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Office of the Principal Scientific Adviser
to the Government of India

MSV
2035
A SNAPSHOT
PART - 2

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Foreword

Prof. Ajay Kumar Sood

*Principal Scientific Adviser to the
Government of India*



Foreword

The second issue of Vigyan Dhara on Mega Science Vision-2035 (MSV-2035) Exercise is before us — focusing on the MSV-2035 Reports on High Energy Physics (HEP) and Astronomy & Astrophysics (A&A).

HEP (together with Nuclear Physics) can be aptly called the progenitor of Mega Science Projects (i.e. Mega Science). The search for the most fundamental constituents of matter and the way they interact has taken us to the sub-nuclear scales and required the development of accelerators of higher and higher energy along with more and more sensitive and accurate detectors — all this culminating in the Large Hadron Collider (LHC) at CERN which stands as the contemporary high-point of experimental high energy physics. At the other end, the astronomers and astrophysicists have been trying to look at astronomical objects at larger and larger distance scales, and/or with greater and greater resolution, to unravel the large-scale structure of the Universe. This quest in the other direction (though ultimately complementary to the knowledge gained through the Particle Physics route) has also necessitated development of larger and larger telescopes (on the route) Earth or in the Space) for different kinds of “messengers” coming from the distant Universe towards us and detectors of unbelievable accuracy to understand what is there, and what is happening, in the Universe at large. So, Mega Science Projects (MSPs) have also become common in A&A now — with the JWST (James Webb Space Telescope) and LIGO (Laser Interferometer Gravitational-Wave Observatory) standing out as the two recent high points. LIGO confirmed the existence of gravitational waves after 100 years of Einstein's General Relativity through an interferometer that is a marvel in its accuracy. Gravitational waves have opened an entirely new observational window to the Universe. Needless to say, the mega science development in these disciplines has pushed the technological frontiers to unprecedented levels, revolutionising a wide range of scientific disciplines and technological sectors. The list is just too long! I must, however, mention that both these disciplines have also greatly aided in the foundational development and early use of big data, machine learning, etc.

From the few examples of MSPs that I have just mentioned, it is amply clear that such long-term, hugely collaborative projects of extreme technological complexity require huge resources — capital, financial, and human. Consequently, one can only have a few such projects being planned, constructed, or operated in any particular domain at any given time. Therefore, the concerned scientific communities, nationally as well as globally, go through intense and extensive consultations about the choice of such projects, typically over decadal

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timeframes. In the Indian context, such 'roadmap exercises' have come to be known as Vision Exercises. These were earlier conducted by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST) in the fields of Nuclear Physics (NP), High Energy Physics (HEP), and Accelerator S&T and Applications (ASTA); complemented by similar exercises in A&A by the Astronomical Society of India. The MSV-2035 Exercise, this time, has been facilitated by the Office of the Principal Scientific Adviser to the Government of India (OPSA). OPSA decided to enlarge the scope of the Exercise to include Climate Research (CR) and Ecology & Environmental Science (E&ES) as well. Five roadmap reports charting the Mega Science journey in NP, HEP, ASTA, A&A, and CR till 2035 have been released and are available on the OPSA website.

For wider dissemination, we decided to bring out some special issues of OPSA magazine Vigyan Dhara focusing on MSV-2035 Reports — this second one covering the ones on HEP and A&A. The first article by Dr Praveer Asthana, PSA Fellow in OPSA, gives a detailed background of the MSV-2035 Exercise and the elaborate and comprehensive consultation process that have led to these Reports.

The issue then contains short overviews of the two reports by eminent members of the two Working Groups — Prof. Amol Dighe from TIFR, Mumbai, and Prof. GC Anupama, formerly from IIA, Bengaluru. Apart from their own formidable expertise, they were very closely involved with the evolution and drafting of the two reports. I am sure these overviews will entice the readers to read the two detailed reports as well.

We also felt that it would be extremely valuable to bring for our readers conversations with two eminent and senior scientists who would be able to recall for our readers the mega science journey of the country in HEP and A&A, and their own take on the mega science enterprise in general. For this, we approached Prof. Atul Gurtu, formerly from TIFR, Mumbai, and Prof. Ajit Kembhavi, formerly from IUCAA, Pune. I am extremely happy that they readily agreed and were very generous with their time. We are carrying only excerpts from the two interviews — the full-length interviews are being put up on YouTube. I would invite the readers to listen to them for the rich information and words of wisdom that they contain.

This issue also contains two articles covering the national R&D ecosystems in HEP and A&A; their historical contexts, achievements, and future outlook. Once again, two very eminent scientists — Prof. Sreerup Raychaudhuri, BHU,

Foreword

Varanasi, and Prof. JS Bagla, IISER, Mohali — agreed to author these articles. Apart from their own impressive research standing in the field, they are both committed communicators of science — something that the readers will immediately discern.

This special issue would have remained incomplete without the perspectives from DAE, DST, and DOS, the three premier agencies which have been spearheading mega science projects and activities in HEP and A&A in the country. The chiefs of these agencies — Dr AK Mohanty, Prof. Umesh Waghmare, and Dr V. Narayanan — agreed to respond to some specific queries formulated by us that together present the perspectives of the government agencies from the point of view of management of MSPs in the country.

I am confident that the material contained in this special issue of Vigyan Dhara will convince our readers about the necessity and role of MSPs, especially in HEP and A&A; the scientific, engineering, technological, financial, and management challenges associated with such projects; and finally, the scientific and technological benefits that accrue from such mega science ventures. This should encourage you to read the detailed reports on our website. That will make all our effort in putting this special issue together especially fulfilling!

Mega Science and MSV-2035

1

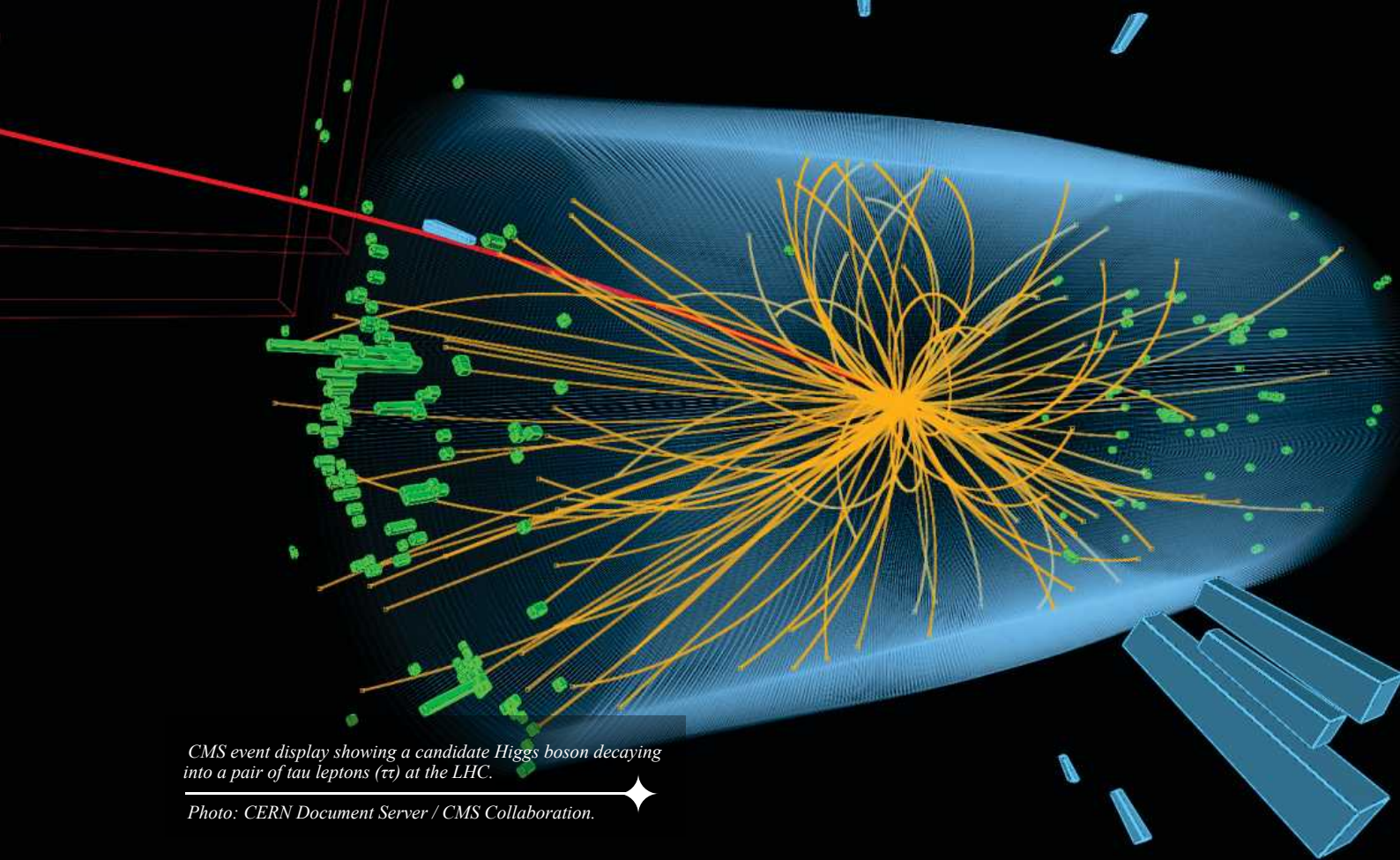
An Introduction



Dr Praveer Asthana
PSA Fellow, OPSA

Mega Science Projects (MSPs) or “Mega Science” — as they are popularly called — have become almost synonymous with the field of High Energy Physics (HEP) or Particle Physics. Whenever one thinks of MSPs, one's thought almost naturally veers towards the Large Hadron Collider (LHC), the giant particle accelerator operating at CERN, Geneva. MSPs are large and technologically complex experimental facilities requiring considerable human, capital, and financial resources to conceive, build, and operate;

making large-scale collaborations (often international) almost inevitable. Following a similar pattern as HEP, modern research in Astronomy & Astrophysics (A&A) also employs large experimental facilities to advance the frontiers of knowledge. Here, the James Webb Space Telescope (JWST), Laser Interferometer Gravitational-wave Observatory (LIGO), the planned Square Kilometre Array (SKA), or Thirty Meter Telescope (TMT) can be cited as more contemporary examples.



CMS event display showing a candidate Higgs boson decaying into a pair of tau leptons ($\tau\tau$) at the LHC.

Photo: CERN Document Server / CMS Collaboration.

It is important to point out at this stage itself for our non-specialist readers why such experimental facilities become necessary in certain fields. This is essentially because the scale at which one is trying to study physical phenomena in these fields requires such sophisticated instruments (that often happen to be large in size). Let us take the example of HEP. Here, one wants to find out what the most elementary constituents of matter are and how they interact to form the Universe. Over the decades, this quest has taken us from molecules and atoms (atomic and molecular physics) to nuclei and nucleons (nuclear physics) to quarks and leptons (sub-nuclear or high energy or particle physics). In order to explore matter at sub-nuclear distances, one needs projectiles of higher and higher energies, detectors of increasing sophistication, and extensive computing power to analyse the data. In essence, these are analogous to Rutherford's experiment, but at much tinier distance scales, and hence require facilities like the LHC to produce high-energy projectiles.

What have we gained so far by all this effort and investment? Well, we now have a Standard

Model of Particle Physics (SM) that tells us that matter is made up of six quarks and six leptons, interacting via strong and electroweak interactions (gravitation can be ignored at these scales); and also tells us how the Universe evolved roughly from 10^{-12} second to the first three minutes after the Big Bang. The SM also governs all processes involving these elementary particles even now, be those at accelerators/labs or in astrophysical settings. The theoretical consistency of the SM and the accuracy of its experimental confirmations are some of the greatest feats of human scientific endeavor. Befitting the human thirst for unravelling the ultimate mysteries of nature, the quest continues!

Studies in A&A take over from where HEP leaves us. As the Universe cooled and matter agglomerated, gravity became the decisive interaction and led to the large-scale structure of the Universe, the planets, the stars, the galaxies, the black holes, etc. In a way, both these disciplines complement each other and complete the story of cosmic evolution from Big Bang onwards. In A&A, we have moved outwards, trying to study farther and farther

objects in greater and greater detail. This has required telescopes/instruments that enable study of fainter and fainter objects, or observations at higher and higher resolution, with a variety of messengers such as electromagnetic waves, neutrinos, cosmic rays, gravitational waves, etc. sent towards us by various astrophysical objects. This has led to humankind building larger and more sensitive telescopes of various kinds on the Earth, or taking telescopes outside the Earth's atmosphere to avoid the interference from atmospheric processes. Here also, our understanding of astrophysical processes and their theoretical underpinnings has been very impressive. The very fact that we confirmed the existence of gravitational waves after 100 years of Einstein's General Relativity shows the ingenuity of theoretical foresight and the dogged perseverance to confirm it — opening, in the process, an entirely new window of observational astronomy. Be it the Higgs boson or be it the gravitational wave — these are some of the pinnacles of human scientific achievement. None of this would have been possible without the MSPs that the global scientific community jointly built. The author hopes that he has been able to convince the readers why such complex scientific ventures are undertaken and what they achieve. Being extremely complex experimental facilities, they push the very frontiers of technology with them. Apart from unravelling some of the deepest mysteries of the Universe, they are engineering marvels too!

Given their technologically-complex and resource-intensive nature, it is clear that at any given time, there will be only a few such facilities being built or operated nationally or even globally, serving the scientific ambitions of the concerned scientific communities. It follows as a simple corollary that the decision regarding which facilities to create or operate will be made after widespread consultations among the concerned scientific communities, nationally as well as globally. Such consultative exercises are periodically undertaken in all scientifically-mature nations of the world. They are known by different names in different nations. In the Indian context, these have come to be known as “Vision Exercises”. The last such Exercise in the fields of Nuclear Physics (NP), High Energy Physics (HEP), and Accelerator S&T and Applications (ASTA) was undertaken in 2014. As expected, this was facilitated by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST), these being the major funding agencies pushing R&D in these areas in the country. In the case of Astronomy & Astrophysics (A&A), the Astronomical Society of India (ASI) had been facilitating such exercises.

By 2020, it was widely felt by various scientific communities in the country that a time had come to embark on the next Mega Science Vision (MSV) Exercise. The reasons were broadly as follows:



Most of the MSPs identified in the earlier Vision Exercise (and also a few new ones that had emerged later) had moved forward towards funding and/or execution



India was being approached by the international scientific communities to become a part of several ongoing and new global projects



An increasing need was also being felt to launch several new-generation MSPs nationally to bolster our technological self-reliance in important areas



The mega science community in the country in areas like NP, HEP, ASTA, and A&A had grown across institutions and also in absolute numbers, and had become scientifically more confident and ambitious



India's economy was becoming competitive and emerging on the global scene



The Indian industry had also matured in high-tech-intensive areas and was well-poised to take on newer challenges



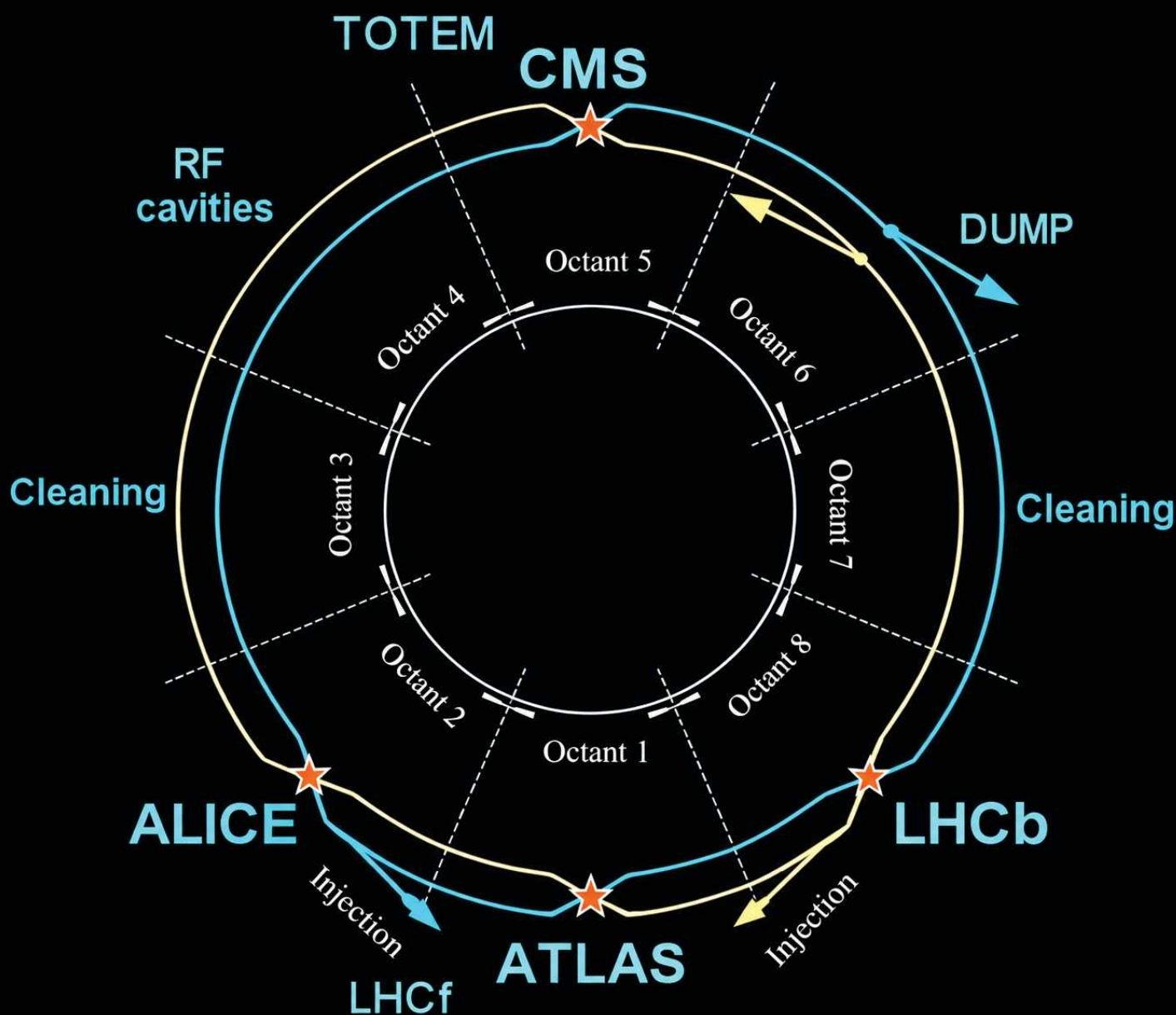
Steps were needed to continuously nurture the mega science eco-system in the country so that the availability of human resource and technological knowledge could be sustained

It was also felt that the culture of mega science had moved beyond the traditional areas of NP, HEP, ASTA, and A&A, and hence a more broad-based exercise was needed. After consultation with DAE and DST, it was thus decided that it would be more appropriate if the Office of the Principal Scientific Adviser to the Government of India (OPSA) facilitated the next Exercise, given its pre-eminent policy and coordination role in the government. As for the time frame, it was felt that the period till 2035 would be an appropriate period, given

the typical timelines of MSPs and the lifecycle projections for various ongoing projects. Thus started the Mega Science Vision-2035 (MSV-2035) Exercise facilitated by the OPSA. The OPSA also decided to enlarge the scope of the Exercise to include two additional disciplines, viz., Climate Research (CR) and Ecology & Environmental Science (E&ES)--- thus bringing the total number of disciplines to be covered to six (NP, HEP, ASTA, A&A, CR and E&ES). The outcome was to be one “Roadmap Report” in each of the six areas

containing a prioritised list of MSPs, and associated feeder eco-system activities, to be undertaken till 2035 after assessing the needs, strengths, weaknesses, and potential for mega science activities. Five of the six MSV-2035 Reports have now been released and are available on the OPSA website. This special issue of OPSA magazine, *Vigyan Dhara*, brings for its readers the highlights

of the MSV-2035-HEP and MSV-2035-A&A Reports, along with interviews with, and articles by, eminent scientists associated with the national R&D system in these two disciplines. As has been described in the beginning of this article, these two disciplines scientifically form a natural pair, and that is why they have been clubbed together.



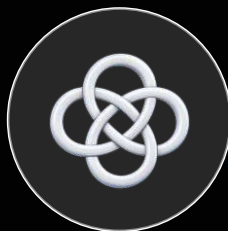
To kick-start the MSV-2035-HEP Exercise, OPSA requested TIFR, Mumbai to act as the Nodal Institution and also nominate a Nodal Scientist. TIFR readily agreed to this and nominated Prof. Amol Dighe as the Nodal Scientist. For the MSV-2035-A&A Exercise, IUCAA, Pune, and IIA, Bengaluru, were requested to act as the Nodal Institutions. They also agreed and nominated Prof. R. Srianand from IUCAA as the Nodal Scientist. In consultation with these Nodal Institutions and Nodal Scientists, a Working Group (WG) was constituted by OPSA, one each for HEP and A&A. These were chaired/co-chaired by

the Director/s of the respective Nodal Institution/s. Prof. Amol Dighe served as the Member-Secretary of the WG-HEP and Prof. R. Srianand, as the Member-Secretary of the WG-A&A (it so happened that towards the end of the MSV-2035-A&A Exercise, Prof. R. Srianand became the Director of IUCAA and he acted for some time both as the co-Chair of the WG-A&A, as well as its Member-Secretary). A sub-group of each WG acted as its Drafting Group (DG). The compositions of the two WGs have been given in Boxes 1 and 2 below.

Nodal Institutions For MSV- 2035 (HEP and A&A)



**Tata Institute of
Fundamental Research**
MSV- 2035- HEP



**Inter-University
Centre for Astronomy
and Astrophysics**
MSV- 2035- A&A



**Indian Institute of
Astrophysics Bangalore**
MSV- 2035- A&A

Both the WGs produced several drafts of the Report after carrying out widespread electronic consultations with the national research community (750 researchers in case of HEP; and 1000, in case of A&A), and also with eminent national/international experts (24 experts in case of HEP; and 19, in case of A&A). These drafts were also thoroughly discussed several times among the members of the WGs. The penultimate drafts were also presented before the PSA and the Scientific Secretary in the OPSA. After incorporating their comments as best as possible, the final Reports were prepared and submitted to the OPSA by the Nodal Institutions on behalf of the two communities.

These Reports are “Community Documents” and they express the dreams and aspirations

of the two scientific communities about their Mega Science journey till 2035, as best as they can foresee now. Given the fast pace of developments in S&T, it is possible that there may be some momentous developments in the two fields in the meantime. These will have to be accommodated at the appropriate moments, if and when they arise. And these Reports will anyway get updated during the next MSV Exercise, perhaps after another 5 years.

Finally, a few words about the utility of these Reports. We are confident that the two scientific communities will find these useful while formulating project proposals for various MSPs and other allied activities/facilities identified in these Reports. In addition, the funding agencies should find

these useful while evaluating those proposals and in putting appropriate decision-making processes in place. They should also find these useful while evaluating proposals for international collaborative projects received through diplomatic channels. As these reports contain the distilled, considered, and prioritised views of the HEP and A&A communities in the country, we expect that they will prove valuable in nurturing the entire mega science eco-system in the country in HEP and A&A.

A Collaborative Process for Generation of MSV Reports



Box 1
WORKING GROUP (WG-A&A)
Nodal Institutions: IUCAA (Pune) and IIA (Bengaluru)

Chairperson
Co-Chairperson

Dr Somak Raychaudhury / Dr R. Srianand (Director, IUCAA, Pune)
Dr Annapurni Subramaniam (Director, IIA, Bengaluru)

Drafting Group

Member
Member
Member
Member

Dr G. C. Anupama, IIA, Bengaluru
Dr Jasjeet Singh Bagla, IISER-Mohali
Dr Ritaban Chatterjee, Presidency University, Kolkata
Dr Shashi Bhushan Pandey, ARIES, Nainital

Other Expert Members

Member
Member
Member
Member
Member
Member

Dr Yashwant Gupta, TIFR-NCRA, Pune
Dr D. K. Ojha, TIFR, Mumbai
Dr Anandamayee Tej, IIST, Thiruvananthapuram
Dr Dibyendu Nandi, IISER-Kolkata
Dr Sanjit Mitra, IUCAA, Pune
Dr Hum Chand, Central University of Himachal Pradesh, Dharamshala

Agency Representatives

Member
Member
Member

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Shri Gaurav Aggarwal, DST, New Delhi (Nominee of Secretary-DST)
Dr V. Girish, ISRO, Bengaluru (Nominee of Secretary-DOS)

Representatives of O/o PSA

Member
Member

Dr Praveer Asthana, PSA Fellow & National Coordinator
Dr Arun Bhardwaj, Former Scientist-F (now, Department of Space)

Member-Secretary

Nodal Scientist - Dr R. Srianand, IUCAA, Pune

Box 2

WORKING GROUP (WG-HEP)

Nodal Institution: TIFR (Mumbai)

Chairperson

Dr Jayaram Chengalur
(Dr S. Ramakrishnan)
(Dr Sandip P. Trivedi)
Director, TIFR, Mumbai

Drafting Group

Member

Dr Amol Dighe, TIFR, Mumbai

Member

Dr Sreerup Raychaudhuri, TIFR, Mumbai

Member

Dr Sudhir Vempati, IISc, Bengaluru

Member

Dr Seema Sharma, IISER Pune

Member

Dr Anirban Kundu, University of Calcutta, Kolkata

Member

Dr Pratik Majumdar, SINP, Kolkata

Other Expert Members

Member

Dr Kajari Mazumdar, TIFR, Mumbai

Member

Dr Pravata K. Mohanty, TIFR, Mumbai

Member

Dr Jim Libby, IIT Madras, Chennai

Member

Dr Bipul Bhuyan, IIT Guwahati

Member

Dr Brajesh Chaudhary, University of Delhi

Member

Dr Manas Maity, Visva Bharati, Santiniketan

Member

Dr Bhawna Gomber, University of Hyderabad

Member

Dr Sanjay Swain (India-CMS Spokesperson), NISER, Bhubaneswar

Agency Representatives

Member

Mr Sanjay Malhotra, BARC, Mumbai
(Nominee of Chairman-AEC/Secretary-DAE)

Member

Shri Gaurav Aggarwal, DST, New Delhi
(Nominee of Secretary-DST)

Representatives of O/o PSA

Member

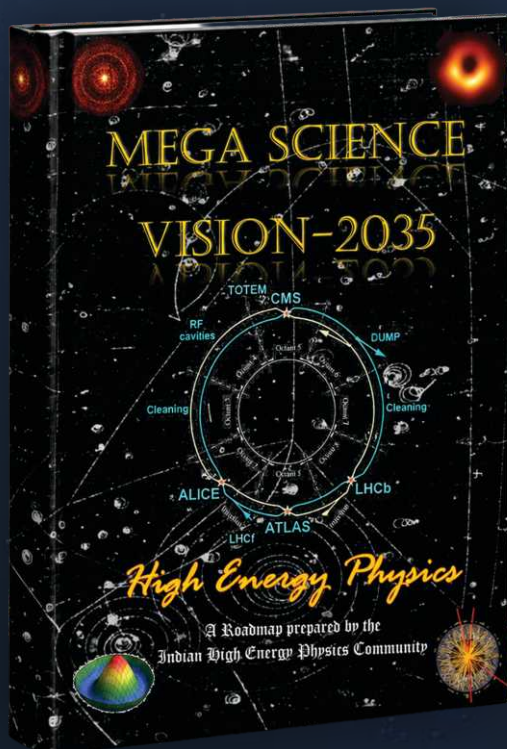
Dr Praveer Asthana, PSA Fellow and National Coordinator

Member

Dr Arun Bhardwaj, Former Scientist-F (now, Department of Space)

Member-Secretary

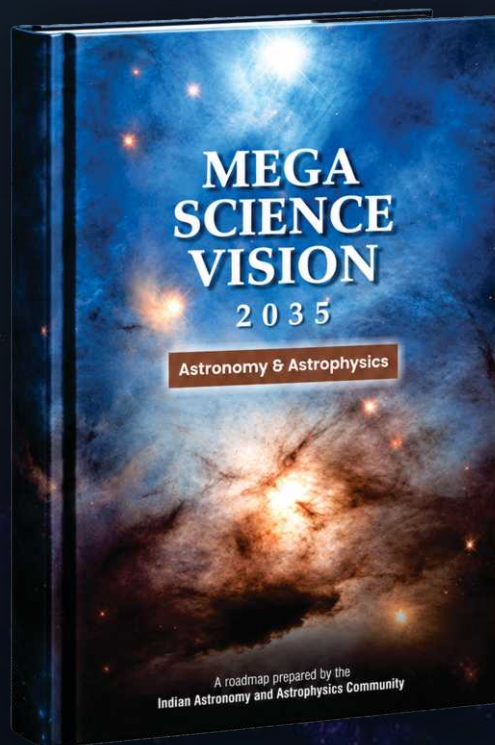
Nodal Scientist- Dr Amol Dighe, TIFR, Mumbai



Scan to Read
**Mega Science
 Vision- 2035:
 High Energy
 Physics**



Scan to Read
**Mega Science
 Vision- 2035:
 Astronomy &
 Astrophysics**



Mega Science Vision-2035 (High Energy Physics)

A Quest Towards Understanding Nature
at its Smallest



Dr Amol Dighe

*Professor, Department of Theoretical Physics,
Tata Institute of Fundamental Research*

The field of High Energy Physics (HEP) explores minute subatomic particles – already present as components of nuclei, produced at the particle colliders by conversion of the collision energy into mass, or coming to the Earth in the form of cosmic messengers of astrophysical phenomena taking place in the Universe. It studies the interactions among these particles to understand how they make up the world around us and scientifically approaches the question of existence of particles that have not yet been observed directly but would be needed to make our understanding of the Universe complete.

