Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo,
Gustavo Medina-Tanco, José F. Valdés-Galicia (eds.)
Universidad Nacional Autonóma de México,
Mexico City, Mexico, 2009
Vol. 6, pages 3-18

The Highest Energy Cosmic Rays: Some Historical Perspectives

JAMES W. CRONIN
Enrico Fermi Institute, Univ. of Chicago, 5640 S. Ellis Ave. Chicago, Illinois, 60637, USA
jwc@hep.uchicago.edu

Abstract. This lecture honors Victor Hess, the discoverer of cosmic rays nearly 100 years ago. Research on cosmic rays spawned the entire field of particle physics. In the early 50's the investigation of the elementary particles shifted to accelerators as marked by the famous conference at Bagnères de Bigorres in 1953. Remaining to investigate were all the astrophysical aspects of cosmic rays which has been the principal subject of the ICRC meetings ever since. One of the most fascinating and least understood topics is the existence of cosmic rays of enormous energy. Pierre Auger in 1938 demonstrated that cosmic rays were incident on the earth with energies in excess of 10^{15} eV. In 1962 John Linsley observed a cosmic ray with an energy of 10^{20} eV. In this lecture I will trace the efforts to understand how Nature produces this extraordinary phenomenon. Having only recently joined this effort, I approach the subject with great humility. In reviewing the past one is impressed with the ingenuity and courage of all the individuals who have participated in this adventure.

Fig. 1. Photograph of one of the balloons provided by the Austrian military for Hess's flights.

The discovery of cosmic radiation

In the first decade of the 20th century it was realized that electroscopes discharged spontaneously. The discovery was made by Crookes in 1879 [1], and was studied by many scientists including Ernest Rutherford [2]. Following the discovery of radioactivity it was thought that the discharge was due to residual radioactivity from the surface of the earth. This naturally led to experiments in which an electroscope was removed from the proximity of the earth with the expectation that the rate of discharge would be reduced. The first effort was that of Father Wulf [3], who transported an electroscope to the top of the Eiffel tower and the Swiss physicist Gockel [4] who was first to take an electroscope up in a balloon. Neither of these experiments was conclusive. The Austrian physicist Victor Hess then began a series of balloon flights taking an electroscope to ever increasing altitudes. Only on the 7th flight did he achieve a conclusive result and what a discovery it was!

In Fig. 1 a balloon used by Hess is shown. The balloons were normally filled with illuminating gas. However to achieve the altitudes required to obtain conclusive results large balloons (1680 cubic meters) filled with hydrogen were required. Fig. 2 shows the results of Hess's successful flight in 1912 [5]. Three electroscopes were employed. The electroscope labeled q_3 was open to the air. When corrected for the reduced air pressure at

7. Fahrt (7. August 1912).

Ballon: „Böhmen" (1680 cbm Wasserstoff). Führer: Hauptmann W. Hoffory.
Meteorolog. Beobachter: E. Wolf. Luftelektr. Beobachter: V. F. Hess.

Nr.	Zeit	Mittlere Höhe absolut m	Mittlere Höhe relativ m	Beobachtete Strahlung Apparat 1 q_1	Apparat 2 q_2	Apparat 3 q_3	Apparat 3 reduz. q_3	Temp.	Relat. Feucht. Proz.
1	15h 15—16h 15	156	0	17,3	12,9	—	—	—	—
2	16h 15—17h 15	156	0	15,9	11,0	18,4	18,4	1½ Tag vor dem Aufstiege (in Wien)	
3	17h 15—18h 15	156	0	15,8	11,2	17,5	17,5		
4	6h 45— 7h 45	1700	1400	15,8	[illegible],4	21,1	25,3	+6,4°	60
5	7h 45— 8h 45	2750	2500	17,3	12,3	22,5	31,2	+1,4°	41
6	8h 45— 9h 45	3850	3600	19,8	16,5	21,8	35,2	—6,8°	64
7	9h 45—10h 45	4800 (4400—5350)	4700	40,7	31,8	—	—	—9,8°	40
8	10h 45—11h 15	4400	4200	28,1	22,7	—	—	—	—
9	11h 15—11h 45	1300	1200	(9,7)	11,5	—	—	—	—
10	11h 45—12h 10	250	150	11,9	10,7	—	—	+16,0°	68
11	12h 25—13h 12	140	0	15,0	11,6	—	—	(nach der Landung in Pieskow. Brandenburg)	

Fig. 2. Data from Hess's 7th flight.

higher altitude this electroscope showed a factor of two increase in ionization between ground level and 4000 meters. This was the first evidence that radiation (Hohenstrahlung) was entering the earth from outer space. Fig. 3 shows a portrait of Victor Hess on the occasion of his receipt of the Nobel Prize in 1937.

In the following two years Werner Kolhörster [6] ascended to 9000 meters and showed that the ionization increased by a factor eight with respect to sea level.

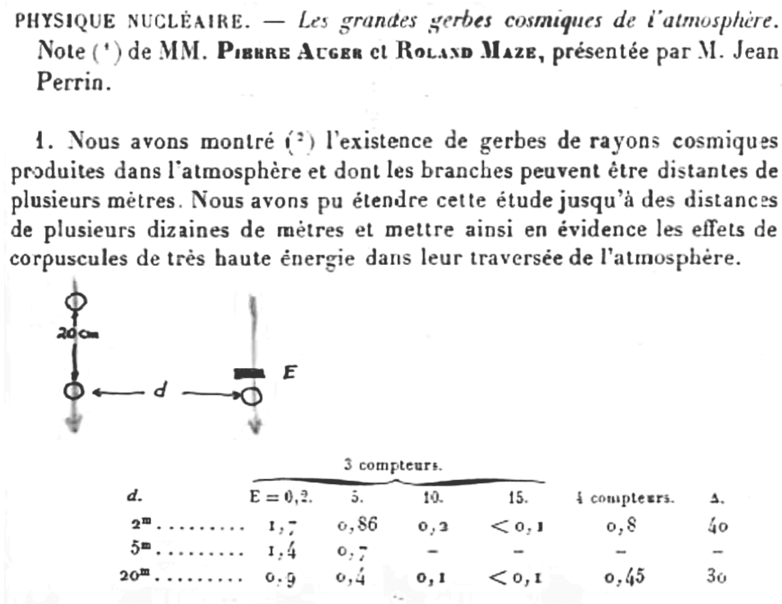
The term "cosmic rays", which replaced Hohenstrahlung, can be attributed to Robert Millikan [7]. In a lecture at Leeds University in 1928 Millikan is quoted: "*…all this constitutes pretty unambiguous evidence that the high altitude rays do not originate in our atmosphere, very certainly not in the lower nine tenths of it, and justifies the designation 'cosmic rays'* ".

The discovery of the highest energy cosmic rays

In 1938 Pierre Auger [8] and his collaborators performed in his Paris laboratory a very simple experiment, which in modern parlance would be called a decoherence curve. A cosmic ray particle was defined by a coincidence between two Geiger counters. An additional coincidence was demanded in a third counter placed at a variable distance from the defining counters. They found coincidences even when the third counter was placed at a distance of 20 meters. Data from this experiment is reproduced in Fig. 4.

This experiment was only possible because of improved electronics devised by Roland Maze [9]. He decreased the resolving time of the Geiger counters to less than 5 μ-sec by using an inductor to shorten the pulse. He decreased the dead time of the counters by electronic quenching rather than

Fig. 3. Photograph of Victor Hess at the time of his Nobel Prize,1937.



