Extragalactic ultra-high energy cosmic rays
II. Comparison with experimental data

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Abstract
The hot spots of powerful Fanaroff Riley class II radio galaxies and related radio quasars can produce an ultra-high energy particle population observable at earth. The properties of the predicted spectrum are a spectrum which is about $E^{-2}$ below 0.1 EeV, steepening to about $E^{-2.75}$ near 1 EeV, and cutting off due to interaction with the cosmic microwave background after a bump just below 100 EeV (Rachen and Biermann 1992, paper UHE-CR I); the predicted chemical composition is a strong dominance of protons. Here we compare this prediction with observational data from both the Fly’s Eye and the Akeno airshower detectors. These experimental data are now available from the detailed analysis of the chemical composition near to EeV energies (Gaisser et al. (1992) for the Fly’s Eye experiment, and from Stančev et al. (1992) for the Akeno experiment) and demonstrate that below 1 EeV protons show a flatter spectrum than the overall spectrum and thus their relative proportion increases with energy. The comparison of the spectral data and the flux shows that the ultra high energy component of the cosmic rays can indeed be understood as arising from the hot spots of powerful radiogalaxies, in flux, spectrum and chemical composition:

This result put stringent limits on the propagation of high energy cosmic rays and thus on the properties of the intergalactic magnetic field.

1 Introduction
The origin of the cosmic ray particles with energies beyond the knee at about 5 PeV is still a matter of debate, and has recently been speculated to be extragalactic (Protheroe and Szabo 1992, Salamon and Stecker 1992). Both papers argue that these particles gain their energy as protons in the active cores of quasars or other active galactic nuclei, make a transition to a neutron in a proton-photon collision, and then escape unbound by magnetic fields. Finally, outside the parent galaxy, these neutrons decay back to a proton. As a consequence, both these theories predict that the cosmic rays beyond the knee should be mostly protons. Other contender theories put the origin of these particles i) in a galactic wind shock (Jokipii and Morfill 1987, 1991), ii) from reacceleration of existing energetic particles (Ip and Axford 1992), iii) from neutron stars (Hillas 1984; Méscáros and Rudak 1991), and iv) from acceleration by a supernova shock racing through a stellar wind (Völk and Biermann 1988; Biermann 1993, paper CR I; Biermann and Cassinelli 1993, paper CR II). Recently (Biermann 1993, paper CR I, and Stančev et al. 1992, paper CR IV) we have demonstrated that the theory tracing the cosmic ray particles beyond the knee to supernova shock waves in stellar winds, can simultaneously explain spectrum, chemical composition and flux from 10 TeV to 3 EeV.

\(^{a)}\) We note for reference, that $10^9$ eV = 1 GeV, $10^{12}$ eV = 1 TeV, $10^{15}$ eV = 1 PeV, $10^{18}$ eV = 1 EeV.
Near 3 EeV the situation becomes simpler insofar as a spectral change suggests that the origin changes. Since the Larmor radii of such particles become larger than the thickness of the galactic disk, it is likely that the origin of cosmic rays beyond several EeV is extragalactic. It is those particles with extremely high energies which we wish to address in this communication.

The central thesis discussed in paper UHE-CR I (Rachen and Biermann 1993) is that these particles originate in the hot spots of radio galaxies (Fanaroff and Riley 1974, Miley 1980). These hot spots are believed to be the sites of very strong shock waves (Meisenheimer et al. 1989); shockwaves are believed to be the sites of particle acceleration (Drury 1983). Such a theory has several advantages:

1. First of all, it can be tested since we know the space density of radio galaxies and their cosmological evolution (Peacock 1985), and we can directly calculate what the integrated contribution can be. In addition, the radio synchrotron emission spectrum gives us the spectral behaviour of relativistic particles. These observed spectra suggest particle spectra very close to $E^{-2}$.

2. We obtain i) particle energies, ii) particle flux and iii) spectrum for reasonable assumptions for the chemical composition of the energetic particles. We also put a constraint on the particle propagation through the cosmos.

With the new data analysis of the Fly’s Eye data (Gaisser et al. 1992) and an analysis of Akeno data (paper CR IV) we have now information on both the chemical composition and spectrum of the ultra-high energy cosmic rays. Furthermore, we can use the world data set on the cosmic rays to obtain an averaged spectrum of all cosmic rays beyond 0.1 EeV as a basis for the absolute normalization of the new component.