By its very nature, which needs knowledge and expertise from multiple subdisciplines –

including powerful particle accelerators, ultrasensitive detectors, precision electronics, large quantity of data processing, high-performance computing, and phenomenology that connects the observations to theories – the pursuit of HEP is a collective and collaborative endeavour. Further, some of the crucial questions in HEP can potentially be addressed with astrophysical observations of high-energy particles, making the field of astroparticle physics an inseparable part of HEP. Given the need for large amount of human resource with scientific and technical expertise as well as funding, it is important to have a consolidated view of the activities in this area that can be carried out over the next couple of decades.



The CMS experiment, seen on the left, is one of the two general purpose detectors at LHC

Photo: The Institute for High Energy Physics and Astrophysics, University of Florida

The Mega Science Vision – 2035 (HEP) is the outcome of a community exercise that focused on:



Which science questions are important to pursue collectively;



Which questions can be addressed practically in the next decade, given the experience, expertise, and resources available;



What needs to be done to build up the infrastructure / ecosystem;



What would facilitate the inception of new mega science projects;



What spinoffs may be generated;



How the interaction with industry can be increased;



How much human resource and funding needs are envisaged.

The Report is also a repository of information about current mega science projects that Indian scientists are involved in. The discussion of these issues within the community has led to an introspection about what we have learnt over the years, what expertise we have gained, and projects of what scale we can implement.

The Science Questions and Pathways to Address Them

There is a reasonable consensus in the global HEP community about the crucial scientific questions in this area. Some of the most important among these are deciphering the precise nature of electroweak symmetry breaking that gives masses to most particles, the origin of masses and their connection with the existence of particles hitherto unknown, the nature of dark matter and dark energy, the origin of the matter-antimatter asymmetry in the Universe, etc. The pathways to find how Nature answers these questions is to perform experiments at three frontiers:



Energy frontier: interactions at high energies produces heavy short-lived particles;



Intensity frontier: precision measurements can enable us to measure quantum corrections due to such heavy particles that do not even have to be produced; and



Cosmic frontier: multiple cosmic messengers can be observed and their energy content measured to find signals of even ultralight particles that may never have been seen before.

Figure 1 shows a schematic depiction of such pathways. Note that the progress along these paths depends crucially on a strong foundation of detector R&D (instrumentation, electronics, data processing, etc.) and high-performance computation (using machine learning, artificial intelligence, lattice-based computations, etc.)

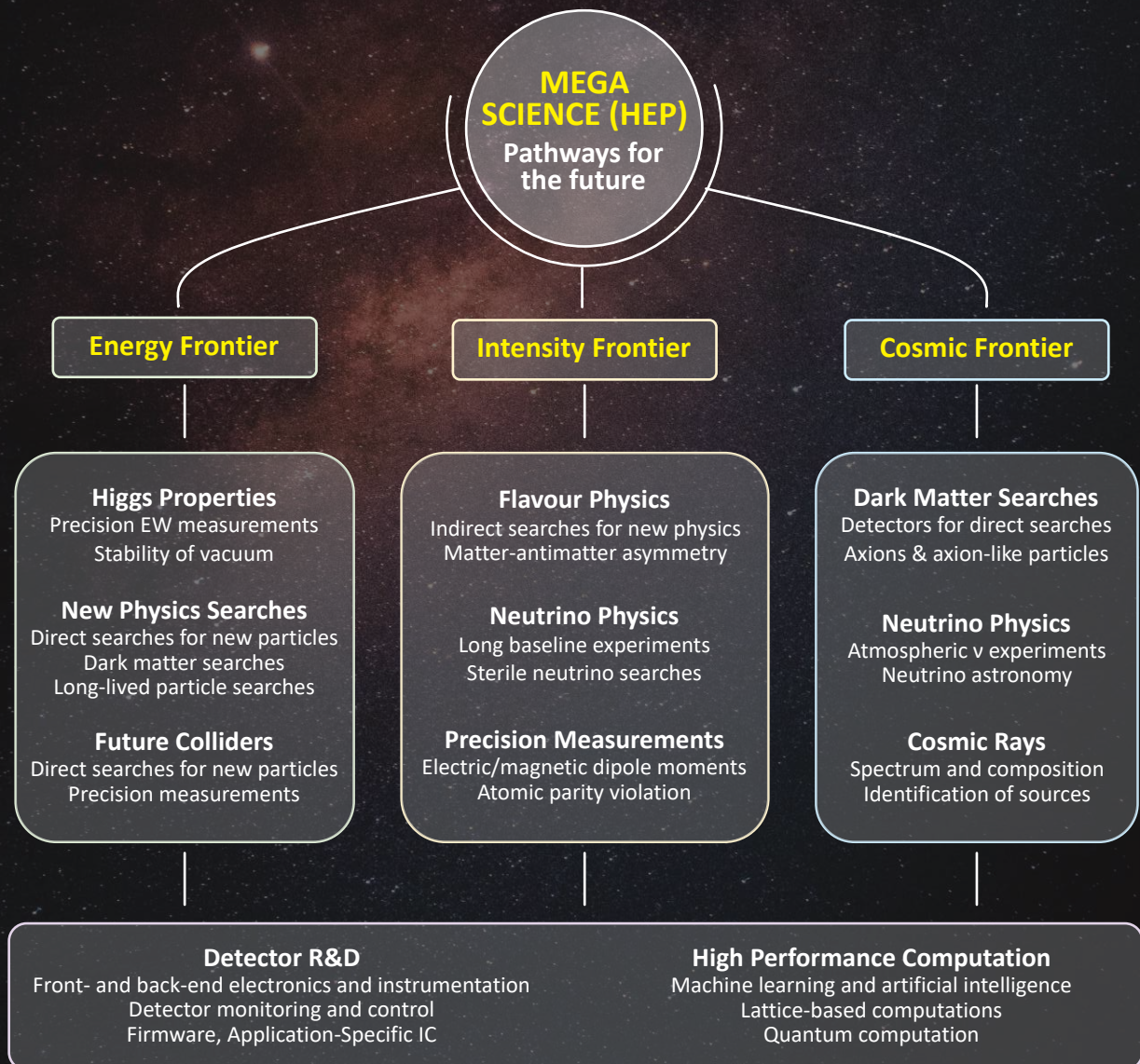


Figure 1: Schematic depiction of pathways to answer fundamental questions of Nature

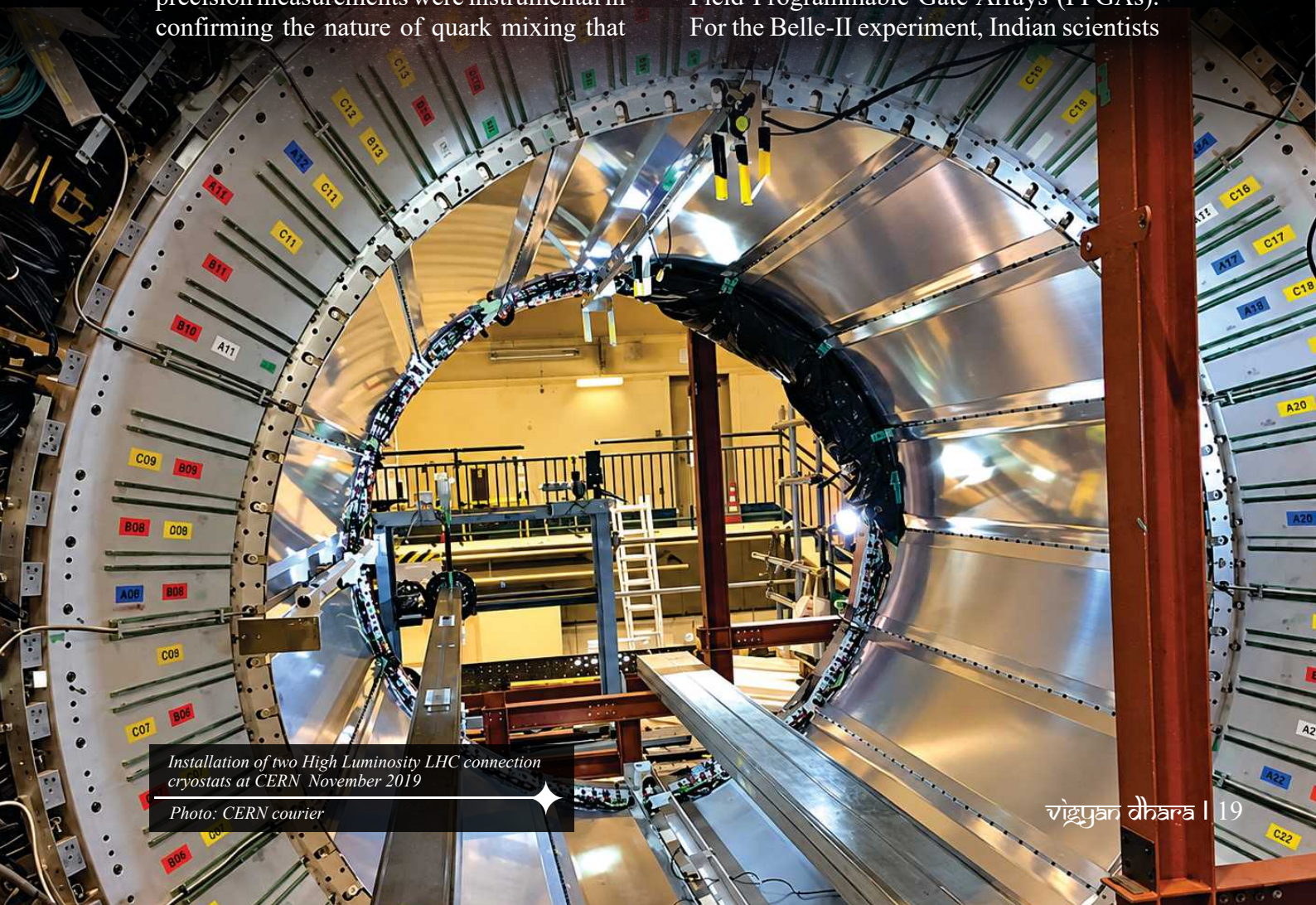
Where We Are and What We Have Achieved

At this point, it may be worth recounting the activities Indian HEP community has been involved in over the last few decades, which would give us a perspective on what our current capabilities are and what we can realistically aim to achieve in the near future.

As far as experiments at particle colliders are concerned, Indian scientists have been involved in past experiments such as the DØ at Fermilab (USA), the L3 at CERN (Switzerland), and are currently a part of the CMS and ALICE experiments at CERN. During this time, they have been part of the collaborations that discovered the top quark (1995) and the Higgs boson (2012, a discovery that completed the Standard Model of particle physics and led to the Nobel Prize in 2013), and measured the width of the Z boson precisely enough to confirm that there can be no more than three active neutrinos. They have also worked with the Belle and Belle-II experiments at KEK (Japan), whose precision measurements were instrumental in confirming the nature of quark mixing that

led to the Nobel Prize in Physics in 2008. India is now an Associate Member of CERN, further opening opportunities for our scientists, technologists, engineers, and industry.

Indian HEP participation in these experiments has been at the level of physics analysis, key software development, and as in-kind contributions to the detector, which has resulted in capacity building in the relevant technologies in-house. The Indian community has supplied silicon-strip modules for the pre-shower detector of the CMS experiment as well as Silicon Photomultiplier (SiPM) readout boards, control systems, and calibration modules for the CMS hadron calorimeter. They are developing next-generation trigger readout boards to adapt to much larger particle multiplicity at the High-Luminosity Large Hadron Collider (HL-LHC), with technology based on high-speed optical links and fast Field-Programmable Gate Arrays (FPGAs). For the Belle-II experiment, Indian scientists



Installation of two High Luminosity LHC connection cryostats at CERN November 2019

Photo: CERN courier

have contributed parts of the Silicon Vertex Detectors (SVDs). In the near future, the community is committed to deliver silicon-based detector modules for the outer tracker upgrade for the HL-LHC, and to develop thin-sensor strip detectors with a finer pitch for the Belle-II experiment.

In astroparticle physics, over the years, the Gamma Ray Astronomy at Pev Energies (GRAPES) experiment has succeeded in making high-quality plastic scintillators with high light-output and timing. It also excels in indigenous development and production of ultra-fast amplifiers, discriminators, fan-in/fan-out modules, Time-to-Digital Converters (TDCs), FPGA-based signal-processing, and data-recording electronics at

a fraction of the cost of imported modules. As a part of the R&D for the High Altitude Gamma Ray (HAGAR), Major Atmospheric Cherenkov Experiment (MACE), and Cherenkov Telescope Array (CTA) experiments, SiPM-based cameras are being developed. Resistive Plate Chambers (RPCs) developed for the CMS experiment have enabled the capability for producing large-size RPCs for the Iron Calorimeter (ICAL) experiment that was proposed to be carried out as a part of the India-based Neutrino Observatory (INO) project. A prototype mini-Magnetized ICAL recorded cosmic ray data at Madurai for more than 5 years. Such a detector has the potential to be used for future underground experiments.

Where We Want to Go Next: The Priority Mega Science Projects

Based on the foundations of where we are, and an assessment of what our capabilities are, the following are the top priority MSPs recommended:

Collider Experiments

Continued support should be provided to the current HEP MSPs: CMS and Belle II. Planning and R&D efforts for experiments at future colliders such as FCC-ee/FCC-pp and/or a muon collider should start. Instrumentation R&D for new technologies for future detectors (e.g. quantum sensors) should be a priority.

Underground Experiments

Efforts to establish an underground observatory in the country for experiments in HEP, Nuclear Physics, and Astrophysics should continue. A dark matter search experiment using new technologies may be a flagship experiment at such a facility.

Neutrino Experiments

Participation in Deep Underground Neutrino Experiment (DUNE) should be encouraged, especially if there is a possibility of building an important component of detector.

Cosmic Ray Experiments

Continued support for GRAPES-3 and MACE, and the neutrino scattering experiment-Indian Coherent Neutrino-nucleus Scattering Experiment (ICNSE). Stereo MACE to be aggressively pursued. Participation in CTA is strongly recommended, given its synergy with MACE.

From a long-term strategy perspective, it is also important to encourage and develop indigenous projects that may be currently small-scale but have the potential to grow into MSPs. Some such projects are

- The dark matter detection experiment such as Indian Dark Matter Search Experiment (InDEX)
- Observation of low-energy solar neutrinos using Deuterated Liquid Scintillator (DLS)
- The neutrinoless double beta decay experiment (TinTin)
- The reactor monitoring and sterile neutrino search experiment such as Indian Scintillator Matrix for Reactor Anti-Neutrinos (ISMARAN)
- Satellite-based experiments exploring the Universe in medium-energy gamma rays

Jaduguda Underground Science Laboratory (JUSL), Jharkhand established for rare-event physics experiments such as InDEX

Photo: Strategic Front

How To Facilitate the Initiation of an MSP

Initiating and successfully carrying out an MSP needs a critical mass of scientists, engineers, and other trained personnel, as well as financial support from funding agencies. The proposed mechanisms for increasing the ease, transparency, accountability, and efficiency of the process of initiating a new MSP includes a clear pathway for interested scientists and

collaborators: (i) come together to propose specific mega science projects, utilising some of the recommendations in the MSV documents as evidence of community support for the science case, (ii) try to convince the broader community of the scientific worth and feasibility of the project, by carrying out a Community Planning Exercise, and writing a White Paper for the

Suggestions on the Administrative Side



Mega Science Coordination Unit

The formation of a Mega Science Coordination Unit (MSCU) which can act as a single-window system for submissions of MSP proposals and further communications regarding them



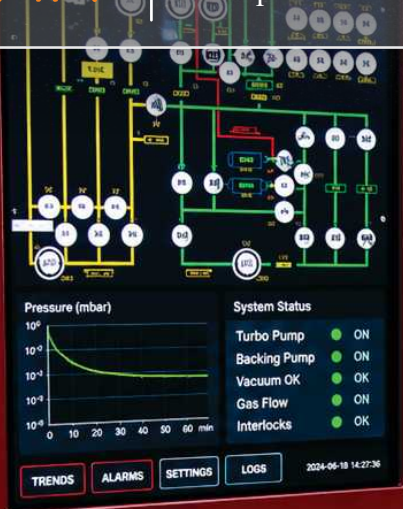
Dedicated MSP Budget

Introducing MSPs as a separate line item in the budgets of funding agencies



Support Future MSPs

Including those experiments for funding under the MSP activities that may not reach the level of an MSP at the moment but have the potential to develop into MSPs over a longer duration or to act as feeder projects



TIN.TIN Detector: Cryogenic bolometer setup at TIFR for neutrinoless double-beta decay experiment.

Photo: TIFR

How to Create Infrastructure/Ecosystem for Future MSPs in the Country

The participation in MSPs located internationally, though crucial for being a part of the international community and having access to new technologies, is not what an aspirational economy such as India should be satisfied with. The aim should be to have MSPs in the country where the international community would be attracted to participate. Ongoing projects such as the GMRT are already glowing examples of success, and LIGO-

India is expected to start within a decade. However, the HEP/NP community still lacks such a major experiment on the Indian soil.

If we indeed believe in this long-term aim, we need to take steps for infrastructure-building, identifying niche opportunities, training of scientific personnel, as well as science outreach for getting the public at large on board. Some high-priority ones are:



A national detector development and training centre for MSP-related activities in HEP as well as NP is the need of the hour. The centre may host common facilities for detector development, state-of-the-art laboratories and/or workshops for instrumentation, testing, and computation (to be available for all MSPs). This is not to replace local research activities in universities and institutes, but to enable these scientists to be users as well as leaders of common facilities to carry out coordinated instrumentation and training.



World-class Underground Science Facilities (USFs) for MSPs that look for rare events and hence need a location that is relatively free from the cosmic ray background, may be created. This would go a long way towards making India an attractive location for hosting future international MSPs.



There could be a centralised training/outreach unit for HEP Mega Science activities, which can also regularly organise specialised advanced schools. Large-scale multi-city events informing general public about mega science activities (such as the Vigyan Samagam in 2019) may be made a regular feature. Close collaboration with international training/outreach groups should keep us updated with new ideas and opportunities in this sector.

Synergy Among Mega Science Visions in Multiple Areas

The visions outlined in four Mega Science Vision-2035 reports released by the Office of PSA (namely, those on Nuclear Physics, Accelerator S&T and Applications, Astronomy & Astrophysics and High Energy Physics) are not independent of each other. For example, nuclear and high energy physics have synergies among themselves (dark matter, neutrinos, QCD, heavy-ion collisions, quark-gluon plasma, detector development) as well as with the accelerator R&D and applications (particle colliders, accelerators, cyclotrons, pelletron-LINAC, high-intensity ion beams, radioactive ion beams) and with astronomy and astrophysics (astroparticle physics, multi-messenger astronomy, gravitational waves). The long-term mega science visions of Indian scientists in these four related fields should therefore be developed and implemented together. सह वीर्यम् करवामहे।

LIGO detects the collision of neutron stars, 130 million light-years from Earth, producing gravitational waves and a gamma-ray burst.

Photo: IEEE Spectrum

Mega Science Vision-2035 (Astronomy & Astrophysics)

From the Sun to the
Cosmic Horizon



Prof G. C. Anupama

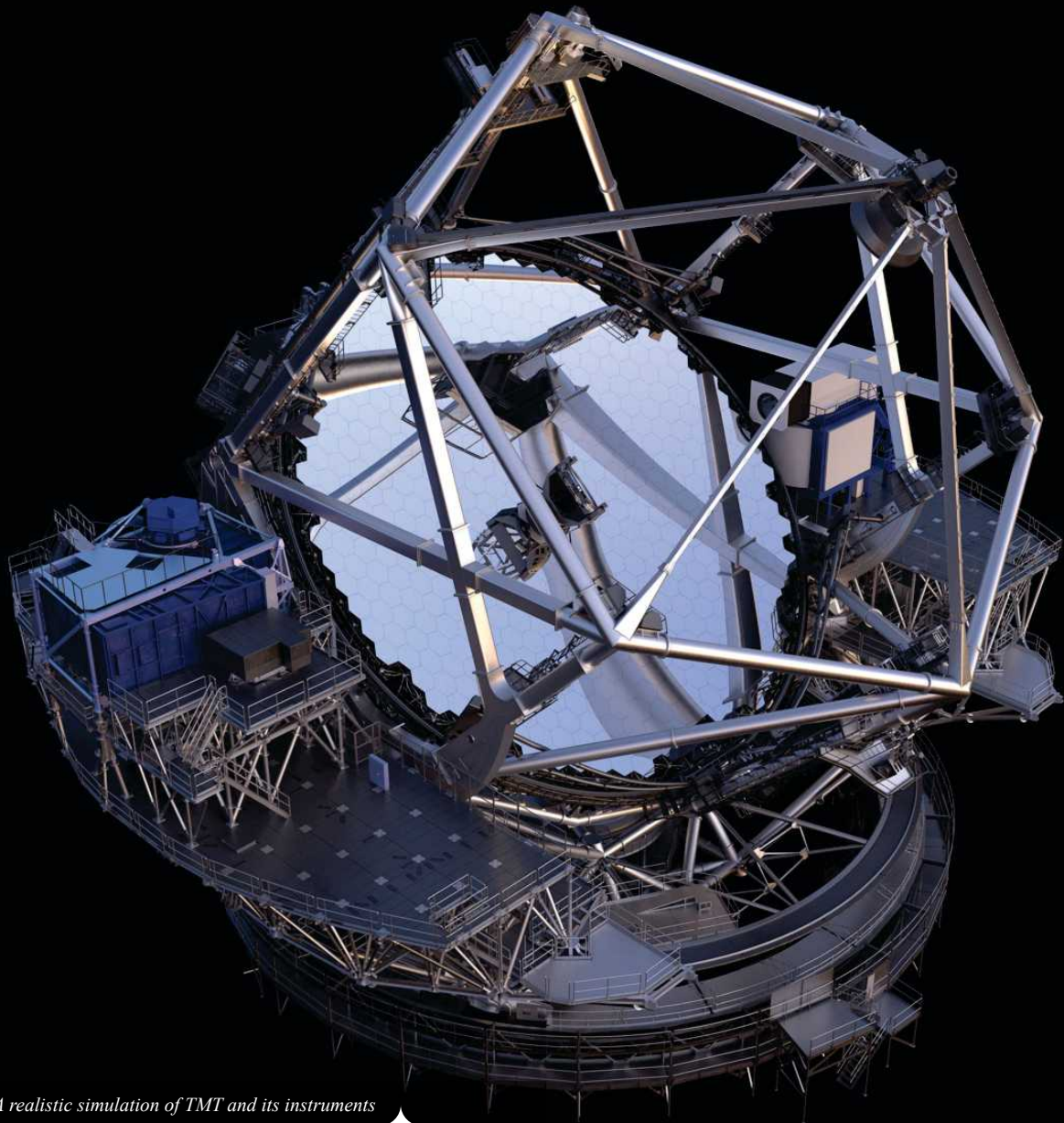
INSA Senior Scientist;

*Senior Professor (Retd) and Former Dean,
Indian Institute of Astrophysics*

Photo: Shutterstock

Astronomy and Astrophysics (A&A) is entering a transformational era, driven by rapid advances in observational capability, computational power, data science, and multi-messenger astronomy. Over the coming decades, facilities such as the Extremely Large Telescopes (ELTs), Square Kilometre Array Observatory (SKAO), Vera C. Rubin Observatory, next-generation gravitational-wave detectors, and advanced space observatories will open new windows to the Universe. Together, these platforms – supported by artificial intelligence, high-performance computing, and international collaboration – promise major discoveries about the origin, structure, and evolution of the Universe. India, with its strong legacy in observational and theoretical astronomy,

indigenous facilities, international partnerships, and a growing scientific community, is well-positioned to contribute to and benefit from this global transformation. In this context, the Office of the Principal Scientific Adviser (OPSA) to the Government of India constituted six Working Groups, each supported by a Drafting Group, to prepare Mega Science Vision (MSV-2035) reports in six areas, including Astronomy and Astrophysics. The A&A report was prepared through a community-wide consultation process, with extensive participation from the Indian astronomy community, and was discussed with eminent national and international experts and the OPSA before finalisation.



A realistic simulation of TMT and its instruments

Photo: TMT International Observatory

Key Science Questions in Astronomy and Astrophysics

The major scientific challenges that will define astronomy over the next decade spans an enormous range of scales – from fundamental particles to the large-scale structure of the Universe.

Fundamental Physics and Cosmology

Among the most pressing questions are the nature of dark matter and dark energy, the validity of General Relativity under extreme conditions, and the possible variation of fundamental physical constants across cosmic time. Understanding the origin of the matter-antimatter asymmetry and probing physics beyond the Standard Model remain central goals.

The Early Universe presents equally compelling mysteries. Researchers seek to understand the inflationary epoch, the origin of primordial fluctuations, the emergence of the first stars and galaxies, and the reionisation of the Universe. Precision cosmology aims to determine the topology of the Universe, constrain neutrino masses, and reveal the role of cosmic magnetic fields in structure formation.

Galaxy Formation and Evolution

Galaxies are the observable tracers of cosmic structure. Key questions include how galaxies assemble over cosmic time, the relationship between baryonic matter and dark matter halos, the growth of supermassive black holes, and the role of feedback processes in regulating star formation. Understanding the interstellar, circumgalactic, and intergalactic media is essential for constructing a complete picture of galaxy evolution.

The Milky Way and Nearby Galaxies

The Milky Way serves as a laboratory for studying galaxy formation in exquisite detail. Ongoing and future astrometric and spectroscopic surveys will reveal the Galaxy's assembly history, stellar streams, dark matter distribution, and chemical evolution. Nearby dwarf galaxies offer opportunities to investigate dark matter properties, star formation histories, and the evolution of low-mass systems.

Star Formation, Cosmic Chemistry

Understanding how molecular clouds collapse to form stars and planetary systems remains a major challenge. Key issues include the role of turbulence, magnetic fields, feedback, and accretion processes. Simultaneously, studies of stellar nucleosynthesis and chemical evolution seek to explain the origin of elements and isotopes throughout cosmic history.

Exoplanets

Exoplanet science has emerged as a frontier area, with goals extending from characterising planetary atmospheres to detecting biosignatures on Earth-like worlds.

Transients, Compact Objects, Multi-Messenger Astronomy

Black holes, neutron stars, and gravitational-wave sources provide unique laboratories for testing gravity and matter under extreme conditions. Exploding transients such as supernovae provide insights into stellar evolution and the formation of extreme objects. The era of multi-messenger astronomy – combining electromagnetic radiation, gravitational waves, neutrinos, and cosmic rays – has opened entirely new observational windows.

Sun and Solar System

Solar and heliospheric physics seeks to understand magnetic activity, coronal heating, solar eruptions, and their impacts on space weather and technological infrastructure. The study of the composition and structure of planetary atmospheres, particularly for bio-signatures, and the observations of comets, asteroids, and Near Earth Objects (NEOs) for constraining their dynamical, collisional, thermal and compositional evolution, are some of the main areas aimed to be probed in the study of solar system objects.

The Indian Landscape

Astronomy and Astrophysics research in India spans an exceptionally broad scientific landscape, from understanding the detailed physics of the Sun – our nearest star – to investigating the origin, evolution, and large-scale structure of the Universe. Indian researchers have made internationally recognised contributions to theoretical and observational studies of black holes, gravitational waves, the cosmic microwave background, cosmology, and the formation of cosmic structures.

From the latter half of the twentieth century, the establishment of state-of-the-art observatories and the development of indigenous facilities across optical, near-infrared, and radio wavelengths have transformed the national research ecosystem. While the 1980s saw the indigenous development of the 2.3m Vainu Bappu Telescope, ground-based optical facilities in the country have not seen major development, with the largest telescopes available being 4-m class telescopes at the Devasthal Observatory. The Giant Metrewave Radio Telescope (GMRT), built in the 1990s, has been available to the national and international community since 2002. Recently upgraded, this facility remains among the most sensitive instruments in its frequency class. Space astron-

omy, which began in the mid-1970s and was dominated by X-ray instruments, underwent a paradigm shift with the successful launch and operation of India's space observatory AstroSat, opening the X-ray and Ultraviolet (UV) skies to the community. Likewise, the solar space observatory Aditya-L1 has provided a major boost to solar and heliospheric research in the country.

Combined with access to major international observatories and space missions, these facilities have enabled frontier research on exoplanets, stellar abundances, star formation in the Milky Way and nearby galaxies, star clusters, pulsars and other compact objects, active galactic nuclei, galaxy formation and evolution, galaxy clusters, solar and stellar activity, and a wide range of transient phenomena, including novae, supernovae, gamma-ray bursts, fast radio bursts, and gravitational-wave sources. This diverse scientific portfolio positions India as an important contributor to global efforts in advancing our understanding of the Universe across all spatial and temporal scales. This is also reflected in India's partnership in international A&A megaprojects: the Square Kilometre Array Observatory (SKAO), the Thirty Meter Telescope (TMT), and LIGO-India.



Giant Metrewave Radio Telescope (GMRT) — Antenna array, 2019.

Photo: National Centre for Radio Astrophysics (NCRA), TIFR

The Global Landscape

The international astronomy community is investing heavily in facilities that will define scientific discovery through the mid-21st century. In optical and infrared astronomy, the James Webb Space Telescope has already transformed our understanding of the early Universe. Large survey facilities such as the Vera Rubin Observatory will revolutionise time-domain astronomy and produce petabyte-scale datasets. Future ground-based ELTs will provide unprecedented sensitivity and spatial resolution. Radio astronomy is entering a new era through the SKA, which will probe cosmic dawn, galaxy evolution, pulsars, and fundamental physics. Gravitational-wave astronomy is rapidly evolving beyond the pioneering discoveries of LIGO and Virgo toward future observatories such as the Einstein Telescope, Cosmic Explorer, and the space-based LISA mission. These facilities will detect thousands of compact-object

mergers and enable precision tests of gravity.

Space-based astronomy remains crucial across ultraviolet, X-ray, gamma-ray, and infrared wavelengths. Missions targeting exoplanets, transient phenomena, and high-energy astrophysics will complement ground-based observatories.

Simultaneously, advances in computational astrophysics, artificial intelligence, and high-performance computing are becoming indispensable for extracting scientific knowledge from massive datasets. Global astronomy is increasingly characterised by four defining features: multi-messenger astronomy, multi-wavelength observations, data-intensive science, and large international collaborations. India's future strategy must align with these trends to remain scientifically competitive.

