Reprinted from the Proceedings of the Indian National Science Academy
Vol. 44 *Part A, No.* 3, (1978), *pp.* 125-143

HOMI JEHANGIR BHABHA MEDAL LECTURE — 1977

COSMIC RAY PHYSICS AND ASTROPHYSICS

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(*Delivered* 2 January 1978*)

FIRST OF ALL I would like to express my deep felt gratitude to the Council of Indian National Science Academy and its President, Prof. Ramanna, for awarding the Homi Bhabha Medal for the year 1978 to me. I am particularly happy about this award since it is associated with the name of Dr. Homi Bhabha, with whom I worked for a period of 18 years—from 1948 when I joined TIFR as a student, till 1966 when Dr. Bhabha was a victim of the tragic air crash of January 24. I was one of his first Ph.D. students in experimental physics in TIFR. I have had the unique privilege of spending the last 30 years, undoubtedly the best years of my life, as a member of the Tata Institute of Fundamental Research, an institution founded by Dr. Bhabha. I am also happy that I have the opportunity of delivering this lecture at the Physical Research Laboratory founded by the late Dr. Vikram Sarabhai. The PRL has been a sister institution to TIFR right from the beginning. It is very gratifying for me to note that in the audience today, by a very fortunate circumstance, we have Prof. B. Peters who played an important role in the early phase of my research career at TIFR.

The discovery of an extra-terrestrial radiation that is incident all over the world from all directions and at all times which was given the name Cosmic Radiation by Milikan in 1925, has a long and interesting history. It was the brilliant scientist Coulomb, who is famous for his pioneering work in the field of electricity, that first noticed more than 150 years ago that an insulated metal sphere charged with electricity did not retain its charge for a long time but continuously leaked out. The mystery which persisted for about 70 years was solved only in 1912 by Victor Hess (Pl. I.) when he discovered through a series of manned balloon flights in which he himself went up to 16,000 feet in the atmosphere, the presence of a penetrating ionizing radiation whose intensity *increased* with altitude. In the last 65 years of investigations, the very many facets of cosmic radiation have been uncovered. It has now become clear that there is a "primary radiation" that is incident on the top of the atmosphere which is distinctly different from the "secondary radiation" that is observed lower down at mountain altitudes, sea level and underground (Table I). The primary radiation consists mainly of protons and to a small extent alpha particles and heavy nuclei. The heavy primaries in cosmic radiation were first discovered

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*The Lecture was delivered by the Author at the Physical Research Laboratory, Ahmedabad, during the Academy's General Meeting.

TABLE I

Components of the primary and secondary cosmic radiation

Cosmic Rays

Primary Radiation	Secondary Radiation
Astrophysical ↙ Information	High Energy Physics ↘
Protons	Pions
α–Particles and	Kaons
heavy nuclei	$N\bar{N}$
Electrons	New Particles
Photons (X-Ray, γ-Ray)	Muons
	Electrons
Neutrinos	Photons
Composition	Neutrinos
Spectrum	Cerenkov
Anisotropy	Radio
Discrete Sources	

by Prof. Peters and his colleagues around 1948. In addition, there is an electron component which is a few percent of the proton component in intensity, a photon component and a neutrino component. The intensities of the neutral particles are of several orders of magnitude lower than that of charged particles. The secondary radiations which principally consist of pions, nucleons and anti-nucleons, and kaons arise in the nuclear encounters of the primary particles with air nuclei. The charged secondary pions either interact with air nuclei as they travel down and give rise to more secondary particles or decay into muons and neutrinos which form the charged and neutral penetrating components of the cosmic radiation. The neutral pions decay into gamma rays which through cascade multiplication give rise to electrons and positrons. While the different components of the primary radiation provide information on astrophysical aspects, the secondary radiation is being very effectively used for eliciting information on the characteristics of ultra high energy nuclear interactions particularly at energies above the currently available accelerator energies. In the past three decades the incentive for building higher and higher energy accelerators has come mainly from the exciting and new results that have initially emerged from cosmic ray studies which in themselves have moved to higher and higher energies as the technology of instrumentation, particle detector systems, methods of analysis using computers, became available and enabled the design and execution of experiments that could overcome the problems connected with decreasing fluxes at higher energies of the primary radiation.

Thanks to the foresight of Dr. Homi Bhabha who realised the advantage of this particular field of investigation for a developing country like India, Cosmic Ray research has been a major field of research activity in the Tata Institute of Fundamental

PLATE I

Victor Hess in the Gondola in which he went up to an altitude of 16,000 ft. for measurement of Cosmic ray intensity in 1912.

PLATE II

Dr. Bhabha and Mr. A. S. Rao with a typical Cosmic ray telescope — of the type that was being launched from the Central College grounds, Bangalore in the late forties, on clusters of rubber balloons.

Research right from the time of its inception in 1945. In the first few years experiments were in progress on the measurements of the penetrating components of cosmic radiation as a function of altitude using GM counter telescopes, sent up to stratospheric altitudes using clusters of rubber balloons (Plate II). Experiments were also started in the late 1940s on the scattering of muons using counter controlled cloud chambers, and nuclear interaction studies using nuclear emulsions flown to balloon altitudes. Over the years, the balloon technology at TIFR has been developed indigenously to such an extent by the efforts of Profs. Gokhale and M. G. K. Menon that today we are in a position to fabricate and fly plastic balloons of capacity 4–5 M cft which can carry payloads up to 500 kg to altitudes of 36–38 km. Plate III shows a typical X-ray astronomy payload that is launched now a days from the Hyderabad Balloon Facility. Apart from a variety of experiments on high energy interactions, primary charge composition, isotopic composition etc., using nuclear emulsions stacks and electronic detection systems, very significant and pioneering results have been obtained on the primary electronic component by Prof. Daniel and his collaborators based on nuclear emulsion flights carried out from Hyderabad. In recent years, the emphasis of the High Altitude Studies group has shifted to Infrared, X-ray and Gamma ray astronomies using stratospheric balloons.

