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Combined fit of spectrum and composition data as measured by the Pierre Auger Observatory

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Abstract. We present a combined fit of a simple astrophysical model of ultra-high energy cosmic rays UHECR sources to both the energy spectrum and composition data measured by the Pierre Auger Observatory. The fit has been performed for energies above 5×10^{18} eV, i.e. the region of the all-particle spectrum above the so-called "ankle" feature. The astrophysical model we adopted consists of identical sources uniformly distributed in a comoving volume, where nuclei are accelerated through a rigidity-dependent mechanism. The fit results suggest sources characterized by relatively low maximum injection energies, hard spectra and heavy chemical composition.

Resumo. Apresentamos um ajuste combinado de um modelo astrofísico simples de fontes UHECR de raios cósmicos de energia ultra alta tanto para o espectro de energia como para os dados de composição medidos pelo Observatório Pierre Auger. O ajuste foi realizado para energias acima de 5×10^{18} eV, ou seja, a região do espectro de todas as partículas acima do chamado recurso de "tornozelo". O modelo astrofísico que adotamos consiste em fontes idênticas uniformemente distribuídas em um volume comovente, onde os núcleos são acelerados através de um mecanismo dependente da rigidez. Os resultados de ajuste sugerem fontes caracterizadas por energias de injeção máximas relativamente baixas, espectros duros e composição química pesada.

Keywords. cosmic ray experiments - cosmic rays - composition

1. Introduction

The origin of UHECRs, particles reaching the Earth with energies over 10^{18} eV up to 10^{20} eV and beyond, is still unknown. Nevertheless, a general consensus has emerged that the most energetic cosmic rays are extragalactic, with the transition between galactic and extragalactic cosmic rays taking place somewhere between 10^{17} and a few times 10^{18} eV. The flux of cosmic rays above 10^{18} eV is of the order of 1 km^{-2} yr^{-1} . Therefore, very large arrays of particle detectors are needed to study them; the largest such array is the Pierre Auger Observatory in Argentina.

The propagation of such particles across cosmological distances can affect their observed energy spectrum and mass composition in nontrivial ways.

In this work, we attempt to simultaneously reproduce both the Auger spectrum and X_{max} data with a simplified model of UHECR sources, characterized by: sources accelerate different amounts of nuclei; injection of five representative stable nuclei: Hydrogen (H), Helium (He), Nitrogen (N), Silicon (Si) and Iron (Fe), which are approximately equally spaced in lnA; power-law spectrum with rigidity-dependent broken exponential cutoff

$$\frac{dN_{inj,i}}{dE} = \begin{cases} J_o a_i (E/E_o)^{-\gamma}, & \frac{E}{Z_i} < R_{cut} \\ J_o a_i (E/E_o)^{-\gamma} \exp[1 - E/(Z_i R_{cut})] & E/Z_i > R_{cut} \end{cases} \quad (1)$$

where J_o is a normalization factor, $E_o = 10^{18}$ eV, and Z_i is the atomic number of the $i-th$ injected nuclide, whose fraction in the sources, a_i, is normalized in such a way that $\sum_i a_i = 1$. This model is not able to reproduce the data measured over the entire energy range.

2. The data set and the simulations

The data we fit in this work consist of the SD event distribution in 15 bins of 0.1 of $\log_{10}$(E/eV), (18.7 ≤ log 10 (E/eV) ≤ 20.2) and X_{max} distributions (in bins of 20 g/cm^2).