In this paper we propose to compare theory and experimental data for the ultra-high energy particles. In the following we first discuss the world set of cosmic ray data and how to obtain from them a good average spectrum beyond the knee, then the prediction, the new chemical composition and spectral data from Fly’s Eye and Akeno, then combine prediction and data and discuss the implications, and finally give an outlook on what to do next.

## 2 The world data set on ultra-high energy cosmic rays

The measurement of the flux of ultra high energy cosmic rays is difficult because of their small flux (less than 0.05 particles per m$^2$.ster.year above $E = 10^8$ GeV). Still a relatively large statistics has been collected during the last 20 years by four experiments, three of which are still active (Akeno (Nagano et al. 1984; 1992), Yakutsk (Efimov et al. 1990) and the Fly’s Eye (Cassiday et al. 1990; Loh et al. 1991)). The array at Haverah Park (Cunningham et al. 1980) does no longer exist. A recent presentation and comparison of the results of the four arrays is made by Sokolsky et al. (1992).

The first impression of these results is that significant variations exist in the absolute normalization and the spectral details of the fluxes measured by different arrays (see Fig. 1). This impression is however deceiving. The energy measurement in individual air showers is no better than 20% because of fluctuations in shower development and very small ratio of sensitive to effective area which emphasizes the fluctuations. The small coverage is necessary in conventional shower arrays with effective area approaching 100 km$^2$. Systematic errors of the same order are not only possible but very likely. The estimate of the primary energy relies heavily on calculations of the shower development and estimates of the acceptance of the array, which are very difficult and may not be exact. The absolute normalization of the cosmic ray flux given by two different sets of detectors at Akeno (the 1 km$^2$ and the 20 km$^2$ arrays) is different by about 1.5 (Nagano et al. 1992).

The usual presentation of the flux ($E^3 \times f$) exaggerates the large differences in the normalization on the $E^3 \times f$ plot. We will attempt to look for very small systematic energy shifts that may bring data points from different experiments in good agreement.

Apart from the differences in normalization all data sets show the same slope ($\gamma = 3.0 - 3.1$) in the region $3 \times 10^{17} - 3 \times 10^{18}$ eV. We use the data in this range to normalize experiments to each other. First an average spectrum is calculated using the original experimental errors. Then we calculate for each experiment the energy shift $\Delta E$ that brings the data set in best agreement with the average spectrum. The resulting shifts are smaller than the suspected systematic errors – we obtain $\Delta E = -16\%$ for Yakutsk, $-13\%$ for Akeno, $-3\%$ for Haverah Park (which has the smallest statistical errors) and $+6\%$
Fig. 1: The high energy cosmic ray data, both in their original form – shaded – and after shifting to a common normalization near 1 EeV, and averaging with weighting. The various symbols denote the different experiments: Akeno, circles; Yakutsk, triangles; Fly’s Eye, hexagons; Haverah Park, squares.
for the Fly’s Eye. We apply these energy shifts to the full data sets and obtain a world data set where
the scatter is smaller than the individual error bars. Finally we bin in logarithmically equal energy
bins, combine individual data points within the same bin and produce the average flux shown with
black squares on Figure 1. This is the flux that we shall use to estimate the strength of different
chemical components further down.

This procedure is not unique and does not eliminate the systematic errors in the energy derivation.
We claim, however, that it introduces a standard systematic error, which is nearly the same for
all data sets. The energy shifts required for the averaging are remarkably small. A better way to
achieve a standard energy derivation from different experiments is a detailed study of the experimental
algorithms (Lawrence et al. 1991) and a comparison and possible improvement of their theoretical
bases.

3 The prediction: Hot spots of powerful radiogalaxies

Hot spots of powerful radio galaxies and the related radio quasars have been argued to be sites of
strong particle acceleration for some time (Biermann and Strittmatter 1987, Meisenheimer et al. 1989).
After some initial analytical arguments (Biermann 1990, 1991) we demonstrated in paper UHE-CR I,
following Berezinsky and Grigor’eva (1988), that a proper calculation of the source evolution as well
as the cosmic ray particle transport through the evolving universe is capable to produce spectra with
the following properties:

1. Assuming the ratio of energetic protons to electrons to be of order 10 and all other unknown
efficiencies to average out to a factor near unity, one obtains a flux of extragalactic cosmic rays
very close to the observed flux at 10 EeV.