UNDERGROUND EXPERIMENTS AT K.G.F. : MUONS AND NEUTRINOS

I will concentrate on those aspects of cosmic ray research in TIFR in which I have had close involvement in the last three decades. I would like to start with the experiment which we initiated in the Kolar Gold Fields in 1951 at the suggestion of Dr. Bhabha. Some of you may recall that Dr. Bhabha was the General President of the Indian Science Congress held in January 1951 at Bangalore. A few weeks before this Congress he called me and said that I should plan to take a cosmic ray telescope down the Kolar Gold mines and measure first the vertical intensity of the penetrating component as function of the over-burden of earth and later plan in terms of a detailed analysis of the composition of particles present at the various depths, and see whether they are all muons or whether there are other new particles. I recall that we went to survey the mines from the point of view of carrying out experiments there immediately after attending the Science Congress session at Bangalore and on this occasion the present President of INSA, Dr. Ramanna, who was then at TIFR, had accompanied us on this visit to the mines. In October-December 1951, Dr. Naranan and myself carried out the first investigations in the Kolar Gold mines using a hodoscoped geiger counter telescope and measured the intensity of cosmic rays up to a depth of 1000 ft. below ground. Since 1951, we have been practically at the KGF except for a few years between 1955 and 1958. A large number of experiments have been carried out on very many aspects of muon and neutrino radiations. In some of these experiments we have had international collaboration with the University of Durham, U.K., and the Osaka City University, Japan. Fig. 1 shows the most accurate measurements up to the largest depths possible of the intensity of the penetrating component measured at KGF and based upon a variety of experiments carried out over two decades. In 1961, when the first large depth intensity measurements were being carried out with a telescope having a combination of scintillation and GM counters, it was realised that no cosmic ray

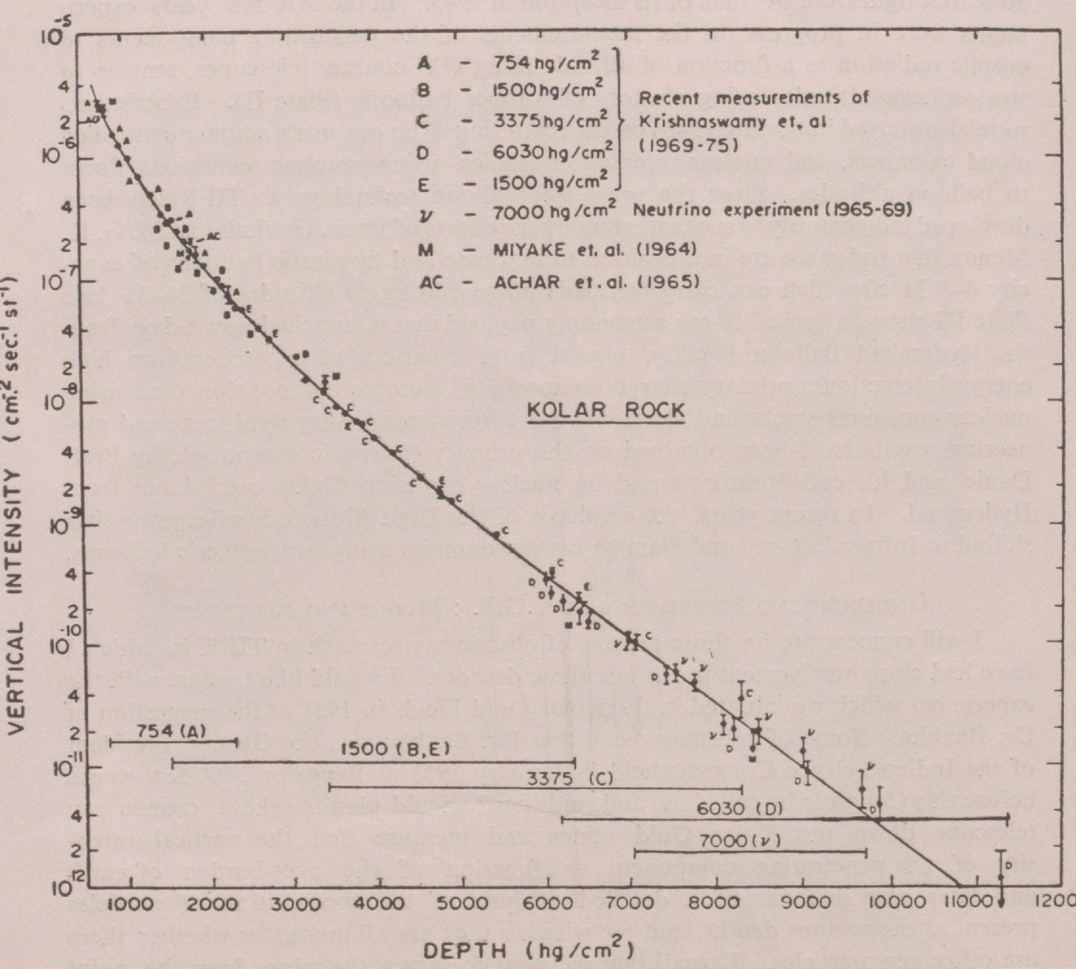

FIG. 1. The variation of intensity of penetrating particles as a function of depth—based on a variety of experiments at the Kolar Gold Fields.

count was registered at the deepest level of 8400 m.w.e. in an operation time of three months. It is this somewhat negative result that suggested the feasibility of carrying out experiments for the detection of cosmic ray neutrinos at such deep underground levels taking advantage of the near absence of charged cosmic ray particle background. The first neutrino telescope was set up in the mines in 1965 as a collaborative venture of TIFR, University of Durham and the Osaka City University. Fig. 2 shows the experimental arrangement used. The first clear evidence for the interaction of a cosmic ray neutrino was obtained within a few months of operation and one of the interesting examples is shown in Fig. 3. The important point to note is that the penetrating tracks meet at a point below the horizon at the depth of 7500 m.w.e. and therefore the event is clearly due to the interaction of a neutrino giving rise to penetrating particles. While my own interest in the neutrino investigations ceased

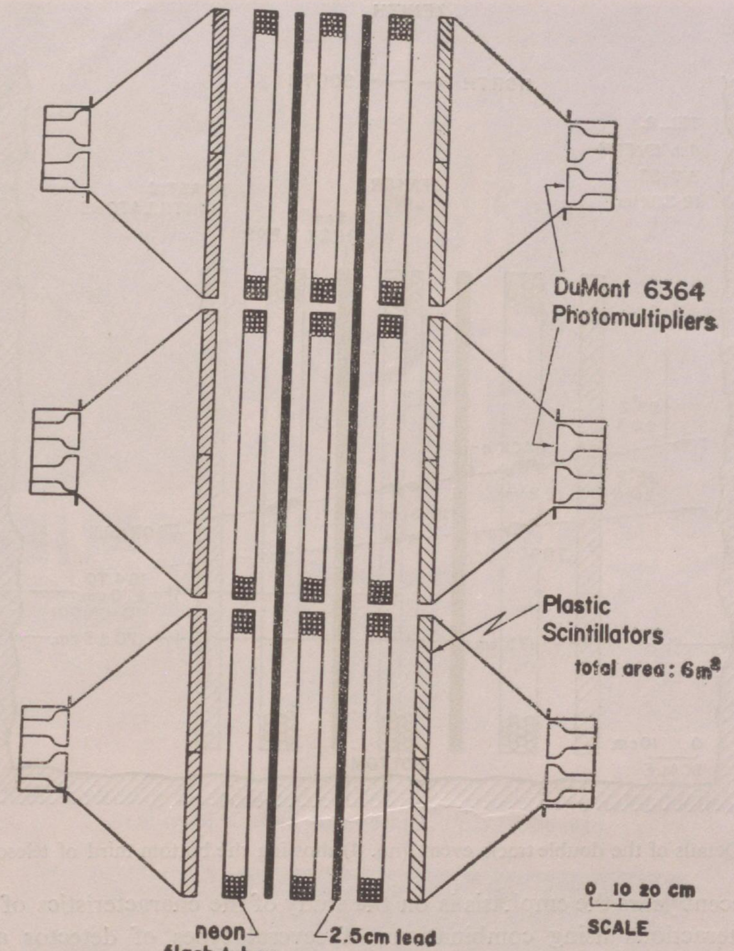

FIG. 2. The first KGF Neutrino Telescope — comprising of vertical walls of plastic scintillators and neon flash tubes assemblies.

in 1966, the continued involvement and stimulus provided by Prof. Menon, Prof. Miyake and Dr. Narasimham has led to the installation of a very large number of telescopes underground at KGF and some very interesting new results suggesting the possibility of the production of new types of particles in high energy neutrino collisions have emerged and are being pursued.