PHYSIQUE NUCLÉAIRE. — *Les grandes gerbes cosmiques de l'atmosphère.* Note (*) de MM. **Pierre Auger** et **Roland Maze**, présentée par M. Jean Perrin.

1. Nous avons montré (²) l'existence de gerbes de rayons cosmiques produites dans l'atmosphère et dont les branches peuvent être distantes de plusieurs mètres. Nous avons pu étendre cette étude jusqu'à des distances de plusieurs dizaines de mètres et mettre ainsi en évidence les effets de corpuscules de très haute énergie dans leur traversée de l'atmosphère.

	3 compteurs.					
d.	E = 0,2.	5.	10.	15.	4 compteurs.	Δ.
2ᵐ.........	1,7	0,86	0,2	< 0,1	0,8	40
5ᵐ.........	1,4	0,7	–	–	–	–
20ᵐ.........	0,9	0,4	0,1	< 0,1	0,45	30

Fig. 4. Data of Pierre Auger and Roland Maze in 1938.

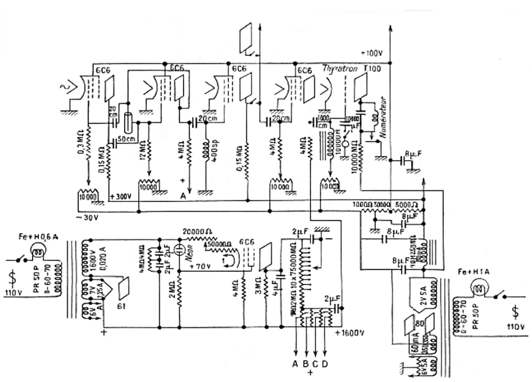


Fig. 5. Electronics designed by Roland Maze.

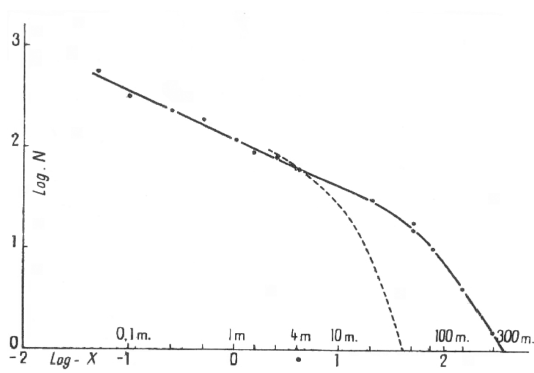


Fig. 6. Decoherence curve measured by Auger at high altitude. The dashed curve is the measurement in the Paris laboratory.

a using a large series resistance. Maze's circuit is shown in Fig. 5

Auger repeated the Paris measurements at high altitudes at the Jungfraujoch. Fig. 6 shows his results. Coincidences were seen at distances up to 300 meters. The coincidence experiments showed that cosmic ray particles separated by large distances had a common origin. Auger was able to estimate that the original particle which initiated the shower had an energy of 10^{15} eV. This was an energy 10^8 times greater than radioactive sources or accelerators could produce in 1938.

An international conference on cosmic rays was held at the University of Chicago in July 1939. At that time cosmic rays were a subject of immense interest for both theory and experiment. The conference was attended by many distinguished physicists, among them Hans Bethe, Robert Oppenheimer, Arthur Compton, Werner Heisenberg, Bruno Rossi and Edward Teller. Auger [10] gave an extensive report on his work concluding with the following remark:

"One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} *eV is that it is actually impossible to imagine a single process able to give a particle such an energy. It seems more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of very great extension."*

Other physicists noticed the effects of the extensive air showers. Bruno Rossi writes in his book on cosmic rays [11]:

"After physicists began to experiment with coincidences, it became a common practice to test the operation of the equipment by placing the counters out of line, usually on a horizontal plane. Then there could be no true coincidences caused by a single particle traversing all the counters. And without any heavy material above the counters, the number of true coincidences resulting from showers produced locally was negligible. Several experimenters must have noticed that the number of coincidences recorded under these circumstances was too large to be accounted for entirely by chance. I know I did, and I also noticed that the unexplained coincidences were more abundant at high altitude than at sea level. From these observations I concluded, if I may be forgiven from quoting from one of my own papers [12], 'It would seem that occasionally very extensive groups of particles arrive upon the equipment.' That was in 1934. Gradually the idea began to emerge that these 'very extensive groups of particles' were the result of cascade processes in the earth's atmosphere, just as ordinary showers were the result of cascade processes occurring in lead or other dense materials."

Kolhörster [13] also published a decoherance curve in 1938, but he did not follow up the measurement with the vigor of Auger and his colleagues.

The parting of the ways

Following the Second World War cosmic ray research resumed. Many fundamental discoveries concerning the elementary particles were made. A decisive conference in 1953 was organized by Louis Leprince-Ringuet at the Pyrenees town Bagnères-de Bigorres. Except for one morning session the entire conference was devoted to the elementary particles. Fig. 7 shows the official photograph of the conference. In the front row one can recognize Leprince-Ringuet, Blackett, Rossi, and C. F. Powell. On the front row, third from the right wearing a hat is Manuel Sandoval Vallarta of Mexico. It was recognized that research with the new Gev accelerators would soon takeover from cosmic rays the investigations of the fundamental particles. Vallarta and John A. Simpson whose interest was in the origins, nature and astrophysics of cosmic rays resolved to continue the conferences on cosmic rays which led to the ICRC series of which this conference is the 30th. The first of this new

Fig. 7. The official conference photograph. Bagnères-de-Bigorres, 1953.

series was held in Guanajuato Mexico in 1955, being the 4th ICRC. The conferences on fundamental particles and high energy physics continued as the "Rochester Conferences".

Surface arrays

Following the Second World War major efforts were made to discover how energetic the cosmic rays were. At first many Geiger counters were arranged in arrays. These had the disadvantage that fast timing was not available to determine the directions of the showers. By the early 50's the cosmic ray spectrum was found to extend beyond 10^{17} eV and if the directions could be determined correlations with respect to the galactic plane might be expected. Fast timing became possible with the use of scintillation counters, a technique pioneered by the MIT group [14] under the leadership of Bruno Rossi, No correlations were found which came as a surprise.

Larger and larger arrays were built by the MIT group culminating in the first array with a surface enclosing many km^2 built by John Linsley[15] at Volcano Ranch in New Mexico. It consisted of 19 scintillators of 3.3 m^2 arranged on a 884 m grid. Fig. 8 shows the Volcano Ranch array. In 1963 a cosmic ray of $\sim 10^{20}$ eV was detected at Volcano Ranch. The densities of this huge event are given in the figure. At a distance of 2.4 km from the core the average density of particles was 0.5/m^2

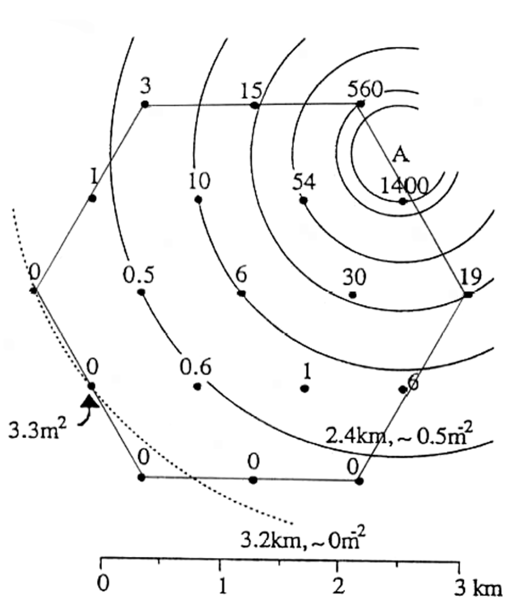


Fig. 8. The Volcano Ranch Array. The densities for the 10^{20} eV event are shown.

