# Chapter 3

# Observations of the Highest Energy Cosmic Rays

## 3.1 Background

The aim of this chapter is to introduce the observations of the highest energy cosmic rays and to describe the conclusions drawn about the energy of the events detected above $10^{18}$ eV. In the 1920s and 1930s studies of the trajectories of cosmic ray particles in the Earth's magnetic field demonstrated that some had energies in excess of 20 GeV, more than 2,000 times that of the most energetic particles from radioactive sources[118]. In the 1930s Auger and his group discovered[2] the phenomenon now known as "extensive air showers", EAS, and soon showed that the energy spectrum of cosmic rays extends beyond $10^{15}$ eV - a jump of five orders of magnitude from the previous highest energy particles. The estimates of energy made by Auger were based on the understanding of electromagnetic cascades at that time; in hindsight the estimates were probably quite conservative. It is now possible to use massive emulsion chambers, flown to high altitude by balloons, to detect individual cosmic rays of nearly $10^{15}$ eV and to identify, from their ionization trails, the charges of the individual particles. Relatively conventional calorimetric techniques, using emulsions interleaved with lead, permit estimates of the primary energy; an example of this work is the JACEE project[104], funded by American, Japanese and Polish agencies.

Above a few $\times 10^{15}$ eV, the cosmic ray flux decreases more rapidly with energy than at lower energies (recall Figure 2.1 in the last chapter). The rate is so low that individual events can no longer be detected efficiently by aircraft or balloon-borne calorimeters at a useful rate and one relies instead on developments of the technique pioneered by Auger. The post-war availability of large area scintillation counters led to a series of important experimental advances, particularly by the MIT group under Rossi. A detailed understanding of the shower phenomenon was acquired, and the ability to measure both the size of the shower and its arrival direction with considerable accuracy was developed. The regular registration of events having energies greater than 1 Joule ($6.24 \times 10^{18}$eV) resulted from the construction of the first giant shower array, by Linsley's MIT group [3, 105] at Volcano Ranch, New

Mexico, during the late 1950s. This work was innovative and the experiment was the first to claim the detection of an event with an energy of about $10^{20}$ eV.

The Volcano Ranch work, and all other work carried out in this field until 1966, was motivated largely by the recognition that a proton of $10^{18}$ eV in a magnetic field of $2\mu$G (typical of our Galaxy) has a Larmor radius of about 0.5 kpc, somewhat greater than the thickness of the disc of the galaxy. It was thus a reasonable expectation that study of the arrival directions of cosmic rays above $10^{18}$ eV would reveal, at least, large scale anisotropies, the amplitudes of which were expected to increase with energy. Point sources, perhaps associated with neutrons which have a mean free path before decay of about 10 kpc at $10^{18}$ eV, were also anticipated and there was considerable interest in what the ultimate energy of detectable cosmic rays might be. Following the recognition by Greisen[12] and by Zatsepin and Kuzmin[13] in 1966 that cosmic rays above $4 \times 10^{19}$ eV would be exceedingly rare if the cosmic ray sources were at cosmological distances ($> 100$ Mpc or so) attention focussed more and more strongly on searching for an end to the cosmic ray spectrum. At the same time it was recognized (see [23] for a detailed review) that $10^{20}$ eV was rather close to the limit of acceleration by known mechanisms.

It is now known that the rate of cosmic rays above $10^{19}$ eV is about 0.5 km$^{-2}$sr$^{-1}$yr$^{-1}$. How that energy scale is established will be discussed below and in the following chapters but it is clear from this rate that one requires a large collecting area ($>> 10$ km$^2$) to obtain a useful sample of events. With one exception, the approach adopted has been to cover the monitoring area, more or less uniformly, with a relatively small number (a few tens) of detectors, each having an area greater than about one square meter. The original configuration of the Volcano Ranch array is shown in Figure 3.1; here the spacing between the 3.3 m$^2$ scintillators was 884 meters. At each detector of such an array the particle density - more strictly the energy loss - is measured together with the arrival time of the signal at the detector relative to the other detectors. The event shown in Figure 3.1 was initially ascribed an energy of $10^{20}$ eV: this was subsequently revised upwards to $1.3 \times 10^{20}$ eV[106]. No Monte Carlo calculations were used to make these estimates but rather a detailed analytical understanding of the physics of electromagnetic cascades was invoked.

The shower particles travel in a thin disc or "pancake" which moves, essentially at the speed of light, in the direction of the incoming primary cosmic ray particle. The relative arrival times at separated detectors allow reconstruction of the primary's direction to 2° or better, this accuracy being a strong function of the number of detectors hit and of the area of each detector.

Other arrays at Yakutsk (Russia), Akeno (Japan), and Narrabri (Australia) were also constructed using scintillation detectors. At Haverah Park (UK) the detectors were water Čerenkov detectors (1.2 m deep and of various areas from 1 m$^2$ to 34 m$^2$) spread over 12 km$^2$; the array ran more or less continuously for twenty years. Much of the design information from the Monte Carlo calculations used by the Auger collaboration has been checked against results from this experiment (described in Chapters 4 and 5). A particular advantage of the deep water Čerenkov detectors lies in their ability to respond to the large number of photons of relatively low energy (less than 10 MeV) present in the shower.

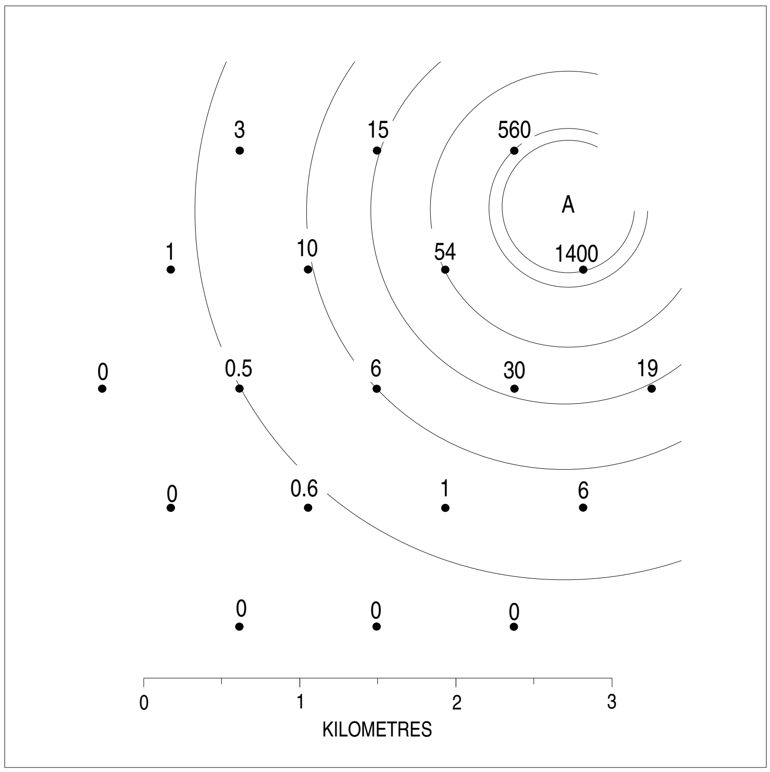


Figure 3.1: An extensive air shower recorded by the Volcano Ranch array with energy above $10^{20}$eV. The numbers indicate the observed particle densities ($m^{-2}$).

