Chapter 1

Executive Summary

One of the foremost issues in astrophysics today is that of the origin of the most energetic cosmic rays. Eighty years ago in a series of pioneering balloon flights Victor Hess discovered that the earth was bathed in a sea of ionizing "cosmic" radiation. Three decades later Pierre Auger observed showers of secondary particles at ground level produced by energetic cosmic rays interacting high in the atmosphere[2]. Based on the size of these "air showers" Auger concluded that the spectrum of primary particle energies extended up to and perhaps beyond 10^{15} eV. More recently, in 1962, an air shower event was observed with an energy approaching 10^{20} eV, one-hundred million times more energetic than the highest energy attained by terrestrial accelerators[3]. Since that time only a handful of similarly energetic events have been detected, the maximum to date reported at 3×10^{20} eV([4]-[7]).

Today substantial progress has been made in understanding the nature of cosmic rays of relatively modest energy (those greater than about 10^{15} eV). Indeed, our understanding is now such that we are forced to consider the possibility that the highest energy primary particles, those with energies above about 10^{19} eV, have an entirely different origin than lower energy cosmic rays. Unfortunately, the nature of these remains as enigmatic today as when they were first observed. The failure to solve this puzzle despite three decades of effort stems both from practical and theoretical difficulties.

The flux of cosmic rays above 10^{19} eV is extraordinarily low: on the order of one per square-kilometer per year. Only detectors of exceptional size, thousands of square-kilometers, can hope to acquire a significant number of events. The nature of the primary particles must be inferred from properties of the associated air showers. Two techniques are used: surface arrays sample the lateral density profile of the muon and electromagnetic components in the shower front; atmospheric fluorescence detectors observe the evolution of air showers — their growth and subsequent attenuation — as they develop.

Addressing the theoretical issues surrounding the production and propagation of 10^{20} eV primaries is problematic as well. At these energies, cosmic rays typically have a mean free path less than 50 Mpc ($\sim$ 150 million light-years) — a short distance on a cosmological scale. Cosmic rays, regardless of their nature, lose energy in their interaction with the 2.7K cosmic microwave background radiation: protons photo-produce pions, nuclei photodisintegrate via the giant dipole resonance, photons produce e^+e^- pairs. Only neutrinos propagate freely. Thus, the source or sources must be relatively nearby, within 50 - 100 Mpc. But models of the acceleration of protons or nuclei to these extreme energies have proven very difficult to construct. Few sufficiently energetic astrophysical environments lie within the requisite distance. The existence of these extraordinarily energetic cosmic rays is a puzzle, the solution of which must lead to new discoveries in astrophysics, fundamental physics, or both.

In this Report, we present a design for the Auger Observatory whose primary goal is to solve this mystery. Separate, identical sites in the Northern and Southern Hemispheres will measure the arrival direction and energy of the primary particle, the muon content of the extensive air shower it induces, and for a subset of events, the longitudinal development of the shower in the atmosphere.

Analysis of these shower parameters, guided by Monte Carlo simulations, can be used to select event samples enriched in either light ($A \leq 16$) or heavy ($A \geq 16$) primaries. Correlations among the various parameters — energy, arrival direction, and mass — may reveal a number of components contributing to the total observed cosmic ray flux. For example, it is possible that a significant fraction of heavy primaries around 10^{19} eV are produced in our galaxy. If so, their arrival directions ought to be correlated with the mass distribution in our own galaxy (i.e. they should appear to come from the direction of the *plane*, as opposed to the *poles*, of the galaxy). This component, nearly unaffected by the cosmic microwave background radiation, would exhibit an energy spectrum directly reflecting the production mechanism within galactic accelerators. If the lighter sample (including protons) is isotropic and exhibits a cut-off near 10^{20} eV, then we may conclude that it represents a universal extragalactic component which has suffered attenuation due to its interaction with the cosmic microwave background.