There was adventure in the building and operation of these early arrays. Fig. 9 shows Professor Zatsepin laying out cables for a Geiger counter array in the Pamir mountains. Fig. 10 shows John Linsley looking for rattlesnakes hidden in one of the Volcano Ranch detectors.

The discovery of the Cosmic Microwave Background (CMB) in 1965 had a very profound influence on the study of the highest energy cosmic

Fig. 9. Professor Zatsepin laying cables for an air shower array in the Pamir mountains.

Fig. 10. John Linsley searching for rattlesnakes lurking in the insulating hay of a Volcano Ranch detector.

rays. The energy of the center of mass of a collision between a 10^{20} eV proton and a CMB photon of 10^{-3} eV is about 200 MeV, where the cross section for photo-pion production is very large. As a consequence cosmic ray protons with energy $\geq 10^{20}$ eV rapidly loose energy. This phenomenon (GZK effect) was independently recognized by Greisen [16] and Zatsepin and Kuz'min [17]. Fig. 11 shows the mean energy loss of protons of different initial energies as a fraction of propagation distance. The GZK effect limits the distance of sources of cosmic rays with energy $\geq$ 7x10^{19} to $\leq$ 100 Mpc. This phenomonon is an advantage Nature offers in that within 100 Mpc the number of sources is limited and the extra-galactic magnetic fields may not significantly deflect cosmic ray protons. Thus at the very highest energies an astronomy of cosmic rays can be imagined and

Instrument	period	area	exp
Volcano Ranch	1960-1980	8	0.2
Haverah Park	1967-1987	12	2.6
SUGAR	1968-1980	60	2.6
Yakutsk	1974-1975	18	1.4
Fly's Eye	1981-1992	fluor	2.6
HiRes	1998-2006	fluor	10
AGASA	1992-2004	100	6.0
Auger	2004-	3000	16

Table 1. Instruments and arrays seeking the highest energy cosmic rays. Area is measured in km^2. Exposure is measured in units of 10^{16}-m^2-sec-sr. The exposures for the fluorescence detectors are for mono operation. The exposure of Auger is for the equivalent of 80 % of a single year of operation.

thus reward the efforts to reach the very highest energies.

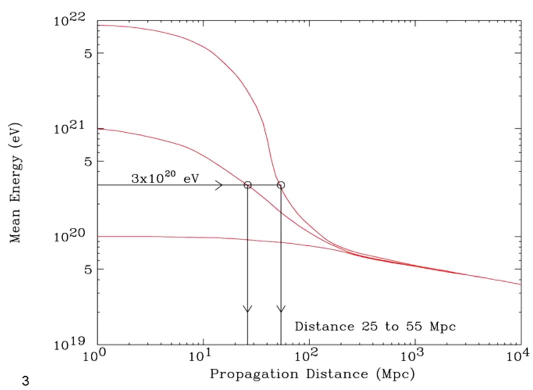


Fig. 11. Mean energy vs distance for cosmic ray protons due to interaction with the cosmic microwave background

In Table 1 we list the instruments that have been developed over the past 47 years which seek to measure the cosmic ray spectrum at the highest energies [18]. Does the spectrum continue as a power law or does it have an end as the GZK effect might suggest? The first group of five instruments have long since ceased operation, but they include innovations, such as replacement of Geiger counters with scintillator in the case of Volcano ranch. An important innovation was the introduction of the fluorescence technique first successfully implemented by the Fly's Eye detector at the University of Utah. The second generation of detectors, HiRes and AGASA, have only recently ceased operation. At present the only operating detector concerned with the end of the cosmic ray spectrum is the Pierre Auger observatory. We should note that the Yakutsk array continues to operate having been reconfigured to emphasize lower energies. We also note that the Telescope Array is under construction in central Utah. Its emphasis is also on the lower energies. In the next section we discuss the technical developments that have led to present day detectors.

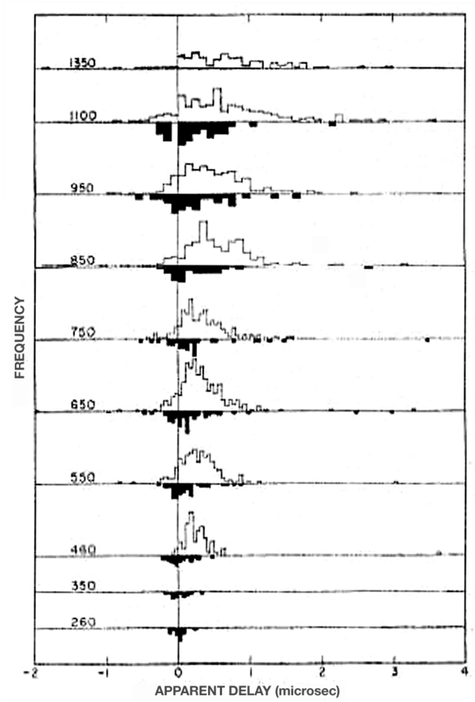


Fig. 12. Time spread of shower particles as a function of distance from the shower core.

Technical innovations for surface arrays

John Linsley used the Volcano ranch array to *measure* many properties of cosmic ray showers. One of the most important was the study by Linsley and Scarsi [19] of the spread of time of arrival of shower particles as a function of distance from the shower core. Knowledge of these details became crucial in the design and operation of subsequent arrays. Fig. 12 taken from their paper shows the time of arrival distributions for shower particles for primary energy $\geq 10^{19}$ eV. Fig. 13 shows the time spread of the shower particles for a single event as a function of distance. These are Flash ADC (FADC) traces from a modern experiment. The spread is several μ-sec for distances greater than a kilometer. This phenomenon has a number of consequences. For example the trigger for an detector in an array may consist of the coincidence between two adjacent scintillators. If the resolving time of the coincidence is too small (≤ 1 μ-sec) the trigger for shower particles far from the core can become inefficient creating a distorted lateral distribution. The designers of the Yakutsk array had to be aware of this phenomenon.

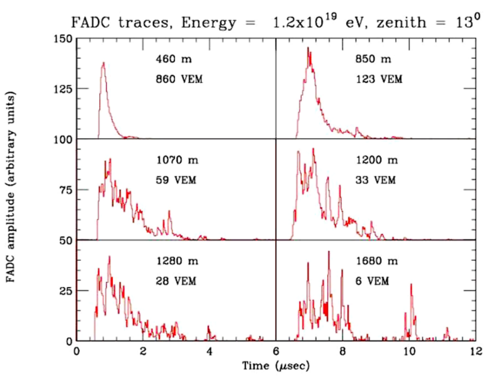


Fig. 13. FADC traces from a single event showing the time spread of shower particles as a function of distance.

The pulse spread phenomenon can be used to advantage in the case where the signal is integrated as a function of time by, for example, an oscilloscope. By measurement of the rise time of the integrated signal in a scintillator or water tank, one can discriminate between small local showers which have a short pulse and large showers with a slow rise time. This technique was exploited by the Haverah Park array.

