

THE COSMIC RAY SPECTRUM ABOVE 10^{19} EV AT VOLCANO RANCH AND HAVERAH PARK

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ABSTRACT

The cosmic ray energy per particle spectrum above 10^{19} eV is measured the same way that energy spectra are measured at much lower energies, by counting all of the particles in a specified energy range that are incident per unit time with trajectories within specified geometrical limits. Difficulties with background or poorly known detection efficiency are markedly less than in some other cosmic ray measurements. The fraction of primary energy given to muons, neutrinos and slow hadrons is less than 10% in this region, so the primary energy equals the track length integral of the secondary electrons with only a small correction for the energy given to other kinds of particles.

In practice the Volcano Ranch and Haverah Park results depend for energy calibration on 'field parameters'. These quantities are accurately measured and reproducible, but relating them precisely to the primary energy without recourse to detailed models of hadron interactions has taken additional experimental work which still goes on. The field parameter $S(600)$ (particle density measured with a scintillator at a core distance of 600 m) provides a common link between the Volcano Ranch, Haverah Park and Yakutsk experiments. There is good agreement as to the relation between this parameter and the primary energy. There is also good agreement as to the vertical intensity corresponding to a primary energy of 10^{19} eV, not only among these 3 experiments but also with the preliminary Fly's Eye results. Above 10^{20} eV there is some disagreement between the Yakutsk experiment and the others.

The first observation of the spectrum above 10^{19} eV, at Volcano Ranch, showed that the spectrum extends to 10^{20} eV without a sign of any cutoff. The spectrum appeared to be flatter in this region than in the decades just below it. These features have been confirmed by the Haverah Park and Sydney experiments, each of which has recorded more than a half dozen events with energy greater than 10^{20} eV. The Volcano Ranch array registered not only the density but also the arrival time distribution of shower particles, at widely separated locations, so it was difficult to doubt that the 10^{20} eV shower was in fact 10 times as large, and 10 times as energetic, as the showers that were assigned an energy of 10^{19} eV. The amount of density and timing information on several of the $> 10^{20}$ eV showers recorded at Haverah Park is even greater. Thus the lack of recorded events of this size from the Yakutsk array must be understood as a problem of detection efficiency, or else as an unexpectedly large statistical fluctuation. The lack of such events from the Fly's Eye is not surprising in view of the relatively small exposure to date.

1. Introduction. To explain how air showers are used to measure the primary energy spectrum, I will use examples from the history of this kind of work, beginning with a period of rapid progress following World War II. The general requirements are to measure the energy of particles incident on some target—in this case the earth's surface—and determine their directional intensity. One uses the fact that very high energy particles striking the earth invariably generate extensive air showers. The secondary particles making up these showers are concentrated in a core that lies along the path of the incident particle, and the number of these secondaries at a given distance from the start of the shower reflects the energy of the incident particle. (One now determines the primary energy more precisely from the total energy deposited in the form of ionization, making small corrections for the energy used to produce neutrinos and excite or disrupt nuclei.) Thus it was evident even before this period began that it would be possible to determine the energy spectrum at very high energies in the canonical manner, just as at much lower energies, letting air showers play the same role as individual tracks in a cloud chamber or emulsion.

2. Finding the Trajectories. The initial step in carrying out this program was taken by R.W. Williams as a member of Rossi's group at MIT. Using an array of four pulse ionization chambers set up on Mt. Evans in Colorado, he recorded the density of shower particles in each chamber for individual showers. From these densities, relying somewhat on calculations of the lateral structure function by Molière but largely just on the expected symmetry, he found estimates of the core location and the number of particles, event by event (Williams 1948).

To learn the trajectory of the primary particle one must find the direction as well as the point where the target was struck. In another MIT experiment it was shown by Bassi, Clark and Rossi (1953) that shower directions can be measured electronically, from arrival times, without using cloud chambers. Their method depends on the fact that all of the important collisions in a shower, and nearly all of the secondary particles produced in the collisions, are highly relativistic. Hence most of the secondary particles travel forward at practically the speed of light, occupying a region that is thin in the direction of motion, and nearly planar.

