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Conclusions about properties of high-energy cosmic-rays drawn with limited recourse to hadronic models

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Abstract

Determining the energy and mass of the highest energy cosmic rays requires knowledge of features of particle interactions at energies beyond those reached at the LHC. Inadequacies of the model predictions set against a variety of data are summarised and it is clear that firm statements about primary mass are premature. Nonetheless, conclusions of significance about the origin of the highest-energy cosmic rays can be deduced from the data.

This paper is dedicated to my great friend and colleague, Jim Cronin, who died suddenly on 25 August 2016, without whom the Auger Collaboration would not have happened.

Keywords: high-energy cosmic–rays, hadronic interactions, cosmic-ray origin

1. Introduction

The origin of the highest-energy cosmic rays, which are explored exclusively through study of the extensive air-shower, remains one of the major puzzles in high-energy astrophysics. One reason is that the majority of the particles are charged so that intervening magnetic fields make it difficult to track them to their birthplace. A second issue is that interpretation of data bearing on mass composition is hampered by lack of knowledge of key features of hadronic interactions, including cross-section, multiplicity, inelasticity and features of pion-nucleus collisions at energies above about 300 GeV, the latter being extremely numerous in air-showers. A collision of a 100 PeV proton with a nucleus has a centre-of-mass energy of ~14 TeV so that the properties of the energy domain beyond this, at trans-LHC energies, are unknown. A conservative assumption is that key properties change smoothly as the energy increases, but one cannot exclude surprises – the *'unknown unknowns'*. Even at ~0.5 PeV, where the air-shower regime begins, the lack of knowledge of some details of the hadronic physics is a serious handicap to extracting mass information and to making accurate estimates of primary energy.

Below I will show first that the extant shower models lead to contradictory deductions about the primary mass at a given energy. Ideally one might envisage that, with the range of independent evidences available, progress in defining the key features of the hadronic interactions would be possible. Although we are still some way from this goal, understanding is increasing. I will then argue that, despite these limitations, key astrophysical information can be extracted from the observations.

2. Measurements targeted at obtaining the primary mass: evidence for deficiencies in hadronic models

Above 100 PeV, several methods have been developed that target measurement of the primary mass. The best-known one makes use of fluorescence detectors to study the change of the depth of shower

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maximum, X_{max}, with energy. If, for example, one had a beam of cosmic rays of a single nuclear species then elementary considerations about shower development lead to the expectation that the position at which the particle number, or rate of energy deposition, maximises will move deeper into the atmosphere as the primary energy increases. The rate of change of X_{max} with energy is called the elongation rate, a term introduced by Linsley [1]. Specifically he showed that while for a photon the elongation rate is $2.72X_0$ g cm^{-2} per decade, where X_0 is the radiation length, for a single nuclear species it must be considerably smaller.

Measurements of X_{max} as a function of energy made at the Auger Observatory [2] are shown in figure 1 together with similar results reported by the Telescope Array (TA) Collaboration [3]. Different approaches to the analyses make point-by-point comparisons impossible. In figure 1 predictions from the Sibyll 2.1 model are also shown.

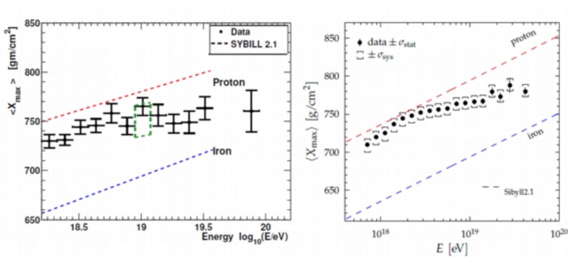

Fig.1. The variation of the depth of shower maximum with energy, as measured by the TA Collaboration (LH) and the Auger Observatory (RH) [3, 2] compared with predictions with the Sibyll 2.1 model for proton and iron primaries.

Neither data set can be fitted adequately with the single straight line expected for a mass composition that does not change with energy: even with the large uncertainties of the TA measurements, the reduced χ^2 for a linear fit to all data is unacceptably large (7.1 for 10 degrees of freedom). Thus the mass composition must be changing as the energy increases, *unless* features of the hadronic model change in a perverse way (for example a marked change in the multiplicity or the cross-section with energy). It is evident that *if* the Sibyll model is correct then both data sets indicate a mass composition that is proton-dominated below ~5 EeV, while at higher energies, because the elongation rate is flatter – as evident in both data sets - the mean mass must be becoming heavier. Note that with a revised Sibyll model it is found that depths of shower maxima are pushed deeper into the atmosphere than found with Sibyll 2.1 [R Engel, these Proceedings]. Moreover, as will be shown shortly, other hadronic models fail to describe data where muons are involved and thus the strongest remark that can be made, independent of model assumptions, is that the mean mass increases above ~5 EeV. This important and unambiguous conclusion is counter to that strongly espoused by the HiRes and TA groups, and often accepted uncritically by theorists, namely that the ultra-high energy cosmic rays are all protons.

If one accepts the models then deductions about the natural logarithm of the atomic mass (ln A = 0 for protons and 4 for Fe) can be made. Estimates of ln A from Auger data using two other models are shown in figure 2 [2]: the Sibyll result lies between those shown. Also displayed are estimates of <ln A> from two other studies. In one [4] the depth of the maximum of the muons in the shower, $\langle X_\mu^{max} \rangle$, is measured and results compared with predictions. In the other [5], the attenuation of showers across the surface detectors of the Auger Observatory was studied. An asymmetry in the distribution of arrival times of particles is found which is dependent on the development of showers so that mass information can be evaluated. The quantity derived, $((\sec\theta)_{max})$, depends on the radial distance from the shower axis, with muons becoming an increasingly dominant component at larger distances.

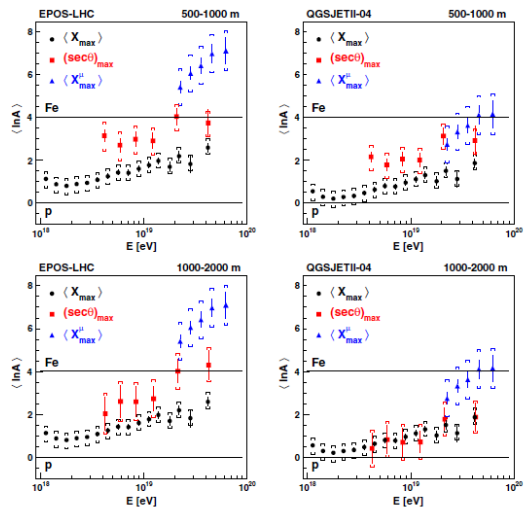

Fig.2. <ln A> as is function of energy as reported in [2, 4, 5] is compared with predictions as a function of energy made using the EPOS-LHC and QGSJETII-04 models. The figure is from [5].

From figure 2 it is evident that the two shower models do not adequately describe the data: an accurate model would be expected to give consistent estimates of <ln A> for different measurements. Further evidences of problems come from sources other than the Pierre Auger Observatory, such as IceTop/IceCube [6], DELPHI [7] and ALEPH [8]. At the South Pole, the IceCube/IceTop Collaboration study muons detected in IceCube in coincidence with showers seen with IceTop. Primary energies from ~4 PeV to ~1 EeV are explored with multi-TeV muons. Estimates of the mean mass as a function of energy from the South Pole work are shown in