Instruments built before the advent of inexpensive FADC's often used simple electronics to convert the integrated charge into a time interval proportional to its logarithm. The time was easily measured with an oscillator. This technique had the advantage of a large dynamic range but the effects of the spread of pulse arrival times had to be carefully considered. In Fig. 14 some possible problems with the use of the logarithmic technique are shown. The three curves in panel 1 present the ideal operation of the logarithmic converter. The integrated charge produced by the shower particles is placed on a capacitor. The capacitor discharges with a time constant RC. In the ideal case the integrated charge arrives in a time short compared to RC. When the charge on the capacitor rises above a threshold a pulse appears on the output of the device. When the voltage on the capacitor drops below the threshold the output pulse is terminated. Its length is proportional to the logarithm of the initial charge.

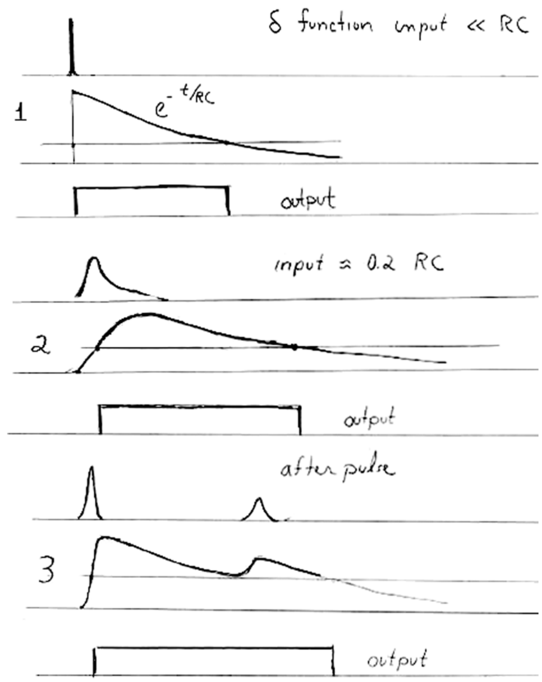


Fig. 14. Three possible situations for a logarithmic charge to time converter.

In panel 2 the charge integration time is a significant fraction of RC. In this case the length of the output pulse is no longer exactly proportional to the logarithm of the integrated charge. It was necessary to be aware of the work of Linsley and Scarsi to produce a converter where the effect of the pulse spread was negligible.

In panel 3 a more insidious phenomenon plays a role. If the photomultiplier is prone to afterpulse then the length of the output pulse is prolonged, giving a false charge. A similar situation can occur when a delayed slow neutron in the shower produces a recoil proton in the scintillator. Such pulses can be quite large, equivalent to many minimum ionizing particles. This somewhat technical discussion is presented to stress how the fine details of the shower play an important role in the design of surface

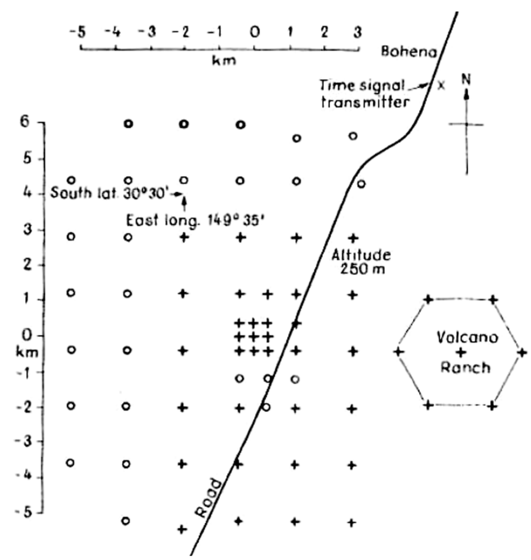


Fig. 15. Layout of the Sidney array.

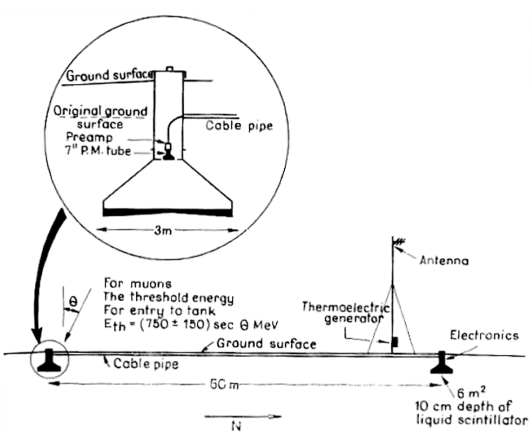


Fig. 16. Arrangement of an individual detector in the Sidney array.

The Sidney array: ahead of its time

Of the list of instruments in Table I, the Sidney array [20] in Australia stands out with its area of 60 km^2. The layout of the array is shown in Fig. 15. The array consisted of 46 detectors. The architecture of this array anticipates the design of modern arrays. To reach large areas the detectors were placed about 1.6 km apart. The consequence of this spacing was a high energy threshold with most events triggering only three tanks. It was not practical to connect each detector to a central station. Each detector was autonomous. Fig. 16 shows a sketch of one of the detectors. Each detector consisted of two liquid scintillators buried about 3.5 meters below the surface. They were placed below the surface to reduce the accidental coincidences in the twofold trigger. Having the detectors buried meant that essentially only the muon component of the shower was detected, making the energy calibration by simulation more difficult. The power for the electronics was provided by batteries or thermoelectric generators. Relative timing was provided by a transmitter picked up a local antenna. Data were recorded locally on tape and collected once a week and brought to a center where the space-time coincidences produced by showers were found by computer. Only after operation for several years was it realized that there was a serious problem with after pulsing which affected the logarithmic converters as described above. The results for the energy spectrum were compromised but the arrival directions were the only ones available in the southern hemisphere. Yet the Sidney array was a pioneer in the design of a sparse array of autonomous detectors which was needed to achieve large areas. If the Austrailians had the technology of today, solar power, GPS timing, FADC's, and LAN technology, their task would have succeeded.

Other innovations for surface arrays

The Haverah Park array was the first to detect the shower particles by Cherenkov radiation using deep water tanks. An advantage is that almost all of the electromagnetic particles in the shower are detected. A disadvantage is that a significant fraction of the signal comes from the muon content of the shower particles which increases the model dependence of the simulated energy response. The array ran for more than 20 years with the water from a local well remaining clear to the very end. In fact the water was quite drinkable as shown in Fig. 17

The Yakutsk array was calibrated by measurement of the atmospheric Cherenkov light produced by the shower particles. This calibration reduced the dependence of the energy scale on simulations. Fig. 18 shows the author with Professor Efimov inspecting one of the Cherenkov detectors in 1986.

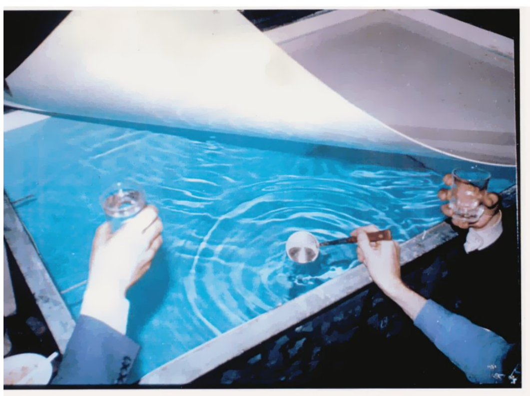


Fig. 17. Drinking the water from a tank of the Haverah Park array after 20 years.