Within a few years these ideas had been combined in an experiment carried out in 1954-1957 at Agassiz Station of Harvard University, near Boston. Using only about a dozen 0.9 m^2 scintillators, the shower size spectrum was measured up to a size corresponding to 10^{18} eV (Clark *et al.* 1961; shower size means the number of particles in a shower). Clearly the method was so economical that it should be used on a much larger scale. In 1957 it was decided to do this, and a site was chosen at Volcano Ranch, near Albuquerque, New Mexico.

3. Finding the Energies. A weak point of the Agassiz experiment was the uncertainty in converting from shower size to primary energy. This was done using cascade calculations by Olbert, another member of Rossi's group. The calculations showed that, as expected from general arguments, there is a systematic uncertainty in this conversion, due to dependence on

some model of high energy hadron interactions. This uncertainty is substantial for relatively small showers at sea level, but it decreases at higher altitudes, becoming comparatively small at an atmospheric depth x_m corresponding to the maximum in the longitudinal development curve. Moreover, for showers registered past the maximum there are comparatively large fluctuations in size for a given primary energy. Since the energy spectrum is quite steep, these fluctuations introduce a systematic shift which must be compensated using calculated corrections (Kraushaar 1958, Clark *et al.* 1961). Difficulties associated with the location of the maximum become less at higher energies even at sea level. By choosing to locate the first giant array at Volcano Ranch, which is about a mile above sea level, these difficulties were reduced still further.

The choice of model also affects $E_{\mu\nu h}$, the amount of shower energy given to muons, neutrinos and low energy hadrons. For the comparatively small events registered in the Agassiz experiment, $E_{\mu\nu h}$ is a significant fraction of the primary energy, but this fraction decreases with increasing energy, so it was expected that $E_{\mu\nu h}$ would be relatively unimportant in the region of the spectrum the new array was intended to explore. Nevertheless, in order not to be caught unawares by unexpected behavior of the muon component, one of the Volcano Ranch detectors was provided with a lead shield.

Besides MIT, another important center of air shower research in the US was Cornell University. At the same time Williams was laying the groundwork for modern experiments, in which showers are dealt with as individuals, Greisen, with Cocconi and other collaborators, was making detailed studies both at mountain altitude and at sea level, using the statistical methods pioneered earlier by Auger and his co-workers in France. These studies encompassed the muon and low energy hadron components as well as the soft component. Combining the Cornell results with similar results in the literature of the time, Greisen (1956) made an estimate of the energy of air shower primaries along the lines of an earlier estimate by Rossi, in which Rossi tested low energy measurements of the primary intensity against data on the various secondary components throughout the atmosphere in a search for possible 'missing energy' (Rossi 1948, Puppi 1956). Applied to air showers, this kind of analysis yields a so-called 'calorimetric' evaluation of the primary energy. Greisen found the energy of primary cosmic rays having a vertical intensity (integral) of $1.7 \cdot 10^{-6} \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ to be $(1.4 \pm 0.3) \cdot 10^{15} \text{ eV}$, remarkably near the present best value, $(1.0 \pm 0.1) \cdot 10^{15} \text{ eV}$ (Linsley 1983). The calorimetric method of finding the energy of air shower primaries is regarded by all concerned to be the proper ideal for experiments up to the highest energies that have been observed.

Soon after its introduction, this method was used by Nikolskii (1962) and Zatsepin *et al.* (1963) with independent data from experiments in the Pamir mountains, including data on the atmospheric Cerenkov light produced by the showers. This light is practically not absorbed in the atmosphere. Moreover, the production efficiency can be calculated from classical electrodynamics, so there is practically no dependence on atomic or nuclear models. This makes the atmospheric Cerenkov light an especially reliable measure of the total energy deposited in the atmosphere, which is the largest term in the equation for balancing the energy. Alternatively, this term can be evaluated from N_m , the size at maximum development, and an estimate of the shower profile width.

For the Volcano Ranch experiment the latter approach had been chosen. It was important, therefore, that the altitude of the experiment be about equal to the altitude where the largest showers are expected to reach maximum development. Even at that time there were ways of determining x_m empirically, from the energy dependence of zenith angle distributions or the behavior of size spectra (Clark 1962). The conversion factor between N_m and primary energy was thought to be "about 2 GeV per particle for all models of shower development" (Clark 1962). (According to more recent evidence this figure is too high; it should be 1.3-1.4 GeV per particle; see Hillas 1972 and Linsley 1983.)

