High Energy Cosmic Ray Extensive Air Showers

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This review concerns itself with papers on four subjects from HE 3.1, 3.3, 3.4 and 3.5 sessions. The subjects include

1. Shower front fluctuations with applications to mini-arrays.
2. Cherenkov Light and shower front timing differences for photon and proton initiated EAS.
3. The detection of ultra-high energy EAS by very low frequency (VLF) radio signals.
4. Properties of EAS at greater than PeV energy. These include the study of electron, muon, and Cherenkov light lateral distribution functions, the average Xmax dependence on energy, and the value of the proton-air total inelastic cross-section.

1. Shower Front Fluctuations at Large Core Distances
   (HE 3.3 - 6, 3.3 - 11, 3.3 - 12)

These experiments attempt to check the Linsley hypothesis (1) that measurement of the dispersion of arrival times of EAS far from the core contains significant information about core distance and the primary particle energy. Three experiments correlate their measurements with results from the Akeno array.

Hunda et. al. (HE 3.3 - 11) use three derived variables: ó$_t$, the time dispersion; T_{28}, the integrated 20-80 percent rise time of the shower, and ô, the exponential time constant of a fit to the integral rise time. They find that the mean values of the arrival time dispersions agree with results given by Linsley, but that these values are distributed widely around the expected curves (see Fig.1).

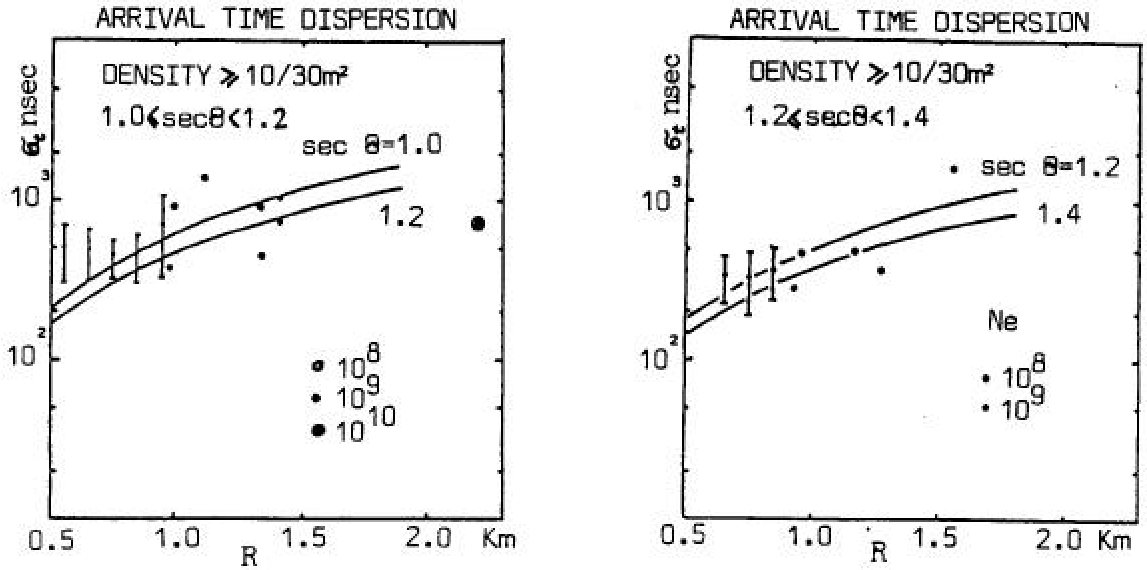

Fig. 1. Arrival time dispersion for two zenith angle bins

Similar results were presented by Kakimoto and Nishi (HE 3.3 - 6). They estimate that they can determine the core distance to +/-100 to 150 meters and the size with +120%/-70% errors for core distances of near 1.5 km. using the Linsley technique. Halzen et al. (HE 3.3 - 12) estimate a size error from measuring the core distance and the particle density. The core distance is found by using the predicted ót - r correlation and the size is calculated from the relation

$$N = cpr^n,$$

where n = 3.8 for 100 < r < 200 m and n = 4.0 for 1000 < r < 2000 m. The measured uncertainties in r imply

äN/N - 2.5 to 3.4 for 700 < r < 940 m.

The net result of these measurements is to confirm the average behavior of the dispersion proposed by Linsley and to show that fluctuations about the average are large. The reported data make it questionable that the mini-array technique will produce sufficiently accurate results.

2. Gamma - Hadron Discrimination

HE 3.3 - 9 (Mikocki et al) focus on differences in electron and muon arrival times to discriminate between proton and gamma ray induced showers.