EXPERIMENTS ON HIGH ENERGY INTERACTIONS AND EXTENSIVE AIR SHOWERS AT OOTY

Since December 1955, we have been operating a Cosmic Ray Laboratory at Ootacamund at an altitude of 2.2 km. The laboratory is situated in the premises of the Raj Bhawan and overlooks the famous Botanical Gardens at Ooty. In the initial years, the emphasis in this laboratory was on the study of the production of strange particles using a pair of multiplate cloud chambers one above the other and

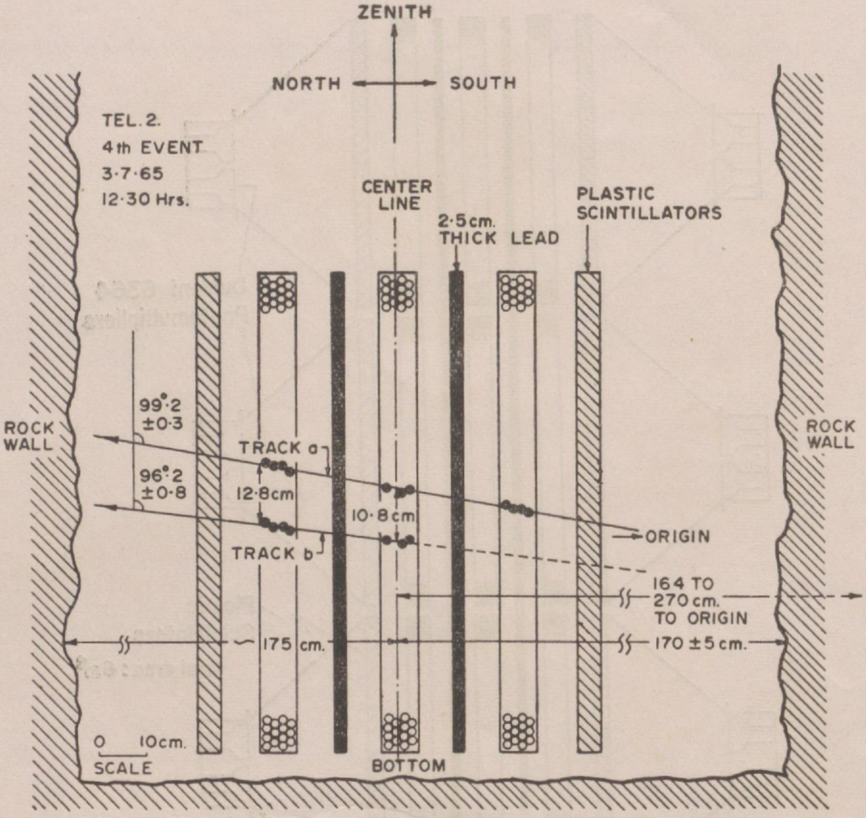

FIG. 3. Details of the double track event (no. 4) showing the bottom third of telescope no. 2.

in more recent years,the emphasis is on the study of the characteristics of ultra high energy interactions using combinations of several types of detector assemblies. Plate IV shows a large multiplate cloud chamber, perhaps the largest in the world, of dimensions 2.5 m × 1.5 m × 1 m and with 7 tons of iron inside in the form of plates that has been in continuous operation at Ootacamund since 1965. The type of very high energy events that have been recorded with this chamber under different experimental conditions are shown in Plate V, *a* and *b*. They show the development and absorption of nuclear and electromagnetic cascades initiated in the chamber by the incidence of hadrons of energy 10^{12} eV or more. Very sophisticated methods of analysis using extensive Monte Carlo simulation methods had to be developed to derive quantitative information on the characteristics of high energy interactions from such photographs. Fig. 4 shows a unique set-up of air Cherenkov counter, multiplate cloud chamber and total absorption spectrometer that was used to discern the differences in the characteristics of interactions of pions and protons in the energy range 10-100 GeV, before such investigations became possible with accelerators.

The large cloud chamber and the total absorption spectrometer have been operated for several years as part of the Ooty Extensive Air Shower array. An

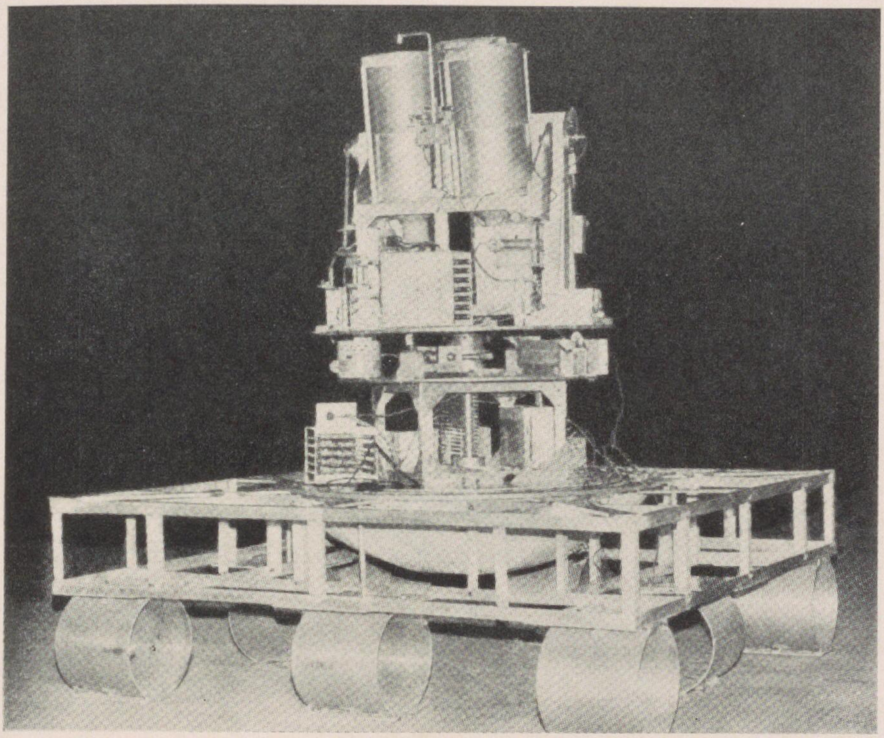

PLATE III
A typical X-ray astronomy telescope that is sent up now a days on a large plastic balloon to altitude of more than 35 kms, from Hyderabad.