History of the Universe

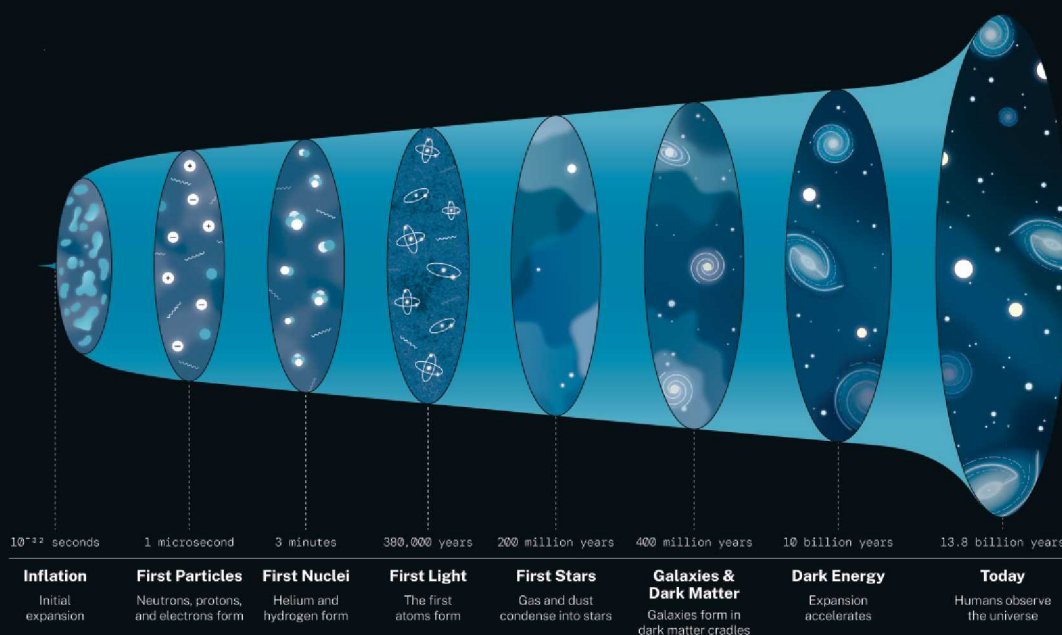


Photo: NASA

Strategic Directions and Priorities

The MSV-2035 framework emphasises a balanced strategy involving international participation, national capability development, and technological self-reliance, providing a roadmap for structured implementation.

Secure Leadership in Mega Science Projects

The highest priority must remain India's commitments to the international megaprojects already undertaken. These projects provide access to world-leading facilities while simultaneously developing domestic expertise in advanced instrumentation, precision engineering, optics, detectors, and computing.



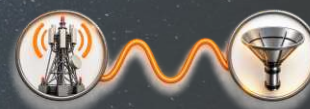
Develop National Flagship Facilities



India must bridge the gap between the existing 3-4 m optical telescopes and future access to TMT. The proposed 10-m class National Large Optical-NIR Telescope (NLOT) is therefore strategically critical. Similarly, the National Large Solar Telescope (NLST) would establish India as a global leader in solar astronomy. Recognising their importance, both facilities have now been announced in the Budget 2026.

Expand Multi-Wavelength Capability

Sustained scientific leadership requires observational coverage across the electromagnetic spectrum. Development of submillimetre, gamma-ray, X-ray, UV, and radio facilities must continue alongside optical astronomy.



Strengthen Computational Infrastructure



The scale of future astronomical datasets demands national investments in high-performance computing, data centres, artificial intelligence, simulation facilities, and long-term archival systems.

Human Resource Development

Infrastructure alone cannot guarantee scientific success. Human capital is the foundation of sustained scientific excellence. MSV-2035 also provides a framework for addressing human resource development.

The astronomy community in India has grown rapidly, with increasing numbers of researchers, students, and publications. However, growth must extend beyond specialised institutes into universities and colleges across the country through initia-

tives that include expanding graduate programmes, establishing national astronomy schools and workshops, expanding fellowships and postdoctoral programmes, developing instrumentation training centres, computational astrophysics programmes, and industry-linked technology training. Future growth should emphasise geographic diversity, gender balance, and participation from underrepresented institutions. Wider access to facilities and data can significantly broaden the research base.

Photo: AI Generated

Public Outreach

Astronomy remains one of the most effective gateways for inspiring scientific curiosity. Initiatives such as citizen science programmes, development of public observatories and digital educational platforms, teacher training programmes, and national astronomy festivals and exhibitions would enable wider reach. Scientific achievements should be widely communicated to foster public engagement and societal support.

Synergy with Other Mega Science Endeavours

A&A is inherently interdisciplinary, both benefiting from and contributing to advances across science and technology.



Physics and Fundamental Science

Studies of dark matter, dark energy, neutrinos, and gravitational waves complement high energy physics.



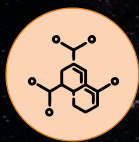
Plasma and Fusion Science

Solar and astrophysical plasmas provide natural laboratories for processes relevant to fusion and laboratory plasma research.



Nuclear Science

Nuclear astrophysics connects stellar evolution and nucleosynthesis with experimental and theoretical nuclear physics.



Chemistry and Biology

Astrochemistry and astrobiology explore the origin of complex molecules and the conditions for life.



Quantum Technologies

Quantum sensors, precision timing, and quantum-enhanced measurements will influence next-generation astronomical instrumentation.



Artificial Intelligence and Data Science

Astronomy is a major driver of big-data science, advancing machine learning, statistical inference, and data analytics with applications across science and industry.

Strengthening these synergies will accelerate scientific discovery, foster technological innovation, and maximise the impact of national investments in mega science initiatives.

Conclusion

India's scientific achievements in A&A have enabled participation in several frontier international mega-science projects that will become operational in the coming years, while also supporting the development of advanced national facilities. Coupled with the rapid growth of the country's A&A community over the past two and a half decades, these advances provide the foundation for the MSV-2035 roadmap.

The roadmap emphasises maximising the scientific return from past investments, strengthening international partnerships to build technological capability in specialised areas in collaboration with industry, and pursuing complementary national initiatives.

Realising this vision will require sustained investment in A&A over the coming decade. Such investment will enable current and future Indian astronomers to address fundamental scientific questions, assume leadership in global astronomy, and develop a highly skilled scientific and technological workforce. It will also catalyse innovations with a potential for wider societal and economic impact.

MSV-2035 presents a coherent strategy to sustain India's scientific leadership, strengthen national capabilities, and ensure that Indian astronomy remains at the forefront of global discovery in the decades ahead.

Key Recommendations

- Maintain strong commitments to TMT, SKA, and LIGO-India.
- Establish a 10-m class National Large Optical-NIR Telescope. Prioritise the National Large Solar Telescope and preserve India's leadership in solar physics.
- Enhance GMRT's capabilities to ensure competitiveness in the SKA era.
- Invest in national computing and data infrastructure, including centralised archives and high-performance computing centres.
- Strengthen instrumentation development, enabling India to design, build, and upgrade to state-of-the-art astronomical instruments.
- Expand astronomy education and research across universities to create a broader, more inclusive talent pipeline.
- Promote industry-academia partnerships to enhance technological innovation and indigenous manufacturing capabilities.
- Support exploratory technology-development programmes, enabling future breakthrough facilities and missions.
- Integrate outreach and societal engagement into all major astronomy initiatives.

Himalayan Chandra Telescope (HCT), Hanle, Ladakh, beneath the Milky Way, with Mars shining overhead.

Photo: Dorje Angchuk

Featured Interview

Glimpses into the World of High Energy Physics



Prof. Atul Gurtu

*Experimental high energy physicist, (Retd, 2011) TIFR;
Worked in CERN based emulsion, Bubble Chamber and
L3 and CMS Collaborations*



Scan to watch
the full interview

In an exclusive interaction with **Dr Praveer Asthana, PSA Fellow, OPSC** for Vigyan Dhara, **Prof. Atul Gurtu** explains the field of High Energy Physics as the experimental gateway to Particle Physics. The discussion traces India's post-Independence journey from early emulsion and bubble chamber experiments led by pioneers to front-ranking roles in more modern experiments involving large international collaborations. Prof. Gurtu also presents his views on the importance of “in-kind” partnerships and the Mega Science Vision-2035 Report. This article presents excerpts from the conversation, with the video version accessible through the QR code provided.



Dr Praveer Asthana

Prof. Atul Gurtu

Q. What are the primary scientific goals of High Energy Physics? And why is it also called Particle Physics?

Prof. Gurtu: High Energy Physics is a way of investigating Particle Physics, actually. Particle Physics is probably, arguably, the most basic science because, in Particle Physics, one is trying to investigate what every object, what everything that we see in this world, in the Universe, is ultimately made up of, and how does it all come together? Earlier they used to be called atoms, but then the atoms have also got subdivided; there is a structure inside. So, what are the most fundamental constituents, and how do they remain together? Basically, that is what Particle Physics is.

And, what is High Energy Physics? High Energy Physics is a way of experimentally finding out what do things consist of. About 100 years or more back, the sort of start of really modern Particle Physics or High Energy Physics came about with the Rutherford Experiment. In that experiment, there were radioactive decaying atoms and what are called alpha particles coming out of them. Mr. Rutherford thought, *"Okay, these particles are coming out, I will shoot them against some material and see what happens to*

these particles." He actually did it, and then it was realised the atom is not one big object, but the basic thing is actually very small inside, which is now called the nucleus.

Now, it has reached another level because now you have these accelerators. So, you say, "Okay, I will accelerate protons and hit them one against the other and see what happens." Basically, that is what really Particle Physics and High Energy Physics (are) all about.

And lastly, I just want to mention one thing that is very important to remember in modern-day very high energy experiments: Mr. Einstein's formula of $E=mc^2$. When you have these modern-day particle accelerators accelerating one proton to very high energy and hitting it against another, this is kinetic energy-energy of motion. When that gets converted according to Einstein — energy and mass are equivalent — it can produce new kinds of particles. If you want to discover new particles and see what happens, that's how you do it.

Muonic atoms can now unlock nuclear secrets, thanks to a breakthrough that minimizes polarization concerns.

Source: SciTechDaily

Q. It is often said that science is science because it is experimental. So, what are the different ways in which experimental investigations are carried out in High Energy Physics?

Prof. Gurtu: As I said, if you want to really delve into matter at a deeper, more basic level, then you will need higher and higher energy because then you can hit harder and go more into detail what it is.

It was discovered in the early part of the 20th century that our Earth has been constantly bombarded by some radiation. It turned out they were also some kinds of particles which are continuously raining down upon the Earth. And, we have an atmosphere which consists of (now we know) oxygen and nitrogen, etc. So when these cosmic ray particles — and they are actually particles, some of them are protons, alpha particles, higher element nuclei — when they come, the first thing they encounter is the atmosphere. Some of them will then hit the nuclei of this atmosphere. That is how these kinds of high energy interactions actually take place.

In fact, it was only in the 1950s or so when man-made accelerators truly came into

their own. Before that, the way of discovering new particles was by people actually carrying out experiments with these cosmic rays interacting in the atmosphere. Just to name a few particles, the anti-electron was actually discovered like that; another new particle, unexpectedly, which came out, was the so-called muon, which is a kind of heavy electron, etc. These were all actually detected using these cosmic ray particles hitting the atmosphere and then detecting the particles down below with some detectors.

So, cosmic rays have been used. In fact, even now, some cosmic ray particles are the most energetic things that can be there. Even man has not yet been able to reach those kinds of energies; but they are very few. Of course, if you have your own man-made accelerator, you have much finer control on it. But still, some of the cosmic ray particles are so energetic that one can still use them actually for that.

Q. Why do Mega Science Projects become necessary in advancing High Energy Physics?

Prof. Gurtu: The kind of apparatus and the tools needed in order to carry out these experiments require huge outlays. For example, a modern-day particle accelerator costs billions of dollars these days.

Then, wherever the protons or electrons collide, you want to see what happened, what is all the debris; you want to detect all those particles. So, these regions where they collide are surrounded by very sophisticated detectors in order to detect the passage of these particles. Remember, they are traveling almost at the speed of light, so you need timing to nanoseconds,

you need accuracy to a micrometer, and so these are very expensive detectors. Then you need enormous computing systems because you are collecting petabytes of data. You can't do it all alone, so you have these distributed computing systems all around the world.

But the most important ingredient are the human beings who do it. In fact, to understand why they become "mega" (apart from the cost) in the four major experiments currently running at the Large Hadron Collider, if you combine the people working in all four of them,

there are about 10,000 scientists who will be on those papers — about 3,000 - 3,500 each in the two big experiments, and

another 1,500 each in the two slightly smaller ones. So that is the scale; it is really mega.

Q. And even in case of cosmic ray experiments, I think some of these detectors are of very large size!

Prof. Gurtu: Yes, normally you want to study very high energy particles, these will interact somewhere high up in the atmosphere and produce all kinds of interactions on the way. These then spread out, so sometimes you need a very

widespread array of detectors, which also, in fact, costs a lot. And again, you need quite a bit of computing power, manpower, etc. So yes, they can also be almost mega science projects; sort of equivalent.

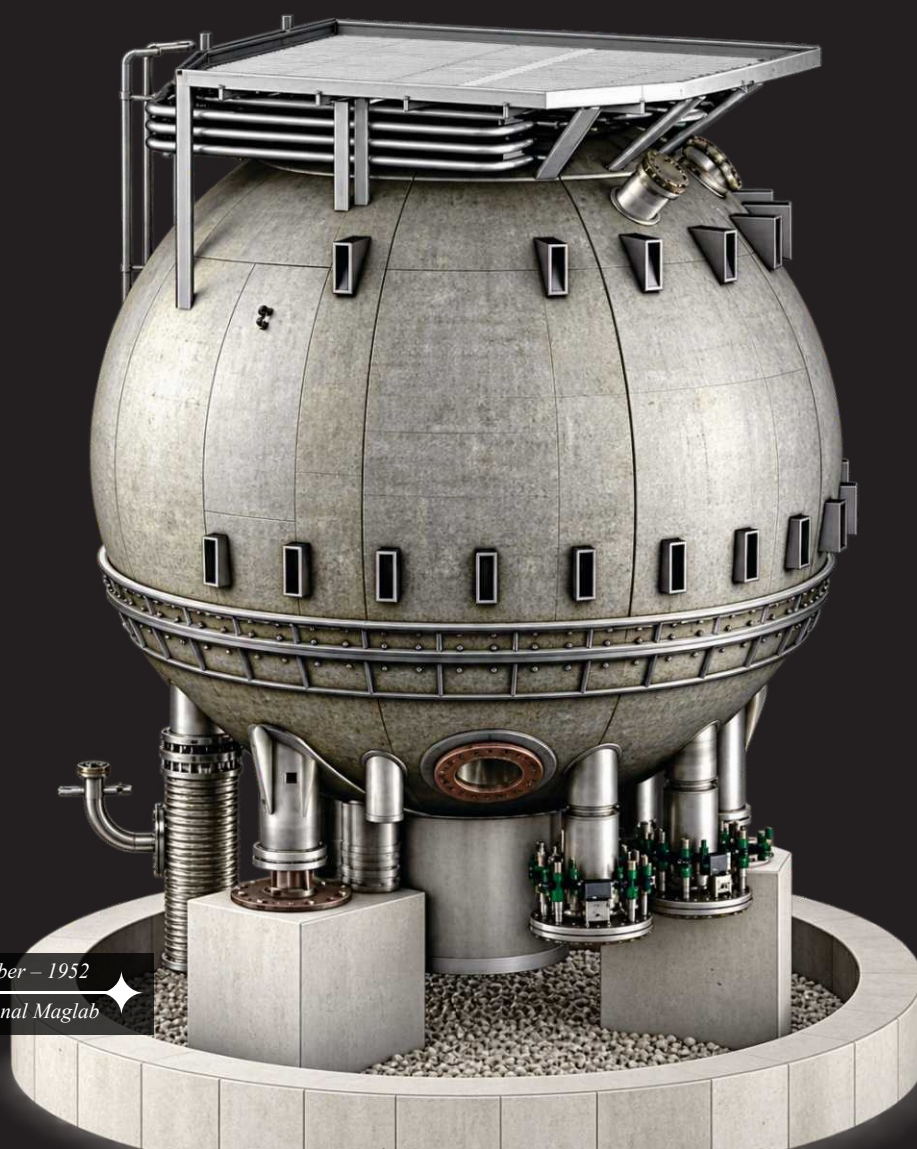
Q. Looking back, what were India's early experimental engagements in High Energy Physics after Independence?

Prof. Gurtu: This thing started in the mid-50s. Most of us are aware of the doyen of Indian science, M.G.K. Menon, who started as a particle physicist and was into cosmic rays, etc. He had worked in this lab in Bristol, which was actually quite famous at that time because one of the particles- the pi-meson was actually discovered using a technique which had been perfected in that lab. The person who had basically developed that technique, C.F. Powell, was awarded the Nobel Prize in 1950.

So, Menon worked there, and it just so happened that he and another colleague, an English gentleman called Owen Lock (W.O. Lock), became friends.

Menon joined TIFR in 1955, and then Mr. Lock joined CERN, which is the European Laboratory for Particle Physics, in 1959. Through this connection with CERN — which then became the premier laboratory for Particle Physics within 15 or 20 years after that — TIFR developed a connection. Then, the whole community — and there were many universities, Delhi University, Panjab University, and later on Jammu University — they were all getting into it. That is how the whole thing started.

I think the first person to go to CERN from TIFR was a gentleman called Mr. N.K. Rao. He was in that Emulsion Group; emulsion is a technique to actually detect particles.



Bubble Chamber – 1952

Source: National Maglab

Q. There is this nice story about the invention of the bubble chamber and how it was done!

Prof. Gurtu: Yes, I've so far talked about the emulsions. Let me just little bit explain because everybody may not know; it's an outdated technique by now. It is basically a thick photographic film. If you have some charged particles passing through it, they just leave a track. Then, like a photographic film, you had to develop it, fix it, and all that, and then you could see with a microscope inside that.

We carried out a lot of experiments using emulsions, there was a TIFR-Panjab University Collaboration, etc. But by the end-1950's and early '60s, it became clear that you could not collect enough data just because of the effort involved with a microscope and all. And so, this bubble chamber technique came up.

That's an interesting story which I think one should share with people because it's a little bit funny also. Here was this gentleman — I think it was in early-1950's — who was sitting in a restaurant with a glass of beer. He saw these bubbles coming out because there is this gas inside. While sitting there, he said, *"Oh well, okay, but suppose you have some kind of superheated liquid, which means that it's under pressure so it doesn't boil. And suppose some particle passes through it, and if you suddenly release the pressure, then it should form bubbles along where this particle had passed."*

So, he sort of said, *"All right, let's see if it works."* They actually tried it out, and it worked. In fact, by the late 1950s, there were these little, small, biggish bubble chambers operating in these accelerator laboratories in the US, in the USSR, in the UK, and a few places. In fact, this gentleman got the Nobel Prize for the invention of the Bubble Chamber. Then bubble chamber technique actually became the "in" thing, and there were lot

of bubble chamber experiments carried out. I think TIFR took a lead in that. They actually sent out three or four of their staff.

Let me mention some names. Prince Kumar Malhotra was sent to the USA. Subramanian, also from TIFR, was sent to the USA, to Wisconsin. Ganguli was sent to CERN, who actually spent about two years there. They all came back, and by the late 1960s when I joined TIFR (I joined in 1969) there was a Bubble Chamber Group, and we just had got this film exposed. Actually, let me explain what they did with the bubble chamber thing!

So, you are at an accelerator, you have a bubble chamber, and you fire a beam of particles. The first one was antiproton beam. As soon as it goes in, as I said, you release the pressure — this was a liquid hydrogen bubble chamber — and then these tracks form along that. Of course, you want to see them eventually. How do you see them? You want to reconstruct them in three dimensions. You photograph this from three or four different directions so that you can reconstruct a three-dimensional picture. Then you take the film, develop it, etc. You have these machines in which you project this, and then you do your measurements and all, and you can then reconstruct the whole interaction. That is what we actually did.

This continued, and many experiments were carried out. In fact, other university labs also got involved- Panjab University, Delhi University, Jammu University got involved. I must mention here again a few names: at Panjab University, there was I.S. Mittra; at Jammu University, there was Yog Prakash. And in Delhi University, there used to be — I'm forgetting the old man — later on, it was

Shivpuri who then continued that.

All these collaborations which I'm talking about were actually intercontinental collaborations. There were groups from CERN, there were other European groups from France, then some other people joined in from Japan- so we had these

huge collaborations. These were the front-ranking experiments of the day. Actually, right from the mid-1950s or late '50s onward, many Indian universities and labs got involved in these front-ranking experiments in international collaborations.

Q. Before we come to accelerator-based research, and more from the point of view of completeness, could you kindly recount some of the achievements of India in the Non-Accelerator Particle Physics domain such as the cosmic rays and other things?

Prof. Gurtu: Well, the main thing, as I said, were the cosmic rays. In fact, let me again give some names. Of course, Bhabha's name is pretty well known. But some names which you may not know, let me mention: there was Debendra Mohan Bose, who was incidentally the nephew of JC Bose. Then, there was one of the first women scientists Bibha Chowdhuri; she was associated with TIFR also for some time. Bhabha was, to start with, a theoretical physicist. You had Bhabha-Heitler theory of cosmic showers. It just so happened that he was the Director of TIFR, and then this whole group was set up there. Then Menon joined. Bhabha, unfortunately, had that plane crash in Mont Blanc and he died in 1966. But the next two directors, M.G.K. Menon and B.V. Sreekantan, had already got into cosmic rays. So, it got a huge impetus. The major achievements are a few which actually need recounting.

One was, of course, the TIFR group setting up this underground laboratory in the Kolar Gold Fields. They wanted to do neutrino experiments. Neutrinos can, of course, penetrate, so they set up this detector very deep underground (many thousand meters) where everything else, the background, would not be there. They did that.

However, in the early 1970s, these

theories were being developed to unite these different theories of electromagnetism and the nuclear interaction and so on. If you do that, then the protons should actually decay; earlier people used to think maybe protons are very stable. And they should have a lifetime greater than 10^{35} , 10^{36} years, etc.

These people in the Kolar Gold Fields realised that since we (are) sitting in this deep hole in the ground where we have our detectors, and where there is no background, if the protons in our material are going to decay, we can actually determine if they decay or not. They carried out those experiments. I think by the mid-to-late 1970s or early '80s, they actually published papers on that and said, "*Yes, we have set limits.*" The proton lifetime had to be larger than 10^{31} or 10^{32} years. At that time, actually it was the most accurate or the best limit of the proton lifetime that anybody had in the whole world. So, for a few years, they were really in the forefront of this kind of work.

The other thing which one should mention is that, as I said, Sreekantan was the Director, and then there were others also (Ramanamurthy, Tonwar, etc.) who were interested in experimentally studying all these cosmic rays coming down. As I said, they cause interactions,

and those new particles cause further interactions. So, they wanted to study the propagation of the whole thing experimentally, and you have to set up these huge detectors on the ground. In Ooty, they set up the Cosmic Ray Laboratory (CRL). That was another step which still continues. This experiment was called GRAPES. GRAPES then became GRAPES-2, GRAPES-3; they upgraded it, and it produced very good results.

The third thing which I would like to mention, which may not be well known, is this group from BARC: Razdan and Bhat. By that time, astronomy people had

detected gamma rays. So they wanted to actually detect these very high energy, Tera-electron-Volt (TeV) gamma rays. For that, they wanted to use a different technique: Cherenkov technique, which means that if you have a medium, and have these very high energy gamma rays, they produce particles which are traveling within the medium faster than the speed of light. Then, they emit this so-called Cherenkov radiation. So, if you detect that, then you know that the energy has to be greater than so-and-so. They actually set that up.

So I think these were the three highlights.

Q. And there were activities at PRL, Aligarh!

Prof. Gurtu: I talked about TIFR founded in 1945 by Bhabha. Then in 1947, Vikram Sarabhai — who then later became very well known for his space activities and so on — actually did a similar thing, establishing the PRL in Ahmedabad. And the third name, which many people would not know, is in Aligarh Muslim University; where there

was a gentleman called PS Gill (Piara Singh Gill) who also set up a similar thing.

In that period of 5 years spanning our Independence time around 1947 — in '45 you had TIFR, in '47 PRL, and then in '49 at Aligarh Muslim University, P. S. Gill — all this was happening.

GRAPES-3 experiment in Ooty, India

Source: TIFR

Q. I'm sure our listeners and readers would really like this because many people may not know this. Now, let us focus on accelerator-based experimental HEP because this is where its mega character really comes to the fore. When did India start engaging with mega accelerator facilities and projects, and what were the achievements of this engagement in the pre-LHC days?

Prof. Gurtu: Okay. The pre-LHC is pretty interesting. I already recounted that we had the emulsion era up to, sort of mid-1960s, then it tapered off because of limitations, and we got into the bubble chamber era.

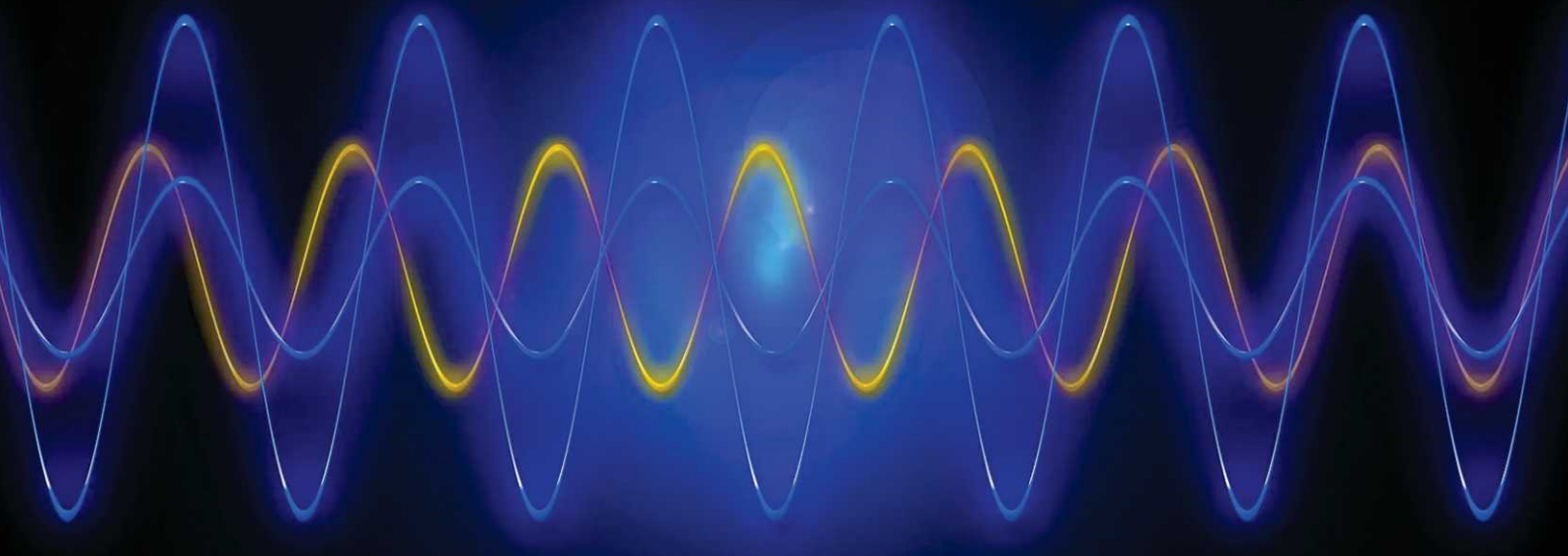
By the end of that, there were two experiments, which were pre-LHC and which could also be sort of called mega science. One was when the TIFR group joined the Large Electron Positron (LEP) accelerator experiment at CERN in 1984. Later on, in the early '90s, a different group from TIFR and two university groups — Panjab University and Delhi University — joined the D0 experiment at the Tevatron- that was an antiproton-proton collider.

Let me give you a little bit of background about what was actually happening during this whole era. As we said, we had this emulsion era, then we had the bubble chamber era where many new particles were discovered, and new theories came out. There was a theory for how the

nucleus stays together which was the strong force theory, the so-called QCD or Quantum Chromodynamics.

And then one had this theory for electromagnetism, which basically came about when Maxwell unified electricity and magnetism into electromagnetic theory. Later on, radioactive decays were discovered, the so-called beta decays; and those are called weak decays because it is over a longer lifetime. Eventually, in the 1960s, people got together (Sheldon Glashow, Weinberg, and Salam) and they combined these two together; electromagnetic theory and weak decay theory. That became the electroweak theory.

One of the new predictions of the electroweak theory was that there should be another particle — a neutral particle — which they called the Z^0 . It was a neutral particle, fine, but it was supposed to be so heavy. It was predicted to be something like 80 to 90 times the mass of a proton. So it's almost like a uranium nucleus, but as a single particle. It could not be



discovered immediately because it was very heavy and you needed very high energy to produce it according to $E=mc^2$.

By the end of the 1970s, we already had the Quark Model, which stated that the protons and neutrons inside the nucleus are not fundamental either, but there is something more inside them. So you had a model of matter where the nucleus consists of protons and neutrons, with electrons around in the atom. These quarks are inside, and they have to stay together. Therefore, they are held together by something. Not being particularly imaginative, physicists said something is gluing them together, so they called them gluons. Then you had this understanding that what you observe in radioactive decay needs a neutrino to balance the energy and momentum.

Towards the end of the '70s, you had this model of matter and these theories of the forces — the strong force, and the electromagnetic and weak forces which were now put together.

Then what happened — and I think credit has to be given to this gentleman, Carlo Rubbia, who was at CERN at that time — he suggested that CERN already had a large proton accelerator. He proposed to use that to produce antiprotons, which could be produced in small numbers but collected into a beam, and then collide these antiprotons with protons. That would provide a lot of energy to produce all these heavy particles.