A completely different method of recording the extensive air showers relies upon the fluorescence light produced through interactions of the charged particles with atmospheric nitrogen molecules. The light is produced predominantly in the 300-400 nm band and although the fluorescent yield is small (typically 4.5 photons are emitted isotropically per meter of electron track) a detector has been built to observe the emission. The light can be seen above the sky background on clear, dark nights. This feat was achieved by the University of Utah group who have built a device containing two separated "Fly's Eyes" made up of 880 and 460 photomultiplier tubes respectively, 3.3 km apart[8]. With these units it was possible to map out the longitudinal development of individual shower events for the first time.

## 3.2 Energy measurements

The unique feature of a fluorescence detector is that it allows direct measurements of the depth in the atmosphere of the maximum numerical size of the shower ($X_{max}$), as well as of the shape of the cascade curve. The energy of the particle which initiates each cascade is obtained from the track length integral of the shower-development curve, i.e.,

$$E_{em} = \frac{E_c}{\lambda_r} \int N_e(x)dx$$

where $E_{em}$ is the total energy dissipated in the electromagnetic channel, $E_c/\lambda_r$ is the ratio of the critical energy of electrons to the radiation length, and $N_e(x)$ is the observed number of electrons in the shower as a function of atmospheric depth, $x$. Strictly speaking, the integration sums the total number of charged particles in the shower, but electrons vastly outnumber other particles. The amount of fluorescence light observed is determined by the number of particles. In terms of how the total energy is apportioned among shower particles however, a significant fraction is carried by other particles. An upward correction of about 10% must be made to $E_{em}$ as computed above in order to obtain the energy of the primary cosmic ray particle, to account for the energy which goes into muon, neutrino and hadronic channels.

The inference of $N_e$ from the amount of detected fluorescence light depends on accurate knowledge of the factors responsible for light production and transmission through the air, calibration of the optical detection system and determination of the shower trajectory. Over the years of operation of the Fly's Eye experiment an ongoing program of study of atmospheric effects has evolved. Allowances for these factors have been discussed in detail by the Fly's Eye group [10, 107]. Recent laboratory measurements[108] of the fluorescence efficiency of gaseous nitrogen have confirmed these calibration factors.

In both the Fly's Eye detector and ground arrays, analogies can be seen with the calorimeters used in accelerator based high energy physics experiments. In the former case the atmosphere acts as a calorimeter just as would a block of scintillator, but on a vastly different scale, and the shower is observed by a large number of photomultipliers to give spatial information. The ground array is a sampling calorimeter, by far the most common type in accelerator experiments, but with a single detector layer located near $X_{max}$ that is only sparsely implemented. In this case the atmosphere is analogous to the absorber of the calorimeter, usually lead or iron plates.

In a sampling calorimeter, even though only a small fraction of the energy is actually detected, the principle of calorimetry is that the detected energy is proportional to the incident particle energy. In the ground array, the relationship of signal to primary energy is calculated by Monte Carlo simulations, many features of which (such as the transverse shower shape) can be checked against real showers. Still, this calorimeter cannot be calibrated in a well defined beam. Nevertheless, measurements of the same cosmic ray events by both the ground array and the fluorescence detector provide crucial cross calibrations. This is a strength of the hybrid design of the Auger Observatory. Any systematic energy differences will be studied and understood.

There are differences in the character of measurements made in high energy physics experiments and those by air-shower experiments. Air showers have enormous numbers of particles so fluctuations contribute negligibly to the fractional errors in energy. The variation of the depth in the atmosphere where the shower begins is the dominant source of variation in shower size at the ground. Ground arrays measure the lateral density profile, which exhibits minimal fluctuation at a certain intermediate core distance (600 m for the Haverah Park analysis, including dependences on array spacing), ultimately permitting energy resolution $\delta E/E$ of about 10%, based upon calibrating the observed density with primary energy via simulations. This effect is not significant in fluorescence detectors which measure the shower profile, but errors in characterizing the scattering properties of the atmosphere for distant events can introduce energy reconstruction errors of similar magnitude.

If showers are measured by *both* a ground array and a fluorescence detector, both problems are greatly reduced and the resulting energy calculation correspondingly improved. The Auger Observatory will use both techniques, ensuring the most robust and cost-effective reconstruction of events.

### 3.2.1 Energy spectrum

Determination of the cosmic ray energy spectrum from ground-based arrays, and primary energy computation generally, are closely tied to Monte Carlo model calculations. Ingenious methods have been devised to reduce this dependence but, until the calorimetric measurements of the Fly's Eye device were finalized, considerable doubt existed about the validity and systematic errors associated with the various approaches. This was despite efforts at cross-calibration made, for example, by operating independent arrays within the Haverah Park facility.

The proof of the efficacy of these efforts lies in the excellent agreement between the spectral shapes and absolute intensities deduced by Akeno and AGASA, Fly's Eye, Haverah Park and Yakutsk. All groups [15, 106, 109] are agreed that:

- The shape of the differential energy spectrum from $10^{17}$ to $\sim 6 \times 10^{17}$ eV is a power law $E^{-\gamma}$ with $\gamma = 3.0 \pm 0.05$.

| Array | $m^{-2}\ s^{-1}\ sr^{-1}\ eV^{-1}$ |
|---|---|
| AGASA | $2.91 \times 10^{-33}$ |
| Fly's Eye | $2.38 \times 10^{-33}$ |
| Haverah Park | $2.22 \times 10^{-33}$ |
| Yakutsk | $3.39 \times 10^{-33}$ |

Table 3.1: Cosmic ray intensity measurements at $10^{19}$ eV from several experiments. In each case, the experimental uncertainty is about $\pm$ 20%.

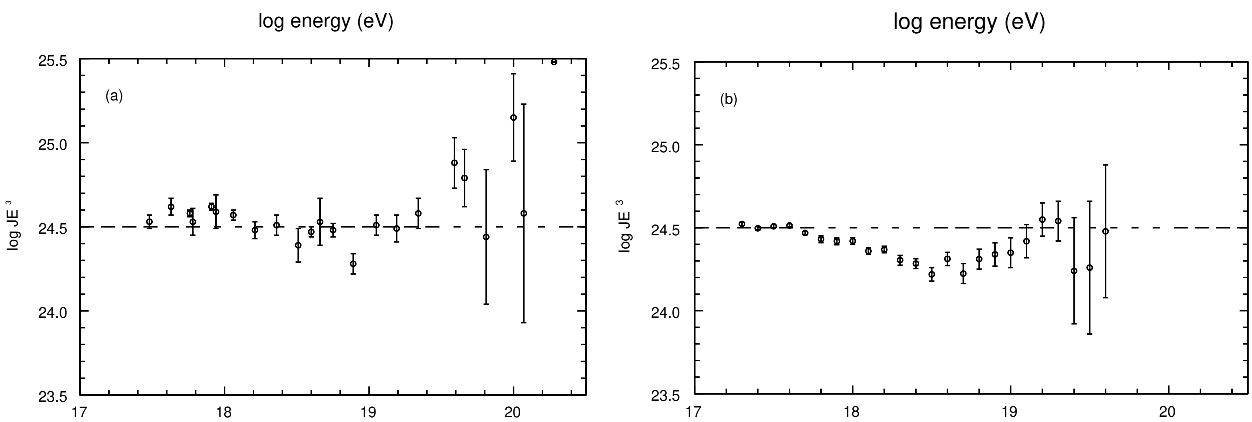


Figure 3.2: Differential energy spectrum ($\times E^3$) as observed by, (a) the Haverah Park array, (b) the Fly's Eye experiment. Note that the exhibited spectrum for the Fly's Eye is for events recorded by more than one of the Eyes ("stereo" events), and so does not include their largest event at $E = 3 \times 10^{20}$ eV).

