

Auger Fluorescence Detector and Hybrid Philosophy

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A key feature of the Auger Observatory design is its capability for “hybrid” measurement of air showers. The longitudinal shower development is measured by an atmospheric fluorescence detector and used in conjunction with shower particle density measurements made at ground level by the surface array. Combined timing gives excellent geometric reconstruction. The subset of hybrid showers will yield extra information for composition analysis, and it will provide a precision energy distribution with unambiguous exposure. Also, the solid hybrid measurements will form a standard for minimizing systematic errors in the surface array reconstruction methods. The design of the Auger fluorescence detector is based on the Fly’s Eye and HiRes experience. A new electronics system has been developed, and a Schmidt optics system gives each telescope a large field of view (30x30-degrees). The Fly’s Eye “Winston cones” have become smaller “mercedes” light collectors. Italian and German collaborators have spearheaded the production of two prototype telescopes in Argentina for commissioning and evaluation this year.

§1. Hybrid Philosophy

The Pierre Auger Cosmic Ray Observatory is an international project dedicated to unraveling mysteries of the highest energy cosmic rays and identifying their sources. Its design calls for a surface array of 3000 km² in both the southern and northern hemispheres. This will yield 14,000 km²·sr full-time aperture with almost uniform exposure to the entire sky. In addition, the design calls for air fluorescence telescopes which cover the same aperture on clear dark nights (10% expected duty cycle). Working together, the surface detector (SD) and the fluorescence detector (FD) constitute a “hybrid” cosmic ray observatory. The project is presently in an engineering phase to demonstrate that all aspects of the design are correct. Construction of the southern site will occur during 2002-2004.

The Air Shower Division of ICRR is famous for the successful construction and operation of AGASA, which has the largest exposure of any cosmic ray observatory up to the present time. The same group has designed and prototyped fluorescence detectors for the ambitious Telescope Array Project in the central part of Utah. It is to be hoped that the Telescope Array and a northern Auger surface detector will work together as a premier *hybrid* cosmic ray observatory. The operation of a surface array in conjunction with fluorescence detectors has some notable advantages:

• *Cross check on measurement methods*

There is a history of dispute and skepticism between advocates of the different methods. The hybrid detector offers the only sure way to resolve those differences and gain the confidence of the entire community. Moreover, the combination of techniques will make it possible to compare results with other experiments of either type.

The hybrid data set allows shower-by-shower comparison of the SD and FD measurements. By intercalibrating

the surface array with the FD as discussed below, systematic errors in SD air shower measurements can be eliminated. The data set from the full-time exposure should then be a reliable high-statistics basis for the energy spectrum, anisotropy, and mass composition analyses.

• *Complementary techniques*

The surface array has the advantage of full-time operation in contrast with an approximate 10% duty cycle for a fluorescence detector. It operates automatically, whereas a fluorescence detector requires an operator at least to watch for bad weather. The SD aperture is invariant, independent of atmospheric conditions. Through-going muons provide a reliable calibration tool for the surface detectors, in contrast to the FD which has no natural calibration light source. The signals in the Auger water Cherenkov detectors have sensitivity to the primary particle mass. At least in the Auger case, the cost per shower is substantially less for the surface array than for the fluorescence detector, mainly because of the duty cycle advantage.

A fluorescence detector, on the other hand, measures the longitudinal profile of an air shower instead of sampling particles at just one atmospheric depth. This provides a kind of calorimetric measurement of shower energy, whereas a surface array relies to some extent on a model for hadronic interactions in order to convert its density measurements into a total energy for the air shower. By viewing the shower development in the atmosphere, a fluorescence detector is especially sensitive to the shower development speed (as indicated for example by depth of maximum X_{max}) and hence to the primary mass.