CERN went ahead with that. They built this antiproton-proton collider which started operating in 1981. Rubbia himself was the spokesperson of one of the experimental collaborations, UA1. In 1983, after a couple of years of the accelerator starting, they discovered the Z^0 and the other particles which were known earlier even before the unification of the theories, which confirmed the

unification of the theories.

Of course, once you have discovered the Z^0 particle, you say, "*Okay, so looks like this theory is good,*" but you want to really study the properties of this particle and find out whether it agrees with the theory or not.

CERN came up with a proposal to build an accelerator — and no more protons and antiprotons for the time being — but an electron-antielectron accelerator which will collide (electron and antielectron) and it will have enough energy to directly produce the Z^0 in the tens of thousands or hundreds of thousands, and we could study its properties very nicely. They agreed to that in 1981 or '82, and these collaborations were being formed. Our TIFR group joined one of the collaborations, named L3.

Interestingly enough, the L3 experiment was led by Samuel Ting, who had been awarded the Nobel Prize for the discovery of the charm quark in 1974. It happened to be the third experiment to be approved, so he said, "*Oh, let's call it L3.*" So, it was called L3 and the TIFR group joined that.

Let me spend a little bit of time on this because this was a very important milestone. The TIFR group joined in 1984 (we really got into it) and the group contributed toward detecting particles in the forward-backward directions. Let me mention one more name — someone who very significantly contributed toward the specialised software for the experiment. This was Sunanda Banerjee. He actually did an extremely fine job.

That group was very deeply involved with the physics analysis, and three major things were part of our group's activity there. One was to determine with high accuracy the properties of the Z^0 particle — its mass, width, etc. — which was the main purpose of the experiment. The

second was the study of the so-called b-quarks (bottom quarks), which are another kind of quark you only produce in interactions. And the third was related to Quantum Chromodynamics.

The main thing was that to begin with, three or four different groups from different universities were (involved), but eventually, our group was selected by the collaboration to be the official group to carry out this determination of Z^0 properties. That analysis of the data proved to be extremely successful. CERN recognised the whole effort and set up a dedicated working group.

Following that, CERN nominated me to the Particle Data Group collaboration, which assimilates and collects data for use by other physicists globally. They nominated me and another colleague from the DELPHI collaboration, Carlo Caso. The two of us got nominated to that, and it continued for a long time. So I think that was a very successful thing.

The other experiment which is sort of pre-LHC involved another TIFR group. The other TIFR group — led by Narasimham and Mondal, etc.—together with Delhi University and Panjab University, joined the D0 experiment at the Tevatron, which was also a very high energy proton-antiproton collider. From there, another very important discovery came up— that was the top quark. It had been predicted that there should be six quarks, and that sixth one was discovered by both collaborations at the Tevatron: the D0 collaboration as well as the other collaboration called CDF collaboration.

As you see, this whole progression of things was going on. In the 1990s, the

LEP experiments were being done, and the last, sixth quark predicted by the quark model was discovered. So, the stage was set and the future was in front of us as the Large Hadron Collider (LHC) was being approved.

I give great credit to our funding agencies because in the early '90s, Dr P.K. Iyengar, who was then the Chairman of the Atomic Energy Commission (AEC) and the Secretary of the Department of Atomic Energy (DAE), realised that in order to get high technology, high science for our country, CERN is a very good source. They then signed an Agreement of Cooperation between the CERN Director General, who was Carlo Rubbia at that time, and P.K. Iyengar, our DAE chief. They signed that Cooperation Agreement for five years.

Then in 1996 — by that time, of course, the leadership on both sides had changed; the CERN Director General was Llewellyn Smith, who was a theorist, and on the Indian side it was Chidambaram, who had by that time become the DAE Secretary and Chairman of the AEC — they signed a 10-year Protocol to that Agreement, and after that, it just took off.

I think that was the turning point because it led to a very comprehensive engagement. By the end of the 1990s, by 2000, the theories had been well-studied and established by LEP and the Tevatron. Indian groups had taken very active part in that — hardware, software, and everything. And LHC had been approved, and the DAE the DST now on board were happy to support a big, comprehensive national collaboration. That is the whole story leading up to the LHC.

Q. What do you think were the important considerations that went into India's participation in LHC? If we had not participated, what would we have lost?

Prof. Gurtu: If it had not been for this comprehensive participation, one or two or three or four groups from India would have joined one or two collaborations. However, it would have been a very limited participation. Of course, one would have contributed some hardware, some software, and some analysis, but then it would not even have come to the notice of people so much. As I said, it was basically the funding agencies which actually provided this. What happened was, in fact, extremely good because it was a comprehensive participation, not only in the experiments but also in the accelerator. DAE laboratories together with industry actually provided things for

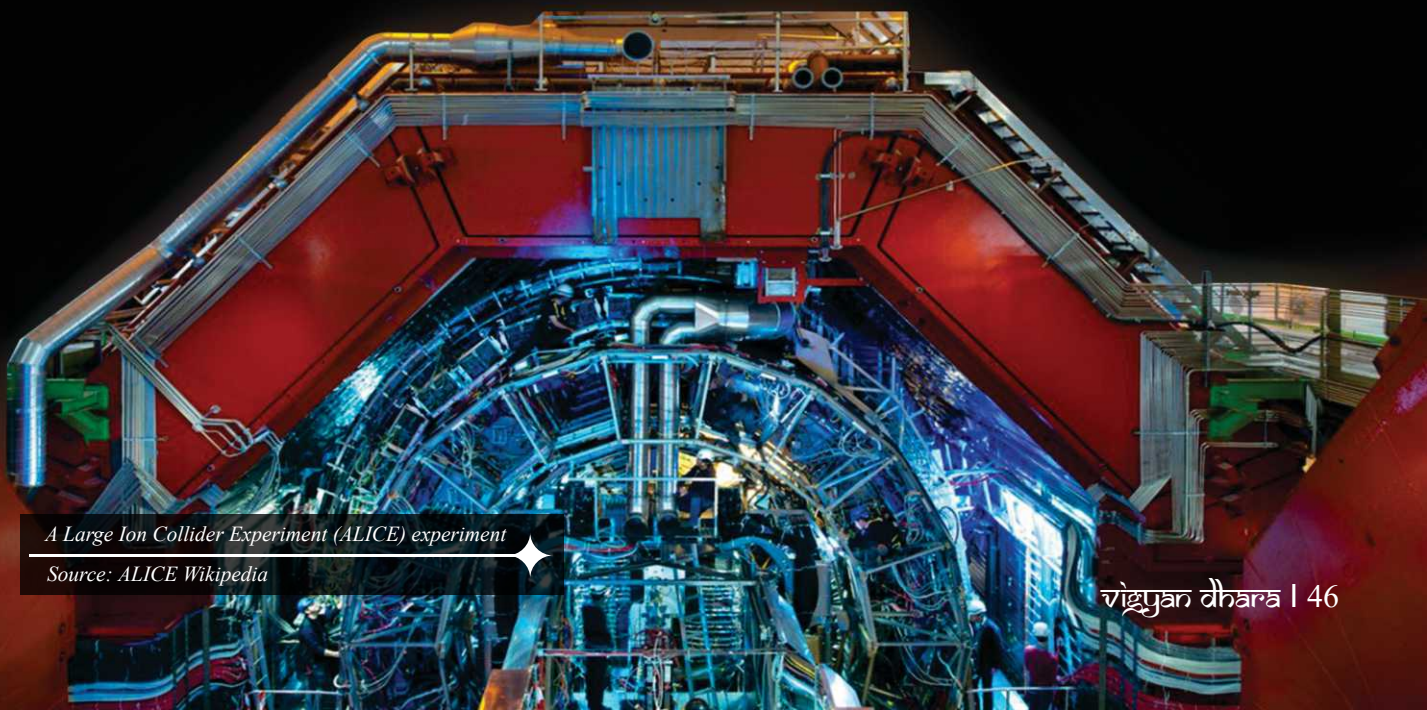
the accelerator. They did many things, for example, this precision positioning system, the corrector magnets, liquid nitrogen tanks. In the end, very sophisticated tests had to be done on these huge superconducting magnets. They had been tested one by one wherever they were made in the factory, but then you had to make a string of these magnets and then test. DAE people actually went and spent a lot of time there testing them out. That was a very important contribution. In the experiments again, I think it was a much bigger effort, on a much larger scale, which led to this big and satisfactory kind of thing, although one can always do things a bit better.

Q. Do you think that the in-kind model of participation in international MSPs have been in our national interest. If yes, why? Could you give us some concrete examples?

Prof. Gurtu: Oh yes, certainly. If you don't contribute in kind, how would you contribute- in cash? To me, that would be totally unsatisfactory. Simply because you don't want to just give cash and say, *"Okay, I will now just take your data and do something with it."* No, building that whole experiment, starting from the detectors, doing the hardware, interacting with people, developing software, and

learning and developing new techniques—that is the whole thing. You then bring back that knowledge to be used for your own experiments within India, or it passes on to the industry.

I'll give you two examples from these LHC experiments: from CMS and from ALICE. In CMS, we were tasked with making silicon strip detector modules for



A Large Ion Collider Experiment (ALICE) experiment

Source: ALICE Wikipedia

the detection of gamma rays, which were necessary for the detection of the Higgs. Two groups, BARC and the Delhi University group, got into that; but the actual assembly was done in Indian industry, at BEL in Bangalore. India had to make a certain number of these modules for our contribution which was successfully done and delivered to CERN.

It so happened that Greece, the other country which was to contribute, I think, some thousand modules, couldn't do it for some reason. So, CERN and Greece contacted BEL in Bangalore and asked if

they could do these additional modules. They actually did it, and it was outside the scope of the Indian contribution; Greece and CMS paid them.

The same thing happened with ALICE. They had developed these readout chips, the MANAS chips. The ALICE collaboration found them so useful, they asked for them for other detector systems as well. We saw already in our first venture that this technology transfer has taken place. This is the kind of feedback you get. Unless you contribute in kind, to me, you should not contribute at all.

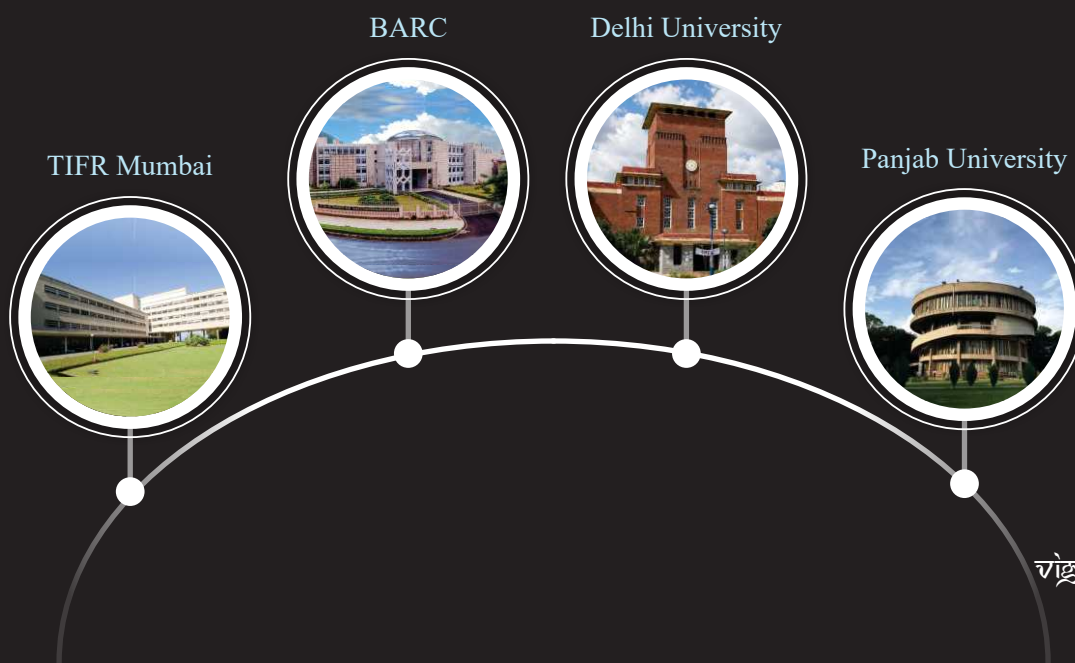
Q. Are you happy with the growth of the high energy physics community in the country, number-wise and institutional distribution-wise? What role did Mega Science Projects play in this growth?

Prof. Gurtu: I'm quite happy. In CMS, we were five groups that originally joined: three from Mumbai (two from TIFR, one from BARC), Delhi University, and Panjab University. Today, you have groups ranging from IIT Madras in Chennai to Bangalore, Bhubaneswar, Guwahati, and of course Panjab and Delhi University. The whole thing has got completely transformed, and the distribution across the country has gone much wider.

What I feel good about is many of our people who did their PhDs on these projects came back and joined smaller

universities, associated themselves with nearby groups, and started contributing. It has really spread out geographically.

Mega science projects have long lifetimes. The LHC started in 2010 and may extend to 2035 or 2040. The machines and detectors get upgraded. For example, I recently visited the CMS laboratory at IIT Madras. Because of their expertise, they are making components for the future High-Luminosity LHC. Different capabilities of our different institutions are being used now. That is very nice.



Q. This question is very frequently asked, and I would like to know your view on so-called "return on investment" on such projects, because such projects require large investments. Since you have been a first-hand researcher yourself, we would like to hear your views about this.

Prof. Gurtu: The question is: when do you want your return? Do you want it tomorrow, in one year, or in ten years? It is known that you have to invest in basic education and health, and these things

take time to show results. Similarly, investment in basic science, from which technology finally flows, requires a long-term view. You have to have a long-term view; this is how nations get built.

Q. What are your comments on the Mega Science Vision-2035 Report on High Energy Physics? Are you happy with the ambitions the HEP community has expressed in the Report? As a very senior and eminent scientist in the field, what would be your message for your younger colleagues because they have to carry the mantle forward?

Prof. Gurtu: I went through these recommendations and I'm actually very happy with them. The message is simply that if you are in science — whatever aspect of it, science or technology-related — just follow what you want to do. That is most essential. If our young people are idealistic, energetic, and enthusiastic enough, it will work.

very good start; starting this 30 years back when this whole thing got going and mega projects started with that. As you know, this was the first time for the LHC experiments that the DAE and DST developed this template of even how to fund all the institutions, which had not been done earlier. That is worked out and after that it has been used for other (projects). I think it (the Vision) is damn good and it should be done!

The funding agencies have now made a



Detector at LHC

Source: CERN

Featured Interview

Unlocking the Frontiers of the Celestial World

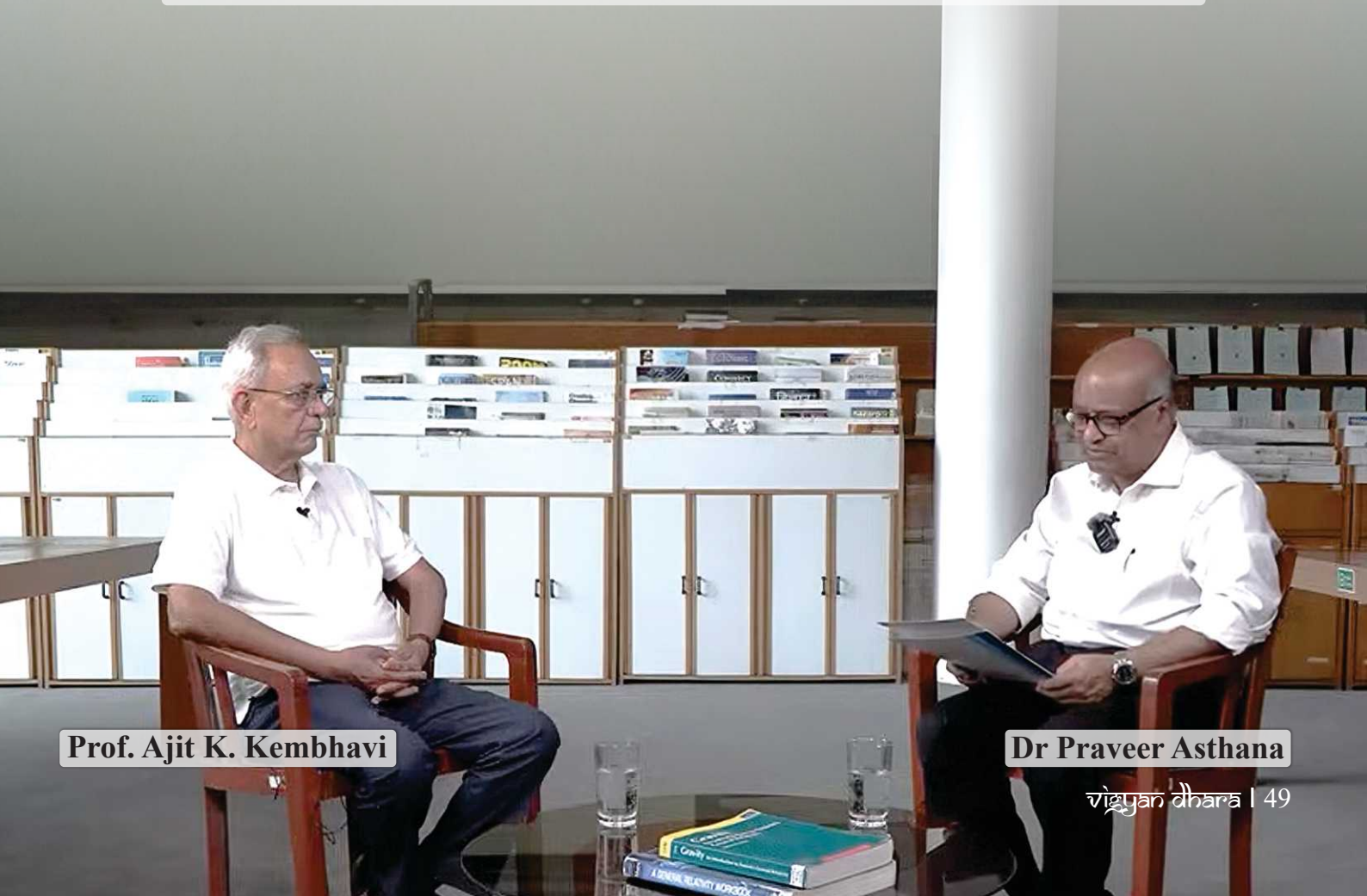


Prof. Ajit K. Kembhavi
*Emeritus Professor,
Inter-University Centre for
Astronomy and Astrophysics*



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the full interview

In an exclusive interaction with **Dr Praveer Asthana, PSA Fellow, OPISA** for Vigyan Dhara, **Prof. Ajit K. Kembhavi** highlights India's rich scientific heritage from Aryabhata to pre-Independence visionaries like Meghnad Saha to more recent developments. The interview explores the historical importance, evolutionary stages, and technological requirements of Astronomy and Astrophysics. It also covers the critical transition toward "mega science" projects, the importance of "in-kind" international partnerships, and the invaluable role being played by artificial intelligence and big data analytics in Astronomy. This article presents excerpts from the conversation, with the video version accessible through the QR code provided.



Prof. Ajit K. Kembhavi

Dr Praveer Asthana

Q. It is really surprising that Astronomy has captured the imagination of humankind since very ancient times. Why do you think it is so? And then, what are the primary scientific goals of Astronomy & Astrophysics?

Prof. Kembhavi: The answer is actually quite obvious. Astronomy is liked so much by everybody because, first of all, it is very splendidous, and second, it is immediately useful. So, you only have to look at the night sky, which unfortunately does not help very much these days. But until quite recently, we looked at the night sky and saw all the stars spread there, and the Milky Way, and the planets moving from place to place over a period of time. It has always been very fascinating and therefore, people relate to it very well. Second, as you know, it is the

North Star which guided people wherever they wanted to go; and the movement of the planets, the movement of the sun and the moon—they were very important for people to regulate their lives, to make a calendar, and so forth. Therefore, there was always a relationship between people and astronomy, and that has carried forward. As astronomy has become more complex, it has become more abstract, and you cannot really see the most important objects—you can see the stars—but nevertheless, it has always remained a part of the public imagination.

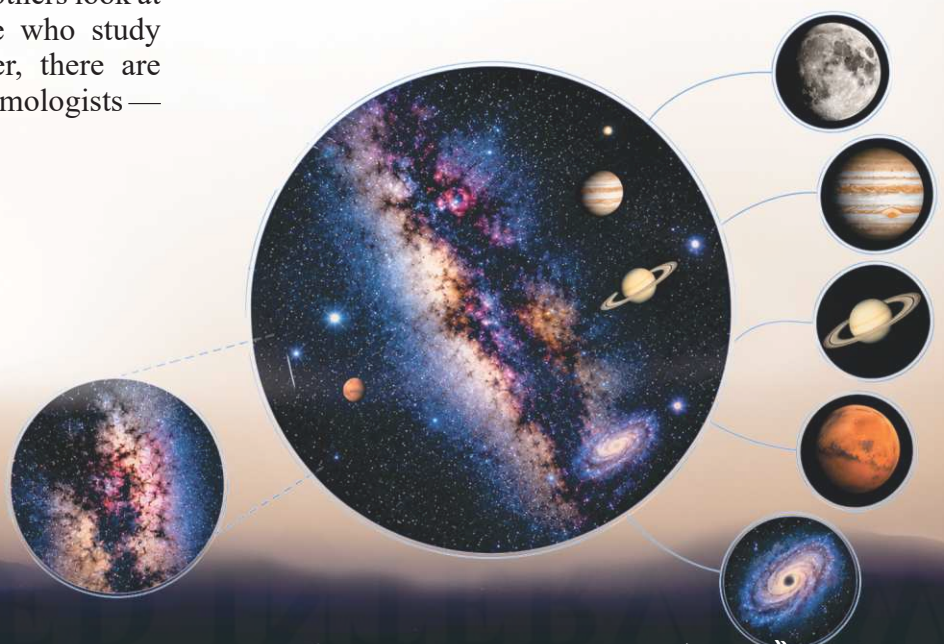
Q. What is it that we try to study in Astronomy & Astrophysics?

Prof. Kembhavi: If you look at the objects which are nearest to us—there are the sun and the moon—and then you have got the planets, you could see five planets with naked eye, but there are more planets there. And then there are the stars—you can see about 4,000 stars in the sky if you've got good enough eyesight. There are all the stars in our galaxy, which are about 100 billion or so, and there are many, many galaxies. There are astronomers who study comets, asteroids, planets, and everything in our solar system; others look at the stars; then there are those who study galaxies. As you move further, there are astronomers — we call them cosmologists —

who study the whole Universe. The sun is 150 million kilometers from us, the moon is of course much, much nearer, whereas the nearest star is five light-years away from us, and the Universe was born 13.7 billion years ago or so. Therefore, it is a vast system of which we see small parts around us, and astronomers study everything on all scales using all sorts of instruments. It is a very complex study.



Photo: AI Generated



Q. And even exotic objects like black holes and so on.

Prof. Kembhavi: And black holes and quasars. You can never see a black hole by definition, but nevertheless, it's most

interesting to the astronomer as well as to the public.

Q. You have nicely explained the kind of objects and problems one tries to address in Astronomy and Astrophysics. How do we study those objects experimentally? What are the tools and instruments employed for studying them?

Prof. Kembhavi: You see, the first tool available to us was our eye, and ancient astronomers had to depend only on the eye; and then they had simple instruments like you find even now in our Jantar Mantars. But otherwise, astronomers require complex instruments. So, a person who is doing physics for example, would actually create an experiment to test out some hypothesis or understand a system. We cannot create an astronomical object, we can only observe those which are there—and the objects are all very far off. The moon, for example— we actually walked on the moon; hopefully, that will happen to other more distant objects in the future. But right now, we simply observe them. And in order to observe them, we require bigger and bigger instruments. So, we require telescopes, and then we require detectors on the telescopes—we require cameras, spectrographs—and each one of these instruments becomes bigger and bigger as the scope of what we want to study increases.

Second, there's the Earth's atmosphere. The Earth's atmosphere protects us from harmful radiations, but we may want to study those radiations—we want to study ultraviolet emissions, infrared emissions, X-ray emissions from distant objects. For that, a telescope based on the Earth is not good enough, and what we require is an observatory in space, and then observe these emissions from those observatories. These observatories could be going round the Earth in orbit around it, or they could go to many more distant parts—some of them simply go away to infinite distances eventually. So, it's a complex set of instruments that is needed, and astronomers have been very good at building those instruments, and they've been very fortunate in having public and government support to provide the funds which are needed for these endeavors.

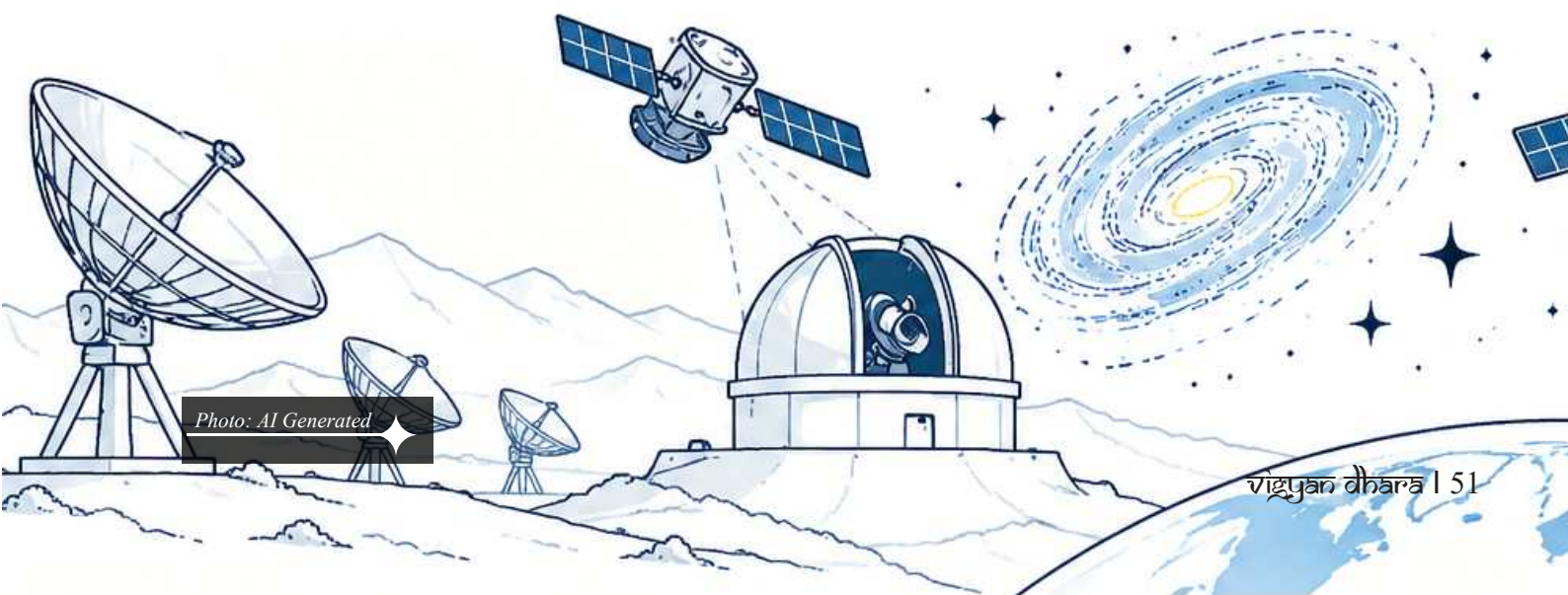


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Q. And they employ different kinds of signals, electromagnetic as well as cosmic rays.

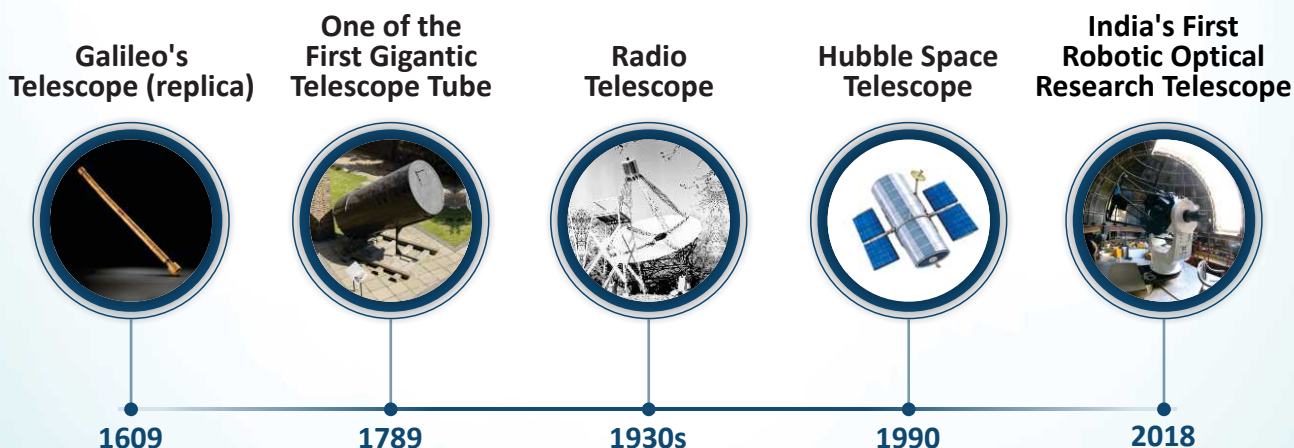
Prof. Kembhavi: Until recently, we were completely limited to the electromagnetic band, and cosmic ray particles of course, which itself is very wide. At the longest wavelengths, we have got the radio waves, and then you move towards shorter wavelengths— millimeter, infrared, ultraviolet, optical, X-ray—each band requires its own very complex and very different instrumentation. Until the Second World War, they were completely limited to using optical light for the study of objects. But after that, people started observing them in the radio, and then in the '60s, X-ray astronomy became available. In more recent times, in 2015, was the first-ever detection of

a gravitational wave source by the LIGO detectors, which opens a completely different way of observing the Universe. Because, for example, if there are two black holes which are going in orbit around each other, they emit a great deal of gravitational waves, but they don't emit anything else—they could be there completely invisible. It's only the recent gravitational astronomy which lets you find that these objects actually exist, and that they are in great abundance and they are of such wonderful variety. We realise that our knowledge of the Universe, about which we are so proud, is still very limited. There are many new things to be discovered.