- Above about $6 \times 10^{17}$ eV the energy spectrum steepens ($\gamma = 3.2 \pm 0.1$) before recovering at about $5 \times 10^{18}$ eV to a slope of $\gamma = 2.7 \pm 0.2$ (flatter than the slope near $10^{17}$eV). The differential intensities at $10^{19}$ eV are in excellent agreement and within the experimental uncertainties (see Table 3.1 and discussion below), demonstrating that the processes of energy derivation and the systematic errors are well understood.

The spectra from the Haverah Park, Fly's Eye and AGASA work are shown separately in Figures 3.2a, 3.2b and 3.3. Figure 3.4 combines the spectra from these three experiments along with the Yakutsk data[15]. The slope changes just described are clearly seen in these figures. Note also that the Haverah Park and AGASA plots each exhibit combined points from different analyses of their data. In each case, less restrictive criteria were imposed on events in higher energy data sets than in lower energy ones, in order to obtain sufficient numbers of events at the high energy (low flux) end of the spectrum.

In order to compare the *shapes* (without regard to the absolute scales) of the energy spectra of the different experiments, the data are plotted together in Figure 3.4. The energy scale of each experiment has been separately adjusted[15] in order that all match the AGASA measurement near $10^{18}$ eV. The scale factors used were 1.0 (Haverah Park), 1.1 (Fly's Eye),

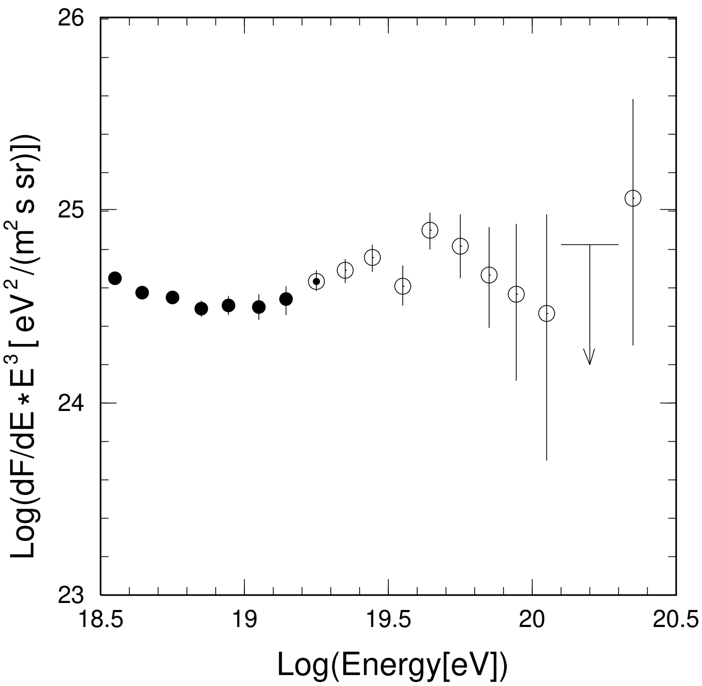


Figure 3.3: Differential energy spectrum ($\times E^3$) as observed by the AGASA experiment, for an integrated exposure of 630 km$^2$ yr sr. The upper limit shown is at 90% confidence. (This figure is an updated version of a plot originally given in reference [15]).

and 0.9 (Yakutsk). These factors are within the quoted systematic energy uncertainty of each experiment. Thus, the four results clearly are in good agreement on the shape of the energy spectrum. It is encouraging that these experiments, employing very different techniques to estimate the energy, arrive at the same qualitative result. It is to be emphasized that this exercise can *not* be used to quantitatively evaluate the energies at which any possible spectral features may be occurring.

At $10^{20}$ eV the flux is $\sim 0.5$ km$^{-2}$ century$^{-1}$ sr$^{-1}$ and with the present exposures it is not surprising that there are uncertainties. A recent analysis of a subset of available data [15] noted a total of 7 events exceeding $10^{20}$ eV. An extrapolation of the experiments' $E^{-2.7}$ differential power-law observed at lower energy predicts that about 20 should have been seen. But the slope of the power laws is also uncertain, so the significance of any deficit is difficult to assess. With the present limited statistical power of the available data, significant "cutoffs" or "gaps" in the cosmic ray energy spectrum are not observed. Still, it is interesting to compare the measurements in Figure 3.4 with the spectral structure expected from the GZK effect as was shown, for example, in last Chapter's Figures 2.6 and 2.7.

The purpose of the Auger Observatory is to study the origin and nature of cosmic rays with energies above $10^{19}$ eV. The integrated exposures of past and present experiments achieved so far at 5 x $10^{19}$ eV are shown in Table 3.2. For the particle detector arrays, these exposures correspond to showers detected within $45^0$ of the zenith. Even at $10^{20}$ eV the maximum of the shower is above the level of the detectors, and its amplitude is attenuated at a rate which depends on the shower components detected. For scintillators the attenuation

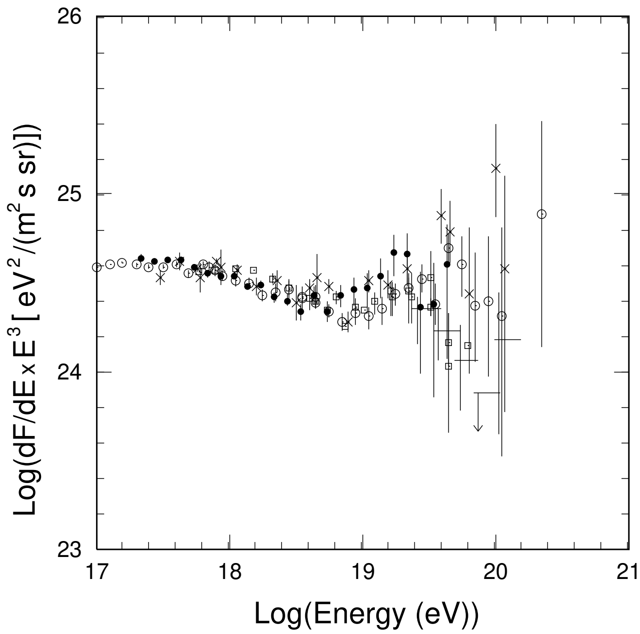


Figure 3.4: Combined differential energy spectra ($\times E^3$) from the Haverah Park ($\times$), Fly's Eye (stereo, $\bullet$), Yakutsk ($\square$), and Akeno/AGASA ($\odot$) experiments. The energy scale of each experiment has been slightly shifted to match the AGASA result around $10^{18}$ eV. (This figure is an updated version of a plot originally given in reference [15]).

length is $\sim$ 320 g/cm$^2$. For water Čerenkov detectors, which are relatively more sensitive to muons in air showers, the corresponding figure is 750 g/cm$^2$, so that showers can be detected at a useful rate at even larger angles. This is most clearly seen by comparing the declination distributions registered by Volcano Ranch (all zenith angles) and Haverah Park (zenith angle $< 60^0$) shown in Figure 3.5. The combined acceptance of the two separated sites of the Auger Observatory can be estimated based on the Haverah Park data; this is shown in Figure 3.6. It is evident that having sites in the Northern and Southern Hemisphere will give coverage (with some overlap) of the entire celestial sphere. The current total exposure of 1000 km$^2$ y sr will thus be exceeded by <u>one</u> of the two 3000 km$^2$ detectors of the Auger project in about 100 days.