The SD is simple and robust, but some model dependence enters the data analysis; the FD relies less on interaction models, but its sensitivity is time-dependent and it requires diligent atmospheric monitoring. A hybrid

observatory can exploit the advantages of both detector types and overcome their handicaps. To determine the cosmic ray energy spectrum, for example, it is necessary to have precise energy measurements together with accurate knowledge of the exposure at each energy. For the hybrid data set, the shower energies may be determined primarily by the FD while the exposure is accurately determined by the fixed SD aperture and the FD on-time. The atmospheric variability of the FD aperture and the model-dependence of SD energy measurements are eliminated problems.

Hybrid reconstruction of the air shower geometry requires only one fluorescence eye (not stereoscopic measurement). The shower-detector plane is determined by the set of coplanar directions of pixels with high amplitudes in the one eye. The angular velocity of the fluorescence spot across the focal surface limits the candidate shower axes to a one-parameter family. (The mean angular velocity can be preserved by moving the true axis away from the eye while slanting it more toward the eye or by moving it toward the eye and slanting it away from the eye.) Each of these allowed geometries gives a definite prediction for the time of arrival of the shower front at any point on the ground. By using the arrival time at one or more surface detectors, the 1-parameter degeneracy is broken and the correct shower axis is determined.¹⁾ Simulations show that the angular resolution with hybrid measurements is as good as with fluorescence stereo measurements.²⁾

Note that the shower axis is determined in hybrid mode without using relative amplitudes of the surface detectors. The core distances of density measurements are therefore determined without reference to the measured densities.

•Shower-by-shower comparisons and special composition sensitivity

It may be conceptually useful to think of the surface array as providing two measured quantities for each shower: ρ_{mu} , the muon density one km from the core, and ρ_{em} , the electromagnetic particle density 1 km from the core. Given any specific model (e.g. AIRES, CORSIKA, Sibyllized MOCCA, etc.), there is a mapping from shower energy and primary mass (E,A) to (ρ_{mu}, ρ_{em}) . The map gives the expected values for the measured quantities, determined by many simulations of showers with fixed E and A. (The mapping also depends on zenith angle, but it can be determined separately for each zenith angle.) Figure 1 shows this mapping schematically. The inverse mapping is also well defined, and this is how the measured quantities are used to infer E and A. For any measured pair (ρ_{mu}, ρ_{em}) , there is a unique energy and mass combination which gives that pair as the expected measured quantities. It is not required that the energy or mass be a simple function of the two measured quantities.

Energy and primary mass can be regarded as functions on the space of measured quantities. Curves of constant A, when mapped to (ρ_{mu}, ρ_{em}) space, tend to be diagonal lines in (ρ_{mu}, ρ_{em}) space. (Increasing E while keeping A fixed tends to increase both ρ_{mu} and ρ_{em} .) The curves

of constant E are diagonals transverse to the constant-A curves. (Increasing A while E is fixed tends to increase the muon content but decrease the electromagnetic particles since ground level would be further past the maximum of the more rapidly developed shower.)

Mapping all recorded showers to (E,A) space yields a 2-dimensional histogram. Fixing an interval of A-values then gives the energy distribution for that mass component; fixing an energy range gives the mass distribution at that energy.

Similarly, you can think of the fluorescence detector as providing two measured quantities: E_{em} , the electromagnetic cascade energy, and X_{max} , the atmospheric depth of the cascade maximum. There is also a two-way mapping between this space and the (E,A) space. In this case, the curves of constant E are roughly parallel to the lines of constant E_{em} . The constant-A curves slope upward in X_{max} with increasing E in accordance with the elongation rate. It should be noted that the Fly's Eye data, in this picture, originally gave a 2-dimensional scatter plot which was unphysical inasmuch as it extended to A-values in excess of 56. This suggested that the hadronic interaction model used to map from (E_{em}, X_{max}) to (E,A) was unsatisfactory. The Gaisser-Stanev-Tilav minijet model (similar to Sibyll) was adopted to bring the scatter plot into the physically sensible region.³⁾ It has been argued⁴⁾ that any plausible model which is physically acceptable in this sense will preserve the observed feature of the scatter plot points moving to lower A-values with increasing energy. Hence the Fly's Eye data have been used both to constrain the hadronic interaction models and make a statement about composition changing over the measured energy range.