However, it is the origin and nature of the cosmic rays which have been observed with the highest energies ($E \geq 10^{20}$ eV) which is most perplexing. We have virtually no information as to their fundamental nature. Are they protons? Nuclei? Or perhaps something exotic? How and where do they acquire such enormous energies? Do their arrival directions cluster about any known, particularly energetic astrophysical objects? Or about any extended mass distribution such as the super-galactic plane? Do they exhibit any directional anisotropy? If not, then perhaps they are among the products created in the decay of topological defects. Their energy distribution should then be characteristic of a "top down" source: the product of a cascade from still higher energies. In the absence of greatly increased statistics even the wildest speculation can hardly be ruled out.

The Auger Observatory is to be a *hybrid* detector, employing two complementary techniques to observe extensive air showers. A giant array of particle counters will measure the lateral and temporal distribution of shower particles at ground level. An optical air-fluorescence detector will measure the air shower development in the atmosphere above the surface array. Operating together, the surface array and fluorescence detector characterize showers to a greater degree than either technique alone. Both methods are well established by prior experiments. The surface array resembles the array successfully employed by the Haverah Park group for over twenty years[7], although on a much larger scale. The optical device uses the *fluorescence* technique pioneered by the University of Utah's Fly's Eye[8].

Measurement of atmospheric fluorescence is possible only on clear, dark nights. About 10% (possibly more) of all Auger showers will be measured by both techniques.

The decision to use the two techniques together is based upon the following considerations:

Intercalibration: The two methods measure shower energy, direction, and primary particle type in independent, complementary ways, providing invaluable redundancy and cross checks. The two kinds of detector have not yet been operated in coincidence on a large scale. A hybrid device will reveal any systematic effects which might be inherent to either method alone.

Enhanced composition sensitivity: Both kinds of detector have sensitivity to primary particle type, but the two techniques together provide a much clearer picture. Each method obtains information about the nuclear type of the primary cosmic ray by measuring air shower quantities which correlate with it. Together, these data are much less susceptible to fluctuations leading to misidentification.

Hadronic interactions: Measurement of both the muon and electromagnetic particle densities together with the shower's longitudinal development profile imposes tighter constraints on hadronic interaction models than either technique can provide by itself. The interaction energies of Auger events is well beyond the reach of accelerator based experiments.

Uniform exposure: Patterns of cosmic ray arrival directions, whether isotropic or not, provide the most compelling evidence for their sources. Surface arrays in both hemispheres, operating 24 hours per day year-round, provide data with nearly uniform celestial exposure. This enables a straightforward search for excesses from discrete sources and also a sensitive large scale anisotropy analysis.

Cost: The cost per event for the Auger surface array, operating continuously, is substantially less than for a *stereo* fluorescence detector with its small duty cycle. For a cosmic ray experiment based solely on fluorescence detectors, stereo detection (the shower recorded simultaneously by at least two separated installations or "Eyes") is required for accurate shower direction reconstruction. In contrast, data from only one of the Eyes (*monocular* detection), when combined with that from the surface array, gives equivalently good direction resolution. For a given acceptance, a fluorescence design based on monocular reconstruction is less expensive than stereo, because each of the Eyes is not required to "see" as far.

Auger's hybrid configuration is the most economical and robust way to obtain the necessary data, including a subset with especially high reconstruction resolution and independent cross checks.

Each of the two surface arrays of the Auger Observatory will consist of about 1600 detectors spaced on a grid with about 1.5 km separation between individual detectors. Each array encompasses an area of 3000 km^2. The angular and energy resolution of a ground array (without coincident fluorescence data) are typically less than 1.5° and less than 20%, respectively. If an event trigger is assumed to require five detectors above threshold, the array is fully efficient at 10^{19} eV. New technologies are employed, making it practical to operate thousands of detectors spread over such an area. Each detector will be solar powered (consuming less than 10 watts) and will communicate via modern wireless techniques. Inter-detector relative timing is accomplished by individual Global Positioning Satellite (GPS) receivers.