### 3.2.2 The highest energy events

The limited data available above $5 \times 10^{19}$ eV have, until recently, made it difficult to answer unequivocally the question of whether or not events exist above the GZK cut-off. However the early claims by Volcano Ranch[3] and Haverah Park[7] that events with energies close to $10^{20}$ eV do exist have recently been supported by results from the other groups. In 1990 the Yakutsk group described[5] an event with an energy of $(1.1 \pm 0.4) \times 10^{20}$ eV. While this is undoubtedly an event which has been produced by a very energetic primary, the almost completely muonic nature of the particles detected and its relatively large zenith angle ($58.7^0$) make it hard to be definite about the energy assignment.

| Array | $km^2$ yr sr |
|---|---:|
| AGASA (100 $km^2$) | 630 |
| Fly's Eye (stereo) | 151 |
| Fly's Eye (monocular) | 930 |
| Haverah Park (12 $km^2$) | 270 |
| Yakutsk (25 $km^2$) | 490 |
| Total | 2471 |
| Total (Exc. FE mono) | 1541 |

Table 3.2: Comparison of integrated exposure at $\sim 5 \times 10^{19}$ eV for different experiments. Only the AGASA experiment is still operating.

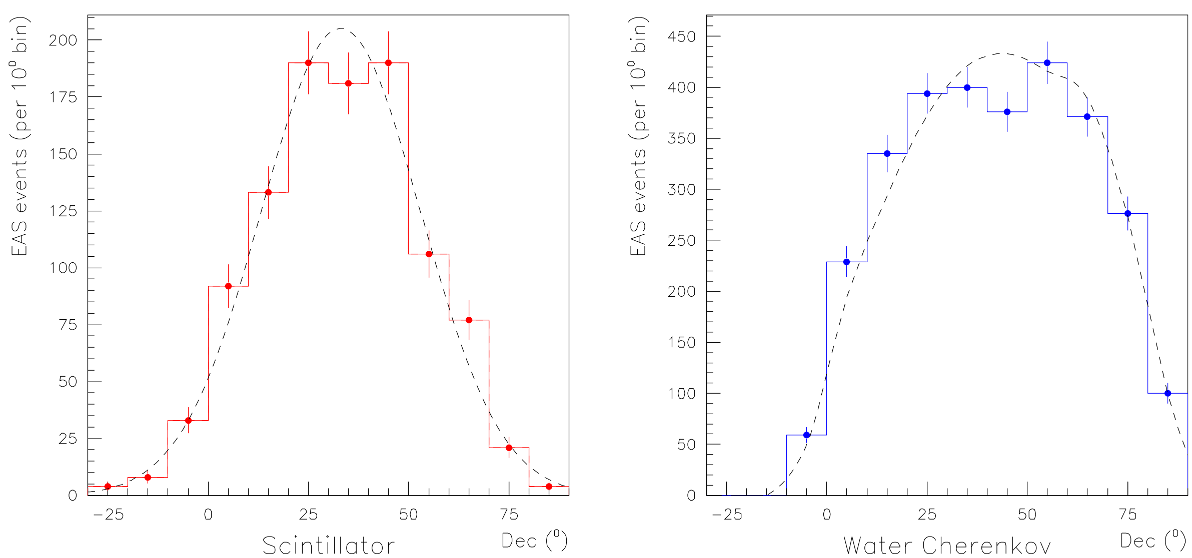


Figure 3.5: A comparison of the declination distributions of showers recorded by large water Čerenkov and scintillator EAS arrays. The water Čerenkov data is taken from the Haverah Park array at an atmospheric depth of 1020 g cm$^{-2}$ and latitude of $54^0$ N, and the scintillator data from the Volcano Ranch array at an atmospheric depth of 834 g cm$^{-2}$ and latitude of $35^0$ N. Shower size is $1 \times 10^{18} < E < 4 \times 10^{18}$ eV. Haverah Park data are restricted to zenith angles $< 60^0$, whilst the Volcano Ranch data are for all zenith angles. The FWHM of the Haverah Park distribution is $\approx 75^0$ as opposed to $\approx 40^0$ for Volcano Ranch. The water Čerenkov array has approximately twice the solid angle sky coverage.

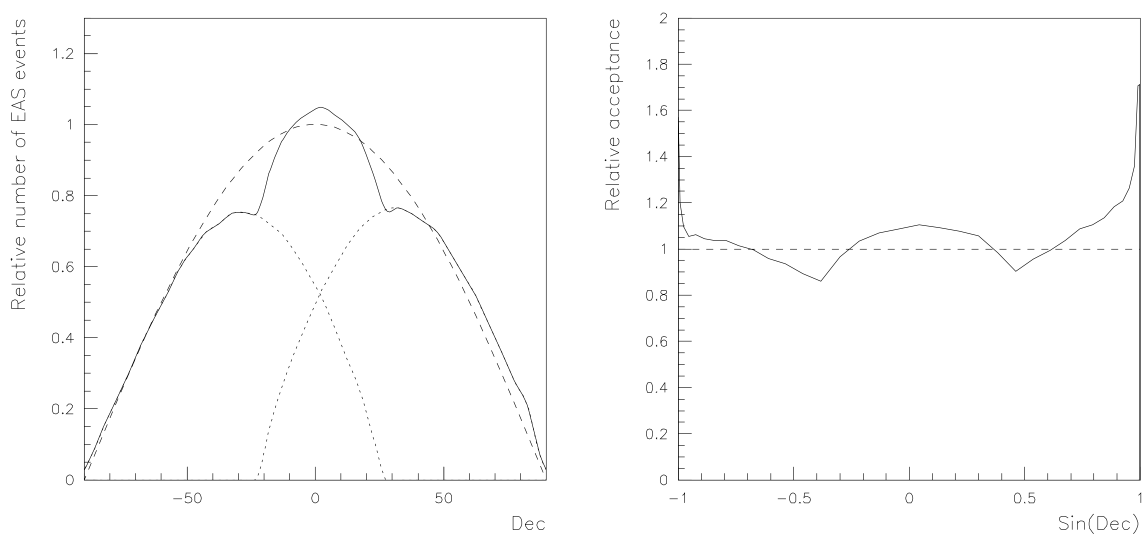


Figure 3.6: Left, solid line is the expected declination distribution of events from the combination of the two Auger ground arrays (at latitudes 39.1° N and 35.25° S). Dotted lines show the separate contributions of the each site. The calculation assumes events are accepted within 60° of the zenith, and uses the shape of the Haverah Park experiment's declination distribution (shown in the previous Figure). The dashed curve is the distribution which would be obtained from an "ideal" detector with uniform solid angle acceptance (i.e., cos(Dec)). On the right, the ratio of the predicted to the ideal is plotted against sin(Dec). In this form the area below the curve is proportional to the product of acceptance and available solid angle. It is seen that although there is relative over-exposure at the celestial poles and equator, the acceptance of the two water Čerenkov arrays is good over the whole sky.