2. The spectrum is approximately the source spectrum below 0.1 EeV, i.e., approximately $E^{-2}$
– known from the synchrotron radio emission of hot spots – then steepens to approximately
$E^{-2.75}$, and cuts off just below 100 EeV in particle energy (Greisen 1966; Zatsepin and Kuzmin
1966; Stecker 1968). Depending on the source cutoff, there is a more or less pronounced bump
at particle energies just below the cutoff. The exact shape of the spectrum is obtained by a
proper calculation of propagation and redshift. Already above 0.1 EeV a slight steepening from
$E^{-2}$ sets in to approximately $E^{-2.15}$ due to galactic evolution effects.

3. The shock, which produces the acceleration is due to the violent interaction of a jet emanating
from an active nucleus with the medium in intergalactic space, and thus is expected to have
chemical abundances between those typical for the inner parts of big elliptical galaxies (“normal”
abundances, with heavy elements enriched by a factor up to 3 over solar) and those typical for
intercluster gas (heavy element enrichment weak to 1/3 solar), as known from X-ray spectroscopy
of clusters of galaxies. This means, that protons dominate, and Helium is of order 10% in number
density relative to Hydrogen; the elements Carbon, Nitrogen, Oxygen, to Iron should be between
a maximum of 3 times solar, and negligible. Obviously, the propagation of nuclei heavier than
Hydrogen in the intergalactic space can lead to spallation by photonuclear interactions with
both the infrared and the microwave background, and thus lower the observed abundances of
these nuclei.

In Fig. 2 we present a series of model calculations for an input spectrum of $E^{-2}$ with an intrin-
sic exponential cutoff at different energies in the range about 100 EeV, and a Hubble constant of
75 km sec$^{-1}$ Mpc$^{-1}$. Such calculations involve an estimate for the conversion of radio luminosity to jet
power (Rawlings and Saunders 1991), from jet power to energy in energetic particle populations, and,
most importantly, the ratio between the energy density of the energetic electrons, and the energetic
nuclei – after all, the observed synchrotron emission traces only the relativistic electrons. The com-
bination of these factors we refer to as the “fudge factor”, and since it is dominated by the nuclei to
electron ratio, it is expected to be below 10. Indeed, low energy fits to the Fly’s Eye data for protons
(see below) imply this factor to be near 3, and so suggest that the proton to electron ratio is of near
20 or less (see UHE-CR I).
Fig. 2: Model calculations for the extragalactic cosmic ray proton population observed near earth, assuming FR-II galaxies to be the dominant sources. We assume an input spectrum of $E^{-2}$ with an exponential cutoff – the logarithm of the respective cutoff Lorentz factor is indicated – and a Hubble constant of 75 km sec$^{-1}$ Mpc$^{-1}$

4 The new Fly’s Eye and Akeno data analysis: high energy protons

We have used two independent methods to estimate the extragalactic flux from different air shower experiments. First we fit the shower size distributions published by the Akeno experiment (Nagano et al. 1984) for different zenith angles. Then we use the results of a recent analysis (Gaisser et al. 1992) of the cosmic ray composition around $10^{18}$ eV from the measurements of the Fly’s Eye detector (Cassiday et al. 1990).

The Akeno shower array is a traditional detector that measures the number of charged particles in the shower ($N_e$) that reach the observation level. We use data sets for vertical (secan $\theta = 1.0$, atm. depth = 920 g/cm$^2$) and slightly inclined (secan $\theta = 1.2$, atm. depth = 1104 g/cm$^2$) showers. The fitting procedure is described in detail in paper CR IV and consists of stepping through the energy spectrum of each chemical component with a small logarithmic step ($10^{0.01}$) and calculating the size of a number of showers at that energy and primary mass with the parametrization of Gaisser (1979). The resulting sizes at both depths are binned with the appropriate weight, and the sum for all components is then compared with the experimental data.

In the spectrum and composition model of CR IV all galactic nuclear components have the same spectral index of 3.07 at energies above $4 \times 10^{16}$ eV. The comparison with the experimental $N_e$ distribution demonstrates that galactic cosmic rays fit well the shower size distribution up to $N_e = (1 - 3) \times 10^7$, but are insufficient to maintain the calculated spectrum, especially for inclined showers, in agreement with experimental data for bigger $N_e$. A better fit requires the introduction of a flatter cosmic ray component at energy above $10^{16}$ eV. The agreement is achieved by introducing a component, consisting of pure Hydrogen, with an energy spectrum of $(1.4 \pm 0.3)10^{-7} \times E^{-2}$ (cm$^2$ ster s GeV)$^{-1}$ at energies between $10^{16}$ and $5 \times 10^{17}$ eV and $(0.47 \pm 0.09) \times E^{-2.75}$ (cm$^2$ ster s GeV)$^{-1}$ at higher energy, where $E$ is measured in GeV. Because the spectral shape of this component is entirely different from those of the galactic cosmic rays it is very likely to represent an emerging extragalactic cosmic
ray flux. This flux is shown with a box on Figure 3.