Table 1. The parameter values obtained for the first and second minimum.

reference model (SPG - EPOS-LHC)	main minimum best fit	average	2nd minimum best fit	average
$\mathcal{L}_0$ [10^{44} erg Mpc^{-3} yr^{-1}]	4.99		9.46 (from $E_{min} = 10^{15}$eV)	
γ	$0.96^{+0.08}_{-0.13}$	0.93 ± 0.12	2.04 ± 0.01	$2.05^{+0.02}_{-0.04}$
$\log_{10}(R_{cut}/V)$	$18.68^{+0.02}_{-0.04}$	18.66±0.04	19.88±0.02	19.86±0.06
f_H(%)	0.0	$12.5^{+19.4}_{-12.5}$	0.0	$3.3^{+5.2}_{-3.3}$
f_{He}(%)	67.3	$58.6^{+12.6}_{-13.5}$	0.0	$3.6^{+6.1}_{-3.6}$
f_N(%)	28.1	$24.6^{+8.9}_{-9.1}$	79.8	$72.1^{+9.3}_{-10.6}$
f_{Si}(%)	4.6	$4.2^{+1.3}_{-1.3}$	20.2	$20.9^{+4.0}_{-3.91}$
f_{Fe}(%)	0.0		0.0	

The free parameters of the fit are: the injection normalization factor J_o, the injection spectral index γ, the cutoff rigidity R_{cut} , and the element fractions at injection (four free parameters a_H, a_{He}, a_N, a_{Si}; the fifth is bound by a_{Fe}=1-a_H-a_{He}-a_N-a_{Si}).

Main and second local minimum parameters for the reference model. Errors on best-fit spectral parameters are computed from the interval $D \leq D_{min} + 1$.

The best fit obtained occurs for $\gamma \approx 1$, low maximum rigidity around $R_{cut} = 10^{18.5}$ V, a hard spectrum and a composition dominated by Helium and heavier elements.

There is also a second relative minimum, which appears less extended, around the pair γ = 2.04 and $\log_{10}$ (R_{cut}/V)=19.88.

3. Fit results

Top: simulated energy spectrum of UHECRs (multiplied by E^3) at the top of the Earth's atmosphere with the best-fit parameters and the local minimum at $\gamma \approx 2$, along with Auger data points.

Bottom: average and standard deviation of the X_{max} distribution as predicted (assuming EPOS-LHC UHECR-air interactions) for the model (brown) versus pure H (red), He (grey), N (green) and Fe (blue), dashed lines. Only the energy range where the brown lines are solid is included in the fit.

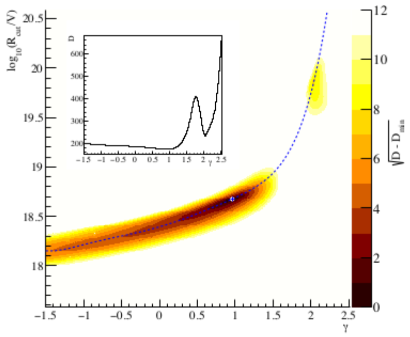

Figure 1. Deviance $\sqrt{D - D_{min}}$, as function of γ and $\log_{10}(R_{cut}/V)$. The dot indicates the position of the best minimum, while the dashed line connects the relative minima of D (valley line).