In 1993 the Fly's Eye group reported[4] a monocular event for which the assigned energy is $(3.2 \pm 0.9) \times 10^{20}$ eV. This is the highest energy event ever recorded and its reconstructed cascade curve is shown in Figure 3.7. Although the shower size at maximum is extraordinary, there is nothing unusual about the shape of the longitudinal profile. The amplitude rises and falls with the characteristic smooth functional form of air showers predicted by Monte Carlo simulations. This event was not measured stereoscopically, so there is some uncertainty in the geometric reconstruction. If the shower were closer to the detector, the inferred size would be smaller, so the geometric uncertainty implies an energy uncertainty also. The shower depths would also be different, however, if the shower were closer. Changing the geometry to bring the energy down below $10^{20}$ eV would require the primary particle to have penetrated more than 800 g/cm$^2$ before interacting. That would mean an incredible penetration of more than 20 mean free paths as well as an implausibly large error in the geometry. Another source of energy uncertainty is atmospheric attenuation of the fluorescence light. If the light suffered less attenuation than calculated, then the true light production and shower size would have been smaller than estimated. However, even using a perfectly clear atmosphere (Rayleigh scattering only), the energy is still calculated to be $2.2 \times 10^{20}$ eV. It should also be noted that the fluorescence energy measurement is a calorimetric measure of the electromagnetic cascade. The electromagnetic cascade energy measurement for this event was $2.9 \times 10^{20}$ eV, and it was assumed that 10% additional energy is in muons and neutrinos. Although some systematic error in energy calculations can be attributed to uncertainty in the atmospheric fluorescence efficiency, this uncertainty is not greater than 20%, having been measured in accelerator beam experiments [108]. The lower bound on this particle's energy is still above $10^{20}$ eV.

Using their 100 km$^2$ array of 111 2.2 m$^2$ scintillators, the AGASA group have observed a particularly clean event, at a zenith angle of 23°, for which the primary energy is measured [6] to be in the range of 1.7 to 2.6 x $10^{20}$ eV. This event fell in such a position that the core of the shower is in a part of the array which is relatively densely populated with detectors. The largest recorded particle density is $\sim$ 25,000 m$^{-2}$ and is only about 250 m from the core. The primary energy is derived by first obtaining the area density of particles at 600 m, $S(600)$, from the density data, normalizing this to what would have been observed had the event come from the zenith rather than from $23^0$ and then converting this number to primary energy using a Monte Carlo calculation. There are thus three sources of uncertainty in the energy estimate. These will be discussed briefly in turn. For this event $S(600)$ is measured as 892 m$^{-2}$.

The use of $S(600)$ as an energy estimator is a standard technique with long history. It is a development of an earlier idea of Hillas's first applied extensively to the Haverah Park water Čerenkov array. Extensive model calculations by him and others have shown that variations in shower models and mass composition affect the primary energy estimates only weakly. $S(600)$ can be found rather accurately from the data: Monte Carlo studies of the analysis techniques give the uncertainty as +21% and -6.6%. The normalization from $23^0$ to the vertical depends upon empirical information about the attenuation length (see above). The vertical value of $S(600)$ is between 892 and 1065 m$^{-2}$, where the smaller value would apply if there was no attenuation correction to be made. Taking the smaller figure and subtracting 6.6%, gives a lower bound (68% confidence) limit of 833 m$^{-2}$. The conversion of

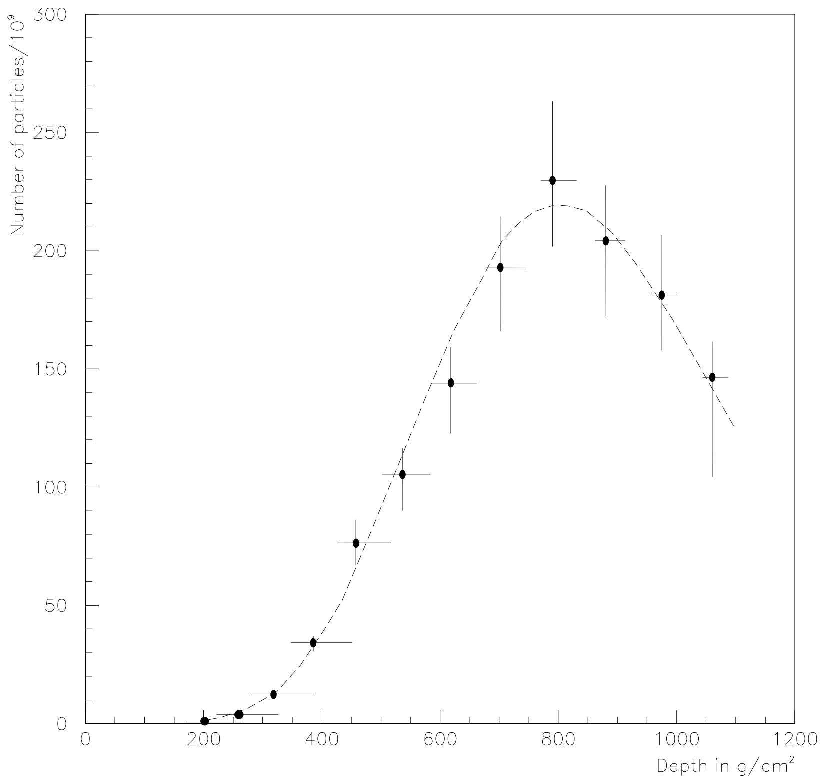


Figure 3.7: Longitudinal cascade development profile for the Fly's Eye $3 \times 10^{20}$ eV event, the largest cosmic ray air shower ever recorded.

the vertical $S(600)$ value to primary energy is model dependent; that used by the AGASA group is a QCD model which gives $E = 2.0 \times 10^{17}$ eV $\times (S(600)/1\ m^{-2})$. The systematic error which may be present can be estimated by comparison of the $10^{19}$ eV differential intensities measured by AGASA and Fly's Eye (see Table 3.1 or discussion in text for Figure 3.4). This would suggest that the two quite different approaches to energy estimation agree within 10%, with the published AGASA energies being systematically greater than the Fly's Eye estimates at $10^{19}$ eV.

The extrapolation by a further order of magnitude is, of course, uncertain. However, the fall off with distance of the unshielded scintillator signals is not anomalous by comparison with expectation from lower energies. Furthermore muons are detected in seven detectors at a normal density level. The temporal distribution of the signal in the 30 $m^2$ scintillation counter at 1920 m from the shower axis is also consistent with expectation. There is thus high confidence that the AGASA event is above $10^{20}$ eV and well above the GZK cut-off.