The exact shape and normalization of the extragalactic component quoted above is not an unique solution of the experimental data fit. A slightly steeper spectrum ($\gamma = 2.1 - 2.2$) in the lower energy range would produce a somewhat better fit. The absolute normalization below and above the break at $5 \times 10^{17}$ eV is a result of the assumption that this flat component consist only of Hydrogen nuclei. Since protons are more efficient in generating shower size at the observation level, any admixture of He and heavier nuclei would require a higher overall normalization. The spectrum quoted above is thus the minimum flux of extragalactic cosmic ray nuclei necessary for a fit of the Akeno shower size spectra. As discussed in CR IV an important source of uncertainty in the fit are the uncertainties from the extrapolation of the particle physics input to air shower energies.

For the second estimate we use the recent results from the analysis of the Fly’s Eye measurements of the depth of maximum ($X_{\text{max}}$) distribution in terms of cosmic ray composition. The Fly’s Eye is a different type of detector, which observes directly the longitudinal development of air showers through the detection of the fluorescent light from the atmospheric Nitrogen atoms, induced by the shower charged particles. The amount of fluorescent light is proportional to the number of charged particles after an account is made for light scattering and absorption. The data analysis fits individual data points (taken at various atmospheric depths) to a shower profile and derives the depth ($X_{\text{max}}$) and size ($N_{\text{max}}$) of the shower maximum. $X_{\text{max}}$ is proportional to the energy of the primary nucleus and $X_{\text{max}}$ depends on the energy and mass of the primary nucleus. The sensitivity to the primary mass comes from the rate of energy dissipation, which is faster in showers initiated by heavy nuclei. $X_{\text{max}}$ of Fe generated showers is about 100 g/cm$^2$ shallower than that of proton generated shower of the same energy.

The basic idea of the shower analysis is to simulate a large number of air showers and compare the results to data. The simulation includes a thorough account for the light production process and the experimental triggering and efficiency as a function of energy, distance to the detector and angle of the detected shower. The results of the simulation are reconstructed with the algorithm developed for and used in the analysis of experimental data. Showers of three composition groups (Hydrogen, CNO, and Fe) were simulated for two different equally valid extrapolations of the properties of hadronic interactions to $10^9$ GeV. The composition groups are defined by the sensitivity of the procedure to primary mass. At the energies in question Hydrogen and Helium showers are almost indistinguishable because these nuclei have nearly the same cross section for inelastic interactions. All nuclei with $A$ greater than 20 are also indistinguishable, because the mass dependent difference in $X_{\text{max}}$ in this range is significantly smaller than the current detector resolution of 45 g/cm$^2$. In this analysis the whole group of nuclei with $A > 20$ is identified as Iron.

The experimental $X_{\text{max}}$ distribution is then fitted with the simulated distributions for primary nuclei of different mass. The best fit ($\chi^2$ minimization) determines the composition in terms of the three distinguishable components. The procedure is repeated for two interaction models that fit the data equally well and the following fractions of proton showers are determined: $0.13 \pm 0.05$, $0.23 \pm 0.12$ and $0.43 \pm 0.11$ at energies of 0.38, 0.63 and 1.41 EeV, respectively. The error bars above include both the statistical errors from the experimental statistics and the fitting procedure and the systematic errors from the particle physics input in the simulation, which also make the errors very asymmetric.

The corresponding proton flux (from the average spectrum of Fig. 1) is $(8.9 \pm 3.4) \times 10^{-25}$, $(3.2 \pm 1.1) \times 10^{-25}$ and $(5.1 \pm 1.3) \times 10^{-26}$ (cm$^2$ ster GeV)$^{-1}$ at the three energies, respectively. These three data points are plotted on Fig. 3 and represent the upper limits for the extragalactic proton flux measured by the Fly’s Eye. Since the detector cannot differentiate between Hydrogen and Helium these flux values reflect the sum of the two components.

## 5 Prediction and experiment

In Fig. 3 we now combine the best curve selected from Fig. 2, that curve with an intrinsic cutoff of 100 EeV, which is nearly $E^{-2.75}$ between 1 EeV and 30 EeV. We selected this curve because it fits best the experimental data simultaneously in the low and the high energy range. The fit is quite good, considering the error bars on the data, fitting to about $2\sigma$ or better.

