

Chasing the highest energy cosmic rays: From 1948 to the present



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ABSTRACT

After a brief review of the discovery of extensive air showers, I summarise the remarkable advances made in the decade 1948–1958. During this period many of the techniques of instrumentation and analysis that are used today were introduced. I then discuss current data with emphasis on recent work on the measurement of the mass composition between 10^{15} and 10^{17} eV and above 10^{18} eV, and on the energy spectrum at the highest energies.

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1. Introduction

The idea that there might be cascades of particles in the atmosphere produced by energetic cosmic rays was discussed by a number of people in the mid-1930s. The notion was based in part on interpretation of the work of Rossi [1] and of Regener [2]. Rossi had observed the rise and fall of coincidence rates as he increased the thicknesses of lead over three non-aligned Geiger counters while Regener, with Pfitzer, had seen the rise of the rate of ionisation in the atmosphere reach a maximum at a depth $\sim 50 \text{ g cm}^{-2}$. Cascade showers had been observed in Wilson chambers by Blackett and Occhialini [3] while Schmeiser and Bothe [4] and Kolhörster et al. [5] made targeted and successful searches for ‘Luftschauer’ in 1938. Bhabha and Heitler, in interpreting the work of Regener as a demonstration of their ideas about cascade development, reached the conclusion that cascade showers should be found in the atmosphere [6].

Auger et al. [7] independently and serendipitously made similar observations in 1939 which were more extensive in the range of counter separations studied. Crucially, through observations at high-altitude at the Jungfraujoch (3471 m), they were able to demonstrate that the primaries initiating some of the cascades or air showers had energies of $\sim 10^{15}$ eV [8]. The results from these early observations are summarised in Fig. 1 [9].

Auger and his group are often credited with the discovery of extensive air showers and seem to have been unaware of the activity in Germany. At the time the world was preoccupied with other matters and communication between scientists was relatively poor. Also Auger was in a position to follow up his studies during the early years of the War, particularly in Chicago, but in fact Rossi

had beaten everyone by about 4 years [10]. His translation [11] of his description of his observations made in Eritrea (2370 m) reads

“The frequency of coincidences ... appears to be greater than would have been predicted from the resolving power of the coincidence circuit ... it seems that once in a while the recording equipment is struck by *very extensive showers of particles*.....(in Italian ‘*sciame molto estese di corpuscoli*’). Unfortunately I did not have the time to study this phenomenon more closely.”

After World War II, Rossi played a huge role in the flowering of the field of extensive air showers building a large group at MIT.

2. 1948–1958: Decem Anni Mirabiles

It is a remarkable tribute to a relatively small number of people that many of the experimental and analytical techniques used today had their genesis in a decade of frenetic activity between 1948 and 1958. Here I shall review some of these advances and insights.

2.1. Contributions from the MIT group

Following his work on the Manhattan Project Rossi set up a group at MIT targeted at the measurement of the characteristics of individual air showers. He first encouraged Williams to study individual events with an array of four fast ionisation-chambers which were used to sample the density of particles across the shower. This was an advance over the Geiger-counter method as the number of particles could be determined directly rather than in a statistical manner [12]. Williams made measurements at 3500 and 4300 m using the ionisation chambers in a star-shaped geometry with a central detector and the other three, on a plane, 7 m away. The time resolution of the chambers was about $1 \mu\text{s}$, too long to make determination of directions feasible. However, during the run at the lower altitude, Williams took advantage of

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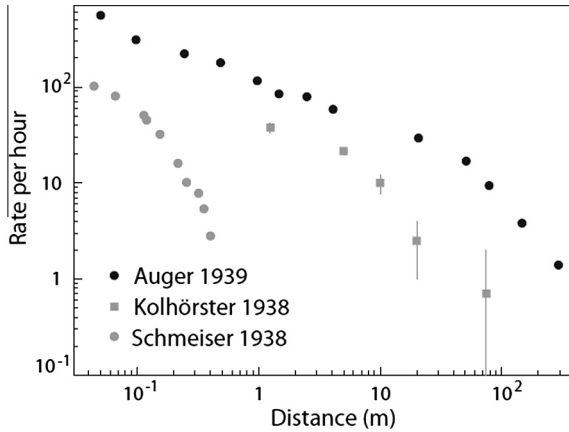


Fig. 1. Decoherence curves measured with Geiger counters separated by up to 300 m. Data are from [4,5,8]; the figure is from [9].

a cloud chamber operated there by Wayne Hazen to tag the arrival direction of a small fraction of his events finding that 80% of them had zenith angles less than 20° . Thus he was able to make his analysis under the assumption that the showers were vertical. Using charts of the signal size as a function of distance derived from the shower theory then available, he could determine the position on the ground where the signal size was greatest, the so-called core of the shower. Modern analyses with fast computers use essentially this method for core location.

