

THE UNREASONABLE EFFECTIVENESS OF THE AIR-FLUORESCENCE TECHNIQUE IN DETERMINING THE EAS SHOWER MAXIMUM

P. Sokolsky [*]***, R. D'Avignon***

Department of Physics and Astronomy, University of Utah
84112, Salt Lake City, USA

Received September 13, 2021,
revised version December 2, 2021
Accepted for publication December 2, 2021

Contribution for the JETP special issue in honor of A. E. Chudakov's 100th anniversary

DOI: 10.31857/S0044451022040083
EDN: DPXBSA

1. Introduction. One of the great advances in the study of UHECR is the development of the air-fluorescence technique [1]. The ability to reconstruct the development of an extensive air shower (EAS) produced by cosmic rays at $> 10^{17}$ eV in the atmosphere has given us a much improved, essentially calorimetric, energy determination. This allows both direct measurement of the cosmic rays (CR) spectrum and the inter-calibration of the older surface array technique where only the footprint of the EAS on the surface is sampled with scintillation or water Cherenkov counters. The air-fluorescence method also gives the ability to determine, albeit with some uncertainty, the cosmic ray composition. This is done by determining the distribution of the depth of EAS shower maxima or X_{max} (see [2] for an early discussion of this technique). Heavy nuclei interact early and produce showers at smaller atmospheric depths while protons interact later and have deeper X_{max}. Intermediate nuclei lie between these two extremes. Thus, the fluctuations of X_{max} and the actual shape of the distribution of X_{max}'s contain information about the composition. The limitation of this method is the necessity of comparing the observations with detailed simulations based on hadronic interaction models. These models deal with interactions well beyond current accelerator data and hence have significant uncertainties. This is reflected in the uncertainty in the inferred composition. Determining the X_{max} of an EAS is also more subject to systematic uncertainties than its energy. Detailed fits to the data distributions to extract the CR composition thus suffer from multiple systematic issues.

It is possible, however, to ask a different question. Whatever the components of the cosmic ray flux may be, is this composition changing as a function of energy? Such changes may reflect propagation effects from the sources, changing acceleration efficiency at the astrophysical sources, or the appearance of different sources. A sensitive indicator of such a change in composition is the so-called elongation plot, or the dependence of the mean X_{max} on $\log(E)$. For a single component composition, it is easy to show [3] that

$$X_{max} = D \ln(E/E_c),$$

where E_c is the critical energy and D depends on the particle and the hadronic model assumed.

Irrespective of the actual mixture, for a constant composition, the slope of the elongation

$$d(X_{max})/d(\log_{10}(E))$$

is constant. However, if the composition is changing over an energy interval, then this slope, or elongation rate, will exhibit a corresponding change. While the precise correspondence of the elongation rate to the composition is hadronic model dependent, the energy dependence of interaction parameters such as total cross section, inelasticity and multiplicity are typically logarithmic and are not expected to produce a rapid change in the elongation rate. Thus, a rapid change in the rate is most simply explained in terms

[*] E-mail: ps.protopop@gmail.com

of a change in composition assuming no hadronic "new physics" thresholds.

The major advantage of studying the UHECR elongation rate is that one can come to certain conclusions about the composition in an essentially hadronic model independent way. However, this kind of study is still sensitive to systematic effects inherent in the air-fluorescence measurement technique. It is therefore important to have multiple independent measurements to determine how well the systematic errors are controlled.

In this paper, we will compare results from all the historic air-fluorescence experiments in the Northern and Southern hemispheres, and look for consistency, or lack thereof, in reported elongation rates — for evidence of a change. The eight experiments considered span a time period of 40 years and reflect a wide variety of reconstruction techniques, calibration procedures and atmospheric corrections. As we will see, somewhat incredibly, in the energy range from 10^{17} to $3 \cdot 10^{18}$ eV there is remarkable agreement about the elongation rate for Northern hemisphere experiments. Even the absolute values of average X_{max}'s lie well within the estimated systematic errors of 20–30 g/cm^2. We also present the comparison of the mean elongation rate of all the experiments in the Northern hemisphere with the result of the Auger experiment, which is the single detector in the Southern hemisphere. We will see that with the reversion to the mean of the seven Northern results, the agreement with Auger below $3 \cdot 10^{18}$ eV is remarkable.

