

**Sixty Years of
the Tata Institute of Fundamental Research 1945-2005***

(The Role of Young Men in the Creation and Development of this Institute)

B V Sreekantan

National Institute of Advanced Studies
Indian Institute of Science Campus
Bangalore 560 012

*Talk delivered on 18th August 2005 at the Tata Institute of Fundamentals Research as one of JRD Tata Birth Centenary Events organized by TIFR Alumni Association

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It is indeed a great honour, pleasure and privilege for me to have been invited to give a public lecture in the JRD Tata Birth Centenary Celebrations Series. I would like to express my sincere thanks to the president Dr. Kesav Nori, patron and Director of TIFR Prof. Shobu Bhattacharya, and the Honorary Secretaries and office bearers of the TIFR Alumni Association. Though physically I am away from these surroundings for the past 13 years, my mind is still very much here.

In this Birth Centenary year of Bharata Ratna Sri. J.R.D. Tata, several eminent men from different walks of life have highlighted in different places, the outstanding and very rich contributions of Sri. J.R.D. Tata to the fields of industry, science, technology, education and human welfare. Many institutions came into existence in the country because of his appreciative and magnanimous support and personal involvement. TIFR is one such institution, which has just completed 60 years of its existence. Sri JRD Tata not only helped the creation of this institute, but also guided the course of development of this institute as the Chairman of the Governing Council for over three decades. Let me narrate the circumstances that created TIFR in the words of the Founder Director Homi Bhabha himself.

From Dr Bhabha's Address on the occasion of the Inauguration of the new buildings of TIFR at Colaba on January 15, 1962

"The Tata Institute of Fundamental Research started its work in June 1945. It is therefore the oldest of our post-war national laboratories. And yet it is only today, 16½ years later, that its own buildings are being inaugurated by the Prime Minister. This fact alone shows that the manner in which this Institute has been built up is different from that of the other national laboratories, where attention was first directed towards providing them with a building. There are, however, a number of other differences in approach also. I would therefore like to take a few minutes to recapitulate the history of this Institute and the manner in which it has grown.

While I was still working as a professor at the Indian Institute of Science in Bangalore during the Second World War, I noted that there was no scientific institution in India devoted solely to fundamental research, especially in the newest branches of physics, namely, nuclear physics and high energy physics.

By fundamental research I mean basic investigations into the behaviour and structure of the physical world without any consideration of their utility or whether the knowledge so acquired would ever be of any practical value. Nevertheless, the support of such research, and of an institution where such research can be carried out effectively, is of great importance to society for two reasons. First of all, and paradoxically, it has an immediate use in that it helps to train and develop, in a manner in which no other mental discipline can, young men of the highest intellectual calibre in a society into people who can think about and analyse problems with a freshness of outlook and originality which is not generally found. Such men are of the greatest value to society, as experience in the last war showed, for many of the

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applications of science, which were crucial to the outcome of the war, were developed by men who, before the war, were devoting their time to the pursuit of scientific knowledge for its own sake. Radar and atomic energy are two examples of fields in which a vast body of established basic knowledge was developed into technology of immense practical importance, largely through the application in war time of the efforts of those who might be called 'pure' scientists.

Secondly, the history of science has shown that "there is no genuine knowledge of the universe that is not potentially useful for man, not merely in the sense that action may one day be taken on it, but also in the fact that every new knowledge necessarily affects the way in which we hold all the rest of our stock". Accordingly, in a letter dated the 19th August 1943 to Shri J. R. D. Tata, I pointed out that "the lack of proper conditions and intelligent financial support hampers the development of science in India at the pace which the talent in the country would warrant", and suggested that the Tata Trusts might consider taking the initiative in setting up an institute for fundamental research. In his reply of the 2nd September 1943 to me, Shri J.R.D. Tata wrote: "from what you say in your letter, it is evident that there is scope for rendering valuable service to the country and to the cause of scientific research in India . . . After all, the advance of science is one of the fundamental objects for which most of the Tata Trusts were founded, If they are shown that they can give still more valuable help in a new way, I am quite sure that they will give it their most serious consideration".

The Trustees of the Sir Dorabji Tata Trust decided to accept financial responsibility for supporting the Institute at a meeting held on the 14th April 1944. I think it should be recalled on this occasion that this decision was taken more than a year before the explosion of the first atomic bomb over Hiroshima and before nuclear physics had become what might be called "the band-wagon" of science.

The location of the Institute in Bombay was decided largely because of the interest of the then Government of Bombay, which was anxious to build up a strong department of physics at the Institute of Science, and which had invited me to undertake this task. As I was already committed to starting an institute of fundamental research I suggested that the Bombay Government might co-operate with the Tata Trust in the founding of this institute. Thus it came about that the Institute was founded as a joint endeavour of the Sir Dorabji Tata Trust and the then Government of Bombay in 1945."

The Cosmic Ray Research Unit at IISc (1939-1945)

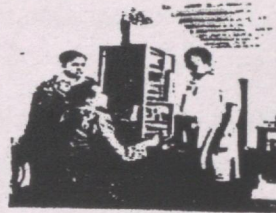
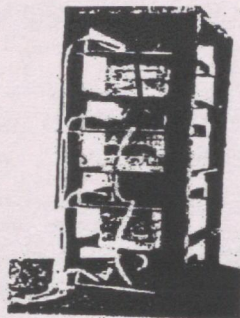
- ❖ Benefits of World War II – Dr Bhabha's return to India
- ❖ In the Department of Physics headed by Prof. C V Raman
- ❖ Professor H.J. Bhabha

- ❖ **Activities** (Theoretical)
 - * Cascade Theory (Bhabha and Chakrabarti)
 - * Collaboration with the mathematicians of the Department of Mathematics, Central College, Mysore University (Prof. K.S.K. Iyengar, Prof. B.S. Madhava Rao)
 - * Relativistic Wave Equations of elementary particles of *any spin* (Equations for spin higher than in the scheme given by Dirac)
- ❖ Students: Harish-Chandra, D. Basu
- ❖ Experimental
 - Variation of intensity of the hard component of cosmic rays at different *aeroplane altitudes* up to 35,00 ft (Bhabha, S.V.C. Aiyar, H.E. Hoteko and R.C. Saxena)

- ❖ Wilson Cloud Chamber Experiment on the scattering of mesons (Bhabha and M.S. Sinha)

The chamber was triggered by a GM telescope.

- ❖ The TIFR commenced its activities in the Unit on 1st June 1945, which is therefore the Foundation Day of the Institute.



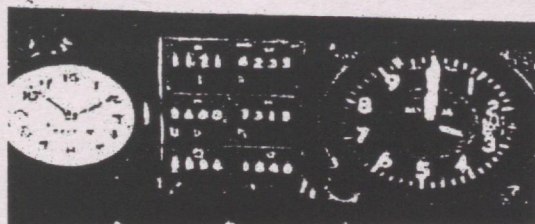
Top: Views of one of the units sent up to 32,000 feet with its sides removed. The top of the unit contains two cosmic ray telescopes. The electrical amplifiers are on the lower shelf. The dry batteries are at the bottom.



Left: A cosmic ray telescope with four counters. The three thick lead blocks traversed by the cosmic rays are seen between the counters.

Bottom right: The new anti-coincidence method for excluding the soft component.

Bottom left: A photographic record taken during the high altitude experiment. The six cosmic ray readings are shown in the middle. The altitude indicated by the altimeter on the right is 30,000 feet.



Dr. Bhabha with his cosmic ray telescopes flown on B-29 aeroplanes from Bangalore in early 40's. Seen in the photograph in discussion with Bhabha are Prof. S.V.G. Ayy and Dr. R.C. Saxena his early collaborators at the Cosmic ray research unit of the Indian Institute of Science.

TIFR at Kenilworth, 53, Pedder Road, Cambala Hills, Bombay

December 19, 1945 to September 1949

- ❖ Budget for 1945-46 was Rs. 80,000 shared as follows:

Sir Dorabji Tata Trust	Rs. 45, 000
Govt. of Bombay	Rs. 25, 000
CSIR	Rs. 10,000

- ❖ The equipment of the cosmic ray research unit of the Indian Institute of Science was bought over with a special grant of Rs. 50,000 given for the purpose by the Dorabji Tata Trust.
- ❖ The Area of the Kenilworth building made available for TIFR was 6000 sq. ft. (see the sketches)

Research Activities at Kenilworth (December 1945-September 1949)

1. Mathematics (D.D. Kosambi, Levy, Masani)
2. Theoretical Physics
Elementary Partical Physics (Students: Abraham, Alladi, K.K. Gupta, Surya Prakash)
3. Cosmic Rays
 - a. High Altitude Balloon Studies (A.S Rao, R.P. Thatte, G.S. Gokhale)
 - b. Nuclear Emulsion (R.R Daniel, G. Sreekantaiah, M.S. Swamy)
 - c. Cloud Chamber (A.B. Sahiar, G.H. Vaze, B V Sreekantan)
 - d. Counter Production (R.V.S Sitharam, K. Chandrasekharan and H.L.N. Murthy (Glass Technician))
 - e. Electronics (D.Y. Phadke, B.V. Sreekantan, R.V.S. Sitharam)

Rubber Balloon flights carried out from different stations in India – Bombay, Pune, Delhi etc.

4. Radiation Meters made for Atomic Mineral Survey (R.V.S. Sitharam)
5. Wednesday Colloquia
6. Some of the Distinguished Visitors:
 - Prof. P.M.S. Blackett
 - Sir. S. Radhakrishnan (UGC Chairman)
 - Prof. K. Chandrasekharan (Princeton)



Homi Bhabha flying a cluster of balloons from the Central College, Bangalore (1940s)

Research and Developmental Activities at Yacht Club Building: September 49 to January 1, 1962

Sudden Large Scale Expansion of activities. Compared to 6000 sq. ft. at Pedder Road, the area made available for TIFR (Half of the Yacht Club Building – the other half for DAE activities) was 35,000 sq. ft.

Research	Development	Others
❖ Mathematics	❖ Electronic Instrumentation	❖ Elementary Particle Physics Conference, December 1950
❖ Theoretical Physics	❖ Plastic Balloons	❖ Courses of Lectures in Mathematics, Statistics (Kosambi)
❖ Cosmic Rays	❖ TIFRAC Computer	❖ Electronics (Kandiah from Harwell)
❖ Nuclear Physics	❖ Vacuum Technology	❖ High Energy Physics (Peters)
	❖ Cyclotron	❖ Meson Theory (Marshak, Wentzel, Rosenfeld, Takagi)
	❖ Plasma	❖ Astronomy (Vainu Bappu)
	❖ Liquid Scintillation Counters	❖ Summer Schools in Theoretical Physics at Bangalore
	❖ Spark Counters	Dalitz, Gell-Mann, Chew, Mottleson, ...
	❖ Neon Hodoscopes	
	❖ Total Absorption Spectrometer	
	❖ Multiplate Cloud Chambers	
	❖ Cockroft Walton Cascade Generator	
	❖ Microwave Technology	
	❖ BF3 Neutron Counters	
	❖ Beta-ray Spectrometers	

Research Activities: Mathematics

Prof. K. Chandrasekharan and Prof. K.G. Ramanathan, both from Princeton University joined TIFR and K.C. was soon appointed as Deputy Director (Mathematics). Both of them were 30 years old when they joined TIFR. The new students who joined were C.S. Sheshadri, M.S. Narasimhan, S. Raghavan, R. Sreedharan, S. Ramanan, Singhbahl, K. Balagangadharan, K. Ramachandra, R. Simha, M.S. Raghunathan, Raghavan Narasimhan, S S Rangachari

In his talk at the inauguration of the TIFR building at Holiday Camp (Navy Nagar), Dr. Bhabha summarized the work of the school of mathematics till then (1962) in the following words:

"..... My task would, however, be incomplete if I do not refer to the work of the school of mathematics and mention that it has established an international reputation for itself through the outstanding contributions which its members have made to various branches of modern mathematics. Credit for this must go to Professor K. Chandrasekharan who has carefully and painstakingly built up an exceptionally fine group of young mathematicians over the years. The Government of India has reason to be proud of the achievements of its National Centre for Mathematics".



This glowing tribute to the school of mathematics was paid by Dr Bhabha in 1962, just 12 years after K.C. and KGR joined TIFR. This high tradition has been maintained by the school in the intervening 43 years. There was a time in the 80's when all the Faculty Members of the school were Bhatnagar Award Winners. In the last decade or so three of them have become Fellows of the Royal Society. An activity in Applications of Mathematics was started by the TIFR Math Faculty in collaboration with the Department of Mathematics of the Indian Institute of Science in Bangalore in the early 70's. A large number of distinguished mathematicians especially from France, UK and USA have lectured at this joint programme. The four yearly International Mathematics Colloquium organized by the math faculty started in the 60's has become a regular feature, which attracts mathematicians from all over the world. The faculty has also provided manpower at senior levels to other mathematical institutions in the country.

Nuclear Physics at TIFR

The Nuclear Physics programme started in 1949 with the recruitment of Dr Raja Ramanna, Dr B.V. Thosar, Dr. S.S. Dharmetti, Dr. S.K. Bhattacharjee, Dr. S. Jha, Dr. Ambuj Mukherjee, Dr. E. Kondaiah and Dr. Balu Venkataraman, all *post docs* who had obtained their Ph.D's from abroad – USA and UK. The first three initiatives were

1. Neutron physics and nuclear reactions: Dr. Raja Ramanna, Dr. Bhattacharjee and Dr. Kondaiah
2. Beta-ray spectroscopy: Dr. B.V. Thosar, Dr. Ambuj Mukherjee, Dr. S. Jha
3. Nuclear Magnetic Resonance (NMR): Dr Dharmetti, Dr. Balu Venkataraman

The early students who distinguished themselves later in various capacities: Dr. P. K. Iyengar – Chairman, AEC; Prof. M. C. Joshi – Head of the Dept. of Physics, Mumbai University; Prof. R. Vijayaraghavan – Sr. Professor, Dean, Physics Faculty TIFR; Dr M.R. Das – Director of Cancer Research Institute, Trivandrum; Sri V.G. Kulkarni – Director, Homi Bhabha Centre for Science Education

Theoretical Physics at TIFR

After moving to Yacht Club, Abraham, K.K. Gupta and Surya Prakash completed their Ph.D. in theoretical particle physics under the guidance of Dr. Bhabha and later moved to universities as professors of theoretical physics. Udgaonkar joined as a student under Dr Bhabha and worked in the area of particle physics. He was also associated with Reactor Physics problems at Trombay. Prof. K.S. Singhvi who joined BARC was also associated with TIFR. His interests were in solid-state physics, reactor physics and multi-particle production in nuclear-collisions. He did not stay on in India for long and left for USA. D. Shankaranarayana joined Bhabha as a student and worked on problems relating to meson production and weak interactions. Virendra Singh joined as a student and was deputed to the university of Berkeley, USA to obtain his Ph.D. Professor Udgaonkar became Senior Professor at TIFR and also member of the UGC. Prof. Virendra Singh became Director of TIFR and Professor Emeritus. Prof. S.S. Jha joined TIFR after his training in the BARC Training School, was deputed abroad and obtained his Ph.D. from Stanford and later became Dean, Distinguished Professor and Director of TIFR.

An important new activity started during this period was the organization of summer schools in theoretical physics every summer. Eminent theoretical physicists like Gell-Mann, Dalitz, Chew, Mottleson ...lectured at these summer schools. Another development was the setting up of the BARC Training School in which in the initial years TIFR played a major role. The TIFR benefited a lot in return by getting some of the best students as research scholars in the various theoretical and experimental programmes of the institute. Most of them became professors and faculty members of the institute and contributed to its development in a major way. For some reason this was discontinued towards the end of 60's and resulted in a serious deficiency of man power for the experimental programmes in particular. TIFR lost a very good channel of recruitment of young scholars.

The Elementary Particle Physics Conference in December 1950

One of the important, I would say landmark events in the early history of TIFR was the organization by Dr Bhabha of the first "Elementary Particle Physics" conference in the world at the Yacht Club premises which was attended by some of the most renowned scientists in the area of elementary particle physics and cosmic rays – Blackett, Leprince Ringuet, Amaldi, Rosenfeld, Auger, Peters, Fowler (representing Powell) Wentzel, Peirls and from India Saha, Sarabhai, Kothari, C.V. Raman and B.S. Madhava Rao. For us youngsters this was a unique opportunity to interact with the galaxy of outstanding scientists whose works we were familiar with. The proceedings of the conference was very elegantly brought out by Prof. K. Chandrasekharan, with the help of some of us.

Expansion of Cosmic Ray Research

By the time we started working at the Yacht Club premises, cosmic ray research had entered into its new phase of elementary particle physics through the discovery of the Pi-meson as the parent of the mu-meson, the mysterious penetrating component of cosmic radiation that had baffled the scientists in this field. The isolated cases of what were called V-particles observed in a cloud Chamber experiment by the Manchester University scientists Rochester and Butler had focused attention on the need for careful study of the particles produced in high energy nuclear interactions, both with nuclear emulsions with which pi-mesons had been discovered by Powell and cloud chambers in which the V-particles had made their appearance. Dr Bhabha, with great foresight had initiated activities using both these techniques – the nuclear emulsion and the cloud chamber for cosmic ray research. Daniel had set up a first rate nuclear emulsion processing laboratory at Pedder Road itself which was moved to the large basement laboratory at Yacht Club. Sahiar who had brought the cloud chamber operating at Bangalore and set it up at Pedder completed his observations on muon scattering and the chamber was moved to Yacht Club. Several other cloud chambers were built over the next ten years.



The study of new particles created by cosmic rays in their collisions became the chief study of most of the cosmic ray groups in the world. In December 1954 two multiplate cloud chambers (named Rani and Maharani) one above the other were set up in the laboratory at Ooty in the premises of Raj Bhavan and adjacent to the Botanical gardens by A.B. Sahar, Naranan, Subramanian and Ramana Murthy. One was 18" in diameter and the other 24" x 24" square chamber. The design of the set-up was to hunt for the production of new types of particles – the V-particles and the stopping particles produced by cosmic ray interactions in the brass plates of the chambers. The cosmic ray laboratory at Ooty has completed 50 years of existence. A variety of experiments on high-energy interactions and extensive air showers have been carried out in this laboratory. The world's largest multiplate cloud chamber (2 m x 1.5 m x 1 m) with 21 iron plates

each of 2.5 cms thickness was operated there as part of the air shower array and very significant results on the high energy nuclear interactions and cores of extension air showers were obtained. This constituted the Ph.D. thesis work of Vatcha.

A triple setup comprising of an Air Cerenkov Counter, a multiplate cloud chamber and a total absorption spectrometer designed by Sreekantan Subramanian and Ramana Murthy, was operated to study the differences in the characteristics of interactions with nuclei of protons and pions in the energy range 10-40 GeV, before the advent of the first CERN accelerator of energy 30 GeV in early 70's. The operation of the Total Absorption Spectrometer in association with the Ooty EAS array enabled the time structure study of the nuclear active component of air showers and led to the discovery that the Nucleon-Antinucleon production cross section considerably increases with energy (thesis work of Tonwar).

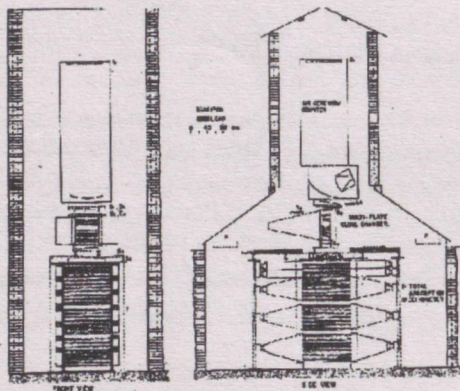
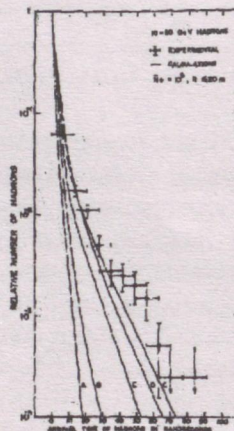
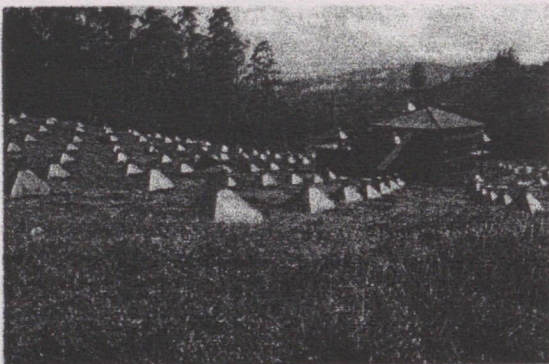


FIG. 4 Triple setup of Air Cerenkov Counter, multiplate Cloud Chamber and Total Absorption Spectrometer at Ooty, for the study of interactions of pions and protons in 10-40 GeV range.



