isotropic infrared/optical background.

The photoproduction energy loss of the extragalactic cosmic rays cause the GZK effect.
Cosmogenic neutrinos are very sensitive to the cosmological evolution of the cosmic ray sources because of the lack of energy loss. This could be useful for establishing a model for the extragalactic cosmic rays.

Note the logarithmic scale in redshift. Cosmological parameters are as in the cosmic ray example. The contribution increases until the source luminosity is significant ($z = 2.7$ in the W&B model). At higher redshift the production is still high because of the $(1+z)^3$ increase of the MBR density and the lower energy threshold for photoproduction.
The figure shows the fluxes of electron neutrinos and antineutrinos generated by proton propagation on (bottom to top) 10, 20, 50, 100 & 200 Mpc in MBR. The top of the blue band shows the proton injection spectrum ($E^{-2}$ in this example).

From: Engel, Seckel & Stanev, 2001

Muon neutrinos and antineutrinos are generated with a spectrum similar to the one of electron neutrinos at twice that rate. As far as neutrinos are concerned the cascade development is full after propagation on 200 Mpc. Even the highest energy protons have lost enough energy to be below threshold. We shall use these results to integrate in redshift, assuming that cosmic ray sources are homogeneously and isotropically distributed in the Universe to obtain the total flux.
The cosmogenic neutrino spectra generated by the two extreme models of the injection spectra of UHECR protons in case of isotropic homogeneous distribution of the cosmic ray sources. The big difference in case of `MBR only' interactions is due to the flat injection spectrum and the cosmological evolution of the sources. The interaction rate is dominated by IRB generated neutrinos in the case of steep injection spectrum. MBR neutrinos dominate the high energy end, especially in the flat injection spectrum case.
It was shown by Hooper et al and Ave et al that heavy nuclei also generate cosmogenic neutrinos, although mostly through neutron decay. Neutrons are released in the nuclear fragmentation in interactions on universal photon fields. Photoproduction neutrinos require injection spectra that reach energies above $10^{21}$ eV per nucleus, so that individual nucleons of energy $E/A$ exceed the photoproduction threshold.

The muon neutrino and antineutrino flux is harder than the $\gamma=2.7$ model. The maximum flux is lower. Electron antineutrino spectrum peaks below the Glashow resonance energy.
Conclusions

Even with the forthcoming much more exact measurements of the UHE cosmic ray spectrum it will be difficult to derive important general parameters of extragalactic space if we do not see any sources. Source observation will give significant information about extragalactic magnetic fields.

Composition measurements are extremely important and they may be coupled with anisotropy data if we are lucky to detect anisotropy at very high energy. Such a combination can help identify the spectral characteristics of Galactic CR and show significant changes in the transition region.

Possible detection of cosmogenic neutrinos will be sensitive to the cosmological evolution of the UHECR sources and will limit the phase space for extragalactic CR models. Future detectors may be able to measure the energy spectrum of cosmogenic neutrinos that will give more information of cosmological UHECR sources.
The energy loss scale of high energy protons in the microwave background.

The pile up at the approach of 100 EeV is due to the decrease of energy loss from photoproduction to BH pair creation.

The dip at 10 EeV was predicted by Berezinsky & Grigorieva.