We briefly describe the seven experiments with elongation rate results in the North. All of these were based in the western deserts of the state of Utah, USA. The oldest and pioneering air-fluorescence experiment was the Fly's Eye [4]. The next generation experiment was the High Resolution Fly's Eye (HiRes) [5] which had smaller pixels and full stereo coverage. A prototype HiRes detector with a limited field of view overlooking the CASA-MIA surface and underground muon array was first built [6]. The currently operating Telescope Array (TA) experiment [7] consists of three air-fluorescence stations with 1 deg by 1 deg pixel size, similar to HiRes, but overlooking a 700 km^2 surface scintillator detector array. In order to extend the air-fluorescence energy range, an additional detector called TALE was added to the MD TA fluorescence station [8].

2. Comparison of results for northern hemisphere. The seven different Northern Hemisphere experimental results, here treated as independent of each other, have different energy thresholds so that the number of mean X_{max} measurements per energy bin will vary. We consider data from 10^{17} eV to $10^{19.2}$ eV only to guarantee that statistical errors are smaller than systematic errors and there is no significant statistical sampling bias. The overall agreement as to the elongation rate for all experiments is impressive. Under the assumption that reversion to the mean will give the most reliable result, we form a mean and a standard deviation for each energy bin. Figure 1 shows the result where the error bars represent the standard deviation of all the experiments that contribute to a particular energy bin.

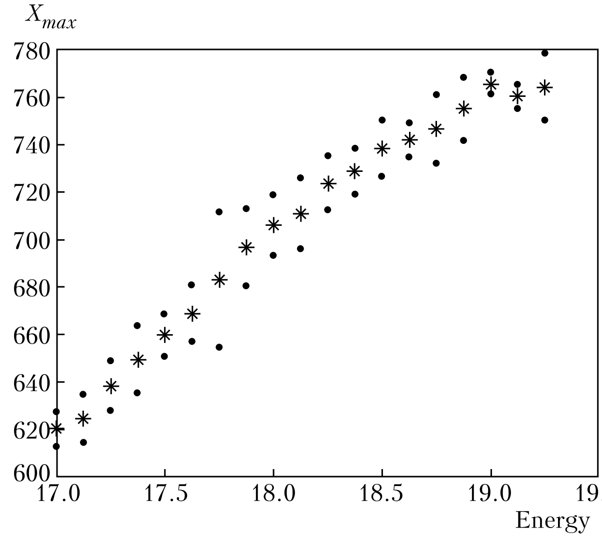

Fig. 1. Mean X_{max} as function of energy averaged over all Northern data. Error bars are the standard deviation of the different experiments about the mean for each energy bin

3. Comparison of north and south elongation rates. The Auger collaboration [9] has constructed a hybrid air-fluorescence surface detector array covering ~ 3000 km^2 in the high desert of Argentina with similar pixel size to TA and HiRes. The Auger elongation rate is in strikingly good agreement with Northern measurements from 10^{17} to $\sim 3 \cdot 10^{18}$ eV. There is an ~ 25 g/cm^2 systematic shift between the measurements, consistent with the estimated systematic errors of ~ 20 g/cm^2 for each experiment. Figure 2 shows the world data with the Auger results shifted down by 25 g/cm^2. The lower energies show a remarkable agreement with elongation rate of ~ 85 g/cm^2/decade for the North and 79.1 g/cm^2/decade for Auger. The slopes above $3 \cdot 10^{18}$ eV are different, however. Auger determines a rate of 26 ± 2 while the average of the Northern experiments gives a rate of 47.8 g/cm^2/decade with a standard deviation of 10.4.