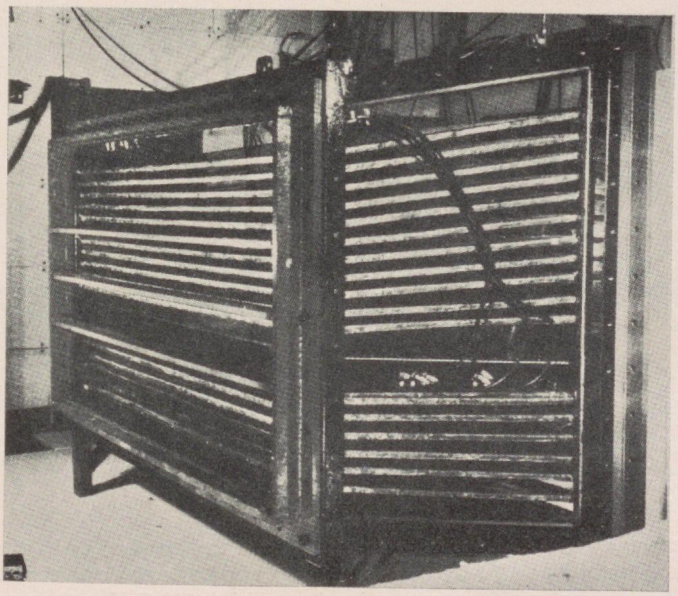

PLATE IV
The main framework of the large multiplate cloud chamber at Ooty with 21 iron plates each 2 cms thick and of dimension 2 m × 1 m.

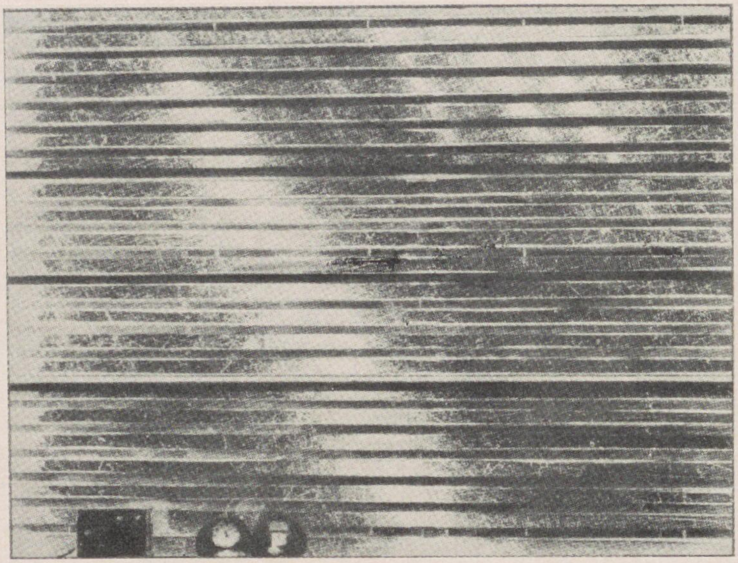

PLATE V, *a*

A cascade having an elongated tube-like structure which is not completely absorbed even after 20 radiation lengths. The estimated energy is 2.4 TeV.

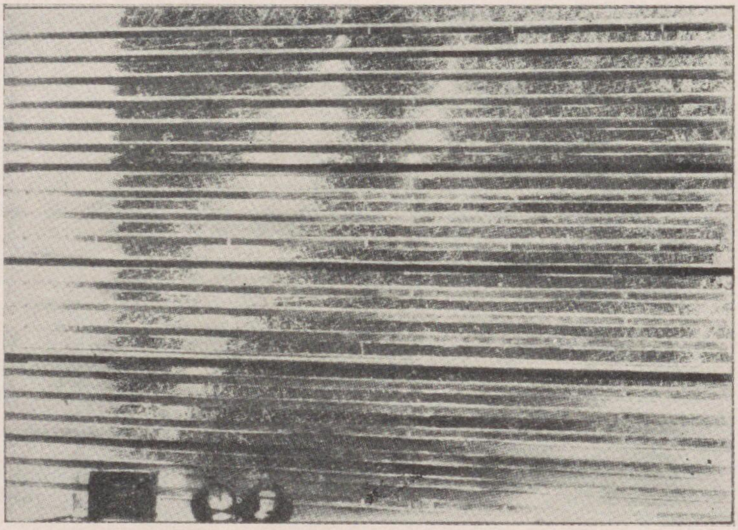

PLATE V, *b*

A cascade which develops from the first plate of the chamber and shows a rapid absorption after the maxima. The method of cascade widths has been used for energy estimation which is 750 GeV.