Most of the existing theoretical proposals to explain the origin of the cosmic ray particles at energies beyond the knee can be excluded on the basis of the presented data:
Fig. 3: Data and model calculations for the different components of the UHE cosmic ray population observed near earth. The best fit extragalactic proton component is taken from Fig. 2 and fitted to the Fly’s Eye data for the proton/He component. The difference to the total cosmic ray spectrum gives an indication for the heavy nuclei contribution and can be fitted by an $E^{-3.1}$ spectrum with an exponential cutoff at 5 EeV. The errors of this difference component are clearly underestimated since the theoretical uncertainties of the extragalactic contribution are disregarded.

1. Beyond the knee the particles are dominantly heavy nuclei and not all protons as follows from the proposals by Protheroe and Szabo (1992), and by Salamon and Stecker (1992).

2. The galactic wind model by Jokipii and Morfill (1987) would give normal, i.e. close to solar, abundances for these cosmic ray particles, as would the reacceleration model (Ip and Axford 1992) except for the highest particle energies. Again, the observed abundances clearly disagree with these models.

The difference curve ought to correspond to the galactic contribution of heavy nuclei; this is first of all confirmed by the Fly’s Eye analysis, which does suggest, that in this particle energy range there are very few nuclei of Carbon, Nitrogen, and Oxygen, and many heavier nuclei. Second, over the particle energy range which is well measured, i.e. below a particle energy of about 10 EeV, the curve is well described by a powerlaw with an exponential cutoff near 5 EeV, just as suggested by the earlier cosmic ray arguments (papers CR I, CR II, and CR IV) for the galactic contribution of cosmic rays. At energies above 30 EeV the subtraction is clearly unreliable, since the difference is between two large numbers of similar numerical value.

We note that an incorporation of a putative infrared radiation background would slightly lower the theoretical curve in the powerlaw section below 0.3 EeV particle energies, so that theory and observation would come closer. We also emphasize that Helium and heavier nuclei in the extragalactic contribution would influence the high energy behaviour near 30 EeV, and the heavier nuclei would probably add some flux there.
6 Outlook

We conclude first that a detailed check of the existing prediction with the new data now available is successful. The extragalactic contribution can be readily modeled in a) flux, b) spectrum, and c) chemical composition.

There is a second important conclusion: Strong shocks in extragalactic jets and their associated hot spots do produce energetic nuclei. This is of interest, since in all arguments about Gamma-ray sources like the quasar 3C279, Mkn 421 and the like (Hartman et al. 1992, Punch et al. 1992), there is always the question whether active galactic nuclei accelerate nuclei at all in their jets. The successful fit made here suggests strongly, that this is the case, and that protons dominate the process. This gives strong support to hadronic interaction models to explain the gamma-ray emission from such quasars (Mannheim and Biermann 1992; Mannheim 1993).

However, there are areas where we should improve the calculation:

1. Clearly, using an universal source cutoff in particle energy in form of an exponential cutoff, is much too simple. The detailed shape of the cutoff of any single source might be much softer than an exponential attached to a powerlaw, and the cutoff energy of various sources could be quite different. Both effects would soften the average shape of the source cutoff spectrum. This requires a better understanding of the source structure and shock topology.

2. We have used straight line propagation through the universe. Clearly, this can only be an approximation to a situation where particles are weakly scattered. Our model predicts, that we see particles from nearby radiogalaxies. That we observe these particles at the expected spectrum, implies that the mean free path for scattering is of order 1/3 of the typical distance to nearby powerful radiogalaxies, or larger, for all particle energies above 0.1 EeV. This mean free path is of an order similar to the bubble size seen in the galaxy distribution, of order 50 Mpc (e.g. Einasto et al. 1989).

3. Helium and heavier nuclei are likely to become important near the high energy cutoff of the Hydrogen population. Here, photonuclear interactions have to be taken into account, and this is one of the next steps we plan to undertake. Limits may be possible from future data on the high energy photon background.

4. The infrared background can be estimated from the cosmological evolution of galaxies, using deep CCD and HST data as well as the IRAS counts. Such estimates can also be limited by determining the microwave background fluctuations at redshifted FIR frequencies corresponding to early galaxy formation and evolution, observable now near 1 mm wavelength.

5. An independent estimate can be made for the extragalactic cosmic ray contribution from normal and starburst galaxies, using all the same models as discussed in the paragraph immediately above. Normal galaxies also produce cosmic rays, which leak out to intergalactic space and can add up to appreciable fluxes over cosmological time scales (see, e.g., Biermann 1991). Such a calculation should be done properly.

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