The energy estimates for the largest events are subject to still uncertain systematic errors, such as the unknown particle types of the primaries. Nevertheless, the very good agreement between the intensity measurements at extreme energy, from four rather different experiments (Table 3.1 and Figure 3.4), argues strongly that there is a proper understanding of the uncertainties at the 20% level near $10^{19}$ eV. Furthermore, the characteristics of the showers recorded by Fly's Eye and by AGASA are consistent with what is expected from ordinary hadronic cosmic ray primaries by straightforward extrapolation from well-studied behavior near $10^{19}$ eV. The agreement of the different methods makes it quite convincing that the discovery of these two well-measured events, at least two or three times more energetic than any other prior cosmic ray, clearly settles the question of the existence of cosmic rays above the GZK cutoff. What is not yet decided is the particle type, the spectral shape, and, of course, the fundamental question of the limit to the energy reached by cosmic rays. These are further problems which the Auger Observatory is designed to answer.

## 3.3 Direction measurements

### 3.3.1 Anisotropy

Most theories of energetic particle production predict that the source locations are correlated with the cosmic matter distribution. Extremely energetic particles are magnetically rigid enough to point back to their sources with only small deflection, even for rather large source distances (recall Figure 2.9 in the last chapter). It is also true that such particles have not traveled more than $\sim 200$ Mpc (or much less, depending on energy) since attenuation from the GZK effect would become severe. Within this volume of space, the mass density is dominated by the so-called *supergalactic plane*.

The supergalactic plane appears as a line on the sky, intersecting the Milky Way at nearly a right angle. It was defined through the observation that the nearest optically bright galaxies lie not far from and on either side of this line. Radio-galaxies closer than $z \approx 0.02$

| Energy($10^{20}$ eV) | HP | All | AGASA |
|---|---|---|---|
| $> 0.2$ | 0.68 | 0.31 | 0.52 |
| $> 0.4$ | 0.013 | 0.012 | 0.30 |
| $> 0.6$ | 0.038 | 0.027 | 0.83 |
| $> 1.0$ | | 0.058 | |

Table 3.3: Probability, for several experiments, that an isotropic source distribution of cosmic ray arrival directions fluctuates randomly to exhibit clustering with respect to the supergalactic plane to the degree each observes.

(about 100 Mpc) also tend to concentrate along this band. This appearance is what is expected if the large scale structure of the universe has a mass distribution arranged in bubble-like geometries.

Recent analyses of the data sets of both Haverah Park[50, 51] and AGASA[52] have suggested that the highest energy cosmic ray arrival directions appear to cluster near the supergalactic plane. The enhancements in the data sets are apparent for energies greater than $4 \times 10^{19}$ eV. An energy-dependent anisotropy can result from the increasing magnetic rigidity of particles or if the highest energy cosmic rays have a different source than lower energy particles.

The degree of anisotropy is measured by computing the "latitude" $b^{SG}$ of the arrival directions of cosmic rays with respect to the supergalactic plane.[1] Table 3.3 gives the results of these analyses. Shown is the probability that a uniform arrival direction distribution fluctuates to give a value of $\langle |b^{SG}| \rangle$ as small or smaller than what was observed. The columns marked "HP" and "All" are from reference [50] and refer respectively to the Haverah Park data alone (73 events above $2 \times 10^{19}$ eV) or to a combined set of Haverah Park, AGASA, Volcano Ranch, and Yakutsk (143 events above $2 \times 10^{19}$ eV). The column for "AGASA" is from a more recent analysis[52] which includes a larger data set from this experiment (149 events above $2 \times 10^{19}$ eV) than those used in Ref.[50]. In each analysis, the r.m.s. fluctuation of $b^{SG}$ was also studied and the results were similar.

It can be seen from Table 3.3 that the Haverah Park data shows a clustering along the supergalactic plane with a chance probability of only a few percent. The AGASA result appears inconsistent with this, although the celestial acceptance of the two experiments are different. Furthermore, the AGASA group reports[52] that the data show an anomalous distribution of the parameter $b^{SG}$, shown in Figure 3.8. It is observed that about 30% of the AGASA data above $4 \times 10^{19}$ eV are contained within 10° of the supergalactic plane. However, the significance of this excess is only about $1.6\sigma$.

The evidence for anistropy of cosmic ray arrival directions is suggestive but statistically very weak. Clearly, if the effect is real, it will become very apparent with the increased collecting power and excellent angular resolution of the Auger Observatory.

[1] The latitude $b^{SG}$ is the angular displacement from the supergalactic plane, analogous to our earthly latitude which measures angular distance from the equator.

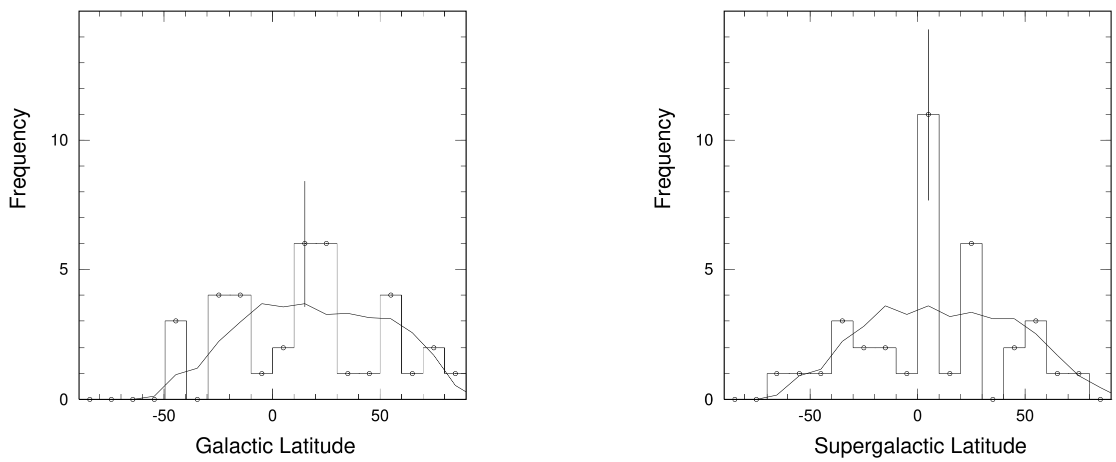


Figure 3.8: Distribution of angular deviation of cosmic ray arrival directions from (a) the Galactic plane and (b) the supergalactic plane, from the AGASA experiment. Lines in each case give the distribution expected if the arrival directions are isotropic.

### 3.3.2 Point sources

In addition to statistical associations with the mass distribution, the arrival directions of individual cosmic rays ought to correlate with their source locations, if the particle energies (rigidities) are high and the sources nearby. There is some evidence in this regard for the highest energy events. It was noted in the previous chapter that galaxies with powerful radio jets, especially FR-II objects with "hot-spots", are excellent candidate accelerators of $10^{20}$ eV particles([40]-[47]). There are very few such objects within 100 Mpc, so the likelihood of a chance association is small. It is therefore interesting that:

- The FR-II galaxy 3C134 is within the error box of the reconstructed direction of the $3 \times 10^{20}$ eV Fly's Eye event. The distance (redshift) of 3C134 is not yet measured, having only recently been detected in the optical continuum. However, based on crude distance estimates, 3C134 is likely to be among the closest of all FR-II galaxies[49].
- Similarly, NGC315 is 10° from the Akeno event at $2 \times 10^{20}$ eV. NGC315 is powerful, asymmetric source only about 50 Mpc distant. (An asymmetric appearance is expected when the axis of the jets is oriented along or near our line of sight).