Q. You have given a very detailed account of different ways in which people study astronomical objects. But in this entire thing, could you tell us why do mega science projects become necessary for advancing the knowledge frontiers in Astronomy & Astrophysics?

Prof. Kembhavi: The telescope which Galileo used 400 years ago or more was just about a 1-inch telescope. He had not invented it himself—it was a fairground toy that people used for amusement. He turned it on the Sun, he turned it on the planets, he turned it on the Milky Way, and he made the most marvelous discoveries. That was the biggest telescope in the world at the time. Then when people started building bigger and bigger telescopes they started probing the Universe

to deeper and deeper extents. So, there was a race to make even bigger telescopes. At every epoch—every 30, 40, 50 years— people built a bigger telescope. Now they have become so big that controlling them requires extremely complex instrumentation and machinery. So, the telescopes become very expensive, each camera can become very expensive. There's a great deal of effort of different kinds required to actually build such a telescope.



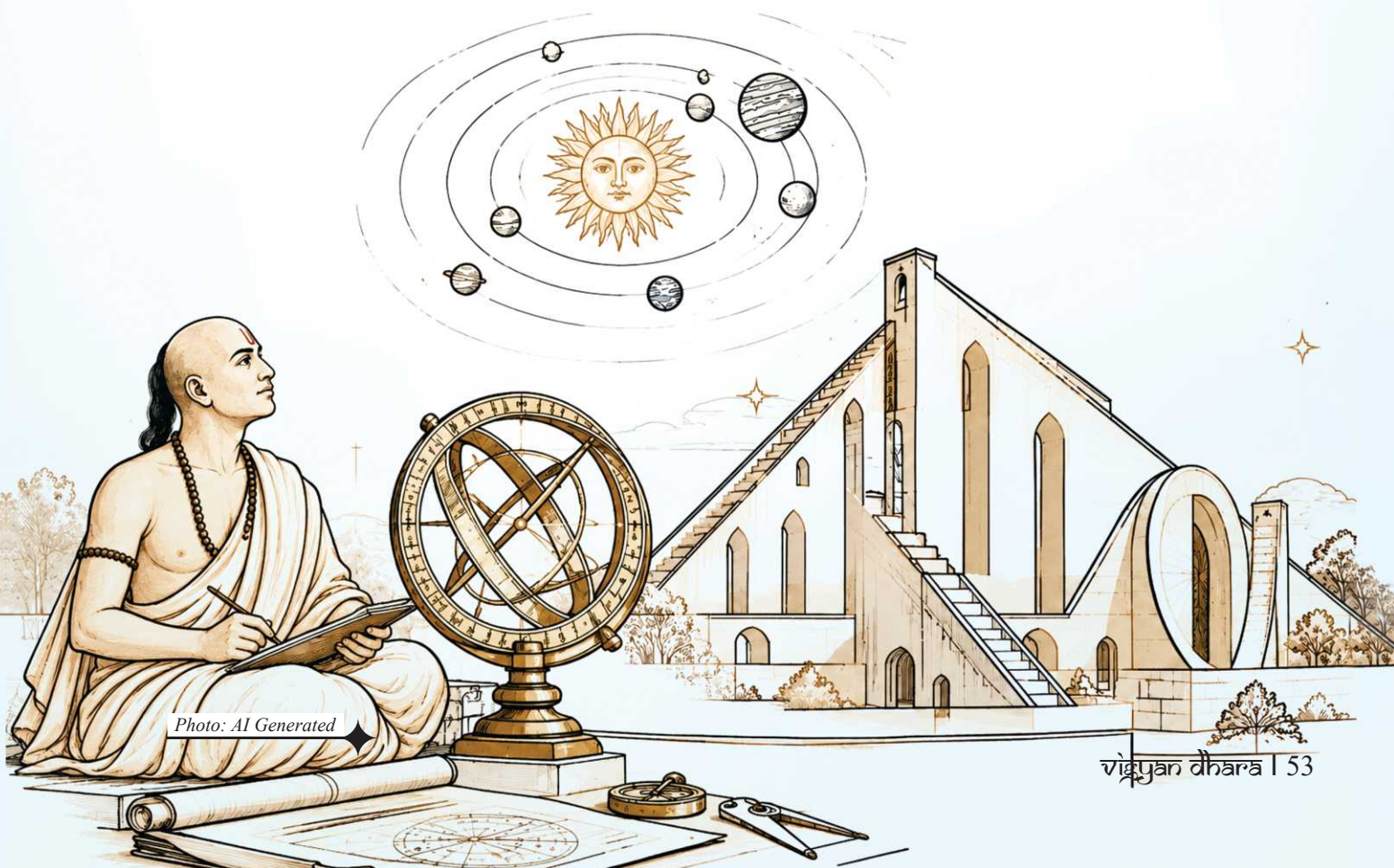
Now you can imagine somebody deciding to build a 30-meter telescope. What do you mean by that? It has got a mirror which has an effective diameter of 30 meters, which is the diameter of a large hall. You have to be able to support this mirror and point it very, very precisely in any direction in space that you want to observe; and then you have to make

very accurate observations with it. So, building it is a phenomenal feat of engineering. No single country, however wealthy, can afford it, and therefore you need many different countries and many different organisations to come together to build it. And that is what is known as a Mega Science Project.

Q. India has made several outstanding contributions to Astronomy right from ancient times. What are those contributions from India which have stood the test of time and guided subsequent scientific investigations globally? Could you tell us a little bit about those? It's a long history—let's focus from ancient times till pre-Independence.

Prof. Kembhavi: The best-known person and the earliest one around 5th century AD was Aryabhata, and Aryabhata was followed by Brahmagupta, then Varahamihira, and Bhaskara II. There were many people in between, and of course, there were many astronomers in Vedic times. But from Aryabhata's time we have specific records — their writings have survived and we know the amount of work that they did. All of these people were mathematicians and astronomers. Why were they mathematicians? Because

they needed to invent methods of doing calculations. As astronomers, they did not have the kind of instruments that we have today. So, they observed things very minutely with their eyes, made records of their positions, and they could talk about how the planets moved in the sky. And then there were phenomena of the rising of the sun, the setting of the sun, the movement of the sun over the celestial sphere through the year, and the positions of the stars. These are all very, very important data, and they gathered this



data. And you must appreciate that to gather the data and to record it in a manner in which other people in other places and at other times can study is a phenomenal achievement.

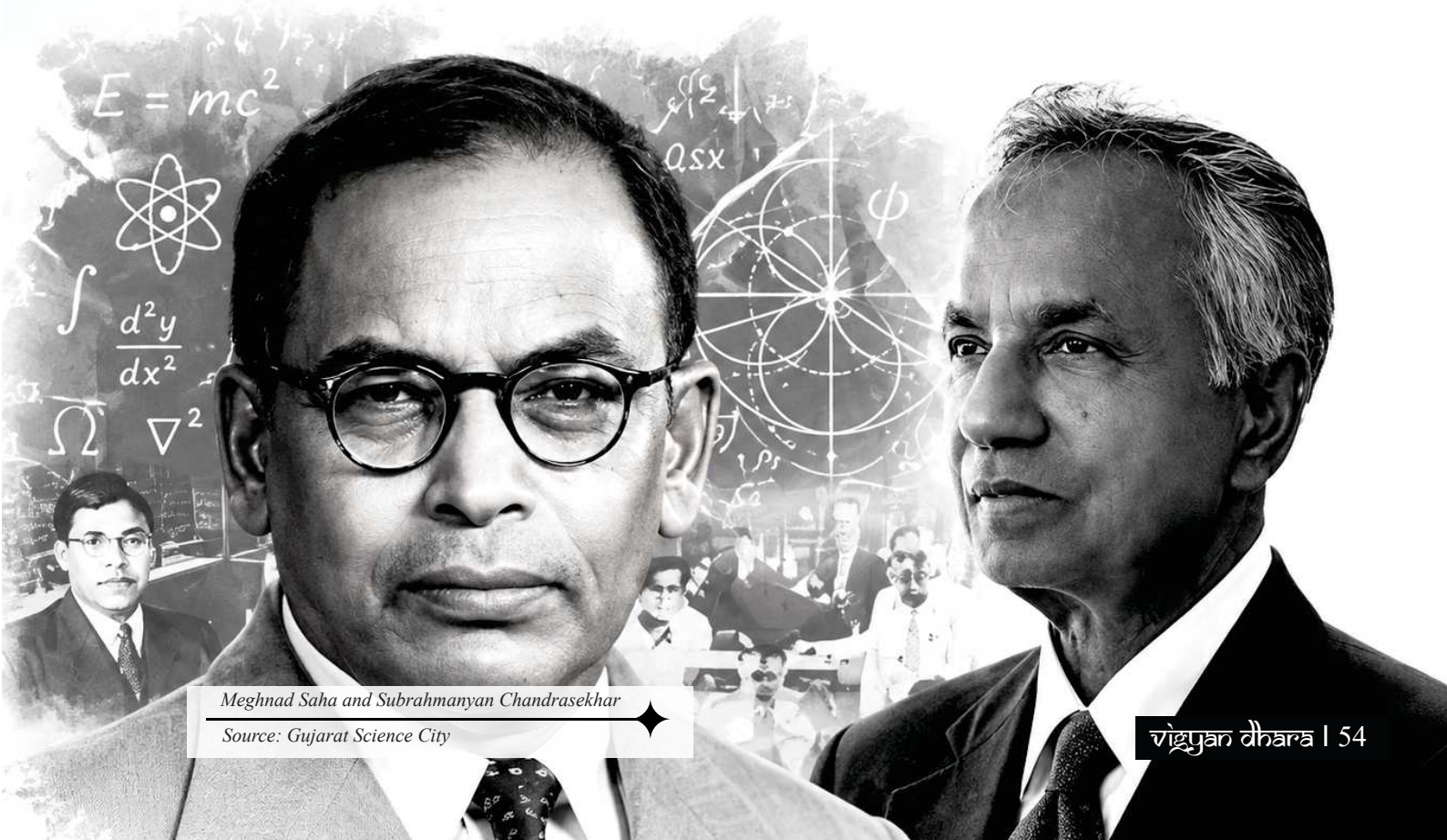
Even outside India, we talk of Hipparchus — he discovered the precession of the equinoxes. What you mean by that is that he discovered that stars were moving in a particular way, which we now know is because of the precession of Earth's axis for a very long period of time. Aryabhata and Bhaskara had also discovered the precession. They couldn't have discovered it from their own observations, because the precession happens over a long period of time — they needed to depend upon observations made by other people in other places. So, they had this

marvelous way of collecting the data. Language changes over short distances, method of writing changes, and in spite of that, they were able to put it all together, which shows that even though we are familiar with these big names, there was a whole continuum of astronomers, and then there was the astronomical method. It was a marvelous contribution, and of course, there was a lot of give and take between different cultures, different civilisations. So, we contributed to the international effort. The only thing which is lacking is present-day knowledge of those ancient efforts, that knowledge has to be collected together and it has to be disseminated in a form which is easy to understand.

Q. Coming to pre-Independence era, we see some very eminent names like Meghnad Saha and Chandrasekhar. If you could add a few words about their important contributions.

Prof. Kembhavi: Meghnad Saha — probably you could call him the first astrophysicist. Because astronomers collected data, they studied objects. When you look at the sun or look at other stars — at that time the spectra of these objects were available (many observations were there), but how do you

interpret those? It was the Saha equation — where he used physics to make predictions about what would be happening in the stars. It is by using the Saha equation that we can say what's the temperature of the star like the sun, what's the temperature inside, what is the density, what's the pressure; so that allows



Meghnad Saha and Subrahmanyan Chandrasekhar

Source: Gujarat Science City

you to study — even think about studying — what is the nature of the star, where did the star come from, how is it going to evolve in the future. So, he was probably the first astrophysicist as such. It's an amazing omission, not giving him the Nobel Prize.

Chandrasekhar did most of his work in England and in the US, but he started his work most remarkably when he was in India, and many of his important results regarding white dwarfs were obtained while he was

traveling as a passenger on a boat between India and England. These are all self-made men. You see, quantum mechanics at that time was a very young science. Relativity had been around just for a little bit longer. And you see a person, who is not yet 20, putting together these amazing sciences which hardly anybody understood at the time — Einstein's theory of relativity and the newly emerging quantum mechanics — to make these marvelous predictions.

Q. In the pre-Independence era, I think we made a lot of observational contributions to solar astronomy.

Prof. Kembhavi: Oh, yes. There were these small observatories set up to study the sun, and one of those was in Kodaikanal. It started somewhere else (in Madras). The observations at Kodaikanal, most amazingly, even now are preserved, and in that observatory observations go on even now. About 10 years ago, I carried out a project to bring all the data together because the Indian Institute of

Astrophysics had digitised all the data by then, and I had a project which was supported by the PSA's Office. Dr. Chidambaram was the PSA at that time, and he gave me the funds to work on data. And one of the things that we did was to unify all the catalogs digitally of the Kodaikanal Observatory. It's an absolutely great piece of observation continued over more than a century.

Q. We find that Astronomy & Astrophysics is one area where a number of Mega Science Projects have been successfully implemented in the country. In other disciplines, a lot of them are outside the country, but in Astronomy, you find a lot of them in the country. Some like GMRT have also proven to be globally competitive. What do you think—because you have been with this journey for a long time—were the underlying reasons that propelled more national Mega Science Projects in Astronomy & Astrophysics than in other disciplines?

Prof. Kembhavi: I would say that it is a happenstance. But on the other hand, one should also look for reasons because other disciplines may want to emulate this. As I already told you right at the beginning, Astronomy is a science which attracts the common person. So, there is inherent support for Astronomy. If somebody like me proposes an astronomical project, people

become interested in it—so, that is a very important factor, they support it.

Second, the astronomical community has not been very large. In fact, people always say that the amount of funding made available to it is disproportionate to the number of users. When you have a meeting of the Astronomical Society of India now, 800



AstroSat: India's first dedicated multi-wavelength space observatory

Source: Photek

people attend the meeting; in my time, there used to be 100 people attending. And glad to say, of the 800, about 700 are very, very young people. So, it is a small community, but there's a great deal of interaction—all the institutes work together.

We also have had a continuous dialogue with people like yourselves. You are on the administrative side, you are on the funding side, you are the people who make these projects possible. We only dream of them, we can build them but you make them possible. There is, I believe, a rather friendly and even affectionate relationship between these

different sectors. Having a relationship like that and a network and an ability of people to work together in spite of a divergence of opinions, divergence of talents—I think that is what has been responsible.

Then, of course, we have shown the world through projects like the GMRT and AstroSat that we can really build top-class, world-leading instruments here. So, people believe in our abilities, and we have wonderful communication with people abroad. All that helps.

Q. You mentioned the two very important community features which have promoted national projects more than in other disciplines. But sometimes I wonder whether it has something to do with the kind of science or objects that Astronomy tries to study. I mean, there's such richness of objects and phenomena available out there that one can always think of very original equipment and instruments to study a particular group of objects. Now, this is something very special with Astronomy, because it brings the richness of the entire Universe before us and so, one can perhaps think of some novel projects which may not require as much resources. Am I right when I say this?

Prof. Kembhavi: That is completely true, you always begin small! I believe that the era of small astronomy has largely passed. Even though you can—I know people who in

recent times use small 20 inch telescopes to do very useful work—but the big progress necessarily comes out of large instrumentation accompanied by very large computing

facilities and then marvelous theoretical work. But still, there are very simple calculations which can be done, and I completely agree with you that the entire

spectrum of possibilities is so large that people keep thinking of new ideas all the time.

Q. You referred to LIGO earlier. You were one of the main persons who were instrumental in bringing the third LIGO observatory to India. Why did you think India needed to host such a facility on Indian soil? And if we had not brought it to India, what would we have lost?

Prof. Kembhavi: Actually, when LIGO was still a dream and just the preliminary ideas were being executed, that was the time that IUCAA had just started and people like Professor Sanjeev Dhurandhar had started studying gravitational waves and had made remarkable progress on the theoretical side. So, they thought that we should build such an instrument. They contacted the DAE people in Indore; and there were some discussions going on. Probably it was considered that we were not sufficiently well prepared at the time, but the seed was sown. And the tree has now grown.

What happened was that the people in the US tried for 20 years to detect gravitational waves and, finally, they succeeded. But about 5-10 years before that, there was again a movement in India, and an informal body called IndIGO was set up. People like Dhurandhar, Bala Iyer and others, were

responsible for doing that, and they again started advocating that we should build a gravitational wave detector. At that time, there was an extremely important factor which was recognised. There are two LIGO detectors. The problem with gravitational wave detectors is that they cannot pinpoint where a source is in the sky. They can detect it, but they can't pinpoint where it is coming from. If you have two LIGO detectors—you have got one in the state of Washington in the US, which is in the northwest, and another in Louisiana, more or less southeast—and there's a distance of a few thousand kilometers between them. Even with this baseline the localisation is not enough. So, you need to put a third LIGO detector somewhere else. There was a smaller detector in Italy which is Virgo, and there is one in Japan now. It was decided that there should be a LIGO detector in Australia, and India was also one possible site.



LIGO - A rendering of the LIGO India site in the state of Maharashtra

Photo: LIGO caltech

At that time, funding was not available in Australia, and in India, we were able to push this idea through. Because it was very expensive, very difficult, the Americans helped us by giving us the needed detectors. But we had to build this giant LIGO (observatory)—two large tubes, 4 kilometers — and our government was very supportive. That is how the project finally was accepted. It is at the stage now where the construction and engineering work has started. It is extremely important to have it in India because of the localisation point of view. Right from the time of the senior Professor V.

V. Narlikar and N. R. Sen in Kolkata, general relativity, gravitational theory have been studied very well in India with a large community of scholars. That is also true with these modern decades. A lot of young people are interested and, because there's going to be LIGO, many, many talented young people have returned to the country. So there is a lot of effervescence in the area and, as I said, what we discover through gravitational waves is not discoverable by any other means whatsoever, like black holes. So I believe it is very important for the country.

Q. Now let me move to Space Astronomy. Space in some sense is open for all and it also offers a lot of advantages because you just mentioned about the light pollution, about the radio pollution, and all kinds of things. Space may be free from some of those, and in fact, we have seen these unbelievable images from Hubble Space Telescope and recently the James Webb Telescope. India has an impressive record in space missions and we have also sent some astronomy missions. How have we performed in your view in space-based astronomy so far, and what are the future possibilities?

Prof. Kembhavi: Our record in space has been quite impeccable. Thanks to ISRO—their determination, their technology, their engineering skills, and they also work with the astronomers. There have been many space missions. For the last 40 years or so, we have been doing experiments on small scale through Space. I suppose the culmination of all that was AstroSat. AstroSat observes in the X-rays, in optical, in the UV. It was built in India. There was some foreign collaboration, but that was only to a very limited extent and the satellite was built in India, and we are making marvelous observations. There are other observing satellites which have been launched and then some very nice projects like Daksha have been planned. So, our record there is very good and

space definitely is the final frontier, or I should say next frontier, because all kinds of new frontiers will come up.

And not only that, we can also consider observatories on the ground, but not on the ground of our own planet, but on the grounds of other satellites and other planets. We've already got to the moon, and India has had experiments being performed on the surface of the moon. There will be Indians on the moon quite soon, and I'm very glad to say that people are actually talking about placing experiments there? There is going to be a lot of excitement, and I believe that we are both very prepared technologically as well as scientifically, and we have a lot of support. So, if we push a little bit harder, we will take the lead.

Q. Do you foresee all astronomical observations shifting to space, or will there be a continuing need for ground-based astronomy? Could you explain for our readers and listeners why only one or both will be required scientifically?

Prof. Kembhavi: From the Earth, we can build bigger and bigger telescopes. But because of the presence of the atmosphere, the light from any object gets smeared out and that is a great limitation. One can get over that limitation by adopting technologies like adaptive optics, which are now quite developed. But on the other hand, if you go outside to space, the resolution improves dramatically. The Hubble Space Telescope—the mirror is just 2.5m across — but it can observe much fainter objects than telescopes from the Earth. The other great advantage in going to space is that you can observe other parts of the electromagnetic spectrum. X-rays cannot penetrate the Earth's atmosphere and reach us on the surface.

So, there are obvious advantages; but you can build very large facilities on the surface of the Earth. It's much cheaper to build a big telescope here than a big telescope in space. Therefore, there are always going to be facilities which are built on the Earth and which continue to be extremely useful. But as I already said, we can seriously think of building facilities on the moon. There will be the advantage that you can build very big facilities, but on the other hand, we will have

to create the entire infrastructure and ecosystem which are needed. One very exciting possibility is to go to the dark side of the moon—the side of the moon which you don't see; because there is complete radio silence at that point. So, there are advantages in both, and I'm sure that both astronomies—ground-based and space-based— and outside of the Earth, based on other planets will flourish.



The Hubble Space Telescope
Source: Sciencesprings

Q. We have been participating in international projects through this so-called "in-kind" model. Do you think that this in-kind model of participation in international Mega Science Projects has been in our national interest?

Prof. Kembhavi: I mean the lack of that would be against our national interest. The thing is that a money-order contribution doesn't take you anywhere. Most of the data now is already public. So, if you just wait for a year, you get access to all the data anyway. I

still feel that India should be getting, buying time on other telescopes, because that can be of strategic importance. But on the other hand, if we participate in a major way in a project, then the contribution in the majority has to be in kind.

Q. The technology for the National Large Optical Telescope—we learnt this by being a partner in the Thirty Meter Telescope; so that's a technological return that we have got. And similarly in LIGO-India project we would be developing these squeezed light sources and other things which are a great thing in quantum technologies these days. So, if we had not participated in kind, then we would have never got access to these technologies. So, you think that the in-kind model which has been almost consistently followed is the only sustainable one?

Prof. Kembhavi: Yes, it is the only sustainable model.

Q. You already alluded to this phrase! Since these projects require large upfront capital investment, this question of Return on Investment keeps on coming back, time and again. Now, you have been a practicing scientist yourself. As a practicing scientist, what is your view about this so-called Return on Investment in such projects?

Prof. Kembhavi: It is an extremely important question. It requires a lot of effort to answer it properly. You can say that, all right, you have discovered nine different kinds of black holes—but who does that help? We are all pleased to discover the black holes and we may make marvelous scientific theories based on those observations. But the process of discovering them required observations, required building of instruments, which actually led to technological development in the country which has got a great deal of fall out.

Second, young people are enthused. When you study Astronomy, when you study data science, it does not mean that you'll forever remain an astronomer. All of us know that it is data science and AI which are leading developments now, and astronomers are extremely well-trained to participate in that. So there are all these tangible and intangible returns. I should also not ignore the economic

activity which is triggered by these projects.

The third one— we have this marvelous facility for polishing mirrors which has been developed as a part of the TMT effort by the Indian Institute of Astrophysics and other collaborating institutions. And now anybody in the world who wants to make a segmented-mirror telescope could as well buy the mirrors from us. We have not just learned the art of polishing mirrors. There is something called active optics, there's something called adaptive optics, and we have world-class expertise in it now. Adaptive optics, for example, is needed in many, many different sectors, but most importantly, in the defence sectors. And we have seen from recent happenings how important it is for us to develop our own defence capabilities.

So, amazingly, it may sound weird, but Astronomy contributes to all these developments.

Q. Now we are coming close to the end of this interview, so I am tempted to ask you this question specifically because you are a first-hand practitioner in the use of artificial intelligence, machine learning, big data in Astronomy & Astrophysics. People don't realise that Astronomy & Astrophysics, High Energy Physics, etc., had a big role to play in the growth of AI and other things. So, number one, what role did Astronomy & Astrophysics play in the growth of these disciplines? And how do you think AI, etc., will help further research in Astronomy & Astrophysics?

Prof. Kembhavi: You see, that's a very important question. I will name two practitioners who collected big data, who did big data and data analytics. One was Aryabhata, 5th century AD, and the other one, Kepler, about a thousand years after that. The data that they analysed for their own purposes was big data, because what is big data? Big data is data which at any given moment is at the limits at which it can be handled, and data analytics are all these kinds of techniques. So, I used to be puzzled by this term until I realised that I've been doing data analytics for 50 years, even though the name has become fashionable only now. Astronomers have contributed to every development in this, including developing all the most marvelous methods of calculation. They have contributed to the development of AI and now they are also practitioners of AI, and we are beginning to use AI in every segment.

I feel that there's a little bit of a problem in Indian astronomy also. We have extremely clever astronomers, but our most senior astronomers have not been using AI. But their young students want to use it. So, there's a gulf between them, and it is extremely important for senior astronomers to make every possible effort to bridge the gulf, because without that, we are completely doomed. Five years ago, seven years ago, when I started using AI, it was just interesting use of AI in astronomical applications. I've also done it in biology and in other fields to a limited extent. But now, particularly over the last year or two, particularly over the last month or two, and particularly over the last day or two—because that is the speed of development—it has become impossible to do without AI. So it's going to be very, very important.



Q. Now let me turn to my last question, Sir. Are you, as one of the senior-most members of the Astronomy & Astrophysics community, happy with the ambitions of the community as expressed in this Report? And what would be your message for your younger colleagues, because ultimately they have to carry forward the mantle?

Prof. Kembhavi: They have to work hard, they have to work together, and they have to push the Government to approve some of these very nice ideas that they have. Sometimes they get very afraid. If there's a gap of 10 years between two large projects, then one generation is lost. And the next generation again will have to start from scratch. This is a continuous process. We cannot spend all our money on mega projects in astronomy, but whatever we want to spend, keeping the national interest in mind, has to be done to a certain cadence and to a certain

timetable. If you don't do that, then all the previous work will be lost. And there's one thing which I miss in the document—there's no mind blowing idea. What would be a mind blowing idea? When Govind Swarup started talking to everybody that he met about a big radio telescope he wanted to build somewhere or the other, that was at that time a mind blowing idea. Then TMT came along, then LIGO, SKA—these are big projects. I believe that we should really start thinking in terms of big projects.

Stargazing at the Very Large Array as the Milky Way stretches across the night sky.

Photo: Abuko D. Estrada, courtesy of The Groove Artspace

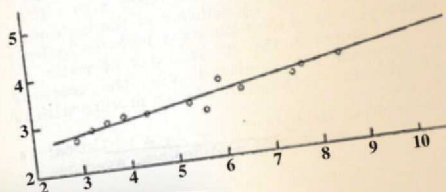
A Brief History of *High Energy Physics* in India

6



Prof. Sreerup Raychaudhuri

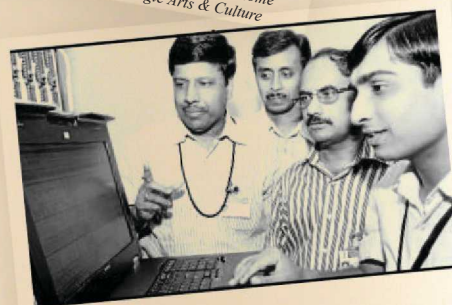
*Department of Physics,
Banaras Hindu University, Varanasi*



Kolar Gold Fields: India's Neutrino Legacy | Photo: The Print

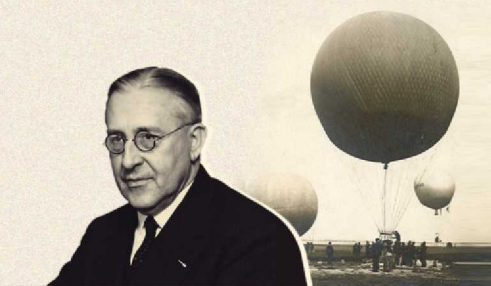


Where TIFR Began Kenilworth, Pedder Road, Mumbai: the first home of TIFR in 1945. | Photo: TIFR Archives, via Google Arts & Culture



1912 1934 1945 1951 1965 1984 1994 2012 2030 2070

1912



Victor Hess

1914



D.M. Bose

1930s



*Homi Bhabha, Walter Heitler
& P.S. Gill*

1934



*Meghnad Saha &
Daulat Singh Kothari*

1936



Max Born

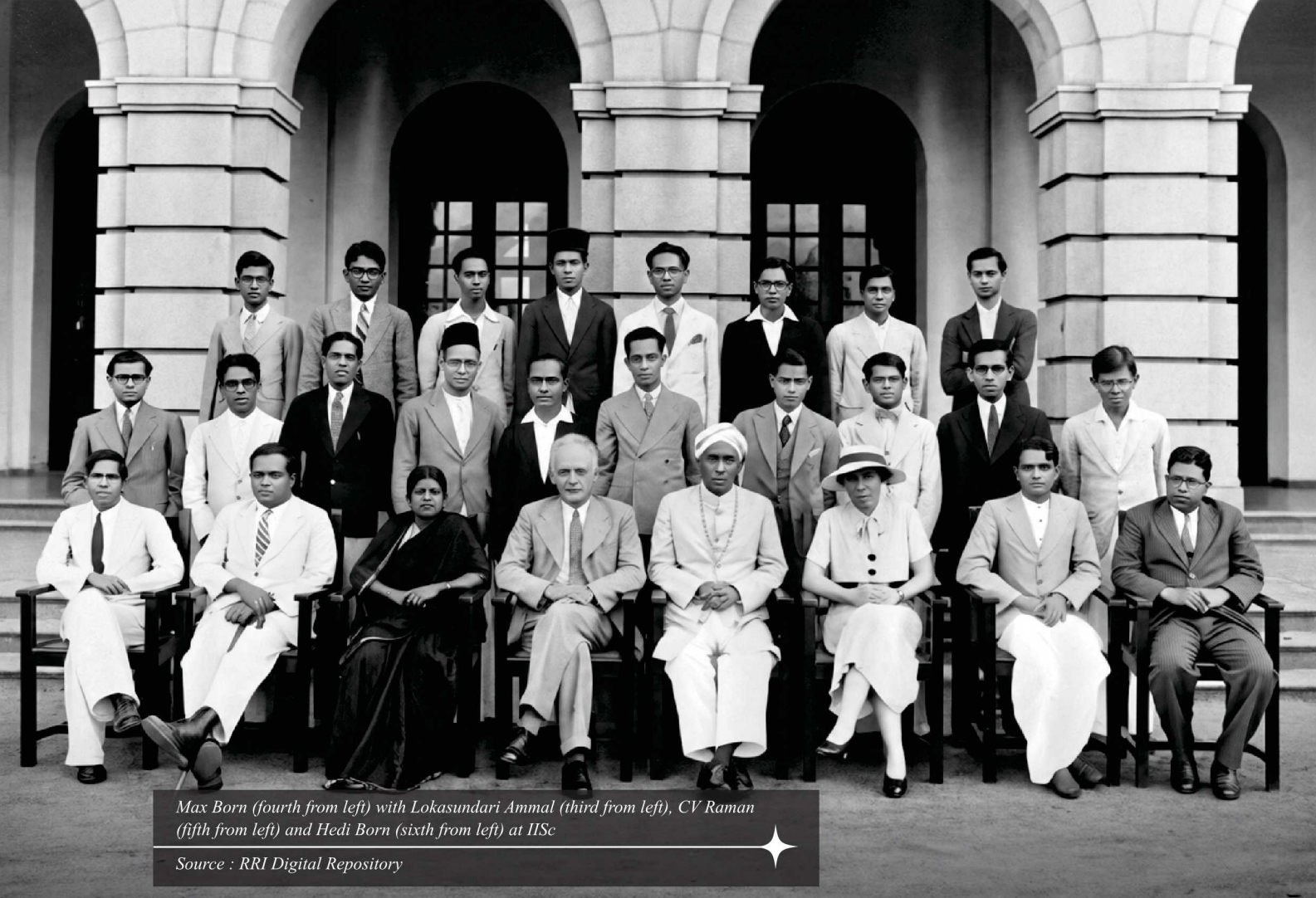
The Pioneering *Beginnings*

High Energy Physics was pioneered by Victor Hess, who serendipitously discovered an unknown radiation hitting the upper atmosphere in 1912, which was eventually named 'cosmic rays'. Two years later, a brilliant young Indian scientist named Debendra Mohan Bose or D.M. Bose, decided to go to Berlin, where Erich Rege-ner was making important cosmic rays' studies. Bose built a cloud chamber there and started photographing the tracks of cosmic ray particles at ground level. Soon, Bose's cloud chamber photographs revealed that when alpha particles in the cosmic rays scatter off hydrogen ions (pro-tons), the latter recoil after the collision. It was the first indication that the standard conservation laws hold at the microscopic scale. Bose then returned to Calcutta, after which he seemed to have lost interest in cosmic rays.