Fig. 18. The author inspecting the Cherenkov calibrator of the Yakutsk array in 1986.

Genesis of the fluorescence technique

The first references to the possibility of observing cosmic ray shower particles by nitrogen fluorescence seems to originate in the Proceedings of the 5th Interamerican Seminar on Cosmic Rays, which took place in Bolivia in 1962. In a contribution Professor K, Suga [21] writes as follows:

"The Cornell and MIT groups have observed several air showers greater than 10^{10} particles and the size spectrum in this range shows no sign of an approaching cut-off. Thus the highest energy of primary cosmic ray particles which seem to have been observed so far turns out to be of the order of 10^{19} eV. It seems inconceivable that such particles could be confined within the Galaxy, even if they are iron nuclei. There are, however, some peculiar galaxies with strong radio emission which seems to provide a means of accelerating cosmic ray particles to energies of $10^{20} \sim 10^{21}$ eV under the assumption that the magnetic fields are 10^{-3} gauss and the dimensions of the order of $3x10^{22}$ cm. Thus it is extremely important to extend the range of observable cosmic ray particles beyond 10^{20} eV."

"The MIT group is working with an array of plastic scintillators which encloses an area of 8 km^2 at the Volcano Ranch station. If one wished to observe showers over 10^{20} eV with such an array, one would have to wait for more than several tens of years. An array which could detect events with a reasonable frequency would have to cover an area of the order of 1,000 km^2. It seems clear that the method of density sampling by large plastic scintillators is basically unsuitable for observing these large events and that essentially different methods must be used for this purpose. Methods based on the detection of scintillation light produced in the air by shower particles and based on the reception of echo radio signals from the ionized air column produced by the shower particles will be discussed."

Suga went on to describe an arrangement of photomultipliers imaged on the sky with a large mirror or lens - the now traditional method.

In the discussion section of the seminar Professor A. Chudakov mentioned that he was thinking in 1955-1957 of detecting cosmic rays by means of their scintillation in air. He had made some measurements of the scintillation yield. However his idea involved the placing a number of open photomultiplier tubes spaced spaced some 7 km apart. The threshold of his proposed arrangement was

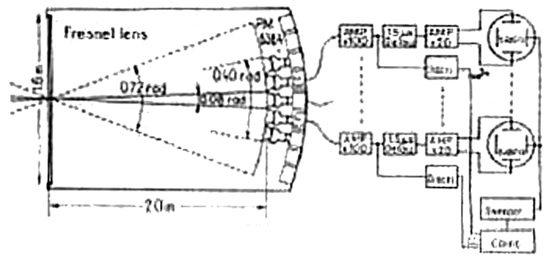


Fig. 1. Schematic sketch of the telescope and the block diagram of the circuit

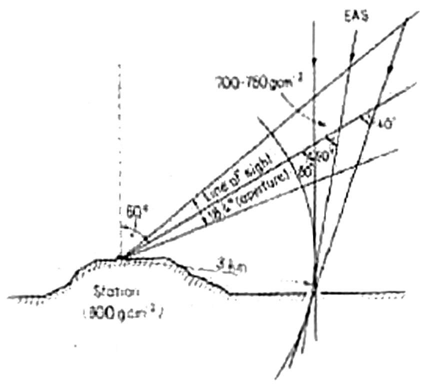


Fig. 7. The estimation of the spatial position of the largest shower. The vertical distance to the shower axis (3 km) is determined from the angular velocity of the shower image, and the angle between the shower axis and the line of sight (40° ÷ 60°) is determined from the fitting of the observed light transition to the calculated one

Fig. 19. Two figures from the paper of Tanahashi et al. showing the first detection of fluorescence light from an air shower.

about 10^{20} eV and complete information about the shower was only measurable for 10^{21} eV.

Tanahashi and collaborators [22] were the first to actually observe fluorescence light from a few showers. These results were reported to the 11th ICRC. Two figures from their paper in the proceedings are shown in Fig. 19. Their apparatus imaged a portion of the sky on a matrix of photomultipliers by means of a Fresnel lens. The light pulses were observed by oscilloscopes. In Fig 7 of their paper they show the reconstruction of their largest shower. While this paper gives the first observation of a shower using the fluorescence technique, a practical instrument was never developed.

Kenneth Greisen and colleagues [23] at Cornell made the first serious attempt to develop the fluorescence technique into a practical instrument. His student Alan Bunner measured in detail the spectrum and yield of fluorescence light produced by charged particles passing through air. It was presented in his PhD thesis and is shown here in Fig. 20. Fig. 21, taken partly from the cover of an issue of *Sky and Telescope*, shows the details of his artistically attractive detector. The fluorescence light was imaged by Fresnel lenses onto banks of photomultiplier tubes in a fashion similar to Tanahashi. Because of the poor sky conditions in Ithaca, no results were ever reported from this detector.

The Utah group led by George Cassiday was the first to develop a successful fluorescence detector called the Fly's Eye. They began by taking one of three prototype detectors to Volcano Ranch [24]. Each prototype detector consisted of 12 photomultipliers imaged on the sky by a 1.5 m diameter spherical mirror. Each photomultipliier saw a 5 degree diameter circle in the sky. They successfully observed coincidences between their fluores-

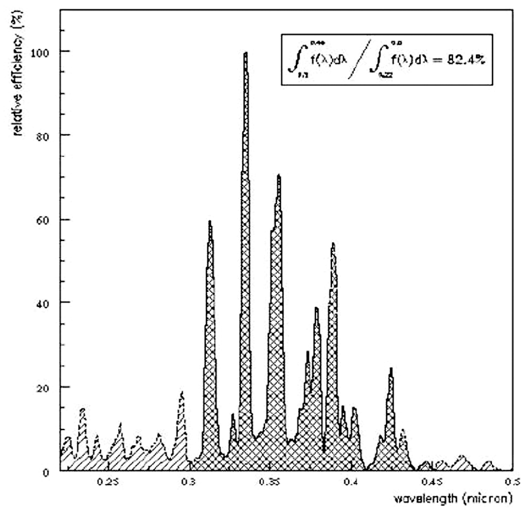


Fig. 20. *Fluorescence spectrun in nitrogen measured by Bunner*

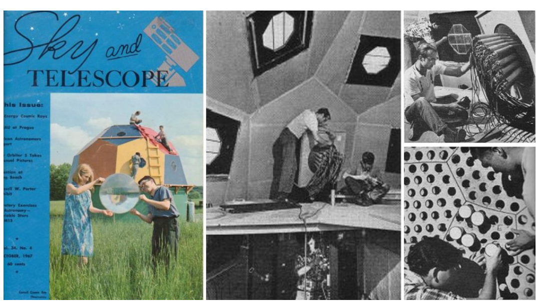
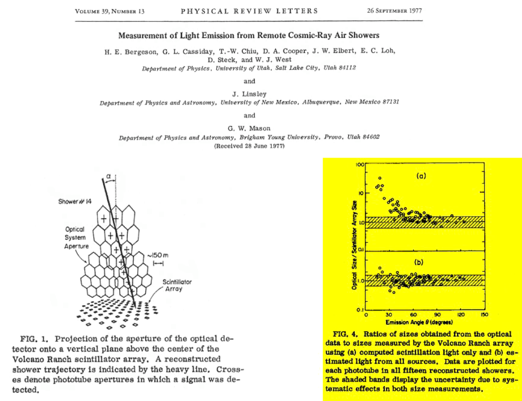


Fig. 21. Views of the fluorescence detector built at Cornell University by Greisen and colleagues



VOLUME 39, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1977

Measurement of Light Emission from Remote Cosmic-Ray Air Showers

H. E. Bergeson, G. L. Cassiday, T.-W. Chiu, D. A. Cooper, J. W. Elbert, E. C. Loh, D. Steck, and W. J. West
Department of Physics, University of Utah, Salt Lake City, Utah 84112
and
J. Linsley
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131
and
G. W. Mason
Department of Physics and Astronomy, Brigham Young University, Provo, Utah 84602
(Received 28 June 1977)

FIG. 1. Projection of the aperture of the optical detector onto a vertical plane above the center of the Volcano Ranch scintillator array. A reconstructed shower trajectory is indicated by the heavy line. Crosses denote phototube apertures in which a signal was detected.