They perform a Monte Carlo simulation using 100 TeV gammas and protons and assume a detection plane at 1034 gm/cm^2 depth and zero zenith angle. The high energy part of the shower is modeled using Wrotniak's SHOWERSIM package of programs while below 10 GeV they use the EGS program widely used in high energy physics. The hadronic model used has mild scaling violation in the fragmentation region. The results of the Monte Carlo are used to search for
time delay differences for muons and electron relative to the arrival of light at the detection plane. Results are shown in Table 1. It appears that electrons tend to arrive earlier for proton showers than for gamma induced showers at core distances of > 500 meters. Muons in proton induced showers arrive significantly earlier than electrons do. No significant differences are apparent at small core distances. The problem with this result is that particle densities are quite small at core distances of > 500 m and large sampling fluctuations will wipe out the effect. It is possible that this technique will work better for higher energy showers and this is being investigated. We note that the early arrival of muons may be useful in reducing puck-thru background for muon counters.

Table 1

Range R [m]	γ-shower		P-shower							
	e		All		e		μ_1		μ_2	
	<t>	σ_t	<t>	σ_t	<t>	σ_t	<t>	σ_t	<t>	σ_t
0-12	1.2	2.3	1.4	3.0	1.4	2.6	0.9	4.0	0.5	1.8
12-25	3.4	4.0	3.1	5.1	3.2	4.1	1.6	5.7	1.1	2.9
25-50	6.8	7.5	5.8	8.4	6.1	7.1	2.8	6.2	2.1	3.8
50-100	12	11	11	16	11	12	6.5	10.6	5	6
100-200	28	20	24	34	25	21	16	18	12	12
200-300	57	28	50	58	54	38	32	29	26	19
300-400	101	50	84	88	96	75	53	41	42	26
400-500	178	69	125	119	151	114	78	54	63	37
500-600	240	74	164	145	204	144	103	65	83	44
600-700			206	171	249	181	135	87	110	58

HE 3.4 - 1 (Galkin et al.) attempt to use the Cherenkov pulse shape to discriminate gamma rays from hadrons in the energy range of 1 to 10 TeV. They model cascades in Monte Carlo and look at a variety of parameters.

They find that reliable correlation between $\hat{o}_{FVHM}$ end core distance must take into account the lateral distribution function for shower electrons. The average pulse shapes for protons and gamma rays at 100 to 300 m core distances appear to be different in width and rise time. However, the effect changes rapidly with primary energy, which is somewhat puzzling. In any case, if this result is correct, using shower size instead of energy will smear the differences out. There may be exploitable differences in pulse shapes but it is not obvious when using real data with experimental resolution and systematic effects that these differences can be effectively used. Searches for such differences should always be in terms of experimentally determined quantities, Ne etc, so that adequate estimates of the effect of fluctuations can be made.

3. VLF Signals for large air showers

HE 3.4 - 13 (Suga) reported on the continuing study of VLF signals from EAS at the Akeno array. The experimenters use a 10 m long vertical antenna coupled to a low noise proportional amplifier, digital wave form recorder and fast Fourier transform signal analyzer. The bandwidth of the device is

$$26 \text{ kH}_z < f < 300 \text{ kH}_z$$

They observe these signals in coincidence with the Akeno array. Typical signals are 5 microseconds wide and have an amplitude of 40 micro-volts for 2 to 2.5 km core distances. The signal amplitude decreases as 1/R. It is clear that large bandwidth is important in getting the signal shape. Fig. 2 shows an example of a pulse seen with two different bandwidths.

The general characteristics of the VLF signals can be summarized: a. Pulses are unipolar and negative, b. Air showers are detected out to 1 km core distance with good efficiency. For .sizes of order 10^{10}, it may be possible to detect showers out to 10 km, c. There is no obvious dependence of signal on Ne, zenith or azimuthal angle or weather.

The experimenters performed a short run with a wider bandwidth of 26 < f < 1000 kHz. The observed pulse widths decreased to 1.5 microseconds, indicating that the real pulse width is less than 5 microseconds. They expect to expand the bandwidth in the future to 8 < f < 2500 kHz, although this may be difficult because of problems with radio interference.