4. The Volcano Ranch Experiment. Figure 1 shows the Volcano Ranch array with the configuration it had in 1960-1963. In 1959-1960, the first year of operation, the detector spacings were half as great. The detectors were 3.26 m^2 scintillators. Nineteen of them were arranged as shown; an additional one was located in various places, usually adjacent to one of the other detectors, sometimes unshielded but usually shielded with 10 cm of lead. Two other arrays similar to the Agassiz array are also shown. The one at El Alto, just outside of La Paz, Bolivia, was an MIT-Bolivian collaboration using scintillators from the Agassiz experiment. The Cornell array was a variable density array made with the same kind of scintillators. Each of them was somewhat larger than the Agassiz array, but the Volcano Ranch array was much larger, with fifty times the area.

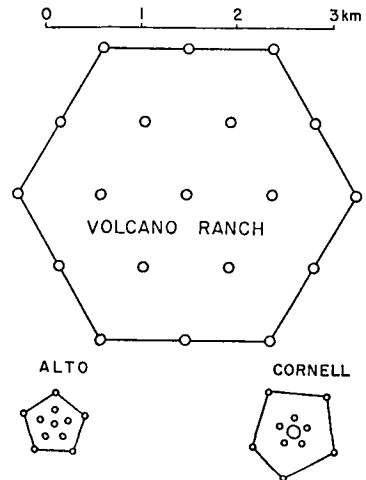


Fig. 1. Plan of the Volcano Ranch array in 1960-1963. The Cornell and El Alto arrays are shown for comparison. The large circle at the center of the Cornell array represents 5 separate 0.9 m^2 scintillators.

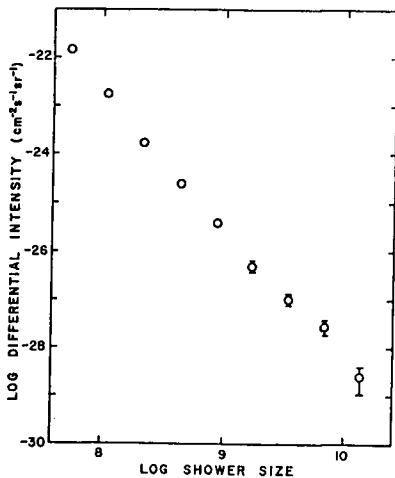


Fig. 2. Differential size spectrum at an atmospheric depth of 835 g/cm^2 .

The shower size spectrum reported at the Jaipur Conference is shown in Figure 2 (Linsley 1963).

The slope was unexpectedly flat compared to similar spectra at lower energies. The energy spectrum reported at that time is shown in Figure 3, superimposed on the best present spectrum. Below a few times 10^9 GeV the primary energy was considerably underestimated by assuming that the smaller showers as well as the larger ones were at maximum development when observed at 835 g/cm^2 , the depth of the experiment. Above 10^{10} GeV , however, the agreement is remarkably good. Figure 4 shows a later version of the size spectrum, extending to higher energies (Linsley 1973).

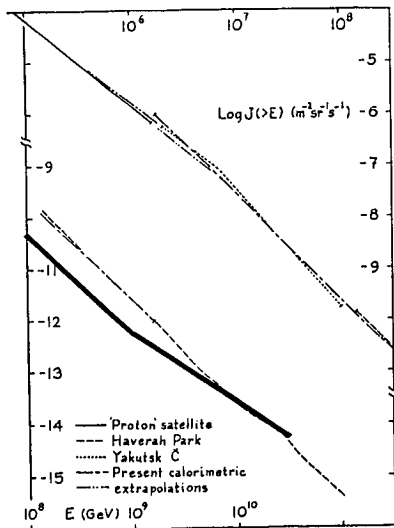


Fig. 3. (left) Volcano Ranch integral energy spectrum (Linsley 1963, heavy line), superimposed on more recent results summarized at the Bangalore Conference (Linsley 1983).

Fig. 4. (below) Later version of the Volcano Ranch size spectrum.