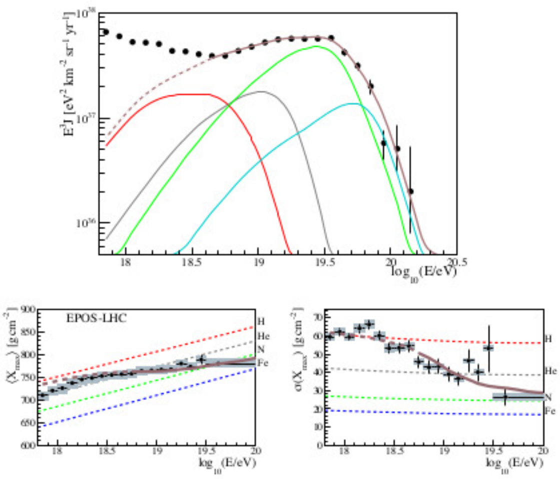

Figure 2. The best-fit parameters for the reference model

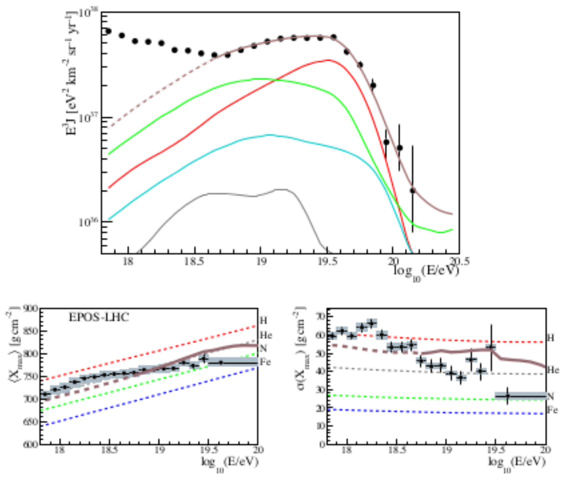

Figure 3. Same as figure 2 at the local minimum at $\gamma = 2.04$, EPOS-LHC UHECR-air interactions.

4. Propagation models

It can be seen that the relationship between γ and R_{cut} and the position of the second local minimum are very similar from one model to another, but the position of the best fit within the 'valley' and the height of the 'ridge' between the two local minima are strongly model-dependent.

To study the effects of uncertainties in the simulations of UHECR propagation, we repeated the fit using the combinations of Monte Carlo propagation code, photo-disintegration cross sections and EBL spectrum listed in the tables that represent Best-fit parameters and 68% uncertainties for the various propagation models.

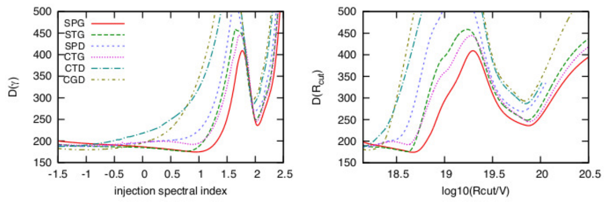

Figure 4. D for each value of γ (first panel) and R_{cut} (second panel) for each propagation model, where the other parameters are chosen so as to minimize D.

Table 2. Best-fit parameters and 68% uncertainties for the various propagation models we used (see table 3). For the CTG model we report the two main local minima.

model	γ	$\log_{10}(R_{cut}/V)$	D	D(J)	D(X_{max})
SPG	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$	174.3	13.2	161.1
STG	$+0.77^{+0.07}_{-0.13}$	$18.62^{+0.02}_{-0.04}$	175.9	18.8	157.1
SPD	$-1.02^{+0.31}_{-0.26}$	$18.19^{+0.04}_{-0.03}$	187.0	8.4	178.6
CTG	$-1.03^{+0.35}_{-0.30}$	$18.21^{+0.05}_{-0.04}$	189.7	8.3	181.4
	$+0.87^{+0.08}_{-0.06}$	$18.62_{\pm 0.02}$	191.9	29.2	162.7
CTD	$-1.47^{+0.28}_{*}$	$18.15^{+0.03}_{-0.01}$	187.3	8.8	178.5
CGD	$-1.01^{+0.26}_{-0.28}$	$18.21_{\pm 0.03}$	179.5	7.9	171.6

*This interval extends all the way down to -1.5, the lowest value of γ we considered.

Table 3. The propagation models used (see Ref. (5))

	MC code	$\sigma_{\text{photodisint}}$	EBL model
SPG	SimProp	PSB	Gilmore 2012
STG	SimProp	TALYS	Gilmore 2012
SPD	SimProp	PSB	Domínguez 2011
CTG	CRPropa	TALYS	Gilmore 2012
CTD	CRPropa	TALYS	Domínguez 2011
CGD	CRPropa	Geant4	Domínguez 2011

5. Conclusions

In this work we have shown that, within given hypotheses on propagation and interaction at Earth, Auger data can bind the physical parameters of the sources in the simple astrophysical model considered.

However several different hypotheses (i.e. atmospheric interaction and choices of photo-disintegration cross sections) can be made with resulting source parameters well outside the statistical uncertainties of the fit. Better models of UHECR-air hadronic interactions, or photo-disintegration cross sections and branching ratios would help reduce these uncertainties.

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