HE 3.4 - 16 (Aleksandrov et al) report similar results using a 2 meter antenna and a 1 to 100 kHz bandwidth at the Yakutsk and Grozny arrays. They also observe that the signal has no correlation with shower size, and zenith angle, but in their case they observe no correlation with core distance either. They do claim a correlation with the weather. They observed larger amplitudes when in thunderstorm or pre-thunderstorm conditions. We should note that this experiment has a smaller bandwidth and a smaller antenna than the one reported by Suga, and this lower sensitivity may explain some of the discrepancies with the Akeno installation.

The physical mechanism for the radio emission is still not clear, but as better data is accumulated, one can begin to rule out certain models.

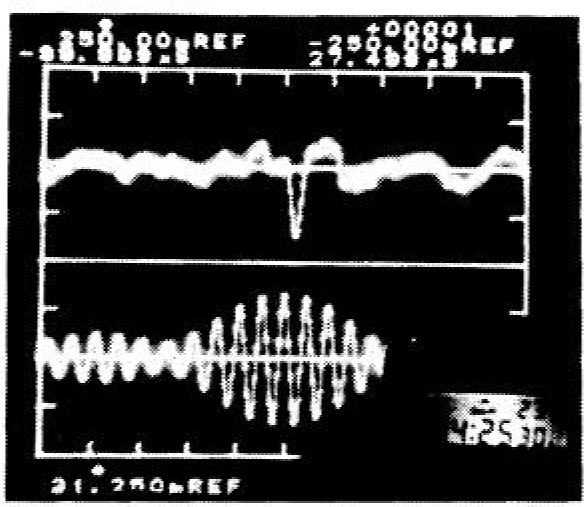

Fig. 2. VLF signal from EAS. Upper trace: 26 - 300 kHz handwidth; lower trace: 155-186 kHz

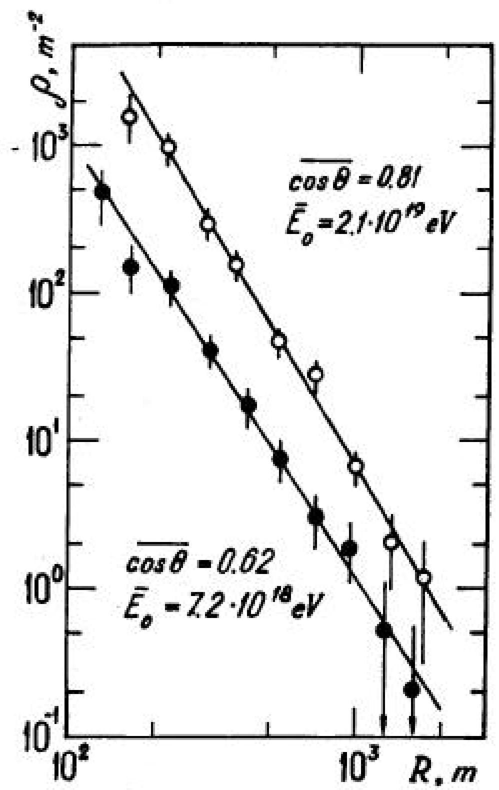

Fig. 3 Charged particle LDF from Yakutsk array

4. EAS Properties

HE 3.1 - 34 reported on a large number of results from the Yakutsk array concerning EAS properties. These results are based on 12 years of operation of the array. The array measures the charged particle, muon and Cherenkov light lateral distributions and the authors report on a number of empirical relations between the parameters of these distributions. a. Average lateral distribution function for charged particles.

Fig. 3 shows the lateral distribution function for average energies of 7x1018 and 2x1019 eV showers. There is a weak dependence of the lateral distribution function shape (LDF) on shower size. If one parametrizes the distribution as

$$\rho(R) \text{ á } R^{-n} \text{ for } 200 < R < 1000 \text{ m and } 7\times10^{18} < E < 2\times10^{19}$$

then n = 2.92 +/- .35 where one expects n = 2.6 from the Greissen formula. This may indicate some steepening of the LDF with increasing energy, but no evidence for an unexpected change of the LDF for very large showers.

b. The average lateral distribution function of Cherenkov light Fig. 4 shows this distribution based on 6000 hours of data. The authors correlate the total energy with Q (200), the light density at 200 m from the shower core. They find

$$E = (2.04 \pm 0.48)\times10^{18} \left(\frac{Q(200)}{10^8}\right)^{.99 \pm .02}$$

Of particular note among the many empirical formulas given in this paper is the relation between the total Cherenkov light flux ϕ and ρ (600)

$$\phi = (1.62 \pm 0.15)\times10^{13} \left(\rho_{600}\right)^{0.98 \pm 0.02}$$

This relation holds for zenith angles less than 45 degrees and for the wavelength interval between 300 to 800 nm.