FIG. 4. Ratios of sizes obtained from the optical data to sizes measured by the Volcano Ranch array using (a) computed scintillation light only and (b) estimated light from all sources. Data are plotted for each phototube in all fifteen reconstructed showers. The shaded bands display the uncertainty due to systematic effects in both size measurements.

Fig. 22. *Two figures from the paper describing the shower coincidences of Fly's Eye prototypes with the Volcano Ranch array.*

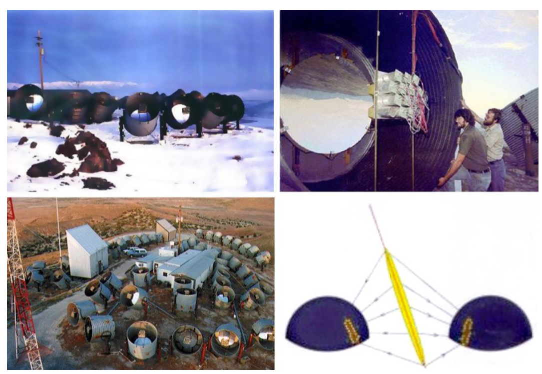


Fig. 23. Some views of the Fly's Eye instrument in Utah. The anticipated stereo arrangement is shown on the left.

cence detector and showers observed by Volcano Ranch. Fig. 22 shows a coincidence detection of a shower and a correlation plot of the fluorescence light and the size measured by the ground array. The correlation plot becomes flat once the direct Cherenkov radiation is taken into account.

The Fly's Eye was then built at the Dugway Proving Grounds in Utah [25] . It covered the entire sky. A second detector was built at a 3.5 km distance to improve the reconstruction accuracy by observation of the showers in stereo. Fig. 23 shows some views of the Fly's Eye instrument. In 1995 the Fly's Eye group observed of the highest energy cosmic ray ever seen [26], with an energy $\sim 3\text{x}10^{20}$ eV. The famous profile of this event is shown in Fig. 24

The success of the fluorescence technique was giant step forward in the effort to observe the highest energy cosmic rays. With careful and tedious absolute calibration of the instrument and the proper evaluation of the absorption of the atmosphere, one could directly measure of the electromagnetic energy deposited in the atmosphere. Then with some small corrections for missing energy in neutrinos and muons, the absolute energy of the primary initiating the shower could be deduced. Simulations of the high energy interactions were not required. The aperture of the fluorescence detector could be enormous, as Suga suggested even accounting for the 10% duty cycle due to the requirement of dark moonless nights. In addition the position in the atmosphere of the maximum

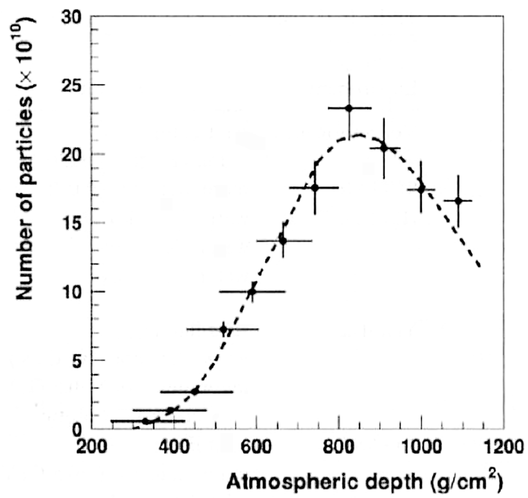


Fig. 24. The highest energy cosmic ray ever recorded by the Fly's Eye group in 1995.

of the shower (Xmax) can be directly measured. A plot of Xmax vs energy, defined by Linsley [27] as the elongation rate, is sensitive to the mean chemical composition of the cosmic rays. The interpretation does depend on the assumed interaction model.

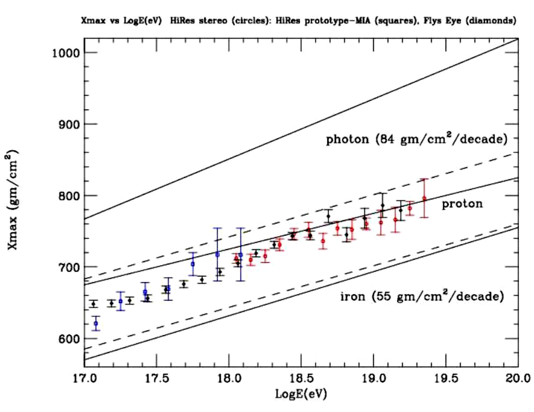


Fig. 25. The elongation rate measured by Fly's Eye and HiRes. The solid and dashed curves represent the expectations for two different interaction models. Photon induced showers are expected to penetrate much deeper.

Fig. 25 shows the elongation rate measured by the Fly's Eye experiment and its successor, the High Resolution Fly's Eye. As photon showers are much more deeply penetrating, they can easily be separated from the hadron induced showers.

Larger surface arrays and fluorescence detectors

During the last 15 years the study of the highest energy cosmic rays was carried out by two large instruments, the AGASA array in Japan and the High resolution Flys Eye (HiRes). Fig. 27 shows the layout of AGASA which was a large array of scintillation counters spread over 100 km^2 in the Japanese country side. It consisted of 111 scintillators of 2.2 m^2 along with a number of muon detectors. The AGASA electronics used logarithmic charge to time converters as cheap FADC's were not available at the time of the design. Data were collected by a system of fiber optics strung along the local telephone and electric lines. It operated from 1992 to 2004.

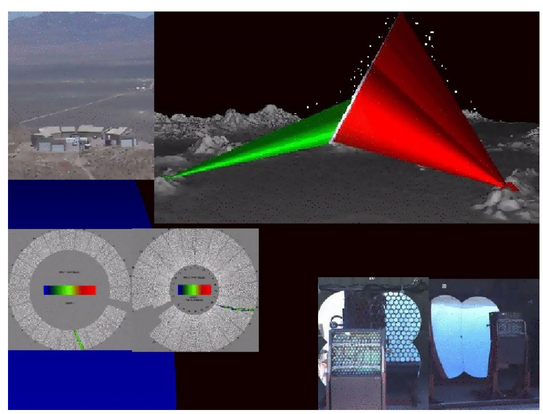


Fig. 26. Views of the HiRes fluorescence detector.