The GRAPES array at Ooty



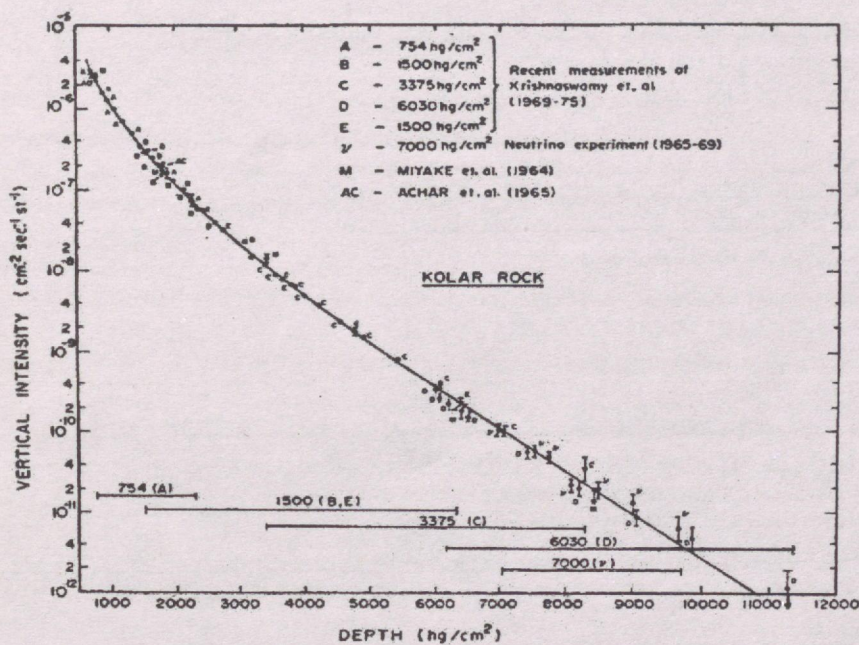
A new air shower array known as GRAPES built by Tonwar, Gupta and a group of Japanese scientists is now operating behind the Ooty Radio Telescope, with the world's largest area muon detector assembly and is expected to lead to important results on the composition of primary cosmic rays.

Prof. B. Peters, Prof. M.G.K. Menon, Prof. S. Biswas, Dr. (Miss) Bibha Chowdhuri, Dr Appa Rao, Prof. Gaurang Yodh joined TIFR during the period 1952-56 and gave a big boost to its cosmic ray activity. Nuclear Emulsion

stacks interspersed with brass plates, were flown from Hyderabad and the analysis resulted in the discovery of the several types of K-mesons. D. Lal and Yashpal had joined the institute as research

scholars, and were part of this most exciting work on K-mesons. This work was extended to the study of Hyper Fragments by Swamy and Ganguli. Some very interesting work on meson production was carried out by Malhotra in collaboration with the Bristol group.

In September 1950, one night when Dr Bhabha was working on the programme details of the conference on elementary particles, he called me and said "Sreekantan, you should plan to take a Geiger Counter Telescope down the Kolar Gold Mines and determine the flux of the penetrating particles as a function of depth and then take your Mu-meson decay detector and see whether they are all muons or whether there are other types of particles there". In September-December 1951, Naranan and I measured the penetrating particle intensity upto a depth of 1000 ft and soon followed this up with another Hodoscope-telescope to measure the angular intensity at various depths. Ramana Murthy had joined us by then and was part of this experiment. Following this the three of us took a multiplate cloud chamber down the mines to a depth of 100 ft to study the interaction characteristics of muons. Some anomalies had been reported by the Manchester group which we wanted to explore further. However, soon we were asked by the mining authorities to vacate and leave since they were closing down all operations in the mines.



We shifted the cloud chamber experiment to an old abandoned railway tunnel in Khandala and completed the observations on muon interactions and no anomaly was found. Since the Kolar Mines did not close down, we went back for a long series of experiments at larger and larger depths. In this endeavor we were joined by two foreign groups, from the University of Durham, UK (Wolfendale and others) and the Osaka City University, Japan (Miyake and others). These experiments started in 1958 lasted for 34 years (till

1992) and the mines were used upto a depth of 8000 ft below ground for a variety of experiments:

1. Intensity and Angular Distribution of Mu-mesons up to a depth of 8000 ft.
2. Neutrino Experiments
3. Proton Decay Experiments

High Energy Muons (>200 GeV) in association with air showers detected at the surface with a large array of scintillators (The KGF Air Shower Array).

How the scope and Range of activities changed with time

Activities of TIFR at Kenilworth, Pedder Road (1945-1949)

1. Mathematics
2. Theoretical Physics
3. Cosmic Rays

Activities of TIFR at Yacht Club, Apollo Pier Road 1949-1962

1. Mathematics
2. Theoretical Physics
3. Cosmic Rays
4. Nuclear Physics
5. Instrumentation

Current Activities of TIFR (2005)

1. School of Mathematics –
(i) at Bombay
(ii) IISc-TIFR Mathematics Programme in Bangalore
2. School of Natural Sciences
Department of Theoretical Physics
Department of Astronomy and Astrophysics
Department of High Energy Physics
Department of Nuclear and Atomic Physics
Department of Condensed Matter Physics and Material Science
Department of Chemical Sciences
Department of Biological Sciences
3. National Centres
Homi Bhabha Centre for Science Education, Mumbai
National Centre for Biological Sciences, Bangalore
National Centre for Radio Astrophysics, Pune
4. School of Technology and Computer Science

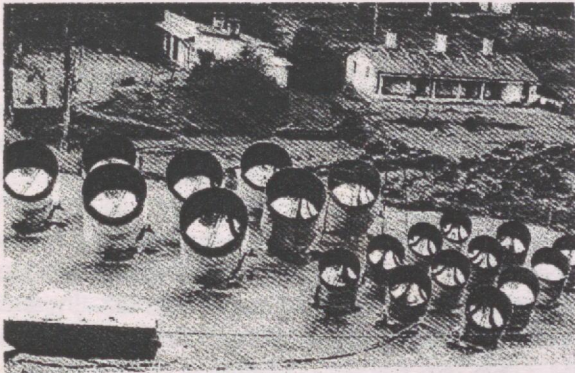
Research and Developmental Activities of TIFR after moving to the permanent buildings at Navy Nagar in 1962

1. Mathematics :
(a) at Bombay
(b) IISc-TIFR joint programme in Applications of Mathematics (>1973) – continuing
2. Theoretical Physics:
Particle Physics, Nuclear physics, Solid State Theory (Udgaonkar, V Singh, S.S. Jha, Probir Roy, S.M. Roy, D.P. Roy, Warke, M. Banerji, Nazakatulla, K.V.L. Sharma)
3. Theoretical Astrophysics - started around 1969:
Cosmology, neutron star physics, solar oscillations, cool stars, pulsars (Narlikar, Vardya, Chitre, Tarafdar, Padmanabhan, A. Ray, P. Ghosh)
4. Nuclear Physics and Atomic Physics:
Cascade Generator, Van-de-Graff at BARC, Pelletron, (S.K. Mitra, R.P. Sharma, K.G. Prasad, Kurup, Pillai, Nagarajan)

5. Cosmic Rays

- ❖ Balloon Facility at Hyderabad – X-ray, gamma-ray astronomies
(Sreekantan, Gokhale, Agrawal, Manchanda, K.P. Singh, A.R. Rao, S. Damle and R.T. Redkar)

- ❖ Rocket Experiments from Thumba (Naranan, K.P. Singh, Sreekantan, Agrawal and R.K. Manchanda)
- ❖ Nuclear Emulsion Studies – High Energy Interactions, primary electrons
(Daniel, Stephens, Anand, Lavakere, George Joseph)
- ❖ Infrared Astronomy (Daniel, K.V.K. Iyengar, Tandon, Rangarajan, Verma)
- ❖ K-mesons, Hyperons etc. (Swamy, Ganguli)
- ❖ Anuradha Satellite Experiment for study of anomalous cosmic rays (Biswas, Durgaprasad, Cowsik)
- ❖ Kolar gold field experiments on muons, neutrons, proton decay
(Narasimhan, Menon, Mondal, Sreekantan, Krishna Swamy)
- ❖ KGF Air Shower Arrays with underground muon detectors
(Sreekantan, Narayan, M.V.S. Rao, Viswanath, Sivaprasad, Acharya, Bhat)
- ❖ Ooty Air Shower Array with TAS and multiplate cloud chamber
(Sreekantan, Tonwar, Vatcha)
- ❖ Ooty GRAPE 1, GRAPE 2 and GRAPE 3 arrays (Tonwar, Gupta + Japanese Groups)
- ❖ TeV Gamma-Ray Studies – Ooty, Pachmari
(Ramana Murthy, G.T. Murthy, Chatterjee, Tonwar, Sreekantan, Bhat, Acharya)
- ❖ Cosmic Ray Induced Radioactivity (Peters, Lal, Rama)
- ❖ Jaipur (1963), Bangalore (1983), Pune (2005), ICRC



The TeV gamma ray experiment at Ooty



7th International Cosmic Ray Conference Jaipur 1963

6. Solid State Physics:

Magnetic Materials, High Temperature Superconductivity, Chemical Physics – NMR Spectroscopy
(Balu Venkataraman, Vijayaraghavan, Gupta, Govil, Nagarajan, Mitra, Multani)

7. Solid State Electronics:

Semi Conductor Materials
(K.V. Ramanathan, Arora, Narasimhan, Pinto)

8. Geophysics – Cosmic Ray Induced radioactivity, Rock Magnetism, Hydrology, C-14 Laboratory (moved to PRL, Ahmadabad in 1973) (Lal, Rama, Venkatavaradhan, Bhandhari, Goswami, Krishnaswamy, D.P. Agarwal, Radhakrishna Murthy, Sahasrabudhe)

9. Computer Science:

TIFRAC; CDC-3600; CYBER (R. Narasimhan, P.V.S. Rao, Pitke, Ramani, Mudur, Sadanandan, Mythili)

Speech Synthesis

ADGES, AREN (Defence Projects); *NCST – New Institute under DOE in 1978

10. Gravitational Experiments:
Torsion Balance, Equivalence Principle, fifth Force, Gowribidanar Underground TB (R. Cowsik, Unnikrishnan, Krishnan)
11. Radio Astronomy*:
Ooty Radio Telescope, GMRT, Pune, NCRA
12. Molecular Biology*:
(1) At Bombay, (2) At NCBS, Bangalore
13. Particle Physics:
(1) At CERN; (2) At Fermi Lab
14. Microwave Engineering*:
TR-Switches, Linac; SAMEER new Institute under DOE in (1978)
- 15 Homi Bhabha Centre for Science Education* (since 1970 : TIFR, Grant Road, Trombay)

Introduction of Molecular Biology in TIFR

In a note that Dr Bhabha had prepared for the Prime Minister Jawaharlal Nehru on the occasion of the laying of the foundation stone of TIFR building, on January 1, 1954, he writes: "In June 1944, when I wrote a letter to Prof. A V Hill, FRS, Nobel Laureate, then Secretary of the Royal Society informing him that the Tata Trust had decided to sponsor the project I put forward for setting up an institute for fundamental research in Bombay and the support of the Bombay Government and co-operations with the Bombay University was expected. In the course of reply dated 22, June 1944, Professor A.V. Hill wrote: "I am very glad, indeed to hear also that the Tata Trust have decided to sponsor your scheme for an institute for advanced research in theoretical and experimental Physics in Bombay. I think you had better take **biophysics** under its wing, too. Apart from Bose Institute in Calcutta, that subject practically does not exist in India. I am sure in many of the most important future applications of physics will be in biology. It sounds a grand scheme you have on hand"

Later in his address to the International Council of Scientific Union at the Birla Hall, Bombay on January 7, 1966 Dr Bhabha said "As early as June 1944, Sir A.V. Hill had written to me suggesting that biophysics was a neglected subject in India and that it should be taken under the wing of the institute. While I agreed with this suggestion, I do not think it would be wise to embark on this line till some one was found mature enough to be able to work on his own and build up a group. When however in 1962 my attention was drawn by Dr. Leo Szilard to a very promising Indian Molecular Biologist, it was decided to start work in molecular biology, which has since then been growing very satisfactorily."

Well, the promising molecular biologist referred to above is Prof. Obaid Siddiqi. When he joined TIFR and undertook the responsibility of setting up the molecular biology unit, he was 30 years old. Prof. P K Maitra who joined soon was also 30 years old.

Almost twenty years later, when we were reviewing the projections to be made of the activities of TIFR for the 7th plan period, Prof. Siddiqi came up with the proposal to set up another centre outside Bombay for pursuing what he called pure (not applied) molecular biology. Initially there was some resistance for this proposal both within the institute and in the Department of Atomic Energy. Some were not convinced about the necessity of setting up another centre. However Prof. Siddiqi made it clear that this new centre will not disturb in any way the present structure, and will be built around new set of post docs in the US who are keen on returning to India and work in this area. As you know this centre has now become the

NCBS-the National Centre for Biological Sciences and has already made a name for itself both nationally and internationally.

In the same ICSU talk Dr. Bhabha also mentioned about the starting of radio astronomy activity as part of TIFR.

"Four Indian radio astronomers had jointly written identical letters to the chairman UGC, Director General of CSIR and to me as the Chairman of the Atomic Energy commission offering to return to India as a group and establish radio astronomy here, if facilities and support could be given to them. Having ascertained that the members of the group had considerable original work to their credit and were of sufficient maturity to be able to work on their own in India, it was decided to take up radioastronomy at the institute. Thirty parabolic dishes presented by CSIRO Australia which had been lying unpacked for several years at the National Physical Laboratory were handed over to the institute by the willing co-operation of Dr. Husain Zaheer and have been installed not far from Bombay for solar radio astronomy work. In the meantime a project has been developed for a large cylindrical radiotelescope for studying quasars and other radio sources and locating them accurately by lunar occultation. The telescope which will have four to five times the collecting area of Jordell Bank will be designed and built entirely by Indian scientists and engineers and is expected to be in operation in two years.

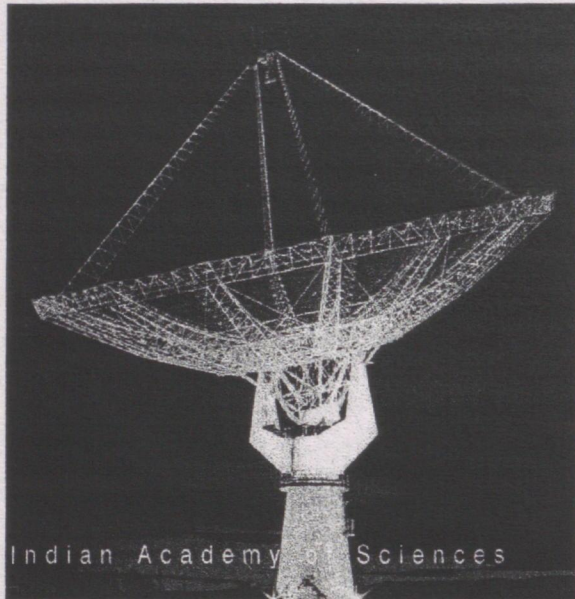
A site for it has been selected after a very extended study, as the axis of the telescope which is 1700 ft. long has to be parallel to the axis of the earth. Work on the site at Ooty has already started. It is proposed to make this radio telescope one of the centre for interuniversity work."

(The four radio astronomers referred to above are Dr G. Swarup, Dr. Kochu Menon, Prof. Kundu and Dr. Krishnan. The first three came to TIFR. In 1962, Swarup was 33, Kochu Menon 34 and Kundu also in early 30's.)

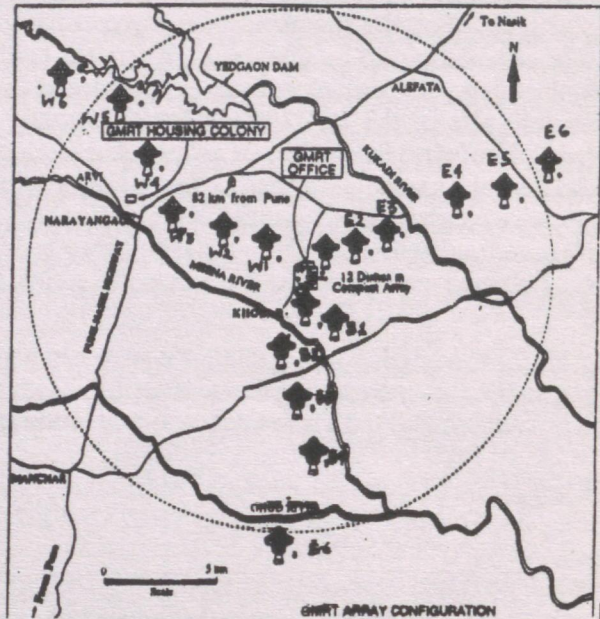
By 1970, the 530 m long and 30 m wide Ooty radio telescope started operating at a frequency of 327 MHz (~92 cms wave length) and several extragalactic radio sources were observed with high angular resolution and led to results of great importance to cosmic evolution. The telescope was also used for interplanetary scintillation studies and also solar phenomena. The Ooty radio telescope was also used for very Long Baseline Interferometric studies in combination with radiotelescopes in Europe and USSR. By adding several small parabolic cylindrical telescopes (22 m x 9 m) up to 4 km, the Ooty telescope also operated for several years as a synthesis telescope and provided radio maps of several galaxies and extragalactic radio sources. The Ooty radiotelescope was extensively used by the Raman Research Institute and the Physical Research Laboratory, Ahmedabad. The members who contributed to the development of the Ooty telescope are: Joshi, Sharma, Kapahi, Anantha Krishna, Veluswami, Bagri, Gopalakrishna, Venugopal, Manohar, Balasubramanian, A.P. Rao, Kulkarni)

At the time of the 7th plan projections, I was able to persuade Prof. Swarup to think of planning and building a radio telescope much bigger than the Ooty radio telescope. He first came up with the idea of building a 2 km long telescope similar to the Ooty one at an equatorial station and investigated the possibility of locating this either in Indonesia or in Kenya. Though extensive discussions were held with astronomers from these countries, it did not work out. Then Swarup came up with the idea of what is now known as the GMRT – a large number of parabolic dishes spread over 10-15 kms and also came with a novel design for the construction of the telescope which he used to call "the Rope Trick" which enabled the dishes to be of relatively light weight and the cost much more economical. When this proposal was being discussed in the meeting of the council of TIFR, Sri. JRD Tata who was the Chariman, wanted Prof. Swarup to be called in. He asked him two questions (1) Is this going to be one of the best world class telescopes? And (2) what should be done to reduce the projected time scale of 7 years to half that time? He told him that in answering, he need not worry about the cost limitations.

Well, the Giant Meter Wavelength Telescope, The GMRT with 30 telescopes each of 45 m diameter spread over a distance of 13 kms in the form of a Y giving an effective collecting area of 30,000 square meters became operational by 1999 at Khodad village about 80 kms north of Pune, not far from the birth place of Sivaji Maharaj. It is a modern state of the art telescope with operating frequency band – 150 MHz, 233 MHz, 325 MHz, 610 MHz and 1000-1450 MHz. The design of the array is such that it provides high sensitivity for detection of diffuse emission and high angular resolution. Though it took almost twice the time projected in the proposal, it has proved itself to be one of the world class telescopes. It is also being used extensively by astronomers from outside the country.



Typical GMRT Telescope



Elementary Particle Physics

In the late 50's and early 60's particle physics which was monopoly of cosmic ray studies was taken over by higher and higher energy man made accelerators. Since India did not have this facility, it was decided to collaborate with accelerator groups at CERN in Geneva and Fermilab in Chicago. To begin with projectors for Bubble Chamber picture analysis were set up after some of the members of the cosmic ray groups had training at these accelerators (A. Subramaninan, P.K. Malhotra, S. Ganguli). Over the years these collaborations have developed into active participation even in the development of various types of detectors required at the accelerators. Some of the collaboration is also with BARC and other institutions in the country. The Indian Collaboration was part of a major international collaboration which resulted in the discovery of a particle called the Top Quark.

Microwave Engineering-SAMEER

In 1950, Dr Bhabha deputed Sri. R.V.S. Sitharam and Sri. G.H. Vaze to the Atomic Energy Establishment at Harwell for training in electronics and Sri. H.L.N. Murthy, the Chief Glass Technician to the Corning Glass Company, England. On his return after a year or so, Sitharam was asked to develop a linear accelerator and at the same time Prof. Phadke had a group working on the construction of a cyclotron. Soon the cyclotron project was given up since the same group (Prof. Phadke, Rama, George Vergeheese, Divatia) was asked to work on the Plasma-Fusion project since Bhabha had learnt from Prof. Cockroft

that Harwell had evidence of neutron emission from their plasma experiments. This proved to be a wrong signal (!). R.V.S. Sitharam continued his work on the development of microwave cavities and electronics for the construction of the linear accelerator, which effort later led to the construction of linear accelerators for medical purposes. In 1962, during the Indo-Chinese War ... the Defense services of the country suddenly realized that they were in short supply of Transit-Receive Switches (Microwave Operated Switches) for their imported Radars and requested Dr. Bhabha for help.

This was undertaken by Sitharam's group and the T.R. Switches were delivered. This was followed by other defence requirements. Thus the microwave engineering group grew from strength to strength.

In 1976, discussions were held with the Department of Electronics to set up an autonomous unit for the production of microwave devices. Prof. M.G.K. Menon was then the Chairman of the Electronics Commission and Secretary to the Department of Electronics. A joint committee of the Department and of TIFR recommended the construction of this separate unit which had very good scope for development and was seriously limited in its then location at TIFR. The SAMEER came into existence with R.V.S. Sitharam as the first Director, in the campus of IIT, Pawai.

Computer Science – NCST

Similarly, around the same time due to the initiative taken by Prof. R. Narasimhan the activities in the computer group of TIFR, were hived off into another unit in the Department of Electronics – the National Centre for Software Training (NCST) and set up in Andheri West Area, with Dr. S. Ramani as the Director. The others members who moved with Ramani are Mudur, and Sadanandan

Homi Bhabha Centre for Science Education

Some of the senior academic members of TIFR (Prof. Udgaonkor, Sri. V.G. Kulkurni, Sri. Lagu and others) realizing that there is need for improvement of school education, revision of syllabus at various levels, proposed the setting up of a small unit at TIFR for this propose and Sri J.R.D. Tata readily agreed and in fact inaugurated the opening of this unit. Support was also forthcoming from Dr. Madhuri Ben who was then the Director of Education, Maharashtra and approved interaction of the teachers of various municipal schools with the centre. A large area was provided in one of the schools near Grant Road. Over the years, this activity picked up and during the 7th and 8th plan periods, it became possible for TIFR to convert this into a National Centre and to-day the Homi Bhabha Centre for Science Education is housed in its own building just outside the BARC complex. The HBCSE is playing a major role in training students for the Olympiads in several subjects – mathematics, physics, biology, etc. and also engaged in research in school education.