The picture of figure 1 provides a useful way to exhibit the advantage of a hybrid detector. A shower measured in hybrid mode gives a rectangular error box in both (ρ_{mu}, ρ_{em}) space and (E_{em}, X_{max}) space. Their images in (E,A) space should overlap, and the true energy E and mass A should be in the intersection region. If the error box images from the two methods are systematically incommensurate, then there is a clear indication of systematic measurement errors or, perhaps more likely, an inappropriate model for the mappings. Once the defects are corrected, the dual measurements will give invaluable cross checks, shower by shower. Together, they should restrict the allowed range of A for each shower more than either component could by itself.

The picture of figure 1 also clarifies what it means to "train the surface array for energy determination." The fluorescence detector's E_{em} leads to a reliable estimate for E. The hybrid data set is used to make sure that the mapping from (ρ_{mu}, ρ_{em}) space to (E,A) at least gets the energy right on average. The surface array by itself can then be trusted to determine the energy spectrum with the full data set. Even if the energy resolution is not as good as for the hybrid data set, at least the systematic errors should be eliminated. In a similar way, the hybrid data set may be able to validate (or adjust) the composition determination that is based on the larger data set of shower measurements by the surface array alone.

The analysis here has focused on just two measurable

quantities for the surface array and the fluorescence detector. The analysis might also be able to take advantage of the signal rise time and a lateral distribution steepness parameter in the case of the surface array. With the fluorescence detector, one can try to measure also the longitudinal profile width (e.g. full width half maximum in g/cm^2) and the steepness of the profile's rising edge. These extra parameters may provide additional sensitivity to the primary mass when used in a multi-dimensional analysis.

Much careful work has been done in analyzing the capability of the Auger surface array on its own to measure shower energies and primary masses. Results can be found in the Design Report⁷⁾ and Auger technical notes.⁸⁾

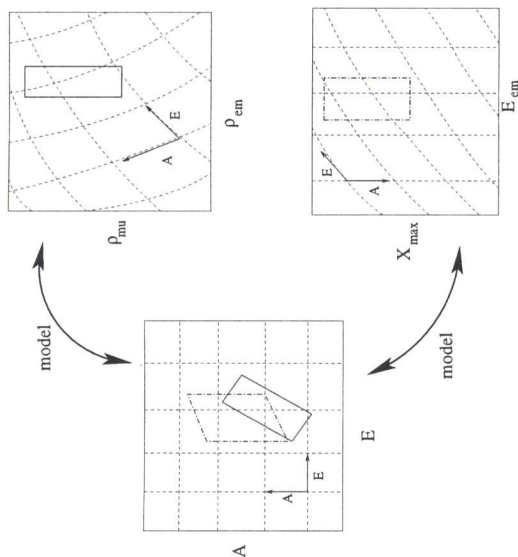


Fig. 1. Shower simulations with a specific hadronic model give mappings from energy and mass (E, A) both to surface array quantities (ρ_{em}, ρ_{mu}) and to fluorescence detector quantities (E_{em}, X_{max}). A measured shower gives an error box in each space of measured quantities, and these can be mapped back to a pair of error boxes in (E, A) space.

§2. The Auger Fluorescence Detector

The Auger fluorescence detector telescope design for the southern hemisphere site is based on the successful Fly's Eye and HiRes designs and is similar in most respects to the TA design. All of these fluorescence telescopes use large mirrors to focus light on cameras with photomultiplier tube pixels. Cosmic ray air showers are recognized as linear patterns of pixels that receive pulses of light with a sensible time progression. The design features of the Auger telescopes that distinguish them from the HiRes or TA designs will be mentioned here, but it should be emphasized that these are only variations on

a well-developed theme. The differences that are being tested in prototype telescopes at the Los Leones FD site in Argentina include the following:

•Larger pixels

The southern Auger FD telescopes use hexagonal pixels of 1.5 degree width. This is 50% greater than the HiRes pixel width, so the solid angle per pixel is approximately twice as large. (The original Fly's Eye pixels were 5.5° in diameter.) The disadvantage of larger pixels is the greater background light. The signal-to-noise ratio is inversely proportional to the pixel diameter for a fixed light-collecting area. Since the cost of phototubes and pixel electronics are a major part of the FD costs, it was important to minimize the number of pixels by making the pixel solid angle larger. The Auger hybrid detector was designed for the fixed aperture of the surface array, and multiple eyes were planned not for stereoscopic observing but to minimize atmospheric uncertainty by limiting the maximum distance from any point in the array to the nearest eye. The median distance from a shower to the nearest eye is less than 15 km. With multiple eyes for the fixed Auger aperture, the 1.5° pixel diameter provides ample signal-to-noise for showers above the observatory's 10^{19} -eV energy threshold. In fact, the pixel size was limited by considering the resolution of the shower-detector plane rather than signal-to-noise. Analytic evaluation⁵⁾ and numerical simulations show that enlarging the pixel size from 1° to 1.5° causes little degradation in geometrical resolution and does not jeopardize any of the observatory's objectives. It is an effective way to reduce the Auger FD costs.

•Schmidt optics

The decision to use an aperture stop (characteristic of Schmidt optics) was based on the objective of having a large field of view per telescope without coma aberration. The Schmidt solution to that challenge was suggested by A. Cordero and the Auger group in Puebla.⁶⁾ In effect, the optical system becomes symmetrical about the mirror's center of curvature. Light coming from off-axis directions uses a different portion of the mirror than light coming on-axis. The focal surface itself has a spherical shape with the same center point as the mirror. The full system is symmetrical about the center-of-curvature point (except for small effects due to the projection of the diaphragm area and changes in the camera shadow). There is no coma aberration such as occurs for off-axis directions when there is no aperture stop. Each Auger telescope has a $30^\circ \times 30^\circ$ field of view.

Even though coma aberration has been eliminated, there is still spherical aberration. The mirror radius of curvature in the Auger design is 3.4m. For an aperture of 1.7m diameter, this gives a spot size of 0.5° due to spherical aberration. The spot size would increase rapidly with aperture diameter beyond 1.7m if uncorrected. In order to increase the light collecting area without enlarging the spot size, the Auger design exploits a corrector ring that fills the aperture in the annulus between 1.7m and 2.2m diameters. It is what a Schmidt corrector plate would be in that region. The inner part is not corrected because

the spherical aberration is tolerable from that part and we do not wish to sacrifice part of that signal to surface reflection losses. Even after considering those losses in the corrected annulus, the 2.2m aperture provides twice as much signal as a 1.7m aperture (which is partly shadowed by the camera).

The use of Schmidt optics means that there is a relatively small opening for the incoming light. It is then sensible to put the optical filter across the diaphragm. In this way, the mirrors and cameras can be isolated from the outdoor environment. The telescopes operate at constant temperature, avoiding temperature-induced gain changes and optical spot changes. The filter windows also keep the mirrors and camera free of the desert dust. Moreover, the indoor environment is protected from damage by rodents and insects. Another advantage is that the doors for daylight protection are smaller and therefore simpler and more reliable.

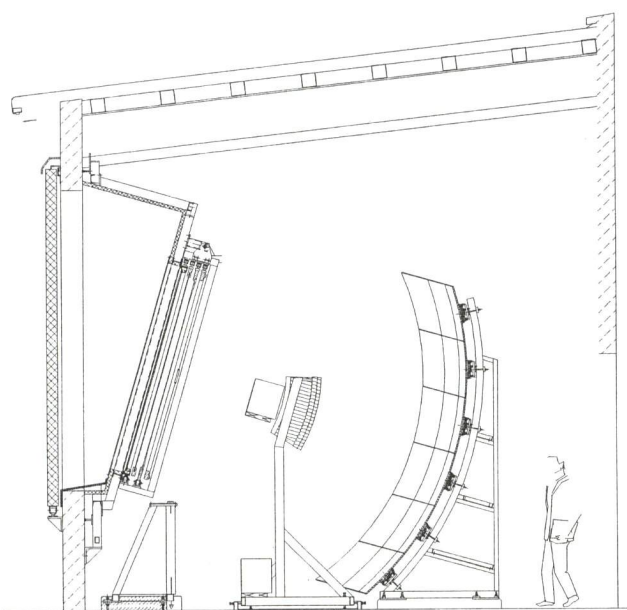


Fig. 2. Diagram of an Auger FD telescope bay, showing the aperture stop, camera, and mirror.