HiRes was a fluorescence detector consisting of two telescopes separated by 12.5 km. The layout of HiRes is shown in Fig. 26. HiRes I observed the full azimuth of the sky and an elevation of 15 deg. Its stereo companion HiRes II consisted of a full azimuth of telescopes with an elevation of 30 deg. HiRes I ran for nearly 10 years while HiRes II ran for a somewhat shorter period.

Fig. 27. Views of the AGASA array.

Both HiRes and AGASA had similar exposures (see Table 1) and have recently been shutdown. They are the first instruments that have begun to observe cosmic rays in the GZK region ($\geq 5\text{x}10^{19}$ eV) There has been a much discussed disagreement between these detectors as to whether the GZK effect has been observed. Even with the immense apertures of these instruments they do not reach Suga's desire for an effective area of 1000 km^2. Nearly final results of these instruments will be reported at this conference

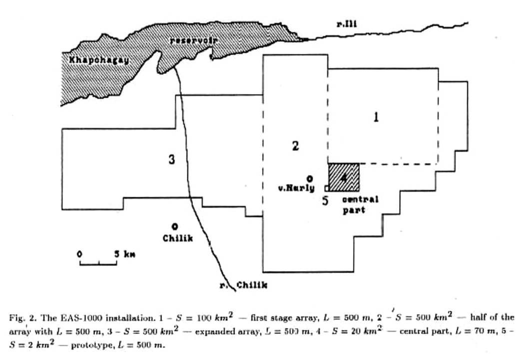


Fig. 28. Plan of EAS1000 proposed by George Khristiansen to be placed near Almaty, Kazakhstan.

Fig. 29. Photo of G. Khristiansen and A. Chudakov during the 20th ICRC in Moscow.

Suga's nightmare becomes Khristiansen's dream: arrays of many 1000 km^2

Suga in 1962 could not imagine instrumenting 1000 km^2 of surface with particle detectors. He did not anticipate developments in technology and new architectures pioneered by the Sidney array. But he was very correct in extolling the fluorescence technique which was a great success for the Fly's Eye and its successor HiRes. But in the late 1980's George Khristiansen proposed an array of 1000 km^2. It was a conservative design which employed 1m^2 detectors spaced 500 m apart. The site was chosen to be near Almaty in Kazakhstan. The proposed layout of the array is shown in Fig. 28. A photo of Khristiansen and Chudakov, is shown in Fig. 29.

In 1991 the author, new to cosmic ray research but endowed with a background of high energy physics where money was no problem realized that a giant leap in detector size was required to advance the study of the highest energy cosmic rays. A workshop [28] was held in Paris in April 1992 where many people gathered to discuss surface arrays of $\geq$ 1000 km^2 and their fluorescence equivalents. Many ideas were discussed but a key feature of the next generation instruments was not explicitly realized at this workshop. This was the notion of an instrument that combined both surface detectors and fluorescence telescopes.

The Pierre Auger Observatory

In the three years following this workshop the concept of the Pierre Auger Observatory evolved. A 6 month study sponsored by Fermilab in 1995 produced a conceptual design consisting of a surface array of 1600 water tanks covering 3000 km^2 overlooked by fluorescence telescopes. This hybrid arrangement had the obvious advantage of observing the showers on dark moonless nights with two independent techniques. The geometrical reconstruction of a shower observed only by the fluorescence detector is very poor. While the plane containing the shower axis and the fluorescence detector is very well determined, the the direction of the shower axis and the position of the core is often very poorly reconstructed. Reconstruction in the plane requires that three parameters be fit simultaneously as shown in the equation at the bottom of Fig. 30. The information available is the time of arrival of the light at each pixel vs the angle of the pixel which when plotted is barely deviating from a straight line giving a degeneracy in the geometry. This degeneracy is completely removed when the constraint of of the time the shower strikes even a single surface detector is added. The hybrid technique is discussed in papers by Sommers [29] and by Dawson [30] The power of this constraint is shown in Fig. 31 shows the uncertainty ellipse in the R$_p$-χ_0 plane. With the additional time from a single surface detector the error ellipse shrinks from the red to the blue. A mono fluorescence detector with the surface constraint determines the shower geometry even more accurately than the stereo view from two fluorescence detectors.

The fluorescence detector can calibrate the energy scale of the surface detector removing the unknown systematic error from a scale determined by a simulated interaction model. The shower direction and core position for hybrid events is determined with much more precision than for the surface array alone. Thus the hybrid events can be used to measure directly the angular accuracy and core position accuracy of the surface array alone.

Fig. 32 shows the Auger Observatory located in Malargüe, Mendoza Province, Argentina. Each red dot is the location of a surface detector which

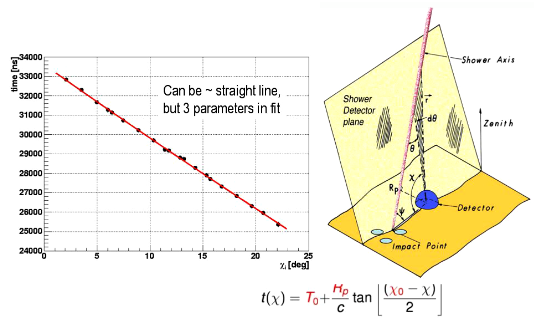


Fig. 30. On the left: plot of signal arrival time vs angle of each pixel. On the right: diagram of the geometrical quantities concerned with the fluorescence reconstruction. On the bottom: the equation relating the quantities to be determined in the geometrical reconstruction.

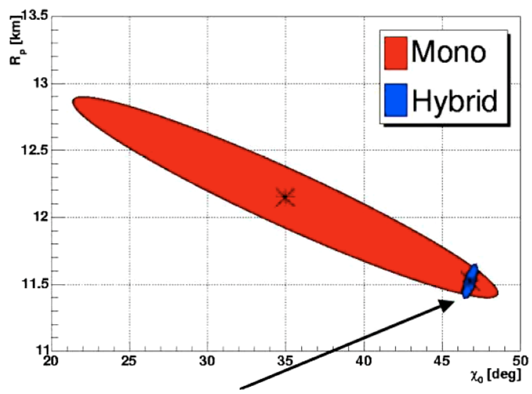


Fig. 31. Error ellipses for geometrical reconstruction of a fluorescence detector.

is a tank of area10 m^2 filled with 12 metric tons of water. The shower particles are detected by the Cherenkov light they produce in the water. The surface detectors use solar power, measure time from the GPS satellites, and communicate with a central computer by radio. These autonomous detectors are functionally the same as the Sidney array, but profit from the many advances in technology. Operating tanks as of June 2007 are located in the area outlined in blue. The four fluorescence detectors are all in operation. At this conference there are many papers on the technical details of the Auger Observatory and the results.

Fig. 33 shows a particularly fine example of a hybrid event. The upper left panel shows the pattern of pixels illuminated on the camera. The upper right panel shows the time vs pixel angle. The

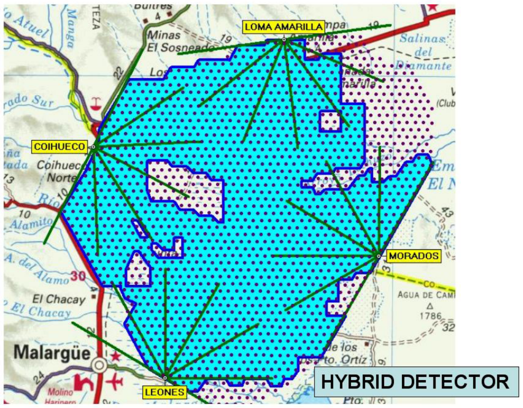


Fig. 32. Plan of the Auger Observatory. Completed surface array is outlined in blue. The location of the fluorescence detectors is indicated in yellow.

black circles are for the actual fluorescence pixels. The green points are the additional information from the surface array in the form of extended virtual pixels. The lower left panel shows the surface tanks triggered by the shower particles. The lower right panel shows the longitudinal profile of the shower reconstructed from the intensity of the fluorescence light.