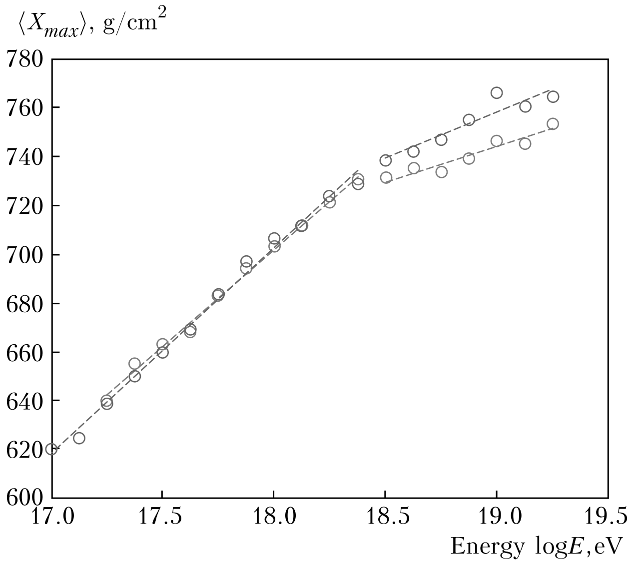

Fig. 2. (Color online) North and South elongation rates after 25 g/cm^2 shift. Red points are Auger data. Blue points are the mean Northern data. Dashed lines are linear fits with an assumed break at $3 \cdot 10^{18}$ eV. Error bars have been suppressed for clarity. Auger data points have been slightly interpolated to correspond to the energy binning

4. Discussion. There has been a divergence of interpretation of X_{max} data at the highest energies between Auger and the various Northern experiments for some time. Detailed studies of X_{max} distribution data shapes in the North, particularly the most recent TA hybrid results [10] have been most easily understood as being protonic, or nearly so, with some admixture of He and CNO possible at energies above $5 \cdot 10^{18}$ eV. Auger data above $3 \cdot 10^{18}$ eV when analyzed in a similar way tend to prefer a heavier composition. Until recently, comparisons, done by the Joint Composition Working Group [11] have only been made in a limited energy region of $2 \cdot 10^{18}$ to $2 \cdot 10^{19}$ eV. Reasonable agreement in the X_{max} distributions themselves (if not the hadronic model dependent interpretations) could be found if one shifted either experiment's results bin by energy bin by between 5 and 20 g/cm^2. However, the elongation rates between the two experiments above $2 \cdot 10^{18}$ eV remained different, though the evidence for this was weakened by the small energy range available and lack of statistics at the highest energies.

The present analysis using all available data paints a clearer picture. At lower energies, the agreement between North and South is highly reassuring. But the much increased lever arm available shows a real difference in measured elongation rate, beginning at $3 \cdot 10^{18}$ eV. If we assume there are no unexplored systematic effects, then this would indicate that the composition of cosmic rays in the Northern and Southern hemisphere begins to diverge at this energy, remaining relatively light in the North and getting heavier more rapidly in the South. The sources of the UHECR in the North and South could be different.

5. Conclusions. The remarkable agreement in elongation rate for eight different measurements gives strong impetus to using the divergence above $3 \cdot 10^{18}$ eV as a tool for exploring differences in North/South composition. However, a consensus needs to be achieved that there are no improperly understood systematic effects in this region. In this regard, [12] gives a historical account of North/South measurements from a different perspective, but comes to a similar conclusion about the existence of a break near $3 \cdot 10^{18}$ eV.