While it has not been possible for me to cover all the areas of research and development undertaken by TIFR in the last 60 years because of lack of time, I have only been able to give you just a flavour of a few of the activities, I am more familiar; how these came about and the persons behind these developments. The particular point I would like to emphasize is that the methodology was quite different and became possible because of the policies initiated by Dr. Bhabha – confidence and trust in young people, full support and freedom given to them, the timely advice given by the visiting foreign scientists, the opportunities for spending short and long periods in laboratories abroad, the induction of foreign trained scientists at various levels at the appropriate times, evaluation of the projects and personnel involved by peers in the field, flexibility to start new programmes of research as and when required, emoluments at TIFR being relatively higher than in other institutions, housing facilities near to the campus and so on. In the early years of TIFR when foreign exchange was scarce, and the Indian industry was still very backward, the only way out was self-reliance and in-house development. To-day the scenario has

changed. There is no dearth for foreign exchange and the industry has also developed by leaps and bounds.

If you look back at what the institute has achieved in its 60 years of existence you find that TIFR has contributed significantly not only to several areas of fundamental research, but also as the mother institution for several others – BARC, NCST, SAMEER, and also by setting up National Facilities – GMRT, NCBS, HBCSE and also providing manpower at senior levels to many institutions and universities in the country.

In my talk I have mentioned the names of many scientists who have made TIFR what it is to-day. I must however mention one name again – that is of Prof. M.G.K. Menon who succeeded Dr. Homi Bhabha as the Director of TIFR during 1966-1975 and later held various positions in Delhi – Chairman, Electronics Commission, Secretary DST, Director General CSIR, Minister Science and Technology and so on. His personal participation in research, and continued interest in TIFR, his advice as member of the council of TIFR was indeed a great source of support for all the succeeding Directors of TIFR.

My esteemed colleague and dear friend Prof. D. Lal has made a relevant observation in his speech delivered here a few months back, that TIFR has not made any major path-breaking discovery in the last several decades. While I agree with this observation, I feel that this is not due to lack of effort or due to unproductive lines of research followed. There have been many near misses. Major discoveries, as is well known, are matter of luck and serendipity plays an important role. Discovery of radioactivity, of radio astronomy, pulsars, x-ray sources in the sky, 3°K microwave radiation, all belong to the class of serendipitous discoveries.

I am sure with the absolutely front ranking research in String Theory, the wonderful opportunities with GMRT and the efforts at NCBS, the Prospects with the Astrosat and several new areas that have been initiated in recent years in solid state physics (Nanophysics) and the maintenance of the rich tradition of the mathematics faculty, some truly outstanding discoveries will emerge in the not too distant future. Wonderful opportunities are opening up in theoretical and experimental cosmology with the staggering discoveries of accelerating universe, dark matter, dark energy and also in the field of neurobiology. I have been an optimist and I would like to remain one. Thank you.

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Sixty Years of the Tata Institute of Fundamental Research 1945-2005*

(The Role of Young Men in the Creation and Development of this Institute)

B V Sreekantan

National Institute of Advanced Studies

Indian Institute of Science Campus

Bangalore 560 012

In this Birth Centenary year of Bharata Ratna J.R.D. Tata, several eminent men from different walks of life have highlighted in different places, the outstanding and very rich contributions of J.R.D. Tata to the fields of industry, science, technology, education and human welfare. Many institutions came into existence in the country because of his appreciative and magnanimous support and personal involvement. Tata Institute of Fundamental Research, Mumbai (TIFR) is one such institution, which has just completed 60 years of its existence. Sri JRD Tata not only helped the creation of this institute, but also guided the course of development of this institute as the Chairman of the Governing Council for over three decades. Let me narrate the circumstances that created TIFR in the words of the Founder Director Homi Bhabha himself, While speaking on the occasion of the Inauguration of the new buildings of TIFR at Colaba on January 15, 1962, Bhabha said "The Tata Institute of Fundamental Research started its work in June 1945. It is therefore the oldest of our post-war national laboratories. And yet it is only today, 16½ years later, that its own buildings are being inaugurated by the Prime Minister. This fact alone shows that the manner in which this Institute has been built up is different from that of the other national laboratories, where attention was first directed towards providing them with buildings. There are, however, a number of other differences in approach also. I would therefore like to take a few minutes to recapitulate the history of this Institute and the manner in which it has grown.

While I was still working as a Professor at the Indian Institute of Science in Bangalore during the Second World War, I noted that there was no scientific

* Based on a talk delivered on 18th August 2005 at TIFR as one of JRD Tata Birth Centenary Events organized by TIFR Alumni Association

institution in India devoted solely to fundamental research, especially in the newest branches of physics, namely, nuclear physics and high energy physics.

By fundamental research I mean basic investigations into the behaviour and structure of the physical world without any consideration of their utility or whether the knowledge so acquired would ever be of any practical value. Nevertheless, the support of such research, and of an institution where such research can be carried out effectively, is of great importance to society for two reasons. First of all, and paradoxically, it has an immediate use in that it helps to train and develop, in a manner in which no other mental discipline can, young men of the highest intellectual calibre in a society into people who can think about and analyse problems with a freshness of outlook and originality which is not generally found. Such men are of the greatest value to society, as experience in the last war showed, for many of the applications of science, which were crucial to the outcome of the war, were developed by men who, before the war, were devoting their time to the pursuit of scientific knowledge for its own sake. Radar and atomic energy are two examples of fields in which a vast body of established basic knowledge was developed into technology of immense practical importance, largely through the application in, war time, of the efforts of those who might be called 'pure' scientists.

Secondly, the history of science has shown that "there is no genuine knowledge of the universe that is not potentially useful for man, not merely in the sense that action may one day be taken on it, but also in the fact that every new knowledge necessarily affects the way in which we hold all the rest of our stock". Accordingly, in a letter dated the 19th August 1943 to Shri J. R. D. Tata, I pointed out that "the lack of proper conditions and intelligent financial support hampers the development of science in India at the pace which the talent in the country would warrant", and suggested that the Tata Trust might consider taking the initiative in setting up an institute for fundamental research. In his reply of the 2nd September 1943 to me, Shri J.R.D. Tata wrote: "from what you say in your letter, it is evident that there is scope for rendering valuable service to the country and to the cause of scientific research in India . . . After all, the advance of science is one of the fundamental objects for which most of the Tata Trust were founded, . . . If they are shown that they can give still more valuable help in a new way, I am quite sure that they will give it their most serious consideration".

18/12/05

Send
to Prof.

R. N. Rao

19th Dec.

05

Correct
Science

The Trustees of the Sir Dorabji Tata Trust decided to accept financial responsibility for supporting the Institute at a meeting held on the 14th April 1944. I think it should be recalled on this occasion that this decision was taken more than a year before the explosion of the first atomic bomb over Hiroshima and before nuclear physics had become what might be called "the band-wagon" of science.

The location of the Institute in Bombay was decided largely because of the interest of the then Government of Bombay, which was anxious to build up a strong department of physics at the Institute of Science, and which had invited me to undertake this task. As I was already committed to starting an institute of fundamental research I suggested that the Bombay Government might co-operate with the Tata Trust in the founding of this institute. Thus it came about that the Institute was founded as a joint endeavour of the Sir Dorabji Tata Trust and the then Government of Bombay in 1945."

The Cosmic Ray Research Unit at IISc (1939-1945)

After a brilliant career at Cambridge where he obtained a tripos in engineering and another i in physics and a PhD from Cambridge University, Homi Bhabha spent a few years in doing advanced theoretical research in elementary particle physics and cosmic rays which were the most fundamental frontier areas of research in those days and returned to Indian in 1939 more for a holiday than with the intention of pursuing research here. He had been offered professorial position both in Europe and USA. However, destiny was different for him. Because of the second world war he could not go back to the west, which proved to be a great boon for India. He was offered a research position by C.V. Raman at the Indian Institute of Science where Bhabha set up a Cosmic Ray Research unit as part of the Physics Department and initiated activities in cascade theory in collaboration with the Department of Mathematics in Central College, Bangalore in particular with K.S.K. Iyenger who was a mathematics tripos from Cambridge and B.S. Madhave Rao. One of his distinguished students working in the area of Relativistic Wave Equation of Elementary Particles of any spin was Harish Chandra, who later became a famous mathematician at the Princeton Institute of Advanced Studies. Bhabha also initiated

experimental research in cosmic rays which were then the only source of high energy elementary particles.

Bhabha took advantage of the availability of a B-29 air craft in Bangalore which had been brought as part of the war activities in the middle east and far east and studied the variation of the penetrating component of cosmic rays as a function of altitude at the air-plane altitudes. In this he collaborated with S.V.C. Aiya of the Department of Communication Engineering of the IISc. Figure 1 shows the GM Counter Telescope and the recording system for these experiments fabricated at IISc.

Bhabha also got constructed a 12" diameter Wilson Cloud Chamber with which he studied the scattering properties of mu-mesons with M.S. Sinha as his student collaborator.

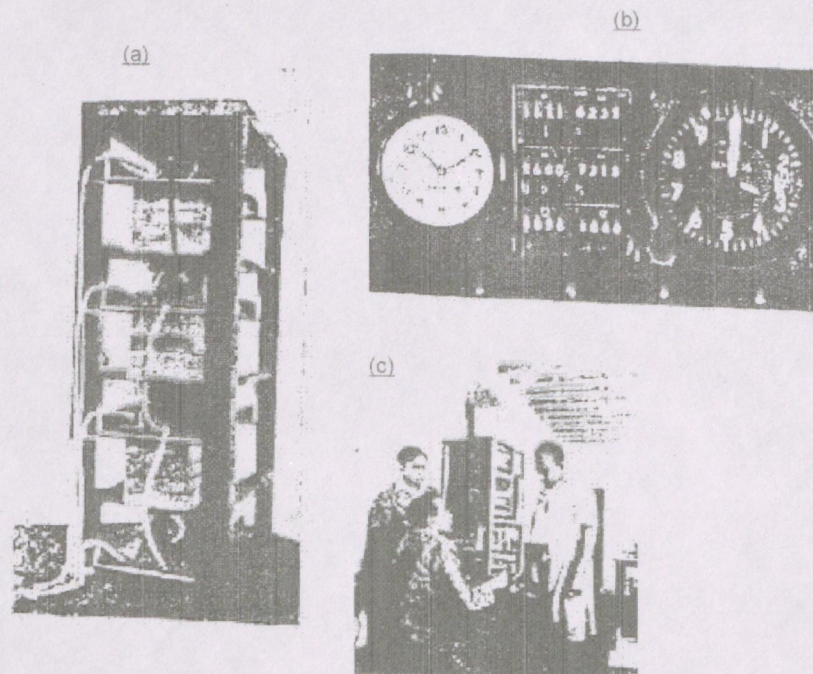


Figure 1. (a) Views of one of the units sent up to 32,000 feet with its sides removed. The top of the unit contains two Cosmic ray telescopes. The electrical amplifiers are on the lower shelf. The dry batteries are at the bottom. (b) The recording system for the experiment. (c) Dr Bhabha with his comic ray telescopes flown on B-29 aeroplanes from Bangalore in early 40's. Seen in the photograph in discussion with Bhabha are Prof. S.V.C. Aiya and Dr R.C. *Saxena*

Saxena his early collaborators at the Cosmic ray research unit of the Indian Institute of Science.

TIFR was initially housed at Kenilworth, 53, Pedder Road, Cambala Hills in December 1945. It would be interesting to note the budget projections for the year 1945-46 which was as follows: Sir Dorabji Tata Trust - s. 45, 000, Govt. of Bombay Rs. 25, 000, CSIR Rs. 10,000; Total Rs. 80,000/-. The equipment of the cosmic ray research unit of the Indian Institute of Science was bought over with a special grant of Rs. 50,000 given for the purpose by the Dorabji Tata Trust. The Area of the Kenilworth building made available for TIFR was 6000 sq. ft.

Research Activities at Kenilworth (December 1945-September 1949) included Mathematics – with D.P. Kosambi, Levy and Masani as Professors); Theoretical Physics (H.J. Bhabha as Professor); Elementary Partical Physics (Students: Abraham, Alladi, K.K. Gupta, Surya Prakash); Cosmic Rays studies based on High Altitude Balloon Studies (A.S Rao, R.P. Thatte, G.S. Gokhale; Nuclear Emulsion (R.R Daniel, G. Sreekantaiah, M.S. Swamy); Cloud Chamber (A.B. Sahiar, G.H. Vaze, B V Sreekantan); Counter Production (R.V.S Sitharam, K. Chandrasekharan and H.L.N. Murthy (Glass echnician)); Electronics (D.Y. Phadke, B.V. Sreekantan, R.V.S. Sitharam), Rubber Balloon flights were carried out from different stations in India, namely from Bombay, Pune, Delhi etc., Radiation Meters were made for Atomic Mineral Survey by R.V.S. Sitharam.

Wednesday Colloquia were a regular weekly feature of the Institute. Some of the Distinguished Visitors during this period at the Institute were P.M.S. Blackett (Nobel Laureate), Sir. S.Radhakrishnan (UGC Chairman), and K. Chandrasekharan (Princeton).



Fig 2 Homi Bhabha in preparation for flying a cosmic ray payload with a cluster of balloons from the Central College, grounds at Bangalore (1940s)

Homi Bhabha flying a cluster of balloons with his cosmic ray payload from the grounds of Central College, Bangalore (1940s)

Bold Letter

[Research and Developmental Activities at the Yacht Club Building during September 1949 to January 1, 1962 led to sudden large scale expansion of activities.] Compared to 6000 sq. ft. at Pedder Road, the area made available at the Yatch Club for TIFR (Half of the Yacht Club Building – the other half for DAE activities) was 35,000 sq. ft. Table 1 lists the various research, development and other activities.

Research	Development	Others
Mathematics	Electronic Instrumentation	Elementary Particle Physics Conference, December 1950
Theoretical Physics	Plastic Balloons	Courses of Lectures in Mathematics, Statistics (Kosambi)
Cosmic Rays	TIFRAC Computer	Electronics (Kandiah from Harwell)
Nuclear Physics	Vacuum Technology	High Energy Physics (Peters)
	Cyclotron	Meson Theory (Marshak, Wentzel, Rosenfeld, Takagi)
	Plasma	Astronomy (Vainu Bappu)
	Liquid Scintillation Counters	Summer Schools in Theoretical Physics at Bangalore
	Spark Counters	Dalitz, Gell-Mann, Chew, Mottleson, ...
	Neon Hodoscopes	
	Total Absorption Spectrometer	
	Multiplate Cloud Chambers	
	Cockroft Walton	
	Cascade Generator	
	Microwave Technology	
	BF3 Neutron Counters	
	Beta-ray Spectrometers	

Research Activities: in Mathematics K. Chandrasekharan and K.G.

Ramanathan, both from Princeton University joined TIFR and K.Chandrasekharan was soon appointed as Deputy Director (Mathematics). Both of them were 30 years old when they joined TIFR. The new students who joined were C.S. Sheshadri, M.S. Narasimhan, S. Raghavan, R. Sreedharan, S. Ramanan, Singhbahl, K. Balagangadharan, K. Ramachandra, R. Simha, M.S. Raghunathan, Raghavan Narasimhan, S S RangachariIn his talk at the inauguration of the TIFR building at Holiday Camp (Navy Nagar), Bhabha summarized the work of the school of mathematics till then (1962) in the following words (see figure 3) : "..... My task



(a) (b) (c)
Figure 3(a,b,c) Pandit Jawahar Lal Nehru at TIFR on the occasion of the inauguration of the new building at Colaba

would, however, be incomplete if I do not refer to the work of the school of mathematics and mention that it has established an international reputation for itself through the outstanding contributions which its members have made to various branches of modern mathematics. Credit for this must go to Professor K. Chandrasekharan who has carefully and painstakingly built up an exceptionally fine group of young mathematicians over the years. The Government of India has reason to be proud of the achievements of its National Centre for Mathematics".

This glowing tribute to the school of mathematics was paid by Bhabha in 1962, just 12 years after K.C. and KGR joined TIFR. This high tradition has been maintained by the school in the intervening 43 years. There was a time in the 80's when all the Faculty Members of the school were Bhatnagar Award Winners. In the last decade or so three of them have become Fellows of the Royal Society. An activity in Applications of Mathematics was started by the TIFR Math Faculty in collaboration with the Department of Mathematics of the Indian Institute of Science in Bangalore in the early 70's. A large number of distinguished mathematician especially from France, UK and USA have lectured at this joint programme. The four yearly International Mathematics Colloquium organized by the math faculty started in the 60's has become a regular feature, which attracts mathematicians from all over the

world. The faculty has also provided manpower at senior levels to other mathematical institutions in the country."

Nuclear Physics at TIFR

The Nuclear Physics programme started in 1949 with the recruitment of Raja Ramanna, B.V. Thosar, S.S. Dharmetti, S.K. Bhattacharjee, S. Jha, Ambuj Mukherjee, E. Kondaiah and Balu Venkataraman, all *post docs* who had obtained their Ph.D's from abroad – USA and UK. The first three initiatives were : a) . Neutron physics and nuclear reactions (Raja Ramanna, Bhattacharjee and Kondaiah) b) . Beta-ray spectroscopy: B.V. Thosar, Ambuj Mukherjee, S. Jha c). Nuclear Magnetic Resonance (NMR):(Dharmetti, Balu Venkataraman)The early students who distinguished themselves later in various capacities included P. K. Iyengar (later to be Chairman, AEC); M. C. Joshi – Head of the Dept. of Physics, Mumbai University; R. Vijayaraghavan – Sr. Professor, Dean, Physics Faculty TIFR; M.R. Das – Director of Cancer Research Institute, Trivandrum; Sri V.G. Kulkarni – Director, Homi Bhabha Centre for Science Education

Theoretical Physics at TIFR

After moving to Yacht Club, Abraham, K.K. Gupta and Surya Prakash completed their Ph.D. in theoretical particle physics under the guidance of Bhabha and later moved to universities as professors of theoretical physics. Udgaonkar joined as a student under Bhabha and worked in the area of particle physics. He was also associated with Reactor Physics problems at Trombay. K.S. Singhvi who joined BARC was also associated with TIFR. His interests were in solid-state physics, reactor physics and multi-particle production in nuclear-collisions. He did not stay on in India for long and left for USA. D. Shankaranarayana joined Bhabha as a student and worked on problems relating to meson production and weak interactions. Virendra Singh joined as a student and was deputed to the university of Berkeley, USA to obtain his Ph.D. Udgaonkar became Senior Professor at TIFR and also member of the UGC. Virendra Singh became Director of TIFR and Professor Emeritus. S.S. Jha joined TIFR after his training in the BARC Training School, was

deputed abroad and obtained his Ph.D. from Stanford and later became Dean, Distinguished Professor and Director of TIFR.

An important new activity started during this period was the organization of summer schools in theoretical physics every summer. Eminent theoretical physicists like Gell-Mann, Dalitz, Chew, Mottleson ... lectured at these summer schools. Another development was the setting up of the BARC Training School in which in the initial years TIFR played a major role. The TIFR benefited a lot in return by getting some of the best students as research scholars in the various theoretical and experimental programmes of the institute. Most of them became professors and faculty members of the institute and contributed to its development in a major way. For some reason this was discontinued towards the end of 60's and resulted in a serious deficiency of man power for the experimental programmes in particular. TIFR lost a very good channel of recruitment of young scholars.

The Elementary Particle Physics Conference in December 1950

One of the important, I would say landmark events in the early history of TIFR was the organization by Bhabha of the first "Elementary Particle Physics" conference in the world at the Yacht Club premises which was attended by some of the most renowned scientists in the area of elementary particle physics and cosmic rays – Blackett, Leprince Ringuet, Amaldi, Rosenfeld, Auger, Peters, Fowler (representing Powell) Wentzel, Peirls and from India Saha, Sarabhai, Kothari, C.V. Raman and B.S. Madhava Rao. For us youngsters this was a unique opportunity to interact with the galaxy of outstanding scientists whose works we were familiar with. The proceedings of the conference was very elegantly brought out by K. Chandrasekharan, with the help of some of us.

Expansion of Cosmic Ray Research

By the time we started working at the Yacht Club premises, cosmic ray research had entered into its new phase of elementary particle physics through the discovery of the Pi-meson as the parent of the mu-meson, the mysterious penetrating component of cosmic radiation that had baffled the scientists in this field. The isolated cases of what were called V-particles observed in a cloud Chamber experiment by the Manchester University scientists Rochester and Butler had focused attention on the

need for careful study of the particles produced in high energy nuclear interactions, both with nuclear emulsions with which pi-mesons had been discovered by Powell and cloud chambers in which the V-particles had made their appearance. Bhabha, with great foresight had initiated activities using both these techniques – the nuclear emulsion and the cloud chamber for cosmic ray research. Daniel had set up a first rate nuclear emulsion processing laboratory at Pedder Road itself which was moved to the large basement laboratory at Yacht Club. Sahiar who had brought the cloud chamber operating at Bangalore and set it up at Pedder completed his observations on muon scattering and the chamber was moved to Yacht Club. Several other cloud chambers were built over the next ten years

The study of new particles created by cosmic rays in their collisions became the chief study of most of the cosmic ray groups in the world. In December 1954 two multiplate cloud chambers (named Rani and Maharani) one above the other were set up in the laboratory at Ooty in the premises of Raj Bhavan and adjacent to the Botanical gardens by A.B. Sahiar, Naranan, Subramanian and Ramana Murthy. One was 18" in diameter and the other 24" x 24" square chamber. The design of the set-up was to hunt for the production of new types of particles – the V-particles and the stopping particles produced by cosmic ray interactions in the brass plates of the chambers. The cosmic ray laboratory at Ooty has completed 50 years of existence. A variety of experiments on high-energy interactions and extensive air showers have been carried out in this laboratory. The world's largest multiplate cloud chamber (2 m x 1.5 m x 1 m) with 21 iron plates each of 2.5 cms thickness was operated there as part of the air shower array and very significant results on the high energy nuclear interactions and cores of extension air showers were obtained. This constituted the Ph.D. thesis work of Vatcha.