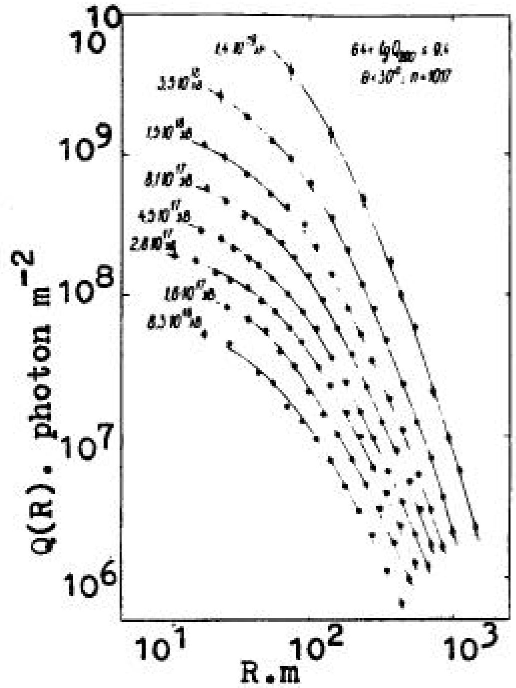

Fig. 4. Cherenkov light LDF from Yakutsk

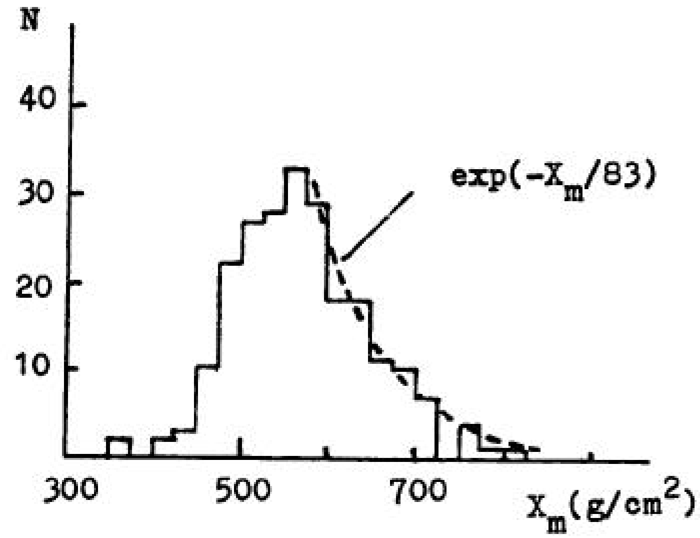

Fig. 5 Xmax distribution for <E> - 1.5 x 1016 eV

c. Xmax vs Energy (the Elongation Rate)

Three experiments reported new results and one experiment the result of a reanalysis of their old data. HE 3.5 - 6, 3.1 - 35 (Efimov et al), (Dyakonov et al), HE 3.4 - 8 (Prosin et al.) and OG 5.1 - 13 (Baltrusaitis et al.) gavenew results using the Cherenkov and fluorescent light techniques. The lowest energy new data comes from a Cherenkov array run by Moscow State University and the Institute for Cosmophysical Research, Yakutsk. This array measures the Cherenkov pulse width using 150 kHz bandwidth digital pulse shape analyzers. They determine the core location using scintillation counter and the zenith angle using timing between Cherenkov light detectors. They claim a resolution is Xmax of 45 gm/cm^2 from measurement of the pulse width at 250 m from the center of the array and span the energy range between 10^{16} and 10^{17} eV. The energy of an event is determined from the relation

$$E - Q(100) \times 10^{14.12}/k_{rel}$$

where k_{rel} is an atmospheric transparency coefficient and Q(100) is the

Cherenkov photon density at 100 meters. Of particular interest is their reconstruction of the Xmax distribution of 225 well measured events: These events have a mean energy of $1.5x10^{16}$ eV, and average depth of <Xmax> of 570 +/- 5 gm/cm^2 and a ó of 77 +/-3 gm/cm^2. Fig. 5 shows the resultant Xmax distribution. The exponential tail of the distribution (slope A_t) can be assumed to be mostly composed of protons and the experimenters extract an p-air attenuation length of ë$_{p\text{-}air}$ = 56 ± 9 gm/cm^2 using the model-dependent relation ë$_{p\text{-}air}$ = kA_t with k = 1.2 from results of the quark-gluon-string model.