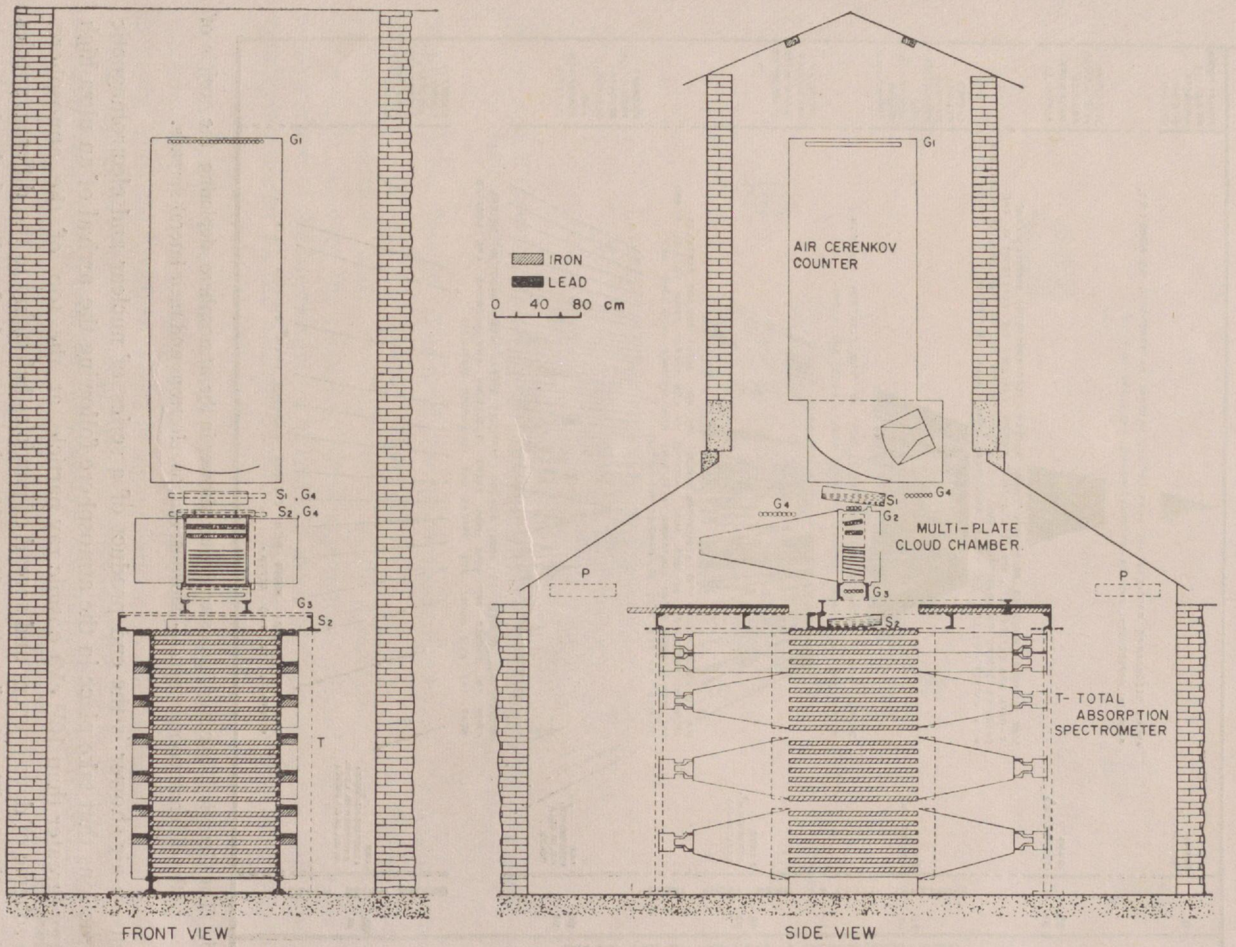

FIG. 4. Triple arrangement of Air Cerenkov Counter, Multiplate Cloud Chamber and Total Absorption Spectrometer at Ooty, for the study of interactions of pions and protons in 10-100 GeV range.

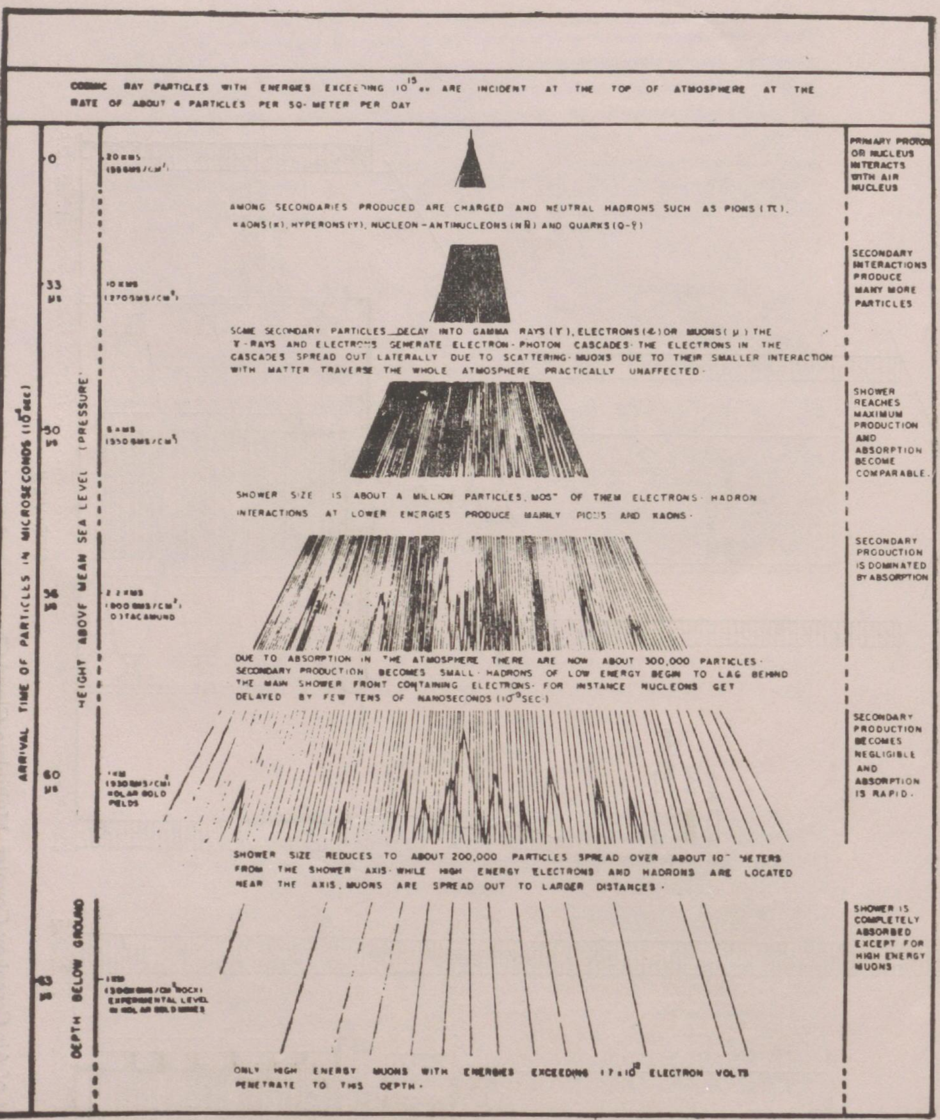

FIG. 5. The Generic Diagram of an extensive air shower in the atmosphere depicting the origin of the different components — hadrons, muons, electrons and their lateral spreads.

extensive air shower is the end product of a series of nuclear and electromagnetic interactions that take place in the atmosphere following the arrival of an ultra high energy (greater than 10^{13} eV) cosmic ray particle at the top of the atmosphere. The scheme of development and spread of particles belonging to the different species is shown in the Fig. 5. It takes about 30 micro seconds for the whole shower to develop and pass through the entire atmosphere. At any level of observation, say at Ooty, the rain of particles last only for a few tens of nano seconds. The array of scintillators (Fig. 6) is designed to measure the charged particle intensity at various