A triple setup (Figure 4) comprising of an Air Cerenkov Counter, a multiplate cloud chamber and a total absorption spectrometer designed by Sreekantan, Subramanian and Ramana Murthy, was operated to study the differences in the characteristics of interactions with nuclei of protons and pions in the energy range 10-40 GeV, before the advent of the first CERN accelerator of energy 30 GeV in early 70's. The operation of the Total Absorption Spectrometer in association with the Ooty EAS

array enabled the time structure study of the nuclear active component of air showers (Figure 5) and led to the discovery that the Nucleon-Anti-nucleon production cross section considerably increases with energy (thesis work of Tonwar).

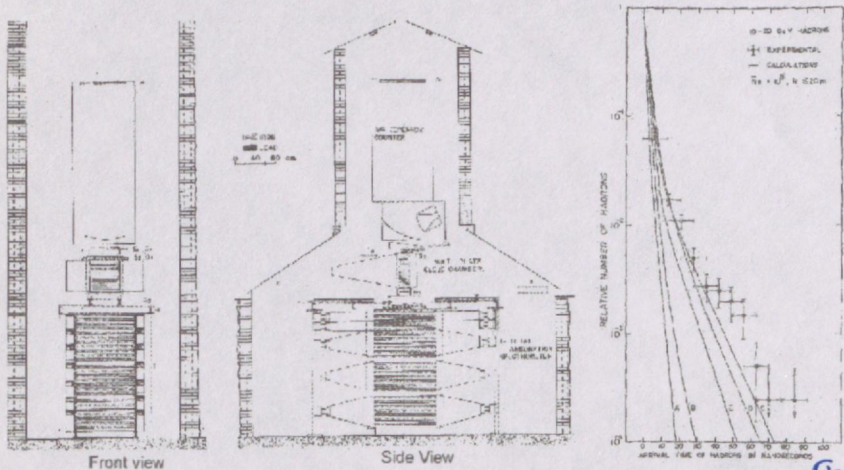


Figure 4. Triple arrangement of Air Cerenkov, Multiplate Cloud Chamber and Total Absorption Spectrometer at Ooty, for the study of interactions of pions and protons in 10-100 GeV range.

Fig 5. Time Structure of Nuclear Active Particles in Air Showers (ooty results)



Figure 6. The GRAPES array at Ooty

B. Peters, M.G.K. Menon, S. Biswas, (Miss) Bibha Chowdhuri, Appa Rao, Gaurang Yodh joined TIFR during the period 1952-56 and gave a big boost to its cosmic ray activity. Nuclear Emulsion stacks interspersed with brass plates, were

flown from Hyderabad and the analysis resulted in the discovery of several types of K-mesons. D. Lal and Yashpal had joined the institute as research scholars, and were part of this most exciting work on K-mesons. This work was extended to the study of Hyper Fragments by Swamy and Ganguli. Some very interesting work on meson production was carried out by Malhotra in collaboration with the Bristol group. In September 1950, one night when Bhabha was working on the programme details of the conference on elementary particles, he called me and said "Sreekantan, you should plan to take a Geiger Counter Telescope down the Kolar Gold Mines and determine the flux of the penetrating particles as a function of depth and then take your Mu-meson decay detector and see whether they are all muons or whether there are other types of particles there". In September-December 1951, Naranan and I measured the penetrating particle intensity upto a depth of 1000 ft and soon followed this up with another Hodoscope- telescope to measure the angular intensity at various depths. Ramana Murthy had joined us by then and was part of this experiment. Following this the three of us took a multiplate cloud chamber down the mines to a depth of 100 ft to study the interaction characteristics of muons. Some anomalies had been reported by the Manchester group which we wanted to explore further. However, soon we were asked by the mining authorities to vacate and leave since they were closing down all operations in the mines.

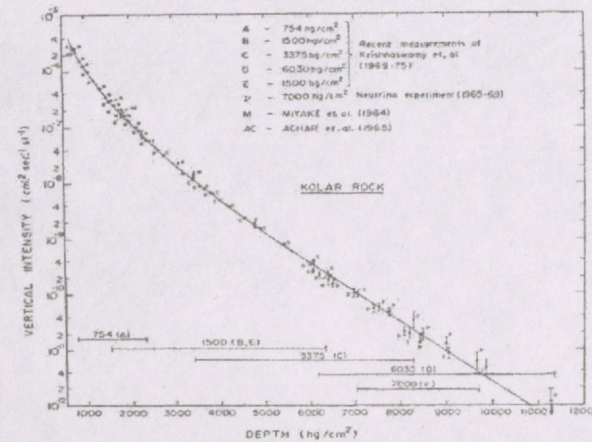


Figure 7. Muon intensity Vs. Depth measured at KGF

We shifted the cloud chamber experiment to an old abandoned railway tunnel in Khandala and completed the observations on muon interactions and no anomaly was found. Since the Kolar Mines did not close down, we returned to the mines for a long series of experiments at larger and larger depths. In this endeavor we were joined by two foreign groups, one from the University of Durham, UK (Wolfendale and others) and the other from the Osaka City University, Japan (Miyake and others). These experiments, started in 1958, lasted for 34 years (till 1992) and the mines were used upto a depth of 8000 ft below ground for a variety of experiments, namely for, Intensity and Angular Distribution of Mu-mesons up to a depth of 8000 ft. (Fig T). Neutrino Experiments, Proton Decay Experiments and High Energy Muons (>200 GeV) in association with air showers detected at the surface with a large array of scintillators (The KGF Air Shower Array). *Here Carried out in the mines over several decades.*

Research and Developmental Activities of TIFR after moving to the permanent buildings at Navy Nagar in 1962 are given in Table II

↓ Table II *(Bold Letter)*

1. Mathematics :

(a) at Bombay

(b) IISC-TIFR joint programme in Applications of Mathematics (>1973) continuing

2. Theoretical Physics:

Particle Physics, Nuclear physics, Solid State Theory (Udgaonkar, V Singh, S.S. Jha, Probir Roy, S.M. Roy, D.P. Roy, Warke, M. Banerji, Nazakatulla, K.V.L. Sharma

3. Theoretical Astrophysics - started around 1969:

Cosmology, neutron star physics, solar oscillations, cool stars, pulsars (Narlikar, Vardya, Chitre, Tarafdar, Padmanabhan, A. Ray, P. Ghosh)

4. Nuclear Physics and Atomic Physics:

Cascade Generator, Van-de-Graff at BARC, Pelletron, (S.K. Mitra, R.P. Sharma, K.G. Prasad, Kurup, Pillai, Nagarajan)

5. Cosmic Rays

- Balloon Facility at Hyderabad

(i) Cosmic Rays - composition (V.K. Balasubramanian, Gokhale);

- (ii) X-ray, gamma-ray astronomies (Sreekantan, Gokhale, Agrawal, Manchanda, K.P. Singh, A.R. Rao, S. Damle and R.T. Redkar)
- Rocket Experiments from Thumba (Naranan, K.P. Singh, Sreekantan, Agrawal and R.K. Manchanda)
- Nuclear Emulsion Studies - High Energy Interactions, primary electrons (Daniel, Stephens, Anand, Lavakere, George Joseph)
- Infrared Astronomy (Daniel, K.V.K. Iyengar, Tandon, Rangarajan, Verma)
- K-mesons, Hyperons etc. (Swamy, Ganguli)
- Anuradha Satellite Experiment for study of anomalous cosmic rays (Biswas, Durgaprasad, Cowsik)
- Kolar gold field experiments on muons, neutrons, proton decay (Narasimhan, Menon, Mondal, Sreekantan, Krishna Swamy)
- KGF Air Shower Arrays with underground muon detectors (Sreekantan, Naranan, M.V.S. Rao, Viswanath, Sivaprasad, Acharya, Bhat) Ooty Air Shower Array with TAS and multiplate cloud chamber (Sreekantan, Tonwar, Vatcha)
- Ooty GRAPE 1, GRAPE 2 and GRAPE 3 arrays (Tonwar, Gupta + Japanese Groups). *Figure 7* gives a view of the new air shower array at Ooty.
- TeV Gamma-Ray Studies - Ooty, Pachmari (Ramana Murthy, G.T. Murthy, Chatterjee, Tonwar, Sreekantan, Bhat, Acharya). *Figure 8* gives a view of an early versions of the TeV Gamma ray telescope at Ooty. *(Red)*
- Cosmic Ray Induced Radioactivity (Peters, Lal, Rama)
- **International Cosmic Ray Conferences:** Jaipur (1963), Bangalore (1983), Pune (2005), ICRC. *(Fig 9) So Fig 9 shows Prof C.P. Pokhel addressing the delegates of the Cosmic Ray Confere at Jaipur 1963.*

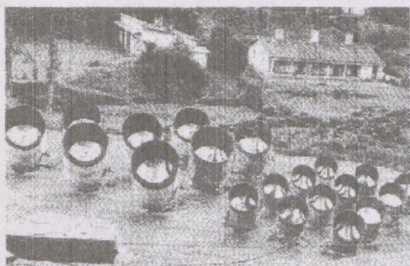
So Fig 9 shows Prof C.P. Pokhel addressing the delegates of the Cosmic Ray Confere at Jaipur 1963.



Dr. Hani Bhathe, MGK Menon, Dobrotin, Kesaketa, Sreekantan, Alledi, Ramakrishnan and D. Lal are seen sitting on the dias.

Figure 7

Fig 6b Shift next to previous page to fig 6a



The TeV gamma ray experiment at Ooty

Figure 8. The TeV Gamma Ray Telescope at Ooty



Figure 9 C.F. Powell at the Jaipur International Cosmic Ray Conference 1963

A new air shower array known as GRAPES built by Tonwar, Gupta and a group of Japanese scientists is now operating behind the Ooty Radio Telescope, with the world's largest area muon detector assembly and is expected to lead to important results on the composition of primary cosmic rays.

6. Solid State Physics:

Magnetic Materials, High Temperature Superconductivity, Chemical Physics – NMR Spectroscopy (Balu Venkataraman, Vijayaraghavan, Gupta, Govil, Nagarajan, Mitra, Multani)

7. Solid State Electronics:

Semi Conductor Materials (K.V. Ramanathan, Arora, Narasimhan, Pinto)

8. Geophysics – Cosmic Ray Induced radioactivity, Rock Magnetism, Hydrology, C-14 Laboratory (moved to PRL, Ahmadabad in 1973) (Lal, Rama, Venkatavaradhan, Bhandhari, Goswami, Krishnaswamy, D.P. Agarwal, Radhakrishna Murthy, Sahasrabudhe)

9. Computer Science:

TIFRAC; CDC-3600; CYBER (R. Narasimhan, P.V.S. Rao, Pitke, Ramani, Mudur, Sadanandan, Mythili)
Speech Synthesis ADGES, AREN (Defence Projects)

NCST – National Institute for Software Technology was set up as a separate institute under department of Electronics in 1978

10. Gravitational Experiments:

Equivalence Principle, fifth Force, Gowribidanar Underground Torsion Balance (R. Cowsik, Unnikrishnan, Krishnan)

11. Radio Astronomy*:

Ooty Radio Telescope, GMRT, Pune, NCRA

12. Molecular Biology*:

(1) At Bombay, (2) At NCBS, Bangalore

13. Particle Physics:

(1) At CERN; (2) At Fermi Lab

14. Microwave Engineering*:

TR-Switches, Linac

SAMEER – Society for Microwave Engineering and Research was set up under DOE in (1978)

15. Homi Bhabha Centre for Science Education* (since 1970 : TIFR, Grant Road, Trombay)

Introduction of Molecular Biology and Radio Astronomy in TIFR

In a note that Bhabha had prepared for the Prime Minister Jawaharlal Nehru on the occasion of the laying of the foundation stone of TIFR building, on January 1, 1954, he writes: "In June 1944, when I wrote a letter to A V Hill, FRS, Nobel Laureate, then Secretary of the Royal Society informing him that the Tata Trust had decided to sponsor the project I put forward for setting up an institute for fundamental research in Bombay and the support of the Bombay Government and co-operations with the Bombay University was expected. In the course of reply dated 22, June 1944, Professor A.V. Hill wrote: "I am very glad, indeed to hear also that the Tata Trust have decided to sponsor your scheme for an institute for advanced research in theoretical and experimental Physics in Bombay. I think you had better take biophysics under its wing, too. Apart from Bose Institute in Calcutta, that subject practically does not exist in India. I am sure in many of the most important future applications of physics will be in biology. It sounds a grand scheme you have on

hand”Later in his address to the International Council of Scientific Union at the Birla Hall, Bombay on January 7, 1966 Bhabha said “As early as June 1944, Sir A.V. Hill had written to me suggesting that biophysics was a neglected subject in India and that it should be taken under the wing of the institute. While I agreed with this suggestion, I do not think it would be wise to embark on this line till some one was found mature enough to be able to work on his own and build up a group. When however in 1962 my attention was drawn by Leo Szilard to a very promising Indian Molecular Biologist, it was decided to start work in molecular biology, which has since then been growing very satisfactorily.”Well, the promising molecular biologist referred to above is Obaid Siddiqi. When he joined TIFR and undertook the responsibility of setting up the molecular biology unit, he was 30 years old. P K Maitra who joined soon was also 30 years old. Almost twenty years later, when we were reviewing the projections to be made of the activities of TIFR for the 7th plan period, Siddiqi came up with the proposal to set up another centre outside Bombay for pursuing what he called pure (not applied) molecular biology. Initially there was some resistance for this proposal both within the institute and in the Department of Atomic Energy. Some were not convinced about the necessity of setting up another centre. However Siddiqi made it clear that this new centre will not disturb in any way the present structure, and will be built around new set of post docs in the US who are keen on returning to India and work in this area. As you know this centre has now become the NCBS-the National Centre for Biological Sciences and has already made a name for itself both nationally and internationally.

In the same ICSU talk Bhabha also mentioned about the starting of radio astronomy activity as part of TIFR : “Four Indian radio astronomers had jointly written identical letters to the chairman UGC, Director General of CSIR and to me as the Chairman of the Atomic Energy commission offering to return to India as a group and establish radio astronomy here, if facilities and support could be given to them. Having ascertained that the members of the group had considerable original work to their credit and were of sufficient maturity to be able to work on their own in India, it was decided to take up radioastronomy at the institute. Thirty parabolic dishes presented by CSIRO Australia which had been lying unpacked for several years at the National Physical Laboratory were handed over to the institute by the willing co-operation of Husain Zaheer and have been installed not far from Bombay for solar

radio astronomy work. In the meantime a project has been developed for a large cylindrical radiotelescope for studying quasars and other radio sources and locating them accurately by lunar occultation. The telescope which will have four to five times the collecting area of Jordell Bank will be designed and built entirely by Indian scientists and engineers and is expected to be in operation in two years.

A site for it has been selected after a very extended study, as the axis of the telescope which is 1700 ft. long has to be parallel to the axis of the earth. Work on the site at Ooty has already started. It is proposed to make this radio telescope one of the centre for interuniversity work.” (The four radio astronomers referred to above are G. Swarup, Kochu Menon, Kundu and Krishnan. The first three came to TIFR. In 1962, Swarup was 33, Kochu Menon 34 and Kundu also in early 30's.)By 1970, the 530 m long and 30 m wide Ooty radio telescope started operating at a frequency of 327 MHz (~92 cms wave length) and several extragalactic radio sources were observed with high angular resolution and led to results of great importance to cosmic evolution. The telescope was also used for interplanetary scintillation studies and also solar phenomena. The Ooty radio telescope was also used for very Long Baseline Interferometric studies in combination with radiotelescopes in Europe and USSR. By adding several small parabolic cylindrical telescopes (22 m x 9 m) up to 4 km, the Ooty telescope also operated for several years as a synthesis telescope and provided radio maps of several galaxies and extragalactic radio sources. The Ooty radiotelescope was extensively used by the Raman Research Institute and the Physical Research Laboratory, Ahmebadad. The members who contributed to the development of the Ooty telescope are: Joshi, Sharma, Kapahi, Anantha Krishna, Veluswami, Bagri, Gopalakrishna, Venugopal, Manohar, Balasubramanian, A.P. Rao, Kulkarni)

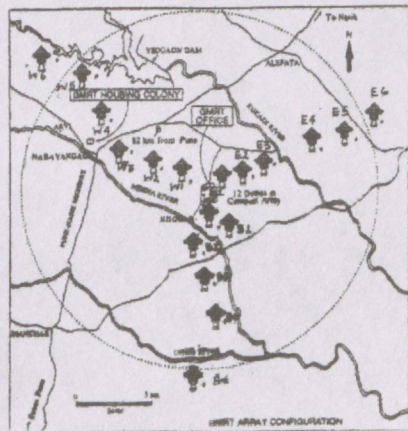
At the time of the 7th plan projections, I was able to persuade Swarup to think of planning and building a radio telescope much bigger than the Ooty radio telescope. He first came up with the idea of building a 2 km long telescope similar to the Ooty one at an equatorial station and investigated the possibility of locating this either in Indonesia or in Kenya. Though extensive discussions were held with astronomers from these countries, it did not work out. Then Swarup came up with the idea of what is now known as the GMRT – a large number of parabolic dishes spread over 10-15

kms and also came with a novel design for the construction of the telescope which he used to call "the Rope Trick" which enabled the dishes to be of relatively light weight and the cost much more economical. When this proposal was being discussed in the meeting of the council of TIFR, JRD Tata who was the Chariman, wanted Swarup to be called in. He asked him two questions (1) Is this going to be one of the best world class telescopes? And (2) what should be done to reduce the projected time scale of 7 years to half that time? He told him that, in answering, he need not worry about the cost limitations.

Well, the Giant Meter Wavelength Telescope, the GMRT with 30 telescopes **Figures 10a, 10b** each of 45 m diameter spread over a distance of 13 kms in the form of a Y giving an effective collecting area of 30,000 square meters became operational by 1999 at Khodad village about 80 kms north of Pune, not far from the birth place of Sivaji Maharaj. It is a modern state of the art telescope with operating frequency band – 150 MHz, 233 MHz, 325 MHz, 610 MHz and 1000-1450 MHz. The design of the array is such that it provides high sensitivity for detection of diffuse emission and high angular resolution. Though it took almost twice the time projected in the proposal, it has proved itself to be one of the world class telescopes. It is also being used extensively by astronomers from outside the country.



(a)



(b)

Figure 10. (a) Typical GMRT Telescope; (b) The GMRT Array

Elementary Particle Physics

In the late 50's and early 60's particle physics which was the monopoly of cosmic ray studies was taken over by higher and higher energy man made accelerators. Since India did not have this facility, it was decided to collaborate with accelerator groups at CERN in Geneva and Fermilab in Chicago. To begin with projectors for Bubble Chamber picture analysis were set up after some of the members of the cosmic ray groups had training at these accelerators (A. Subramanian, P.K. Malhotra, S. Ganguli). Over the years these collaborations have developed into active participation even in the development of various types of detectors required at the accelerators. Some of the collaboration is also with BARC and other institutions in the country. The Indian Collaboration was part of a major international collaboration which resulted in the discovery of a particle called the Top Quark.

Microwave Engineering-SAMEER

In 1950, Bhabha deputed R.V.S. Sitharam and G.H. Vaze to the Atomic Energy Establishment at Harwell for training in electronics and H.L.N. Murthy, the Chief Glass Technician to the Corning Glass Company, England. On his return after a year or so, Sitharam was asked to develop a linear accelerator and at the same time Phadke had a group working on the construction of a cyclotron. Soon the cyclotron project was given up since the same group (Phadke, Rama, George Vergheese, Divatia) was asked to work on the Plasma-Fusion project since Bhabha had learnt from Cockroft that Harwell had evidence of neutron emission from their plasma experiments. This proved to be a wrong signal (!). R.V.S. Sitharam continued his work on the development of microwave cavities and electronics for the construction of the linear accelerator, which effort later led to the construction of linear accelerators for medical purposes. In 1962, during the Indo-Chinese War ... the Defense services of the country suddenly realized that they were in short supply of Transit-Receive Switches (Microwave Operated Switches) for their imported Radars and requested Bhabha for help. This was undertaken by Sitharam's group and the T.R. Switches were delivered. This was followed by other defence requirements. Thus the microwave engineering group grew from strength to strength.

In 1976, discussions were held with the Department of Electronics to set up an autonomous unit for production of microwave devices. M.G.K. Menon was then the Chairman of the Electronics Commission and Secretary to the Department of Electronics. A joint committee of the Department and of TIFR recommended the construction of this separate unit which had very good scope for development and was seriously limited in its then location at TIFR. The SAMEER came into existence with R.V.S. Sitharam as the first Director, in the campus of IIT, Pawai.