recessed behind the focal surface. A “mercedes star” is formed by three adjacent pixel edges that meet at a point. They are constructed of aluminized plastic. All together, the constellation of mercedes stars make small “light-collecting cones” for all the pixels. Their efficiencies have been tested carefully with UV light flashes using the distribution of incidence angles that results from light that focuses from the mirror after passing through the diaphragm and being partially shadowed by the camera. The focal surface sensitivity is not perfectly uniform. The average collection efficiency is 93% of the maximum, and the worst efficiency (when the focused spot is on a vertex between 3 pixels) is 85%. Without knowledge of the spot position or size, an efficiency of 93% will be assumed, and the maximum error at any instant due to the focal surface non-uniformity is about 8%. The mean error is 0, and the magnitude of the error is usually less than 4%, even without using any knowledge about the spot position and shape.

The light flux is measured in time intervals of 100 nanoseconds. Analog head electronics and ADC digitizers have been developed specifically for the Auger telescopes. The pixel trigger is based on a running sum of amplitudes from 10 consecutive time slices. (That number is adjustable in software.) The trigger threshold for that sum is dynamically adjusted to keep the pixel trigger rate at a fixed value (e.g. 100 Hz). A special chip is programmed to scan continuously for approximately linear patterns of 4 or more pixels that trigger within 20 microseconds of each other. Real time filters can then reject unsequenced accidentals and super-fast Cherenkov flashes.

The prototype head electronics includes an opto-coupled monitor of the anode current so that the background light level is known accurately at the time of any event. It also provides an automatic way to measure stars. This determines precisely the pixel pointing directions and may also be useful for cloud detection and aerosol monitoring.

In conclusion, it should be reiterated that the Auger telescopes are in a prototype stage. German and Italian groups have led the development of two telescopes at the Auger site in Argentina. These variations on the HiRes design will be tested this year prior to full production of the Auger southern observatory, which is scheduled for 2002-2004.

•Mercedes reflectors in camera

Once the geometry of an air shower’s axis known, the longitudinal profile can be determined from the flux $F(t)$ of fluorescence light as a function of time. The Auger analysis plan is to collect the light with uniform sensitivity in order to measure $F(t)$ accurately. The Schmidt optics provides uniformity of the light at the focal surface. The task is then to make the focal surface itself uniformly sensitive. The boundaries between pixels are the main problem. There is a significant gap between active cathode areas even if the phototubes are packed as tightly as possible. In order to resurrect these “dead spaces,” the Auger camera includes steeply-sloping reflective walls above the perimeters of all phototubes so that all light is reflected onto active cathodes. The tops of adjoining walls are edges that lie in the focal surface and define the pixel boundaries. The phototubes are

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- 2) B.R. Dawson et al., *Astropart. Phys.* **5**, 239 (1996)
- 3) T.K. Gaisser et al., *Phys. Rev.* **D47**, 1919 (1993)
- 4) L.K. Ding et al., *Ap.J.* **474**, 490 (1997)
- 5) “Maximum Pixel Size Criteria Based on Shower Detector Plane Accuracy,” B. Fick (unpublished, available at <http://www.physics.utah.edu/~sommers/hybrid/papers/>) (1996)
- 6) “Proposal for the Optical System of the Fluorescence Detector of the Auger Project,” A. Cordero et al., Auger technical note GAP-1996-039 (1996).
- 7) Pierre Auger Design Report, printed by Fermilab (Second edition, November 1996); available electronically at www.auger.org/admin/DesignReport/index.html
- 8) Auger technical notes (GAP papers) at www.auger.org under “Technical Info.”