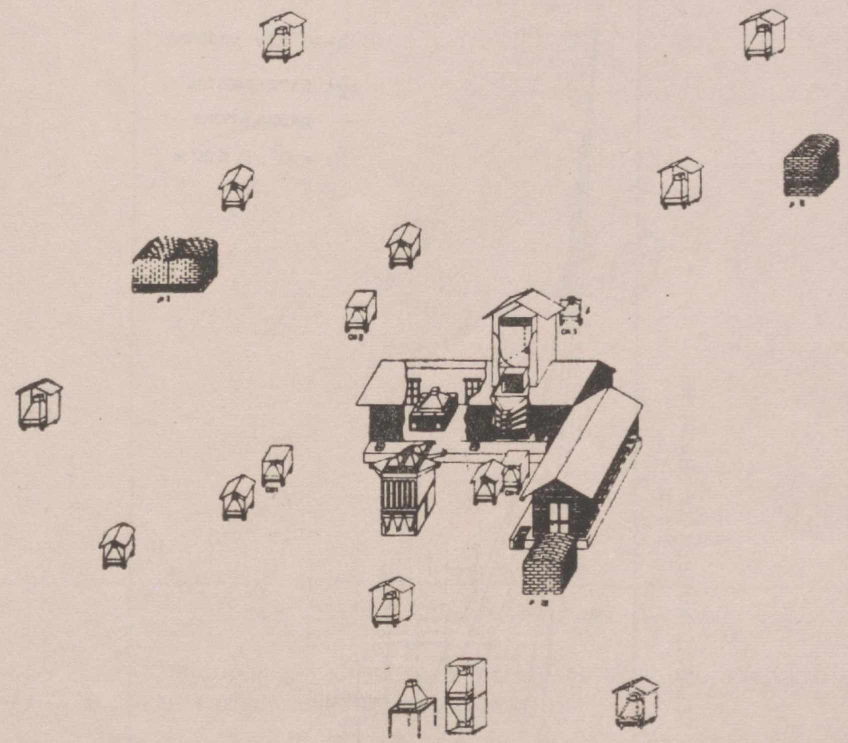

FIG. 6. One of the early versions of the Ooty extensive air shower array comprising plastic scintillator assembly, total absorption spectrometer, multiplate cloud chamber etc.

locations of the shower. The total absorption spectrometer and the multiplate cloud chamber respond to the nuclear active particles (hadrons) in the shower and the arrays of counters under thick absorbers to the penetrating component, namely, the muons. One of the most important experiments carried out at Ooty is the measurement of the time structure of hadrons in air showers using the total absorption spectrometer as the hadron detector. Fig. 7 shows the time distribution of hadrons of energy 10-20 GeV in air showers of size 10^5 particles. This result led to the important conclusion that the cross-section for the production of nucleon-antinucleon pairs increases with energy, a result later confirmed by experiments at accelerators. The time structure results at higher hadron energies indicated the possibility of the production of heavy mass particles (greater than few GeV, with life time 10^{-10} seconds) in high energy collisions and the large cloud chamber is currently under operation for establishing by means of visual detector the possible existence of such heavy mass particles in air showers. Some of the important results that have emerged from the Ooty air shower array may be summarised as follows:—

1. Increase in $N\bar{N}$ production cross-section ($E \geqslant 10^{12}$eV) from time structure of hadrons and Charge to Neutral Ratio (C/N) of hadrons in air showers.

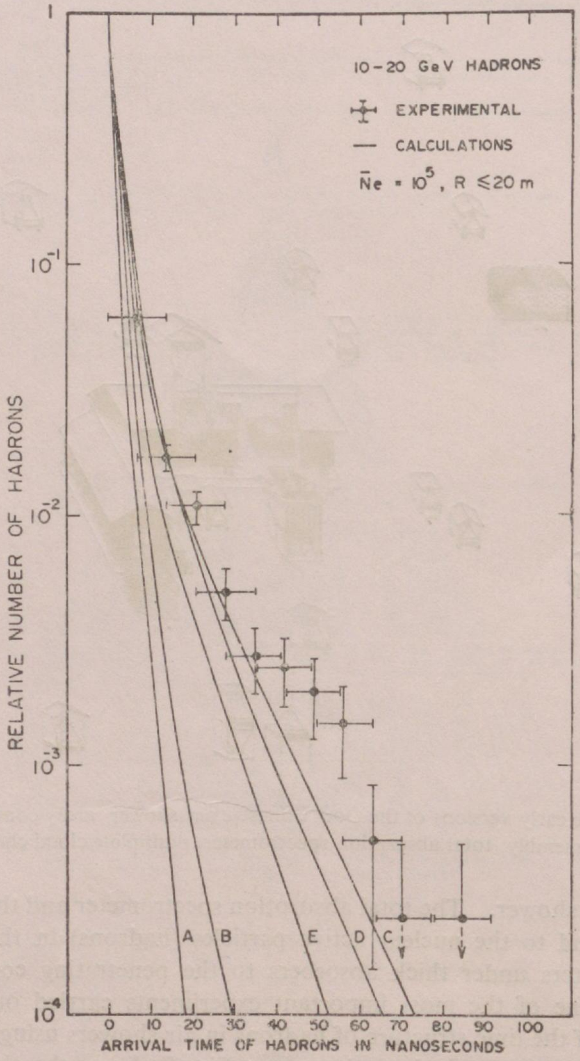

FIG. 7. The arrival time distribution of hadron 10-20 GeV in air shower of ~ 10^5 particles at distances less than 20 m from the core.

2. Further increase in $N\bar{N}$ cross-section at $E > 10^{14}$eV — from the decrease of (C/N) ratio at higher energies.
3. Increase in inelasticity or total cross-section at air shower energies from fractional hadron energy spectrum and steepening of hadron spectra.
4. Gammaisation hypothesis — preferential transfer of energy to soft component in hadron collisions from the study of the relation between observed shower size and primary energy.
5. Suppression of High Energy Isobar production — from the slow increase of High Energy muons with shower size in the K.G.F. experiment.

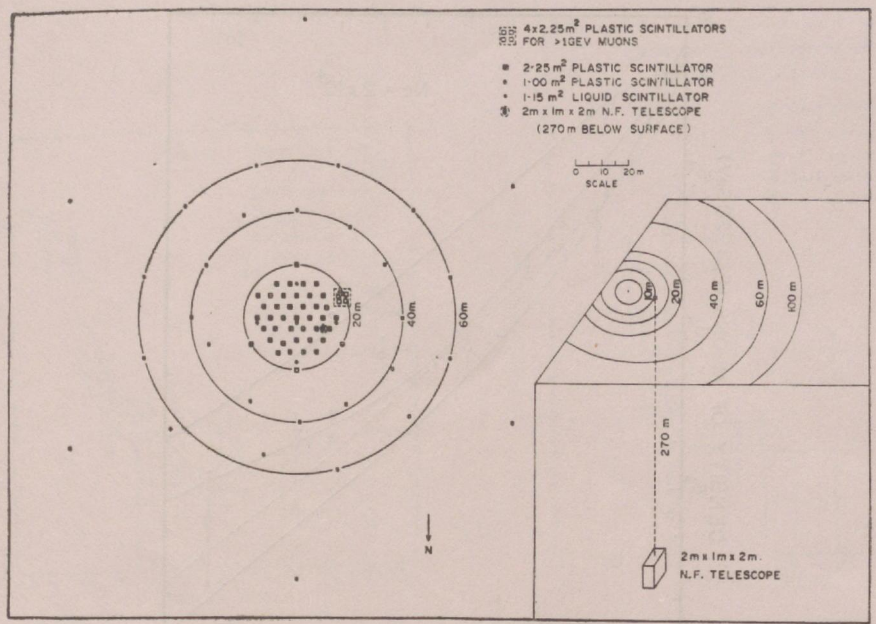

FIG. 8. The K.G.F. Air Shower Array

6. $E^{1/2}$ Law of multiplicity — from the observed absolute number of hadrons and muons at various air shower energies.