The first two journal publications from India which can unambiguously be called particle physics came in the 1930s. The first of these was written from Allahabad in 1934 by Meghnad Saha and Daulat Singh Kothari; and it tried to provide an alternative beta decay theory to that of Pauli. The Saha-Kothari theory was published in Nature, but it is not correct. Then, in 1936, Max Born spent a year at the IISc. There, with a bright young student, N.S. Nagendra Nath, he pursued an intriguing idea where the photon was considered as a bound state of a neutrino-anti-neutrino pair, analogous to positronium. This is also incorrect, but the idea later became useful.

Particle tracks in bubble chamber

Source: CERN

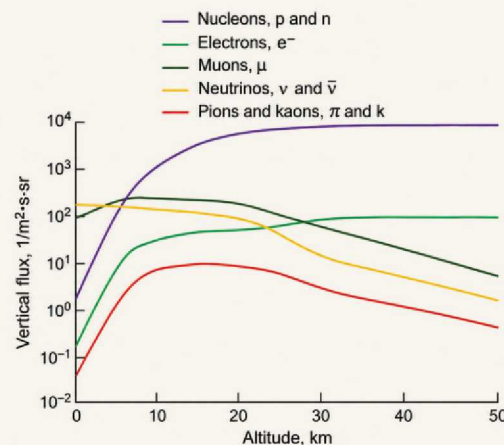
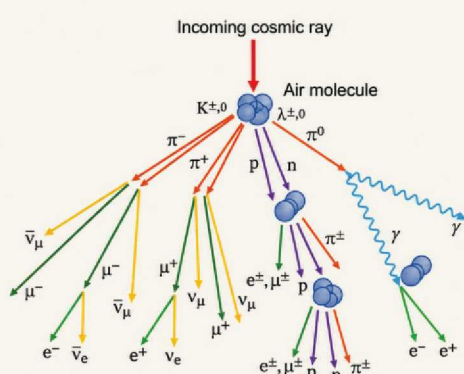


Max Born (fourth from left) with Lokasundari Ammal (third from left), CV Raman (fifth from left) and Hedi Born (sixth from left) at IISc

Source : RRI Digital Repository

By far the most important and lasting Indian contributions to particle physics happened in the 1930s, but not in India. The first was by Homi Bhabha at Cambridge, whose pioneering calculation of electron-positron scattering is still known in the textbooks as Bhabha scattering. Even more influential is a theory, worked out by Bhabha with German physicist Walter Heitler, which is known as the theory of cosmic ray showers

or sometimes, just air showers. The other significant contribution by an Indian to this field was made across the Atlantic by Piara Singh Gill, or P.S. Gill, a doctoral student of Nobel Laureate Arthur Holly Compton at Chicago. Compton had discovered the so-called 'latitude effect' in cosmic rays, but his data was limited. It was Gill who collected the data which established the 'latitude effect' beyond any reasonable doubt.



Primary cosmic particle collides with a molecule of atmosphere, creating an air shower

Source : Cosmicray.com.au



From the 1930s to the 40s

In 1938, the Silver Jubilee of the Indian Science Congress was organised as an international conference in Calcutta (now Kolkata), where the German Walther Bothe introduced the participants to a path-breaking discovery made by Marietta Blau, viz., that a stack of photographic plates can act as an excellent detector of charged particles. Present at these discussions was the now-senior physicist D.M. Bose, who was excited by this technique and resolved to use it to try and discover Yukawa's meson - the pion. He found a brilliant and energetic assistant in Miss Bibha Chowdhuri. The Calcutta duo travelled to the Darjeeling Himalayas, where they exposed plates at Tiger Hill (2,590 m), Sandakphu (3,636 m), and Pharijong (4,300 m). The result of these investigations, carried out between 1939 and 1945, was a great number of meson tracks. However, it is almost sure that they were made by the mu-meson or muon, which had already been discovered in 1937. It was left to the post-War period for the photographic companies to create customised plates for Powell's laboratory at Bristol, and it was there that pion tracks were clearly seen.

In 1939-40, just as World War II started, three brilliant Indian cosmic ray scientists returned to India. One was Homi Bhabha, aged 30, already famous; the second was 20-year-old Vikram Ambalal Sarabhai and they joined the IISc. The third was the 29-year-old P.S. Gill who returned to India in 1940 and joined the Forman Christian College in Lahore.

There was another player in this field, a middle-aged Anglican priest named Harold John Taylor, an expert on particle detection through photographic plates. There was, therefore, plenty of cosmic ray research done in India during the War years. Each of these stalwarts were aware of the work being done by the others but chose to do their own work independently and they all went their separate ways after the War. Homi Bhabha persevered, however, in building up a cosmic ray group at his own institute TIFR, and for many years it remained stellar. He had brilliant assistants like Roy Daniel, B.V. Sreekantan and, briefly, Alladi Ramakrishnan. He was able to bring renowned nuclear scientist Bernard Peters and promising youngsters like M.G.K. Menon, Sukumar Biswas, and Bibha Chowdhury. Brilliant theoreticians like E.C.G. Sudarshan and S.N. Biswas also spent some time there. Two graduate students who went on to make great names for themselves were Devendra Lal and Yash Pal. The TIFR cosmic ray group mostly studied air showers and sent up balloons carrying payloads to study how these originated in the stratosphere. Soon they moved to the altitudes of Ootacamund or Ooty and set up experiments there — which are still running in newer and more sophisticated avatars. From 1949, Homi Bhabha took up the onerous task of building up India's nuclear energy programme, but the flag of cosmic ray science was kept flying by Peters, Menon, and the others.

*View from Tiger Hill
Darjeeling and
Lebong in Foreground*

*Source: University of
Kentucky Libraries*

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Surface Detection of Cosmic Rays in India



Prof. Sunil K. Gupta

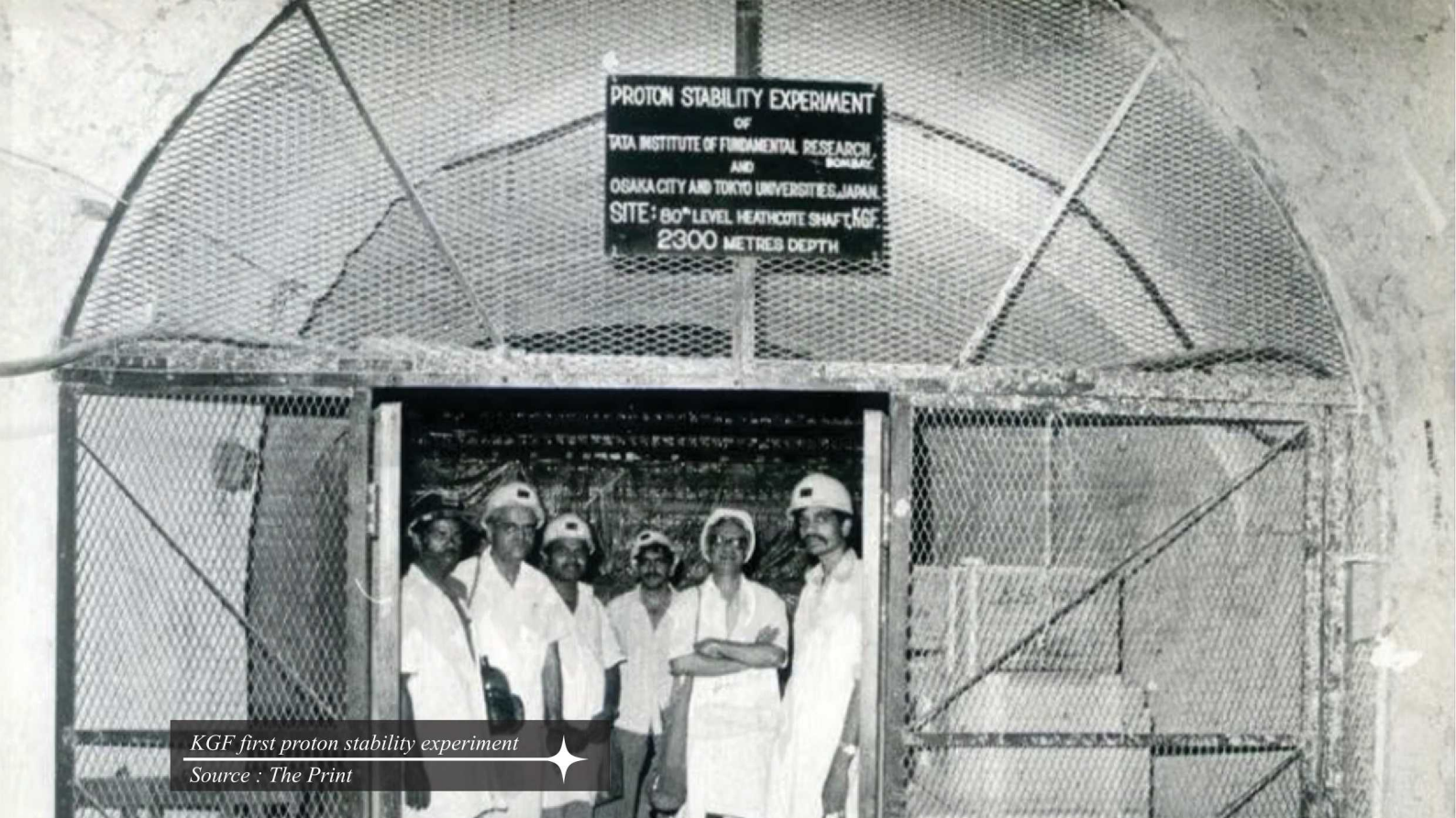
President-Designate, The International Union of Pure and Applied Physics (IUPAP); Cosmic ray physicist, retired from TIFR in 2020; Led the GRAPES-3 experiment at Udhagamandalam (Ooty) and presently still associated with it

Cosmic ray (CR) research was the central theme around which TIFR was founded in 1945, making it a centre of excellence owing to indigenous development of cutting-edge detector technologies and electronics. Homi Bhabha leveraged this infrastructure to launch atomic energy program. Similarly, the time variation studies of CRs led to initiation of space program by Vikram Sarabhai.

In 1955, TIFR set up the Cosmic Ray Laboratory (CRL), Ooty to study high-energy CR interactions beyond the reach of accelerators. The advent of extremely high-energy accelerators shifted the focus to astrophysics of CRs, their sources, composition, energy spectra etc. In 1993, GRAPES-3, the largest astroparticle physics experiment in India was setup in collaboration with Japan. The 1980s had witnessed decline in experimental CR research, but GRAPES-3 reversed this trend through indigenous development of world-class detectors- plastic scintillators after 3-years of R&D and 71 unsuccessful attempts; maintenance-free large proportional counters with lifetime of 30-years after 3-years of R&D; and ultra-fast electronics following 5-years of R&D. This led to an unprecedented rise in sensitivity of GRAPES-3 experiment resulting in new discoveries like “transient weakening of Earth’s magnetic field by solar storms” and “generation of Gigavolt potentials in thunderstorms”, attracting world-wide acclaim and turning CRL into a global centre of excellence solar and atmospheric physics.

Eminent scientists Profs. M.G.K. Menon, B.V. Sreekantan, K. Kasturirangan, A. Kakodkar, while applauding these achievements that had paid huge dividends, noted that no shortcuts exist in technology development. Nobel Laureate Prof. Sam Ting stated “I believe that the quality of science depends on the sensitivity of detectors used and development of world-class detectors in Ooty is an excellent example of that.” These developments benefitted numerous scientific programs in India and abroad culminating in global recognition of GRAPES-3 leadership. It also highlighted how quest for fundamental research drives technological innovation with far-reaching national and global consequences.

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KGF first proton stability experiment
Source : The Print

The *Golden Days* of Cosmic Ray Physics

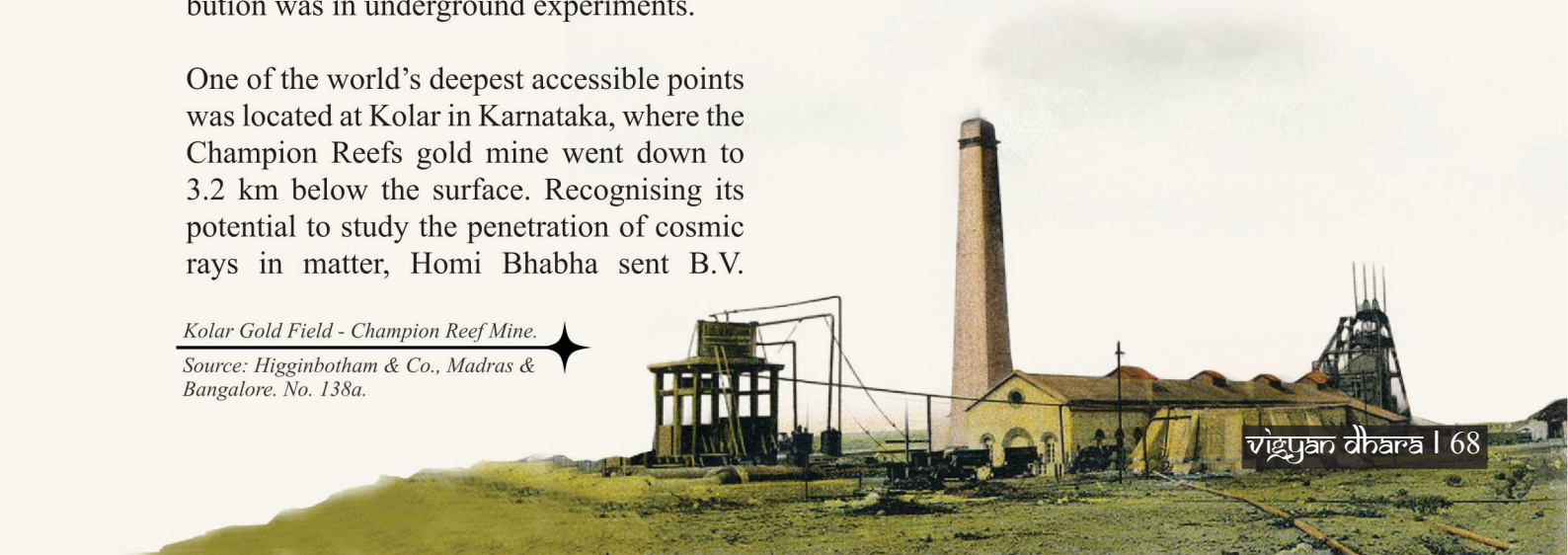
The 1950s were the golden days of cosmic ray physics, with the discovery of many new particles and the advent of many new ideas in high energy theory. Unfortunately, none of these developments happened in India, nor were there Indian physicists involved in these discoveries. But the one area where Indian scientists could make a major contribution was in underground experiments.

One of the world's deepest accessible points was located at Kolar in Karnataka, where the Champion Reefs gold mine went down to 3.2 km below the surface. Recognising its potential to study the penetration of cosmic rays in matter, Homi Bhabha sent B.V.

Sreekantan and S. Narayan in 1948 to measure the muon flux in the mine as a function of depth. There was then a hiatus of a few years as the mine was scheduled to be closed down, but this closure did not happen as the Indian government formed a new public sector company to continue mining gold. Seizing the opportunity, the TIFR cosmic group moved back to Kolar, this time in collaboration with Japanese expert Saburō Miyake, from Osaka. By 1963, they had discovered that the muon flux in cosmic rays dies down to zero at a depth of 2.3 km below the surface. This made it an ideal place to look for the 'atmospheric neutrinos'.

Theoretically postulated in 1930, the neutrino was detected in 1955. In 1962, it was

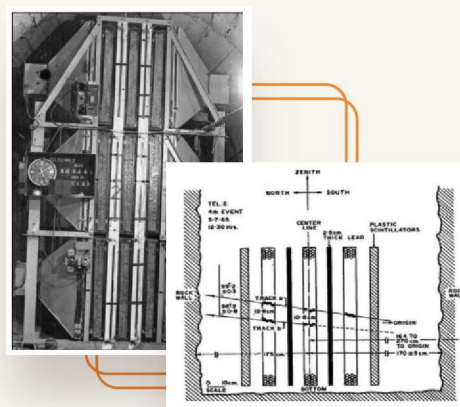
Kolar Gold Field - Champion Reef Mine.
Source: Higginbotham & Co., Madras & Bangalore. No. 138a.



discovered that there are two kinds of neutrino. It was theoretically predicted that cosmic ray cascade decays would produce a bunch of these neutrinos, which, because of their extremely weak interactions with matter, would shoot downwards and pass into the rocks below ground. These are the ‘atmospheric neutrinos’.

However, every once in a while, one of these atmospheric neutrinos can interact with a proton or neutron in a nucleus somewhere in the Earth’s crust and produce a muon by a process known as inverse beta decay. It followed that if muons moving sideways could be detected at the depth of 2.3 km at the Champion Reefs Mine, they would be unambiguous evidence of the existence of atmospheric neutrinos. This is precisely what the TIFR group set out to find. This time, in addition to the Osaka group, they collaborated with Sir Arnold Wolfendale and his group from Durham. The experiment was rewarded with success, and in August 1965, the Durham-Osaka-TIFR collaboration reported the discovery of atmospheric neutrinos. It was the high-water mark of underground cosmic ray studies in India.

By 1974, Grand Unified Theories unifying strong, electromagnetic, and weak interactions had been proposed. These theories had an important prediction, viz. that protons, generally believed to be absolutely stable, actually decay once in a while. The TIFR-Durham-Osaka collaboration therefore decided to run a proton-decay search deep in their familiar mine at Kolar. The experiment was set up in 1975 and ran till 1992. While no protons were observed to decay, the limit on proton lifetime put by this experiment was among the best at that time. Since the mines were closing, the Kolar experiments had to be shut down in 1992.



One of the detector setups of the KGF atmospheric neutrino experiment (1960s). This experiment was built and operated 2,300 m below surface in the Kolar Gold Mines. operated 2,300 m below surface

Source: The Print



Proton decay detector used in the second phase of proton decay experiments at KGF.

Source: The Hindu

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KGF: India's Pioneering Venture into Underground Particle Physics



Prof. Naba K. Mondal

Cosmic ray and high energy physicist retired from TIFR in 2016; Worked in the underground experiments at the KGF, led TIFR's contributions to the DZERO experiment at Fermilab and, briefly, the CMS experiment at CERN; Pioneered and spokesperson for the abortive Indian Neutrino Observatory project

The underground experiments at the KGF in Karnataka constitutes one of India's most significant contributions to experimental particle physics and cosmic-ray research. The programme was initiated in 1951 by Prof. B. V. Sreekantan and his colleagues at TIFR to study the intensity and properties of cosmic-ray muons deep underground. Measurements were carried out at depths of up to about 300 m within the KGF mines, providing valuable information on the penetration of high-energy particles through rock

In 1954, the experiments were temporarily discontinued when the mining authorities indicated that the mines might be closed. However, mining operations continued under new management, first under the State of Mysore and later under the Government of India. This enabled a revival of the underground Science programme at KGF in 1961. Under the leadership of P. V. Ramanamurthy, together with V. S. Narasimham and the Japanese physicist Saburo Miyake, a new series of measurements was undertaken at unprecedented depths. The team extended muon intensity measurements to nearly 2.7 km underground, reaching a region where cosmic-ray muons became exceedingly rare. During two months of observations at the deepest level, no muons were detected, demonstrating the extraordinary shielding provided by the overlying rock and establishing KGF as one of the deepest underground laboratories in the world.

These pioneering studies paved the way for two landmark experiments at KGF. The first was the atmospheric neutrino experiment, a collaboration between TIFR, Durham University (UK), and Osaka City University (Japan) led by M. G. K. Menon. This effort culminated in the detection of the world's first atmospheric neutrino interaction in 1965, a discovery that opened a new window on neutrino physics. The second was the proton decay experiment initiated in the early 1980s through collaboration between TIFR and Osaka City University, well ahead of many of the large underground proton-decay searches elsewhere in the world. Together, these pioneering programmes secured KGF a unique place in the history of particle physics and established India as a global leader in underground science.

The closure of the KGF mines in 1992 brought this remarkable scientific enterprise to an end, drawing the curtain on more than four decades of pioneering underground experiments that had placed India at the forefront of cosmic-ray, neutrino, and proton-decay research.

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India-CERN Collaboration Over the Years



Prof. Atul Gurtu

Cosmic ray and high energy physicist, retired from TIFR in 2011; Worked in the emulsions group, studying cosmic ray tracks from the CERN Bubble Chamber, and L3 and CMS Collaborations at CERN; Distinguished Professor at the King Abdulaziz University at Jeddah

India and CERN established a connection within a few years after CERN was established in 1954. As happens often, personal friendship and camaraderie become a catalyst in establishing institutional collaborations. During the early 1950's, M.G.K. Menon and a British physicist W. Owen Lock worked together in the Bristol lab led by C.F. Powell, who had been awarded the Nobel Prize for establishing the nuclear emulsion detection technique and subsequent discovery of the pi-meson. Menon was invited by Homi Bhabha to join TIFR in 1954 and Lock joined CERN in 1959. This set the stage for a TIFR-CERN and eventually an India-CERN connection that became stronger with time.

In the early 1960's, emulsions were exposed to particle beams at CERN and the TIFR emulsion group carried out the scanning and physics analysis of the data. Panjab University got involved during mid-1960's. By late 1960's the bubble chamber technique came into vogue and a bubble chamber group was established in TIFR and later in the universities of Jammu & Panjab. International bubble chamber collaborations involving the Indian groups, CERN and groups in Japan and Europe, published many papers on antiproton-proton interactions at 760 MeV/c. From end-1970's till mid-1980's TIFR collaborated in "Hybrid" bubble chamber + downstream spectrometer experiments to study strange and charm particle properties.

In 1984, the TIFR group joined the L3 collaboration at LEP-CERN. The LEP era lasted till the early 2000's and the collaborations put the seal of validity on the extant theories: QCD and the Electro-Weak theory. Then game-changing events took place: DAE signed a "Cooperation Agreement" with CERN in 1991, followed by a "Protocol to the Agreement" in 1996. The DAE-DST jointly funded the Indian participation at the LHC, including participation in the LHC machine construction and testing and groups joining two LHC collaborations: CMS and ALICE. The highlight was the discovery of the Higgs boson in 2012. One looks forward to enhanced collaboration between India and CERN on the continually upgraded LHC and beyond.

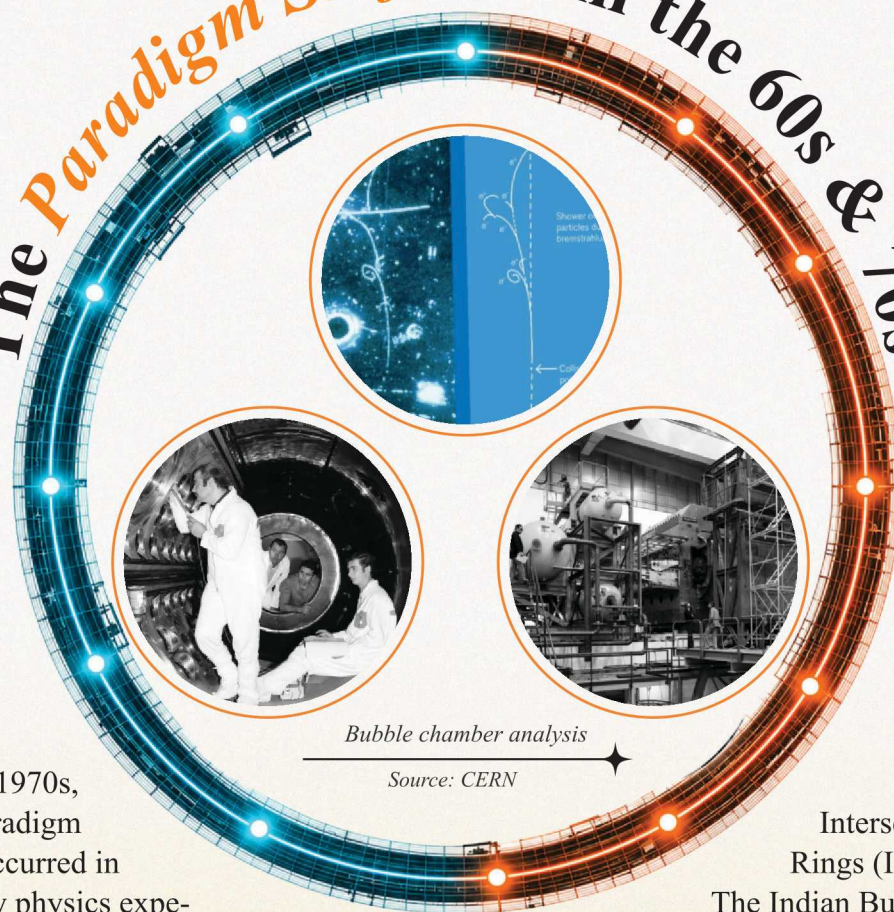


The Paradigm Shift From the 60s & 70s

During the 1960s and 1970s, a major paradigm shift had occurred in high energy physics experiments with the incoming of giant accelerator machines having much higher particle fluxes. In India, it was again TIFR which spearheaded this change towards accelerator-based physics. TIFR had built a working relationship with the CERN - the world's largest particle physics laboratory, founded in 1954. Soon, Panjab University at Chandigarh joined in. Meanwhile, the bubble chamber had been invented in 1952, and it had supplanted both cloud chamber and photographic emulsions. TIFR, therefore formed an Indian Bubble Chamber Group, whose young Turks were Prince K. Malhotra, A. Subramanian, R. Raghavan, and Somnath Ganguli. They worked with the Big European Bubble Chamber (BEBC), commissioned in 1966, and the even-larger Gargamelle, built in the 1970s. After a few years, Yog Prakash's new group at Jammu also joined in. As the 1960s proceeded, another new era dawned in accelerator physics

with the advent of the Intersecting Storage Rings (ISR) at CERN. The Indian Bubble Chamber Group and collaborators were not behind-hand in using the ISR. They proposed and set up an experiment to measure photons emitted in proton-proton collisions.

The decade 1973-83 produced the consolidation of theoretical ideas developed in the preceding two decades with a number of new particle discoveries, once again, without much Indian involvement. However, in the 1980s, CERN planned a huge underground tunnel, 27 km in diameter, where the first experiment would be a Large Electron-Positron (LEP) collider which would later be dismantled and replaced by a Large Hadron Collider (LHC) with proton-proton collisions. Indians were welcomed into the L3 Collaboration at LEP. This time, it was not only TIFR and the Panjab University, but also BARC and several smaller groups across the country. The MOU was signed in 1984.