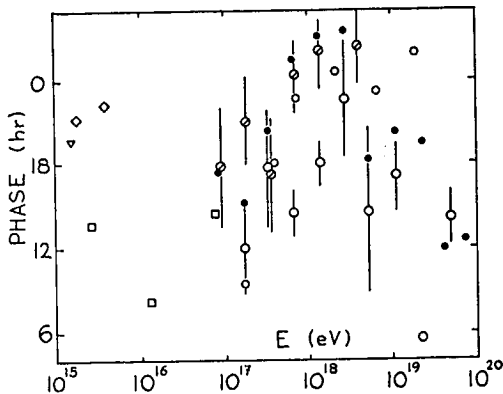
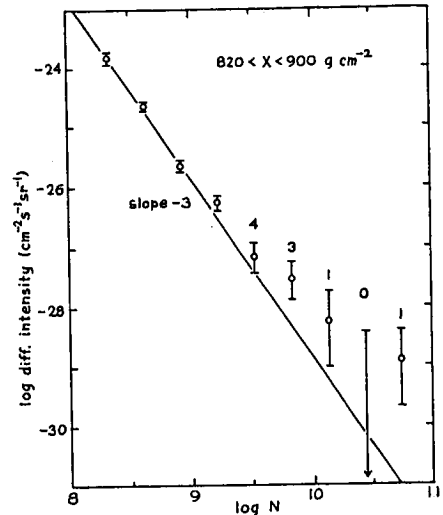


Fig. 5. Volcano Ranch evidence for anisotropy of the highest energy cosmic rays (Linsley 1975), compared to a recent summary of similar results (Linsley 1983). The dependent variable is the phase of the first harmonic of the counting rate in sidereal time. Large circles, Volcano Ranch (points with slash are from 1959-60; without slash, from 1960-63); small filled circles, Haverah Park; small open circles, Yakutsk; squares, Cornell; diamonds, Pic du Midi; triangle, Chacaltaya.

The Volcano Ranch experiment also contributed importantly to showing that the arrival directions of the highest energy cosmic rays are anisotropic. The pattern that stands out most clearly above statistical noise is a modulation in the direction of maximum intensity observed by arrays in the northern hemisphere, with changing energy (see reviews by Linsley, 1983, and Hillas, 1984). It was noted at the time of the Munich Conference that patterns of this kind were present in data from Volcano Ranch and Haverah Park, and that they were similar (Linsley 1975, Edge et al. 1975). Since then, additional confirmation has come from the Yakutsk array. Figure 5 shows these results.

5. The Haverah Park Experiment. Work on a giant air shower array to be built

in England began with a meeting called by Blackett in 1958, attended by representatives of cosmic ray groups at Imperial College and the Universities of Leeds, Durham and Bristol. Later that year the site was chosen:

Haverah Park, near Leeds. For detectors it was decided to use larger versions of water-Cerenkov tanks that had been used previously by the Imperial College group in a small air shower experiment at Silwood, the site of a field station belonging to the College. A good deal of experience with large air showers had been gained earlier through a notable series of experiments at Culham airfield, using groups of Geiger tubes distributed over an area of some 0.5 km^2 . (I am indebted to Harold Allan and Neil Porter for background information about early air shower work in the British Isles.)

Operation at Haverah Park began near the end of 1962 with 4 detectors, a central one with 3 other units placed symmetrically at a distance of 500 m, each detector consisting of 15 tanks with a total area of 34 m^2 . In following years six clusters of similar detectors were put in service at distances of about 2 km from the central set, so that by 1968 the size of the array was about the same as Volcano Ranch. Large muon detectors had been added, and the University of Nottingham had joined the list of those using the site. At a later stage shown in Figure 6, smaller water-Cerenkov

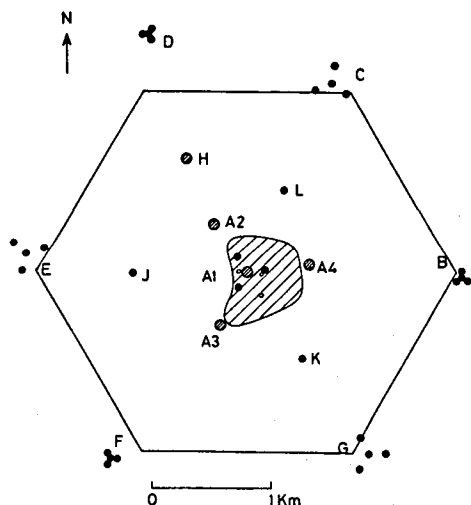


Fig. 6. The Haverah Park array. The triggering detectors A1-A4 are of area 34 m^2 . The sub-arrays B-G comprise $4 \times 13.5 \text{ m}^2$ detectors. At H there is 13.5 m^2 , at JKL, 2.25 m^2 and at the 3 locations 150 m from A1 there is 9 m^2 . Within the shaded area is a lattice ($\sim 150 \text{ m}$ spacing) of $30 \times 1 \text{ m}^2$ detectors, the 'infilled' array. There are muon detectors at the positions inside the shaded area marked with open circles (Watson 1980). The hexagon shows the perimeter of the 1960-1963 Volcano Ranch array to the same scale.