Since the important difference is in the slope, this systematics, if they exist, must increase with energy, but only above $3 \cdot 10^{18}$ eV. They must either increasingly push X_{max} to smaller values (the Auger case), or increasingly push X_{max} to larger values (the Northern case). Two candidates for such effects are: cuts which increasingly throw out deep X_{max}, and increasingly poor X_{max} resolution resulting in an increasing deep X_{max} tail not modeled in the simulations. Neither of these possibilities is supported by the work of the experimental groups. Nevertheless, the Joint TA–Auger Composition Working Group should press on with further elucidation of such possible effects. Absent such effects, the divergence in composition North and South joins the emergence of different anisotropies (Cen A and Starburst Galaxies in the South [13]; the Hot Spot and the Perseus–Pices supercluster enhancement in the North [14]) as a strong indication of the diversity of cosmic ray sources at the highest energies.

It is remarkable that a technique that is based on the observation of the emission of ~ 4 photons/particle/m at distances of up to 30 km, in the presence of significant sky noise, and which has to take into account molecular and aerosol scattering in the atmosphere as well as the stability and calibration of thousands of pixels can produce such reliable and reproducible experimental results. The pioneers of this idea ~ 60 years ago (Chudakov [15] in the USSR and others in Japan and the United States) would be pleased at what their original insight has brought forth.

The full text of this paper is published in the English version of JETP.

REFERENCES

1. K Greisen, Ann. Rev. Nucl. Sci. **10**, 63 (1960); J. Delvaille, F. Kendziorski, and K. Greisen, J. Phys. Soc. Japan **17**, Suppl. A-III, 76 (1962); K. Suga, *Proc. 5th Interamerican Seminar on Cosmic Rays*, La Paz, Bolivia, Vol. II, XLIX (1962); A. E. Chudakov, *Proc. 5th Interamerican Seminar on Cosmic Rays*, La Paz, Bolivia, Vol. II, XLIX (1962).
2. G. L. Cassiday, R. Cooper, S. Corbato et al., Astrophys. J. **356**, 669 (1990).
3. J. Linsley, *Proc. 15th ICRC*, Plovdiv, Bulgaria **8**, 353 (1977).
4. R. M. Baltrusaitis, G. L. Cassiday, R. Cooper et al., Nucl. Instr. Meth. A **240**, 410 (1985).
5. J. M. Matthews, *Proc. 27th ICRC*, 07-15 (2001); R. U. Abbasi, T. Abu-Zayyad, J. F. Aman et al., Phys. Rev. Lett. **92**, 151101 (2004).
6. T. Abu-Zayyad, K. Belov, J. Boyer et al., Nucl. Instr. Meth. A **450**, 253 (2000); T. Abu-Zayyad, K. Belov, D. J. Bird et al., Astrophys. J. **557**, 686 (2001); A. Borione, C. E. Couvault, J. W. Cronin et al., Nucl. Instr. Meth. **346**, 329 (1994).
7. K. Martens, Nucl. Phys. B, Proc. Suppl. **165**, 33 (2007).
8. R. U. Abbasi, T. Abu-Zayyad, M. Allen et al., Astrophys. J. **909**, 178 (2021).
9. A. Aab, P. Abreu, M. Aglietta et al., Nucl. Instr. Meth. A **798**, 172 (2015).
10. R. U. Abbasi, M. Abe, T. Abu-Zayyad et al., Astrophys. J. **858**, 76 (2018).
11. V. de Souza, *Proc. of 2017 ICRC*, Beijing, China, PoS(ICRC2017) 301.
12. A. Watson, *Proc. of UHECR 2018*, EPJ Web Conf. **210** (2019); doi.org/10.105/ epjconf/201921000001.
13. A. di Matteo, *Proc. of 2021 ICRC*, Berlin, Germany, PoS(ICRC2021) 308.
14. K. Kawata, A. di Matteo, T. Fujii et al., *Proc. of 2019 ICRC*, Madison, USA, PoS(ICRC2019) 310; T. Fujii, D. Ivanov, C. C. H. Jui et al., *Proc. of 2021 ICRC*, Berlin, Germany, PoS(ICRC2021) 392.
15. V. A. Belayev and A. E. Chudakov, Bull. USSR Acad. Sci., Phys. Ser. **30**, 1700 (1966).