KOLAR GOLD FIELD AIR SHOWER EXPERIMENTS

A large air shower array (Fig. 8) comprising 73 scintillators has been set up at the surface of the Kolar Gold Field mines and is being operated in conjunction with arrays of particle detectors at underground depths of 270, 600 and 1972 metres. A two square metre crossed neon flash tube telescope at the depth of 270 metres, records the direction of muons of energy greater than 220 GeV to an accuracy of a quarter of a degree enabling the determination of the point of entry of the muon at the surface to an accuracy better than a square metre. The surface air shower array enables the location of the core of the air shower to a similar accuracy. This experiment has enabled the determination for the first time of the lateral distribution of high energy muons in air showers of small size ($\approx 10^{14}$ eV). Fig. 9 shows the first results from the array and these have an important bearing on the transverse momentum distribution of secondary particles in the high energy collisions and on the composition of the primary radiation in the energy range around 10^{14} eV.

SEARCH FOR HIGH ENERGY PULSED GAMMA RAYS

Ever since the discovery of pulsars a series of experiments have been carried out at Ootacamund in search of pulsed emission in the high energy gamma ray region (greater than 10^{12} eV) using the night air cherenkov technique. The high energy gamma rays give rise to electromagnetic cascades and the high energy electrons in the cascade produce cherenkov radiation in travelling through the air. A large

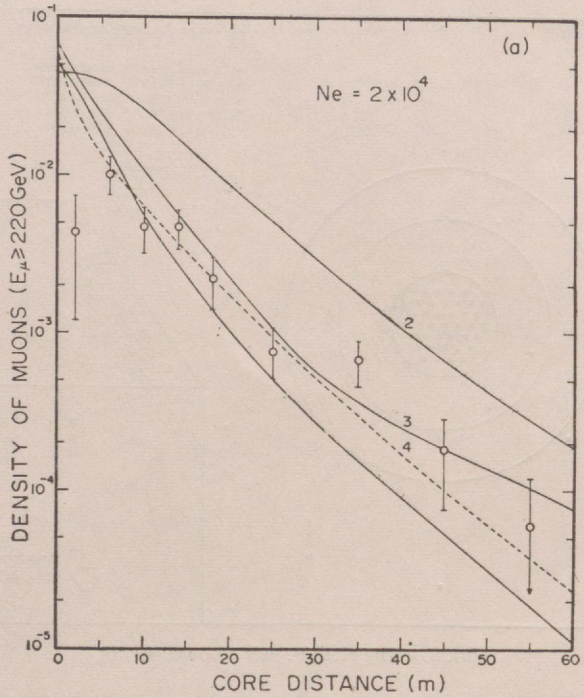

FIG. 9. The lateral distribution of muons of energy greater than 220 GeV in showers of [2 × 10^4 particles

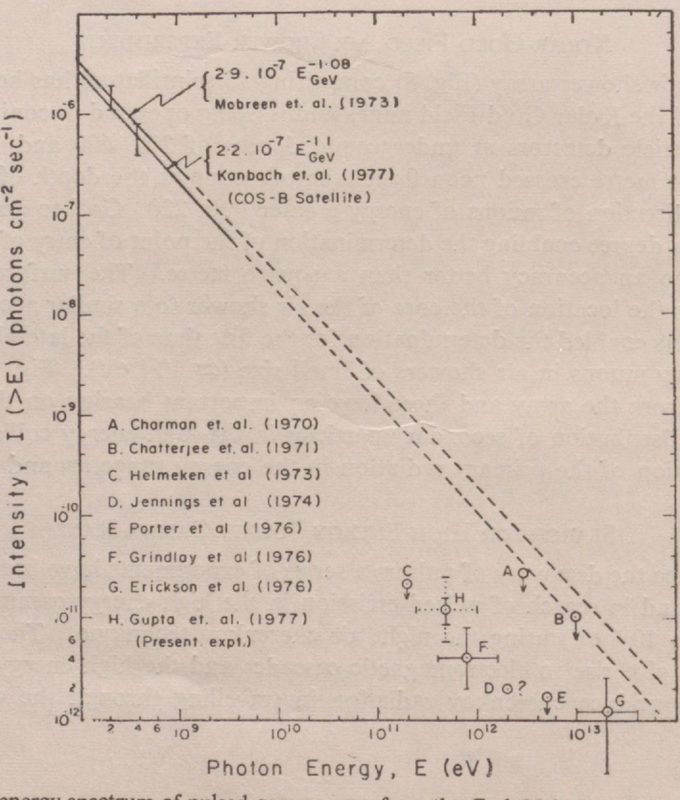

FIG. 10. The energy spectrum of pulsed gamma rays from the Crab Nebula pulsar PSR0531+21

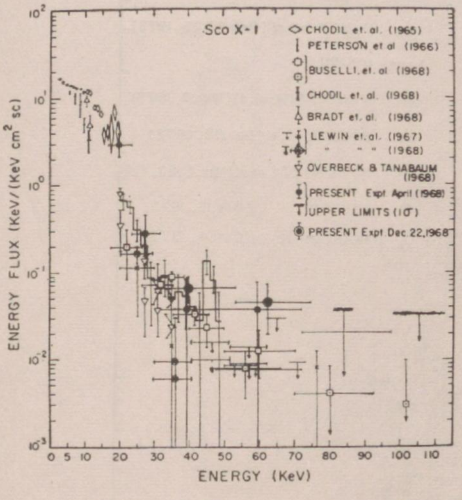

FIG. 11. X-ray intensities of Sco X-1 measured in the present experiments on 28.4.1968 and on 22.12. 1968 together with available spectral information on Sco X-1

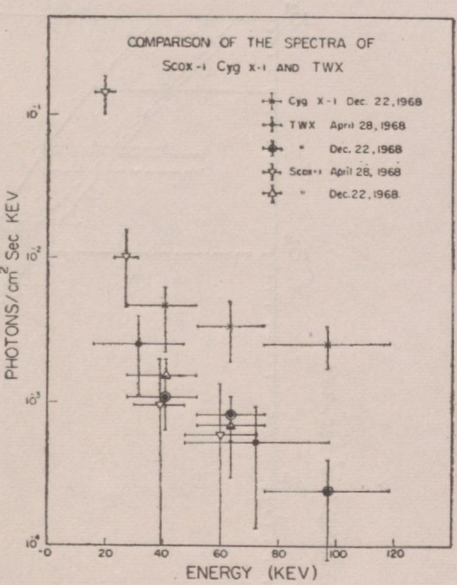

FIG. 12. Comparison of the spectra of the new source (TWX) and Sco X-1 measured on 28.4.1968 and 22.12.1968 and of Cyg X-1 on 22.12.1968.

number of search light mirrors mounted on a set of orientation platforms are used to gather the cherenkov radiation and focus the radiation on to a system photomultipliers located at the foci of the mirrors. The system responds to the simultaneous incidence of a large number of photons on the mirrors. The orientation system is manoeuvred electronically to track known pulsars for several hours on dark cloud free nights. Recent results with a 10 mirror assembly operated during the winter of 1976 and summer of 1977 have indicated the possibility of pulsed emissions from one of the nearest pulsars, namely, CP0950 and also from the crab pulsars at energies of a few hundred Ge V. Results from the crab pulsar are shown in the Fig. 10.