tanks were added, enabling more accurate location of shower cores and more detailed measurements of structure, within a certain portion of the array. More recently scintillators have been added, at first for the purpose of comparing their response to that of the water-Cerenkov tanks, but after the Cygnus X-3 discovery, for the purpose of improving the angular resolution in portions of the installation that now are devoted to UHE γ -ray astronomy.

By 1977, work at Haverah Park had produced results on the energy spectrum and anisotropy of $> 10^{19} \text{ eV}$ cosmic rays with substantially better statistical accuracy than any previous results. This is shown by a comparison with Volcano Ranch in Figure 7. (In deriving the Volcano Ranch points from the size spectrum shown in Fig. 4, the crude assumption used previously about x_m vs N at 835 g/cm^2 was replaced with a more realistic one, taking advantage of experimental and theoretical advances in the interim.) Above 10^{19} eV there is agreement, within the large statistical errors of the Volcano Ranch points. Comparison of the points below 10^{19} eV indicates that the systematic differences are within 30%. The evidence for a flattening of the spectrum above 10^{19} eV , which was only an indication in

the Volcano Ranch spectrum, is quite strong statistically in the Haverah Park result. Both spectra extend beyond 10^{20} eV with no sign of any cutoff. Figure 8 shows the Haverah Park spectrum as it was published a few years later in *The Astrophysical Journal* (Cunningham et al. 1980).

6. Giant Arrays in Sydney and Yakutsk, and the Fly's Eye.

Planning of a giant array in Australia began in 1963. The Sydney University Giant Air-shower Recorder (SUGAR) started full operation in 1968 and continued giving data until 1979. The array had an area of some 50 km^2 , giant indeed! Technical problems in the data reduction, eventually overcome, delayed publication of the final results of this experiment until recent years.

In 1965, plans for a giant array in the Soviet Union were described. Located near the Siberian city of Yakutsk, its 3 km^2 central area began operating in 1970. The full array, covering an area twice as large as the one at Volcano Ranch, began to furnish data in 1974, and it continues to run, the equipment being modernized according to a regular schedule. A special feature is the emphasis on recording the atmospheric Cerenkov light of very large showers, as well as the muon component, so that the calibration will be calorimetric to the greatest possible extent.

The notion that air fluorescence detectors might be employed for studying very large air showers seems to have occurred independently to scientists in the USA, Japan and the USSR (Greisen 1960, Delvaille et al. 1962, Suga 1962, Chudakov 1962). In 1965 Greisen showed in detail how such devices can be used to determine trajectories, energies and development profiles of individual showers. At that time, preliminary work at Cornell University using a relatively simple arrangement of photomultipliers had already been reported in the form of a thesis (Bunner 1964). Work on a full scale device, called a "fly's eye telescope", continued at Cornell until 1972 but then was dropped. Shortly afterward the idea was taken up by Keuffel's group at the University of Utah. Redesigned prototype units were tested successfully at Volcano Ranch in 1976. A complete fly's eye,

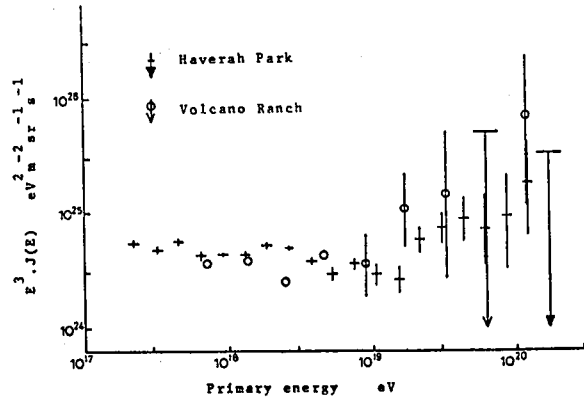


Fig. 7. Comparison of the 1977 Haverah Park energy spectrum and the Volcano Ranch spectrum (Cunningham et al. 1977).