In 1953 Bassi et al. [13], with an array of three liquid-scintillation counters, showed that close to the shower axis the thickness of the shower disk was only about 10 ns, thus opening the way to measurement of the direction of the primary particle. This pioneering work led to the construction of a shower array which can be seen as the prototype of the many that have followed. The MIT group soon replaced liquid scintillators by solid ones [14] and 15 of them, each of 0.87 m^2 , were arranged as shown in Fig. 2 [15]. During the early MIT studies many of the analyses techniques that are still used were developed.

The program also spawned two remarkable ground-breaking experiments at Chacaltaya, Bolivia (5200 m) and at Volcano Ranch, New Mexico (1700 m) where an array of 8 km^2 , the first of the giant arrays, was constructed, largely single-handedly, by John

Linsley. At both stations the solid scintillators developed at MIT were deployed [14].

2.2. The Culham shower array

Contemporaneously with the MIT work, an array of Geiger counter stations covering 0.6 km^2 was developed at Culham in southern England [16]. A major interest was the study of the arrival direction distribution of showers produced by primaries of $\sim 10^{17} \text{ eV}$ to evaluate a theory advocated by Richtmeyer and Teller [17] and by Alfvén [18], namely that cosmic rays were produced by the sun and then isotropised in a local magnetic field of $\sim 10^{-5} \text{ G}$. The anisotropy was shown to be below 10% thus ruling out this hypothesis.

Perhaps a more important outcome from Culham was the development of practical water-Cherenkov detectors in which unfiltered water could be kept in a stable condition for long periods. The credit for this achievement goes to Neil Porter who used ‘Darvic’, a material developed by ICI for sandwich boxes and containing a bacterial inhibitor, to form the reflecting surfaces of the detectors [19]. Porter’s detector can be seen as the prototype of the Cherenkov detectors used at Haverah Park (1967–1987) and at the Auger Observatory from 2000. Indeed there has been remarkably little development of his design as can be seen from Fig. 3.

2.3. Work in Russia

While work with Geiger counters was phased out rather rapidly towards the end of the 1950s in Japan, Western Europe and the USA, a vibrant program continued in the Soviet Union where limitations of manpower were less of a problem than elsewhere. Hodoscopic systems of up to 2000 counters were built along with the associated monitoring equipment. These instruments required teams of 20–30 people for their operation and maintenance, a distinctive innovation at a time when a typical group working on a cosmic ray problem comprised only a few persons. The Russian workers also introduced the technique of the hadronic calorimeter in which ionisation chambers were interleaved between layers of lead, thus extending the capabilities of the cloud chamber method for the measurement of the energy of an incoming hadronic particle. A major goal of the Russian work was the study of hadronic interactions with the hodoscopes generally being deployed at high altitude.

Parallel activities at sea-level were developed at Moscow State University under the leadership of Vernov and Khristiansen. The key output from this work, which led to studies by many groups

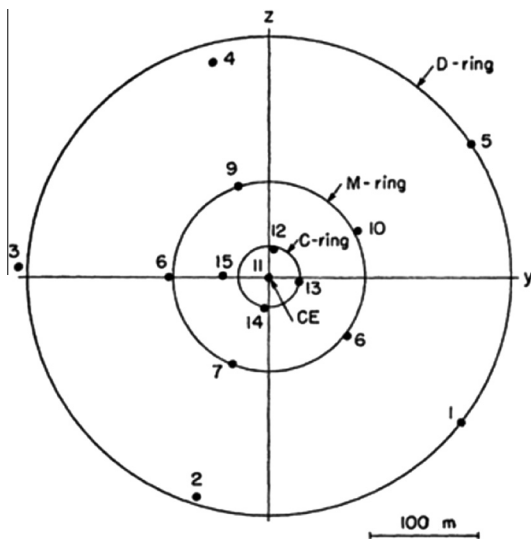


Fig. 2. The MIT array of plastic scintillation counters, from [15].

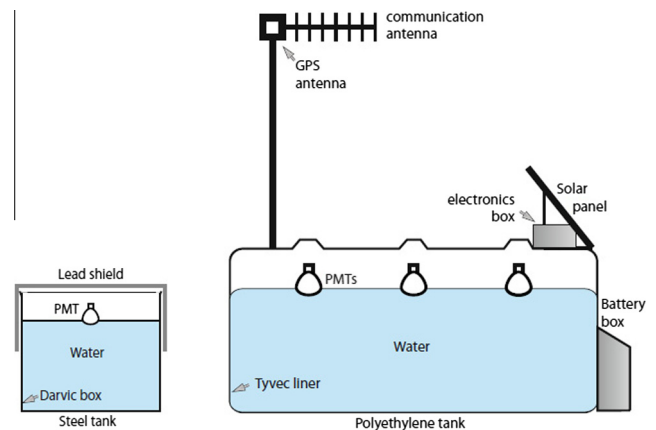


Fig. 3. Scale comparison of the first water-Cherenkov detector designed by Porter [19] and that used at the Pierre Auger Observatory [20, figure from 9].

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