A number of options for the surface detectors (e.g., water Čerenkov, scintillator-lead sandwich) were explored during a six month design study held at the Fermi National Accelerator Laboratory. Their performance was investigated using Monte Carlo techniques; prototypes were constructed at various laboratories around the world. Care was taken to ensure that these results agreed with experimental data available from existing cosmic ray detectors. Based on a combination of cost, simplicity, and performance, the Water Čerenkov Detector (WCD) was selected. Such a detector is relatively simple, consisting of a water tank of 10 m^2 area and 1.2 m depth with an efficient, diffusely reflective lining. The Čerenkov light produced by the shower particles is viewed by three downward facing photomultipliers. WCD, in comparison to scintillation detectors or gas chambers, are simple, stable, inexpensive, and, perhaps most important, have significantly better sensitivity to showers at large zenith angles. Twenty years of WCD experience of the Haverah Park experiment provides an important check of the design work.

Air showers at 10^{19} eV may contain 10^{10} charged particles and extend over an area of twenty square kilometers. Due to the 1.5 km detector separation in Auger, the properties of showers at a distance of a kilometer or more from the core are the most relevant to the detector design. Here, the particle density has fallen to a few per square meter. The "thickness" of the shower front — the time it takes to pass through the detector — is several microseconds. The electromagnetic components (electrons, positrons, and photons) are some 100 times more numerous than are the muons. However, their mean energy is only 10 MeV while that of the muons is about 1 GeV. The former produce a large number of relatively small Čerenkov pulses whereas muons produce a small number of large pulses. Given the breadth of the arrival time distribution, it is feasible, using only moderately fast flash-ADCs, to estimate the muonic and electromagnetic components of the showers independently. Similarly, the *rise-time* of the shower front is related to the relative proportion of muons in the shower (muons are typically "leading" particles within the shower front). The ratio of muons to the electromagnetic component is sensitive to the nuclear type of the primary cosmic ray particle.

The Auger fluorescence detector consists of many meter-sized mirrors, each of which is equipped with a cluster of a hundred or more photomultipliers. Each mirror and associated cluster will view its own segment of the sky. Together, the system of mirrors observes most of the sky above the surface array. The magnitude of the photomultiplier signals gives the number of electromagnetic particles in the shower, and hence the energy. Fast timing of the sequence of signals yield the trajectory of air showers passing in the field of view of the detector. In the hybrid mode of operation, the surface and fluorescence detectors together have a directional reconstruction resolution of about $0.3°$ for events near 10^{20} eV.

Events which are observed by both the fluorescence and the surface detectors can be effectively reconstructed even if only two surface detectors are registered. Thus, the event trigger for the hybrid arrangement will permit "sub-threshold" surface array triggers (i.e., less than five stations), provided that the fluorescence detector also reports its own event trigger. The Auger hybrid threshold therefore extends down to about 10^{18} eV. These events, at lower energy than the targeted energy range of Auger, provide a valuable set with which to compare to the extensive data of previous (and current) cosmic ray experiments.

The most significant uncertainty in air shower simulations used to guide the design arises from variations in the models for the first few interactions in the developing shower. These occur at energies well beyond the range of accelerator measurements. The uncertainties do not significantly affect the shower properties relevant to the overall design of the detector. For example, reasonable variations in the physics of the first few interactions lead to a 60% variation in the measured ratio of muon to electromagnetic energy deposition in the water tank. The absolute value of this ratio will not uniquely identify a particular primary with certainty. Nevertheless, the difference between heavy primaries and light ones, the width of the distribution, and its correlation with the depth of shower maximum are less sensitive to the physics assumptions. The latter two measures will reveal whether the primary flux is composed of a single or multiple species, with very little model dependence.

The Auger Observatory sites require a great deal of accessible, yet lightly populated land. The altitude above sea level is not of paramount importance in the study of air showers at such high energy, but the skies must be astronomically clear. A survey team has evaluated twenty candidate sites worldwide; a dozen sites have been visited and studied in detail. Beyond the physical attributes of the sites, selection criteria include the anticipated scientific and infrastructure support.

The survey team identified three finalist countries in each hemisphere: in the Southern Hemisphere, excellent candidates were nominated in Argentina, South Africa, and Australia; in the Northern Hemisphere, the United States, Mexico, and Spain were presented to the international collaboration as acceptable possibilities. A site in the Province of Mendoza, Argentina, was selected as the southern location of the Auger Observatory in November 1995. The collaboration voted in September 1996 to select the Northern Hemisphere location to be in Millard County, Utah, in the United States.