Computer Science – NCST Similarly, around the same time due to the initiative taken by R. Narasimhan the activities in the computer group of TIFR, were hived off into another unit in the Department of Electronics – the National Centre for Software Training (NCST) and set up in Andheri West Area, with S. Ramani as the Director. The other members who moved with Ramani were Mudur, and Sadanandan

Homi Bhabha Centre for Science Education

Some of the senior academic members of TIFR (Udgaonkor, V.G. Kulkurni, Lagu and others) realizing that there is need for improvement of school education, revision of syllabus at various levels, proposed the setting up of a small unit at TIFR for this propose and Sri J.R.D. Tata readily agreed and infact inaugurated the opening of this unit. Support was also forthcoming from Dr Madhuri Shah who was then the Director of Education, Maharashtra and approved interaction of the teachers of various municipal schools with the centre. A large area was provided in one of the schools near Grant Road. Over the years, this activity picked up and during the 7th and 8th plan periods, it became possible for TIFR to convert this into a National Centre and to-day the Homi Bhabha Centre for Science Education (HBCSE) is housed in its own building just outside the BARC complex. The HBCSE is playing a major role in training students for the Olympiads in several subjects – mathematics, physics, biology, etc. and also engaged in research in school education. While it has not been possible for me to cover all the areas of research and development undertaken by TIFR in the last 60 years, I have only been able to give you just a flavour of a few of the activities, I am more familiar; how these came about and the persons behind these developments. The particular point I would like

to emphasize is that the methodology was quite different and became possible because of the policies initiated by Bhabha – confidence and trust in young people, full support and freedom given to them, the timely advice given by the visiting foreign scientists, the opportunities for spending short and long periods in laboratories abroad, the induction of foreign trained scientists at various levels at the appropriate times, evaluation of the projects and personnel involved by peers in the field, flexibility to start new programmes of research as and when required, emoluments at TIFR being relatively higher than in other institutions, housing facilities near to the campus and so on. In the early years of TIFR when foreign exchange was scarce and the Indian industry was still very backward, the only way out was self-reliance and in-house development. To-day the scenario has changed. There is no dirt for foreign exchange and the industry has also developed by leaps and bounds. If you look back at what the institute has achieved in its 60 years of existence you find that TIFR has contributed significantly not only to several areas of fundamental research, but also as the mother institution for several others – BARC, NCST, SAMEER, and also by setting up National Facilities – GMRT, NCBS, HBCSE and also providing manpower at senior levels to many institutions and universities in the country. I have mentioned the names of many scientists who have made TIFR what it is to-day. I must however mention one name again – that is of Prof. M.G.K. Menon who succeeded Homi Bhabha as the Director of TIFR during 1966-1975 and later held various positions in Delhi – Chairman, Electronics Commission; Secretary DST; Director General CSIR; Minister Science and Technology and so on. His personal participation in research and continued interest in TIFR, his advice as member of the council of TIFR was indeed a great source of support for all the succeeding Directors of TIFR. My esteemed colleague and dear friend D. Lal has made a relevant observation in his speech delivered here a few months back, that TIFR has not made any major path-breaking discovery in the last several decades. While I agree with this observation, I feel that this is not due to lack of effort or due to unproductive lines of research followed. There have been many near misses. Major discoveries, as is well known, are matter of luck and serendipity plays an important role. Discovery of radioactivity, of radio astronomy, pulsars, x-ray sources in the sky, 3°K microwave radiation, all belong to the class of serendipitous discoveries. I am sure with the absolutely front ranking research in String Theory, the wonderful

opportunities with GMRT and the efforts at NCBS, the Prospects with the Astrosat and several new areas that have been initiated in recent years in solid state physics (Nanophysics) and the maintenance of the rich tradition of the mathematics faculty, some truly outstanding discoveries will emerge in the not too distant future.

Wonderful opportunities are opening up in theoretical and experimental cosmology with the staggering discoveries of accelerating universe, dark matter, dark energy and also in the field of neurobiology. I have been an optimist and I would like to remain one. After the talk, many scientists suggested that in the written version of this talk I should include the highlights of the research especially in the early years. I requested some of my old colleagues to send brief write-ups about their perception of the research activities in their areas. Many were kind enough to respond. I have included these in the appendix. I am most grateful to these scientists.

Appendix:

School of Mathematics at TIFR: M.S. Raghunathan

During the decade starting with the late fifties, several brilliant contributions came from members of the School who were still in their twenties. Raghavan Narasimhan proved the imbedding of open Riemann surfaces in IC^3 . C.S. Seshadri made the first big dent in a question (on projective modules over polynomial rings) raised by Serre. M.S. Narasimhan (in collaboration with S.Kotake, a Japanese) came up with beautiful results that are among the precursors of the theory of Pseudo Differential Operators. C.P. Ramanujam came up with an elegant solution of a problem in Number Theory that had eluded attack by such greats as C.L. Siegel; K. Ramchandra wrote on the "Knorecker Limit Formula" inspired by the great Siegel. M.S. Narasimhan and S. Ramanan raised and answered a question in Differential Geometry which was to form the basis for the development of the Chern-Simons invariant that was to impact on Theoretical Physics. M.S. Narasimhan and C.S. Seshadri wrote a ghraet paper on "Stable Vector Bundles", one of the most influential articles in this area. M.S. Raghunathan's work on "Rigidity" brought recognition to the institute in another area: Algebraic Groups and Discrete Groups.

Theoretical Physics: M. Barma (From a consolidated report prepared by Theoretical Physics Group, TIFR, January 1997)

(a) THE PERIOD 1945-1969

The need for building a strong Theoretical Physics group was recognized from the very inception of TIFR, but it took several decades to achieve. During the first decade (mid 1940's – mid 1950's), Homi Bhabha's research in High Energy Physics constituted the overriding component of the output in Theoretical Physics. Along with a few associates and students, he worked on the theory of cosmic ray showers, meson production and nuclear forces. The principal contributions were the extension of the Fermi theory of meson production, the attempt to develop a postulational basis for the theory of elementary particles and the study of wave equations for arbitrary spin (Bhabha equations). Bhabha's strong involvement with the Indian Atomic Energy programme began towards the end of this period.

The next decade (mid 1950's -- mid 1960's) was a period of expansion, with concomitant diversification of activity. Research programmes in theoretical Nuclear Physics and Solid State Physics began at this time. Members of the Theory Group taught in the Atomic Energy Training School Programme, which in turn provided a pool of talent for TIFR as a whole, and the group in particular. Also, the organization of Summer Schools in Theoretical Physics, which played a seminal role in exposing Indian physicists to new areas of Theoretical Physics, began in this period. Some of the research areas covered in this period were nuclear model calculations, nuclear many-body problem, Bose gas, acceleration mechanism for cosmic radiation, stability and other problems in magnetohydrodynamics and hydromagnetic turbulence, neutron scattering, and various problems in the strong, electromagnetic and weak interactions of elementary particles and their symmetries.

Over the next five years, the group consolidated its position. However, a significant number of members working in the area of plasma physics left the group around 1968 to join the Physical Research Laboratory in Ahmedabad. This was followed, a few years later, by several more members moving to form the nucleus of the Theoretical Astrophysics group at TIFR.

Some of the research areas in which significant contributions were made in this period are given below. Work in plasma physics and astrophysics is, however, not included.

High Energy Physics: (1) S-matrix theory and field theory; bootstraps; strong coupling theory; bounds on cross-sections arising from general constraints of analyticity, unitarity and crossing (2) High energy scattering, using Regge poles and other phenomenological models (3) Symmetries of strongly interacting particles: SU(3); SU(6); noncompact groups (4) Infinite component wave equations (5) Current algebra;

sum rules and representation theory; chiral symmetries (6) Weak interactions; CP-violation; symmetry-breaking effects; higher order weak interactions (7)

Electromagnetic interactions; electromagnetic self-masses; exact low energy theorems; electro-production and photo-production at high energies.

Nuclear Physics: (1) Nuclear Structure from the many-body theory point of view: more specifically, effective nucleon-nucleon interaction, spherical and deformed Hartree-Fock theory, generator coordinate method, equation of motion and random-

phase-approximation methods, group theoretical techniques. (2) Nuclear Reactions: statistical hypothesis in compound nucleus reactions; large momentum transfer direct reactions and low energy nucleon scattering.

Solid State Physics: (1) Linear and nonlinear optical properties of solids; electronic and phonon Raman scattering (2) Positron annihilation in solids (3) Electronic band structure calculations; (4) Heisenberg Hamiltonian in magnetism (5) Theory of phase transitions (6) Superconductivity (7) Quantum fluids.

(b) THE PERIOD 1970-96

Between 1970 and the present, the Theoretical Physics Group has made research contributions at the frontiers of practically all areas of physics. The major advances and trends in physics in this period -- the advent of gauge theories of strong and weak interactions, their supersymmetric extensions and the search for new particles predicted by these theories; the renormalization group; the emergence of string theory as the leading candidate for a unified theory of all particles and forces including gravity; high temperature superconductivity; nonequilibrium statistical mechanics -- have been reflected in, and in some cases spurred by, the research activities of the group.

These trends have been reflected in a change of the composition of the group. While a number of important contributions came from this group in the area of traditional Nuclear Physics in the earlier part of this period, in recent years the interests of group members have shifted to areas in High Energy Nuclear Physics like quark structure of the nucleon, and quark-gluon plasma. A strong group has emerged in the area of string theory. In recent years another significant change has been the large scale use of computers to solve physical problems in particle physics phenomenology, lattice gauge theory, condensed matter physics and statistical mechanics.

Over the past twenty-seven years the research activities of the Theoretical Physics Group fall into three broad areas: Particles and Fields, Nuclear Physics and Condensed Matter Physics. The work in Particles and Fields falls under two broad areas - (1) Particle Physics, and (2) Field Theory and String Theory. The first covers phenomenological aspects of particle physics along with lattice gauge theory and perturbative field theory. The second covers nonperturbative techniques in field theory, string theory, conformal field theory, black hole physics and foundations of

quantum theory. In Nuclear Physics, the work was primarily on Nuclear Structure. In Condensed Matter Physics, the sub-areas are (1) Quantum Fluids and Superconductivity (2) Electronic and Optical Properties of Solids (3) Nonlinear and Quantum Optics and (4) Statistical Physics.

Over the years, the group attracted many research students and postdoctoral associates who contributed strongly to all activities. During this time, 46 Ph.D. theses were written, spanning all areas of Theoretical Physics.

Radio Astronomy at TIFR: Govind Swarup

The radio astronomy group was formed at TIFR in 1963. During 1965 to 1970, a 530m long and 30m wide cylindrical radio telescope was designed and fabricated fully indigenously at Ooty. The Ooty Radio Telescope (ORT) has a unique design. The 530 m long axis of the parabolic cylinder has been made parallel to the Earth's rotation axis, by locating it in the north-south direction on an existing hill which has the same slope as the geographical latitude (about 11 degrees) of the station, thus enabling the telescope to track radio sources in the sky for about 10 hours at a time by a simple mechanical rotation of its long axis. The Ooty Radio Telescope was designed to exploit the technique of lunar occultation to obtain high angular resolution and sensitivity to study the structure of faint extragalactic radio sources.

One of its main objectives was to distinguish between the Big Bang and Steady State models of the universe. The telescope provided high-resolution (about 1 to 10 arcsec) angular structures of over 1000 weak radio galaxies and quasars for the first time. A close relationship between the angular sizes of radio sources and their apparent flux density provided new and independent evidence against the Steady-State model of the Universe and implied evolution in the physical sizes of powerful radio galaxies and quasars with cosmic epoch. Over the last 35 years ORT has led to over 500 papers in refereed journals concerning pulsars, interplanetary scintillations, coronal holes, HII regions, supernova remnants, Centre of our Galaxy, radio galaxies and quasars.

In 1987 the radio astronomy group started design and construction of the Giant Microwave Radio Telescope located about 80 km north of Pune. GMRT consists of

30 parabolic dishes (each 45m in diameter) spread out over a region of about 25 km. The 45m antennas have a very economical and innovative design with the reflecting surface of the antennas consisting of wire mesh made of thin wires supported by rope trusses. GMRT became fully operational in 2000. Operating at 5 different frequency bands between 100 MHz and 1500 MHz, GMRT is one of the most complex and challenging projects undertaken by Indian scientists in the field of basic sciences. GMRT, the world's largest telescope operating in the above frequency range, is currently being used by over hundred astronomers from India and abroad for studying a variety of celestial radio sources from nearby Jupiter to the most distant radio galaxies and quasars in the universe.

Amongst many outstanding results yielded by GMRT, we may cite only a few: recent discovery of a pulsar in a Crab-like supernova remnant with a deduced age of about 4000 years, another in a Globular cluster with a very high ellipticity, discovery of 3 more pulsars in distant parts of our Galaxy, HI and OH observations giving constraints on fine structure constant, studies of HI in our Galaxy, nearby galaxies, particularly dwarf galaxies with much higher sensitivity than available before, discovery of several supernova remnants, search for microquasars in our Galaxy associated with gamma ray sources, studies of the Galactic Centre, nearby galaxies, giant radio galaxies, X-shaped radio sources, etc.

Space Astronomies: P.C. Agarwal

Research in X-ray Astronomy and Far Infrared Astronomy has been carried out in TIFR using space-borne instruments. The X-ray astronomy observations have been made using balloon, rocket and satellite-borne instruments. The balloon observations in the hard X-ray band (20-100 keV) have yielded new and interesting results on variability and energy spectra of binary sources like Cyg X-1, Sco X-1, Her X-1 etc. The most interesting results include first detection of a hard X-ray flare in Cyg X-1 and observation of a change in the shape of X-ray pulse from a single-peak pulse to a double-peak pulse in the X-ray pulsar GX1+4. A major event in X-ray astronomy work at TIFR was launch of the Indian X-ray Astronomy Experiment (IXAE) on the Indian satellite IRS-P3 in March 1996. The IXAE yielded new and exciting results on rapid X-ray variability in black hole binaries and pulsation characteristics of X-ray pulsars. An important result was discovery of quasi-regular

X-ray bursts from microquasar GRS 1915+105 with unique features which was interpreted as due to disappearance of matter behind the event horizon of the black-hole.

The TIFR group has developed a 1 meter aperture sensitive balloon-borne telescope for Far infrared photometry in 150 to 210 micron band. This telescope has been flown a large number of times and has provided new and interesting results. Major results include detection of protostellar candidates, energetic of warm gas in Galactic star forming regions and distribution of cold dust. This telescope has also been used for mapping of C II line at 158 micron in our Galaxy.

Currently the TIFR group is deeply involved in the development of science instruments for the ambitious Indian astronomy satellite Astrosat aimed at multiwavelength studies of cosmic sources.

Theoretical Astrophysics: S.M. Chitre

The highlights of the Theoretical Astrophysics group which came into existence at TIFR only in the early 70's may be summarized as follows:

- ♦ Central role played by molecular energy bands in physical processes in stellar atmospheres and giant molecular cloud complexes.
- ♦ *Physics and chemistry of comets
- ♦ Use of accurately measured oscillation frequencies of the Sun to deduce its physical makeup (sound speed, density, temperature and chemical composition) and to understand the problem of the flux of missing solar neutrinos. Inference of the internal rotation rate and magnetic fields and their variations with activity cycle. Use of f-mode frequencies to accurately determine the solar radius and also its temporal variation. Setting constraints on the heavy element abundance on the core and on the p-p cross section.
- ♦ Equation of state for very high density matter and models of neutron stars
- ♦ Trajectories of particles around black holes and magneto-hydrodynamics around rotating black holes
- ♦ Accretion flows and winds around compact stars such as neutron stars and black holes

- ♦ Quasi-periodic oscillations of black holes due to shocks
- ♦ Evolution of Stellar Binaries formed by tidal captures
- ♦ Nature of matter distribution permitted by general consideration of global hyperbolicity of space time and causality
- ♦ Gravitational collapse, singularity theorems and existence of naked singularities
- ♦ Existence of dark matter in the form of weakly interacting particles left over from the big bang providing the gravitating background of invisible matter
- ♦ Gravitational bending of light rays giving rise to the phenomenon of gravitational lensing and superluminal separation of VLBI components in quasars: Prediction of Einstein Rings in lensed systems
- ♦ Topological defects in the Universe and acceleration of particles to ultra-high energies and consequent radiation. Cosmological implications of cosmic strings
- ♦ Quantization of the conformal degrees of freedom for studying cosmological effects of quantum gravity
- ♦ Alternative cosmological models to big bang scenario

High Energy Physics: A. Gurtu

The advent of multi-GeV high energy accelerators in the mid-1950's led to TIFR scientists' participation in the study of controlled high energy interactions. The earliest experiments used nuclear emulsions which acted as target as well as detector. A detailed study of hypernuclei (in which one neutron is replaced by a lambda particle) was carried out. From late-1960's the bubble chamber technique was adopted and TIFR participated in various international collaboration experiments. Many studies on strange and charmed particles were carried out. From mid-1980's TIFR groups joined the L3 collaboration at LEP, CERN for the study of 100-200 GeV e interactions, and later the D0 experiment at the Tevatron, FNAL to study 1.8-2.0 TeV antiproton-proton interactions. At LEP the W and Z boson masses were precisely determined, the number of matter generations fixed as 3, detailed $Z \rightarrow b \bar{b}$ studies done and running of the strong coupling constant established as per QCD. At FNAL the top quark was discovered in mid-90's and searches for SUSY and other new particles, including Higgs, is continuing. In short the standard model was consolidated. Both TIFR groups are now jointly participating

in the future CERN-LHC program, having joined the CMS collaboration. The main aim of the LHC program with 14 TeV colliding proton-proton beams expected in 2007, is to understand the mechanism of mass generation in the universe by discovering or ruling out the Higgs boson and to search for new particles.

Solid State Physics: R. Vijayaraghavan

To start, self reliance in instrumentation was stressed by Bhabha, which motivated us to construct nuclear magnetic resonance spectrometer, with its associated highly stable homogenous and stable electromagnet system capable of detecting nmr of signals from Deuterium and oxygen -17 isotopes from natural water [2, 4 parts in 10000] with such an instrument, nmr of chemicals, metals, alloys, were studied. An important discovery in metal science was the correlation between a bulk quantity, like susceptibility and microscopic nuclear magnetic resonance shifts, in platinum alloys this work was widely hailed. Then we showed that conduction electron polarization in metals is oscillatory paving way to understand rare earth magnetism. Such work propelled us in early sixties as leaders in nmr of solids, valence fluctuation, in rare earth alloys, heavy fermion behaviour. Using both nuclear techniques like nmr, Mossbauer, neutron and bulk techniques like susceptibility, specific heat, resistance to get one fundamental property of solids was universally hailed by leading experts as unique TIFR contribution, thin film study of high temperature superconductors stabilizing stable high Tc systems [not available in bulk was another noteworthy contribution. The most remarkable discovery is superconducting nickel borides at very elevated temperatures for alloys. This has been given a special slot in physical review index system. Recently low temp. magnetic studies in newly synthesised [CMR.GMR] compounds have made this Solid state group a leader in condensed matter physics studies.

Cosmic Rays: D. Lal (Extract from the talk of D. Lal in the JRD Centenary Series at TIFR)

A very distinguished cosmic ray physicist, Bernard Peters, who had discovered the presence of multiply charged heavy nuclei in cosmic radiation, came to India in 1950 to conduct balloon flights for studying the composition of and nuclear interactions of energetic particles in the cosmic radiation. In 1951, Bhabha invited him to join the

TIFR, which he did. The joining of Peters made a huge impact on the quality of research in the fields of cosmic radiation, high energy and elementary particle physics and geophysics, within a period of less than 8 years that he spent at the TIFR. *It would be fair to say that the contributions of the cosmic ray group during the fifties helped greatly in putting TIFR on the global science map.*

Peters' approach to science was simple but one that is difficult to practice! He asked himself if he could find answers to questions that were important: questions, which could immediately open further critical questions. The tremendous output of science in the short period that Peters spent at TIFR caused strong waves all over the TIFR, and in the country. Being privileged to be his student, I realized how hard it was to ask the right questions, the key to doing good science. I would often go to him asking his approval for carrying out certain experiments. Most of the time he quickly sent me home after asking a few simple questions such as what I expected to gain by doing the experiment. He said: assume a certain result of the experiment which you expect, and then ask yourself the question: what would I then learn?

What Bernard Peters did was to establish within a short span of time an important fact that we in India had all the capability to make discoveries and to do fundamental research, at par with the West, only if we had confidence in ourselves. And he assured us that we had the basic capability and that the confidence had to be built by asking good questions and doing well thought-out science. What was considered good science? Again here the answer can be found in the fundamental approach of Peters: to ask critical questions and then to try to answer them. One does not have to leave one's room to get the answer to this fundamental question.

Peters demonstrated the power of his approach by his researches in the fields of cosmic ray physics, elementary particles, high energy physics and cosmic ray geophysics. During 1952-1958, a large number of discoveries were made in the fields related to cosmic rays:

- i. Composition of cosmic rays at the highest energies, from direct observations of cosmic rays, and also from phenomenology of extensive air showers.
- ii. Studies of properties of elementary particles. This was made possible by the development of a continuously sensitive block of nuclear emulsion pellicles, which allowed tracing tracks of secondary particles to their origin.

Besides providing valuable data, this study established associated production of two different types of elementary particles in one nuclear interaction, and the nuclear capture of negative K-meson, as it was called at that time.

- iii. Discovery of ^{10}Be produced by cosmic rays, opening up the field of cosmic ray geophysics.
- iv. Discovery of more than a half a dozen cosmic ray produced radionuclides, further highlighting the role of cosmic radiation in studying terrestrial processes in diverse branches of earth sciences; meteorology, hydrology and oceanography. ^{10}Be and several cosmogenic nuclides were in fact discovered whilst the group was working in the naval barracks, a few years before they moved into the new TIFR buildings.