Physics conference in New York (Left to right: Homi Bhabha, Robert Marshak, and J. Robert Oppenheimer)

Source: AIP Emilio Segrè Visual Archives, Marshak Collection

India had always been strong in theoretical physics, and theoreticians of the calibre of B.M. Udgarkar and Virendra Singh were already at TIFR in the 1960s. Soon, their group was enriched by the addition of S.M. Roy, D.P. Roy, Probir Roy, Virendra Gupta, K.V.L. Sarma and A.K. Raina. At the Saha Institute of Nuclear Physics (SINP) in Kolkata, prominent names were T.N. Pradhan, Binayak Dutta-Roy, and Manoj Kumar Banerjee. Later Pradhan moved to Bhubaneswar to found the Institute of Physics (IOP), where he brought in S.P. Misra, Jnan Maharana, and Avinash Khare. At the IISc, a Centre for Theoretical Studies (CTS) was created under the initiative of E.C.G. Sudarshan, and included N. Mukunda, R. Rajaraman, J. Pasupathy, and Romesh Kaul. Later, the CTS, which had absorbed Rohini Godbole, Diptiman Sen, Apoorva Patel and others, morphed into the present Centre for High Energy Physics (CHEP). At Chennai, Alladi Ramakrishnan had founded the Institute of Mathematical Sciences (IMSc), where a strong group in theoretical high energy physics developed, including R. Parthasarathy, R. Anishetty, R. Simon, R. Jagannathan, N.D. Hari Dass, G. Date, T.R. Govindarajan, and Rahul Basu. G. Rajasekaran moved from TIFR to IMSc and so did Romesh Kaul from IISc. An active school of particle physics was created at Calcutta and Jadavpur Universities by Amitava Raychaudhuri and Amitava Datta respectively; Delhi University already had two stalwarts S.N. Biswas and A.N. Mitra, who had set up

active groups in the wake of pioneers D.S. Kothari and R.C. Majumdar. At the Physical Research Laboratory (PRL), a high energy theory group was set up by J.C. Parikh, Anjan Joshipura, Saurabh Rindani, and Utpal Sarkar. All these pioneers trained a whole generation of students and caused theoretical high energy physics to spread to almost every major academic institution in the country.

To come back to the CERN experiments, the TIFR-led Indian group joined hands with the German Aachen group to build brass-tube proportional chambers for the hadron calorimeter end caps. Eventually more than a thousand small tubes were fabricated in India and installed in the L3 detector by 1988, where they collected data and ran till the machine was dismantled in 2002. At such powerful high energy machines, data-taking is done by computers, and it requires very sophisticated software to collect, interpret, and analyse the raw data. Sunanda Banerjee from TIFR was one of the leaders of this effort at the L3 Collaboration, and eventually the software developed — GEANT and HEPDB — became standard tools for all high energy machines. The TIFR group also carried out physics analyses from the raw data. Somnath Ganguli and Atul Gurtu worked on the Z lineshape; Sunanda Banerjee studied QCD processes, and, in a pioneering work, Tariq Aziz and his students used neural network techniques to analyse Z boson decays.

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High-End Computation for High Energy Physics in India



Prof. Sunanda Banerjee

High energy physicist who has worked at several institutions, including Imperial College, London, CERN, TIFR, Fermilab, SINP, and IACS Kolkata; Renowned expert on the computational aspect of high energy physics analysis; Major contributions towards development of software used across the world to analyse medium and high energy scattering data

Experimental activities in High Energy Physics are broadly classified into four parts: building the equipment to record high energy collision among particles, recording information of high energy collisions including selection of some specific processes of interest, converting the digital information coming from the detectors into attributes of the particles participating in the collision, and analysing the converted attributes with some existing ideas to verify or to discard the theoretical ideas.

Software is required for all these aspects, but the so-called grey area is the third aspect, which needs software written by experts in the field of high energy physics. Though experiments in high energy physics were attempted by Indian physicists for over 80 years, the first effort on building a general software useful for all high energy experiments started only from the mid-80's when an Indian group joined the L3 collaboration, an experiment to study electron-positron collisions at the LEP in CERN. Apart from building a substantial portion of the offline software for that experiment, Indian(s) contributed to two general purpose software efforts: a toolkit (GEANT3) used in many experiments of that time to carry out detector simulation and a piece of software (HEPDB) used by many experiments for database related work. Both these software packages were maintained and distributed by CERN. The toolkit to carry out detector simulation was enlarged and improved with modern computing technology. This toolkit (GEANT4) is used not only for high energy physics and nuclear physics experiments, but also for medical research and space programs. It now records the highest cited piece of work in the field of high energy and nuclear physics (both theoretical and experimental).

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The Discovery of Quarks and Higgs Boson & *India's* Contribution

The underground physics group at TIFR decided, in 1990, to join the Tevatron experiment at Fermi National Accelerator Laboratory (FNAL) or Fermilab near Chicago. There had already been a Fermilab-India connection through the University of Delhi, where R.K. Shivpuri's group was working since 1986. The TIFR group included V.S. Narasimham, Naba Mondal, B.S. Acharya, Shashi Dugad, M.R. Krishnaswami, M.V.S.

Rao and, later, Sudeshna Banerjee. They participated by building 120 large scintillation detector components for the giant DZERO detector and writing the software to integrate it into the overall system. In 1992, the Delhi group joined in, followed by the Chandigarh group with J.M. Kohli, P.M. Sood, M.M. Aggarwal, V.S. Bhatia, Jasbir Singh, Suman Bala Beri, and Manjit Kaur. These groups were thus able to participate in the greatest triumph of the DZERO experiment, namely the discovery of the top quark in 1994.

However, neither LEP nor the Tevatron had found the Higgs boson, one of the cornerstones on which the Standard Model of particle physics is built. The stage was thus set for a new machine, and this made its appear-



GRID Computing Facility Lab during initial years

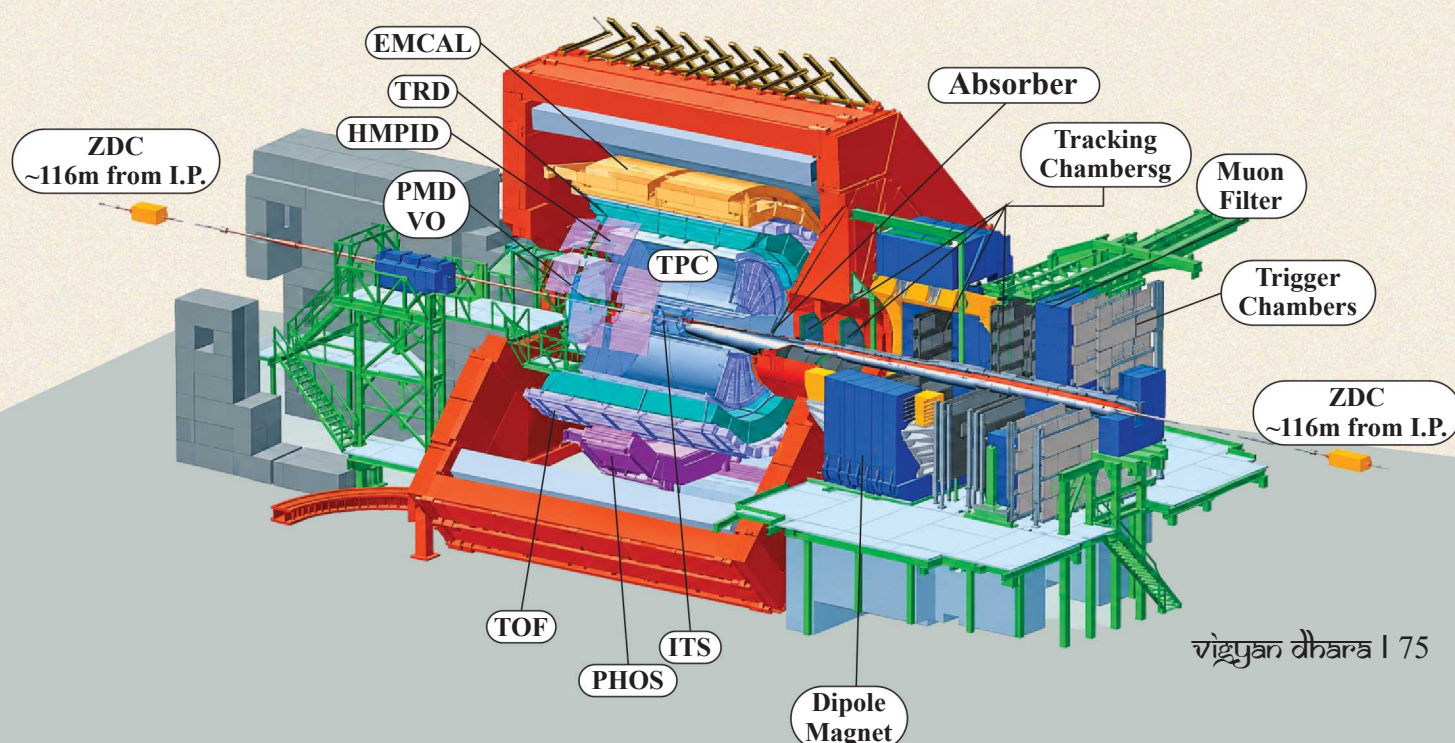


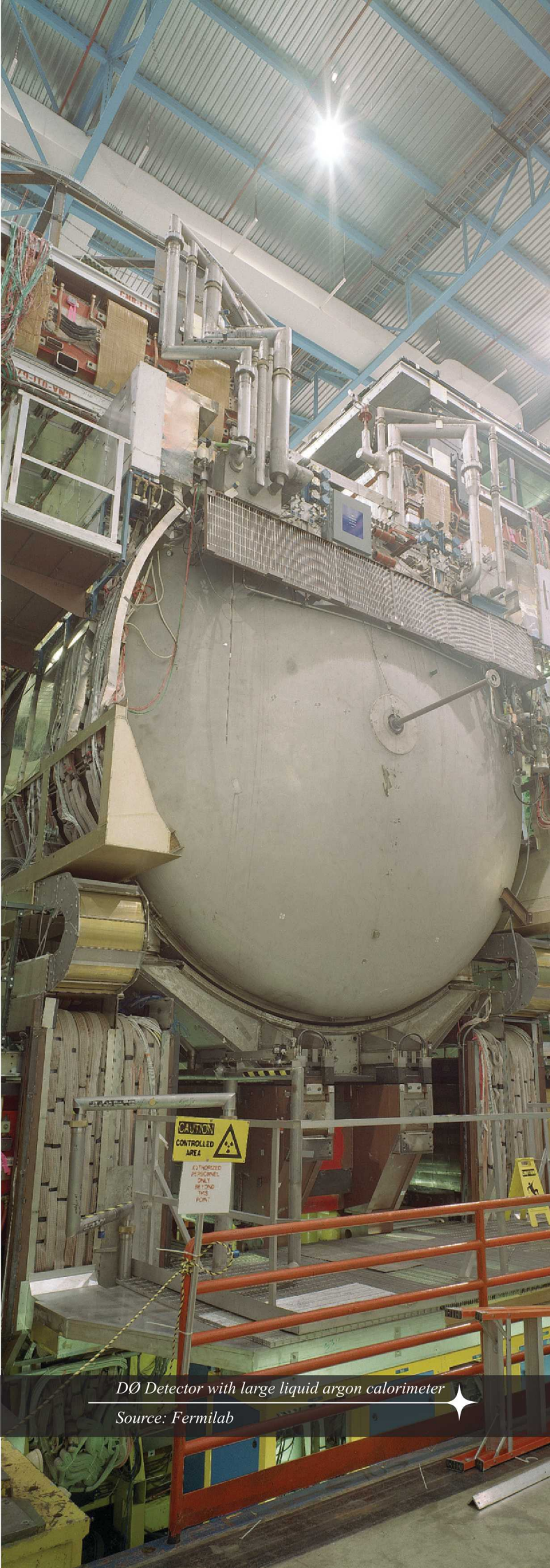
Source: Vikas Singhal, VECC Kolkata India



ALICE setup during RUN Slide from Tapan Nayak -2

Source: Vikas Singhal, VECC Kolkata India





DØ Detector with large liquid argon calorimeter

Source: Fermilab

ance in the LHC, running at 13.6 TeV. Of the four giant detectors on this accelerator, Indian institutions joined the international collaboration for the CMS detector (and the collaboration for the ALICE detector for relativistic heavy ion physics). The India-CMS contribution to hardware at the LHC consists of the Outer Hadron Calorimeter, built by TIFR and Panjab University; and the Silicon pre-shower detector, built by BARC and the Delhi group. In addition, Sunanda Banerjee and his collaborators continued to build up the software. The massive computation required for the LHC engendered the concept of grid computation, and TIFR became a Tier-II centre for the LHC Grid (VECC-Kolkata also became a Tier-2 Centre for the ALICE Collaboration). One of the very first successes of the LHC was to find the long-sought Higgs boson in 2012. It is a matter of pride that the author list of the CMS Higgs-discovery paper contains no less than 71 names of scientists working in Indian institutions.

However, this initial euphoria has now got substantially tempered with realism. While the LHC has discovered a whole zoo of new quark bound states, including the long-postulated tetraquarks and pentaquarks, and also produced large amount of valuable data on various Standard Model processes, the hunt for heavy new particles and processes beyond the Standard Model has drawn a complete blank so far. The LHC has just shut down for four years, for an upgrade in the beam intensities. It will resume running in 2030, and may, perhaps find the Holy Grail of new interactions. And then, far on the horizon, is a new behemoth, with the deceptively simple name of Future Circular Collider or FCC, planned to collide protons at the staggering energy of 100 TeV. This wondrous machine is not likely to come up before 2070, but plenty of exciting discoveries can happen between now and that remote date.

Landscape of Astronomy & Astrophysics in India

From Carte du Ciel to Computational Modelling



Prof. Jasjeet Singh Bagla
*Professor, Indian Institute of Science
Education and Research (IISER), Mohali*

AI Generated



India has had a tradition of astronomy since ancient times. Growth of astronomy continued during colonial times with many important discoveries being made from India, e.g., discovery of Helium in the Sun.

An observatory in Hyderabad participated in the first international project (Carte du Ciel) to map the stars more than a hundred times fainter than the faintest stars we can see with unaided eyes from a dark location on a clear night. This project was initiated in 1887 by the Observatory de Paris and a total of twenty observatories around the world contributed photographic plates taken over several decades.

The first modern observatory that survives

till date was set up in Kodaikanal and has completed more than 125 years of observations; the observatory was originally established in Madras (now Chennai) and moved to Kodaikanal by 1899. Daily observations of the Sun made at the observatory have been digitised and are available to researchers for free download. The Evershed Effect was discovered here in 1909 — this is the radial flow of plasma at the periphery of sunspots.

In this article we will give an overview of significant discoveries in A&A during the last century with greater emphasis on the last three decades. We have organised the article by themes, though there is considerable overlap between different themes given the nature of the subject.



Attempts to take a daily photoheliogram using the 6-inch Refractor Telescope at the Kodaikanal Solar Observatory (KSO)

Photo: Abhishek Chinappa (Getty Images)

Optical Astronomy

Use of telescopes for quantitative astronomical observations was initiated during the colonial period. After Independence, institutions to manage these observatories and do research in astronomy were established and new observatories were set up. Leading institutions and observatories at present are: Indian Institute of Astrophysics — manages observatories at Kodaikanal and Kavalur (Tamilnadu), and Hanle (Ladakh); Physical Research Laboratory (PRL) — manages observatories at Mt. Abu and

Udaipur (Rajasthan); Aryabhata Research Institute of Observational Sciences (ARIES) — manages observatories at Nainital and Devasthal (Uttarakhand); Inter-University Centre for Astronomy and Astrophysics (IUCAA) manages the Observatory in Girawali (Maharashtra). While these observatories host telescopes that are considered small given contemporary standards, these have been used to make some significant contributions and discoveries.



Himalayan Chandra Telescope (HCT)

Photo: Dorje Angchuk (IIA)

Observations confirming the existence of rings around Uranus were made in 1977 during the occultation of a star by the planet. In an occultation, the planet passes in front of the star, thereby eclipsing it. Independent observations of the same event were made from the Kavalur observatory as well as from the Sampurnanand telescope (Nainital, at that time this was a part of the Uttar Pradesh State Observatory; now the telescope is a part of observatories maintained by ARIES). The complete event was observed from the Kuiper airborne observatory. Three independent observations provided the required confirmation.

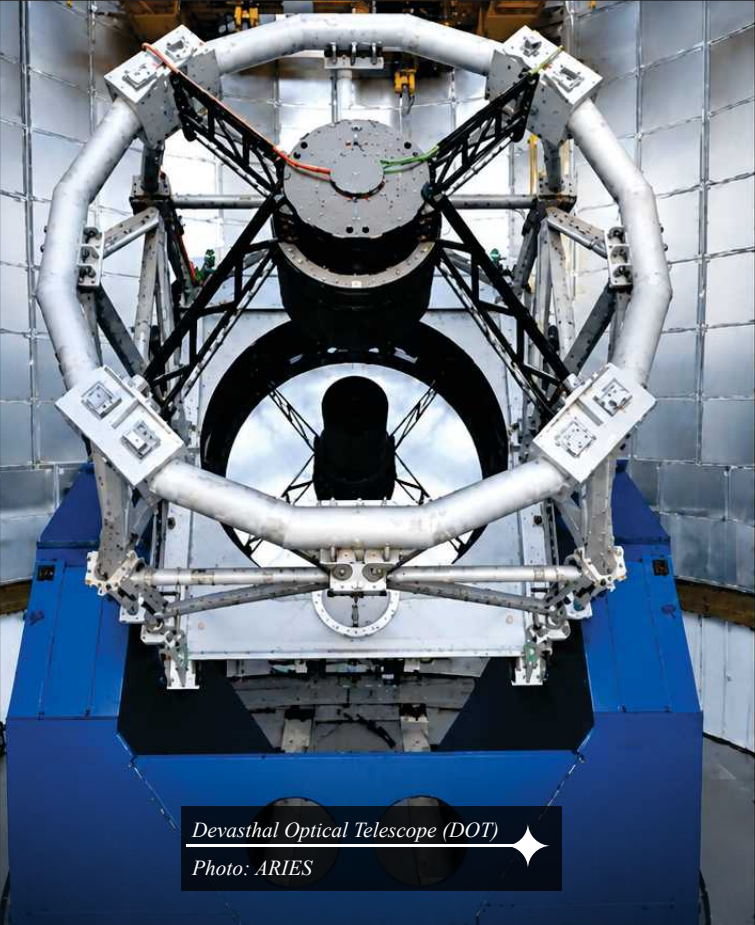
The first 2m class telescope was set up in

Kavalur, christened the Vainu Bappu telescope (VBT). VBT was made in India and inaugurated in 1986. Observations with this telescope started in the mid-1980s. Since then, India has added other telescopes of similar size (Hanle, IIA; Girawali, IUCAA; Mt. Abu, PRL). At present, the Devasthal Observatory near Nainital managed by ARIES has the largest optical telescopes in India: a 3.6m telescope (Devasthal Optical Telescope (DOT)) and also a 4 m International Liquid Mirror Telescope (ILMT).

India: a 3.6m telescope (Devasthal Optical Telescope (DOT)) and also a 4 m International Liquid Mirror Telescope (ILMT).



Map is not at scale



Devasthal Optical Telescope (DOT)

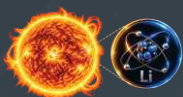
Photo: ARIES

PRL Ahmedabad has built an extremely high-resolution spectrograph that has been used to study spectroscopic binaries and planets around other stars. This is being used at the Mt. Abu Observatory. This is the first Indian instrument capable of detecting planets in the habitable zone around low mass stars. It has been used to study low mass



binary systems, brown dwarfs, and exoplanets.

Indian telescopes have contributed to studies of transients. This is an area where smaller telescopes can be of considerable use in completing the longitudinal coverage. Some other key results from India includes:



A spectroscopic survey of 2000 red giants that led to discovery of 15 new Lithium-rich giants, and follow-ups established that these stars are predominantly core helium-burning red clump stars, contributing significantly to the resolution to the well-known problem of Lithium overabundance in stars. Lithium is one of the elements that was synthesised in the early Universe and hence its abundance is of interest for cosmology.



Helioseismology studies of the deep meridional circulation in the Sun provided one of the first robust detections of the deep return flow, which was extended recently to uncover dynamic links between subsurface flows, magnetic-flux transport, and solar-cycle evolution.

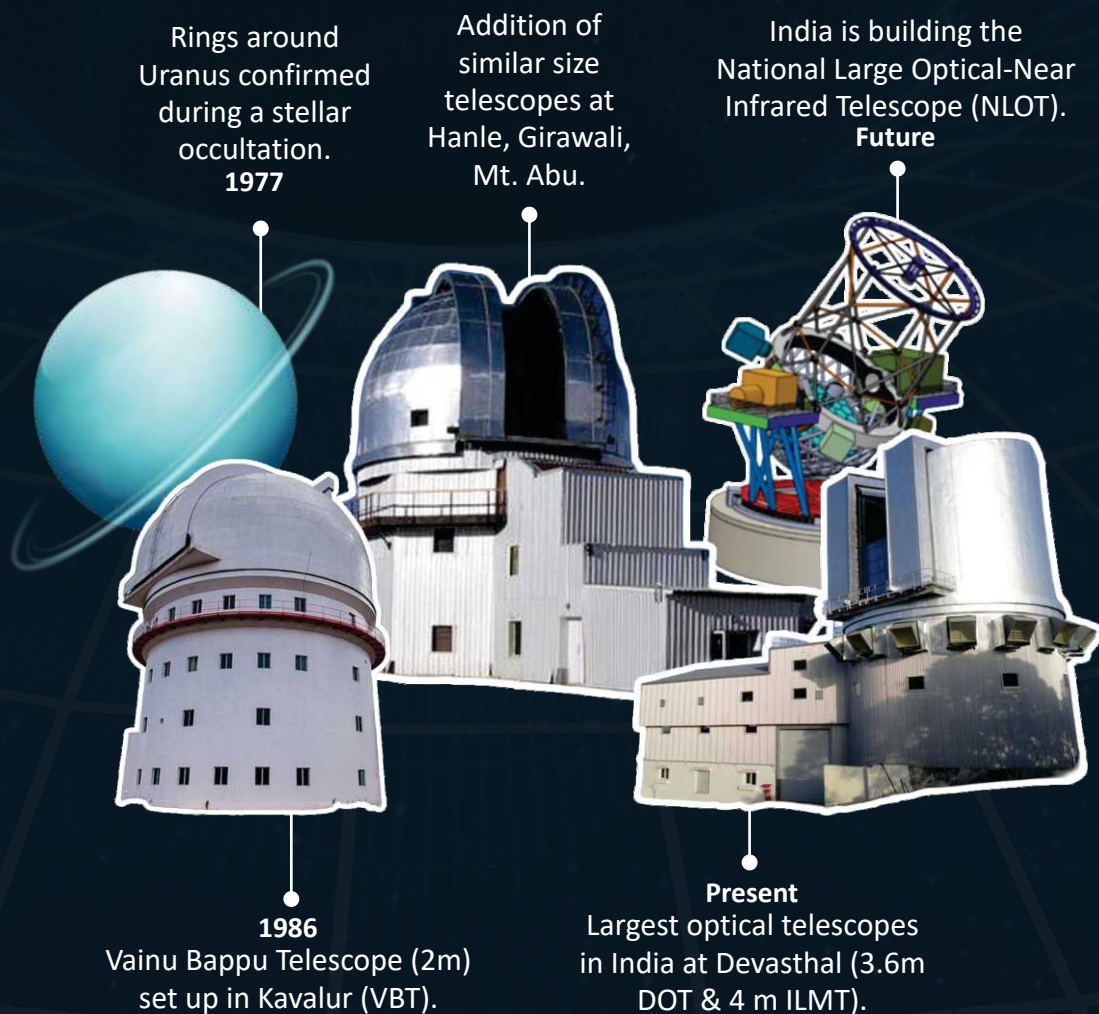


Studies of the Magellanic Clouds done by combining large datasets mapped their 3D structure and uncovered interaction-induced stellar and kinematic substructures.

Going forward, India is a partner in the forthcoming Thirty-Meter Telescope (TMT) project. India is producing mirrors for the telescope amongst other components and contributing to the development of key instruments and science cases. With this, India has gained access to segmented mirror technology, which is going to be used in building the National Large Optical-Near Infrared Telescope (NLOT) that has been announced in the National Budget for 2026. This is planned to be set up at the Hanle site which is a very good site for a telescope of this size and will give a tremendous boost to Indian astronomy.

Another major astronomy-related announcement made in the National Budget for 2026 is the setting up of the National Large Solar Telescope (NLST) on the bank of the Pangong Lake in Ladakh. This site is considered to be one of the best in the world for solar astronomy, and the availability of a large solar telescope there will give a significant push to solar astronomy in the country. This project will also have global significance as it will longitudinally complement the other large solar telescope in Hawaii, enabling round-the-clock solar observations. NLST and NLOT will demonstrate the potential of globally competitive astronomy sites in India for advanced observational facilities.

India's Optical Astronomy Journey



Radio Astronomy

Several institutes in India are working on various aspects of radio astronomy. This activity started in the 1960s at the TIFR. Govind Swarup took the lead and set up an array in Kalyan near Mumbai to make observations of the Sun. The array was brought from Australia where it was being dismantled by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). This was followed by an ambitious project — the Ooty Radio Telescope.

The proposal was to build a large equatorially mounted radio telescope. A north pointing slope with a gradient coinciding with the latitude was found; and the 500m x 30m cylindrical telescope was set up. This is one of the largest steerable radio telescopes in the world. It is fascinating to note that the telescope was entirely made in India. This was a phased array operating at 1m wavelength. Given the geometry, it had very good resolution along the North-South direction. To achieve good resolution along the East-West direction astronomers used the occultation or eclipsing of radio sources by the Moon. Although this strategy restricted high resolution observations to a narrow band of the sky, considerable work was done

to uncover the detailed structure of radio galaxies before the advent of radio interferometers. A gravitationally lensed system was discovered in the radio-band, thanks to this innovative strategy. One very interesting outcome was the initiation of a long-standing collaboration between the Raman Research Institute (RRI) and the Radio Astronomy Group at Tata Institute of Fundamental Research (TIFR). It is also worth mentioning that this collaboration led to an interest in theoretical aspects of gravitational lensing and data analysis. Use of maximum entropy methods was refined in the context of analysis of radio data to address the question of how much information can we extract from observations given the number of independent data points. The telescope was inaugurated in 1969 and continues to be in use after two major upgrades of the backend electronics. It has played a very important role in studies of numerous astronomical sources as well as studies of space weather. Raman Research Institute, Indian Institute of Astrophysics, and Physical Research Laboratory also set up low-frequency radio observatories to observe the Sun. These were used to observe other sources as well.

Radio Astronomy Centre, Ooty

Photo: Ooty Tourism

In the 1970s, the radio astronomy community worldwide started to push towards radio interferometry, and the Very Large Array (VLA) was built in New Mexico. Govind Swarup made the case for a radio interferometer to be built in India. He wanted to exploit the stable weather in the Indian peninsula and focus on frequencies below 1 GHz to complement the VLA and construct an array

at a significantly lower cost. The proposal was refined over time to increase the frequency range up to 1.42 GHz. This change was triggered by suggestions from RRI in view of the very important spectral line of atomic Hydrogen at 1.42 GHz. RRI supplied the 1.4 GHz feed for the telescope. A site was identified near Pune and construction began in 1989.

Indian Radio Astronomy: A Short Timeline



Setting up an array in Kalyan

TIFR began radio astronomy activity in India, with an array brought from Australia to observe the Sun.

Ooty Radio Telescope inaugurated
The 500m × 30m telescope became one of the largest steerable radio telescopes, entirely made in India.



Push towards radio interferometry

Indian astronomers began developing an interferometer to expand radio observations and complement the Very Large Array, built in New Mexico

Construction of GMRT began
A site near Pune was selected, and construction started on what would become a major Indian radio astronomy facility.



GMRT made available for observations

The GMRT opened for observations, enabling studies across a wide frequency range and new discoveries about galaxies, pulsars, and the Universe.

The Giant Meterwave Radio Telescope (GMRT) was made available for observations in 1999. This has seen two major upgrades since then and continues to be one of the finest facilities in India. At present, it offers nearly continuous coverage over the

frequency range 150 - 1420 MHz with a simultaneous bandwidth of up to 400 MHz. The array consists of 30 antennas, 45m diameter each. For comparison, the A320 Neo passenger aircraft is only 37.6m long. Each antenna is fully steerable and can be

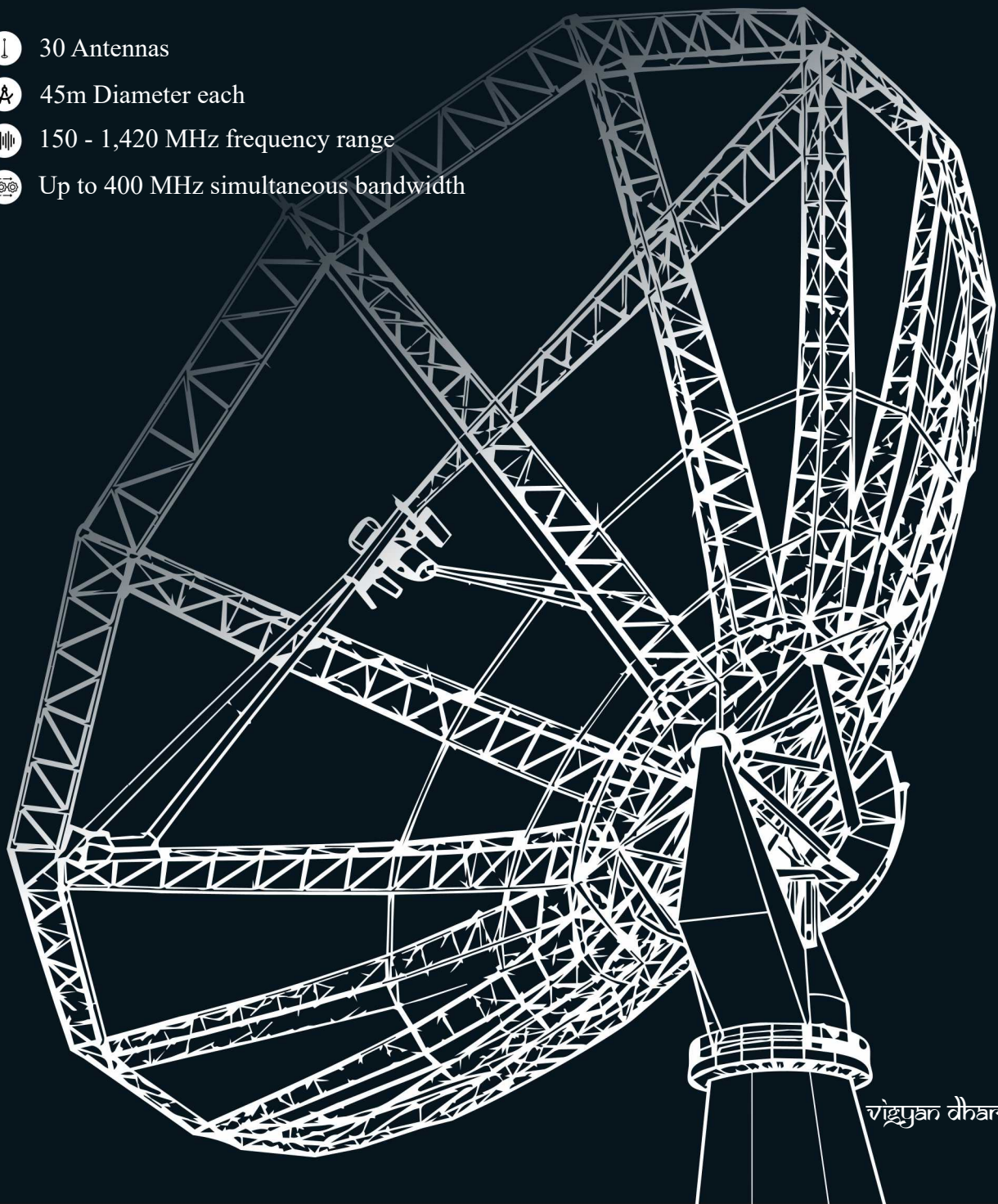
pointed to any direction in the sky and follow any given source from rise time to setting. The antennas have a wire mesh for reflecting surface that lowers the weight. The design that made this possible was patented by the team. Like the Ooty Radio Telescope, this too was made in India, and the same approach has been used in the upgrades of the facility. A number of innovations were deployed to limit the weight of individual antennas.