X-ray Gamma ray Astronomy Experiments

As already mentioned a series of experiments in the field of X-ray, Gamma ray astronomies have been carried out using stratospheric balloons launched from Hyderabad since 1968. A number of X-ray sources, particularly Sco X-1, Cygnus X-1,, Hercules X-1, Tau X-1 are available for observation at rather high zenith angles at the time of meredian transit around Hyderabad which is a special advantage. An additional advantage is the low background because of proximity to the geomagnetic equator. Some of the important results on aspects relating to the spectrum, time variations, burst activity, pulsed fraction etc., of these sources obtained from a

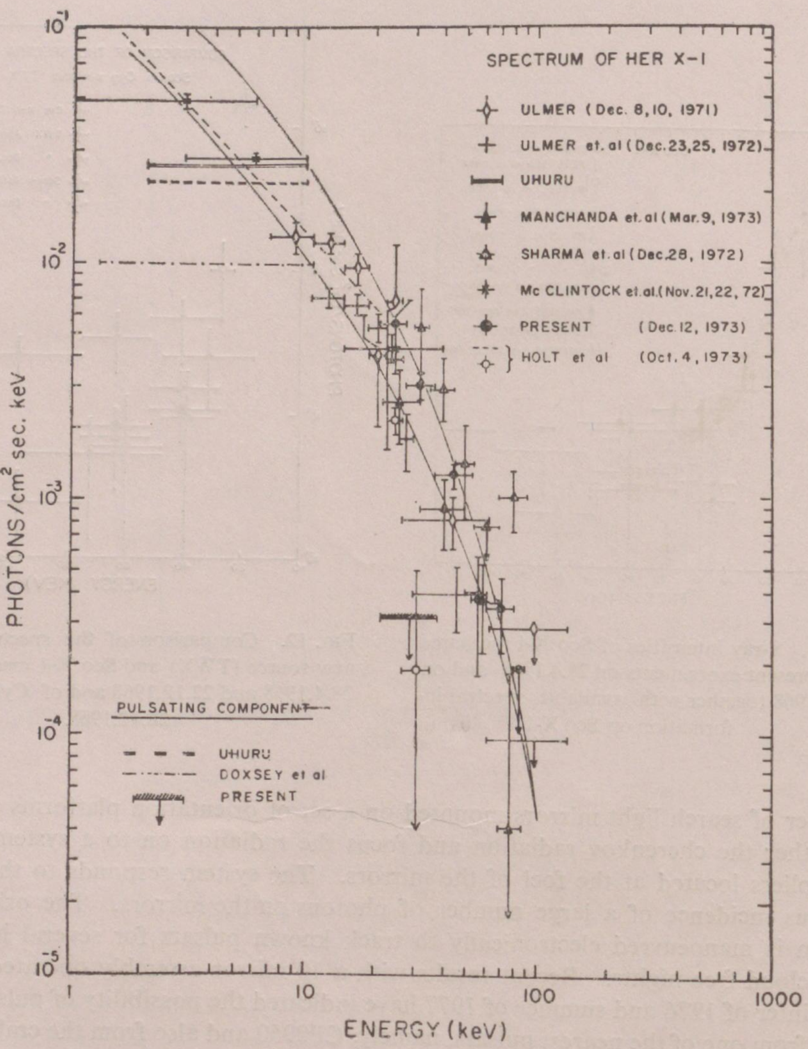

FIG. 13. The energy spectrum of the X-ray source Her X-1.

series of flights from Hyderabad are shown in the Figs 11-13. A series of collaboration experiments have also been carried out with Japanese group from University of Nagoya and the Institute for Space and Astronautical Science, Tokyo in the field of X-ray gamma ray astronomies. Fig. 14 shows the observations on the Crab Nebula made on January 24, 1975 as part of a collaboration experiment. The observations were made on this day on the Crab Nebula when it was occulted by the moon. The observations gave important information on the size of the hard X-ray source, the structure of the hard X-ray emitting region and the fraction of pulsed emission from the Crab Nebula.

In the limited time of about an hour made available to me, I have attempted to highlight some aspects of our experimental investigations in the last two decades on

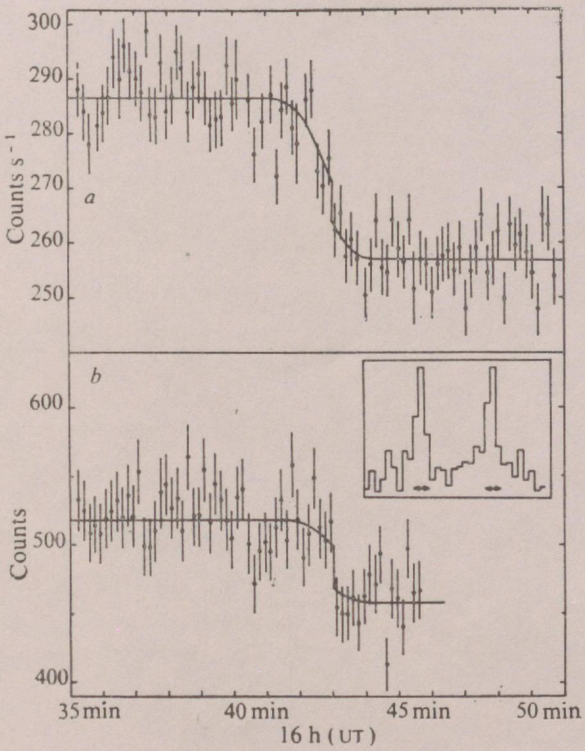

FIG. 14. The total counting rate (*a*) and the counts in 10s bins for the pulsation peaks as indicated by arrows in the insert (*b*). The solid curve in the upper figure represents the total counting rate expected for the Gaussian diffuse source of FWHM of 95s and centroid displaced by 16s from a point source. The contribution of the point source (pulsar) relative to the total Crab X rays is 26.5%, judged from the pulse profile assuming no steady emission from the pulsar, and the contribution of the pulstation peaks as indicated in the insert is 51% of the total emission. The solid curve in the lower figure represents the counts in 10s bins with phase corresponding to the peaks.

the primary and secondary cosmic radiation and in the field of X-ray and Gamma ray astronomies. These are all continuously expanding and developing fields and as in many other fields of science in the attempts to solve old problems many new ones arise and keep the field perennially going. At the same time technological advances enable the tackling of more difficult and challenging problems. As J. J. Thomson said at the beginning of the Century, scientific knowledge is not a convergent series but a divergent one.

Thank you.