These were new areas of research. The field of cosmic ray geophysics was so 'new' that it was considered a very risky area to go into. I would like to narrate an interesting personal anecdote at this point. The year was 1954. Peters' group was busy discovering elementary particles and studying high-energy nuclear interactions. In 1947, Willard Libby had discovered ^{14}C , produced as a product of nuclear interactions of cosmic ray produced thermal neutrons with nitrogen nuclei in the atmosphere. He subsequently applied it for dating archaeological samples. Peters then had the idea that we look for the radionuclide, ^{10}Be , expected to be produced by cosmic rays in the atmosphere, since it would prove an excellent radio-tracer for determining geochronology of sediments, which contained rich information about the past history of the Earth. I was then spending most of my time studying elementary particles and had discovered about 20 events in nuclear emulsions. The proposed ^{10}Be idea of Peters appealed to me greatly, and although it involved delving in new experimental areas, such as radiochemistry, I switched overnight and put all my efforts on discovering the cosmic ray produced ^{10}Be as a geophysics venture. Several of my close friends then discouraged me from switching to ^{10}Be , telling me frankly that I was stupid; that I was going from high-energy physics to zero-physics. The story of development of cosmic ray geophysics began in 1954. ^{10}Be was discovered in late 1955 in marine sediments. Peters' group took up this field putting full force on (i) discovering new nuclides expected to be produced by cosmic rays, and (ii) determining accurately the expected rates of production of various

radionuclides by cosmic radiation in the atmosphere, because it became clear to us that cosmic rays provided a natural source of a large number of radiotracers for studying earth sciences, whose source functions could be determined precisely. Fifty years later, it is still a very busy field and ^{10}Be itself is one of the two most important tracers in geophysics (the other being ^{14}C); it is employed as a tracer in many branches of earth sciences including paleo-climatology. With the present sensitivity of measurement of isotopes, the cosmic ray produced ^{10}Be can be measured in about 1 milligram of soil from the surface of the Earth and ^{14}C in about 0.1 milligram of carbon from any of the dynamic carbon cycle reservoirs.

Sixty years of the Tata Institute of Fundamental Research 1945–2005: The role of young men in the creation and development of this institute*

B. V. Sreekantan

In this Birth Centenary year of Bharat Ratna J. R. D. Tata, several eminent men from different walks of life have highlighted in different places, the outstanding and rich contributions of J. R. D. Tata to the fields of industry, science, technology, education and human welfare. Many institutions came into existence in the country because of his appreciative and magnanimous support and personal involvement. Tata Institute of Fundamental Research (TIFR), Mumbai is one such institution, which has just completed 60 years of its existence. J. R. D. Tata not only helped in the creation of this Institute, but also guided the course of development of this Institute as the Chairman of the Governing Council for over three decades. Let me narrate the circumstances that created TIFR in the words of the Founder-Director Homi Bhabha himself. While speaking on the occasion of the inauguration of the new buildings of TIFR at Colaba on 15 January 1962, Bhabha said:

'The Tata Institute of Fundamental Research started its work in June 1945. It is therefore the oldest of our post-war national laboratories. And yet it is only today, 16½ years later, that its own buildings are being inaugurated by the Prime Minister. This fact alone shows that the manner in which this Institute has been built up is different from that of the other national laboratories, where attention was first directed towards providing them with buildings. There are, however, a number of other differences in approach also. I would therefore like to take a few minutes to recapitulate the history of this Institute and the manner in which it has grown.

'While I was still working as a Professor at the Indian Institute of Science (IISc) Bangalore during the Second World War, I noted that there was no scientific institution in India devoted solely to fundamental research, especially in the newest branches of physics, namely nuclear physics and high energy physics.

*Based on a talk delivered on 18 August 2005 at TIFR, Mumbai as one of the J. R. D. Tata Birth Centenary Events organized by TIFR Alumni Association.

'By fundamental research I mean basic investigations into the behaviour and structure of the physical world without any consideration of their utility or whether the knowledge so acquired would ever be of any practical value. Nevertheless, the support of such research, and of an institution where such research can be carried out effectively, is of great importance to society for two reasons. First of all, and paradoxically, it has an immediate use in that it helps to train and develop, in a manner in which no other mental discipline can, young men of the highest intellectual calibre in a society into people who can think about and analyse problems with a freshness of outlook and originality, which is not generally found. Such men are of the greatest value to society, as experience in the last war showed, for many of the applications of science, which were crucial to the outcome of the war, were developed by men who, before the war, were devoting their time to the pursuit of scientific knowledge for its own sake. Radar and atomic energy are two examples of fields in which a vast body of established basic knowledge was developed into technology of immense practical importance, largely through the application in war time, of the efforts of those who might be called "pure" scientists.

'Secondly, the history of science has shown that "there is no genuine knowledge of the universe that is not potentially useful for man, not merely in the sense that action may one day be taken on it, but also in the fact that every new knowledge necessarily affects the way in which we hold all the rest of our stock". Accordingly, in a letter dated the 19 August 1943 to J. R. D. Tata, I pointed out that "the lack of proper conditions and intelligent financial support hampers the development of science in India at the pace which the talent in the country would warrant", and suggested that the Tata Trust might consider taking the initiative in setting up an Institute for fundamental research. In his reply of the 2 September 1943 to me, J. R. D. Tata wrote: "from what you say in your letter, it is evident that there is scope for rendering valuable service to the country

and to the cause of scientific research in India After all, the advance of science is one of the fundamental objects for which most of the Tata Trust were founded If they are shown that they can give still more valuable help in a new way, I am quite sure that they will give it their most serious consideration".

'The Trustees of the Sir Dorabji Tata Trust decided to accept financial responsibility for supporting the Institute at a meeting held on the 14 April 1944. I think it should be recalled on this occasion that this decision was taken more than a year before the explosion of the first atomic bomb over Hiroshima and before nuclear physics had become what might be called "the bandwagon" of science.

'The location of the Institute in Bombay was decided largely because of the interest of the then Government of Bombay, which was anxious to build up a strong department of physics at the Institute of Science, and which had invited me to undertake this task. As I was already committed to starting an institute of fundamental research, I suggested that the Bombay Government might cooperate with the Tata Trust in the founding of this Institute. Thus it came about that the Institute was founded as a joint endeavour of the Sir Dorabji Tata Trust and the then Government of Bombay in 1945.'

The Cosmic Ray Research Unit at IISc (1939–45)

After a brilliant career at Cambridge, where he obtained a tripos in engineering and another in physics and a Ph D from Cambridge University, Homi Bhabha spent a few years in doing advanced theoretical research in elementary particle physics and cosmic rays, which were the most fundamental frontier areas of research in those days and returned to India in 1939, more for a holiday than with the intention of pursuing research here. He had been offered a professorial position both in Europe and USA. However, destiny was different for him. Because of the Second World War, he could not go back to the West, which proved to be a great boon for India.

He was offered a research position by C. V. Raman at IISc, where Bhabha set up a Cosmic Ray Research Unit as part of the Physics Department and initiated activities in cascade theory in collaboration with the Department of Mathematics in Central College, Bangalore, in particular, with K. S. K. Iyenger, who was a mathematics tripos from Cambridge and B. S. Madhava Rao. One of his distinguished students working in the area of relativistic wave equation of elementary particles of any spin was Harish Chandra, who later became a famous mathematician at the Princeton Institute of Advanced Studies. Bhabha also initiated experimental research in cosmic rays, which were then the only source of high-energy elementary particles.

Bhabha took advantage of the availability of a B-29 aircraft in Bangalore, which had been brought as part of the war activities in the Middle East and Far East, and studied the variation of the penetrating component of cosmic rays as a function of altitude at

the airplane altitudes. In this he collaborated with S. V. C. Aiya of the Department of Communication Engineering, IISc. Figure 1 shows the GM counter telescope and the recording system for these experiments fabricated at IISc.

Bhabha also got constructed a 12" diameter Wilson cloud chamber with which he studied the scattering properties of mu-mesons with M. S. Sinha as his student collaborator.

TIFR was initially housed at Kenilworth, 53, Peddar Road, Cambala Hills in December 1945. It would be interesting to note the budget projections for the year 1945-46 which was as follows: Sir Dorabji Tata Trust, Rs 45,000; Govt of Bombay, Rs 25,000, CSIR, Rs 10,000; total Rs 80,000. Equipment for the Cosmic Ray Research Unit of IISc was bought over with a special grant of Rs 50,000 given for the purpose by the Dorabji Tata Trust. The Area of the Kenilworth building made available for TIFR was 6000 sq ft.

Research activities at Kenilworth (December 1945-September 1949)

These included mathematics (with D. D. Kosambi, Levy and Masani as Professors); theoretical physics (H. J. Bhabha as Professor); elementary particle physics (students: Abraham, Alladi, K. K. Gupta, Surya Prakash); cosmic rays studies based on high altitude balloon studies (A. S. Rao, R. P. Thatte, G. S. Gokhale); nuclear emulsion (R. R. Daniel, G. Sreekanthiah, M. S. Swamy); cloud chamber (A. B. Sahiar, G. H. Vaze, B. V. Sreekantan); counter production (R. V. S. Sitharam, K. Chandrasekharan, H. L. N. Murthy (Glass technician)); Electronics (D. Y. Phadke, B. V. Sreekantan, R. V. S. Sitharam). Rubber balloon flights were carried out from different stations in India, namely from Bombay, Pune, Delhi, etc. (Figure 2). Radiation meters were made for Atomic Mineral Survey by R. V. S. Sitharam.

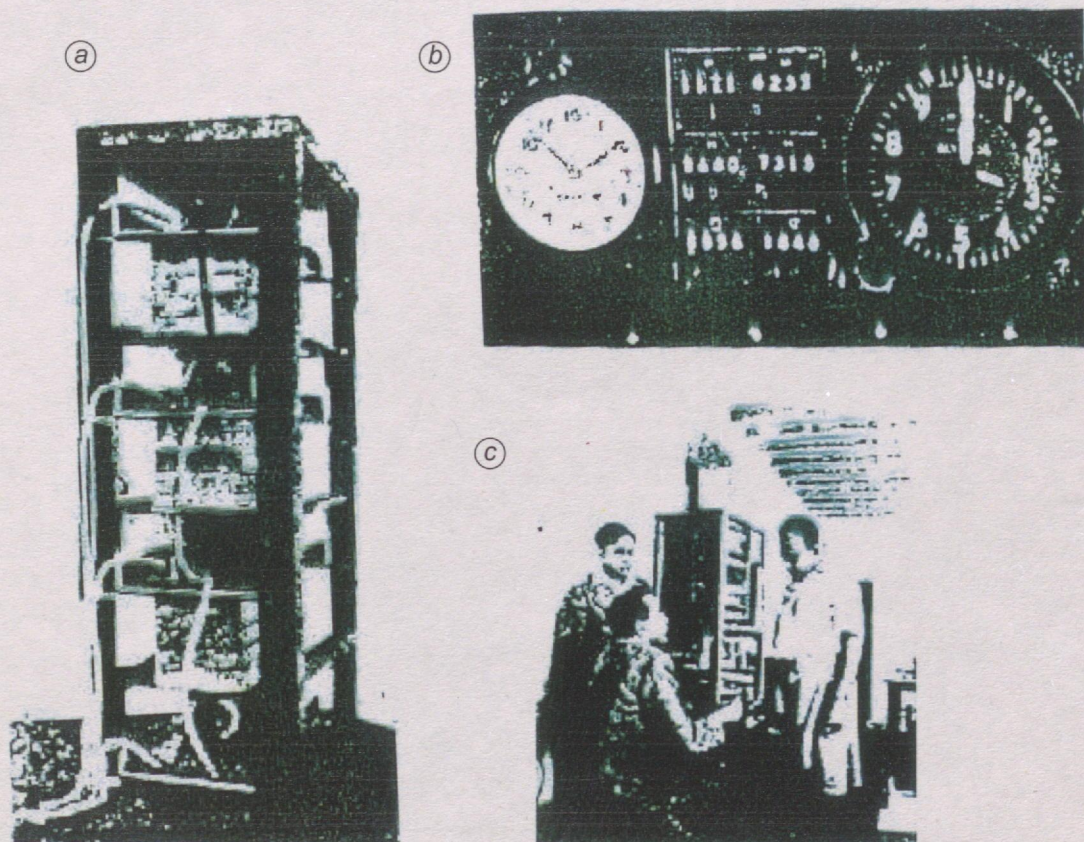


Figure 1. *a*, View of one of the units sent up to 32,000 ft with its sides removed. The top of the unit contains two cosmic ray telescopes. Electrical amplifiers are on the lower shelf. Dry batteries are at the bottom. *b*, Recording system for the experiment. *c*, Bhabha with his cosmic ray telescopes flown on B-29 aeroplanes from Bangalore in the early 40s. Seen in the photograph in discussion with Bhabha are S. V. C. Aiya and R. C. Saxena, his early collaborators at the Cosmic Ray Research Unit of the Indian Institute of Science.

Table 1. Various research, development and other activities at TIFR (during late 1940s)

Research	Development	Others
Mathematics	Electronic instrumentation	Elementary Particle Physics Conference, December 1950
Theoretical physics	Plastic balloons	Courses of Lectures in Mathematics, Statistics (Kosambi)
Cosmic rays	TIFRAC computer	Electronics (Kandiah from Harwell)
Nuclear physics	Vacuum technology	High Energy Physics (Peters)
	Cyclotron	Meson Theory (Marshak, Wentzel, Rosenfeld, Takagi)
	Plasma	Astronomy (Vainu Bappu)
	Liquid scintillation counters	Summer Schools in Theoretical Physics at Bangalore
	Spark counters	Dalitz, Gell-Mann, Chew, Mottleson, ...
	Neon hodoscopes	
	Total absorption spectrometer	
	Multiplate cloud chambers	
	Cockroft-Walton	
	Cascade generator	
	Microwave technology	
	BF3 neutron counters	
	Beta-ray spectrometers	



Figure 2. Homi Bhabha in preparation for flying a cosmic ray payload with a cluster of balloons from the Central College grounds at Bangalore (1940s).

Wednesday Colloquia were a regular weekly feature of the Institute. Some of the Distinguished Visitors during this period at the Institute were P. M. S. Blackett (Nobel Laureate), S. Radhakrishnan (UGC Chairman) and K. Chandrasekharan (Princeton).

Research and developmental activities at the Yacht Club building during September 1949 to 1 January 1962 led to sudden large scale expansion of activities. Compared to 6000 sq ft at Peddar Road, the area made available at the Yacht Club for TIFR (half of the Yacht Club building – the other half for DAE activities) was

35,000 sq ft. Table 1 lists the various research, development and other activities.

Research activities in mathematics

K. Chandrasekharan (K.C.) and K. G. Ramanathan (K.G.R.), both from Princeton University joined TIFR and K.C. was soon appointed as Deputy Director (Mathematics). Both of them were 30 years old when they joined TIFR. The new students who joined were C. S. Sheshadri, M. S. Narasimhan, S. Raghavan, R. Sreedharan, S. Ramanan, Singhbahl, K. Balagan-gadharan, K. Ramachandra, R. Simha, M. S. Raghunathan, Raghavan Narasimhan and S. S. Rangachari. In his talk at the inauguration of the TIFR building at Holiday Camp (Navy Nagar), Bhabha summarized the work of the school of mathematics till then (1962) in the following words (see Figure 3): ‘... My task would, however, be incomplete if I do not refer to the work of the school of mathematics and mention that it has established an international reputation for itself through the outstanding contributions which its members have made to various branches of modern mathematics. Credit for this must go to Professor K. Chandrasekharan who has carefully and painstakingly built up an exceptionally fine group of young mathematicians over the years. The Government of India has reason to be proud of the achievements of its National Centre for Mathematics’.

This glowing tribute to the school of mathematics was paid by Bhabha in 1962, just 12 years after K.C. and K.G.R. joined TIFR. This high tradition has been maintained by the school in the in-

tervening 43 years. There was a time in the 80s when all the faculty members of the school were Bhatnagar Award winners. In the last decade or so, three of them have become Fellows of the Royal Society. An activity in applications of mathematics was started by the TIFR math faculty in collaboration with the Department of Mathematics, IISc in the early seventies. A large number of distinguished mathematicians, especially from France, UK and USA have lectured at this joint programme. The four-yearly International Mathematics Colloquium organized by the math faculty started in the sixties has become a regular feature, which attracts mathematicians from all over the world. The faculty has also provided manpower at senior levels to other mathematical institutions in the country.

Nuclear physics at TIFR

The nuclear physics programme started in 1949 with the recruitment of Raja Ramanna, B. V. Thosar, S. S. Dharmetti, S. K. Bhattacharjee, S. Jha, Ambuj Mukherjee, E. Kondaiah and Balu Venkataraman, all postdocs who had obtained their PhDs abroad (USA and UK). The first three initiatives were: (a) Neutron physics and nuclear reactions (Raja Ramanna, Bhattacharjee and Kondaiah); (b) Beta-ray spectroscopy (Thosar, Ambuj Mukherjee, Jha); (c) Nuclear magnetic resonance (Dharmetti, Balu Venkataraman). The early students who distinguished themselves later in various capacities included P. K. Iyengar (later to be Chairman, AEC); M. C. Joshi (Head, Department of Physics, Mumbai University); R. Vijayaraghavan (Senior Professor, Dean, Physics

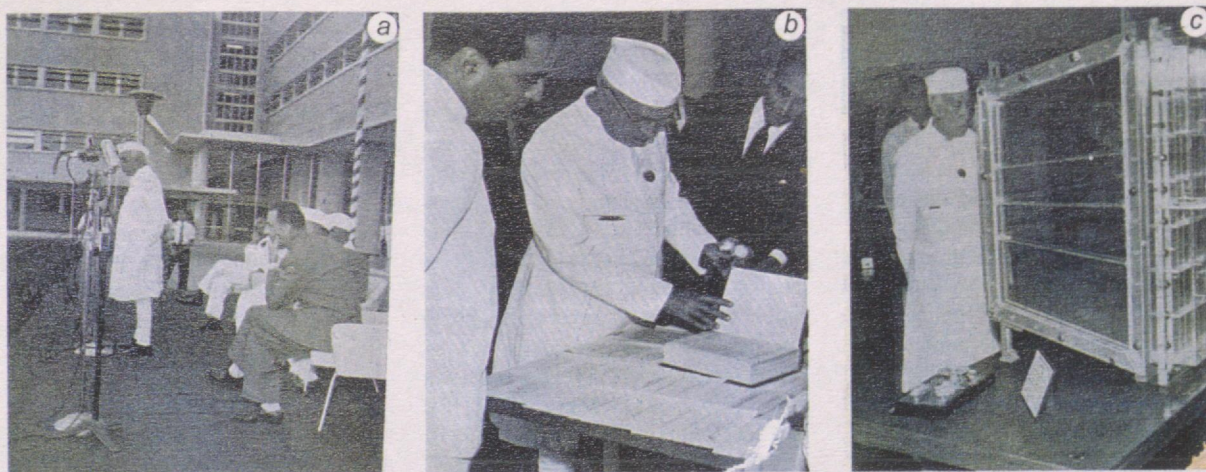


Figure 3. Pandit Jawaharlal Nehru at TIFR on the occasion of the inauguration of the new building at Colaba.

faculty TIFR); M. R. Das (Director of Cancer Research Institute, Thiruvananthapuram) and Sri V. G. Kulkarni (Director, Homi Bhabha Centre for Science Education).

Theoretical physics at TIFR

After moving to Yacht Club, Abraham, K. K. Gupta and Surya Prakash completed their PhDs in theoretical particle physics under the guidance of Bhabha and later moved to universities as professors of theoretical physics. Udgaonkar joined as a student under Bhabha and worked in the area of particle physics. He was also associated with reactor physics problems at Trombay. K. S. Singhvi who joined BARC, was also associated with TIFR. His interests were in solid-state physics, reactor physics and multi-particle production in nuclear collisions. He did not stay on in India for long and left for USA. D. Shankaranarayana joined Bhabha as a student and worked on problems relating to meson production and weak interactions. Virendra Singh joined as a student and was deputed to the University of Berkeley, USA to obtain his Ph D. Udgaonkar became Senior Professor at TIFR and also member of the UGC. Virendra Singh became Director of TIFR and Professor Emeritus. S. S. Jha joined TIFR after his training at the BARC Training School, was deputed abroad and obtained his Ph D from Stanford and later became Dean, Distinguished Professor and Director of TIFR.

An important new activity started during this period was the organization of summer schools in theoretical physics

every summer. Eminent theoretical physicists like Gell-Mann, Dalitz, Chew and Mottleson lectured at these summer schools. Another development was the setting up of the BARC Training School in which, in the initial years, TIFR played a major role. TIFR benefited a lot in return by getting some of the best students as research scholars in the various theoretical and experimental programmes of the Institute. Most of them became professors and faculty members of the Institute and contributed to its development in a major way. For some reason this was discontinued towards the end of the sixties and resulted in a serious deficiency of manpower, for experimental programmes in particular. TIFR lost a very good channel of recruitment of young scholars.

The Elementary Particle Physics Conference in December 1950

One of the important, I would say landmark events in the early history of TIFR was the organization by Bhabha of the first 'Elementary Particle Physics' conference in the world at the Yacht Club premises, which was attended by some of the most renowned scientists in the area of elementary particle physics and cosmic rays – Blackett, Leprince Ringuet, Amaldi, Rosenfeld, Auger, Peters Fowler (representing Powell) Wentzel, Peirls, and from India Saha, Sarabhai, Kothari, Raman and Madhava Rao. For us youngsters this was a unique opportunity to interact with the galaxy of outstanding scientists whose works we were familiar with. The proceedings of the

conference was very elegantly brought out by K.C., with the help of some of us.

Expansion of cosmic ray research

By the time we started working at the Yacht Club premises, cosmic ray research had entered into its new phase of elementary particle physics through the discovery of the pi-meson as the parent of the mu-meson, the mysterious penetrating component of cosmic radiation that had baffled the scientists in this field. The isolated cases of what were called V-particles observed in a cloud chamber experiment by the Manchester University scientists Rochester and Butler, had focused attention on the need for a careful study of the particles produced in high-energy nuclear interactions, both with nuclear emulsions with which pi-mesons had been discovered by Powell and cloud chambers in which the V-particles had made their appearance. Bhabha, with great foresight, had initiated activities using both these techniques – the nuclear emulsion and the cloud chamber for cosmic ray research. Daniel had set up a first-rate nuclear emulsion processing laboratory at Peddar Road itself, which was moved to the large basement laboratory at Yacht Club. Sahiar, who had brought the cloud chamber operating at Bangalore and set it up at Peddar Road, completed his observations on muon scattering and the chamber was moved to the Yacht Club. Several other cloud chambers were built over the next ten years.