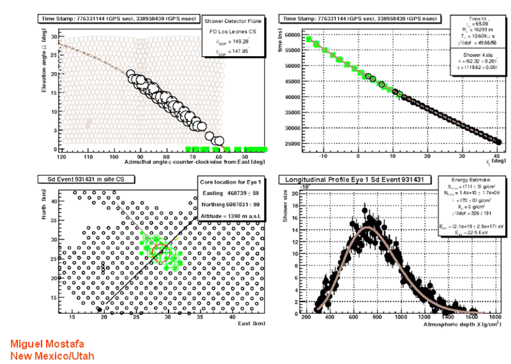


Fig. 33. Example of a hybrid event.

Knowledge of the fluorescence spectrum and the absolute yield is essential for the calibration of the surface array. At present the error on the absolute fluorescence yield is $\pm$ 16 %. A number of groups are remeasuring the fluorescence spectrum and absolute yield. Fig. 34 shows the fluorescence

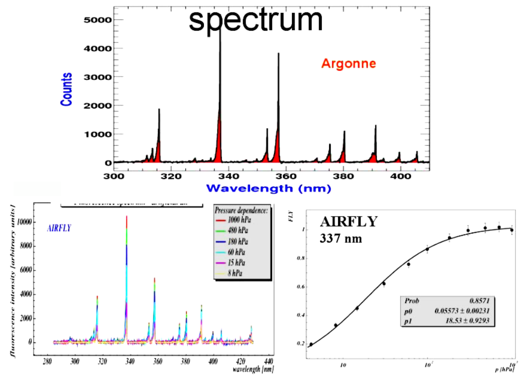


Fig. 34. New measurement of the fluorescence spectrum.

spectrum measured by a subgroup of Auger. It is expected that the absolute yield will be measured with a precision of 5%. The ability to measure the yield and spectrum has also benefitted from developments in technology. (Compare Fig. 34 with the spectrum of Bunner in Fig. 20.)

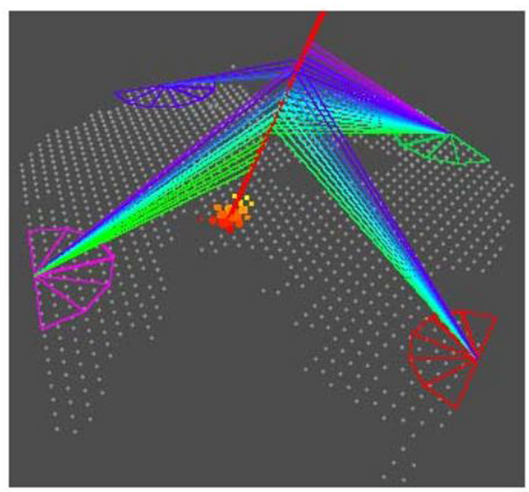


Fig. 35. Example of an event seen by all four fluorescence detectors.

The Auger Observatory is the culmination of a huge effort by many researchers to develop techniques for the solution of the mystery of the highest energy cosmic rays. Its potential for success is symbolized a beautiful event in which a shower is recorded by all four fluorescence detectors. The event is shown in Fig. 35.

Conclusions

Detectors for the highest energy cosmic rays have become large enough that a reasonable number of events can be accumulated over some ten years. We are at the point where we have some confidence that the angles and energies of these highest energy cosmic rays can be measured accurately. Good progress is being made for a statistical determination of the composition. However, it remains to make a connection with the cosmic accelerators. This remaining goal requires patience on the part of the physicists and benevolence on the part of Nature.

Acknowledgments

I thank the organizers of the 31st ICRC for the invitation to present the Hess Lecture. I want to thank many colleagues, too numerous to mention, for welcoming me to the community of cosmic ray physicists and teaching me many things. I specifically want to thank Bruce Dawson and Alan Watson for supplying specific material on the early stages of the development of the fluorescence technique.

References

[1] Crookes, Proc. Roy. Soc., 1879, 28, p. 347.
[2] E. Rutherford and H.L. Cooke, Phys. Rev. 16 (1903) 183.
[3] Th. Wulf, Phys. Zeit. 11 (1910) 811.
[4] A. Gockel, Phys. Zeit. 12 (1911) 595.
[5] V. Hess, Phys. Zeit. 13 (1912), 1084.
[6] W. Kolhörster, Ber. Deutsche Phys. Ges. 16 (1914) 719.
[7] R.A. Millikan, Nature (suppl.) 121 (1928) 19.
[8] P. Auger and R. Maze, Comptes Rendues 206 (1938) 1721.
[9] R. Maze, J. de Phys. 9 (1938) 162.
[10] P. Auger, Rev. Mod. Phys. 11 (1939) 288.
[11] B. Rossi, *Cosmic Rays* (McGraw-Hill, 1964).
[12] B. Rossi, Ric. Sci. Suppl. 1 (1934) 579.
[13] W. Kolhörster, Naturwiss. 26 (1938) 576.
[14] P. Bassi, G. Clark, and B. Rossi, Phys. Rev. 92 (1953) 441.
[15] J. Linsley, Phys. Rev. Lett. 10 (1963) 146.
[16] K. Greisen, Phys. Rev. Lett. 16 (1966) 748.
[17] Z.T. Zatsepin and V.A. Kuz'min, JETP Lett. 4 (1966) 144.
[18] M. Nagano and A.A. Watson, Rev. Mod. Phys. 72 (2000), 689. Descriptions and references to all the instruments described in Table 1 are presented in this review.
[19] J. Linsley and L. Scarsi, Phys. Rev. 128 (1962) 2384.
[20] C.J. Bell et al., J. Phys. A. 7 (1974) 990.
[21] K. Suga, Proceedings of 5th Interamerican Seminar on Cosmic Rays, La Paz, Bolivia, 1962 (I. Escobar et al., Laboratorio de Fisica Cosmica de la Universidad Mayor de San Andres), Vol. 2, p. 49.
[22] T. Hara et al., Acta Phys. Acad. Sci. Hung. 29 (1970) 361.
[23] A.N. Bunner et al., Canad. J. Phys. 46 (1968) S266.
[24] H.E. Bergeson et al., Phys. Rev. Lett. 39 (1977) 847.
[25] R.M. Baltrusaitis et al., Nucl. Instrum. Methods Phys. Res. A. 240 (1985) 410.
[26] D. Bird et al., Astrophys. J. 441 (1995) 144.
[27] J. Linsley, Proceedings of the 15th ICRC, Sofia, Bulgaria, 1977, Vol. 12, p. 89.
[28] J. Cronin and A.A. Watson, Workshop on the Design of Instruments to Study Cosmic Rays With Energies $\geq 10^{19}$ eV, (M. Boratav, 1992).
[29] P. Sommers, Astropart. Phys. 3 (1995) 349.
[30] B. Dawson et al, Astropart. Phys. 5. (1996) 239.