The Fly's Eye group has installed a second fly's eye, 3.3 km from the first, allowing full stereoscopic reconstruction of about 20% of their events. These events have very well reconstructed geometries. The Xmax for each event is determined directly from the measurement of the longitudinal development curve derived from the fluorescent light yield as a function of atmospheric depth. The result for two energy bins is

$3x10^{17} < E < 7x10^{17}$	<Xmax> = 675 ± 4 gm/cm^2	ó = 82±3 gm/cm^2
$E > 7x10^{17}$	<Xmax> - 700 ± 5 gm/cm^2	ó = 79±3 gm/cm^2

Note that the quoted sigmas include the detector resolution.

The Yakutsk Xmax distribution in the energy region between 1017 and 1019 eV is found from the Cherenkov light lateral distribution using the following empirical formula Xm =556 (n - 1.82) + 576 - sec θ where n is the exponent in

Q(R) á R^{-n} for 400 < R < 1000 m

They show their results for two zenith angles, 17 and 37°. The resultant spread in <Xmax> is an indication of the systematic errors inherent in this technique. The experimenters use the technique suggested by Linsley to extract the proton-air total inelastic cross section from their data. This method assumes that the fluctuation in Xmax, äXmax is proportional to ë$_{p\text{-}air}$ for a pure proton composition. If the composition is mixed, but still has a significant fraction of protons, then the total fluctuation will still be dominated by the proton fluctuation, though small corrections need to be

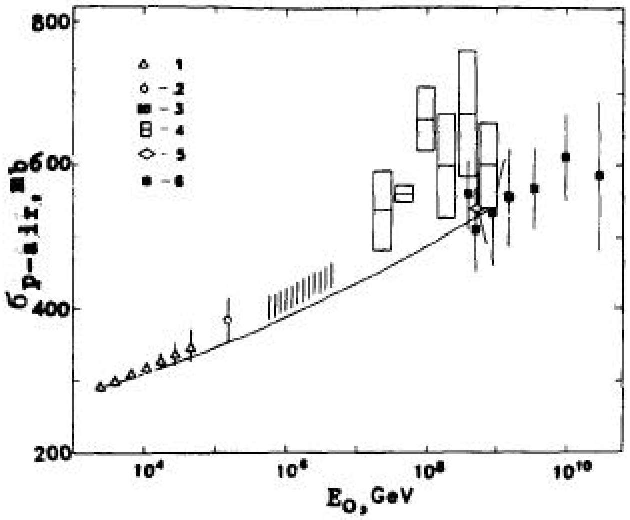

Fig. 6 ó$_{p-air}$ Filled squares: Yakutsk data; open diamond: Fly's Eye; open rectangles: Akeno data

made. The net result is shown in Fig. 6 together with the old Akeno, Fly's Eye and lower energy results. Given the differences in techniques, the amount of agreement between the different experiments is surprising.

The Samarkand group (HE 3.4 - 4, Aliev et al) has reanalyzed their old data using the Cherenkov pulse width technique in the energy range of 10^{15} to 10^{16} eV. They now use a more precise relation between the pulse width ô$_{FWHM}$, the core distance R, the zenith angle θ and Hm, the distance to shower maximum. They also try to estimate the effect of event selection on the shape of their Xmax distribution. Both these effects, they claim, can lead to up to 50 gm/cm^2 shifts in position of Xmax. Their re-analized data points are about 50 gm/cm^2 lower.

The elongation rate resulting from combining data from these four experiments is shown in Fig. 7. This new data is consistent with an elongation rate of 60 to 70 gm/cm ^{2} from about $3x10^{15}$ eV to $1x10^{19}$ eV. There is no evidence for rapid elongation variations between $3x10^{15}$ and 10^{17} eV.

The results from fits to the Xmax distribution measured by the Fly's eye and the MSU-Yakutsk data are consistent with a mixed composition including between 40 and 50 percent protons. A three component fit to the Fly's eye data yields excellent agreement with a standard light composition. This, combined with a constant elongation rate implies no significant changes in the cosmic ray composition as a function of energy. Other experiments around the knee of the spectrum favor a heavy composition (See