The study of new particles created by cosmic rays in their collisions became the chief study of most of the cosmic ray groups in the world. In December 1954,

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two multiplate cloud chambers (named Rani and Maharani), one above the other, were set up in the laboratory at Ooty in the premises of Raj Bhavan and adjacent to the Botanical Gardens by A. B. Sahiar, Naranan, Subramanian and Ramana Murthy. One was 18" in diameter and the other 24" × 24" square chamber. The design of the set-up was to hunt for the production of new types of particles – the V-particles and the stopping particles produced by cosmic ray interactions in the brass plates of the chambers. The cosmic ray laboratory at Ooty has completed 50 years of existence. A variety of experiments on high-energy interactions and extensive air showers have been carried out in this laboratory. The world's largest multiplate cloud chamber (2 m × 1.5 m × 1 m) with 21 iron plates, each of 2.5 cm thickness was operated there as part of the air shower array and very significant results on the high energy nuclear interactions and cores of extension air showers were obtained. This constituted the Ph D thesis work of Vatcha.

A triple set-up (Figure 4) comprising of an Air Cerenkov Counter, a multiplate cloud chamber and a total absorption spectrometer designed by Sreekantan, Subramanian and Ramana Murthy, was operated to study the differences in the characteristics of interactions with nuclei

of protons and pions in the energy range 10–40 GeV, before the advent of the first CERN accelerator of energy 30 GeV in the early seventies. The operation of the Total Absorption Spectrometer in association with the Ooty EAS array enabled the time structure study of the nuclear active component of air showers (Figure 5) and led to the discovery that the nucleon–anti-nucleon production cross-section considerably increases with energy (thesis work of Tonwar).

B. Peters, M. G. K. Menon, S. Biswas, (Miss) Bibha Chowdhuri, Appa Rao, Gaurang Yodh joined TIFR during the period 1952–56 and gave a big boost to its cosmic ray activity. Nuclear emulsion stacks interspersed with brass plates, were flown from Hyderabad and the analysis resulted in the discovery of several types of K-mesons. D. Lal and Yashpal had joined the Institute as research scholars, and were part of this most exciting work on K-mesons. This work was extended to the study of hyper fragments by Swamy and Ganguli. Some very interesting work on meson production was carried out by Malhotra in collaboration with the Bristol group. In September 1950, one night when Bhabha was working on the programme details of the conference on elementary particles, he called me and said 'Sreekantan, you should plan to take a

Geiger Counter Telescope down the Kolar Gold Mines (KGF) and determine the flux of the penetrating particles as a function of depth and then take your mu-meson decay detector and see whether they are all muons or whether there are other types of particles there'. In September–December 1951, Naranan and I measured the penetrating particle intensity up to a depth of 1000 ft and soon followed this up with another hodoscope–telescope to measure angular intensity at various depths. Ramana Murthy had joined us by then and was part of this experiment. Following this, the three of us took a multiplate cloud chamber down the mines to a depth of 100 ft to study the interaction characteristics of muons. Some anomalies had been reported by the Manchester group which we wanted to explore further. However, soon we were asked by the mining authorities to vacate and leave since they were closing down all operations in the mines.

We shifted the cloud chamber experiment to an old abandoned railway tunnel in Khandala and completed the observations on muon interactions, and no anomaly was found. Since the Kolar mines did not close down, we returned to the mines for a long series of experiments at larger

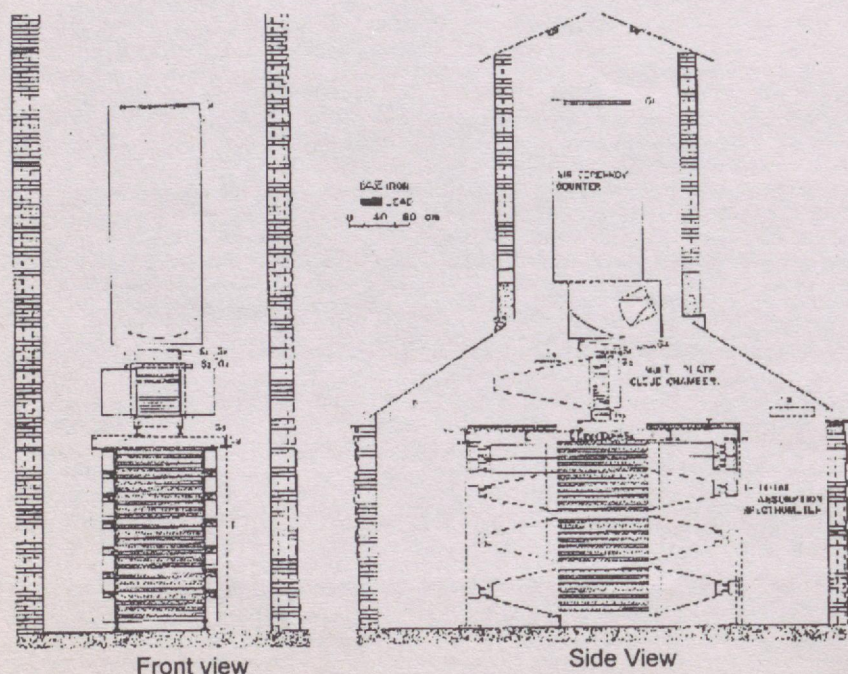


Figure 4. Triple arrangement of Air Cerenkov, multiplate cloud chamber and total absorption spectrometer at Ooty for study of interactions of pions and protons in 10–100 GeV range.

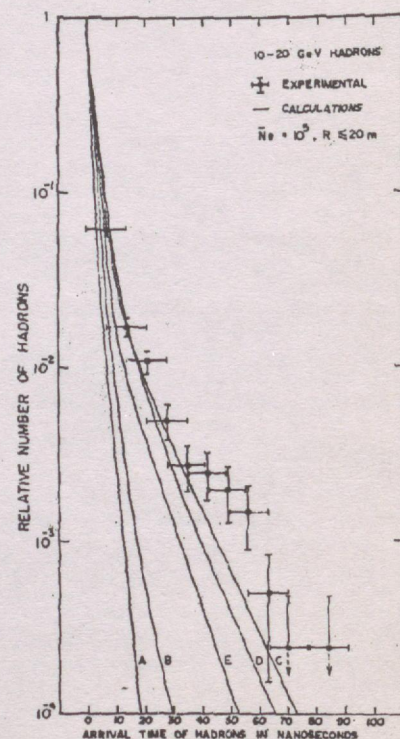


Figure 5. Time structure of nuclear active particles in air showers (Ooty results).

and larger depths. In this endeavour we were joined by two foreign groups, one from the University of Durham, UK (Wolfendale and others) and the other from the Osaka City University, Japan (Miyake and others). These experiments, started in 1958, lasted for 34 years (till 1992) and the mines were used up to a depth of 8000 ft below ground for a variety of experiments, namely for intensity and angular distribution of mu-mesons up to a depth of 8000 ft (Figure 6). Neutrino experiments, proton decay experiments and high energy muons (> 200 GeV) in association with air showers detected at the surface with a large array of scintillators (the KGF air shower array) were carried out in the mines over several decades.

Research and developmental activities at TIFR after moving to the permanent buildings at Navy Nagar in 1962 are given in Table 2.

Introduction of molecular biology and radio astronomy in TIFR

In a note that Bhabha had prepared to the Prime Minister Jawaharlal Nehru on the occasion of laying of the foundation stone of the TIFR building, on 1 January 1954, he writes: 'In June 1944, when I wrote a letter to A. V. Hill, FRS, Nobel Laureate, then Secretary of the Royal Society, informing him that the Tata Trust had decided to sponsor the project I put forward for setting up an institute for fundamental research in Bombay, the support of the Bombay Government and co-operations with the Bombay University was expected'. In the course of reply dated 22 June 1944, Professor A. V. Hill wrote: 'I am very glad, indeed to hear also that the Tata Trust has decided to sponsor your scheme for an institute for advanced research in theoretical and experimental physics in Bombay. I think you had better take biophysics under its wing, too. Apart from Bose Institute in Calcutta, that subject practically does not exist in India. I am sure many of the most important future applications of physics will be in biology. It sounds a grand scheme you have on hand . . .'. Later in his address to the International Council of Scientific Union at the Birla Hall, Bombay on 7 January 1966 Bhabha said, 'As early as June 1944, Sir A. V. Hill had written to me suggesting that biophysics was a neglected subject in India and that it should be taken under the wing of the Institute. While I agreed with this suggestion, I do not

think it would be wise to embark on this line till someone was found mature enough to be able to work on his own and build up a group. When however in 1962 my attention was drawn by Leo Szilard to a very promising Indian molecular biologist, it was decided to start work in molecular biology, which has since then been growing very satisfactorily. 'Well, the promising molecular biologist referred to above is Obaid Siddiqi. When he joined TIFR and undertook the responsibility of setting up the molecular biology unit, he was 30 years old. P. K. Maitra, who joined soon, was also 30 years old. Almost twenty years later, when we were reviewing the projections to be made of the activities of TIFR for the 7th Plan period, Siddiqi came up with the proposal to set up another centre outside Bombay for pursuing what he called pure (not applied) molecular biology. Initially there was some resistance to this proposal both from within the Institute and also from the Department of Atomic Energy. Some were not convinced about the necessity of setting up another centre. However, Siddiqi made it clear that this new centre will not disturb in any way the present structure, and will be built around new set of post-docs in the US, who are keen on returning to India and work in this area. As you know, this centre has now become the NCBS - National Centre for Biological Sciences and has already made a name

for itself both nationally and internationally.

In the same ICSU talk, Bhabha also mentioned about the starting of radio astronomy activity as part of TIFR: 'Four Indian radio astronomers had jointly written identical letters to the Chairman - UGC, Director General - CSIR and to me as the Chairman of the Atomic Energy Commission, offering to return to India as a group and establish radio astronomy here, if facilities and support could be given to them. Having ascertained that the members of the group had considerable original work to their credit and were of sufficient maturity to be able to work on their own in India, it was decided to take up radio astronomy at the Institute. Thirty parabolic dishes presented by CSIRO, Australia, which had been lying unpacked for several years at the National Physical Laboratory were handed over to the Institute by the willing co-operation of Husain Zaheer and have been installed not far from Bombay for solar radio astronomy work. In the meantime, a project has been developed for a large cylindrical radiotelescope for studying quasars and other radio sources and locating them accurately by lunar occultation. The telescope which will have four to five times the collecting area of Jordell Bank, will be designed and built entirely by Indian scientists and engineers and is expected to be in operation in two years.

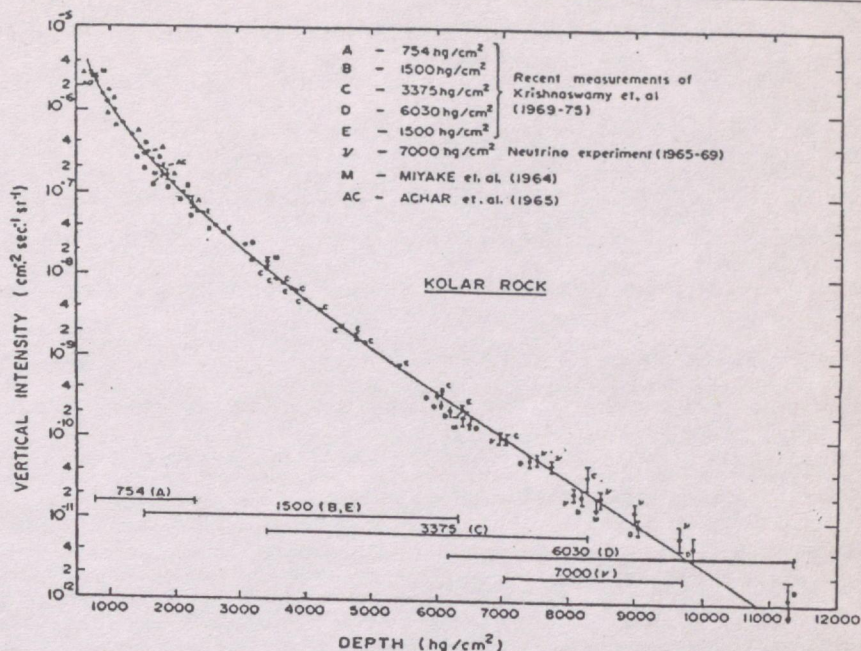


Figure 6. Muon intensity vs depth measured at KGF.

Table 2. Research and development activities at TIFR after 1962*

1. Mathematics (a) At Bombay and (b) IISc-TIFR joint programme in applications of mathematics after 1973.
2. Theoretical physics including particle physics, nuclear physics, solid state physics.
3. Theoretical astrophysics – started around 1969, covering cosmology, neutron star physics, solar oscillations, cool stars, pulsars.
4. Nuclear physics and atomic physics based on Cascade generator and Pelletron at TIFR and Van-de-Graff at BARC.
5. Cosmic rays studies based on
 - Balloon facility at Hyderabad addressing composition of Cosmic Rays and X-ray & gamma-ray astronomies
 - Rocket experiments from Thumba
 - Nuclear emulsion studies dealing with high energy interactions, primary electrons
 - Infrared astronomy
 - K-mesons, hyperons, etc.
 - Anuradha satellite experiment for study of anomalous cosmic rays; KGF experiments on muons, neutrons, proton decay
 - KGF air shower arrays with underground muon detectors Ooty air shower array with TAS and multiplate cloud chamber
 - Ooty GRAPE 1, GRAPE 2 and GRAPE 3 arrays [Figure 7 gives a view of the new air shower array at Ooty].
 - TeV Gamma-Ray Studies-Ooty [Figure 8 gives a view of an early versions of the TeV gamma ray telescope at Ooty]
 - Cosmic ray-induced radioactivity

It may be noted that International cosmic ray conferences were held at Jaipur (1963), Bangalore (1983) and at Pune (2005).

A new air shower array known as GRAPES built in collaboration with a group of Japanese scientists is now operating behind the Ooty radio telescope, with the world's largest area muon detector assembly and is expected to lead to important results on the composition of primary cosmic rays.

6. Solid state physics encompassing studies in magnetic materials, high temperature superconductivity, chemical physics – NMR spectroscopy.
7. Solid-state electronics and study of semi conductor materials.
8. Geophysics dealing with cosmic ray-induced radioactivity, rock magnetism and hydrology.
9. Computer science – the computers TIFRAC, CDC-3600 and CYBER were located at TIFR. In addition, speech synthesis studies and other projects were also undertaken. NCST (National Institute for Software Technology) was set up as a separate institution under the Department of Electronics in 1978.
10. Gravitational experiments related to equivalence principle, fifth force, Gowribidanur underground torsion balance.
11. Radio Astronomy at Ooty radio telescope, GMRT, NCRA, Pune.
12. Molecular biology (i) at Bombay and (ii) at NCBS, Bangalore.
13. Particle physics (i) at CERN and (ii) at Fermilab.
14. Microwave engineering dealing with TR-switches and Linac.
SAMEER – Society for Microwave Engineering and Research was set up under DOE in (1978).
15. Homi Bhabha Centre for Science Education (since 1970: TIFR, Grant Road, Trombay).

*See Boxed Items for details of some of these activities

Box I. School of Mathematics at TIFR

During the decade starting with the late fifties, several brilliant contributions came from members of the School who were still in their twenties. Raghavan Narasimhan proved the imbedding of open Riemann surfaces in IC^3 . C. S. Seshadri made the first big dent in a question (on projective modules over polynomial rings) raised by Serre. M. S. Narasimhan (in collaboration with S. Kotake, from Japan) came up with results that are among the precursors of the theory of pseudo differential operators. C. P. Ramanujam came up with an elegant solution of a problem in number theory that had eluded attack by such greats as C. L. Siegel. K. Ramchandra wrote on the 'Knorecker limit formula' inspired by Siegel. M. S. Narasimhan and S. Ramanan raised and answered a question in differential geometry which was to form the basis for the development, of the Chern-Simons invariant that was to impact on theoretical physics. M. S. Narasimhan and Seshadri wrote a great paper on 'Stable vector bundles', one of the most influential articles in this area. M. S. Raghunathan's work on 'rigidity' brought recognition to the institute in another area: algebraic groups and discrete groups.

– M. S. Raghunathan

A site for it has been selected after a very extended study, as the axis of the telescope which is 1700 ft long, has to be parallel to the axis of the earth. Work on the site at Ooty has already started. It is proposed to make this radio telescope one of the centres for inter-university

work'. (The four radio astronomers referred to above are G. Swarup, Kochu Menon, Kundu and Krishnan. The first three came to TIFR. In 1962, Swarup was 33, Kochu Menon 34 and Kundu also in the early 30s.) By 1970, the 530 m long and 30 m wide Ooty radio telescope started

operating at a frequency of 327 MHz (~92 cm wavelength) and several extragalactic radio sources were observed with high angular resolution and led to results of great importance to cosmic evolution. The telescope was also used for interplanetary scintillation studies and

Box II. Theoretical Physics: (an abridged version from a consolidated report prepared by M. Barma, Theoretical Physics Group, TIFR in January 1997)

The need for building a strong Theoretical Physics group was recognized from the very inception of TIFR, but it took several decades to achieve. During the first decade (mid-1940s–mid-1950s), Homi Bhabha's research in high energy physics constituted the overriding component of the output in theoretical physics. Along with a few associates and students, he worked on the theory of cosmic ray showers, meson production and nuclear forces. The principal contributions were the extension of the Fermi theory of meson production, the attempt to develop a postulational basis for the theory of elementary particles and the study of wave equations for arbitrary spin (Bhabha equations). Bhabha's strong involvement with the Indian atomic energy programme began towards the end of this period.

The decade, mid-1950s – mid-1960s was a period of expansion, with concomitant diversification of activity. Research programmes in theoretical nuclear physics and solid state physics began at this time. Some of the research areas covered in this period were nuclear model calculations, nuclear many-body problem, Bose gas, acceleration mechanism for cosmic radiation, stability and other problems in magnetohydrodynamics and hydro-magnetic turbulence, neutron scattering, and various problems in the strong, electromagnetic and weak interactions of elementary particles and their symmetries.

Some of the research areas in which significant contributions (plasma physics and astrophysics not included) included (a) *High energy physics*: (i) S-matrix theory and field theory, (ii) High energy scattering, (iii) Symmetries of strongly interacting particles, (iv) Infinite component wave equations, (v) Current algebra; sum rules and representation theory; chiral symmetries, (vi) Weak, (vii) Electromagnetic interactions, electro-production and photo-production at high energies. (b) *Nuclear physics*: (i) Nuclear structure and (ii) Nuclear reactions. (c) *Solid state physics*: (i) Linear and nonlinear optical properties of solids; electronic and phonon Raman scattering, (ii) Positron annihilation in solids, (iii) Electronic band structure calculations, (iv) Heisenberg Hamiltonian in magnetism, (v) Theory of phase transitions, (vi) Superconductivity (vii) Quantum fluids.

After 1970, the Theoretical Physics Group made research contributions at the frontiers of practically all areas of physics. The major advances and trends in physics in this period: the advent of gauge theories of strong and weak interactions, their supersymmetric extensions and the search for new particles predicted by these theories; the renormalization group; the emergence of string theory as the leading candidate for a unified theory of all particles and forces including gravity; high temperature superconductivity; nonequilibrium statistical mechanics.

In recent years, studies in high energy nuclear physics like quark structure of the nucleon and quark–gluon plasma and string theory emerged.



Figure 7. The GRAPES array at Ooty.

also for studies of solar phenomena. The Ooty radio telescope was also used for very long baseline interferometric studies in combination with radiotelescopes in Europe and USSR. By adding several small parabolic cylindrical telescopes (22 m × 9 m) up to 4 km, the Ooty telescope also operated for several years as a synthesis

telescope and provided radio maps of several galaxies and extragalactic radio sources. The Ooty radio telescope was extensively used by the Raman Research Institute, Bangalore and the Physical Research Laboratory, Ahmedabad. (Members who contributed to the development of the Ooty telescope are Joshi, Sharma,

Kapahi, Anantha Krishna, Veluswami, Bagri, Gopalakrishna, Venugopal, Manohar, Balasubramanian, A. P. Rao and Kulkarni.)

At the time of the 7th Plan projections, I was able to persuade Swarup to think of planning and building a radio telescope much bigger than the Ooty radio tele-

Box III. Theoretical astrophysics

The highlights of the Theoretical Astrophysics Group which came into existence at TIFR only in the early seventies may be summarized as follows:

- Central role played by molecular energy bands in physical processes in stellar atmospheres and giant molecular cloud complexes.
- Physics and chemistry of comets.
- Use of accurately measured oscillation frequencies of the sun to deduce its physical make-up (sound speed, density, temperature and chemical composition) and to understand the problem of the flux of missing solar neutrinos. Inference of the internal rotation rate and magnetic fields and their variations with activity cycle. Use of f-mode frequencies to accurately determine the solar radius and also its temporal variation. Setting constraints on the heavy element abundance on the core and on the p-p cross-section.
- Equation of state for very high density matter and models of neutron stars.
- Trajectories of particles around black holes and magneto-hydrodynamics around rotating black holes.
- Accretion flows and winds around compact stars such as neutron stars and black holes.
- Quasi-periodic oscillations of black holes due to shocks.
- Evolution of stellar binaries formed by tidal captures.
- Nature of matter distribution permitted by general consideration of global hyperbolicity of space-time and causality.
- Gravitational collapse, singularity theorems and existence of naked singularities.
- Existence of dark matter in the form of weakly interacting particles left over from the big bang, providing the gravitating background of invisible matter.
- Gravitational bending of light rays giving rise to the phenomenon of gravitational lensing and superluminal separation of VLBI components in quasars: Prediction of Einstein Rings in lensed systems.
- Topological defects in the universe and acceleration of particles to ultra-high energies and consequent radiation. Cosmological implications of cosmic strings.
- Quantization of the conformal degrees of freedom for studying cosmological effects of quantum gravity.
- Alternative cosmological models to big bang scenario.

