Inferences about the mass composition of cosmic rays from data on the depth of maximum at the Auger Observatory

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Abstract: In this paper we outline the details of a method used to estimate the mass composition of ultra-high energy cosmic rays, which is based on interpretation of the data on shower maximum, $X_{\rm max}$, measured using the fluorescence telescopes of the Pierre Auger Observatory. The analysis is performed using a variety of hadronic interaction models. The results of our analyses will be presented at the Conference.

Keywords: Pierre Auger Observatory, ultra-high energy cosmic rays, depth of shower maximum, mass composition.

1 Introduction

The composition of ultra-high energy cosmic rays (UHECRs) is yet to be fully understood. The atmospheric depth where the longitudinal development of the air shower reaches the maximum number of particles, $X_{\rm max}$, is a standard observable used to extract composition information as different nuclei produce different mean values of $X_{\rm max}$ and different dispersions in $X_{\rm max}$. Conversion of $X_{\rm max}$ to mass is inferred through air-shower simulations. In particular, the mean and dispersion of $X_{\rm max}$ are commonly used to infer the mass composition.

We report a method that parameterises the mean value of the depth of shower maximum, $\langle X_{\rm max}\rangle$, and its dispersion, $\sigma(X_{\rm max})$, and these observables are converted to the first two moments of the log-mass distribution, $\langle \ln A\rangle$ and $\sigma^2_{\ln A}$. Refinements to the method have been made over those originally proposed [1].

The reliance on hadronic interaction models mean that the mass composition measurement is subject to some level of uncertainty, as different physics assumptions are used to extrapolate interaction properties beyond man-made accelerator energies. Hence results must always be interpreted within the context of the models used.

The Pierre Auger Collaboration will present the results of the updated analysis on the mass composition derived from the $X_{\rm max}$ data using the updated hadronic interaction models at the Conference. This paper discusses only the method and not the results.

2 Utilising the moments of $X_{\rm max}$

The superposition model allows simple scaling between masses and a log-linear dependence of energy. This model is generalized to include additional energy and mass dependent terms and is better able to accommodate all the hadronic interaction models used. The $\langle X_{\rm max}\rangle$ is now expressed as

$$\langle X_{\rm max}\rangle = X_0 + D\log\left(\frac{E}{E_0 A}\right) + \xi \ln A + \delta \ln A \log\left(\frac{E}{E_0}\right), \quad (1)$$

where X_0 is the mean depth of proton showers at energy E_0 and D is the elongation rate, and the parameters ξ and δ are derived for each hadronic interaction model.

From Eq. (1), the mean and dispersion of $X_{\rm max}$ for a mixed composition are derived as

$$\langle X_{\rm max}\rangle = \langle X_{\rm max}\rangle_p + f_E \langle \ln A\rangle \quad (2)$$

$$\sigma^2(X_{\rm max}) = \langle \sigma^2_{\rm sh}\rangle + f_E^2\, \sigma^2_{\ln A}\,. \quad (3)$$

The linearity of the mean with respect to $\langle \ln A\rangle$ is demonstrated in Eq. (2), where the first term is the mean of $X_{\rm max}$ for a proton. The dispersion of Eq. (3) has two terms, where the first term denotes the shower-to-shower fluctuation is contained in $\langle\sigma^2_{\rm sh}\rangle$ and the second term reflects the dispersion in $\ln A$ arising from the mass distribution of the composition. The energy-dependent parameter f_E is expressed as

$$f_E = \xi - \frac{D}{\ln 10} + \delta \log\left(\frac{E}{E_0}\right). \quad (4)$$

The first two moments of $\ln A$ can be obtained by inverting Eqs. (2, 3);

$$\langle \ln A\rangle = \frac{\langle X_{\rm max}\rangle - \langle X_{\rm max}\rangle_p}{f_E} \quad (5)$$

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{\rm max}) - \sigma^2_{\rm sh}(\langle \ln A\rangle)}{b\,\sigma^2_p + f_E^2}\,. \quad (6)$$

To obtain an explicit expression for $\langle\sigma^2_{\rm sh}\rangle$ we need a parameterization for $\sigma^2_{\rm sh}(\ln A)$. We assume a quadratic law in $\ln A$:

$$\sigma^2_{\rm sh}(\ln A) = \sigma^2_p[1 + a\ln A + b(\ln A)^2]\,, \quad (7)$$

where σ^2_p is the $X_{\rm max}$ variance for proton showers. The evolution of $\sigma^2_{\rm sh}(\ln A)$ with energy is included in σ^2_p and the parameter a:

$$\sigma^2_p = p_0 + p_1\log_{10}\left(\frac{E}{E_0}\right) + p_2\left[\log_{10}\left(\frac{E}{E_0}\right)\right]^2 \quad (8)$$

$$a = a_0 + a_1\log_{10}\left(\frac{E}{E_0}\right). \quad (9)$$

The parameters necessary to calculate Eqs. (5) and (6) for each of the hadronic interaction models have been derived using the air shower generator CONEX [2] and are available in Ref. [3] for EPOS 1.99 [4], QGSJet 01 [5], QGSJet II-03 [6], and Sibyll 2.1 [7]. In this paper we extend the parameterizations to the LHC-tuned hadronic models EPOS-LHC and QGSJet II-04, available in CONEX v4r37. The corresponding paramaters are given in Tables 1 and 2.

parameter	EPOS-LHC	QGSJet II-04
X_0	806.1 ± 0.3	790.4 ± 0.3
D	55.6 ± 0.5	54.4 ± 0.5
ξ	0.15 ± 0.24	-0.31 ± 0.24
δ	0.83 ± 0.21	0.24 ± 0.21

Table 1: Parameters of Eq. (1) for EPOS-LHC and QGSJet II-04, setting $E_0 = 10^{19}$ eV. All values are expressed in g cm^{-2}.

parameter	EPOS-LHC	QGSJet II-04
$p_0 \times (\mathrm{g}^{-2}\mathrm{cm}^4)$	3284 ± 51	3738 ± 54
$p_1 \times (\mathrm{g}^{-2}\mathrm{cm}^4)$	-260 ± 64	-375 ± 66
$p_2 \times (\mathrm{g}^{-2}\mathrm{cm}^4)$	132 ± 108	-21 ± 109
a_0	-0.462 ± 0.006	-0.397 ± 0.007
a_1	-0.0008 ± 0.0016	0.0008 ± 0.0019
b	0.059 ± 0.002	0.046 ± 0.002

Table 2: Parameters of Eqs. (7-9) for EPOS-LHC and QGSJet II-04, setting $E_0 = 10^{19}$ eV.

Equations (5) and (6) can be used to study the evolution of the moments of the log mass distribution, $\langle \ln A \rangle$ and $\sigma^2_{\ln A}$, as shown in Ref. [3] and infer the mass composition in the energy range of the $X_{\max}$ measurements of the Auger Observatory.

3 Conclusion

The method using the first two moments of $X_{\max}$ and $\ln A$ to infer the mass composition from the $X_{\max}$ data have been discussed. This method can also be used to investigate the validity of hadronic interaction models. The final data analysis using the latest dataset from Auger [8] that also compares the differences between the pre- and post-LHC hadronic interaction models will be presented at the Conference.

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