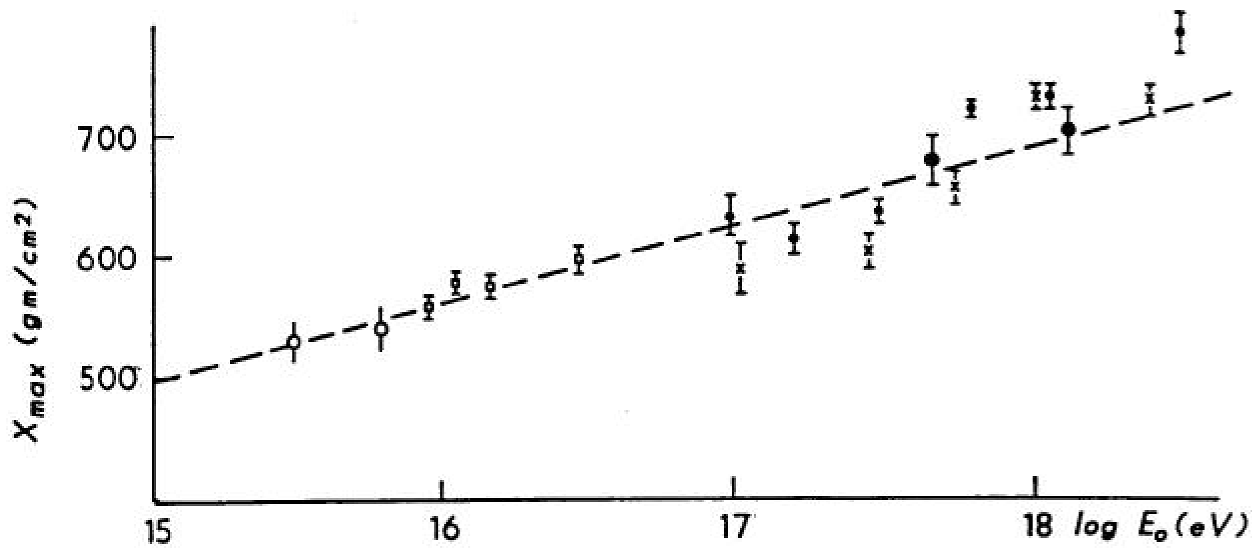

Fig. 7. Elongation rate. Open circles: Samarkand data (re-analyzed); open squares: M.S.U.-Yakutsk; small filled circles and crosses: Yakutsk; large filled circles: Stereo Fly's Eye

R. Clay's raporteur's talk in the LaJolla proceedings). In particular, experimental data from Buckland Park, [2,3] using.both the lateral distribution technique and the pulse shape technique give Xmax that are systematically 50-80 gm/cm^2 lower than the present results. The source of the discrepancy is not understood, but it is extremely important that the discrepancy be resolved because of the implications for cosmic ray composition.

It should be pointed out that every single experiment is consistent with a constant elongation rate over the energy range it spans. There is no evidence for a break in the elongation rate within any one experiment. The impression that such a break exists is due to combining several experiments which span different energy ranges and use different techniques. The problem is compounded by the fact that in the energy range 10^{15} to 10^{17} eV the distribution of measured elongation rates covers all compositional possibilities, indicating severe systematic effects. It may still be the case, of course, that one or several of these experiments is correct. But how are we to find out which one? Without a detailed understanding of the reason for systematic differences, new experiments using this technique cannot conclusively demonstrate their superiority over previous experiments.

Aliev et al (HE 3.4 - 4) suggest that some of this discrepancy is due to the use of inadequate formulas or relating $ô_{FWHM}$ to H_m, in particular to the neglect of the zenith angle dependence. They also point out (correctly) that selection effects were not taken into account in ref. .2. However, such effects were taken into account in a subsequent experiment [3] by the same group with substantially the same results. There is also the issue of normalizing $ô_{FWHM}$, measured at different core distances, discussed by HE 3.4 - 3 (Aliev et al.) and in ref. 4 and 5. It may, of course, turn out that the differences are due to instrumental effects such as time resolution. If so, much more sensitive experiments will have to be done to resolve this issue. It is to be hoped that the new data from M.S.U.-Yakutsk will force a re-examination of this whole issue.

Another approach would be to perform an experiment with broad enough energy range (10^{15} to 10^{17}) and sensitivity to see a change in the elongation rate within its own data. This is quite difficult because of the two order of magnitude change in the shower size. Another possibility is the cross-calibration of the Fly's Eye technique with the Cherenkov pulse width method, since Xmax determination with stereo Fly's Eye data is the most direct approach possible. Unfortunately, such cross-calibration can only be done at energies above 10^{17} eV (possibly down to $8x10^{16}$ eV). Since some of the systematic effects may be related to differences in the analysis of small showers, extrapolation to lower energies of such a calibration may not be warranted.

To mix a metaphor, until more work is done, the "knee" of the cosmic ray spectrum will remain a black-eye in the face of cosmic ray physics.

References

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