– S. M. Chitre



Figure 8. The TeV gamma ray telescope at Ooty.

scope. He first came up with the idea of building a 2-km long telescope similar to the Ooty one at an equatorial station and investigated the possibility of locating this either in Indonesia or Kenya. Though extensive discussions were held with astronomers from these countries, it did not work out. Then Swarup came up with the idea of what is now known as the GMRT

(Giant Meter Wavelength Telescope) – a large number of parabolic dishes spread over 10–15 km and also came up with a novel design for the construction of the telescope which he used to call ‘the rope trick’, which enabled the dishes to be of relatively light weight and the cost much more economical. When this proposal was being discussed in the meeting of the

council of TIFR, J. R. D. Tata, who was the Chariman, wanted Swarup to be called in. He asked him two questions: (i) Is this going to be one of the best world class telescopes? (ii) What should be done to reduce the projected timescale of 7 years to half that time? He told Swarup that, in answering, he need not worry about the cost limitations.

Well, the GMRT with 30 telescopes (Figure 10 a, b) each of 45 m diameter spread over a distance of 13 km in the form of a ‘Y’, giving an effective collecting area of 30,000 m², became operational by 1999 at Khodad village about 80 km north of Pune, not far from the birthplace of Sivaji Maharaj. It is a modern state-of-the-art telescope with operating frequency bands – 150, 233, 325, 610 MHz and 1000–1450 MHz. The design of the array is such that it provides high sensitivity for detection of diffuse emission and high angular resolution. Though it took almost twice the time projected in the proposal, it has proved itself to be one of the world-class telescopes. It is also being used extensively by astronomers from outside the country.

Box IV. Radio Astronomy at TIFR

The Radio Astronomy Group was formed at TIFR in 1963. During 1965 to 1970, a 530 m long and 30 m wide cylindrical radio telescope was fully indigenously designed and fabricated at Ooty. The Ooty Radio Telescope (ORT) has a unique design. The 530 m long axis of the parabolic cylinder has been made parallel to the earth's rotation axis, by locating it in the north-south direction on an existing hill which has the same slope as the geographical latitude (about 11 degrees) of the station, thus enabling the telescope to track radio sources in the sky for about 10 h at a time by a simple mechanical rotation of its long axis. The ORT was designed to exploit the technique of lunar occultation to obtain high angular resolution and sensitivity to study the structure of faint extragalactic radio sources. One of its main objectives was to distinguish between the big bang and steady state models of the universe. The telescope provided high-resolution (about 1 to 10 arcsec) angular structures of over 1000 weak radio galaxies and quasars for the first time. A close relationship between the angular sizes of radio sources and their apparent flux density provided new and independent evidence against the steady state model of the Universe and implied evolution in the physical sizes of powerful radio galaxies and quasars with cosmic epoch. Over the last 35 years ORT has led to over 500 papers in refereed journals concerning pulsars, interplanetary scintillations, coronal holes, HII regions, supernova remnants, centre of our galaxy, radio galaxies and quasars.

In 1987, the Radio Astronomy Group started design and construction of the GMRT located about 80 km north of Pune. GMRT consists of 30 parabolic dishes (each 45 m in diameter) spread out over a region of about 25 km. The 45 m antennas have an economical and innovative design, with the reflecting surface of the antennas consisting of wire mesh made of thin wires supported by rope trusses. GMRT became fully operational in 2000. Operating at five different frequency bands between 100 and 1500 MHz, GMRT is one of the most complex and challenging projects undertaken by Indian scientists in the field of basic sciences. GMRT, the world's largest telescope operating in the above frequency range, is currently being used by over hundred astronomers from India and abroad for studying a variety of celestial radio sources from nearby Jupiter to the most distant radio galaxies and quasars in the universe.

Amongst many outstanding results yielded by GMRT, we may cite only a few: recent discovery of a pulsar in a crab-like supernova remnant with a deduced age of about 4000 years, another in a globular cluster with a very high ellipticity, discovery of three more pulsars in distant parts of our galaxy, HI and OH observations giving constraints on fine structure constant, studies of HI in our galaxy, nearby galaxies, particularly dwarf galaxies with much higher sensitivity than available before, discovery of several supernova remnants, search for microquasars in our galaxy associated with gamma ray sources, studies of the galactic centre, nearby galaxies, giant radio galaxies, X-shaped radio sources, etc.

– Govind Swarup



Figure 9. Prof. C. F. Powell addressing the delegates of the Cosmic Ray Conference at Jaipur in 1963. Homi Bhabha, M. G. K. Menon, Dobrotin, Hayakawa, Sreekantan, Alladi Ramakrishnan and D Lal are seen sitting on the dais.

Elementary particle physics

In the late fifties and early sixties particle physics, which was the monopoly of cosmic

ray studies, was taken over by higher and higher energy man-made accelerators. Since India did not have this facility, it was decided to collaborate with accelera-

tor groups at CERN in Geneva and Fermilab in Chicago. To begin with, projectors for bubble chamber picture analysis were set up after some of the members of the cosmic ray groups had training at these accelerators (A. Subramanian, P. K. Malhotra, S. Ganguli). Over the years, these collaborations have developed into active participation even in the development of various types of detectors required at the accelerators. Some of the collaboration is also with BARC and other institutions in the country. The Indian collaboration was part of a major international collaboration which resulted in the discovery of a particle called the top quark.

Microwave engineering – SAMEER

In 1950, Bhabha deputed R. V. S. Sitharam and G. H. Vaze to the Atomic Energy Establishment at Harwell for training in elec-

Box V. Space astronomies

Research in X-ray astronomy and far infrared astronomy has been carried out in TIFR using space-borne instruments. The X-ray astronomy observations have been made using balloon, rocket and satellite-borne instruments. The balloon observations in the hard X-ray band (20–100 keV) have yielded new and interesting results on variability and energy spectra of binary sources like Cyg X-1, Sco X-1, Her X-1, etc. The most interesting results include first detection of a hard X-ray flare in Cyg X-1 and observation of a change in the shape of X-ray pulse from a single-peak pulse to a double-peak pulse in the X-ray pulsar GX1+4. A major event in X-ray astronomy work at TIFR was the launch of the Indian X-ray Astronomy Experiment (IXAE) on the Indian satellite IRS-P3 in March 1996. The IXAE yielded new and exciting results on rapid X-ray variability in black-hole binaries and pulsation characteristics of X-ray pulsars. An important result was the discovery of quasi-regular X-ray bursts from microquasar GRS 1915+105 with unique features, which were interpreted as due to disappearance of matter behind the event horizon of the black hole.

The TIFR group has developed a 1 m aperture-sensitive balloon-borne telescope for far infrared photometry in 150 to 210 μm band. This telescope has been flown a large number of times and has provided new and interesting results. Major results include detection of protostellar candidates, energetics of warm gas in galactic star-forming regions and distribution of cold dust. This telescope has also been used for mapping of C II line at 158 μm in our galaxy.

Currently, the TIFR group is involved in the development of science instruments for the ambitious Indian astronomy satellite, Astrosat aimed at multiwavelength studies of cosmic sources.

– P. C. Agarwal

Box VI. High energy physics

The advent of multi-GeV high energy accelerators in the mid-1950s led to the participation of TIFR scientists in the study of controlled high energy interactions. The earliest experiments used nuclear emulsions which acted as a target as well as detector. A detailed study of hypernuclei (in which one neutron is replaced by a lambda particle) was carried out. From late 1960s, the bubble chamber technique was adopted and TIFR participated in various international collaboration experiments. Many studies on strange and charmed particles were carried out. From mid-1980s TIFR groups joined the L3 collaboration at LEP, CERN for the study of 100–200 GeV interactions, and later the D0 experiment at the Tevatron, FNAL to study 1.8–2.0 TeV antiproton–proton interactions. At LEP, the W and Z boson masses were precisely determined, the number of matter generations fixed as 3, detailed $Z \rightarrow b \bar{b}$ studies done and running of the strong coupling constant established according to QCD. At FNAL, the top quark was discovered in the mid-90s and searches for SUSY and other new particles, including Higgs, is continuing. In short, the standard model was consolidated. Both TIFR groups are now jointly participating in the future CERN–LHC programme, having joined the CMS collaboration. The main aim of the LHC programme with 14 TeV colliding proton–proton beams expected in 2007, is to understand the mechanism of mass generation in the universe by discovering or ruling out the Higgs boson and to search for new particles.

– A. Gurtu

tronics and H. L. N. Murthy, the Chief Glass Technician to the Corning Glass Company, England. On his return after a year or so, Sitharam was asked to develop a linear accelerator and at the same time Phadke had a group working on the construction of a cyclotron. Soon the cyclotron project was given up since the same group (Phadke, Rama, George Verghese, Divatia) was asked to work on the plasma-fusion project, since Bhabha had learnt from Cockroft that Harwell had evidence of neutron emission from their plasma experiments. This proved to be a wrong signal (!). Sitharam continued his work on the development of microwave cavities and electronics for the construction of the linear accelerator, which later led to

the construction of linear accelerators for medical purposes. In 1962, during the Indo-Chinese War, the defence services of the country suddenly realized that they were in short supply of Transit-receive (TR) switches (microwave-operated switches) for their imported radars and requested Bhabha for help. This was undertaken by Sitharam's group and the TR switches were delivered. This was followed by other defence requirements. Thus the microwave engineering group grew from strength to strength.

In 1976, discussions were held with the Department of Electronics to set up an autonomous unit for production of microwave devices. M. G. K. Menon was then the Chairman of the Electronics Com-

mission and Secretary to the Department of Electronics. A joint committee of the Department and of TIFR recommended the establishment of a separate unit with good scope for development since in its present location at TIFR, there were serious limitations. The SAMEER came into existence with Sitharam as the first Director, in the campus of IIT, Bombay, Powai.

Computer science – NCST

Similarly, around the same time due to the initiative taken by R. Narasimhan, the activities in the computer group of TIFR, were hived-off into another unit in the Department of Electronics – the National Centre for Software Training (NCST)

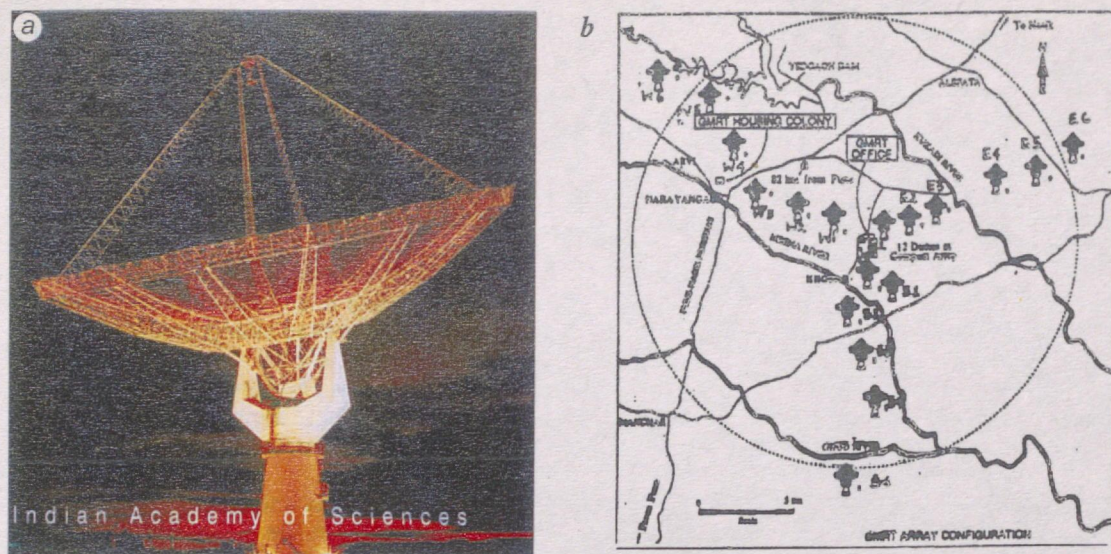


Figure 10. *a*, Typical GMRT telescope; *b*, The GMRT array.

Box VII. Solid state physics

To start, self reliance in instrumentation was stressed by Bhabha, which motivated us to construct a nuclear magnetic resonance spectrometer, with its associated highly stable homogenous and stable electromagnet system capable of detecting NMR signals from deuterium and oxygen-17 isotopes, from natural water [2, 4 parts in 10000]; NMR of chemicals, metals and alloys were studied. An important discovery in metal science was the correlation between susceptibility and microscopic nuclear magnetic resonance shifts in platinum alloys. Other studies related to oscillatory conduction electron polarization in metals, valence fluctuation, in rare earth alloys, heavy fermion behaviour. Thin film study of high T_c superconductors was a noteworthy contribution. The most remarkable discovery is superconducting nickel borides at very elevated temperatures for alloys. Low temperature magnetic studies in newly synthesized (CMR.GMR) compounds is a notable research activity.

– R. Vijayaraghavan

and set up in Andheri West area, with S. Ramani as the Director. The other members who moved with Ramani were Mudur and Sadanandan.

Homi Bhabha Centre for Science Education

Some of the senior academic members of TIFR (Udgaonkor, V. G. Kulkarni, Lagu and others), realizing that there is need for improvement in school education, and revision of syllabus at various levels, proposed the setting up of a small unit at TIFR for this propose. J. R. D. Tata readily agreed and in fact inaugurated the opening of this unit. Support was also forthcoming from Madhuri Shah, who was then the Director of Education, Maharashtra; she approved interaction of teachers of various municipal schools with the Centre. A large area was provided in one of

the schools near Grant Road. Over the years, this activity picked up and during the 7th and 8th plan periods, it became possible for TIFR to convert this into a National Centre and today the Homi Bhabha Centre for Science Education (HBCSE) is housed in its own building just outside the BARC complex. HBCSE is playing a major role in training students for the Olympiads in several subjects – mathematics, physics, biology, etc. and is also engaged in research in school education.

While it has not been possible for me to cover all the areas of research and development undertaken by TIFR in the last 60 years, I have been able to give you just a flavour of a few of the activities, I am more familiar about and how these came about and the persons behind these developments. The particular point I would like to emphasize is that the methodology was quite different and became possible

because of the policies initiated by Bhabha – confidence and trust in young people, full support and freedom given to them, the timely advice given by the visiting foreign scientists, opportunities for spending short and long periods in laboratories abroad, induction of foreign-trained scientists at various levels at the appropriate times, evaluation of projects and personnel involved by peers in the field, flexibility to start new programmes of research as and when required, emoluments at TIFR being relatively higher than in other institutions, housing facilities near the campus and so on. In the early years of TIFR when foreign exchange was scarce and the Indian industry was still very backward, the only way out was self-reliance and in-house development. Today the scenario has changed. There is no dearth for foreign exchange and the industry has also developed by leaps and bounds. If you look back at what the Institute has achieved in

Box VIII. Cosmic rays: (Extract from a talk by D. Lal delivered in the J.R.D. Centenary Series at TIFR)

A distinguished cosmic ray physicist, Bernard Peters, who had discovered the presence of multiply charged heavy nuclei in cosmic radiation, came to India in 1950 to conduct balloon flights to study the composition and nuclear interactions of energetic particles in cosmic radiation. In 1951, Bhabha invited him to join TIFR, which he did. The joining of Peters made a huge impact on the quality of research in the fields of cosmic radiation, high energy and elementary particle physics and geophysics, within a period of less than eight years that he spent at the TIFR. It would be fair to say that the contributions of the cosmic ray group during the fifties helped greatly in putting TIFR on the global science map.

Peters' approach to science was simple but one that is difficult to practise! He asked himself if he could find answers to questions that were important: questions which could immediately open further critical questions. The tremendous output of science in the short period that Peters spent at TIFR caused strong waves at TIFR, and in the country. Being privileged to be his student, I realized how hard it was to ask the right questions, the key to doing good science. I would often go to him asking his approval for carrying out certain experiments. Most of the time he quickly sent me home after asking a few simple questions such as what I expected to gain by doing the experiment. He said: assume a certain result of the experiment which you expect, and then ask yourself the question: what would I then learn?

What Bernard Peters did was to establish within a short span of time an important fact that we in India had all the capability to make discoveries and to do fundamental research, at par with the West, only if we had confidence in ourselves. And he assured us that we had the basic capability and that the confidence had to be built by asking good questions and doing well-thought-out science. What was considered good science? Again here the answer can be found in the fundamental approach of Peters: to ask critical questions and then to try to answer them. One does not have to leave one's room to get the answer to this fundamental question.

Peters demonstrated the power of his approach by his researches in the fields of cosmic ray physics, elementary particles, high energy physics and cosmic ray geophysics. During 1952–58, a large number of discoveries were made in the fields related to cosmic rays:

- (i) Composition of cosmic rays at the highest energies, from direct observations of cosmic rays, and also from phenomenology of extensive air showers.
- (ii) Studies of properties of elementary particles. This was made possible by the development of a continuously sensitive block of nuclear emulsion pellicles, which allowed tracing tracks of secondary particles to their origin. Besides providing valuable data, this study established associated production of two different types of elementary particles in one nuclear interaction, and the nuclear capture of negative K-meson, as it was called at that time.
- (iii) Discovery of ^{10}Be produced by cosmic rays, opening up the field of cosmic ray geophysics.
- (iv) Discovery of more than half a dozen cosmic ray-produced radionuclides, further highlighting the role of cosmic radiation in studying terrestrial processes in diverse branches of earth sciences; meteorology, hydrology and oceanography. ^{10}Be and several cosmogenic nuclides were in fact discovered whilst the group was working in the naval barracks, a few years before moved into the new TIFR buildings.

These were new areas of research. The field of cosmic ray geophysics was so new that it was considered a risky area to go into. I would like to narrate an interesting personal anecdote at this point. The year was 1954. Peters' group was busy discovering elementary particles and studying high-energy nuclear interactions. In 1947, Willard Libby had discovered ^{14}C , produced as a product of nuclear interactions of cosmic ray produced thermal neutrons with nitrogen nuclei in the atmosphere. He subsequently applied it for dating archaeological samples. Peters then had the idea that we look for the radionuclide, ^{10}Be , expected to be produced by cosmic rays in the atmosphere, since it would prove an excellent radio-tracer for determining geochronology of sediments, which contained rich information about the past history of the earth. I was then spending most of my time studying elementary particles and had discovered about 20 events in nuclear emulsions. The proposed ^{10}Be idea of Peters appealed to me greatly, and although it involved delving in new experimental areas, such as radiochemistry, I switched overnight and put all my efforts on discovering the cosmic ray-produced ^{10}Be as a geophysics venture. Several of my close friends then discouraged me from switching to ^{10}Be , telling me frankly that I was stupid; that I was going from high-energy physics to zero-physics.

The story of development of cosmic ray geophysics began in 1954. ^{10}Be was discovered in late 1955 in marine sediments. Peters' group took up this field putting full force on (i) discovering new nuclides expected to be produced by cosmic rays, and (ii) determining accurately the expected rates of production of various radionuclides by cosmic radiation in the atmosphere, because it became clear to us that cosmic rays provided a natural source of a large number of radiotracers for studying earth sciences, whose source functions could be determined precisely. Fifty years later, it is still a busy field and ^{10}Be itself is one of the two most important tracers in geophysics (the other being ^{14}C); it is employed as a tracer in many branches of earth sciences, including palaeoclimatology. With the present sensitivity of measurement of isotopes, the cosmic ray-produced ^{10}Be can be measured in about 1 mg of soil from the surface of the earth and ^{14}C in about 0.1 mg of carbon from any of the dynamic carbon cycle reservoirs.

its 60 years of existence, you find that TIFR has contributed significantly not only to several areas of fundamental research but also as the mother institution for several others – BARC, NCST, SAMEER, and also by setting up National Facilities – GMRT, NCBS, HBCSE and providing manpower at senior levels to many institutions and universities in the country.

I have mentioned the names of many scientists who have made TIFR what it is today. I must however mention one name again – that is of M. G. K. Menon who succeeded Homi Bhabha as the Director of TIFR during 1966–75 and later held various positions in Delhi – Chairman, Electronics Commission; Secretary, DST; Director General, CSIR; Minister of State for Science and Technology and so on. His personal participation in research and continued interest in TIFR, and his advice as member of the council of TIFR were indeed a source of great support for

all the succeeding directors of TIFR. D. Lal has made a relevant observation in his speech delivered here a few months back, that TIFR has not made any major path-breaking discovery in the last several decades. While I agree with this observation, I feel that this is not due to lack of effort or due to unproductive lines of research followed. There have been many near misses. Major discoveries, as is well known, are a matter of luck and serendipity plays an important role. Discovery of radioactivity, of radio astronomy, pulsars, X-ray sources in the sky, 3 K microwave radiation, all belong to the class of serendipitous discoveries. I am sure with the absolutely front-ranking research in string theory, the wonderful opportunities with GMRT and the efforts at NCBS, the prospects with the Astrosat and several new areas that have been initiated in recent years in solid state physics (nanophysics) and the maintenance of the rich tradition of the mathematics faculty, some truly outstanding

discoveries will emerge in the not too distant future.

Wonderful opportunities are opening up in theoretical and experimental cosmology with the staggering discoveries of accelerating universe, dark matter, dark energy and also in the field of neurobiology. I have been an optimist and I would like to remain one. After the talk, many scientists suggested that in the written version of this talk I should include the highlights of the research, especially in the early years. I requested some of my old colleagues to send brief write-ups about their perception of the research activities in their areas. Many were kind enough to respond. I have included these in the Boxed Items. I am most grateful to these scientists.

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