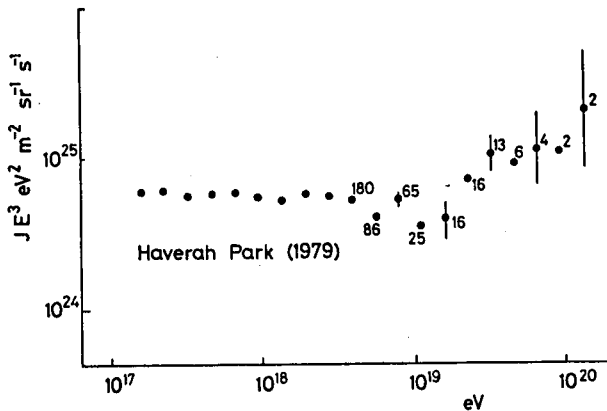


Fig. 8. Haverah Park energy spectrum (Cunningham et al. 1980).

together with a partial eye located near it, has been operating at Dugway, Utah, for several years. The amount of fluorescent light produced in a layer of atmosphere is proportional to the amount of ionization, so when the variation of conversion efficiency with pressure is taken into account the signals from a fly's eye provide a calorimetric measurement of E_{EM} , the energy deposited by the electromagnetic component of showers. In the domain of very high energies only a small correction is required to obtain from this the energy of the primary particle.

7. On Estimating the Energy of Giant Air Shower Primaries. Although preliminary energy spectra from Yakutsk agreed with Haverah Park and Volcano Ranch as to flattening and absence of a cutoff, results given at the 8th European Cosmic Ray Symposium in 1982 showed a deficiency of very energetic events, beginning at a few times 10^{19} eV, as predicted by Greisen (1966) and Zatsepin and Kuzmin (1966) for cosmic rays with a universal origin, due to effects of the 3K background radiation. It was surmised at first that the disagreement might be due to differences in the algorithms for converting from ground parameters to primary energy. It was possible to test this hypothesis in a very direct manner, because the Yakutsk ground parameter $S(600)$ has also been measured for some very large showers at Haverah Park, and it could be derived from Volcano Ranch data for some very large showers with slant depths corresponding closely to the altitude of Yakutsk. These tests were made, and in both cases they show good agreement (Bower *et al.* 1983). One concludes that if the Yakutsk array had detected the same showers that were detected and assigned energies $> 4 \cdot 10^{19}$ eV at Volcano Ranch and Haverah Park, these showers would likewise have been assigned energies above the Greisen-Zatsepin cutoff, energies sometimes exceeding 10^{20} eV, in agreement with the investigators at MIT and Leeds. Another conclusion that can be drawn from these tests is that, insofar as the Yakutsk energy scale is correct calorimetrically, so are the scales employed at Volcano Ranch and Haverah Park.

It should be kept in mind that some of the methods for finding the principal energy term E_{EM} are limited in the range they cover. Only with the atmospheric fluorescence method can one avoid a certain amount of extrapolation; avoid, that is, relying on approximate proportionality to energy of some ground parameter such as $\rho(600)$ at Haverah Park or $S(600)$ at Yakutsk. The method using atmospheric Cerenkov light is limited to $E < 10^{19}$ eV by the low duty cycle of the light receivers, which can be used only on clear, moonless nights. The method using maximum size is limited at present to $E < 10^{18}$ eV by a lack of observations with sufficiently large surface arrays at sufficiently high altitudes. It is reassuring, however, that as far as they go in energy, results by this method agree with the Cerenkov method. This is shown in Figure 9, where the filled circles derive from measurements of N_m while the diamonds are from measurements of atmospheric Cerenkov light. It is notable that the filled circles agree as well as they do with the low energy portion of the Haverah Park spectrum.