Astronomers have worked hard to ensure that this remains an important facility even as the Square Kilometer Array (SKA) is being built and other facilities across the world are upgraded and newer facilities are set up. A major challenge being faced is the radio frequency interference from human activities, as these are far stronger than the radiation from astronomical sources.

THE GIANT METREWAVE RADIO TELESCOPE

“A Larger Sky, a Deeper Understanding.”

- ↓ 30 Antennas
- ⌘ 45m Diameter each
- 📶 150 - 1,420 MHz frequency range
- 📡 Up to 400 MHz simultaneous bandwidth



Key discoveries have been made using the GMRT



The GMRT Sky Survey (TGSS) at 150 MHz was one of the first high resolution all sky surveys at low frequency. Studies of radio galaxies and radio halos in clusters of galaxies have given us many insights into physical processes and time scales at work.



A number of pulsars have been discovered with the GMRT and at present it is a key part of the Pulsar Timing Array consortium where observations of pulsars are being used to determine the gravitational wave background at nano Hz frequencies.



Studies of absorption systems have given us critical clues about the evolution of galaxies and their environments.



Studies of galaxies, especially dwarf galaxies at low redshifts in emission from atomic Hydrogen were made possible by the large collecting area of the GMRT.



The upgraded GMRT has been used to give us first estimates of the atomic gas content of galaxies at intermediate and high redshifts. One very interesting finding is that the atomic Hydrogen content of galaxies changes sharply at redshift of unity, with more distant galaxies being gas rich. Such estimates are essential for understanding formation and evolution of



At present, the GMRT is also being used to observe radio emission from stars and fast radio bursts.



Recently, GMRT has acquired radio antennas that can be used for high frequency observations.

These, and ongoing efforts to build a sub mm radio telescope will increase the range of frequencies accessible to Indian astronomers from within the country.

India has also been an active member of the international radio astronomy community. India is a partner in the SKA project and is leading in some respects and contributing significantly to others. RRI Bangalore participated actively in designing and using one of the SKA precursors — the Murchison Widefield Array (MWA) in Australia.

Efforts are being made to observe the spectrum of the cosmic microwave background radiation. Of particular interest are deviations from the black body spectrum that give us information about the transitions like recombination and the transition from dark

ages to the epoch of reionisation. These are very challenging as the expected deviations are extremely small. The SARAS (Shaped Antenna measurement of the background Radio Spectrum) project from RRI is noteworthy as it has achieved sensitivity that is comparable to the best reported in the field. At present there is a disagreement between the reported measurements from different projects, but it is expected that further improvements will lead to an agreement and an improved understanding of a critical stage of the Universe that cannot be studied with other techniques.

Balloon Borne Astronomy

Earth's atmosphere is opaque for electromagnetic radiation at most wavelengths as well as for high energy cosmic ray particles. Observations in this regime are done from space, or above the dense part of the atmosphere using balloon borne instruments, or observations from the ground that target secondary or tertiary products of the incoming particles or radiation.

TIFR maintained a balloon launch facility in Hyderabad from where launches were done for astronomical studies in the infra-red. Stratospheric balloon missions could stay up for hours to days and hence make extended observations. The facility is now being revived as there is an interest in testing design ideas for space missions as well as lower costs and a shorter turnaround time for deploying equipment.

A spectacular high-altitude balloon launch, marking the beginning of a scientific journey into the atmosphere.

Photo: Tata Institute of Fundamental Research (TIFR)



Rocket and Space Based Astronomy

While balloons can make extended observations, the maximum altitude that they can reach is inadequate for X-Ray observations. Such observations were initially made using rocket launches, where the payload could stay at a high enough altitude for minutes. In later years, several space-based observing systems were used as the payload in this case can operate for many years.

Rocket based astronomy efforts started in the 1970s and created a knowledge base where instrumentation for space-based astronomy could be contemplated. Starting in the 1980s, piggyback instruments for space-based astronomy were added to other space missions. It was only around the turn of the millennium that a space-based observatory was conceptualised. Astrosat was to be a multiwavelength observatory with instruments covering UV, soft X-Rays, hard X-rays and Gamma rays. The UV telescopes (two of them) and the soft X-Ray telescopes were aligned to observe the same source simultaneously. Other instruments had a wider field of view and excellent timing sensitivity. Largely an indigenous effort, the observatory was launched in 2015 and became fully operational in 2016. It had a design lifetime of five years but some of the instruments continue to function even after ten years in space. Development of Astrosat, data reduction pipelines, and data archives have created a resource that can be deployed for future missions. The XPoSat mission launched in 2024 has been made possible through the availability of this experience and knowhow. Similarly, Aditya L-1 mission has also benefitted from the synergy between space sciences and astronomy. Quite a few future missions are now at various stages of development.

AstroSat UVIT is the largest space-based UV telescope and has given us unique insights into star formation in galaxies and evolution of galaxies out to high redshifts. Similarly, the soft X-ray telescope has outperformed expectations, and its high spectral resolution



has been used effectively. It has been used to place limits on spin of black holes, study physics of accretion disks, and active galactic nuclei. LAXPC and CZTI detectors have been used to observe hard X-Rays. CZTI detector has been used for studies of Gamma Ray Bursts, an area that was not envisaged for this instrument.

AstroSat UVIT is the largest space-based UV telescope and has given us unique insights into star formation in galaxies and evolution of galaxies out to high redshifts. Similarly, of the soft X-ray telescope has outperformed expectations, and its high spectral resolution has been used effectively. It has been used to place limits on spin of black holes, study physics of accretion disks, and active galactic nuclei. LAXPC and CZTI detectors have been used to observe hard X-Rays. CZTI detector has been used for studies of Gamma Ray Bursts, an area that was not envisaged for this instrument.

XPoSat, launched in January 2024 is

designed to measure polarisation of X-Rays. This can be used to deduce emission mechanisms, especially it can distinguish between thermal and non-thermal processes.

Aditya L-1 is a mission dedicated to the study of the Sun and the heliosphere. It is located at the Lagrange point L-1 in the Earth-Sun system, which is a feat of space engineering. This mission carries instruments that study the Sun over a wide range of wavelengths, the corona, and the energetic particles that emanate from the Sun, etc. It plays a key role in improving our understanding of solar wind and space weather.

Several missions have been planned and some of these are slated for launch in the coming decade. These are apart from the planetary exploration that has received a significant boost with the success of the Mars Orbital Mission and the Chandrayaan. Future missions to the Moon, Mars, and Venus are also being planned.

From Rockets To Space Observatories



Cosmic Rays and Gamma Rays

Cosmic rays are energetic particles accelerated to extremely high energies in astrophysical processes. The highest energy cosmic rays that have been observed have energy that exceeds the energy of most energetic particles produced in particle accelerators like the LHC by more than seven orders of magnitude. This makes observations of cosmic rays very important. The observations also give us an insight into possible particle acceleration mechanisms. India has had a strong tradition of cosmic ray studies with observatories at

Ooty, Panchagani, and Gulmarg. At present, only the observatory in Ooty is functional. At the international level, several large-scale observatories have been set up to detect ultra-high energy cosmic rays.

The MACE telescope has been set up at Hanle, Ladakh to observe Gamma rays from astronomical sources. This is a large facility, though not comparable to the largest such facility that is in Namibia.

The MACE Telescope has been inaugurated at Hanle, Ladakh

Photo: ISRO Spaceflight Now

Theoretical and Computational Astrophysics

India has had a strong tradition in theoretical studies for more than a century. Meghnad Saha's work on ionisation equilibrium paved the way for determination of the constituents of stars by Cecilia Payne and we learnt that all stars in the Universe are primarily made up of Hydrogen and Helium. This tradition has continued and grown, and India has made many significant contributions to the field of gravitation, cosmology, gravitational waves, gravitational lensing, structure of stars, helioseismology, dynamics of star clusters and galaxies, etc. In the last three decades, the area of computational astrophysics has been

added to the list and today India can boast of important contributions in computational modelling of galaxy formation, accretion disks, neutron stars, etc. The study of gravitation and general relativity took root in India from a very early stage. Pioneers included V.V. Narlikar, Bishveshwar Datt, etc. P.C. Vaidya generalised the Schwarzschild solution to include outgoing or incoming radiation. A high point was the derivation of the Raychaudhuri equation by Amal Kumar Raychaudhuri; this work eventually led to the singularity theorems by Hawking and Penrose.



LIGO - A rendering of the LIGO India site in the state of Maharashtra

Photo: LIGO caltech

Gravitational Wave Astronomy

The discovery of Gravitational Waves in 2015, an effort that had significant participation from India has heralded a new age in A&A with a completely new probe or messenger that brings us information about some of the most energetic phenomena in the Universe. A LIGO detector is being set up in India and is expected to be operational in the coming years. Indian astronomers have contributed immensely to modelling sources

and propagation effects, as well as in optimisation of detection of signals.

There are other areas like astro-chemistry, astro-biology, etc. that are not adequately represented in India. It is expected that this lacuna will be addressed in coming years so that all aspects of A&A are practiced in the country and development of interdisciplinary studies can be carried out in our institutions.



Perspectives 8

Department of Atomic Energy



Dr Ajit Kumar Mohanty,
Secretary, DAE and Chairman,
Atomic Energy Commission (AEC)

1. In the context of HEP, India made a number of in-kind contributions to the India-LHC/CMS Collaboration. How important and useful have these technological know-how's been for other Mega Science Projects (MSPs) in HEP?

Dr Mohanty: Indian scientists and institutions have been participating in experimental activities since the early 1960s. Collaboration started between Indian researchers and CERN, when scientists from the Indian institutions visited CERN to expose emulsion stacks to pion, kaon, and proton beams (TIFR, and later, Panjab University, Jammu University). Later, in the 1980s, there was contribution towards hardware and core-software for the Large Electron Positron Collider (LEP). During the 1990's, collaboration expanded to include heavy ion physics, and the Indian laboratories contributed a scintillator-pad based Photon Multiplicity Detector.

India's in-kind contributions to LHC construction were substantial and technologically diverse. They included around 1,700 superconducting corrector magnets, over 7,000 precision magnet-positioning systems, about 5,500 quench-

heater power supplies, and more than 1,400 local-protection units, along with contributions to magnet testing, cryogenics, controls, power converters, vacuum systems, software, and commissioning.

At present, India is part of two experiments at the LHC, viz., ALICE (A Large Ion Collider Experiment) & CMS (Compact Muon Solenoid), besides hosting computational centers within the country which are part of the Worldwide LHC Computing Grid. Indian scientists have participated in CMS and ALICE detector building, installation, analysis software, detector simulation Monte Carlo studies, physics simulation, and analyses. The notable contributions on the hardware front include Photon Multiplicity Detector (PMD), Muon Spectrometer, MANAS chip (ASIC), and High Level Trigger (HLT) for Muon Spectrometer for the ALICE project. Similarly, Indian groups in the CMS experiment have played a leadership role in building several CMS detector components such as: Hadron Barrel Outer Calorimeter, Silicon strip-based pre-shower detector, Resistive Plate Chambers for the CMS muon system for fast timing and triggering, etc.

The Indian HEP community is also taking part in the upcoming detector upgrade program of both the experiments, where Indian industry will be supplying part of detector hardware, as part of India's in-kind contribution to these experiments. Indian groups are participating in the development of a new detector named FoCal for the ALICE experiment. The group has successfully developed p-type Silicon detector in India in collaboration with Indian industries, viz. Bharat Electronics (BEL), Bangalore; Semi-Conductor Laboratory (SCL), Chandigarh; and Micropack, Bangalore. Similarly, the India-CMS group will be contributing towards hardware of four detector sub-systems: 1) Outer Tracker, 2) High Granularity Calorimeter (HGCAL), 3) GEM chambers for Muon Detector, and 4) Upgraded Trigger System.

Mega Science projects (MSPs) involve greater complexity and require multi-disciplinary, multi-institutional teams for effective implementation. Modern experimental science relies heavily on advanced detectors and high-performance computing. Participation in hardware development and supply to MSPs, such as at CERN, leads to direct technological gains for the country in terms of advanced technologies and equipment building, as well as development of expertise to take on similar projects in future that push the frontiers of technology. The technological know-how from CERN, helped Indian teams with other MSPs such as the STAR (Solenoidal Tracker at RHIC) experiment at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL), USA; Proton Improvement Plan at Fermilab, USA, etc.

India is also participating in FAIR project, Germany, where again Indian scientists /engineers along with Indian industry have delivered power converters etc., the knowledge of which is expected to be beneficial for Radioactive Ion Beam facilities within the country.

2. Some of the detectors developed for India-LHC/CMS Collaboration can have other important uses, for example, for imaging applications in civil as well as security environments. Does DAE plan to develop these technologies for other such important applications?

Dr Mohanty: During the participation at CERN, our researchers have been a part of development and supply of many detector technologies. The two main detector technologies are i) Semiconductor-based detectors such as Silicon-based detectors, Silicon microstrip sensors and ii) Gas Detectors such as Large-area Resistive Plate Chambers (RPCs), Gas Electron Multipliers (GEMs).

The development of such detectors, along with high-end electronics and high-performance computing in India, have provided an opportunity to our industry partners to build indigenous capability in associated niche technologies. Although developed primarily for fundamental physics, many of these technologies have potential applications in other areas. Depending on the particular detector and associated electronics, these may include medical and radiation imaging, dosimetry, radiation monitoring, non-destructive testing, muon-based imaging or tomography, industrial inspection, and security applications.

An important lesson from MSPs is that the development of a technology for a scientific experiment and its eventual translation into a deployable societal or industrial application are often two different stages. The latter generally requires additional R&D, prototyping, validation, engineering, and industrial partnership.

DAE can play an important role in facilitating promising technological spin-offs from research laboratories for further development and translation, together with academic partners and Indian industry.

3. In the context of A&A, DAE, DST, and DOS institutions have complementary (and at times also supplementary) expertise in associated instrumentation. Do you think that the long-time DAE-DST partnership in jointly funding and implementing MSPs will greatly help (together with DOS) in realising major A&A MSPs like LIGO-India, India-SKA, National Large Solar Telescope (NLST) and National Large Optical-Near Infrared Telescope (NLOT), etc.? Do you think that the mega science management structures built by DAE and DST have become even more relevant now with the upcoming MSPs in A&A?

Dr Mohanty: Yes, I agree on both counts. Over several decades, institutions under DAE, DST and DOS have developed complementary expertise in areas relevant to modern A&A, including advanced detectors, optics and lasers, radio-frequency systems, cryogenics, electronics, precision engineering, control systems, high-performance computing, large-scale data analysis, and observational science.

The DAE-DST partnership in jointly funding long-term initiatives has greatly benefited various projects. MSPs managed jointly by DAE and DST cover the complete gamut of required expertise, from instrument design and development to observational science, which allows these new fields of astronomy to develop sustainably in the country. Every aspect of these MSPs in A&A gets addressed by the combined expertise available within DAE and DST.

In particular, several DAE institutions are actively involved in research and development for ground-based cosmic ray, radio, and high-energy gamma-ray observation facilities. They are also integral to multi-messenger astronomy programs at both national and international levels. Take LIGO-India, for example, where the laser, optics, and engineering expertise within DAE has been leveraged for an international partnership in a fundamental science experiment. This

evolving field of multi-messenger astronomy will usher in a new era of A&A across DAE and DST academic institutions.

Therefore, I am confident that the long-standing DAE-DST and DOS partnership in funding and implementing MSPs will play a pivotal role in successfully realising upcoming large-scale national facilities. I also believe that the management structures created by DAE and DST, which may be tweaked in line with departmental mandates to suit our domestic MSPs, are highly relevant for future mega science observational projects in A&A.

4. The DAE-DST partnership has contributed a great deal in the expansion of the HEP and A&A community outside the national laboratories. Large number of active researchers are in the Higher Educational Institutions (HEIs) now. Do you think the enlarged eco-system will be an asset for realising MSPs in these two disciplines in future?

Dr Mohanty: Yes, an enlarged ecosystem in higher academic institutions is extremely important for successful realisation of the MSPs in the country. The larger community of A&A researchers encompassing national labs and Higher Educational Institutions is necessary for the successful implementation and utilisation of MSPs. The MSPs such as LIGO-India provide an opportunity to build a Mega Science facility within the country which is contemporary to international facilities. This would attract the next generation of A&A researchers to national labs and Higher Educational Institutions and enable them to do science in the evolving fields of A&A at world-class levels. Such larger ecosystems are very much needed to ensure successful and meaningful returns to the wider community in the country from MSPs.

National laboratories provide long-term institutional continuity, sophisticated infrastructure, engineering and technical expertise, and the ability to support large

projects over extended periods. Higher Educational Institutions complement this by greatly expanding the scientific user community and, importantly, by bringing large numbers of students and young researchers into frontier research.

Mega Science facilities usually operate for decades. Their success therefore cannot be measured only by successful construction and commissioning. The real return on national investment depends upon having a sufficiently large, capable, and scientifically diverse community that can use the facilities effectively, develop new instrumentation and analysis methods, train the next generation, and continuously generate internationally competitive science.

There is therefore a mutually reinforcing relationship. Mega Science Projects provide HEIs with access to frontier science and advanced technology, while the expansion of research in HEIs creates the human-resource and scientific base needed to make major national and international facilities successful.

5. How will the MSV-2035 Reports in HEP and A&A prepared by the two national communities help DAE in promoting R&D in these disciplines?

Dr Mohanty: DAE has a long history of institutional participation in HEP and A&A. In 2006, DAE accepted as mandate that MSPs should appeal to the scientific curiosity of the researchers in search of answers to some of the important questions

facing the world of science and should be of interest to a large scientific community from various research groups within the country and outside. To bring MSPs to fruition it was observed that apart from the scientific facilities, there would be a need to bring together a large group of researchers who come from different institutions situated within the country and from different parts of the globe. DAE through its consistent approach and sustained effort has been able to build that ecosystem to some extent.

The MSV-2035 was prepared by people of such ecosystem or user groups. MSPs have a long gestation period to develop the expertise, to develop the facilities for fabricating the key components, build the instruments and then commission them to reach the design sensitivity. This would require focused efforts over multiple years to reach the critical levels of expertise for taking up the next generation of MSPs within the country. The documents lay out a blueprint and will be the guiding light for the development of sustainable MSPs in both, HEP and A&A. The reports spell out the current status, strengths, and weaknesses and describe the future plans for potential growth areas. I believe that the above measures, if pursued effectively, are expected to lead to a wider engagement of scientists across the country, and more efficient utilisation of the existing talent pool. This would help the Indian scientific community realise their MSP visions and also make India an attractive location for hosting future international MSPs.

Perspectives

Department of Space



Dr V. Narayanan
Secretary, DOS;
Chairman, Space Commission; and
Chairman, ISRO

1. DOS has major national presence in solar and space astronomy, DST in optical and solar astronomy, and DAE in radio and gamma ray astronomy. Astronomy & Astrophysics (A&A), thus, may be a unique discipline where the national research capacity is distributed among these three premier agencies. Do you think A&A presents itself as a discipline where inter-agency cooperation is manifestly required in the Indian context? Where do you think the cooperation is complementary or supplementary in nature?

Dr Narayanan: Inter-agency cooperation is essential in the Indian context. A&A is inherently multi-wavelength and multi-messenger, which implies that the astrophysical processes and events must be observed through different windows of the electromagnetic spectrum (every part of the electromagnetic spectrum brings out different facets of the astrophysical processes and events), as well as via particles or Gravitational Waves (GW) to construct the complete perspective. This makes the efforts of DOS, DST, and DAE highly complementary. For example, discovering a GW event via DAE-DST's LIGO-India may require follow-up observations using DST's optical telescopes (like the DOT) and ISRO/DOS's X-ray or UV space observatories (like AstroSat- India's multi-wavelength astronomical observatory). Supplementary cooperations include sharing high-performance computing facilities, establishing common Time Allocation Committees (TAC) for national telescopes, or jointly funding and managing international mega-

projects like the Square Kilometre Array (SKA) or the Thirty Meter Telescope (TMT).

2. The A&A payloads for ISRO have been built by consortia of national labs, higher educational institutions and industry. What has been DOS' experience in forging such inter-agency, inter-institutional, and industrial collaborations? What have been the gains and challenges?

Dr Narayanan: DOS' experience in roping in the expertise of the consortia of research and academic institutions for space missions like AstroSat, Aditya-L1, and XPoSat has been largely successful. The major gains include effectively leveraging the specialised expertise of diverse academic institutions (such as IIA, IUCAA, RRI, TIFR) and accelerating indigenous technological capacity. The transition from laboratory concepts to space-qualified hardware (as well as software) often exposes a gap in the payload development capabilities of academic partners who are unaccustomed to space-grade engineering protocols. Ensuring the standard protocols of quality assurance, system reliability measures, and seamless workflow integration between ISRO and academic institutions has been challenging. DOS feels it necessary to revisit and formalise these workflows in order to ensure zero-defect payloads, data-products, as well as to ensure high system reliability.

3. Space is primarily the domain of DOS. Do you think that Space-based astronomy will emerge as the next experimental frontier for A&A? In your view, will it

completely replace ground-based A&A, or it will remain a complementary platform for experimental research in A&A?

Dr Narayanan: Space-based astronomy is already in vogue, and represents a crucial observation technique, but it will not replace ground-based astronomy; rather, it remains a complementary platform. Ground-based facilities, such as the upcoming 30-meter TMT, the proposed National Large Optical-IR Telescope (NLOT), or the giant SKA radio telescope would be helpful to gather enough signals from space, which can be continuously upgraded with state-of-the-art backend instruments over their decades-long lifespans. On the other hand, space-based observatories are essential for probing wavelengths that are absorbed by Earth's atmosphere, primarily the Ultraviolet (UV), X-rays, and far-Infrared. India's AstroSat, Aditya-L1, and future missions capitalise on these unique windows in the electromagnetic spectrum. To solve major astrophysical questions, data from space observatories must be fused with observations from massive ground-based telescopes. Thus, the future relies on a symbiotic relationship between space missions and ground-based observations.

4. DOS institutions also have presence in the field of High Energy Physics (HEP). What are DOS' plans to promote R&D in this area and how does this tie up with the overall space research portfolio of DOS?

Dr Narayanan: DOS is engaged in HEP primarily through its overlaps with astroparticle physics and high-energy astrophysics. DOS focuses on utilising space-based observations to probe fundamental physics under extreme conditions that cannot be replicated (artificially) in terrestrial laboratories. For instance, missions like AstroSat and XPoSat explore astrophysical processes and sources by studying X-ray timing and polarisation around black holes and neutron stars. Future plans include detection of high-energy transients and electromagnetic counterparts to gravitational waves. DOS also supports fundamental HEP

research at its laboratories, such as the work of Physical Research Laboratory (PRL) on neutrino oscillations and shock processing of astromaterials. Furthermore, DOS envisions utilising the upcoming Indian Space Station, i.e. the Bharatiya Antariksha Station (BAS), operating at the Low Earth Orbit, for cosmic radiation experiments, as well as fundamental physics experiments that leverage microgravity. In the long term, DOS's roadmap includes deploying detectors on the Moon for deci-Hz gravitational wave astronomy and probing the cosmic dark ages, directly connecting fundamental HEP questions to India's deep-space exploration roadmap.

5. How will the MSV-2035 Reports in HEP and A&A prepared by the two national communities help DOS in promoting R&D in these disciplines?

Dr Narayanan: The MSV-2035 reports for HEP and A&A provide a comprehensive, community-driven vision that aligns scientific aspirations of two national communities. For DOS, these reports are important to refine the way forward. First, these reports identify and prioritise the critical gap areas, such as the need for UV and broad-band X-ray space missions or space-based gravitational wave detectors, allowing DOS to select missions that ensure global leadership. Second, these reports present the essential infrastructure requirements, strongly recommending the development of national high-performance computing systems and centralised virtual observatories for handling massive mission datasets. Moreover, the reports propose governance frameworks, such as the Mega Science Coordination Unit (MSCU) and Inter-Agency Committees, which will facilitate DOS to streamline the processes of funding, project appraisal, and execution, in coordination with DST and DAE. Finally, these reports emphasise structured human resource development and industry-academia collaborations, providing a pathway to systematically build the specialised workforce and industrial base required to sustain the Space Vision 2047 roadmap.

Perspectives

Department of Science and Technology



Prof. Umesh V. Waghmare,
Secretary, DST

1. The partnership between DST and DAE in funding and managing India-LHC Collaboration (both CMS and ALICE) since the mid-1990's has considerably enlarged the Experimental High Energy Physics (EHEP) community in the country, with large number of groups now participating in this Mega Science Project (MSP) from Higher Educational Institutions (HEIs). Do you think that the two agencies with complementary S&T portfolios displayed great foresight in forging this partnership?

Prof. Waghmare: The number of Indian scientists and researchers participating in the LHC experiments like CMS and ALICE has considerably grown over the last couple of decades. The collaboration between DAE and DST has created a synergy between DAE's expertise in accelerators, particle and nuclear physics infrastructure and instrumentation, and academic pursuits facilitated through DST participation. The complementary nature of our collaboration has enabled the high energy physics community in the country to participate in sectoral product development, gain the necessary skill-set, infrastructure knowledge, and create the testing and validation systems in-house to meet the compliance of intended deliverables for the international consortia. We have also enabled supportive industrial eco-system in this process that had otherwise not existed in the nation. I am sure that the two agencies, DAE and DST, constructively complemented each other, and displayed great foresight in supporting and building national capacity in this domain.

2. As the premier S&T funding agency of the government, cutting across disciplinary and institutional barriers, how do you think DST has helped nurture human resource training and research eco-system in High Energy Physics (HEP), starting with the SERC/SERB Schools in Theoretical (and later also Experimental) HEP?

Prof. Waghmare: DST has an important role in the creation of skilled human resource and nurturing them. The SERC/SERB Schools were an innovative training programme for doctoral-level students in HEP. It provided a platform for the HEP community to promote and spread the domain knowledge and train new generation of high energy physicists in the country. These schools not only created a talent pipeline for high energy physics, but also served as a catalyst and model for starting similar schools in other disciplines. Further, DST has created mobility programs that support theoretical research, visits to international labs, access to accelerators and beamlines, and participation in international accelerator projects in partnership with DAE. These diversified programs of the Departments help ensure the creation of highly accomplished experts and a framework to nurture increasing number of young researchers in HEP.

3. DST has major national presence in optical and solar astronomy, DAE in radio and gamma ray astronomy, and DOS in solar and space astronomy. DAE and DST are now spearheading gravitational wave astronomy too. In today's times of multi-messenger astronomy, do you think that

DST-DAE partnership is not only desirable but necessary?

Prof. Waghmare: Yes, one aspires to capture the first light or first signal from celestial events. In this context, restricting astronomical observations to a particular kind of 'astronomical messenger' is not sufficient to comprehensively understand celestial events in the observable Universe. The partnership of the respective agencies to support research through different channels of astronomical observations is thus extremely significant and necessary. The DST-DAE partnership in astronomy covers almost the whole spectrum of astronomical observations — optical-IR, radio, gamma-rays, and gravitational waves.

4. India has ambitious plans for major MSPs in A&A, for example, LIGO-India, India-SKA, NLST, NLOT, etc. Do you think the complementary domain expertise of DST, DAE and DOS will be helpful in realising these national dreams more efficiently and effectively?

Prof. Waghmare: Yes, the existing Mega Science programs like LIGO-India, India-SKA and the planned national infrastructures like NLST and NLOT are manifestly multi-institutional collaborations between the institutes of DST, DAE, and DOS. The participating institutions possess the necessary expertise to develop the required

technology and realise the projects. For instance, the Indian Institute of Astrophysics has established a state-of-art facility for polishing large mirrors to support the national and international optical-IR telescope projects. NCRA-TIFR, DAE, a global leader in low-frequency radio astronomy is also the lead agency for India-SKA. A single agency or implementing partner may not possess all the necessary know-how's to create such infrastructure. Therefore, the complementary domain expertise of these agencies and their institutions is necessary for realising such mega projects in Astronomy and Astrophysics.

5. How will the MSV-2035 Reports in HEP and A&A prepared by the two national communities help DST in promoting R&D in these disciplines?

Prof. Waghmare: The MSV-2035 Reports published by the Office of PSA provide snapshots of the mega science visions of the national High Energy Physics and Astronomy & Astrophysics communities till 2035. DST programs on Mega Science Projects and mobility of scientific manpower refer to the MSV-2035 documents and align the activities with the communities' vision contained therein. The NLOT, NLST, and the new scheme on National Telescope align well with the MSV roadmap. DST refers to these two documents in various policy matters.



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