It has also been pointed out recently[110] that the direction of a close pair of energetic AGASA events is near to the location of the colliding galaxy system VV338. As noted in the last chapter, Cesarsky [25, 26] has identified such systems as good candidate accelerators. However, the angular distance (about 10°) between the AGASA pair and VV338 may be too large for the association to be real. As is also the case for the single event near NGC315 described above, the intervening magnetic field would have to be much larger than the upper limit on the *average* field ($10^{-9}$ G), at least in some part of the trajectory of the particles.

It is best to be circumspect about attempting to evaluate the statistical significance of the above associations. The only convincing proof of their reality will be through the

| Energy($10^{20}$ eV) | $l^G$ | $b^G$ | $\rho_\mu(1000)/S(1000)$ |
|---|---|---|---|
| 2.10 | 131.2° | -41.1° | $0.08 \pm 0.04$ |
| 0.51 | 130.2° | -42.3° | $0.14 \pm 0.07$ |

Table 3.4: Properties of an AGASA Event Pair (see text)

confirmation of the effect with many more events.

### 3.3.3 Magnetic spectrometry with event pairs

Recently, the AGASA array in Japan has reported[52] three separate cases of two cosmic rays coming from the same direction within its angular resolution of 1.6°. The events in the pairs have different energies, so they undergo correspondingly different deflections if they are charged particles. Under this assumption a number of significant conclusions can be drawn, provided the magnetic field of the galaxy is known with modest precision ($\sim$ 50%). For one specific case reported by AGASA, it can be concluded that the cosmic rays are likely to be protons, and one can place limits on the fluctuating component of the extra-galactic magnetic field.

The event pairs were obtained during 5 years of operation of the AGASA 100 km$^2$ array. There are a total of 36 events above $4 \times 10^{19}$ eV and 20 events above $5 \times 10^{19}$ eV in this data set. Two of the three pairs occur within the sample of 20 events and a third appears if the sample is extended to the 36 events. The probability that these pairs occurred by chance from an isotropic distribution of cosmic rays is 0.01 for the two higher energy pairs each falling within a space angle of 2.5° of one another. Finding three such cases among 36 events has a probability of 0.02. In what follows it is *assumed* that these pairs are *not* accidental and explore the consequences.

The most interesting case is the pair which includes the highest energy event observed with AGASA. The energy and direction (in Galactic latitude $b^G$ and longitude $l^G$) of each event in this pair are listed in Table 3.4.

Note that the energies of the two cosmic rays differ by a factor of four. If the cosmic rays are neutral the difference in energy has no consequence. The last column of Table 3.4 gives the ratio of the observed muon density to the charged particle density measured at 1000m. The values quoted are typical of all the showers in the AGASA sample and are expected for hadronic primaries (the measured values are about three times larger than that expected for a $\gamma$-ray primary). If the source of the cosmic rays is extra-galactic, they are unlikely to be neutrons since the decay length of a $10^{20}$ eV neutron is only 1 Mpc. It is therefore assumed that both cosmic rays are charged, and hence will be affected by Galactic and/or intergalactic magnetic fields. If the magnetic rigidity of the two cosmic rays were equal then there would be no magnetic effects on the relative trajectories. This would be the case, for example, if the higher energy cosmic ray was a Be nucleus while the lower energy particle was a proton. If the two cosmic rays are the same species, then the effect of the galactic

| Primaries | Separation |
|---|---|
| Protons | 0.88° |
| Helium | 3.29° |
| Carbon | 16.1° |
| Observed: | 1.41° |

Table 3.5: Computed and Observed angular separation of an AGASA pair.

magnetic field can be used as an an analytical tool.

The Galactic magnetic field is parametrized as given by Vallée [111]. The field lies in the plane of the galaxy and follows the spiral arms. An approximation places the direction of the magnetic field along concentric circles about the galactic center. In this parameterization the field shows a reversal between 6 and 8 kpc. For the directions of the AGASA events it is only the magnetic field ($\sim 2\mu$G) towards the galactic anticenter that is traversed. Field fluctuations on a sub-kpc scale will be averaged out for cosmic rays with energy $\geq 10^{19}$ eV.

It is also necessary to know how the magnetic field drops off above and below the galactic plane. Parker[112] has suggested a Gaussian fall off:

$$B(h) = B(0) \times \exp\left(-(h/0.8)^2\right),$$

with $h$ the distance out of the galactic plane in kpc.

The trajectories of these two cosmic rays are traced backwards out of the galaxy. If the directions beyond the galactic magnetic field differ by an amount outside the angular resolution of the AGASA detector then it is not possible that the two cosmic rays have the same origin, and their overlap is by chance. The observed space angle difference between the two cosmic rays is 1.41°. The space angle differences calculated under various assumptions about the primary particles' charges are listed in Table 3.5.

Thus, if the two cosmic rays are the same species, it is most likely that they are protons. If the integrated magnetic field were a factor of two weaker then helium would be a possibility. It is more likely that the integrated magnetic field is stronger because of a more extended halo [112]. In this case the argument for proton primaries is strengthened.

This particular pair of events lies close to a cluster of events from prior experiments identified by Chi and Wolfendale [113], who examined the historical data set from previous experiments and identified a cluster of older events whose arrival directions are near the AGASA pair listed in Table 3.4. These two events are also within 3.0° of a Haverah Park event at $6.9 \times 10^{19}$ eV. If the AGASA pair indeed represents a point source there should be additional events at lower energy, which should have arrival directions dispersed in a line roughly perpendicular to the galactic plane. A significant enlargement of the world data set at these energies, such as will be provided by the Auger Observatory, will reveal such a correlation if it exists, strongly supporting the conclusion that protons are the primaries.

Having established that two cosmic rays with energies different by a factor of four come from the same direction within the resolution of the detector implies that the highest energy partner points to its source with negligible magnetic deflection. Then the uncertainty of the source direction is limited by the resolution. It will be shown in later chapters that the detector systems of the Auger Observatory will have good accuracy: at $10^{20}$ eV, the surface array will reconstruct directions within $\sim 1.0°$, while events recorded by both the surface array and the fluorescence detector will have an angular resolution of $\sim 0.4°$.

This particular pair of AGASA events (Table 3.4) was observed in about five years of operation of an array with an area of 100 $km^2$ . Assuming a common source, in one Auger installation of 3000 $km^2$, we expect more than 50 events from this source above $5 \times 10^{19}$ eV in the same length of time. With such a richness of data, the Auger Observatory can:

- establish whether the primaries are protons;
- measure the magnitude of the integrated transverse magnetic field along the trajectory, if the particles are protons or nuclei of known charge, and so decrease the uncertainty in the galactic magnetic field;
- determine the source location to within $0.1°$;
- measure the muon content and the depth of maximum of the showers. This latter measurement will serve as a constraint on the interactions of protons with matter at energies well beyond those that will be accessible at the colliders. If there is a qualitative change in the nature of the strong interaction, it should be evident;

If indeed this AGASA pair originated from a single point source, then there is no doubt that there are other such sources. The AGASA analysis of arrival directions with respect to the supergalactic plane suggests that perhaps a third of all events above $5 \times 10^{19}$ eV are from point sources. An estimated 1200 events will be collected above that energy in 5 years by the Auger Observatory, so about 400 would be associated with point sources.