Unlike the other experiments described here, the SUGAR experiment used muon size as the basis for estimating primary energy. Originally, the plan was to rely on certain cascade simulations for relating N_μ to E . It turns out, however, that these simulations disagree with direct measurements of the N_μ - E relation made in recent years at Akeno and Yakutsk. As a

result the SUGAR spectrum disagrees strongly with others described here when it is based on these simulations. In reviewing the subject for the Bangalore conference I found that by using a 2-constant parametrization of the Yakutsk N_μ -E results instead of the simulation one obtains much better agreement. The constants control the slope and intercept of the log-log energy spectrum. In case of the SUGAR spectrum, the slope is about right, indicating that one of the constants is about right, but the energies are systematically too high by 20-30%, an amount that is small in this context, indicating that the other constant is off the mark, due to residual errors in the N_μ vs E measurements at Yakutsk or to a systematic error in N_μ as measured by SUGAR.

In Figure 10 I compare the Haverah Park spectrum of Figure 8 with a preliminary Fly's Eye spectrum (Baltrusaitis et al. 1985) and a version of the SUGAR spectrum, where in the interest of fairness to proponents of a spectral cutoff I have adjusted

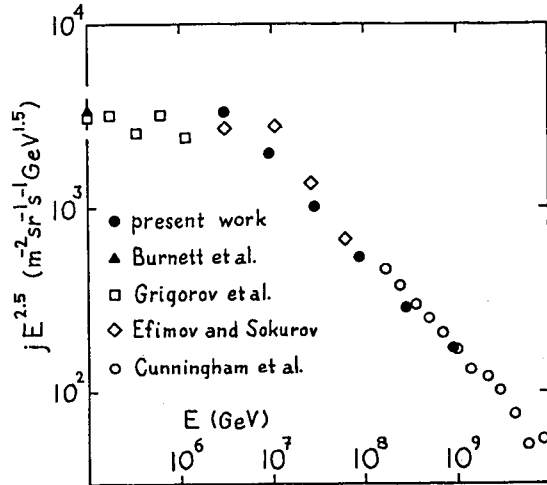


Fig. 9. All-particle energy spectrum. The filled circles are from my conference paper OG 5.1-4, "New Calorimetric All-Particle Energy Spectrum"; see also Linsley 1983, Figures 5-8 and 10.

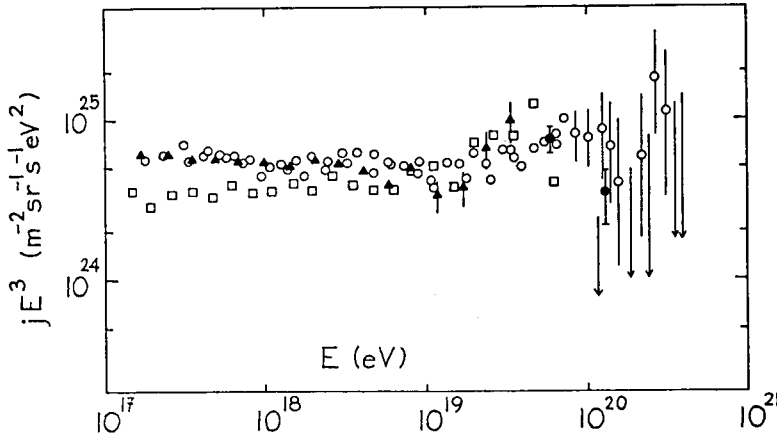


Fig. 10. Differential energy spectrum $j(E)$ plotted as jE^3 . The filled triangles are from Cunningham et al. 1980; the open squares, from Baltrusaitis et al. 1985 (with some of the error bars redrawn so as to conform with usual practice); the filled circles, from Bower et al. 1983 (converted to differential form as in Linsley 1983); the open circles and upper limit arrows, from Horton et al. 1983, with N_μ converted to E as described in the present text.

the offending constant *ad hoc*, bringing down the energy corresponding to a given intensity so as to reach agreement with the Haverah Park spectrum at 10^{19} eV. This value was chosen because at this energy the remaining experiments (Yakutsk, Volcano Ranch and Fly's Eye) already agree rather well. The Haverah Park data base has increased significantly since 1979. A more recent spectrum is given in this conference (paper OG 5.1-3 by Brooke et al.)