Much can be learned about extragalactic magnetic fields with an independent identification of the primaries from point sources, and a measurement of their energy. For example, the r.m.s. magnetic field can be estimated using Eq. 2.3 in the last chapter (section 2.4.3). Assuming in this case that the magnetic multiple scattering difference between the two cosmic rays is of the order of the $1.6°$ resolution, then $B \leq 0.5 \times 10^{-9}$ gauss. This is comparable to the upper limit on the average field strength of $\sim 10^{-9}$ gauss given by radio astronomy studies for the intergalactic medium (i.e., for directions away from our local cluster)[35].

Even an approximate knowledge of the magnetic field should permit the determination of the charge of the primary cosmic rays as the example discussed here suggests. With much more data this procedure can work effectively with checks that it is self consistent. The Galactic magnetic field is used in a similar way that the Earth's magnetic field was used to learn many things about Galactic cosmic rays.

## 3.4 The Immediate Future

The only high energy cosmic ray surface array currently taking data is the 100 km$^2$ scintillator arrays at AGASA. It is planned to continue operating this device until the year 2000, by which time the integrated exposure will have reached about 2000 km$^2$·sr·year. A further 10-20 events might be expected above $10^{20}$ eV, though with only limited information about mass composition. The Yakutsk array has been contracted in size and will focus on specific features of shower properties near $10^{19}$ eV.

Two new projects are under development:

### The HiRes Project

The University of Utah Fly's Eye group has entered into collaboration with the University of Adelaide and Columbia University to construct a next-generation air-fluorescence detector, the High Resolution Fly's Eye or HiRes. The first stage of construction of this detector has been completed. Two sites, twelve kilometers apart, have been chosen at which a total of 56 two meter diameter mirrors will be installed. The mirrors are arranged in rings, each ring subtending 14° of elevation. Two complete rings at one site and one partial ring at the second site will be built. Each mirror will have a 256 phototube array at its focal plane. Each phototube will view a $1° \times 1°$ section of the sky. The signals from the phototubes will be digitized using FADC electronics so that both the amplitude and the detailed pulse shape will be available for later analysis. All events will be recorded by both sites ("stereo") for good control of experimental uncertainties and redundancy of measurement.

The aperture for this Stage I detector is optimized for events greater than $10^{19}$ eV, and approaches $10^4$ km$^2$sr at $10^{20}$ eV. Assuming a 10% duty factor, this detector should record of order 10 events per year above $10^{20}$ eV, and 200 events per year above $10^{19}$ eV, based on scaling the flux observed by previous experiments. This is an order of magnitude increase in statistics over the monocular Fly's Eye. The resolution in energy and $X_{max}$ is also much improved over the Fly's Eye detector, approaching 10% statistical uncertainty in energy and 15 gm/cm$^2$ mean uncertainty in $X_{max}$. This detector can also search for a possible gamma ray and neutrino flux.

Many aspects of the HiRes technical design and data from the prototype have guided our thinking in the development of the fluorescence detector of the Auger Observatory. These will be discussed in later chapters.

### The Telescope Array Project

Another fluorescence detector is at the prototype stage. Known as the Telescope Array, it is proposed by a consortium of Japanese universities and the University of Utah, led by the University of Tokyo. The goal is to build an air fluorescence detector with a pixel size of 0.25° by 0.25° using multi-anode photomultiplier tubes. With this small pixel size, sky noise is essentially negligible. The array is designed to be sensitive also to low energy gamma rays above 100 GeV by detecting Čerenkov light from these showers. It includes 120 fixed and 120 steerable altitude-azimuth, 3 m diameter mirror dishes positioned at two stations 40 km apart. The aperture of such an array at $10^{20}$ eV, excluding the duty cycle, is estimated to be approximately 40,000 km$^2$sr. The energy resolution is 10% and the resolution in $X_{max}$ is 10 gm/cm$^2$. Prototype mirror and PMT clusters are being tested at Dugway and AGASA.

The Japanese groups have indicated their willingness to provide a fully developed version of this detector for one of the sites of the Auger project. The goals of the Telescope Array Project differ somewhat from those of Auger, in that the study of Čerenkov radiation from $10^{12}$ eV showers is as important as the study of the highest energy events. Consequently, this device is not being considered as the main fluorescence component of the Auger Observatory, but rather as a valuable complementary detector.

## 3.5 The Physics and Astrophysics Potential of the Auger Project

The unambiguous discovery of cosmic rays above $10^{20}$ eV is of exceptional astrophysical interest as judged by the recent flood of theoretical papers. The sources of the most energetic events are required, by the GZK cut-off, to be rather close (less than $\sim$ 100 Mpc). Energy arguments [115, 116, 23, 25] imply that these locations must have some of the most extreme physical conditions in the cosmos. The Auger Observatory is planned to provide a high statistics measurement of the energy spectrum (with resolution better than 20%) and arrival direction (with a typical error of $< 1°$) distribution of the highest energy events. At the same time inferences about the mass composition will be drawn from a careful study of detailed shower properties, as well as from differences in the arrival direction patterns of sub-sets of "heavy" and "light" nuclei. There is no doubt that there are events to observe beyond $10^{20}$ eV. In ten years of operation of the two detectors, each of 3000 km$^2$, between 600-1000 events above $10^{20}$ eV are expected from the whole sky. If the $E^{-2}$ integral power law spectrum measured at $10^{19}$ eV continues to $10^{21}$ eV about 5 events will be observed above that energy.

It is important to recognise that detectors in both the Northern and Southern Hemispheres are essential, as the radio galaxies (one of the possible "conventional" sources of the highest energy cosmic rays) close enough to be the sources of such particles are anisotropically distributed around the supergalactic plane, and thus across the two hemispheres. A detector at a single site cannot properly address the arrival direction problem.

The use of a hybrid device, with a fluorescent detector and a ground particle detector combined, offers unique opportunities to study many parameters in the same event. In particular, one will be able to obtain the depth of maximum, the muon-electromagnetic ratio and the spread of the particle arrival times, all of which are crucial parameters in attempting to measure the primary mass composition. Independent measurements of shower energy by the fluorescence detector and ground array give necessary redundancy and crucial cross checks of the assumptions made in the calibration.

High statistics observations of cosmic rays beyond $10^{20}$ eV will increasingly constrain theories of cosmic ray origin whatever the outcome of the observations. Most clear cut would be the identification of specific sources by the observation of clusters of the most energetic events from a few regions of the sky. These regions may correspond with objects known to be powerful in other parts of the spectrum. A spin-off from such an outcome would be much needed information on the magnetic field structure in the region out to 50 Mpc from our galaxy. At the other end of the scale, isotropy at ever increasing energy might favor the exotic models which associate the most energetic events with topological defects or gamma ray bursts. The higher the energy of the most energetic event recorded, the more intriguing the theoretical problems become. The wealth of data to be obtained promises new insights into particle physics, astrophysics, and cosmology.