8. Statistical Fluke, or Inefficiency? Tradeoffs between quality and quantity are common in scientific work. A familiar example illustrating what I wish to say about large air shower experiments is given by the HEAO-3 Heavy Nuclei Experiment. Events selected by a loose electronic trigger were sorted into various subsets with different combinations of size (number of events) and charge resolution. For analyzing nuclei with $Z = 26-46$ it was appropriate to use only subsets with superior resolution, because these nuclei are relatively abundant, but in searching for actinides it was reasonable, in fact essential, to relax the selection criteria and accept the resulting loss of charge resolution in order to obtain results of greater statistical significance on these very rare but extremely important elements.

Beginning with the Agassiz experiment it has been customary to make rather severe data cuts in selecting events to use for finding the energy spectrum. The two main cuts are on the zenith angle and on the core location with respect to the array boundary. There are good reasons for cuts of this nature: the uncertainty in primary energy for a given observed size tends to increase, on the one hand with increasing zenith angle, and on the other, with increasing radial distance of the shower core from the center of an array, for showers striking outside the boundary. To a large extent these uncertainties are reflections of uncertainty about the longitudinal structure and the lateral structure, respectively, of air showers with the size in question.

In the early 1960's such uncertainties were great. They were especially great regarding the first 'giant' showers. Consequently one made severe data cuts. As late as 1973 the Volcano Ranch energy spectrum above 10^{19} eV was based on only 5 events out of 44 described as having this much energy in the *Catalogue of Highest Energy Cosmic Rays*. All but 11 of these were not sufficiently vertical (I required $\theta < 25^\circ$!); out of the 11 that were sufficiently vertical only 5 struck inside the boundary.

In retrospect, the Volcano Ranch cuts were unnecessarily severe, even at the time, because they were imposed across the board, without taking into consideration that with a given array the direction and core location can be measured more accurately for very large showers than small ones. But at the time it didn't matter. There was no demand for better statistical accuracy; it was more important to be as certain as possible about the energy of the single largest high quality event. Anisotropy was a separate question; the selection criteria were much less strict.

Turning to present arrays, and to controversy on the question of a cut-off, I will now argue in favor of publishing the air shower spectrum results *in both of two forms*: one with optimum 'resolution' but necessarily poor statistical accuracy and the other with poorer 'resolution' but optimum statistical accuracy. I have written 'resolution' with quotes because the main rationale for data cuts is still reduction of possible systematic errors (although the cuts do tend to improve the energy resolution). I propose that one should give more recognition to the very great improvement in knowledge of shower structure from intensive experimental studies during the last decade. The effect of this improvement has been to reduce the systematic errors, so that I believe they are now smaller than the statistical errors above 10^{19} eV, even when data cuts are minimal.

Examples of the two forms are the 1979 Haverah Park spectrum ('high resolution') and the SUGAR spectrum, which was found using all of the Sydney events except for a small percentage that could not be analyzed, or when analyzed gave unphysical results (Horton et al. 1985). A step in the direction I advocate was taken by Bower et al. (1983). Integral intensities for $E > 4 \cdot 10^{19}$ and $E > 10^{20}$ eV were found using all "sufficiently well measured" events from Volcano Ranch and Haverah Park combined. Quality control was assured by the fact that detailed data on many of the individual events had already been published in the *Catalogue of Highest Energy Cosmic Rays*. Examination of the detailed data for 'high resolution' and run of the mill events of this size shows that the difference in quality is small, no greater than in the analogous HEAO-3 experiment.

Following this recommendation it will be seen that the evidence against a spectral cutoff lower than a few times 10^{20} eV is strong statistically as well as in regard to energy assignment and energy calibration. This puts a heavy burden of proof on groups reporting a deficiency of events above $4\text{-}6 \cdot 10^{19}$ eV. At present there is no great problem with the Fly's Eye observations; up to $\sim 6 \cdot 10^{19}$ eV there is good agreement with the experiments showing no cutoff. The deficit above that energy has a chance probability of about 10%. There is a greater problem with the Yakutsk observations. The deficit is greater, with a chance probability of only 1 or 2%. If the groups in Yakutsk and Utah have been victims of a statistical fluke, this should be apparent within a few more years. If, on the other hand, the size of the events they register continues to be limited in this way, then I believe it will be necessary to devise some very direct, foolproof method of proving that the detection efficiency for the 'missing events' is as high as assumed. In case of the Fly's Eye this might involve tests using scattered laser light, similar to tests that have already been made but covering a wider range of distances and angles, repeated regularly during the course of the cosmic ray observations.

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